Harnessing a Better Future: Exploring AI and ML Applications in Renewable Energy

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Abstract—Integrating machine learning (ML) and artificial intelligence (AI) with renewable energy sources, including biomass, biofuels, engines, and solar power, can revolutionize the energy industry. Biomass and biofuels have benefited significantly from implementing AI and ML algorithms that optimize feedstock, enhance resource management, and facilitate biofuel production. By applying insight derived from data analysis, stakeholders can improve the entire biofuel supply chain - including biomass conversion, fuel synthesis, agricultural growth, and harvesting - to mitigate environmental impacts and accelerate the transition to a low-carbon economy. Furthermore, implementing AI and ML in combustion systems and engines has yielded substantial improvements in fuel efficiency, emissions reduction, and overall performance. Enhancing engine design and control techniques with ML algorithms produces cleaner, more efficient engines with minimal environmental impact. This contributes to the sustainability of power generation and transportation. ML algorithms are employed in solar energy to analyze vast quantities of solar data to improve photovoltaic systems' design, operation, and maintenance. The ultimate goal is to increase energy output and system efficiency. Collaboration among academia, industry, and policymakers is imperative to expedite the transition to a sustainable energy future and harness the potential of AI and ML in renewable energy. By implementing these technologies, it is possible to establish a more sustainable energy ecosystem, which would benefit future generations.

Keywords— Machine learning; artificial intelligence; renewable energy; biofuel; biomass energy.

I. INTRODUCTION

As we work toward a more sustainable and fair future, the synergies between the Sustainable Development Goals (SDGs), ambitions for reaching net-zero emissions, and machine learning are becoming increasingly apparent [1]–[3]. This comprehensive framework for addressing global concerns, such as poverty, inequality, and climate change, is provided by the Sustainable Development Goals (SDGs) [4], [5]. By emphasizing climate action and environmental sustainability, net-zero targets, which aim to achieve a balance between the removal of greenhouse gases and the emissions of those gases, are closely aligned with these aims [6], [7]. Machine learning is critical in accelerating progress toward the SDGs and net-zero objectives [8], [9]. Machine learning can analyze massive volumes of data and recognize complex patterns [10], [11]. Through the utilization of machine learning algorithms, we can optimize the allocation of resources, enhance the efficiency of energy use, and develop novel solutions for the sustainability of development, system protection, and the mitigation of climate change [12]–[15]. Furthermore, machine learning improves decision-making processes by offering insights and predictive analytics [16], [17]. This enables governments, companies, and communities to make educated decisions that align with the SDGs and contribute to the achievement of net-zero emissions [18]–[20]. Integrating machine learning with the SDGs and net-zero objectives provides a potent way to address urgent global concerns and drive substantial progress toward a more sustainable and resilient future for everyone [21]–[23].

Recently, there has been a significant transformation in the renewable energy sector, establishing it as a crucial element in the global energy landscape, especially during the post-COVID-19 pandemic [24]. Renewable energy sources like solar, biofuels, wind, hydropower, biomass, and geothermal
energy are gaining popularity worldwide [25]–[32]. Solar power has become a significant player in the shift towards renewable energy sources [33], [34], benefiting from factors such as the decreasing costs of photovoltaic technology and supportive legislation [35], [36]. A surge in utility-scale solar installations and rooftop solar panels for residential and commercial buildings has been observed worldwide, aiming to increase the proportion of renewable energy contributing to energy systems and reduce greenhouse gas [37], [38]. In addition, solar energy could also be used for other purposes such as distillation, heat generation, and hydrogen generation [39]–[41]. Similarly, wind energy has experienced considerable growth, especially in regions with favorable wind conditions [42]–[44]. Wind farms, whether on land or at sea, are experiencing significant growth, with advancements in turbine technology enhancing their performance and output [45]–[47]. Both large-scale dams and smaller-scale projects play essential roles in harnessing hydroelectric power, a significant source of energy globally [48]. Aside from aiding in electricity production and heat generation, biomass and bioenergy, including organic and agricultural waste, play a crucial role in reducing carbon emissions across various industries [49]–[51]. In addition, municipal solid waste, including waste tire, plastic waste, and industrial waste, could also be reused to produce energy and value-added chemicals [52]–[55]. Geothermal energy is used to produce electricity and hydrogen, and for heating directly [56], [57]. Acquiring geothermal energy involves extracting heat from beneath the Earth's surface. Several worldwide trends fuel the growth of renewable energy sources [58], [59]. In recent years, there have been many studies relating to waste heat recovery, and the waste-to-energy path could also be a potential and promising solution for achieving green energy [60]–[63]. These trends encompass decreasing costs, technological advancements, regulatory support, efforts to combat climate change, and a growing recognition of the significance of environmental sustainability [64]–[66]. Despite facing challenges like grid integration and intermittency [67], [68], ongoing developments in energy storage [69], [70], using phase change materials [71]–[73], grid infrastructure [74], [75], and renewable energy forecasting [76]–[78] are addressing these issues and creating new opportunities for the expansion of renewable energy. Ultimately, renewable energy has transformed from a niche option to a widely adopted energy source, vital in the global shift towards a sustainable, low-carbon future [79]–[82].

