

Modelling and Assessment of Renewable Energy Production and Utilisation

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ABSTRACT

The growing global need for energy together with negative effects of fossil fuel combustion has been driving humanity to switch to renewable energy resources. This research paper is dedicated to modelling and assessing the use of renewable energy, with an emphasis on reliable prediction, optimization, and performance assessment methods. The types of renewable energy, such as solar, wind, hydropower, biomass, and other forms, will be considered in light of their generation capability, effectiveness, and implementation within the energy industry. This paper covers a wide range of modelling techniques, from traditional mathematical modelling to modern machine learning and artificial intelligence-based approaches that can help to forecast energy generation and demands. Also, assessment tools and performance indices (energy efficiency, economic sustainability, environmental impacts, reliability) will be reviewed with a focus on hybrid energy systems and advanced smart grids. Moreover, challenges of renewable energy intermittency, storage solutions, grid connectivity, and regulatory frameworks will be addressed, with particular attention paid to innovations in energy storage technologies and digital energy systems.

Keywords: Renewable Energy, Sustainability, Energy Storage Modelling Techniques, Machine Learning, Optimization, Regulatory Frameworks.

INTRODUCTION

Renewable energy plays an integral part in the energy infrastructure of the contemporary world because of the urgency of addressing increasing problems associated with growing energy needs, pollution, and climate change due to excessive reliance on fossil fuels. The rapid industrialization process and population growth have caused significant rise in the need for energy sources, which resulted in depletion and deterioration of natural resources. These effects had negative implications for human health and ecological well-being. In order to solve these problems, it has become imperative to use renewable energy sources, including solar, wind, hydro, biomass, and geothermal power. This type of energy helps create energy that is environmentally friendly, unlimited, and sustainable. Nonetheless, even with all the advantages that renewable sources of energy present with respect to environment and economy, there are some problems associated with their use. Firstly, the biggest problem with renewable energy is related to their unstable operation, since their productivity is highly dependent on weather conditions and environmental conditions, such as availability of sun, wind velocity, seasonality, among others. Second, due to the high costs required to set up the infrastructure and the technology required, renewable sources have been seen as expensive by some countries. This may prevent its use, particularly in developing countries [1].

Thus, as far as these problems are concerned, modelling and proper assessment of renewable energy systems should be done in every phase of the energy planning process. Proper modelling would allow the scientific analysis of energy resources available, forecast production capacity, and behaviour according to the conditions and load requirements of every particular case. Also, modelling would optimize the performance of systems according to the particular characteristics that each renewable source presents. Therefore, uncertainties that may arise from the weather conditions could be mitigated. In addition to production modelling, an integrated approach for evaluation of the performance of renewable energy systems in several aspects should be developed. The latter

may include such factors as technical feasibility, economic efficiency, environmental consequences, and sustainability. Among the techniques that may be employed, life cycle assessment (LCA) could be applied to study the impacts of renewable energy systems at all stages, from production through disposal. Cost-benefit analysis can help estimate the efficiency of renewable energy systems in economic terms, thus maximizing investments' outcomes [2].

The development of new approaches for modelling renewable energy systems has received great impetus in the last few decades. In spite of the fact that modern modelling methods have become more sophisticated, traditional classical modelling remains relevant because of its proven theoretical background and high level of interpretation. Physiological models are based on physical principles, whereas statistical models use empirical data to reveal trends and patterns in energy usage. Due to improvements in computer technology and access to big data, ML and AI technologies are among the most useful in renewable energy modelling. They can accommodate non-linear relations and generate precise forecasts for energy production and consumption. The examples of such modelling include the use of neural networks and deep learning for predicting solar irradiance and wind speed, as well as optimization algorithms for designing optimal hybrid energy systems based on several renewable energy sources. One more essential element of renewable energy modelling is grid integration. As the proportion of renewables in energy systems grows, it becomes more difficult to maintain the stability of the grid. Therefore, advanced modelling methods help evaluate the performance of the grid and design energy storage and distribution systems. Batteries and pumped hydro storage systems belong to energy storage technologies that help balance energy production and consumption. The implementation of renewable energy systems is further enhanced by policy and regulatory mechanisms that promote and support these initiatives. Policymakers use various incentives, subsidies, and favourable policies to encourage the implementation of clean energy solutions. Modelling and assessment tools provide guidance and assistance to the policymakers in decision-making processes by helping them understand the consequences of implementing different kinds of energy systems. These technologies allow setting realistic goals and assessing their performance to ensure sustainable development.

