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Reframing the Sustainability: A Conceptual Framework for Integrating Energy, Economic, Environmental, and Social Relationships in a Multilevel Policy Design

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Abstract

This paper introduces an integrated Conceptual Framework designed to examine the relationships between Energy, Economy, Environment, and Society (E-E-E-S) through the lens of ecological sustainability. The framework synthesizes Decoupling Analysis, Environmental Kuznets Curve theory, Decomposition Techniques, and Econometric Tools into a modular system that enables multidimensional analysis of sustainability transitions. It allows for spatial and sectoral flexibility while remaining grounded in ecological indicators and socio-economic dynamics. The proposed model supports the development of informed policy tools and regionally adapted strategies in line with key Sustainable Development Goals (SDGs), particularly SDGs 7, 8, 11, and 13. This approach also establishes a foundation for future empirical investigations and the development of decision-support systems to foster ecological resilience.

Keywords

Energy, Economy, Environment, Society, Decoupling, Decomposition Analysis, Sustainability

1. Introduction & Literature Review

Climate change issues over the past decade have been directly linked to the quality of life in modern societies and have significantly impacted international developments. Greenhouse gas emissions—particularly carbon dioxide (CO_2)—constitute a critical driver of climate change, and their reduction is considered essential for achieving the goals of Sustainable Development (Song & Zhang, 2019). Within this context, the scientific community has shown increasing interest in energy-related processes and the corresponding greenhouse gas emissions. The relationship between energy, economic processes, and development is pivotal to the evolution of the economy, the environment, and ultimately the entire social system.

Given the indispensable role of energy inputs in the production process, economic dependence on primary energy resources can create significant constraints on economic growth. Historically, these limitations were evident during the oil crises of the 1970s. Today, this scarcity is becoming more pronounced and more immediate. With approximately 80% of global energy consumption derived from fossil fuels, this trend signals the depletion of non-renewable resources while simultaneously exacerbating the climate crisis caused by the use of fossil energy. At the same time, the transition toward renewable resources is neither without limitations nor cost-effective. Consequently, the energy-economy relationship has acquired renewed analytical and policy relevance.

In the international literature, it has been widely acknowledged that modeling the relationship between energy use, CO_2 emissions, and economic activity involves a complex synthesis of data and methodological techniques (Greening et al., 2007). A considerable number of studies have systematically examined the correlation between energy consumption or greenhouse gas emissions and economic development, employing diverse tools and approaches (Debone et al., 2021). In recent years, three primary methodological procedures have been very popular (Hatzigeorgiou et al., 2013):

- Decoupling Analysis
- Decomposition Analysis
- Econometric Analysis

Decoupling Analysis focuses on assessing the Energy Intensity of the Economy, examining the evolution of energy input per unit of economic output, typically measured as gross domestic product (GDP). Sanye-Mengual et al. (2019) identify key indicators used in recent Decoupling Analysis applications. The study by Bithas and Kalimeris (2013) proposes an alternative use of the GDP-per-capita ratio, incorporating the population factor as a critical endogenous variable that influences energy intensity. This indicator has been applied globally, and its methodological implications and variations are extensively discussed in Bithas & Kalimeris (2018). As energy intensity trends have been declining internationally, empirical data have contributed to a moderately optimistic outlook. Decoupling Analysis primarily targets long-term periods and aims to identify structural patterns.

The need to investigate the determinants of energy intensity has been addressed through Decomposition Analysis. This method examines the relative influence of historical factors that have shaped the energy intensity of an economy. A key characteristic of Decomposition Analysis is its suitability for analyzing relatively short periods, typically spanning 15 - 20 years. It is broadly categorized into two main approaches (Hatzigeorgiou et al., 2008): Index Decomposition Analysis (IDA) and

Structural Decomposition Analysis (SDA). IDA techniques were first introduced in the late 1970s to study industrial energy use (Ang, 1999). These methods rely on algebraic techniques and are primarily used in energy-related assessments, aiming to quantify the extent to which economic growth and the structure of the energy system contribute to environmental degradation by applying appropriately selected decomposition factors (Ang, 2004).

