

Transitioning from Fossil Fuels to Renewable Energy: A Multi-physics Perspective on Barriers and Opportunities in Multi-criteria Analysis

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Abstract

This research employs a novel multi-physics and multi-criteria analysis framework to study the transition from fossil fuels to renewable energy, wherein energy systems are complex and encompass disparate settings. The research applies sophisticated statistical models, including a Seasonal Auto-Regressive Integrated Moving Average (SARIMA) and Multi-Criteria Decision Analysis (MCDA) to forecast renewable energy production and evaluate different energy sources according to sustainability criteria, including environmental impact, cost, and efficiency, using a comprehensive dataset covering the span from 1997 to 2017. The results show a huge global shift away from fossil fuels towards renewable energy as evidenced by rising solar PV generation and biofuel production. Renewable energy sources slightly surpass fossil fuels, at which point global energy supplies are undergoing a critical transition. The studies correlating different energy forms and regions indicate global synchronisation of energy consumption trends and interdependencies of renewable technologies, pointing toward consistent advancement in line with common technological improvements and policy settings.

This research is novel in unifying multi-physics modelling with MCDA to gain a holistic perspective on technical, economic and social drivers toward the transition to sustainable energy. The findings underscore the significance of strategic interventions aimed at the adoption and efficiency of renewable energies, as well as infrastructure investments. The implications drawn from this study provide a valuable contribution to policymakers, industry stakeholders, and the academic community to inform effective strategies to accelerate a move towards a sustainable energy future.

Keywords: Multi-physics, Multi-Criteria Decision Analysis (MCDA), Renewable Energy, Seasonal Auto-Regressive Integrated Moving Average (SARIMA)

Introduction

The global energy sector is undergoing an essential change, moving away from fossil fuels to renewable energy sources. The essence of this shift is a need to address the impacts of climate change, cut greenhouse gas emissions, and prevent environmental degradation [1]. Although fossil fuels (including coal, oil and natural gas) have historically powered economies, the associated environmental and public health impacts have been incredibly high. This promising pathway to a sustainable energy framework exists with the advent and maturation of renewable technologies, e.g. solar, wind, hydro and bioenergy [2].

There are many difficulties in the transition to renewable energy sources, but yet the transition is clear. The integration of renewable energy technologies faces limitations from intermittent power systems and costly start-up expenses and strong requirements to upgrade current energy systems [3][4]. Renewable energy adoption rates and policy development processes are deeply affected by socioeconomic factors as well as political influences, so they may accelerate growth or block advancement [5].

The research adopts an innovative dual-scale structure that combines multi-physics analysis with multi-criteria evaluation mechanisms to handle the intricate issues of fossil fuels and solar transition. Two layers compose this analytical framework: initially, the multi-physics approach analyses how different physical processes interact, and then the multi-criteria method evaluates elements, including energy generation distribution and end-use consumption [6]. Such integrated methods maintain importance because they operate from an understanding of energy transition obstacles involving multiple linked dimensions.

The research develops an established analytical platform that merges multi-physics simulations with multi-criteria decision analysis for measuring energy transition barriers and opportunities. The study objectives involve identifying and quantifying significant physical barriers while examining economic barriers alongside social barriers, technological opportunities, and environmental consequences. The study seeks to develop practical strategies with corresponding policy options. This framework attempts to detect essential flaws found within existing evaluation frameworks that analyse multiple settings so researchers can better understand technological obstacles alongside economic rules and societal constraints.

The energy transition investigation presents essential findings which could help scientists create profound knowledge of how these systems transform. The research connects technical assessments with social economic data to generate useful intelligence which directs governmental decisions and corporate action and community involvement. The fundamental knowledge gained from these findings becomes vital for building sound economical and sustainable approaches that support both human social goals and maintain environmental health.

Overview of Energy Systems

The modern global energy framework has changed drastically as fossil fuels transition into renewable systems [2]. Coal, natural gas and oil have consistently served as the main drivers of industrial development while creating environmental damage along with rising global temperatures [7]. The transition toward renewable energy including solar power wind power hydroelectric power and geothermal power has emerged due to environmental protection needs that require both reduced greenhouse gas production and comprehensive environmental damage mitigation [8]. The energy mix of global power generation has experienced revitalization due to technological progress combined with policy support and societal changes across sustainability. The integration of renewable power faces two significant barriers because of its irregular supply nature and differences in energy infrastructure systems [9]. Research and development projects powered by the quest for environmentally sound and resilient energy systems keep bringing new solutions and funding streams to this field.

Technological Advancements in Renewable Energy

From renewable energy technology, tremendous progress has been made in all sectors, which adds each of their contributions to the reality of energy. Advances in photovoltaic (PV) cell technology have resulted in significant transformative growth in solar power. Increasing the efficiency and decreasing the cost of PV cells has greatly increased solar energy's accessibility and economic viability [10]. Solar innovations like bifacial solar panels that enable harvesting sunlight on both sides and technology using water bodies to conserve land are extending the reach of solar technology [11]. Together with solar energy integrated into buildings and urban infrastructure, such as transparent solar cells and solar roofing materials, it allows for better aesthetics or higher functionality of energy generation.

The further development of larger wind turbine designs that have significantly increased power output per turbine has continued to drive wind energy. These advances have been beneficial for offshore wind farms, where large turbines can make use of consistent and strong winds offshore [12]. However, previous geographical limits have been overcome by floating wind turbine technology, enabling the expansion of possible areas in which wind energy can be effectively harnessed [12].

Hydroelectric power still retains its standing in renewable energy and remains an area of innovation, providing higher efficiency turbines and minimising the effect on aquatic ecosystems. Supply and demand management has favoured pumped storage hydroelectricity to act as a form of energy storage [13]. Similarly, enhanced geothermal systems (EGS) for geothermal development have progressed, allowing geothermal development in areas without natural geological sources of heat [14].