Classification of Renewable energy sources

Renewable energy sources may be generally classified in relation to their source of origin, means of energy conversion and nature of the resources, all of which have varying impacts on modelling, evaluation and deployment of the technology. Solar energy is one of the most popularly researched forms of renewable energy and falls under photovoltaic and solar thermal categories. In the former category, semiconductors are used to convert sunlight into electrical energy, whereas the latter involves capturing of solar heat which is then used for electricity generation or heating. Availability of solar energy is very location-dependent, hence the importance of modelling solar radiation to achieve maximum efficiency. Wind energy is another form of renewable energy involving the capture of kinetic energy from moving air via wind turbines located both onshore and offshore. Performance of a wind turbine is greatly affected by factors such as wind speed and direction, density and topography of the terrain. As such, probabilistic and time series methods of modelling are applied to the process. Hydropower is one of the most developed and dependable forms of renewable energy and can be subdivided into three categories:

can be subdivided into large scale hydropower, run-of-river facilities, and small or micro hydropower stations. Hydropower exploits the potential and kinetic energy of moving or stored water and depends mainly on the water flow rate, head of water, and precipitation patterns. Hydropower is more reliable than other sources of renewable energy and provides better storage ability; however, the use of large dams can lead to negative environmental and social impacts. The biomass energy can be generated from any form of plant and animal matter, including agricultural residue, wood, manure, and municipal solid waste using methods like combustion, gasification, and anaerobic digestion. Despite being seen as a reliable renewable source of energy, the sustainability of biomass power generation will depend on the availability of biomass feedstocks. The classification of geothermal energy is done depending on enthalpy, which can be low, medium, and high. Geothermal energy is useful both in generating electricity and providing direct heat applications. The main challenge facing the utilization of geothermal energy is that the resource base is geographically limited [3].

Modelling techniques for renewable energy production

Modelling techniques for renewable energy production can be viewed as the key instrument for prediction and optimization in renewable energy production. These techniques try to model the intricate relationship between environmental factors, system components, and energy production systematically. The first type of modelling is physical modelling. It uses basic scientific and engineering rules to predict some output values. For example, there exist solar radiation models that estimate the level of received solar energy based on astronomy data. Moreover, the wind energy models estimate the distribution of wind speed based on probability density function (e.g., Weibull or Rayleigh distributions). Hydroelectric plants' models use various methods to describe water flow through the plant. However, in general, the advantages of physical models are high accuracy and sound theory. On the other hand, these models are extremely dependent on input data reliability.

The models identify the relationship between the input variables, including weather factors, and the output, like energy produced through regression analysis, time series analysis, and stochastic methods. Statistical models are easy to deploy, and they consume fewer computational resources compared to their simulation-based counterparts. As such, they are ideal when conducting initial assessments and long-term forecasts on energy production. Despite being easier to use, statistical models might be inefficient in capturing complex nonlinearity and abrupt changes in renewable energy sources. This challenge has prompted the adoption of modelling by simulation, where technical, economic, and environmental factors are considered in determining the performance of the systems. Common software packages include HOMER, RETScreen, PVsyst, and MATLAB/Simulink, which enable modelling of renewable energy systems, whether stand-alone, grid-connected, or hybrid, as well as optimizing energy production and costs. More recently, hybrid modelling approaches have been gaining considerable attention in literature. In particular, such models integrate the advantages offered by the physical models and data-driven methods to offer improved performance. For instance, while physical models provide an estimate of the response, further refinement can be made based on statistical or machine learning methods [4].

