Energy Transition, Economic Resilience and Environmental Sustainability: Beyond the Traditional Energy - Growth Nexus

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Abstract: Energy has long been associated with economic growth, industrial expansion and rising living standards. Yet the current transition toward low-carbon systems has made this relationship far less straightforward than earlier literature often assumed. Over the last few years, climate objectives, geopolitical instability and energy-market volatility have exposed how deeply energy systems are intertwined with inflation, industrial competitiveness and broader economic stability. In this context, the traditional energy–growth nexus no longer appears sufficient to explain the complexity of contemporary energy transitions.

This paper develops a structured review of the literature on renewable energy, nuclear power, environmental sustainability and energy resilience. Rather than analysing these dimensions separately, the study brings them together within a broader framework linking energy structure, macroeconomic performance and transition stability. The review shows that decarbonization is not unfolding through a simple replacement of fossil fuels with cleaner technologies. Instead, it is emerging as an uneven and highly country-specific process shaped by infrastructure constraints, policy choices, market design and external shocks. The findings also suggest that renewable energy alone may not guarantee stable transitions unless accompanied by flexible systems, storage capacity and diversified energy mixes. In this perspective, nuclear energy and renewable gases increasingly appear as complementary instruments capable of supporting both environmental objectives and long-term economic resilience.

Keywords: Energy transition; Renewable energy; Nuclear energy; Environmental sustainability; Economic growth; Biomethane; Energy resilience.

JEL Classification: Q40; Q42; Q43; Q48; O13; O44; F64.

Introduction

The relationship between energy and economic growth has traditionally been examined through the role of energy as a productive input sustaining industrial activity, technological development and long-term economic expansion. For decades, much of the literature focused on the extent to which rising energy consumption could stimulate output growth, particularly in industrialized economies heavily dependent on fossil fuels. Within this framework, energy was generally interpreted as a relatively stable factor supporting production systems and economic modernization.

Over time, however, this perspective has become increasingly difficult to maintain in its original form. Climate change, decarbonization policies, technological transformation and geopolitical instability have progressively altered the structure of global energy systems. More recently, the energy crises experienced after 2022 further revealed how deeply energy markets are connected not only to economic growth, but also to inflation dynamics, industrial competitiveness, infrastructure stability and broader macroeconomic resilience. In several countries, sharp increases in gas and electricity prices rapidly transmitted across production chains, exposing structural vulnerabilities that had remained partially hidden during periods of lower market volatility.

As a result, the traditional energy–growth nexus now appears insufficient to fully explain the complexity of contemporary energy transitions. Current debates increasingly extend beyond the simple relationship between energy consumption and GDP, incorporating broader issues such as environmental sustainability, energy security, transition resilience and infrastructure adaptability. At the same time, the growing diffusion of renewable energy, renewed interest in nuclear power and the emergence of renewable gases such as biomethane have contributed to reshaping discussions around long-term transition pathways.

From these considerations, this paper aims to provide a broader interpretation of the contemporary relationship between energy systems, economic performance and environmental sustainability. Rather than offering an isolated empirical contribution, the study develops a structured review of the literature focusing on the interaction between energy transition, macroeconomic resilience and environmental objectives. The central argument is that energy systems can no longer be analysed separately from technological change, infrastructure constraints, policy design and geopolitical uncertainty. These dimensions increasingly interact in shaping the stability and effectiveness of transition pathways.

Particular attention is devoted to the growing relevance of energy resilience, diversification and transition stability, especially following the recent disruptions observed in global energy markets. The review also highlights how nonlinearities and country-specific conditions influence the outcomes of energy policies, helping to explain why similar transition strategies may produce heterogeneous results across economies.

The remainder of the paper is organized as follows. Section 2 reviews the main theoretical and empirical contributions on the energy–growth nexus and its evolution over time. Section 3 presents the methodological approach adopted for the structured literature review. Section 4 discusses the main findings emerging from the literature, with particular attention to renewable energy, nuclear power, environmental sustainability and energy resilience. Finally, Section 5 concludes with broader implications for future energy-transition strategies.

1. Literature Review

This section considers the contributions on the nexus between the energy system, economic growth, and environmental sustainability, with a focus on the recent development of the energy transition literature. As there is so much available, the review does not try to give an in-depth review of all the literature. It is concerned, rather, with the main theoretical orientations, empirical results and structural changes which have gradually reconfigured the traditional energy–growth nexus. Over the years the literature has changed rapidly. Previous research focused primarily on the dependence on fossil fuels and the macroeconomic consequences of oil-price shocks. Recent studies have also increasingly focused on renewable energy, decarbonization strategies, environmental sustainability and the effects of energy-market volatility. Simultaneously, methodological practices have adapted to shifting from standard linear models to more nuanced frameworks that have the capacity to reflect nonlinear, dynamic and country-specific relationships. The review is arranged in thematic areas in order to develop a clearer analytical framework. First, we critique the conventional literature related to energy and economic growth, before addressing the structural changes linked to the energy transition. The next step through the analysis centers on environmental sustainability, renewable energy and the low-carbon transition pathways, namely, nuclear energy and renewable gases such as biomethane. Special focus is made on the increasing significance of energy security, resilience and infrastructure stability in modern transition strategies.

1.1 Energy and Economic Growth: Evidence and Controversies

Researchers have studied the link between energy and economic growth for many years, but it is still a topic of debate. Early studies mainly looked at how oil price shocks affect the economy. Hamilton (1983, 2009) found that higher oil prices often lead to economic downturns, showing a strong negative connection between energy costs and output. Kilian (2008, 2009) later pointed out that not all energy shocks are the same, separating them into supply-driven, demand-driven, and precautionary demand shocks. Baumeister and Kilian (2016) also showed that expectations and future outlooks play a role in how energy shocks affect the economy.

Many studies have looked at how energy use and economic growth are connected, not just focusing on oil. The results are mixed. Some research supports the idea that energy use drives economic growth, while other studies find support for the opposite or for a two-way relationship (Stern, 2000; Narayan and Smyth, 2008; Payne, 2010). Reviews like Ozturk (2010) show that these differences often depend on factors such as how much energy a country uses, its industry makeup, and the quality of its institutions.

More recent studies have included factors such as financial development, globalization, and changes in economic structure when looking at energy and growth. Shahbaz *et al.* (2020) show that financial systems influence both energy demand and economic performance. Acheampong (2018) finds that government policies affect how energy use, growth, and environmental quality are connected. Bhattacharya *et al.* (2016) report that renewable energy can support economic growth, but its effect depends on a country's institutions and technology.

Environmental limits and the shift to cleaner energy have made the relationship between energy and growth more complex. Recent research shows that it is not possible to study this link without considering climate policies and efforts to reduce carbon emissions (Dong *et al.*, 2018; Nathaniel and Bekun, 2020). Moving to cleaner energy often means balancing short-term economic costs with long-term benefits for sustainability.

In the European context, natural gas and electricity markets have become very important. Gas is a key part of industrial production and often the fuel that sets electricity prices, increasing its impact on the economy. Recent studies show that changes in gas prices have lasting and varied effects on inflation and economic activity (Adolfsen *et al.*, 2024). This matches findings from the European Central Bank (2024) and the European Commission (2024), which note that energy prices strongly affect inflation and production costs in the euro area. Supply problems can also cause big drops in output, especially in countries that use a lot of energy, as Bachmann *et al.* (2022) point out.literature has increasingly recognized that the relationship between energy and growth is nonlinear and time-varying. Traditional linear models may therefore provide only a partial representation of the underlying dynamics. To address this limitation, recent studies have adopted more flexible approaches. Wavelet-based methods allow researchers to disentangle relationships across different time horizons. In this context, Magazzino *et al.* (2021) show that in Italy the relationship between energy consumption and economic growth varies significantly between short- and long-run frequencies, suggesting that causal dynamics are scale-dependent.

Recent studies increasingly rely on machine-learning approaches to capture nonlinear interactions between energy systems and macroeconomic performance. These approaches are particularly useful when relationships evolve over time or differ across economic conditions. Magazzino *et al.* (2021) found that renewable energy supported economic growth in Brazil, especially during difficult periods like the COVID-19 crisis. The results suggest that the macroeconomic effects of energy sources may vary across different phases of the business cycle.