The efficiency of bioenergy production and the carbon footprint associated with bioenergy have seen improvements in the conversion technologies of biomass to energy in the bioenergy sector. Recently, bioenergy has evolved into more sustainable and versatile applications through innovations, such as gasification, anaerobic digestion, and advanced biofuels [15]. Furthermore, the genetic engineering of energy crops and the development of algae-based biofuels are promising areas of bioenergy development that can improve sustainability and performance [16].

These advances not only raise the energy yield and efficiency of renewable technologies, but they also address these technologies' principal barriers to adoption, namely storage and intermittency. Energy storage systems, such as batteries and other forms of energy storage, are essential research and development for making renewable sources grid-compatible and more reliable. These technologies also contribute to a more varied and sustainable energy portfolio that reduces the world's use of fossil fuels and the environmental ramifications associated with energy service production.

Barriers to Energy Transition

There are numerous large and complex barriers, which are technical, economic and socio-political, to transitioning from fossil fuels to renewable energy sources. The main technical challenges involved with heightened renewable sources of energy such as solar and wind are that they are intermittent and variable and, therefore, present issues of grid stability and reliability. However, these two effects are mitigated using energy storage technologies, such as batteries and pumped hydro storage, which are costly and have complex engineering challenges [17]. Moreover, the current energy infrastructure is built mainly for centralised energy production, posing the integration of decentralised renewable generators as a logistical and technical issue.

The significant economic barrier includes the high initial capital requirement to bring renewable energy installations into operation relative to existing fossil fuel technologies. Even as technologies like solar PV and wind turbines become more affordable, investor risk and uncertainty continue to prevent investment. These investment challenges can be further exacerbated by a lack of adequate financial incentives and variable policy environments [18].

The absence of political will or outdated vested coastal and fossil fuel industries can cause regulatory and policy inconsistencies as faced by socio-political challenges. Another crucial factor is public acceptance; without public acceptance and support, public misconceptions or lack of knowledge about renewable technologies can stop community acceptance [19]. Transitional efforts toward renewable energy generate shifts in regionally dependent fossil fuel labour and income patterns, so proper social equity policy needs to be implemented [20].

Multi-Criteria Analysis in Energy Policy

Multi-criteria analysis serves as a fundamental policy instrument to evaluate complicated energy policy decisions because these choices contain differing priorities. The method proves ideal for energy transition efforts since it requires balancing economic, environmental, and social aspects [21]. Through MCA, policymakers and

stakeholders can evaluate energy sources and their effects on society through a complex framework beyond basic single-parameter evaluations [22].

Various criteria are evaluated when implementing MCA, including measures of cost-effectiveness alongside energy efficiency and carbon emission rates, technological readiness, social acceptability, and economic impacts. The importance of the criterion can vary from policy goals and stakeholder priorities, and each criterion is weighted [23]. It helps ensure that all the right things are evaluated in energy systems at the same time.

Applications of MCA in energy policy include selecting from among various renewable energy projects, designing an energy efficiency program or setting research and development priorities. For instance, determining whether to invest in solar power, wind energy, or bioenergy projects in a particular region can be accomplished by evaluating each option against factors such as the potential energy output, the environmental impact, the cost, and community support [24].

MCA is very effective but depends on the appropriateness of the criteria to be used, the precision of data used, and the inclusiveness of the stakeholder engagement process. While MCA can offer a strong grounding in decision-making, it should be recognised that MCA has drawbacks as well. The subjective criterion of weighting and ranking of criteria, the complexity of the analysis, and the demand for complete, dependable data.

The Role of Multi-physics Modelling

Multi-physics modelling is a powerful tool for understanding and improving complex systems that exhibit a set of simultaneously acting physical interactions. Rigorous analysis, including this approach, is of great importance, especially in the area of renewable energy technologies, which support optimisation and integration of these technologies into the existing energy infrastructures [25]. Multiphysics model means combining different types of physical models, such as thermal, fluidic, mechanical and electrical, to represent the real world better.

A good example is the work of [26], where they reviewed multi-scale and multi-physics simulations of metal additive manufacturing processes. However, the present study highlights the need for the multi-physics approach in the face of overcoming the challenges of metal additive manufacturing, i.e. defect formation and poor processing windows. In the review, the researcher showed that various modelling strategies, including heat transfer, fluid dynamics and solid mechanics, can be used to predict defect formation and assist with the optimisation of manufacturing processes for the production of material having desired mechanical properties efficiently [26].

Renewable energy systems rely on this kind of modelling for designing and optimising devices such as photovoltaic cells, wind turbines and energy storage systems. For instance, multi-physics models can be used to simulate the structural stresses on turbine blades, the aerodynamics of the airflow, and the electromechanical energy conversion, which are all necessary to increase turbine blade efficiency and reliability [27].

Similar multi-physics strategies can be incorporated to address respective challenges of renewable energy technologies, e.g., variability in the energy production in solar panels that depends on temperature changes or stresses in the wind turbines from irregular winds. The multiphysics model not only offers physical insights into the interactions in a single framework but also strengthens the design and integration of renewable energy technologies, thereby increasing robustness as well as efficiency in its operation.

Research Framework

This study develops a research framework to comprehensively assess the transition from fossil fuels to renewable energy via a multi-physics and multi-criteria analysis. This research framework is provided in Figure 1, which starts with the collection and preprocessing of historical energy production according to various types of production with a look at how this translation has affected the sustainability metrics and impact on various

production methods from 1997 to 2017. Both predictive modelling and evaluative analysis require the use of this dataset as the basis of this research.

