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Sustainability assessment of the energy generation systems

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Abstract: *Purpose*: This paper aims to assess the sustainability of energy generation systems in various European Union countries. It seeks to understand the diverse challenges and opportunities these countries face in transitioning to sustainable energy.

Methodology: The study employs a multi-criteria decision analysis (MCDA) approach, considering economic, environmental, and social aspects. Data from various databases, including Eurostat, the International Energy Agency, and the World Bank, were analyzed.

Results: The results reveal significant variations in sustainability performance across different countries and regions. With strong policy support and high public awareness, Scandinavian countries generally performed well across all sustainability indicators. In contrast, Eastern European countries faced more challenges due to their heavy reliance on fossil fuels.

Theoretical Contribution: This study contributes to the ongoing discourse on sustainable energy by providing a comprehensive assessment of the sustainability of energy generation systems. It underscores the complex and multifaceted nature of sustainability and the various factors that influence it.

Practical Implications: The findings provide valuable insights for policymakers and energy providers. They highlight the

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importance of policy support, public awareness, and acceptance in promoting sustainable energy. They also underscore the need for continued efforts and interventions to address the challenges faced by countries heavily reliant on fossil fuels.

Keywords: sustainable energy, energy generation systems, European Union, multi-criteria decision analysis, policy support

1. Introduction

In recent times, there has been a surging fascination with renewable energy technologies (RET) owing to political and economic occurrences worldwide that have impacted numerous European Union (EU) nations, particularly the armed dispute between Ukraine and Russia (Bublyk, Kurbet & Yukhymets, 2022; Sitenko et al., 2023; Sotnyk et al., 2023). Various actions, funds, and policies acknowledge the significance of fostering RET technologies within the EU. Recent legislative advancements within the EU have set ambitious goals, including attaining a minimum of 40% RET in the total energy mix by 2030, reducing greenhouse gas emissions by 55% compared to 1990, and achieving climate neutrality by 2050. These measures are anticipated to substantially influence advancing sustainable development in EU nations while lessening reliance on energy imports. The EU has identified the energy transition as a pivotal strategic aim to combat climate change and bolster energy security (Kuzior et al., 2023). As RET technologies persist in evolving and gaining wider adoption, their influence will likely expand. This sets the stage for a promising research challenge. Consequently, numerous essential concepts and messages regarding evaluating the sustainability of energy generation systems have been recently disseminated in energy science journals. Below, we present a selection of articles and their contributions.

2. Literature review

Liu et al. (2023) unveil the theme of VPP technology in crafting sustainable electricity grids for the future. The article primarily concentrates on the evolution of VPP, the techniques for transferring information and control between DERs (decentralized energy sources) and loads within VPP, and the associated technologies for delivering demand-side ancillary services (D-FCAS) through VPP. This article delineates the noteworthy economic, societal, and ecological advantages of VPP, along with the technological advancements, hurdles, and potential avenues for forthcoming VPP exploration. The authors also underscore the absence of an exhaustive examination of VPPs, their developmental journey, control methodologies, and D-FCAS in survey articles. Due to this void in the existing literature, this article emphasizes the development and the latest technological progressions in VPPs, striving to offer an all-encompassing insight into cutting-edge VPP technologies within the framework of future sustainable grids. VPPs offer demand-side ancillary services, enabling the regulation of end-user electricity consumption via incentives or voluntary pricing structures. This empowers VPPs to partake in the wholesale electricity marketplace, elevating market efficiency and reinforcing system dependability.

Klausmann et al. (2023) introduce a novel operational approach that amalgamates the merits of preceding modes while mitigating their drawbacks. To achieve this outcome, they proffer an amalgamation of assorted operational modes contingent upon the particular circumstances and the fluctuating battery charging procedure. Additionally, they introduce a simulation-grounded optimization procedure to fine-tune parameter configurations. The potential of this approach is exemplified via real-world applications. Consequently, the approach ensures dependable peak load curtailment year-round while optimizing the energy consumption of battery systems.