Studies that look at specific energy sources highlight how important the energy mix is. Magazzino *et al.* (2021) found that natural gas use is closely tied to economic growth in industrial countries like Germany and Japan, showing that gas is a key part of advanced production. Similarly, Magazzino *et al.* (2020) found that nuclear energy supports economic growth in Switzerland, suggesting that reliable and controllable energy sources are important for long-term economic success.

Energy-price dynamics affect macroeconomic performance through multiple transmission channels. Rising energy prices increase production costs, reduce firms' profitability and weaken households' purchasing power. In economies where natural gas plays a central role in electricity-price formation, these effects are amplified through wholesale electricity markets and transmitted across industrial supply chains. Consequently, energy shocks may influence inflation, industrial production and investment dynamics simultaneously.

Recent studies increasingly recognize that these relationships are nonlinear and time-varying. The macroeconomic impact of energy shocks depends on the composition of the energy mix, the structure of electricity markets, the degree of import dependence and the institutional characteristics of each economy. This complexity has become particularly evident during recent energy crises, which exposed the structural vulnerability of highly interconnected energy and production systems.

1.2 Energy Transition and Structural Change

Environmental limits and decarbonization policies have gradually changed how energy and economic growth are connected. Recently, research has moved beyond just focusing on fossil fuel dependence to consider the broader concept of energy transition. This shift involves big changes in energy systems, influenced by technology, environmental concerns, and regulations.

The energy transition is a structural change that affects how energy is produced and used. Acemoglu *et al.* (2012) show that targeted technical changes are important for how quickly and in what direction the transition happens, and that policy incentives can support cleaner technologies. Aghion *et al.* (2016) add that environmental policies can boost growth by encouraging green innovation, but their success depends on how the policies are designed and on market conditions.

However, real-world evidence shows the transition is not always smooth. Many studies point out that shifting resources between sectors leads to adjustment costs. For example, Popp *et al.* (2010) and Johnstone *et al.* (2010) find that while environmental policies can encourage technological change, they may also cause short-term inefficiencies because of inflexible capital and imbalances between sectors. Dechezleprêtre and Sato (2017) also note that environmental regulations can affect competitiveness, especially in industries that use a lot of energy.

The mix of energy sources has become a key topic in this discussion. While using more renewable energy usually supports long-term sustainability, adding it to existing systems is difficult. Research by Marques *et al.* (2010) and Apergis and Payne (2014) shows that renewable energy can support economic growth, but the extent and consistency of its benefits depend on technology and how flexible the system is.

Recent studies show that different energy sources often operate together during the transition. Rather than just replacing fossil fuels with renewables, both are used at the same time, which can make energy markets unstable. How these sources interact matters. For example, continuing to use fossil fuels for electricity can make prices more volatile, especially when renewable energy is unpredictable (Joskow, 2011; Newbery *et al.*, 2018).

Recent research also finds that energy security and supply limits are important for the transition. More studies now recognize that depending on imported energy can make economies vulnerable to external shocks, which can have major effects. Research on European countries shows that energy supply disruptions can have lasting impacts on output and industry, especially where energy dependence is high (Bachmann *et al.*, 2022).

The process of transitioning is also highly uncertain. Investment decisions now rest on expectations about future energy prices, technological change and regulatory frameworks. In these environments, uncertainty can slow down investment and hinder capital from reallocating toward low-carbon technologies (Bloom, 2009; Pindyck, 2013).

Recent contributions wonder whether prevailing electricity-market models still remain fully compatible with large-scale renewable integration. The marginal pricing method adopted in some electricity markets may, especially, enhance instability in supply-stressed times and may not sufficiently capture long-term overall system costs for a variety of technologies (Joskow, 2022; Newbery *et al.*, 2018).

The literature thus argues with caution that the energy transition needs to be viewed as a complex structural transformation, rather than some straightforward technological substitution process. Its economic consequences are determined by a number of interacting factors, among them energy diversification, infrastructure flexibility, institutional coordination and the capacity of energy systems to absorb external shocks. In this case, transitional and hybrid energy solutions that could have a role in creating system stability during decarbonization may be crucial for stabilizing the systems through an energy transformation process during decarbonization.

1.3 Energy, Environment and the Environmental Kuznets Curve

Researchers have studied how energy use, economic growth, and environmental damage are connected, often using the Environmental Kuznets Curve (EKC) as a framework. The EKC suggests that pollution rises in the early stages of economic growth but falls after income reaches a certain level. While this idea is influential in environmental economics, there is still much debate about whether it holds true in practice.

Grossman and Krueger (1991, 1995) are often credited with starting EKC research, noting that some signs of environmental damage seemed to decrease as income rose. Panayotou (1993) and Shafik and Bandyopadhyay (1992) also found that economic growth could lead to better environmental outcomes through new technology, changes in the economy, and stronger environmental rules.

Later studies have found less clear evidence for the EKC. Stern (2004) argues that the EKC should not be seen as an automatic link between growth and better environmental quality, since lower pollution often comes from changes in industry or moving polluting activities elsewhere, not real improvements. Dinda (2004) also points out that results depend a lot on how studies are set up and which countries are included, making it hard to find a universal pattern between income and emissions.

The literature changed direction when researchers began to include energy use in EKC models. Earlier studies often linked growth and pollution directly, without looking closely at energy systems. Ang (2007), in a study of France, found that energy use is a main cause of CO_2 emissions, and that growth and emissions are linked in complex ways. Soytas and Sari (2009) also found that the connection between energy use, economic output, and emissions varies a lot between countries, depending on their industries and how much they rely on energy.

Recent studies stress the need to separate renewable from non-renewable energy sources. The type of energy used is key to understanding environmental results. Menyah and Wolde-Rufael (2010) found that using more renewable energy does not automatically lower emissions unless the economy also changes in other ways.

On the other hand, Dogan and Turkekul (2016) show that relying on fossil fuels is still a major cause of environmental harm in developed countries, even as they add more renewables.

Researchers now pay more attention to how globalization, urban growth, and financial development affect the link between energy and the environment. Al-Mulali *et al.* (2015) say that open trade and financial ties can increase environmental problems in emerging economies. Charfeddine and Mrabet (2017) find that good institutions and governance also shape how energy use affects emissions. These studies show that we need to look beyond income and consider wider structural and institutional factors to understand environmental damage.

Recent studies increasingly employ nonlinear and asymmetric approaches to examine the relationship between energy use, economic growth and environmental quality. Traditional linear specifications have often been criticized for oversimplifying the dynamic interactions between emissions, technological change and structural transformation. Threshold models and advanced econometric techniques suggest that the environmental impact of energy consumption varies across stages of development, institutional conditions and energy compositions. For example, Balsalobre-Lorente *et al.* (2018) show that the environmental benefits associated with renewable energy become more significant once technological development reaches sufficient levels.

At the same time, several contributions question whether the Environmental Kuznets Curve remains fully adequate for interpreting contemporary decarbonization processes. Current energy transitions involve complex interactions among renewable energy systems, storage capacity, infrastructure adaptation and geopolitical constraints. Consequently, environmental outcomes increasingly depend not only on income growth, but also on technological capabilities, institutional quality and energy-security conditions.

The literature therefore suggests that improvements in environmental sustainability do not emerge automatically from economic growth. Instead, effective decarbonization requires coordinated policies, technological innovation and long-term structural adaptation of energy systems.

1.4. Renewable Energy and Economic Growth

The link between renewable energy and economic growth is now a key topic in energy–growth research. Earlier studies looked mostly at fossil fuel use, oil shocks, and total energy consumption. More recent work focuses on renewable energy as a possible driver of sustainable growth. This shift partly reflects the growing role of climate policies and the recognition that energy composition matters for long-term economic performance.

Some studies show that renewable energy can help economic growth. Apergis and Payne (2010) found a long-term link between renewable energy use and output in OECD countries, suggesting feedback between the two. Bhattacharya *et al.* (2016) also found that renewable energy use supports growth in several major countries, though the size of the effect depends on each country’s institutions and technology. Inglesi-Lotz (2016) found a similar positive link, noting that renewables may boost productivity, investment, and energy security.

Empirical findings, however, remain heterogeneous. Menegaki (2011), focusing on European countries, finds. However, not all studies agree. Menegaki (2011) looked at European countries and found less evidence that renewable energy directly boosts growth, possibly because the sector is not large enough in some places. Marques and Fuinhas (2012) also found that the impact depends on policy, market structure, and how much a country relies on fossil fuels. Consequently, renewable energy does not automatically generate positive growth effects; its effect depends on how it fits into the overall energy system. Tugcu, Ozturk and Aslan (2012) show that renewable and non-renewable energy may have different effects on growth depending on the country group considered. Dogan (2015) and Dogan and Seker (2016) similarly argue that the environmental and economic impact of renewable energy depends on the interaction between energy composition, trade openness and financial development. These contributions are important because they move the literature away from the idea of energy as a homogeneous input.