The research utilises Seasonal Auto-Regressive Integrated Moving Average (SARIMA) to generate future renewable energy output estimates based on historical patterns. The developed model provides insight into how renewable energy may expand while showing what barriers might materialize before we reach our destination. Following data forecasting, the research team performs a multi-criteria decision analysis (MCDA) assessment of energy source priorities based on efficiency and environmental impact alongside cost factors and public reception benchmarks. Each energy type is evaluated through this analysis method using a structured weighted scoring system to determine their performance on the defined criteria.

The research combines SARIMA modelling output with MCDA ranking results to create actionable guidelines for strategic energy policy and infrastructure development. The purpose of these recommendations is to assist in renewable adoption while maximizing their operational efficiency so that fossil fuels can transition into the renewable future.

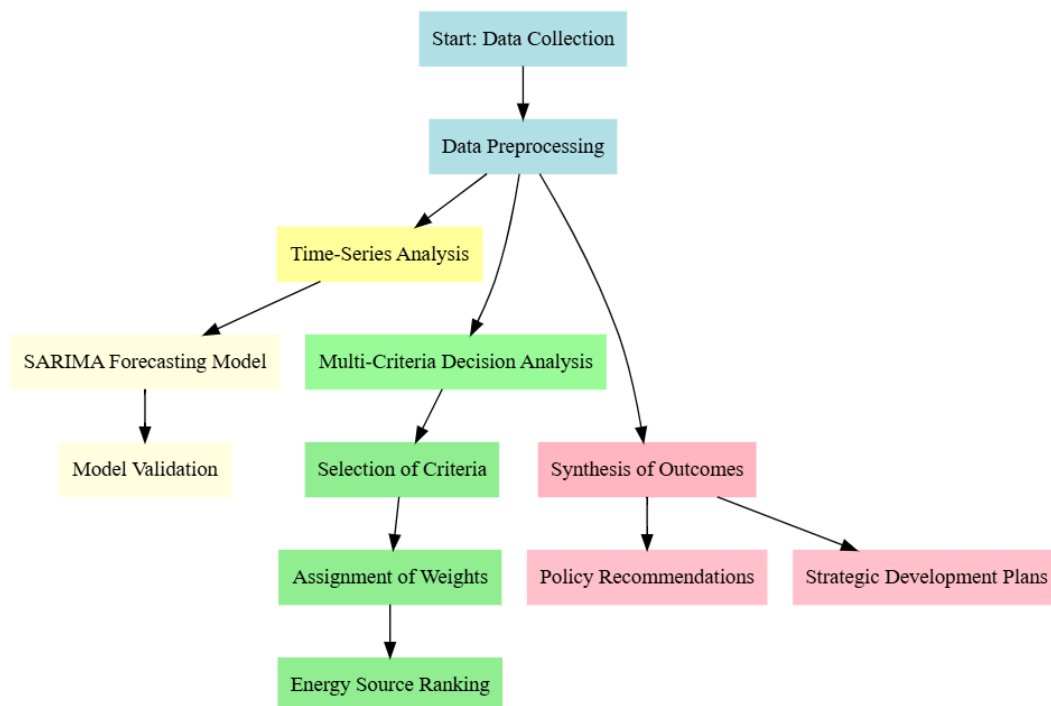


Figure 1. The Research Framework

Research Methodology

For this study, the research design adopts a structured approach for analysis and forecasting the transition of fossil fuels to renewable energies, utilising a synthesis in time series analysis and multi-criteria decision analysis (MCDA). The implementation of this methodology is done in Python, a great programming language for statistical modelling and data analysis of its extensive libraries.

The dataset spans from 1997 to 2017, covering the most comprehensive energy production data available by type (fossil fuels: coal, oil, natural gas and renewables: solar, wind, hydro, bioenergy). The data comes from authoritative international energy databases (Kaggle), making it reliable for analysis. This temporal and geographically diverse dataset serves as an excellent starting point for looking at historical energy patterns and projecting future energy changes. The geographic domain of the dataset spans a global extent as data are aggregated from different countries to create an overall view of energy production trends around the world. Due

to the dataset's large temporal and thematic range, it is an ideal dataset for studying trends in energy production over time. The research analyses this dataset with the objective to explore patterns and changes in the production of energy, i.e. providing better insight into energy transition dynamics from fossil to renewable energy sources. In order to forecast future trends, as well as in order to carry out strategic planning to improve energy sustainability and to serve in developing energy policy globally, it is critical to understand this aspect.

Time-Series Analysis

The first phase in the research is time series analysis based on the Seasonal Auto-Regressive Integrated Moving Average (SARIMA) model. The reason for choosing this model is its effectiveness in dealing with the seasonality and the non-stationarity that characterise energy production data. SARIMA model is implemented using the statsmodels library of Python, which provides detailed parameter optimisation and model fitting. Additionally, the data is divided into a training set (up to 2012) and a test set (post-2012) for model validation of the model's ability to predict.

Multi-Criteria Decision Analysis (MCDA)

Subsequent to forecasting, the study takes the role of using Multi-Criteria Decision Analysis (MCDA) to take into consideration the sustainability criteria such as environmental impact, cost, efficiency, and acceptability via social perspectives and rank them in order of importance. We assign each criterion a weight that reflects its importance, using stakeholder consultations and reviewing literature relevant to the criteria.

The analytical hierarchy process (AHP) is an effective and efficient MCDA method that compares certain criteria or particular alternatives and assigns weights to criteria. Then, the analytical hierarchical process levels useful for complex problems are converted into sub-problems. The requirements and attributes, however, are provided at each sub-problem level. However, they are presented based on their importance and from an additive weighting process. Moreover, in many areas of the ranking, the hierarchical process analysis (AHP) is used due to the pairwise comparison for determining the critical criteria in a hierarchical system [28][6]. The criteria are weighted using the Analytic Hierarchy Process (AHP), whereby pairwise comparisons are made between pairs of criteria, and consistency checks validate the relative weights.