As a computational methodology, IDA techniques constitute a key tool for energy and environmental policymaking and have been widely adopted by international organizations and national governments (e.g., World Bank, 2015; US EIA, 2022). These techniques represent the dominant share of the literature concerning energy and environmental issues. According to Wang & Yang (2023), during the period 2016-2021, a total of 602 academic publications utilized IDA methods in the context of energy and environmental research. SDA methods, on the other hand, are grounded in input-output analysis and emphasize the impact of technological change on energy consumption levels within the broader framework of macroeconomic theory (Hoekstra & van den Bergh, 2003).

Recent studies have combined Decoupling and Decomposition Analysis to investigate the predetermined influential factors in the evolution of energy consumption or CO_2 emissions over specific periods (Kouyakhi, 2022; Koilakou et al., 2023; Koilakou et al., 2024).

Econometric Analysis mainly investigates the directionality of the causal relationship between energy and development (Kalimeris et al., 2014). Since the seminal study by Kraft and Kraft (1978), which first analyzed the causal links between energy consumption and GDP in the United States, a vast body of literature has employed econometric techniques to explore the dynamic interdependencies among energy, economic, social, and environmental variables. These publications, which explore the interaction between economic growth, energy consumption, and carbon emissions, may be classified into two types: a study of a particular country using time series data and research based on panel data conducted by a group of countries. Although a data panel gains from a statistical power viewpoint, it fails to capture the Country-Specific characteristics in several case studies (Menegaki & Tsani, 2018).

For a concise overview of the econometric methods in energy literature, one may refer to Li and Leung (2021). A recent review demonstrates the growing academic interest in exploring energy–economy interactions through econometric modeling: between 2015 and 2020, a total of 182 articles across 75 international peer-reviewed journals employed such techniques (Debone et al., 2021). However, findings vary significantly by region, country, and period, resulting in a lack of consensus strong enough to directly inform policy formulation. Nonetheless, the accumulated research has yielded valuable insights and contributed significantly to methodological advancements in the field.

In the past few years, the exploration of the energy–economy nexus has been further enriched by the innovative proposal to develop Cobb-Douglas-type production functions that incorporate energy as an independent input factor. These functions seek to explain the so-called "residual" in Solow's growth model—typically attributed to technological change—by recognizing the role of energy inputs in the production process (Cobb & Douglas, 1928; Solow, 1956). Professor Ayres has been a pioneer in this approach, having published several influential contributions (Ayres et al., 2003; Ayres & Warr, 2009; Ayres, 2016).

The brief literature review reveals a lack of an integrated methodological framework that synthesizes existing approaches in energy modeling, incorporating different sets of variables and distinct levels of analysis within the Energy–Environment–Economy–Social nexus. A key motivation for the development of the proposed Conceptual Framework originated from a series of academic discussions with Professor Kostas Bithas and PhD candidate Ms. Eleni Koilakou, researchers in the Institute of Urban Environment and Human Resources[1], whose theoretical insights informed key aspects of the analytical design.

2. Research Methodology

2.1. Conceptual Framework

This Subsection introduces the Conceptual Framework developed to integrate the Energy-Economy-Environment-Society (E-E-E-S) nexus under a unified analytical lens. Drawing upon existing theoretical constructions such as the Environmental Kuznets Curve, decoupling theory, and decomposition approaches, the proposed Framework aims to provide a multidimensional understanding of sustainability transitions. **Figure 1** illustrates the overall structure of the framework and serves as a visual guide for the step-by-step methodological process presented in the following subsection.

2.2. Theoretical Analysis and Tools

This Subsection elaborates on the methodological structure and analytical tools used to implement the E-E-E-S Conceptual Framework. It describes a nine-step procedure combining conceptual modeling with mathematical and statistical techniques.

Initially, the variables used to examine the interrelations between the Energy—Environment—Economy—Society complex will be defined based on a comprehensive literature review. For illustrative purposes, **Table 1** presents a selection of variables per domain, including sample indicators and their respective units.

In the subsequent steps, the level of analysis is determined, and data collection is carried out. The evolution of the time series of the selected variables, the percentage changes between critical periods, and the presentation of their key descriptive statistics support the initial exploration of the system under examination.

In the fourth step, the impact of economic development on environmental degradation is depicted through the use of Kuznets Curves—EKCs (Kuznets, 1955).