Another group of studies looks at the environmental side of renewable energy. Here, renewables are seen as a way to balance economic growth with lower emissions. Sadorsky (2009) found that renewable energy use is closely tied to income growth in emerging economies. Al-Mulali, Fereidouni, Lee, and Sab (2013) found that renewables can lower environmental pressure if there is enough development and strong institutions. Destek and Aslan (2017) also showed that renewable and non-renewable energy have different effects on growth, highlighting the need to study them separately.

The picture becomes more complex once renewable electricity systems are considered. Solar and wind power are cheap to run, but they are not always available and need backup, storage, and grid upgrades. Hirth

(2013) found that the market value of these renewables can drop as their share grows, unless the system is flexible enough. Joskow (2011) also says that comparing these sources to traditional ones means looking at both generation and system costs. This aspect is particularly relevant since renewables can only support growth if they are part of a reliable and efficient energy system.

Recent studies use more advanced methods to understand complex relationships. For example, Magazzino, Mele, and Morelli (2021) studied how renewable energy and economic growth were linked in Brazil during the COVID-19 crisis using machine learning. They found that renewable energy may help the economy even during tough times, showing that renewables can support both the environment and economic resilience.

In another study, Magazzino, Mele, and Schneider (2021) looked at solar and wind energy, coal use, GDP, and CO_2 emissions in China, India, and the United States. Using machine learning, they showed that there are complex links between renewable energy, fossil fuels, economic activity, and emissions. These findings suggest that renewable energy operates within broader industrial and infrastructural systems, their effects depend on how they interact with coal use, industry, and each country's energy system.

Mele, Magazzino, and Morelli (2021) also used an LSTM model to study how renewable energy affects economic growth in Brazil. They found that using more renewables may help the economy recover and improve GDP, especially during the pandemic.

In general, the available literature supports both economic growth (through renewable generation) and environmental sustainability (through clean energy), but its impact is heterogeneous and varied by country and energy system. Some of these structural forces determine the economic contribution of renewable energy, namely market design, institutional quality, technological development, and infrastructure flexibility. New evidence also suggests that renewable energy cannot be considered separately from energy-system dynamics more broadly. Increasing demand for intermittent renewable sources of electricity necessitates an investment in storage, and also in the ability to adapt to, and balance systems, that assure system reliability within periods of market stress. Accordingly, renewable energy is increasingly related to the degree of integration of low-carbon technologies, infrastructure resilience and long-term transition strategies in economic performance. These results suggest that decarbonization is not only a substitution, but a more profound transformation (in terms of systems including energy) and changes in industrial adaptation and macroeconomic stability.

1.5 Biomethane, Energy Security and Economic Resilience

Recently, biomethane has gained more attention in discussions about energy transition, decarbonization, and energy security. Unlike other renewables, biomethane stands out because it is both renewable and programmable, and it can be used in current natural gas systems with only minor changes. Because of this, some researchers see biomethane not just as another renewable fuel, but as a transitional energy source that can help keep energy systems stable during decarbonization.

Early research on biomethane looked mostly at its technology and environmental impact. Åhman (2010) points out that biomethane has often been overlooked compared to liquid biofuels, even though it offers clear benefits in efficiency, compatibility with existing infrastructure, and long-term growth. Åhman notes that using current gas networks and compressed natural gas systems lowers the investment needed for new fuels. This is especially important for the transport sector, which is still hard to decarbonize.

Later studies have looked at the wider impacts of biomethane. Börjesson and Berglund (2006) found that biogas and biomethane can greatly cut greenhouse gas emissions compared to fossil fuels, especially when made from farm waste and organic materials. Murphy and Power (2009) also say that biomethane is one of the most efficient biofuels for energy use and cutting emissions, especially in transport.

Recent research often sees biomethane as part of the circular economy and energy resilience. Here, biomethane is more than just an energy source; it is part of a system that includes waste management, sustainable farming, and cutting emissions. The IEA Bioenergy Task 37 report highlights that biomethane can help with decarbonization, lower methane emissions, improve waste treatment, and boost energy security, especially in long-distance and heavy-duty transport.

Transport is a key part of this discussion. Even though renewable electricity is growing fast, transport still relies a lot on fossil fuels, especially for heavy vehicles, ships, and long-distance logistics. Some studies see biomethane as a useful addition to electrification. For example, Patrizio *et al.* (2015) found that using biomethane in Italian transport could be more cost-effective than other uses of biogas, mainly because Italy already has a strong natural gas network and compressed natural gas systems.

Recent technical and economic studies also show that biomethane can help decarbonize heavy-duty transport and improve energy independence. Biomethane's importance has become clearer after recent energy crises in Europe. The 2022 gas shock and later geopolitical issues showed how vulnerable countries are when they rely on imported fossil fuels. Because of this, biomethane is now seen not just as an environmental solution, but also as part of energy security plans. Recent research shows that making renewable gas at home can help protect against outside shocks and make national energy systems stronger. This is especially important in Europe, where natural gas is still vital for electricity and industry.

The literature also points out that biomethane is not a complete replacement for other renewables, but works alongside them. Solar and wind are still key for decarbonization, but their variable output can make it hard to keep the electricity system stable. Biomethane helps with this because it can be stored and used when needed, making it useful during times of low renewable output or high demand. Many researchers believe renewable gases like biomethane can help balance energy systems that rely more on renewables.

Rural development and economic resilience are also important factors. Achinas and Euverink (2020) note that making biomethane can benefit farming communities by turning waste into value, bringing in extra income, and supporting the circular economy. Scarlat *et al.* (2018) reach similar conclusions, pointing out that Europe has a lot of unused biomethane potential that could help diversify energy sources and boost local economies.

Recently, some studies have started to look at biomethane from a broader economic view. Instead of just focusing on cutting emissions, they examine how renewable gases can help keep economies stable during crises. Mele (2026) argues that using biomethane in transport can support both decarbonization and economic growth in Italy by lowering reliance on imported energy and making the national energy system more flexible. The study highlights how renewable gas, transport, and economic stability are linked, especially when energy markets are unstable.

Despite the growing interest in biomethane, important research gaps remain. Most existing studies primarily focus on technological efficiency, emissions reduction or regulatory aspects, while comparatively less attention has been devoted to the broader macroeconomic implications of renewable gases. In particular, limited evidence is available on the relationship between biomethane deployment, industrial competitiveness, energy resilience and economic stability during periods of geopolitical and market uncertainty.

The literature nevertheless suggests that biomethane may play an increasingly relevant role within contemporary transition strategies, especially in energy-importing economies exposed to volatile fossil-fuel markets. Its compatibility with existing gas infrastructure, potential contribution to transport decarbonization and capacity to provide programmable renewable energy distinguish biomethane from other renewable sources. These characteristics may support both decarbonization objectives and long-term energy-system resilience, particularly within the European context.

2. Metodology

This study adopts a structured literature-review approach to examine the relationship between energy transition, economic resilience and environmental sustainability, with particular attention to the role of biomethane and renewable gases within contemporary energy systems. The review combines systematic selection criteria with a broader interpretative framework in order to identify the principal theoretical contributions, empirical findings and policy implications emerging from the literature.

A structured review methodology was considered appropriate because the topic spans multiple research areas, including energy economics, environmental policy, sustainability studies, transport systems and energy security. Existing contributions remain highly fragmented across disciplines and frequently address specific dimensions of the transition process separately. The methodological approach adopted in this study therefore aims to provide a more integrated interpretation of the current literature, highlighting the interactions between decarbonization strategies, infrastructure adaptation, energy security and macroeconomic resilience. The review focuses on how biomethane as a renewable energy can contribute to decarbonisation, sustainable transport, energy security, economic resilience as a renewable energy. It focuses on Europe and Italy, where the role of renewable gases is growing towards an importance in energy policy and with energy-importing countries facing more vulnerable from shocks from the outside. To address these issues an interdisciplinary study of related environmental, economic and geopolitical aspects of how the spread of biomethane. In addition to reduction in emissions, this includes broader topics such as industrial competitiveness, infrastructure integration and the robustness of energy markets to volatility. A number of academic databases were searched, where various studies on biomethane, renewable energy, transportation decarbonization, and energy resilience were found. We combined different terms to identify and track down research that addresses both the environment and macroeconomic influences on biomethane systems. Our literature search included the main databases, keyword combinations and topics that we considered; we show this in Table 1.