The aggregation of weighted criteria scores is conducted using the weighted sum model (WSM), one of the most straightforward MCDA methods, formulated in Equation (1) as:

$$Score_i = \sum_{j=1}^n w_j \times c_{ij} \quad (1)$$

where w_j is the weight of the j^{th} criterion, and c_{ij} is the performance score of the i^{th} alternative on the j^{th} criterion.

Such ability for applications of MCDA with Python is possible through custom functions and libraries tailored to handle the heavy computation needed in the criteria weighting and aggregation. A nuanced future energy scenario analysis is obtained by its integration with SARIMA model forecasts results.

Integration and Strategic Planning

The final phase of the research design is a convergence of the results of the two analytical methods to produce findings that are useful for policy recommendations and strategic planning. The capabilities of this synthesis-based analysis lie in the integration of the MCDA evaluations into the SARIMA forecasting results, where we have a comprehensive analysis of analysis of quantitative and qualitative forecasts. This data melding design gives a multi-dimensional view of future energy scenarios that are essential to guide the making of nuanced policy recommendations and strategic development plans.

This integrated approach results in a final output that provides, in a robust and evidence-based manner, information on how policy adjustments, infrastructure investment, and promotional strategies can promote the adoption of renewable energy. This holistic view of energy transitions outlines not only the practical importance of energy transitions for the present but also helps to steer those working on energy transitions toward being forward-looking and aligned with long-term sustainability goals.

Based on a highly sophisticated framework of rigorous methodologies, which was implemented through Python's analytical capabilities and supports this elaborate research design, this research presents a sophisticated framework through which we can understand the complex dynamics in the move towards the global shift to renewable energy.

Results and Analysis

The dataset spans from 1997 to 2017 and is analysed for significant trends in global energy production, which includes a relatively gradual transformation from fossil fuels to renewable energy sources. The initial analysis of these data suggests a rise in the volume of production in renewable energy sectors from solar, wind, and bioenergy, which is consistent with global sustainability and technological progress in these sectors. It features segmented annual records by energy type at the most detailed level to examine the nature of each energy type's contribution to the total energy mix over time.

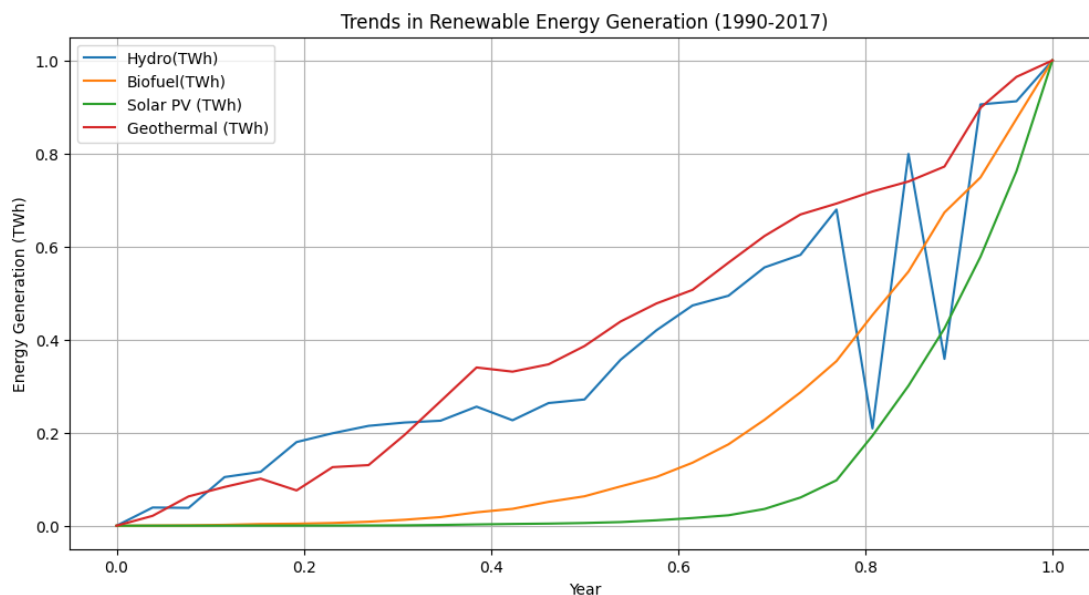


Figure 2. The Growth Trends in Renewable Energy Generation from 1990 to 2017

The growth trends for renewable energy generation are shown for hydroelectric, Biofuel, Solar PV, and Geothermal energy sources from 1990 to 2017, as shown in Figure 2. The growth of hydroelectric power continues to be linear, staying a key component of renewable energy, albeit with a smaller plateau ahead of 60 percent of primary energy. However, in contrast, solar PV experienced a remarkable rise in the post-2005 period; optimised technologies and decreased costs are supported by favourable policies and increased market adoption. Another increasing trend is biofuel production, which spiked in the mid-2000's due to the worldwide encouragement of renewable products to replace oil-derived fossils and boosted delivery modernisations. To date, geothermal energy's growth is also minimal, due in large part to the high up-front costs and geographically restricted resource requirements that prevent it from being more widely adopted and developed from a broader geographic area.