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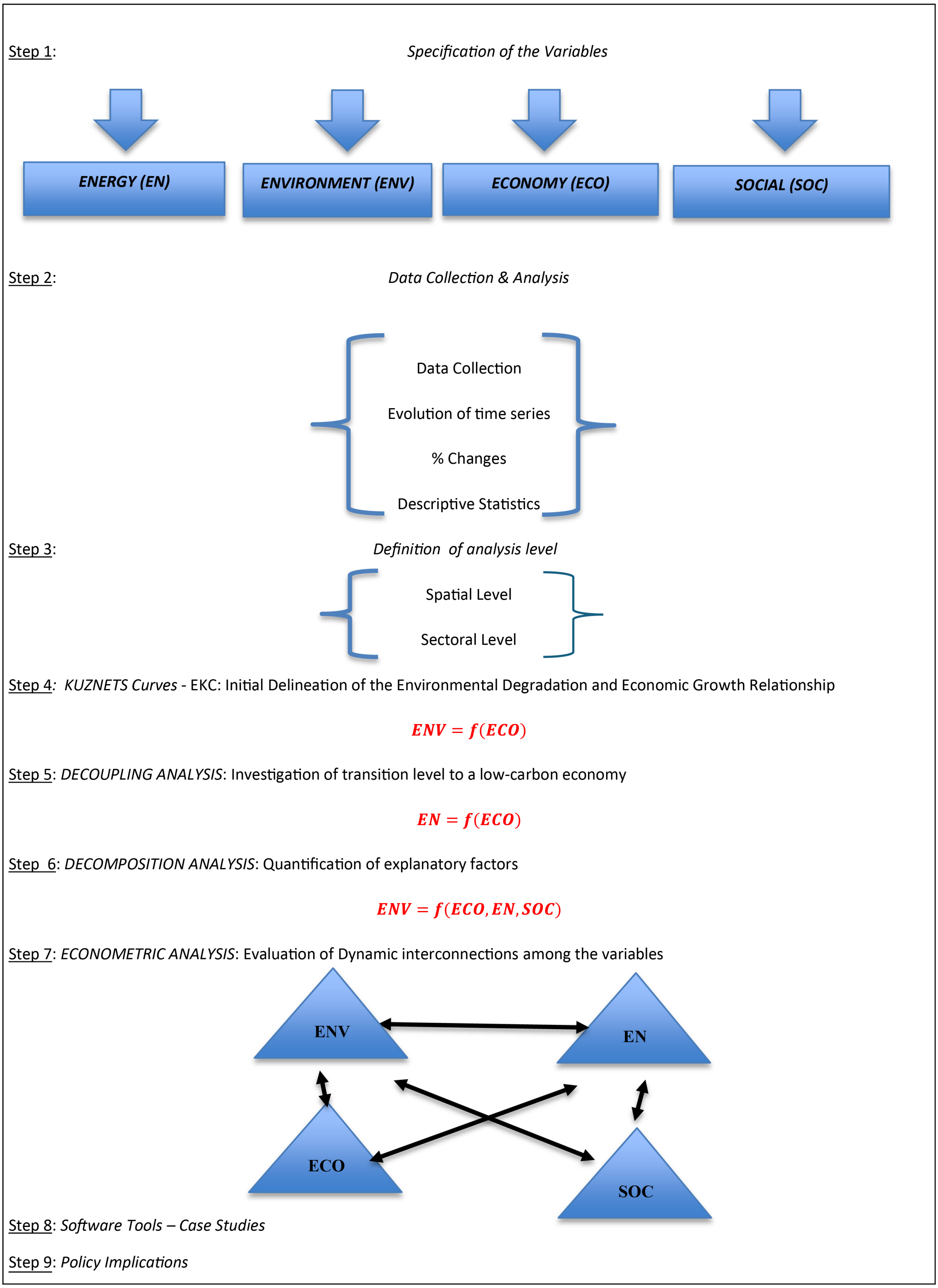
[1] https://www.uehr.gr/en



Step 1: *Specification of the Variables*

Step 2: *Data Collection & Analysis*

- Data Collection
- Evolution of time series
- % Changes
- Descriptive Statistics

Step 3: *Definition of analysis level*

- Spatial Level
- Sectoral Level

Step 4: *KUZNETS Curves* - EKC: Initial Delineation of the Environmental Degradation and Economic Growth Relationship

$$\boldsymbol{ENV = f(ECO)}$$

Step 5: *DECOUPLING ANALYSIS*: Investigation of transition level to a low-carbon economy

$$\boldsymbol{EN = f(ECO)}$$

Step 6: *DECOMPOSITION ANALYSIS*: Quantification of explanatory factors

$$\boldsymbol{ENV = f(ECO, EN, SOC)}$$

Step 7: *ECONOMETRIC ANALYSIS*: Evaluation of Dynamic interconnections among the variables

Step 8: *Software Tools – Case Studies*

Step 9: *Policy Implications*

Figure 1. The proposed Conceptual Framework (E-E-E-S).