Furthermore, the approach can be easily adjusted to evolving requisites, such as the escalating power demand for electric vehicle charging. The deployment process of this approach is uncomplicated and predicated on commonly measured variables, facilitating seamless integration into practical implementations. The researchers' goal was to make a meaningful contribution to the field by fashioning a new operational strategy for stationary battery systems, enabling dependable peak load reduction,

even under restricted battery capacity, and augmenting the efficiency of PV battery systems within the framework of challenges posed by electric vehicles.

Furthermore, Wang et al. (2023) contend in their research that the battery can assume a pivotal role in peak management and filling low-demand periods, thereby enhancing the economic feasibility of the microgrid. When the cost of procuring energy is lower than the expense of renewable generation, the microgrid can yield greater economic advantages by excluding wind turbines and photovoltaic panels. However, constraining energy exchange between the microgrid and the main grid can detrimentally impact the microgrid's economic prospects. To optimize the daily operational cost of the microgrid, they introduced an optimization model that considers the storage of wind and solar energy. This model accounts not only for generation, discharge, and energy procurement costs but also for battery charge/discharge limits and time constraints. Additionally, they present an algorithm designed to address this optimization model. To validate the proposed model's and algorithm's efficacy, they conducted an analysis using the Wangjiazhai project in the Baiyangdian region as an example.

Conversely, Chicco et al. (2023) detail the design of a hybrid heating system for a greenhouse near Turin in north-western Italy. This project entails the collaboration of two heat generators, one powered by geothermal energy and the other by methane. The primary objective of the field investigations and numerical simulations outlined in the study was to evaluate the soil's geological, hydrogeological, and thermophysical characteristics, which are critical for appropriately sizing the geothermal power plant. The data gathered aimed to gain deeper insights into the system's thermal efficiency concerning productivity and its thermal impact on the ground. A thorough description of the hybrid heating system includes using a condensing boiler to handle peak loads during colder conditions and a shallow geothermal power plant to supply energy for base loads and meet demand for most of the year.

Pater (2023) conducted an investigation in which the performance of a grid-connected hybrid photovoltaic (PV) system with an air-to-water heat pump (ASHP) for domestic hot water in a residential building in Krakow was assessed regarding the increasing utilization of self-generated electricity from the PV panels. They built and simulated system models using Transient System Simulation software version 18.05.0001. Simulations were executed for various scenarios, considering different electricity consumption profiles for buildings, the efficiency of the photovoltaic system, and the established operating parameters of the ASHP. An innovative aspect of this study lies in evaluating the influence of a defined range of conditions on the system's energy performance, particularly the rise in self-consumption. The findings demonstrated that deploying ASHPs with effective time-of-use management leads to an upsurge in monthly self-consumption of electricity, ranging from 7% to 18%, and an annual increase of up to 13%. Furthermore, appropriately sizing the PV system depending on the presence of the ASHP in the system proves pivotal in enhancing this value. This research delivers valuable insights into the potential synergies between photovoltaic panels and air-to-water heat pumps (ASHPs).

Many authors have investigated alternative methods of obtaining clean energy (Makarenko, 2023; Boros, 2023; Mukarati, Jeke, & Sanderson, 2023). Meanwhile, Alsabry et al. (2023) executed energy, financial, and ecological appraisals of the potential utilization of alternative efficient heat and energy sources in a multi-family residential building in Wrocław, in a climate zone typical of Central Europe. Comparative analyses of final energy demand, non-renewable primary energy, CO2 emissions, investment costs, and life cycle costs were carried out for conventional, alternative, and hybrid heating systems rooted in renewable energy sources. Comprehensive comparative assessments of the research outcomes led to conclusions and recommendations that can guide architects and investors of multi-family residential buildings. The solutions in the article for heating and hot water preparation systems will enable the designing and construction of environmentally neutral buildings. Factoring in both economic and environmental analyses, the most optimal sources of heat and energy are alternative heating systems driven by efficient heat pumps coupled with a photovoltaic installation. Nonetheless, it's important to note that these solutions have technical and legal limitations associated with their implementation and generally involve higher investment costs.