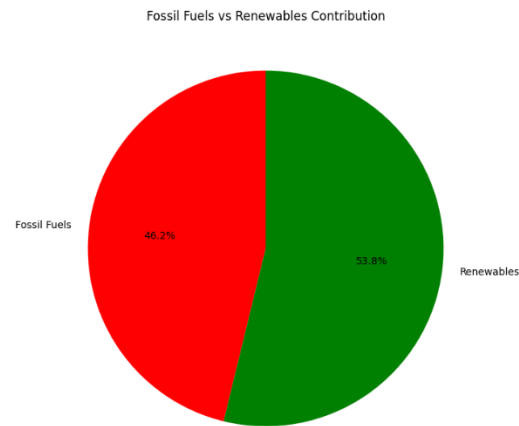


Figure 3. The Distribution of Energy Production

In Figure 3, the pie chart shows the percentage of energy production from fossil fuels and renewable sources. It shows that renewables account for 53.8% of the energy mix, slightly surpassing fossil fuels, which contribute 46.2%. Such a shift in energy sources indicates a need for more sustainable sources of energy and a global intention to decrease dependence on fossil fuels and reap the economic benefit of renewable technologies. The near-equal split marks a critical moment in the energy sector that, by pointing to the importance of renewables not just needed but increasingly essential in global energy supplies, also shows that energy demand is benefiting from both sources.

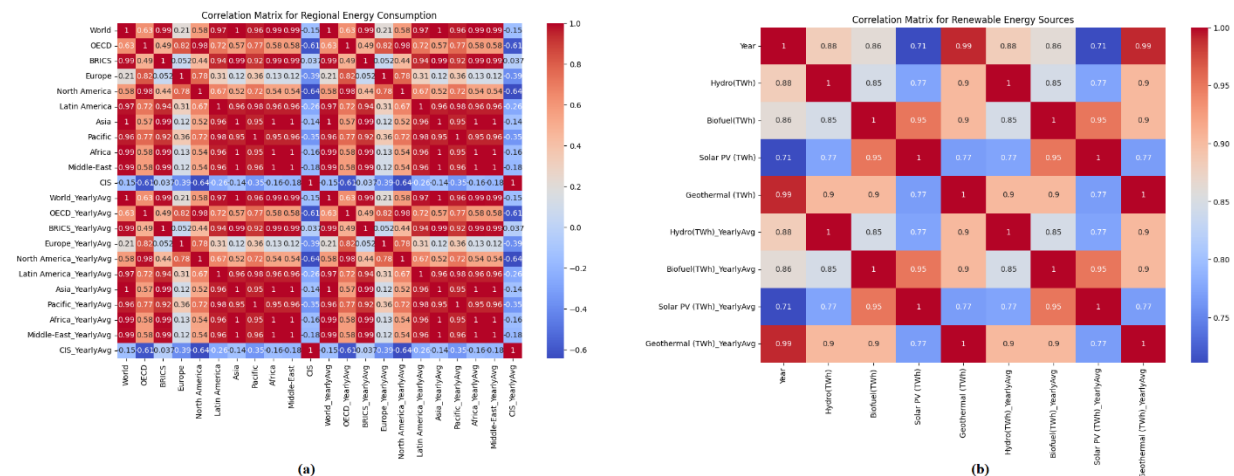
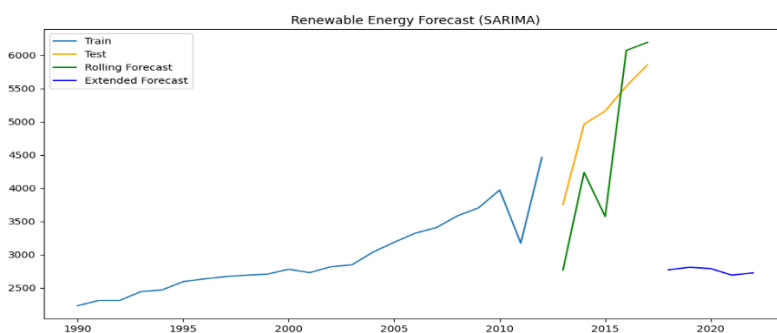
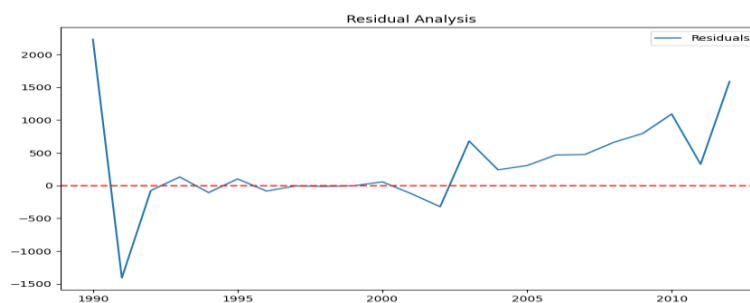


Figure 4. The Correlation Matrices for (a) Regional Energy Consumption and (b) Renewable Energy Sources

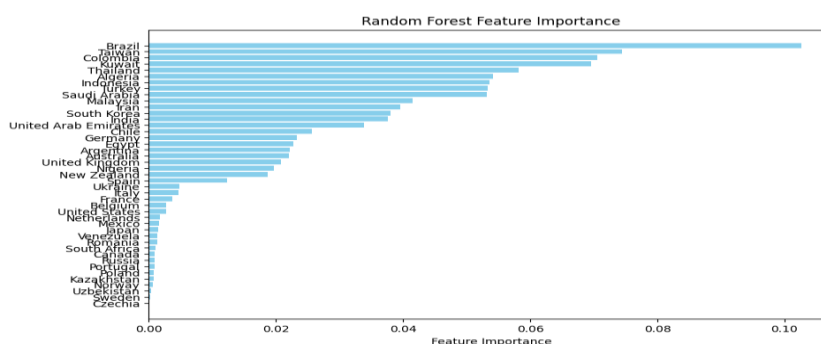
The two correlation matrices in Figure 4 give opposing views on energy data. The first matrix examines the correlation of regional energy consumption. It reveals a number of high positive correlations indicating synchronised consumption trends, most likely related to large-scale economic conditions and international policies. On the other hand, the second matrix observes that there are strong interrelationships between hydro, biofuel, solar PV, and geothermal energy, placing them in the spotlight. In particular, newer technologies, such as Solar PV and Biofuel, have exceptionally high correlations, suggesting an overlap between advancements or investments in one technology and other technologies due to shared technological policy drivers. This implies that advances in renewable technologies have occurred as a whole and that the first matrix, which features broader regional patterns in energy consumption, is more affected by geopolitics and macroeconomics.