Artificial intelligence and machine learning-based models

The significance of artificial intelligence (AI) and machine learning (ML) based models in the renewable energy production modelling process cannot be underestimated because they can work with big data, establish sophisticated nonlinear relations, and adjust to the changes of system operation conditions. In contrast to traditional modelling approaches, which strongly depend on analytical formulae, AI and ML models use historical and current data to learn patterns in the system, which makes these techniques highly applicable for variable and unpredictable renewable energy production processes. AI and ML models are broadly utilized for energy production predictions, fault detections, and energy management in different types of renewable energy technologies [5].

Artificial neural networks (ANNs) are some of the most popular AI methods currently used for modelling renewable energy generation processes. ANNs can approximate nonlinear functions, which makes them useful in solar irradiance, photovoltaic energy, wind speed, and wind power predictions. Support vector machines (SVMs) represent another popular ML technique, which is especially efficient in regression and classification problems when the sample size is small or contains errors. The SVM technique has proven to be reliable in short-term and long-term forecasting of renewable energy and system performance analysis. Algorithms based on decision trees such as random forest and gradient boosting algorithms are popularly used in selecting features and diagnosing performance due to interpretability and heterogeneous data compatibility. Performance evaluation and utilization techniques are integral elements for making sure that renewable energy systems are operated effectively, reliably, and sustainably. Performance evaluation entails measuring the performance of a renewable energy system in terms of how well it is able to utilize available resources to produce energy in practical applications. The common performance metrics applied include yield, efficiency, capacity factor, reliability, availability, and losses. Such factors can be helpful in quantifying the effectiveness of a system and hence optimizing the design and utilization of the technology. Modelling can prove crucial in the evaluation process since it facilitates the comparison of the estimated and actual energy output and identification of potential weaknesses in the system.

The utilisation strategies concentrate on maximising the utilisation of the produced energy and overcoming various problems related to the intermittent nature of renewable energy, the variability of production and distribution of the produced energy, and the discrepancy between supply and demand. An important strategy in this respect includes. There has been increasing interest in using deep learning algorithms in modelling renewable energy generation. Convolutional neural networks (CNN) can be used to model the spatial relationship within high-dimensional datasets such as satellite and weather maps, whereas recurrent neural networks (RNN) and LSTM network are useful in short-term forecasting due to their temporal data capabilities. Deep learning algorithms have proven to perform better than traditional approaches, especially in short-term forecasting. AI and ML models have drawbacks in terms of high demand for training data and complexity. Nonetheless, the use of AI and ML models in renewable energy generation has greatly improved forecasting, operational efficiency, and integration with the smart grid [6].

Performance evaluation and utilization technique

successful grid integration of renewable energy systems, which involves advanced power electronics technology and other innovative techniques. Effective energy storage technologies based on the use of batteries, pumped hydro storage, compressed air storage, and hydrogen energy storage allow solving the problem of imbalance in energy generation and consumption. The application of hybrid renewable energy systems that combine different types of renewable energy sources and incorporate renewable sources into the existing energy generation system provides an effective way of utilising renewable energy. In addition to the performance assessment of renewable energy systems, their proper utilisation ensures efficient functioning and increased economic viability of these systems. Utilisation of renewable energy resources, coupled with accurate performance evaluation, will allow obtaining maximum benefit from the production of renewable energy.