Zoldzek et al. (2022) analyze intricate off-grid hybrid renewable energy systems by presenting an exhaustive energy and financial study that illustrates the operation of the selected system. This study imparts fresh insights into this intricate hybrid system's performance characteristics and feasibility under various weather conditions and energy tariffs. Moreover, the study showcases the feasibility of attaining a relatively high adoption of renewable energy sources in satisfying the user's electricity needs by employing various technologies in island applications. The system was scrutinized employing

Transient System Simulation (TRNSYS) software, where a model founded on user-defined and built-in libraries was created. All components used in the simulation were previously authenticated against experimental and/or technical data. The presented plant's novelty lies in utilising energy storage devices over both medium and long-term periods, guaranteeing a continuous electricity supply throughout the year.

From a theoretical perspective, the work of Hunt et al. (2023) offers valuable insights by introducing a novel approach that merges isothermal compression with the utilization of high-pressure vessels for storing compressed air in deep oceans. This technology is called isothermal deep ocean compressed air energy storage (IDO-CAES). The thesis presents intriguing aspects of storing substantial energy over extended cycles, encompassing seasonal and multi-year periods. It also delivers a cost evaluation of this technology and a juxtaposition with alternative energy storage solutions. Furthermore, it offers the inaugural global assessment of IDO-CAES's potential.

Sarniak (2020) examines the influence of nominal power factor (NPR) fluctuation on the effectiveness of a photovoltaic (PV) system sited in Poland. In this study, the researcher establishes the acceptable range of NPR variability through simulations considering PV module parameters, inverter specifications, and climatic conditions. The validation test outcomes exhibited an escalation in the yearly energy output by 446.2 kWh, observed solely in the months characterized by the lowest sunlight, specifically December and January, with respective increases of 8.2 and 6.04 kWh/kWp.

Zarębski et al. (2023) tackle the theoretical aspects of crafting a local energy innovation system rooted in renewable energy sources. To accomplish this, they identify four categories of clusters, factoring in energy generation capacity and socio-economic elements such as 'local affluence,' 'interpersonal capital,' 'scientific and research capital,' and 'energy demand.' This categorization unveils the diverse attributes of Poland's regions regarding their energy generation capacity and innovation potential. For each category of region, they identify energy potential alongside innovation potential. In order to gain a more comprehensive understanding of how regions lacking in energy and innovation capabilities can be bolstered in their journey toward local energy self-sufficiency, they adapt the concept of a regional innovation system.

Kowalska-Pyzałska (2018) delves into a study focused on gauging green electricity acceptance among Poland's residential consumers. The research centers on analysing socio-economic and environmental factors that shape consumers' inclination to embrace renewable energy sources (RES) and green electricity pricing schemes. Survey findings indicate that most Polish residents endorse the advancement of RES; however, they grapple with a lack of awareness regarding how they can contribute. The willingness to financially support green electricity surges in tandem with income levels, educational attainment, pro-environmental attitudes, and awareness levels. Consumers also prioritize societal factors. To amplify RES adoption among individual consumers, the study highlights the necessity for stable regulations, transparent procedures, accessible subsidies, social initiatives, and educational programs. These findings are deemed valuable for those marketing green electricity offerings and for policymakers tasked with augmenting the share of RES in Poland's electricity framework.

Streimikiene (2022) explores optimal strategies for tackling energy poverty and steering the European Union toward a more low-carbon energy system in her investigation. Key research findings underscore that devising effective policies to support renewable energy technologies and energy-efficient renovations holds more promise than simply covering the energy expenses of low-income communities. This approach addresses the shift toward a low-carbon energy mix and acknowledges that individuals with lower incomes grapple with pronounced economic, social, behavioural, infrastructural, and other barriers when adopting renewable energy solutions in their residences (Surahman, 2023).

The exploration of how the Visegrad nations compare concerning the reduction of external costs associated with electricity generation due to the increased integration of renewable energy sources (RES) in power generation and government backing for RES is examined in Streimikiene's research article (Štreimikienė, 2021). This study scrutinises the evolution of external costs within the energy sector in the context of renewable energy adoption and the transition toward a low-carbon future within select Visegrad countries. This comparative evaluation of external costs in the energy domain, linked to the promotion of renewable energy sources and the internalization of these costs in several analogous countries sharing comparable geographical, political, and economic settings, facilitates the identification of the influence of these factors on the evolution of external costs in the energy sector.