SARIMA – Renewable Energy Contributions**Figure 5: Renewable Energy Forecast (SARIMA)**

The SARIMA model is helpful in predicting renewable energy trends by the use of historical data. The training data between 1990 and 2010 indicate the steady growth in the production of renewable energy, whereas the test data between the dates 2011 and 2015 illustrate the robustness of the model. The extended and rolling forecast indicates an increase in the adoption of renewable energies. The minor fluctuation in prediction illustrates the structural variability and seasonal changes.

**Figure 6: Residual Analysis**

Residuals are the difference between the predicted and actual values. These are usually near zero and indicate a good model fit. Moreover, there have been spikes in residual, suggesting an occasional underestimation of extreme values or unaccounted variables. The increase in residual trend over time signals potential changes in energy production dynamics and has a limitation in the assumption of the model.

Random Forest – Country Consumption**Figure 7: Random Forest Feature Importance (Countries)**

The plot identifies Brazil, Colombia, and Taiwan as the main role in the production of global renewable energy production. These geographic and policy advantages help in the prominence of the company. In contrast,

the Czech Republic and Sweden show lower contributions in the formation of the renewable adoption level or small economies.

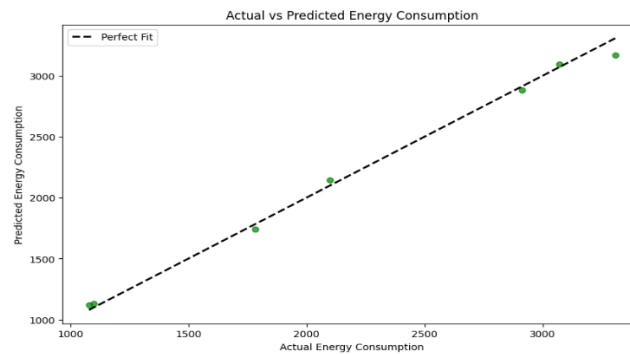


Figure 8: Actual vs. Predicted Energy Consumption

The alignment of the actual and predicted energy consumption along the dashed perfect fit line indicates high prediction accuracy. The minimum deviation indicates the model effectively captures consumption patterns with underestimation or negligible dataset.

LSTM Model – Predicted Renewable Energy Contributions

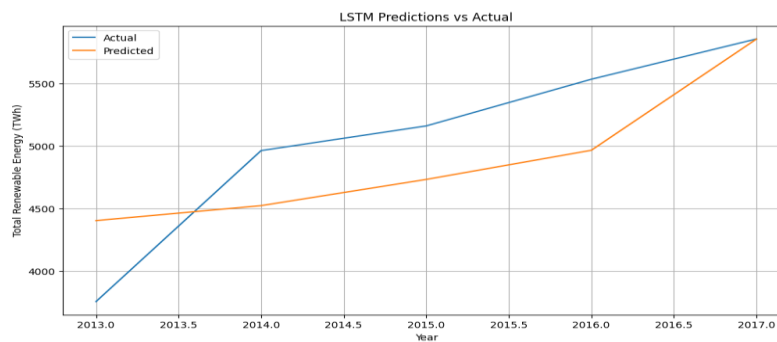


Figure 9: LSTM Predictions vs. Actual

LSTM predictions for renewable energy from 2013 to 2017 closely follow the demonstration of the ability to adapt to non-linear patterns. The underestimations that exist with renewable energy growth are based on the trajectory that is aligned with a broader trend.

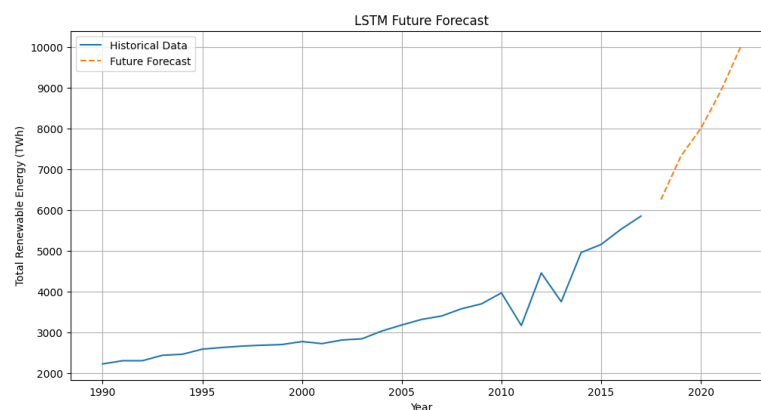


Figure 10: LSTM Future Forecast

The LSTM model indicates that the growth in renewable energy post-2017 will surpass 10,000 Twh by 2025. The steeper slope is compared with historical trends that underscore advancement in technology, global renewable adoption momentum and favourable policies.