Table 1. List of domain variables under investigation.

Variables	Indicators	Units
EN	Final Energy Consumption, Share of Renewables	Toe, percentage
ENV	CO_2 emissions, NO_X/SO_X pollutants	tCO_2, mg/m^3
ECO	Gross Domestic Product – GDP, Total Factor Productivity	Constant USD, Normalized Index, (0 - 1)
SOC	Population size, household structure, and Human Development Index.	Habitants, number of households, Index.

According to the EKC hypothesis, the environmental degradation index follows an inverted U-shaped curve about economic growth, which is typically measured by income. EKCs represent a fundamental link between indicators of environmental degradation and economic development, suggesting that environmental degradation intensifies as economic indicators grow, up to a certain threshold, beyond which further economic development leads to a reduction in the environmental footprint (Seker et al., 2015).

In the fifth step, the relationship between energy consumption and economic activity is assessed using the Energy Intensity Decoupling Index (DI), as proposed in the study by Tapio (2005). This index determines the rate at which energy use per unit of economic activity decreases.

The Decoupling Index (DI) is calculated as follows:

$$DI = \frac{\Delta E}{\Delta GDP} = \frac{\dfrac{E_t - E_{t-1}}{E_{t-1}}}{\dfrac{GDP_t - GDP_{t-1}}{GDP_{t-1}}} \tag{1}$$

where:

ΔE: is the change in energy consumption between the periods $t - 1$ and t.

ΔGDP: is the change in GDP between the periods $t - 1$ and t.

Table 2 depicts typical Decoupling states and the related values of the Decoupling Index (UNEP, 2011).

Table 2. Decoupling states-decoupling index.

Decoupling States	Values of Decoupling Index
Decoupling	DI > 1
Relative Decoupling	0 < DI < 1[2]
Absolute Decoupling	DI < 0

In the sixth step of the proposed Conceptual Framework, we employ IDA techniques to quantify the interrelationships among the selected Energy, Environmen-

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[2] The threshold value DI = 1 represents the tipping point between absolute decoupling and coupling, while DI = 0 marks the transition point between relative and absolute decoupling.

tal, Economic, and Social Indicators of interest. Through the application of these algebraic techniques, the impact of changes in Energy, Economic, and Social Indicators on Environmental Degradation, as represented by CO_2 emissions, will be analyzed at the chosen spatial or sectoral level of analysis (Ang, 2004). The core equation is described by the following formula:

$$\Delta C_{ENV} = \Delta C_{SOC} + \Delta C_{EN} + \Delta C_{ECO} \tag{2}$$

where:

ΔC_{ENV} are the changes of the dependent variable, and ΔC_{SOC}, ΔC_{EN}, ΔC_{ECO} express the decomposition factors.

Following, the platform investigates the dynamic interactions among the proposed variables using econometric techniques. Econometric models provide a rigorous statistical framework that integrates economic theory into energy analysis problems. The starting point for applied econometric techniques is the analytical framework proposed by Granger (1969), who carried out the first systematic attempt to explore causal relationships between economic and energy variables.

Although various time series analysis models (e.g., VAR, ARDL, VECM, GMM) have been employed to examine the interplay among Energy-Economic-Environmental-Social indicators (Engle & Granger, 1987; Yoo, 2005; Shrestha & Bhatta, 2018; Awdeh & Hamadi, 2019), the general approach is presented in **Figure 2**.

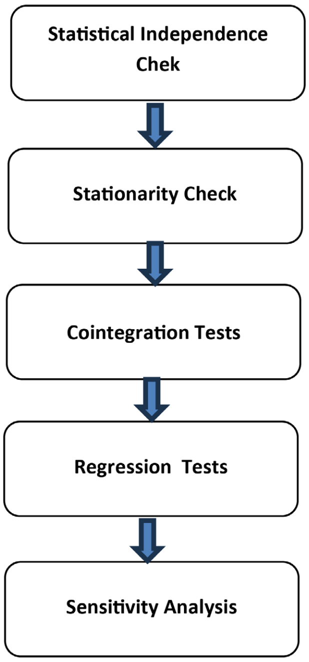

Figure 2. Econometric procedure for the analysis of Environmental—Energy—Economic—Social variables.