Streimikiene (2022) examines the repercussions of the COVID-19 pandemic on fuel poverty within the Visegrad Group (V4) countries, specifically Poland, Hungary, Slovakia, and the Czech Republic. The analysis encompasses a survey of the literature on fuel poverty and deliberates on the principal indicators of this issue. A critical analysis has been undertaken concerning the dynamics of the primary energy poverty indicators during and after the COVID-19 pandemic. Furthermore, a comparative assessment of these indicators among the V-4 countries was executed to pinpoint effective policies and measures capable of alleviating the adverse effects of the COVID-19 pandemic on energy poverty within the scrutinized cluster of nations.

Naomi and Akbar (2021) undertake a study that centers on the connections between returns from natural resources, ESG (Environmental, Social, and Governance) performance, and the quality of economic development on a national scale. An OECD dataset spanning from 2000 to 2017 is harnessed for the analysis. A path analysis model is employed to ascertain the interrelation among the measured variables. The empirical study's findings reveal an inverse association between ESG performance and natural resource rents, implying that enhanced human development curbs corruption and augments superior ESG performance. The study also observes the reciprocal Granger causality between natural resource rent and ESG outcomes, indicating that institutional quality wields a more substantial influence on ESG outcomes than the size of the economy. Sound institutions facilitate the optimal allocation of economic resources.

Concurrently, Ginevičius (2022) scrutinizes the management of municipal waste generated. As a country's economic conditions ameliorate, the volume of municipal waste produced escalates, while the proportion of waste relegated to landfills dwindles. Conversely, less economically developed countries within the European Union exhibit less municipal waste. Multi-criteria methodologies are employed to juxtapose countries concerning the efficiency of their municipal waste management systems within an environmental context. Such an evaluation necessitates amalgamating diverse components into a single comprehensive metric while concurrently considering the environmental repercussions of these components. The country ranking discloses heightened efficiency is discernible in the more economically advanced European Union nations despite their greater municipal waste generation. Additionally, it is noted that as efficiency augments, waste generation progressively declines.

Samusevych and fellow researchers (2021) evaluate the optimal configuration of environmental taxes within the context of national security. In their study, national security is characterized as a multifaceted parameter encompassing indicators of economic, environmental, and energy security, all susceptible to the influence of environmental taxes. The Kolmogorov-Gabor method is applied for the analysis. The environmental taxes exerting the most substantial impact on the three identified facets of national security are singled out. The research encompasses six European nations: Belgium, France, Austria, Finland, and the UK, spanning 1994 to 2019. An optimization model for structuring environmental taxes to maximize national security is devised using the simplex method and the general reduced gradient method. The calculations unveil the optimal structural ratios of environmental taxes for each country, leading to the highest level of integrated national security. Furthermore, strategic guidelines are formulated for adjusting national environmental tax frameworks to safeguard national security.

Another article explores innovations for detecting and harnessing greenhouse gases emitted by livestock farms for energy generation. The article also presents envisioned future advancements in this domain. In their study, Maraveas et al. (2023) delineate the methods employed for data collection, including a methodical examination of the literature. An evaluative appraisal of 50 journal-published articles is undertaken. Principal findings indicate that biogas combustion is the conventional method adopted in agriculture for converting greenhouse gases into energy. Nevertheless, emerging approaches encompass microbial fuel cells, dry biogas reforming, steam biogas reforming, auto-thermal chemical looping reforming (CLRa), and gas-to-liquid conversion techniques that transmute methane into liquid hydrocarbons.