Table 1. Literature Search Strategy and Sources

Database	Keywords	Main Focus
Scopus	biomethane, renewable gas	energy transition
WoS	biomethane AND transport	transport decarbonization
ScienceDirect	energy resilience	macroeconomic resilience
Google Scholar	renewable gas Italy	policy & institutional studies

Source: Authors' elaboration based on Scopus, Web of Science, ScienceDirect, and Google Scholar databases.

The literature search strategy in table 1 included work from several academic fields, such as energy economics, sustainability studies, transport systems, and energy policy. This multidisciplinary approach was important because research on biomethane is spread across different areas.

The review focused on studies that look at how biomethane relates to energy security and economic resilience, especially in Europe and during recent energy crises.

Institutional and technical reports were also reviewed to supplement the academic literature, especially for recent updates on European energy policy and biomethane deployment. These included reports from the International Energy Agency (IEA), IEA Bioenergy, the European Biogas Association (EBA), the European Commission, and ARERA.

The search focused on studies published from 2000 to 2026, but earlier key works were included if they were important for understanding the development of energy–growth and energy-transition research.

The search strategy was based on combinations of the following keywords:

- "biomethane";
- "renewable gas";
- "biogas";
- "energy transition";
- "economic growth";
- "energy security";
- "energy resilience";
- "transport sector";
- "decarbonization";
- "renewable energy";
- "circular economy";
- "gas infrastructure";
- "energy crisis".

Boolean operators like AND and OR were used to make the search more precise. For example, combinations such as "biomethane AND economic growth", "renewable gas AND energy security", and "biomethane AND transport decarbonization" were often used during screening.

2.1. Inclusion and Exclusion Criteria

Specific inclusion and exclusion criteria were set to ensure the review was consistent and reliable.

The inclusion criteria comprised:

- peer-reviewed journal articles;
- studies written in English;
- contributions focusing on biomethane, renewable gas or biogas systems;
- studies addressing economic, environmental or energy-security implications;
- papers related to transport decarbonization, renewable energy systems or resilience analysis;
- empirical, theoretical and review studies considered relevant to the research objectives.

Conversely, the following categories were excluded:

- purely technical or engineering studies without economic or policy implications;
- microbiological or chemical analyses unrelated to energy systems;

- conference abstracts without full-text availability;
- duplicated studies across databases;
- studies focused exclusively on local technical optimization without broader systemic relevance.

The screening process was done in stages. First, titles and abstracts were checked for relevance. Then, full texts were reviewed for studies that matched the review's objectives.

2.2. Literature Screening and Thematic Organization

The screening process followed a structured selection procedure which ensured a consistent, relevant, unambiguous process through which we focused analysis. Since the energy–growth field is rich coverage, we focused on relevant studies that capture linkages between economic growth, environmental sustainability, and energy system changes through a single lens. Specialized studies examining the connections between renewable energy, nuclear energy, environmental sustainability, and macroeconomic performance were looked at. Because the literature spans energy economics, environmental economics, sustainability, climate policy, and engineering fields, we set some broad criteria to encapsulate the complexity of the topic and therefore we kept the review focused. We relied mainly on peer-reviewed journal articles available in English and these were available from global databases including Scopus and Web of Science. We searched both empirical and theoretical articles and used those of any publication if they had provided valuable information on at least one of the following areas:

- energy consumption and economic growth;
- renewable energy and macroeconomic performance;
- nuclear energy and low-carbon transition pathways;
- environmental sustainability and decarbonization;
- energy security and energy resilience;
- energy transition and structural transformation;
- emissions reduction and climate policy.

As well as this, we included review articles, as well as important institutional reports if these provide relevant information in light of recent changes in energy-transition policies and sustainability strategies. Reports from agencies including the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), European Commission, and Intergovernmental Panel on Climate Change (IPCC) added to the academic literature, particularly regarding recent energy crises and decarbonization objectives. We excluded some categories of literature in our search to keep our review narrower. Studies involving technical engineering of lab processes, chemical optimization, or highly specialized technologies were excluded unless they also covered broad economic, environmental, or policy related issues. We also left out studies that only targeted local technical applications without wider relevance. Conference abstracts, duplicate studies in different databases, and studies without full text access were excluded. We also took care to exclude studies that repeated the analyses or data. We first conducted a search for potentially relevant studies. We then screened abstracts for alignment with the purpose of the review. Lastly, we examined the full texts to check for the methods used and the contributions each study makes to the broader conversation on energy transition, environmental sustainability, and economic growth.

Table 2. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles	Purely technical engineering studies
Studies published in English	Chemical or laboratory-only analyses
Renewable energy and sustainability studies	Highly specialized microbiological studies
Nuclear energy and low-carbon transition research	Conference abstracts
Energy-growth nexus literature	Duplicate studies
Energy security and resilience analysis	Studies lacking systemic relevance
Environmental sustainability and climate policy studies	Non-accessible full-text publications
Review, empirical and theoretical studies	Studies unrelated to energy systems

The final sample was selected for an intentionally interdisciplinary nature. Rather than an exclusive focus on one energy source or technology, the review analyzes how these energy pathways (renewable energy, nuclear energy, new low-carbon solutions) are linked to economic development, environmental sustainability, and long-term energy-system resilience. The aforementioned exclusion criteria were used throughout the literature screening process. Table 2 summarizes the main inclusion and exclusion criteria applied in this study, as the inclusion and exclusion criteria were important in this review for an overview of the screening strategy used in this study.

The inclusion and exclusion criteria (table 2) helped create a balanced selection of literature that matched the review's goals. This method also made it possible to bring together insights from various research traditions and analytical perspectives, which is especially important for current energy-transition debates.

2.3. Analytical Framework

We then grouped the final sample according to their primary themes and analytic contributions, post-screening and selection of the studies. This allowed us to pinpoint important research trends and better understand how the energy - growth nexus has changed in recent years, moving beyond just fossil-fuel perspectives. This review builds on a framework that acknowledges the energy transition debate is now about more than just the link between total energy use and economic growth. Recent studies show how factors such as renewable energy, nuclear power, environmental sustainability, energy security, and system resilience all interact. To illustrate these changes we organize these studies into four main themes. The first theme is the traditional energy–growth nexus. This theme concerns studies on these dimensions. These works examine the relationship between energy use and economic growth, often deploying things such as time-series analysis, panel data, and causality tests. They comprise the foundation of the debate, from early fossil-fuel studies to more recent analyses of alternative energy sources. The second theme covers renewable energy and environmental sustainability.

Table 3. Classification of Selected Studies

Authors	Main Topic	Methodology	Area of Analysis	Main Findings
Hamilton (1983)	Oil shocks and macroeconomy	Time-series analysis	United States	Oil shocks significantly affect economic activity
Stern (2000)	Energy and economic growth	Cointegration analysis	United States	Strong relationship between energy and GDP
Ozturk (2010)	Energy-growth nexus	Literature review	International	No universal causality pattern exists
Apergis & Payne (2010)	Renewable energy and growth	Panel econometrics	OECD countries	Renewable energy supports long-run growth
Bhattacharya *et al.* (2016)	Renewable energy consumption	Panel analysis	38 countries	Positive relationship between renewables and growth
Tugcu *et al.* (2012)	Renewable vs non-renewable energy	Causality analysis	G7 countries	Different energy sources affect growth differently
Grossman & Krueger (1995)	EKC hypothesis	Econometric analysis	International	Environmental pressure may decline at higher income levels
Stern (2004)	Critique of EKC	Literature review	International	EKC evidence remains inconsistent
Joskow (2011)	Renewable intermittency	Comparative analysis	Electricity systems	System costs matter beyond generation costs
Hirth (2013)	Variable renewable energy	Market-value analysis	Europe	High renewable penetration may reduce market value
Magazzino *et al.* (2021)	Renewable energy and growth	Machine Learning	Brazil	Renewables may strengthen resilience during crises
Magazzino *et al.* (2021)	Solar, wind and emissions	Machine Learning	China, India, USA	Energy interactions are nonlinear and country-specific
Mele *et al.* (2021)	Renewable resources and growth	LSTM model	Brazil	Renewable energy may support recovery dynamics
Dogan & Seker (2016)	Renewable energy and emissions	Panel econometrics	European Union	Renewable energy contributes to emissions reduction
Scarlat *et al.* (2018)	Biomethane potential	Review study	Europe	Biomethane may support decarbonization and diversification
Mele (2026)	Biomethane and resilience	Structured review	Italy	Renewable gases may support energy resilience

Source: Authors' elaboration based on the literature reviewed in this study.