Economic, Environmental and Sustainability Assessment

understanding of other factors involved in addition to the technical performance of renewable energy systems. This assessment mainly includes evaluating the economic feasibility and economic benefits of renewable energy projects by means of various indicators such as the levelized cost of energy (LCOE), net present value (NPV), internal rate of return (IRR), payback period, and lifecycle cost. It involves evaluating other factors related to economic feasibility as well including the cost of operation and maintenance, financing issues, and incentives. The environmental assessment is important to evaluate the impact of renewable energy systems on the environment. In spite of the fact that the renewable energy systems are regarded as being environmentally friendly, they have some drawbacks as well. In particular, hydropower stations may cause disturbances in ecosystems and affect river ecology. Similarly, wind turbines may pose a threat to birds and bats while biomass energy may have some negative effects on the environment in terms of deforestation or land degradation.

Assessment of sustainability evaluates the techno-economic and environmental factors of renewable energy systems together to have a comprehensive analysis. Multi-criteria decision-making (MCDM) tools like Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and PROMETHEE are some of the common approaches used during the assessment. Sustainability assessment also accounts for social considerations such as availability of the energy resource, job creation, and acceptance among the population, which are important factors in the long-run viability of renewable energy resources. By doing all these evaluations, assessments of economic, environmental, and sustainability help decision-makers choose efficient the economic, environmental and sustainability assessment is another essential part of the evaluation process of renewable energy systems. The reason for that is the importance of having a thorough and economically viable renewable energy technologies while being environmentally and socially responsible [7,8].

Future Directions

The future directions in renewable energy modelling and assessment will include tackling existing problems and developing new trends in relation to modern technologies, which could enhance energy systems in their integration, efficiency, and sustainability. One of the future directions in renewable energy modelling is the development of AI, ML, and big data technologies. The introduction of these technologies will allow improving forecasting, increasing system reliability and efficiency by providing accurate predictions and adaptive energy

management. Digital twin technologies can be considered one more important trend for the future. Digital twin refers to an exact replica of the physical object, which can be used to evaluate its performance and analyse potential scenarios of operation. The integration of IoT devices and AI technologies is also one more direction in which the future system should develop. power from renewables during downtime. Systems utilizing combinations of various types of renewable energy or systems combining renewable energy and traditional energy sources can offer greater stability and reliability of power supply, especially in applications [9].

Another important direction in renewable energy modelling is the development of energy storage systems. These systems will be able to provide of isolated and microgrids. Development of climate and weather modelling at high spatial resolution and combined with regional resource assessment will increase the predictability of renewable energy production, thus making planning, system integration, and policy design easier. Another trend is likely to be the focus on sustainability issues, including life cycle assessment, implementation of circular economy concepts, and social acceptance of renewable energy installations. Sustainable energy optimization methods and models will become increasingly important and should incorporate not only economic and environmental aspects but also take into account long-term perspectives, incentives for policy-makers, and objectives regarding greenhouse gas emissions. Moreover, the design of decentralized energy systems, sector coupling solutions, and new financing instruments can prove effective in speeding up the adoption of renewable energy technologies. In summary, the most promising future developments include the creation of intelligent, resilient, and sustainable energy systems capable of efficient use of renewable energy and able to ensure adequate power supply to consumers [10].

Case Studies on Practical Implementation of Renewable Energy Models

Case studies provide real-world validation of modelling techniques and demonstrate their practical applicability. For instance, hybrid renewable energy systems combining solar photovoltaic (PV) and wind energy have been successfully implemented in remote and island regions using tools such as HOMER and RETScreen. These systems optimize energy production based on local climatic data and demand profiles, significantly improving reliability and reducing dependency on fossil fuels. In Denmark, integrated energy system models have been applied to achieve high renewable penetration while maintaining grid stability through sector coupling and smart energy systems [11].

Similarly, in India, solar microgrid projects in rural areas have demonstrated the effectiveness of AI-based forecasting models in predicting solar output and managing energy storage systems. These case studies highlight how modelling techniques support decision-making, improve system efficiency, and enable scalable deployment of renewable energy technologies [12,13].

Challenges in Integrating Renewable and Conventional Systems

While renewable energy systems offer sustainability benefits, their integration with conventional power systems presents several technical and operational challenges. One of the primary issues is intermittency, as renewable sources such as solar and wind are highly dependent on environmental conditions, leading to fluctuations in power generation. This variability complicates grid management and requires advanced forecasting and balancing mechanisms [11,14].