Random Forest – Predicted Renewable Energy Contributions

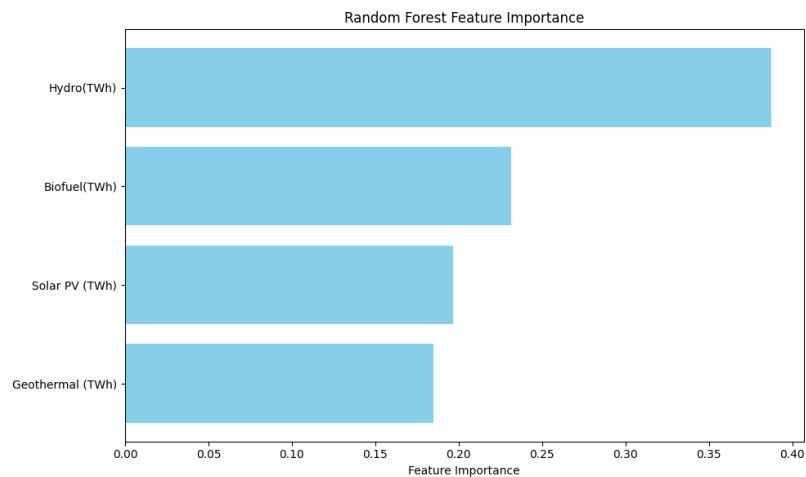


Figure 11: Random Forest Feature Importance (Energy Types)

Hydropower plays a significant role in renewable energy, which is followed on the basis of solar PV and biofuel. Geothermal lower energy represents limited geographic feasibility and high cost regardless of the reliable energy source.

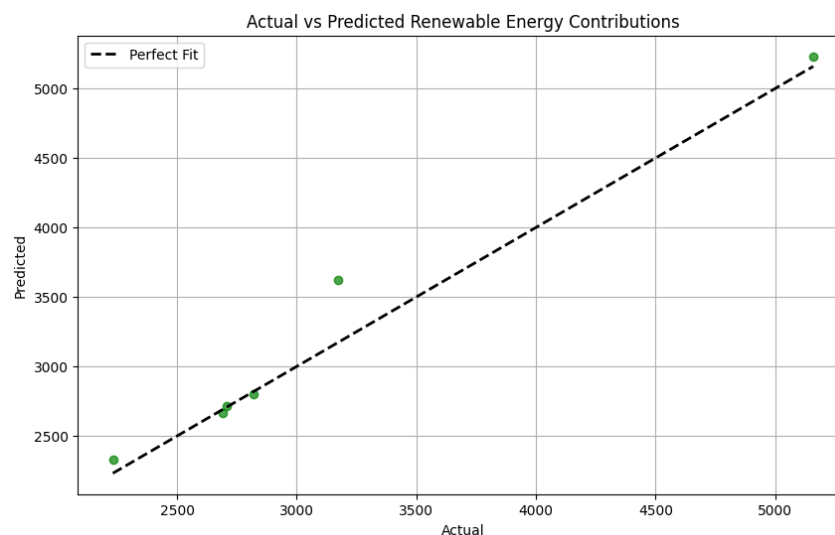
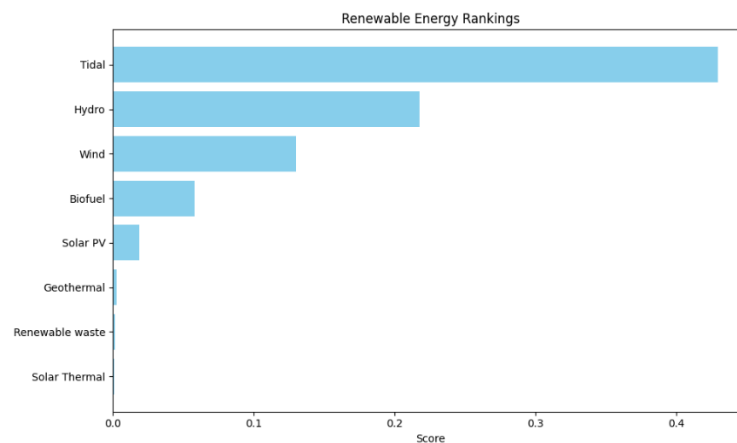
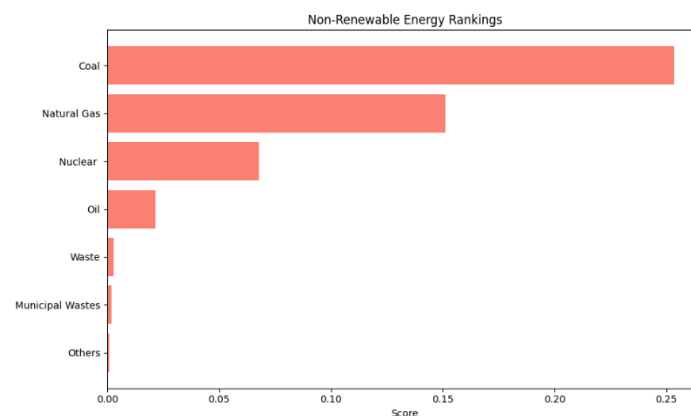


Figure 12: Actual vs. Predicted Renewable Energy Contributions

The near linear fit between predicted and actual contributors indicates the model's accuracy in forecasting renewable energy adoption related to energy types. Outliers focus on the change in policy or unforeseen dynamics in the market.

Multi-Criteria Decision Analysis (MCDA)**Figure 13: Renewable Energy Rankings**

Hydropower and tidal are ranked highest, which reflects their efficiency and reliability. Wind energy focuses on the advancement of offshore turbines. Geothermal and solar PV are ranked lower because of cost barriers and intermittency challenges.

**Figure 14: Non-Renewable Energy Rankings**

Non-renewable energy rankings indicate that coal is dominating among natural gas and nuclear power. This emphasises the role of the global energy system. The lower oil ranking represents the decline in the production of energy because of market shifts and environmental concerns.

Discussion

The results of this study demonstrate a wide-ranging global energy distribution, which shows that renewable energy sources are supplanting fossil fuels as primary power sources. The shift from fossil fuels to renewable energy sources happens because of technological development alongside supporting policies and expanding environmental consciousness about fossil fuels. Predictive models and multi-criteria analysis supplement the study to reveal the complete scope of this transition together with its obstacles.