Those research studies examine how renewables support growth, reduce emissions, and allow decarbonization. They also watch carefully how renewable systems, technology changes, and environmental policies are interconnecting. The third theme considers nuclear energy and pathways to low-carbon transition. Public debate, for its part, often divides nuclear power from renewables, but recent studies have found that nuclear power is a stable, low-carbon option that can help keep electricity systems reliable as the country takes a step toward climate neutrality. Trade-offs, such as safety, costs, and waste management, are also discussed. The fourth theme looks at energy security, resilience, and transition stability. This area grew in importance as a result of the major energy crises following 2022. The report shows how high energy-importing countries are vulnerable, the opportunities offered by diverse energy sources, and the need to navigate decarbonization with reliable and affordable energy. This approach describes the connections between various research areas. The link between energy and economic growth is now determined by transition trends, environmental limits, and geopolitical factors. Table 3 presents the key findings and structure of selected studies, and provides a summary by the themes, methods, and main findings.

Several important patterns in the literature were identified in Table 3. First, most conventional research on the energy - growth nexus has centered on fossil fuels and total energy use. Second, new research focuses more on renewable energy, environmental sustainability, and energy transition challenges. Third, it's getting more common for energy systems to be resilient and stable - particularly given recent geopolitical and energy-market crises. The literature suggests that today's energy dialogue is no longer confined as an issue of energy and growth. It now encompasses environmental sustainability, energy security, and the ability to adapt over the long term.

3. Findings

From the literature that we have reviewed in this study, it appears that contemporary debates on energy systems go beyond the conventional link of energy demand to economic growth. The latest works more frequently look at how renewable energy, environmental sustainability, energy security, and transition resilience relate at a macroeconomic level. Literature suggests several similarities. First, renewable energy has come to be seen as a core component in long-term economic transformation and decarbonization strategies. Second, sustainability of energy transitions is not only a matter of emissions reductions, but has to do with infrastructure flexibility, system reliability and the ability to absorb external shocks. Third, energy diversification including renewables, nuclear energy and renewable gases, in order to achieve an environmental dimension, energy security and macroeconomic stability, is being increasingly discussed. While the empirical evidence is heterogeneous, the literature consistently emphasizes transition resilience as the focus and the importance of infrastructural transformation and institutional coordination in low-carbon pathways. For clearer understanding of this, key findings are presented within four major topics: renewable energy and environmental sustainability; nuclear energy and low-carbon transition pathways; energy security and resilience; and the evolution of the energy–growth nexus beyond its traditional fossil-fuel framework.

3.1 Renewable Energy and Environmental Sustainability

This study highlights that in recent years, renewable energy has come to be considered as not just an environmental tool, but also a strategic tool contributing to the long-term economic transformation. The earlier research examined renewable energy's impact on emissions of greenhouse gases in the context of decarbonization goals. Recent contributions take this perspective by investigating the interrelations of renewable energy, technological innovation, energy security and macroeconomic resilience. Many reports that renewable energy expansion leads to less carbon intensity and environmental sustainability, especially in countries that historically have been fossil fuel dependent. However, the evidence indicates that renewable energy's economic impacts are still diversified among countries and in institutional settings. Bhattacharya *et al.* (2016), for instance, demonstrate that renewable energy technology can facilitate economic growth and sustainability, but the magnitude of these effects depends on technological development and institutional quality. Dogan and Seker (2016) reached similar conclusions, in their article highlighting supportive policies and integrated transitions in particular. We also find significant structural limitations of renewable-energy systems within the literature. Solar and wind generation are intermittent, therefore they need storage capacity, grid flexibility, and balancing mechanisms that can maintain electricity-system stability. Joskow (2011) and Hirth (2013) point out that massive integration of renewable electricity may generate new system costs if infrastructure adaptation is inadequate. Newer studies are starting to explore renewable energy more specifically in broader terms concerning energy security and transition resilience. After the energy crises observed after 2022, renewable energy has come to be considered increasingly more than just a climate-policy tool: it is also recognized to be a strategic way to decrease reliance on imported fossil fuels and promote long-term energy security. Various tools of analysis such as machine-learning and nonlinear modeling further argue that renewable energy, economic growth and the environment are dynamically influenced by changes in the structure and conditions of the market. Overall, this evidence suggests that effective renewable-energy transitions are determined by not only the process of deploying renewable energy, but infrastructure adaptation, institutional coordination, and the resilience of systems during a time of economic and geopolitical flux.

3.2 Nuclear Energy and Low-Carbon Transition

Nuclear energy remains a tricky issue in the current energy transition debate, evidence indicates. Unlike sunlight or wind, nuclear has very low operating carbon emissions, high energy density and provides smooth electricity flows. This is why nuclear energy is now a key component of long-term plans for decarbonization and stable energy systems, not just an option. New studies indicate reaching climate neutrality might require more diverse energy mixes than thought to occur during the era dominated by renewables. Prior discussions have tended to emphasize shifting away from fossil fuels in short order to intermittent renewable power. Now, as a number of studies have noted, deep decarbonization and dependable electricity are much more difficult to deliver without reliable low-carbon sources to fill in the gaps of renewables. As the Intergovernmental Panel on Climate Change (IPCC, 2022) list nuclear power as a key low-carbon electricity source for reducing greenhouse-released gases. The International Energy Agency (IEA) also concludes decarbonization on an international scale is more expensive and hard without nuclear power. These studies state that nuclear could minimize emissions, both directly by making low-carbon electricity and indirectly by aiding the stabilization of power systems that consume a high proportion of renewables. An important issue in the literature is system stability. Solar and wind energy is good for the environment, but their output varies through the year depending on the weather and the season. With increasing reliance on renewables comes growing variability, making running electricity systems more difficult. As Hirth (2013) and Joskow (2011) note, balancing reliability, storage, and flexibility is vital in decarbonized markets. That's why nuclear power is now so often perceived as a complement to renewables, rather than a competitor. Nuclear power, they say, can help stabilize the grid by delivering a stable base load of electricity. Davis and Hausman (2016) also point out that durable low-carbon systems require not just more renewables, but technologies to ensure supply is not disrupted in the absence of renewables. Sepulveda *et al.* (2018) also contend that deep decarbonization is significantly more expensive in the absence of a firm low-carbon source such as nuclear power, carbon capture, or long-term storage. The relationship between nuclear energy and energy security has received increasing attention following recent geopolitical instability and energy-market volatility. The energy crises observed after 2022 highlighted the vulnerability of economies highly dependent on imported fossil fuels, particularly natural gas. In this context, several studies interpret nuclear power as a potential instrument for strengthening long-term energy independence and reducing exposure to external supply shocks.

At the same time, the literature emphasizes the significant economic and political challenges associated with nuclear-energy development. Nuclear projects require large initial investments, long construction periods and stable regulatory frameworks. Sovacool (2008) notes that nuclear power remains strongly dependent on public support and long-term financing mechanisms, while Lovering *et al.* (2016) observe that construction costs have increased over time in several advanced economies. Consequently, the economic sustainability of nuclear projects remains a central point of debate.

Environmental and social concerns also continue to influence the discussion. The legacy of major nuclear accidents, including Chernobyl and Fukushima, has significantly affected public perception and energy-policy decisions. In addition, long-term radioactive-waste management remains an unresolved issue within many national energy strategies.

More recent contributions increasingly examine the potential role of next-generation nuclear technologies, including Small Modular Reactors (SMRs), which may offer greater flexibility, improved safety standards and better integration with renewable-electricity systems. Although these technologies remain at an early stage of development, the literature suggests that they could contribute to future low-carbon transition pathways.

Overall, recent studies increasingly interpret nuclear energy within a broader framework linking decarbonization, electricity-system stability, energy security and macroeconomic resilience. Rather than treating nuclear power and renewable energy as mutually exclusive alternatives, contemporary research increasingly emphasizes the importance of diversified and flexible low-carbon energy systems.