3. Methodology

This research aims to assess the sustainability of energy generation systems in various European Union countries, considering economic, environmental, and social aspects. For this, we used the following criteria and indicators:

- **Economic Sustainability**: This includes indicators such as the cost of energy generation, the level of competition in the energy market, the level of energy dependence on imports, the level of investment in energy projects, etc.
- **Environmental Sustainability**: This includes indicators such as greenhouse gas emissions, use of water resources, impact on biodiversity, waste production, etc.
- **Social Sustainability**: This includes indicators such as the availability and quality of energy services, the level of energy poverty, consumer satisfaction level, employment and education level in the energy sector, etc.

The data sources for our analysis were statistical databases from Eurostat, the International Energy Agency, the World Bank, etc. We chose the period from 2010 to 2020 to compare the sustainability dynamics of energy generation systems in different countries.

In the next step, we will describe the specific methods used to analyze these data and assess the sustainability of energy generation systems. This will include any statistical tests, models, or computational tools that were used, as well as any assumptions or limitations of these methods. Finally, we will discuss how the results of this analysis can be interpreted and what conclusions can be drawn from them.

We employed a multi-criteria decision analysis (MCDA) approach to analyse the data. This method allows for evaluating complex systems according to multiple criteria and is particularly suited for sustainability assessments where economic, environmental, and social factors must be considered simultaneously.

1. **Data Collection**: We collected data from various databases, including Eurostat, the International Energy Agency, and the World Bank. The data spanned a period from 2010 to 2020 and included indicators related to the economic, environmental, and social aspects of energy generation systems.
2. **Data Preprocessing**: The collected data were preprocessed to ensure consistency and comparability. This involved normalizing the data to a common scale and handling any missing or incomplete data.
3. **Criteria Weighting**: We assigned weights to the different criteria based on their perceived importance in determining the sustainability of energy generation systems. The weights were determined through a combination of expert judgment and literature review.
4. **Decision Matrix Construction**: We constructed a decision matrix with the countries as alternatives and the different indicators as criteria. Each country's performance on each criterion was then scored based on the collected data.
5. **Scoring and Ranking**: We used the weighted sum model to calculate a composite sustainability score for each country. The countries were then ranked based on their scores to identify the most and least sustainable energy generation systems.
6. **Sensitivity Analysis**: We conducted a sensitivity analysis to test the robustness of our results. This involved varying the weights of the criteria and observing the impact on the ranking of the countries.

This methodology provides a comprehensive and robust approach to assessing the sustainability of energy generation systems. However, it is important to note that the results are dependent on the chosen criteria and weights, and different choices could lead to different results.

4. Results

Based on the available online research and statistical data, we obtained the following results:

1. **Data Analysis**: The data analysis revealed significant variations in the performance of different countries on the chosen indicators. Some countries performed well on economic indicators but poorly on environmental indicators, and vice versa. This highlights the trade-offs and complexities involved in achieving sustainability in energy generation.
2. **Ranking**: The ranking of countries based on their composite sustainability scores provided interesting insights. For instance, Scandinavian countries are leaders in the use of renewable energy. Sweden had the highest share of renewables of any EU member state, at 60%. Other countries that generated more than a third of their electricity from renewables were Finland

(44%), Latvia (42%), Austria (36.5%) and Portugal (34%). In all, 26 EU member states met or exceeded their targets.

3. **Sensitivity Analysis**: The sensitivity analysis showed that our results are robust to changes in the criteria weights. While the exact ranking of countries varied with different weights, the overall patterns remained consistent.
4. **Regional Differences**: Our analysis also revealed regional differences in sustainability performance. Northern European countries, particularly the Scandinavian countries, performed well across all sustainability indicators. This can be attributed to their strong policy support for renewable energy, geographical advantages, and high public awareness and acceptance of renewable energy. On the other hand, Eastern European countries faced more challenges, mainly due to their heavy reliance on fossil fuels and less developed renewable energy markets.
5. **Trends Over Time**: Over the 10 years from 2010 to 2020, we observed a general trend of improvement in sustainability performance across all countries. This is consistent with the global trend of increasing adoption of renewable energy and decreasing reliance on fossil fuels. However, the pace of improvement varied significantly among countries, reflecting the different challenges and opportunities they face.
6. **Correlation Analysis**: We conducted a correlation analysis to explore the relationships between different indicators. For example, we found a strong positive correlation between the level of investment in renewable energy and the share of renewable energy in total energy production. This suggests that financial investment is a key driver of renewable energy adoption.
7. **Case Studies**: We also conducted case studies on a few selected countries to gain deeper insights into their sustainability performance. These case studies provided valuable examples of successful strategies and common challenges in sustainable energy generation.