The SARIMA model demonstrates superior accuracy at revealing both periodic changes and broad architectural shifts in renewable energy development across the globe as global adoption continues upward. The expansion of renewable energy matches technological advancements in photovoltaic (PV) cell efficiency and wind turbine scale and biofuel refinement advancements. An examination of residuals demonstrates restrictions within

the model regarding its management of extraordinary market patterns and abrupt changes. The model proves insufficient for handling exogenous elements affecting energy output and consumption, so additional analytical structures need to be developed to explain these external influences.

The Random Forest feature importance metrics demonstrate that specific nations generate domination levels of renewable global energy production. Three countries, namely Brazil, Taiwan, and Colombia, achieved positive results from helpful geographical factors combined with comprehensive renewable energy policy implementation. The renewable energy development prospects of nations with lower placement perform poorly because they encounter issues stemming from economic, political or infrastructure limitations. The wide performance gap between countries emphasises the vital need for international collaboration alongside technology transfer programs to bring developing nations up to speed with developed nations.

Long-term forecasted renewable energy production shows an upward trend that is steeply rising because of higher investments and sectoral technological improvements. The Modeling of non-linear energy systems driven by multiple factors, including market tendencies and consumer responses along with regulatory elements, has shown inconsistencies between forecasted and actual data during the initial observation periods. Future forecast systems need to unify deep learning technology with external socioeconomic variables in order to boost estimation precision.

When applied to renewable energy assessments, tidal power and hydropower emerge as the top choices due to their reliable performance and operational efficiency. Solar PV and geothermal power systems demonstrate notable exploration opportunities even though they rank below other renewable energy technologies. These energy resources present significant growth potential once barriers to storage capability, intermittent operation, and expensive start-up costs are solved. The rankings of renewable waste and solar thermal demonstrate zones for additional investment and technological innovation.

The non-renewable energy sector rankings display consistent dominance of coal and natural gas across global energy frameworks. The transition from these energy sources requires complete policy packages to include carbon pricing protocols along with renewable power project support and protection systems for fossil-based communities.

The specific areas where renewable technologies operate are linked to one another according to the correlation matrices. The development of new storage technology capabilities within solar PV space creates parallel improvements throughout other related storage solutions. These global observations prove that there is a need for swift international collaboration to speed up renewable energy projects so mankind can transition correctly.

The current energy transition needs primary obstacle solutions with technological developments to fulfil sustainability across international borders. This research builds an extensive analytical framework to support policy-making activities through its complete assessment of energy transition dimensions that guide stakeholder decisions.

Conclusions

In conclusion, the transformation of energy systems from petroleum fuel consumption to sustainable renewable sources has emerged as a fundamental step in sustainability, resulting primarily from technological advances in policy developments and increased environmental awareness. Predictive Modelling combines with evaluative methods in a multi-lenses framework, which uses this study to assess transition obstacles while creating actionable guidance for research institutions policymakers and industry stakeholders.

The available data reveals a positive upswing in renewable energy generation because solar PV alongside wind and bioenergy produced noteworthy increases in output. The growing affordability and efficiency of renewable technologies, coupled with supportive policies, including international agreements and subsidies, thrust renewables upward according to forecasting models. Forecasting models derived from SARIMA and LSTM

indicate renewable energy will expand through technological progress alongside storage system innovations and worldwide emission reduction goals. Renewable energy's expected dominance in 2025 requires immediate attention to improve network capabilities alongside solutions for intermittent energy generation to protect power grid stability as well as energy system security.

Bridging the energy transition faces ongoing obstacles, according to the study's analysis. The pathway to renewable energy adoption faces multiple key challenges, including excessive implementation expenses, constrained electrical grid facilities, and local resistance to energy transitions from fossil fuel nations. The Random Forest analysis demonstrates uneven renewable energy implementation by countries, which necessitates equal policy frameworks with foreign cooperation to exchange technology, build capabilities and augment financial assistance for growing economies. The failure to address inequalities between nations threatens the creation of a renewable energy transformation that is both unbalanced and challenging to sustain.

The multi-criteria assessment shows that renewable energy systems benefit from multiple energy sources as part of a diversified mix. While hydropower and tidal energy rank highest due to their efficiency and reliability, emerging technologies such as solar PV and geothermal energy offer immense potential. The realisation of sustainable energy storage technologies through advanced batteries and pumped hydro storage represents imperative investments for managing the intermittent nature of solar and wind systems. The development of algae-based biofuels together with genetically engineered crops represents potential breakthroughs that can transform bioenergy into both sustainable and versatile fuel.

Strategic policy interventions need to become central in creating the necessary conditions for an equitable energy transformation. To realise renewable energy investments, policymakers should focus on building risk inhibition tools for projects alongside incentives for innovation and strong regulatory implementations. A comprehensive support framework must exist simultaneously with steps to assist employees and residents who lose their livelihoods because fossil fuel operations wind down. This framework protects vulnerable populations through equitable energy transformation initiatives.

This research generates consequences that go beyond technological frameworks and economic operations. A relationship between renewable energy systems and worldwide commodity consumption patterns exists that requires unified international approaches. Joint research initiatives and cross-border energy trading activities can increase renewable energy system resilience while making installations more efficient. Public education, together with awareness programs, represent essential components to fight misunderstandings about renewable energy systems, specifically among communities that currently show modest adoption levels.

This research offers an extensive methodology which illuminates the diverse aspects of energy transformation while creating essential knowledge for future transition strategies. Through barrier elimination, technological progress, and international partnerships, the world will accelerate its transition to sustainably equitable and resilient energy systems.

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