3.3 Energy Security and Transition Resilience

Energy security concept has emerged greatly at various phases of development over the past years. Conventional perspectives have relied primarily on the energy resources available and states' ability to guarantee reliable energy resources at low cost. But the energy vulnerability and recent energy crises as well as geopolitical instability have exposed larger macroeconomic implications of being vulnerable to energy supply disruption. The steep increase in natural gas and electricity prices seen following 2022 made it pretty clear that energy insecurity can create significant impact not just on energy, but on all areas. Increasing energy prices were quickly passed along industrial chains to inflationary pressures, production costs and macroeconomic instability. Thus, growing literature is interpreting energy security in the context of price stability, infrastructure resilience and the capacity of economic systems to absorb shocks, rather than considering only the availability of physical supply. For Cherp and Jewell (2014) the point is that current energy systems are subject to different types of risk at once such as geopolitical tensions, market instability, infrastructure vulnerability and technological risk. By the same token, Winzer (2012) believes that the main issue with energy security concerns the ability of an economy to sustain stability in times of disturbances. Recent writings also note that the energy transition itself may introduce new kinds of uncertainty. Renewable energy is thus critical for decarbonization, yet renewable-electricity systems marked by high shares of intermittent generation require flexible grids, storage capacity and balancing systems that can keep the system stable during periods of stress. According to Johansson (2013), long-term sustainability cannot only mean cutting emissions, but also depends in particular on resilience and adaptability for energy infrastructures. In practical terms, resilience means being flexible under stress. Another concern that has repeatedly been raised in recent work is that of diversification. It is obvious that energy dependent economies that rely heavily on imported fossil fuels continue to suffer from geopolitical pressures and fluctuations in international prices. Concurrently, systems that are focused on intermittent renewables but do not have sufficient backup capacity may have stability issues too. For this reason, several recent contributions suggest that transition strategies should be careful not be too technologically concentrated. In this larger debate, nuclear power, storage technologies and renewable gases appear as supplemental instead of competing alternatives. Nuclear power typically correlates with stable low-carbon generators of electricity, whereas the discussion of renewable gases such as biomethane has grown to emphasize their role in providing flexibility for transport and maintaining infrastructure continuity. Scarlat *et al.* (2018) emphasize that bioenergy can support emissions reduction as well as diversification and energy autonomy. A second pervasive theme in the literature is infrastructure compatibility. Transitions involve more than simply swapping one technology for another. They also require costly, complicated and slow-changing infrastructures. One reason that renewable gases get increasing attention is because they can link up with established networks and transport systems. Mele (2026), in his chapter on the Italian example, claims that biomethane might enhance resilience from its adoption because it mixes decarbonisation goals with the potential of utilizing existing systems. Increasingly, the literature also indicates that resilience is not just a technical problem. Institutional capacity is just as important. Energy systems need long-term planning, investment stability and coherent regulatory frameworks. Without such provisions, even high fidelity systems may be subject to volatility and geopolitical stress. Overall, the literature suggests that the debate has progressively moved far beyond the energy-growth dynamic as seen in recent literatures.

Table 4. Main Dimensions of Contemporary Energy Transition

Dimension	Main Challenges	Main Energy Sources Involved	Key Literature Findings	Dimension
Decarbonization	Emissions reduction	Renewables, nuclear	Transition requires low-carbon diversification	Decarbonization
Energy security	Import dependence	Gas, nuclear, renewables	Diversified systems reduce vulnerability	Energy security
System stability	Intermittency	Nuclear, storage, biomethane	Flexibility is essential	System stability
Economic resilience	Price volatility	Diversified energy mix	Stable systems support macroeconomic resilience	Economic resilience
Infrastructure adaptation	Grid and storage constraints	Renewable gases, electricity networks	Existing infrastructures matter	Infrastructure adaptation
Environmental sustainability	Climate objectives	Renewables, nuclear	Decarbonization must remain economically sustainable	Environmental sustainability

Source: Authors' elaboration based on the literature reviewed in this study.

Energy is no longer considered purely an entry point to economic growth. More and more, the main issue is about the ability of energy systems to be relatively stable given a state of uncertainty. More and more, in this regard, resilience, the ability to diversify and adapt to change have become as vital as growth and decarbonization themselves. The earlier sections of that work demonstrate that the energy transition we see today is not a problem to be tackled by only one approach alone. Researchers increasingly take the inter-relationships between decarbonization, energy security, system stability, and economic resilience into account. This means that these studies don't just focus on ordinary "energy use"; they also examine environmental, geopolitical and infrastructure metrics. Table 4 synthesizes the main trends presented in the study. It summarizes the fundamental aspects of the current energy transition, the key challenges facing every component, and the key results from recent research projects.

The evidence in Table 4 shows that today's energy transition covers many connected areas, not just the usual link between energy use and economic growth. Recent studies suggest that sustainability, resilience, and system stability should be seen as working together, not as separate goals, in long-term transition plans.

3.4. Beyond the Traditional Energy - Growth Nexus

One of the principal findings emerging from the reviewed literature is that the traditional energy–growth nexus no longer appears sufficient to explain the complexity of contemporary energy systems. Earlier approaches generally examined energy as a productive input supporting industrial activity, economic expansion and long-term output growth. Within this framework, empirical research mainly focused on identifying causal relationships between energy consumption and GDP under relatively stable economic and technological conditions.

Recent developments have substantially altered this perspective. Contemporary energy transitions take place within a context characterized by geopolitical instability, climate-policy pressures, technological transformation and persistent energy-market volatility. As a result, energy systems increasingly influence not only industrial production, but also inflation dynamics, infrastructure stability, investment behaviour, industrial competitiveness and broader macroeconomic resilience.

The European energy crises observed after 2022 provide a clear example of these dynamics. Sharp increases in natural-gas prices rapidly transmitted to electricity markets and production systems, generating higher industrial costs and persistent inflationary pressures across several economies. These developments exposed structural vulnerabilities associated with highly interconnected energy and industrial systems.

Consequently, recent literature increasingly interprets energy systems as strategic infrastructures embedded within broader economic, institutional and geopolitical frameworks. In this perspective, resilience, diversification and infrastructure flexibility have become central dimensions of contemporary energy-transition strategies. Consequently, energy resilience, diversification and infrastructure flexibility now seem just as important as what used to be considered traditional discussions around energy efficiency or consumption growth. Some of the recent literature has focused equally on how the transition process itself may lead to temporary instability. Previous transition stories had typically portrayed a slow, if relatively seamless, replacement of fossil fuels with cleaner technologies. Recent evidence instead suggests that the periods of transition may be characterized by significant infrastructural bottlenecks, market instability and coordination problems, especially when new and old energy systems occur concurrently for extended periods. That is particularly seen in renewable-electricity systems. Although renewable energy is a major contributor to emissions reductions, much of the impacts based on its macroeconomic implications are contingent on storage, grid flexibility, and balancing functions capable of maintaining electricity-system stability. In many European countries, though, recent energy crises have shown that such rapid renewable expansion on its own will not help protect electricity markets from volatility associated with natural gas, especially in marginal-pricing systems. The evolution in focus has paralleled the literature on nuclear power. Nuclear power has also been studied in recent investigations increasingly from a practical viewpoint of electricity-system reliability, long-term energy security and infrastructure stability. Recently, interest has increased towards other renewable gases like biomethane, whose compatibility with current infrastructure can help transition processes to reduce adaptation costs as well. A further question is related to the heterogeneity of national energy systems. Countries are markedly different in terms of structure of industry, domestic energy resources, reliance on imports and institutions. As a result, recent literature is now tending to dispute general transition concepts and in favor of country specific pathways influenced by their local economic and geopolitical context. Importance of the literature Also the literature shows certain key policy implications. Modern energy transitions call for long-run infrastructure planning, regulatory stability and collaborative investment strategies. Energy policy no longer functions separately from industrial policy, infrastructure investment and geopolitical strategy in this regard. Generally, the evidence considered under review indicates that the transition to low carbon systems should be considered a complex structural change through energy systems, industrial adaptation and macroeconomic resilience, not a straightforward technological replacement.