The basic equation of the proposed econometric procedure is:

$$\ln(ENV) = a_0 + a_1 \ln(SOC) + a_2 \ln(EN) + a_{3?} \ln(ECO) + e \tag{3}$$

where:

ln(ENV):	The natural logarithm of the Environmental variable
ln(SOC):	The natural logarithm of the Social variable
ln(EN):	The natural logarithm of the Energy variable
ln(ECO):	The natural logarithm of the Economic variable
a_1, a_2, a_3, a_0	The coefficients of the regression
e:	The error correction term

The integration of Environmental Kuznets Curve (EKC) theory, Decoupling Analysis, Decomposition Techniques, and Econometric Methods constitutes a comprehensive and multidimensional Conceptual Framework. Their systematic synthesis enhances the robustness and precision of the assessment regarding dynamic relationships among the examined variables.

To support and digitally operationalize the proposed methodological approach, the development of an integrated web-based application is recommended (Step 8). This tool would enable users to input the required variables and indicators associated with the four core dimensions of the system, E-E-E-S, and automatically execute the corresponding quantitative analyses. The application will be designed to support all stages of the analytical platform depicted in the methodological framework, ranging from data collection and descriptive statistical analysis to more advanced techniques and econometric procedures.

The software may be developed using Python, utilizing Streamlit or Dash to provide an interactive and customizable interface tailored to the needs of researchers, policymakers, or local authorities. Its functionalities may be empirically illustrated through pilot case studies that underscore the system's adaptability, methodological rigor, and potential utility in evidence-based policymaking. Through the integration of data from various spatial and sectoral levels (Municipalities, Regions, economic sectors), the application will offer dynamic charts, calculations, and comparative results, serving as a decision-support tool with a focus on reducing CO_2 emissions and aligning closely with sustainable development goals (Step 9).

3. Conclusion

This work proposes a comprehensive Conceptual Framework to analyze the interdependencies between energy systems, economic activity, environmental degradation, and social structures, referred to as the Energy-Economy-Environment-Society (E-E-E-S) nexus. Notwithstanding its analytical potential, the framework entails certain constraints. Initially, the issue of data compatibility arising from differing spatial and temporal scales can be addressed by converting absolute values into relative indices using a common base year as a reference point or by applying logarithmic transformations to reduce the impact of scale disparities and facilitate the comparison of variables measured in different units. Numerous scholarly works employ similar approaches to enhance the trustworthiness and rigor of their empirical investigations (e.g. Hatzigeorgiou et al., 2011; Bithas et al., 2020; Zhou et al., 2024). Furthermore, each of the methodological approaches incorporated into the framework carries inherent limitations. Characteristically, the EKC hypothesis has been widely criticized for its simplistic and often deterministic interpretation of the relationship between economic growth and environmental degradation, particularly when examining groups of economies rather than being confined to the national level (Borghesi & Vercelli, 2003; Stern, 2004). Decomposition techniques, although they provide a quantitative assessment of the determinants of critical energy or environmental indicators, are limited in revealing the complex interplays between the examined variables (Wang & Yang, 2023). Econometric analysis, on the other hand, presupposes validation of core statistical assumptions and the implementation of advanced diagnostic tests to ensure the validity and robustness of the results (Eibinger et al., 2024).

Even though these limitations, the proposed Conceptual Framework aspire not only facilitates the interpretation of complex relationships in Energy—Environment—Economy—Social system but also informs value-driven decision-making aligned with the Sustainable Development Goals (SDGs), notably SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). By integrating diverse indicators into a coherent system, the framework provides policymakers with a consistent analytical tool for examining the interplay between energy transitions, socio-economic development, and environmental pressures. In doing so, it supports the formulation of cross-sectoral strategies that are ecologically sustainable and socially equitable.

Declarations

Conflict of Interest Statement

The author declares that there are no conflicts of interest related to the content, authorship, or publication of this manuscript.

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Data Availability Statement

No datasets were generated or analyzed during the current study. The study is conceptual and does not include empirical data.

Ethical Approval

This article does not contain any studies involving human participants or animals performed by the author.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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