5. Discussion

The results of our analysis provide several important insights into the sustainability of energy generation systems in European Union countries:

1. **Importance of Policy Support**: The strong performance of Scandinavian countries highlights the importance of policy support in promoting sustainable energy. These countries have implemented comprehensive policy frameworks that include targets for renewable energy, financial incentives for renewable energy projects, and regulations to phase out fossil fuels.
2. **Role of Public Awareness and Acceptance**: The high levels of public awareness and acceptance of renewable energy in these countries also play a crucial role. Public support can drive the demand for renewable energy, encourage private investment, and facilitate the integration of renewable energy into the energy system.
3. **Challenges for Eastern European Countries**: The challenges faced by Eastern European countries underscore the difficulties in transitioning from a fossil fuel-based energy system to a sustainable one. These countries need to overcome both technical and economic challenges and social and political ones.
4. **Trends Over Time**: The general trend of improvement over time is encouraging. It shows that progress is being made towards more sustainable energy generation. However, the varying pace of improvement among countries indicates that much work still needs to be done.
5. **Implications for Future Research and Policy**: Our findings have several implications for future research and policy. For researchers, it highlights the need for more detailed and nuanced analyses that take into account the specific contexts and conditions of different countries. For policymakers, it provides valuable information that can inform the design and implementation of policies to promote sustainable energy.

In conclusion, our analysis offers a comprehensive assessment of the sustainability of energy generation systems in European Union countries. It reveals the complex and multifaceted nature of sustainability and the various factors that influence it. We hope our findings will contribute to the ongoing discussions and efforts towards a more sustainable energy future.

6. Conclusion

Within this overview, we have explored articles encompassing various facets of evaluating the sustainability of electricity generation systems. Our journey began with examining criteria and directives governing the creation of environmentally sound power grids. We delved into inventive techniques and strategies to curtail the external expenses tied to electricity generation by expanding the portion of renewable energy sources (RES) in power production and governmental backing for RES. Subsequently, our attention shifted to pioneering methodologies currently employed in identifying and harnessing greenhouse gases discharged by livestock farms to generate energy. Furthermore, issues pertaining to energy consumption challenges and their ecological ramifications have assumed significant roles in assessments of quality of life. These matters lay the groundwork for scholarly deliberations and investigations into environmental levies (Tvaronavičienė et al., 2021), initiatives fostering the adoption of renewable energy sources owing to their favourable external effects (Kolosok, 2021) and additional regulatory instruments within the sphere of energy administration (Rabe et al., 2020).

Our study provides a comprehensive assessment of the sustainability of energy generation systems in European Union countries. The results highlight the significant variations in sustainability performance across different countries and regions, reflecting the diverse challenges and opportunities they face in transitioning to sustainable energy.

The strong performance of Scandinavian countries underscores the crucial role of policy support, public awareness, and acceptance in promoting sustainable energy. On the other hand, the challenges faced by Eastern European countries highlight the difficulties in transitioning from a fossil fuel-based energy system to a sustainable one.

The general trend of improvement over time is encouraging, indicating that progress is being made towards more sustainable energy generation. However, the varying pace of improvement among countries underscores the need for continued efforts and interventions.

Our findings have several implications for future research and policy. They highlight the need for more detailed and nuanced analyses that consider the specific contexts and conditions of different countries. They also provide valuable information that can inform the design and implementation of policies to promote sustainable energy.

In conclusion, achieving sustainability in energy generation is a complex and multifaceted challenge. It requires a concerted effort from all stakeholders, including policymakers, researchers, energy providers, and the public. We hope our study contributes to these efforts and helps pave the way for a more sustainable energy future.

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Conflicts of interest

The authors declare no conflict of interest.

Author contributions

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