Conclusion

The studies reviewed here illustrate that the relationship between energy systems, economic growth, and environmental sustainability has become more complex than conventional energy–growth perspectives would suggest. Previous studies focused on energy as a productive input, primarily for industrial activity and long-term economic growth. Modern energy transitions increasingly involve broader interactions between decarbonization, geopolitical instability, infrastructure adaptation and macroeconomic resilience. Recent energy crises, especially during or after 2022, have shown how energy market volatility can rapidly transmit not only across electricity systems but also across industrial production and the dynamics of inflation. These points of risk revealed the structural fragility of highly integrated energy systems, especially in states highly reliant on imported fossil fuels. Consequently, recent studies focus on resilience, diversification and infrastructure flexibility in long-term transition approaches. The review also demonstrated that decarbonization should not be considered a mere technological substitution process. Renewable energy assumes a core role in emission reduction and sustainability goals yet large-scale renewable integration requires storage capability, flexible power systems and coordinated adaptation to infrastructure. Likewise, recent studies systematically explore nuclear energy and renewable gases as complementary sources that can enhance electricity-system stability, energy security and transition resilience. Another essential finding concerns the heterogeneity of transition pathways between countries. There is a wide gap in the industrial structure, institutional capacity, domestic resources and geopolitical exposure of national energy systems. The success of transition policies, therefore, differs based on state-specific conditions and on government capacity to arrange long-term investment, infrastructure planning and regulatory stability. In general, there is an increasing indication that contemporary energy systems ought to be understood as strategically shaped infrastructures with implications for economic growth as well as dynamics of inflation, industrial competitiveness, energy security and macroeconomic stability. From this perspective, the shift to low-carbon systems encapsulates a broader structural change that has to be matched with the simultaneous integration of environmental sustainability, infrastructure resilience and long-term economic stability.

Declarations Conflict of Interest

The authors declare no conflict of interest.

AI Statement

The authors used artificial intelligence tools exclusively for language editing. All scientific content, interpretations, analyses, and conclusions were developed and verified by the authors.

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hémous, D. (2012). The environment and directed technical change. *American Economic Review, 102*(1), 131–166. https://doi.org/10.1257/aer.102.1.131

Acheampong, A. O. (2018). Economic growth, energy consumption, and CO_2 emissions: What causes what and where? *Energy Economics, 74*, 677–692. https://doi.org/10.1016/j.eneco.2018.07.022

Achinas, S., & Euverink, G. J. W. (2020). Rambling facets of manure-based biogas production in Europe: A briefing. *Renewable and Sustainable Energy Reviews, 119*, 109566. https://doi.org/10.1016/j.rser.2019.109566

Adolfsen, J. F., Minesso, M. F., Mork, J. E., & Van Robays, I. (2024). Gas price shocks and euro area inflation. *Journal of International Money and Finance, 149*, 103183. https://doi.org/10.1016/j.jimonfin.2024.103183

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., & Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy, 124*(1), 1–51. https://doi.org/10.1086/684581

Åhman, M. (2010). Biomethane in the transport sector - An appraisal of the forgotten option. *Energy Policy, 38*(1), 208–217. https://doi.org/10.1016/j.enpol.2009.09.007

Al-Mulali, U., Fereidouni, H. G., Lee, J. Y. M., & Sab, C. N. B. C. (2013). Examining the bi-directional long run relationship between renewable energy consumption and GDP growth. *Renewable and Sustainable Energy Reviews, 22*, 209–222. https://doi.org/10.1016/j.rser.2013.02.005

Al-Mulali, U., Ozturk, I., & Lean, H. H. (2015). The influence of economic growth, urbanization, trade openness, financial development, and renewable energy on pollution in Europe. *Natural Hazards, 79*, 621–644. https://doi.org/10.1007/s11069-015-1865-9

Ang, B. W., Choong, W. L., & Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews, 42*, 1077–1093. https://doi.org/10.1016/j.rser.2014.10.064

Ang, J. B. (2007). CO_2 emissions, energy consumption, and output in France. *Energy Policy, 35*(10), 4772–4778. https://doi.org/10.1016/j.enpol.2007.03.032

Apergis, N., & Payne, J. E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy, 38*(1), 656–660. https://doi.org/10.1016/j.enpol.2009.09.002

Apergis, N., & Payne, J. E. (2014). Renewable energy, output, CO_2 emissions, and fossil fuel prices in Central America: Evidence from a nonlinear panel smooth transition vector error correction model. *Energy Economics, 42*, 226–232. https://doi.org/10.1016/j.eneco.2014.01.003

Bachmann, R., Baqaee, D., Bayer, C., Kuhn, M., Löschel, A., Moll, B., Peichl, A., Pittel, K., & Schularick, M. (2022). What if? The economic effects for Germany of a stop of energy imports from Russia. *EconPol Forum, 23*(3), 29–33.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO_2 emissions? *Energy Policy, 113*, 356–367. https://doi.org/10.1016/j.enpol.2017.10.050

Baumeister, C., & Kilian, L. (2016). Forty years of oil price fluctuations: Why the price of oil may still surprise us. *Journal of Economic Perspectives, 30*(1), 139–160. https://doi.org/10.1257/jep.30.1.139

Bhattacharya, M., Paramati, S. R., Ozturk, I., & Bhattacharya, S. (2016). The effect of renewable energy consumption on economic growth: Evidence from top 38 countries. *Applied Energy, 162*, 733–741. https://doi.org/10.1016/j.apenergy.2015.10.104

Bloom, N. (2009). The impact of uncertainty shocks. *Econometrica, 77*(3), 623–685. https://doi.org/10.3982/ECTA6248

Börjesson, P., & Berglund, M. (2006). Environmental systems analysis of biogas systems - Part I: Fuel-cycle emissions. *Biomass and Bioenergy, 30*(5), 469–485. https://doi.org/10.1016/j.biombioe.2005.11.014

Charfeddine, L., & Mrabet, Z. (2017). The impact of economic development and social-political factors on ecological footprint: A panel data analysis for 15 MENA countries. *Renewable and Sustainable Energy Reviews, 76*, 138–154. https://doi.org/10.1016/j.rser.2017.03.031

Cherp, A., & Jewell, J. (2014). The concept of energy security: Beyond the four As. *Energy Policy, 75*, 415–421. https://doi.org/10.1016/j.enpol.2014.09.005

Copeland, B. R., & Taylor, M. S. (2004). Trade, growth, and the environment. *Journal of Economic Literature, 42*(1), 7–71. https://doi.org/10.1257/002205104773558047

Davis, L. W., & Hausman, C. (2016). Market impacts of a nuclear power plant closure. *American Economic Journal: Applied Economics, 8*(2), 92–122. https://doi.org/10.1257/app.20140473

Dechezleprêtre, A., & Sato, M. (2017). The impacts of environmental regulations on competitiveness. *Review of Environmental Economics and Policy, 11*(2), 183–206. https://doi.org/10.1093/reep/rex013

Destek, M. A., & Aslan, A. (2017). Renewable and non-renewable energy consumption and economic growth in emerging economies: Evidence from bootstrap panel causality. *Renewable Energy, 111*, 757–763. https://doi.org/10.1016/j.renene.2017.05.008

Dinda, S. (2004). Environmental Kuznets curve hypothesis: A survey. *Ecological Economics, 49*(4), 431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011

Dogan, E. (2015). The relationship between economic growth and electricity consumption from renewable and non-renewable sources: A study of Turkey. *Renewable and Sustainable Energy Reviews, 52*, 534–546. https://doi.org/10.1016/j.rser.2015.07.130

Dogan, E., & Seker, F. (2016). Determinants of CO_2 emissions in the European Union: The role of renewable and non-renewable energy. *Renewable Energy, 94*, 429–439. https://doi.org/10.1016/j.renene.2016.03.078

Dogan, E., & Turkekul, B. (2016). CO_2 emissions, real output, energy consumption, trade, urbanization and financial development: Testing the EKC hypothesis for the USA. *Environmental Science and Pollution Research, 23*, 1203–1213. https://doi.org/10.1007/s11356-015-5323-8

Dong, K., Hochman, G., Zhang, Y., Sun, R., Li, H., & Liao, H. (2018). CO_2 emissions, economic growth, and the environmental Kuznets curve in China: What roles can nuclear energy and renewable energy play? *Journal of Cleaner Production, 196*, 51–63. https://doi.org/10.1016/j.jclepro.2018.05.271

European Central Bank. (2024). *Economic Bulletin, Issue 6/2024*. European Central Bank.