Another challenge is the lack of adequate energy storage infrastructure. Although technologies such as batteries, pumped hydro storage, and hydrogen storage are evolving, their high costs and limited scalability hinder widespread adoption. Additionally, existing grid infrastructure in many regions is not designed to accommodate decentralized and distributed energy systems, resulting in inefficiencies and transmission losses [13,15].

Importance of Visual Aids in Renewable Energy Modelling

To enhance clarity and improve reader comprehension, the inclusion of visual aids such as flowcharts, system architecture diagrams, and performance comparison graphs is highly recommended. For example, a schematic diagram of a hybrid renewable energy system (solar–wind–storage–grid) can effectively illustrate system components and energy flow. Similarly, graphs comparing predicted versus actual energy output using machine learning models can help validate modelling accuracy. Visualization tools not only simplify complex modelling

frameworks but also facilitate better interpretation of results, especially for interdisciplinary audiences and policymakers [12,17].

Socio-Political Dimensions of Renewable Energy Deployment

Beyond technical and economic considerations, socio-political factors play a critical role in the adoption and success of renewable energy systems. Government policies, regulatory frameworks, and institutional support significantly influence investment decisions and technology deployment. Incentives such as subsidies, tax benefits, and feed-in tariffs have been instrumental in accelerating renewable energy adoption in many countries [13,18].

Public acceptance and social awareness are equally important, particularly in projects involving large infrastructure such as wind farms and hydropower plants. Resistance from local communities due to environmental concerns or land-use conflicts can delay or hinder project implementation. Therefore, stakeholder engagement and participatory planning are essential components of sustainable energy development [19]. Additionally, geopolitical factors and energy security concerns drive nations to transition toward renewable energy to reduce dependence on imported fossil fuels. In developing countries, challenges such as financial constraints, lack of technical expertise, and policy inconsistencies further affect adoption rates. Addressing these socio-political barriers is crucial for achieving long-term sustainability and ensuring equitable energy access [20].

CONCLUSION

To conclude, modeling and assessing renewable energy production and application are crucial processes for successfully managing sustainable energy systems. With various approaches and modelling techniques, such as conventional physics, statistics, simulations, artificial intelligence, and machine learning, accurate insights are provided about the potential of energy sources, system operation, and prediction of energy output. Moreover, performance assessment and utilization strategy for sustainable energy projects help to make them more effective and address challenges associated with renewable sources, for example, their intermittence and variability, or issues related to imbalance between supply and demand. Apart from evaluating the technical performance of a sustainable energy project, its economic and environmental aspects must be taken into account to assess feasibility and viability in the future. Moreover, a sustainability evaluation of an energy source and sustainable system helps to make the development process much more holistic. Research gaps in the domain and perspectives for further development include, but are not limited to, new approaches to modelling energy systems based on AI, digital twins, energy storage facilities, and hybrid systems. The growing global need for energy together with negative effects of fossil fuel combustion has been driving humanity to switch to renewable energy resources. This research paper is dedicated to modelling and assessing the use of renewable energy, with an emphasis on reliable prediction, optimization, and performance assessment methods. The types of renewable energy, such as solar, wind, hydropower, biomass, and other forms, will be considered in light of their generation capability, effectiveness, and implementation within the energy industry. This paper covers a wide range of modelling techniques, from traditional mathematical modelling to modern machine learning and artificial intelligence-based approaches that can help to forecast energy generation and demands. Also, assessment tools and performance indices (energy efficiency, economic sustainability, environmental impacts, reliability) will be reviewed with a focus on hybrid energy systems and advanced smart grids. Moreover, challenges of renewable energy intermittency, storage solutions, grid connectivity, and regulatory frameworks will be addressed, with particular attention paid to innovations in energy storage technologies and digital energy systems.

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