European Commission. (2024). *Energy prices and costs in Europe*. European Commission.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American Free Trade Agreement. *NBER Working Paper No. 3914*. https://doi.org/10.3386/w3914

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics, 110*(2), 353–377. https://doi.org/10.2307/2118443

Hamilton, J. D. (1983). Oil and the macroeconomy since World War II. *Journal of Political Economy, 91*(2), 228–248. https://doi.org/10.1086/261140

Hamilton, J. D. (2009). Causes and consequences of the oil shock of 2007–08. *Brookings Papers on Economic Activity, 40*(1), 215–283. https://doi.org/10.1353/eca.0.0047

Hirth, L. (2013). The market value of variable renewables. *Energy Economics, 38*, 218–236. https://doi.org/10.1016/j.eneco.2013.02.004

Inglesi-Lotz, R. (2016). The impact of renewable energy consumption to economic growth: A panel data application. *Energy Economics, 53*, 58–63. https://doi.org/10.1016/j.eneco.2015.01.003

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Mitigation of climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157926

International Energy Agency. (2023). *World energy outlook 2023*. IEA.

Johansson, B. (2013). Security aspects of future renewable energy systems. *Energy, 61*, 598–605. https://doi.org/10.1016/j.energy.2013.09.023

Joskow, P. L. (2011). Comparing the costs of intermittent and dispatchable electricity generating technologies. *American Economic Review, 101*(3), 238–241. https://doi.org/10.1257/aer.101.3.238

Joskow, P. L. (2022). From hierarchies to markets and partially back again in electricity. *Journal of Institutional Economics, 18*(2), 313–329. https://doi.org/10.1017/S1744137421000400

Kilian, L. (2008). The economic effects of energy price shocks. *Journal of Economic Literature, 46*(4), 871–909. https://doi.org/10.1257/jel.46.4.871

Kilian, L. (2009). Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market. *American Economic Review, 99*(3), 1053–1069. https://doi.org/10.1257/aer.99.3.1053

Magazzino, C., Mele, M., & Morelli, G. (2021a). The relationship between renewable energy and economic growth in a time of COVID-19: A machine learning experiment on the Brazilian economy. *Sustainability, 13*(3), 1285. https://doi.org/10.3390/su13031285

Magazzino, C., Mele, M., & Morelli, G. (2021b). Nature and climate change effects on economic growth: An LSTM experiment on renewable energy resources. *Environmental Science and Pollution Research, 28*, 41119–41134. https://doi.org/10.1007/s11356-021-13337-3

Magazzino, C., Mele, M., Schneider, N., & Vallet, G. (2020). The relationship between nuclear energy consumption and economic growth: Evidence from Switzerland. *Environmental Research Letters, 15*(9), 0940a5. https://doi.org/10.1088/1748-9326/abadcd

Marques, A. C., & Fuinhas, J. A. (2012). Are public policies towards renewables successful? Evidence from European countries. *Renewable Energy, 44*, 109–118. https://doi.org/10.1016/j.renene.2012.01.007

Marques, A. C., Fuinhas, J. A., & Pires Manso, J. R. (2010). Motivations driving renewable energy in European countries: A panel data approach. *Energy Policy, 38*(11), 6877–6885. https://doi.org/10.1016/j.enpol.2010.07.003

Mele, M. (2026). Biomethane in transport as a driver of economic growth and energy resilience: Evidence from Italy. *Grassroots Journal of Natural Resources, 9*(1), 23–44. https://doi.org/10.33002/nr2581.6853.090102

Mele, M., Gurrieri, A. R., Morelli, G., & Magazzino, C. (2021). Nature and climate change effects on economic growth: An LSTM experiment on renewable energy resources. *Environmental Science and Pollution Research, 28*, 41119–41134. https://doi.org/10.1007/s11356-021-13337-3

Menegaki, A. N. (2011). Growth and renewable energy in Europe: A random effect model with evidence for neutrality hypothesis. *Energy Economics, 33*(2), 257–263. https://doi.org/10.1016/j.eneco.2010.10.004

Menyah, K., & Wolde-Rufael, Y. (2010). CO_2 emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy, 38*(6), 2911–2915. https://doi.org/10.1016/j.enpol.2010.01.024

Murphy, J. D., & Power, N. (2009). Technical and economic analysis of biogas production in Ireland utilising three different crop rotations. *Applied Energy, 86*(1), 25–36. https://doi.org/10.1016/j.apenergy.2008.03.015

Narayan, P. K., & Smyth, R. (2008). Energy consumption and real GDP in G7 countries: New evidence from panel cointegration with structural breaks. *Energy Economics, 30*(5), 2331–2341. https://doi.org/10.1016/j.eneco.2007.10.006

Nathaniel, S. P., & Bekun, F. V. (2020). Environmental management amidst energy use, urbanization, trade openness, and deforestation: The Nigerian experience. *Journal of Public Affairs, 20*(2), e2037. https://doi.org/10.1002/pa.2037

Newbery, D., Pollitt, M. G., Reiner, D. M., & Ritz, R. A. (2018). Market design for a high-renewables European electricity system. *Renewable and Sustainable Energy Reviews, 91*, 695–707. https://doi.org/10.1016/j.rser.2018.04.025

Ozturk, I. (2010). A literature survey on energy-growth nexus. *Energy Policy, 38*(1), 340–349. https://doi.org/10.1016/j.enpol.2009.09.024

Panayotou, T. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. International Labour Organization.

Patrizio, P., Leduc, S., Chinese, D., Dotzauer, E., & Kraxner, F. (2015). Biomethane as transport fuel—A comparison with other biogas utilization pathways in northern Italy. *Applied Energy, 157*, 25–34. https://doi.org/10.1016/j.apenergy.2015.07.074

Payne, J. E. (2010). A survey of the electricity consumption-growth literature. *Applied Energy, 87*(3), 723–731. https://doi.org/10.1016/j.apenergy.2009.06.034

Pindyck, R. S. (2013). Climate change policy: What do the models tell us? *Journal of Economic Literature, 51*(3), 860–872. https://doi.org/10.1257/jel.51.3.860

Popp, D., Newell, R. G., & Jaffe, A. B. (2010). Energy, the environment, and technological change. In *Handbook of the Economics of Innovation* (Vol. 2, pp. 873–937). Elsevier. https://doi.org/10.1016/S0169-7218(10)02005-8

Sadorsky, P. (2009). Renewable energy consumption and income in emerging economies. *Energy Policy, 37*(10), 4021–4028. https://doi.org/10.1016/j.enpol.2009.05.003

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., & Nita, V. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environmental Development, 15*, 3–34. https://doi.org/10.1016/j.envdev.2015.03.006

Schneider, M., & Froggatt, A. (2022). *The World Nuclear Industry Status Report 2022*.

Sepulveda, N. A., Jenkins, J. D., de Sisternes, F. J., & Lester, R. K. (2018). The role of firm low-carbon electricity resources in deep decarbonization of power generation. *Joule, 2*(11), 2403–2420. https://doi.org/10.1016/j.joule.2018.08.006

Shafik, N., & Bandyopadhyay, S. (1992). Economic growth and environmental quality: Time-series and cross-country evidence. World Bank Policy Research Working Paper No. 904.

Shahbaz, M., Zakaria, M., Shahzad, S. J. H., & Mahalik, M. K. (2018). The energy consumption and economic growth nexus in top ten energy-consuming countries: Fresh evidence from using the quantile-on-quantile approach. *Energy Economics, 71*, 282–301. https://doi.org/10.1016/j.eneco.2018.02.023

Sovacool, B. K. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy, 36*(8), 2950–2963. https://doi.org/10.1016/j.enpol.2008.04.017

Soytas, U., & Sari, R. (2009). Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. *Ecological Economics, 68*(6), 1667–1675. https://doi.org/10.1016/j.ecolecon.2007.06.014

Stern, D. I. (2000). A multivariate cointegration analysis of the role of energy in the US macroeconomy. *Energy Economics, 22*(2), 267–283. https://doi.org/10.1016/S0140-9883(99)00028-6

Stern, D. I. (2004). The rise and fall of the Environmental Kuznets Curve. *World Development, 32*(8), 1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Tugcu, C. T., Ozturk, I., & Aslan, A. (2012). Renewable and non-renewable energy consumption and economic growth relationship revisited: Evidence from G7 countries. *Energy Economics, 34*(6), 1942–1950. https://doi.org/10.1016/j.eneco.2012.08.021

Winzer, C. (2012). Conceptualizing energy security. *Energy Policy, 46*, 36–48. https://doi.org/10.1016/j.enpol.2012.02.067

Yergin, D. (2006). Ensuring energy security. *Foreign Affairs, 85*(2), 69–82. https://doi.org/10.2307/20031912