There is a critical problem that requires an immediate response. That problem is the rising need for energy (used for industry, agriculture, and daily life) [83]–[85] and fuels (for transportation means such as ships, automobiles, and motive, motorcycles) [86]–[90] throughout the world. It is becoming increasingly vital for us to rely on various renewable energy sources, notably solar energy, as the requirements of humans continue to expand [91], [92]. We must switch to renewable energy sources like solar, wind, and hydrothermal energy because fossil fuels, which were previously the foundation of our energy systems, are now a large contributor to carbon dioxide released into the atmosphere [93], [94]. It is necessary to hasten the transition to clean energy as the dominant energy source to achieve global carbon neutrality [95], [96]. Not only does this need the development of new technologies, but it also necessitates the creation of superior materials that can give continuous energy output. This change is driven chiefly by solar energy, which may be converted into thermal energy by photovoltaic techniques and solar thermal conversion [97]–[99]. In addition, the technology of renewable fuel cells is gaining substantial momentum within the field of clean energy, notably in the context of battery-operated mobility. The following are recent studies discussing and summarizing various renewable energy domains as shown in Table 1.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Main outcomes</th>
<th>Study type</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar stills</td>
<td>The findings indicated that the operational factors of the solar still system with an inclined weir type had a substantial effect on the amount of water produced.</td>
<td>Experimental and modeling</td>
<td>[100]</td>
</tr>
<tr>
<td>Green hydrogen production</td>
<td>According to thorough evaluations and computations, Canada's total capacity for green hydrogen generation is 201.12 Mt, 205.69 Mt, and 211.17 Mt, based on proton exchange membrane, alkaline, and anion exchange membrane electrolyzers.</td>
<td>Analytical modeling</td>
<td>[101]</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>To improve efficiency, radiation is distributed non-uniformly.</td>
<td>Analytical modeling</td>
<td>[102]</td>
</tr>
<tr>
<td>Perovskite solar cells</td>
<td>According to a review of research, perovskite solar cells (PSCs) have potential as photovoltaic (PV) technologies because of their high-power conversion efficiency (PCE) and cheap manufacturing costs.</td>
<td>Review</td>
<td>[103]</td>
</tr>
<tr>
<td>AI-based prognostic modeling</td>
<td>AI-based GEP helped in model prediction and RSM helped in accurate optimization.</td>
<td>Analytical modeling</td>
<td>[104]</td>
</tr>
<tr>
<td>Optimization approach of biohydrogen production</td>
<td>Optimization of biohydrogen synthesis process with high accuracy.</td>
<td>Analytical modeling</td>
<td>[105]</td>
</tr>
<tr>
<td>Management of biochar yield</td>
<td>Application of ML for modeling-forecasting of biochar from biomass.</td>
<td>Review of modeling techniques.</td>
<td>[106]</td>
</tr>
<tr>
<td>Photovoltaic thermal system</td>
<td>Application of neural networks in the complex domain of PCM-based solar system.</td>
<td>Analytical modeling</td>
<td>[107]</td>
</tr>
<tr>
<td>Prediction of biofuel properties</td>
<td>Model-forecasting of biofuel properties and its use in diesel engines.</td>
<td>Analytical modeling</td>
<td>[108], [109]</td>
</tr>
<tr>
<td>Optimization of fuel consumption</td>
<td>AI-based optimization was employed for navigation time as well as fuel consumption.</td>
<td>Modeling</td>
<td>[110]</td>
</tr>
</tbody>
</table>
The field of renewable energy is characterized by a great deal of uncertainty, which is caused by a variety of causes, including variations in the weather, shifts in the demand for energy, and limitations presented by technology [111], [112]. When it comes to effectively integrating renewable energy sources into the existing energy infrastructure, dealing with these uncertainties creates a significant number of hurdles [113], [114]. In spite of this, the development of technologies such as artificial intelligence (AI) and machine learning (ML) is proving a substantial influence in addressing these difficulties and releasing the full potential of renewable energy sources [115][116]. Utilizing artificial intelligence and machine learning algorithms to examine large data sets derived from weather forecasts, historical energy production data, and other relevant sources can result in more accurate predictions for the generation of renewable energy [117],[118]. This can be accomplished through enhanced forecasting and planning. The provision of assistance to energy operators and grid management in the prediction of changes in supply and demand, the optimization of energy production schedules, and the effective planning for grid integration [119]–[121].

The incorporation of renewable energy sources into existing power grids requires the implementation of intricate control and optimization strategies in order to maintain the grid's stability and dependability. The application of artificial intelligence and machine learning techniques can improve grid management by dynamically modifying energy flows, monitoring energy storage installations, and predicting possible disturbances to the grid, minimizing disruptions to the system while ensuring the smooth integration of renewable energy sources of electricity [122], [123]. The application of artificial intelligence and machine learning algorithms to improve the design and operation of renewable energy systems, such as solar farms, wind turbines, and energy storage facilities, is called "enhancing energy systems." These technologies can improve energy efficiency, maximize production, and minimize operating expenditures. This may be accomplished by analyzing data about site conditions, equipment performance, and energy use patterns. The typical application of and timeline ML penetration in this domain is depicted in Fig. 1 [124].

![Fig. 1 Historical perspective of AI & ML penetration in the energy domain](image)

The application of artificial intelligence and machine learning algorithms has the potential to improve resource allocation in renewable energy projects. This can be accomplished by identifying the most suitable locations for new installations, selecting the renewable energy technologies that are most suitable for particular sites, and streamlining the distribution of resources such as land, materials, and labor [125], [126]. The optimization of project development procedures and the enhancement of the overall efficacy of investments in renewable energy are both positively impacted in this way. The utilization of artificial intelligence and machine learning technology enables the forecasting of maintenance needs in renewable energy infrastructure [127]–[129]. This is accomplished by analyzing data from sensors and monitoring equipment in order to identify potential equipment problems in advance. The use of this proactive strategy helps reduce the amount of time that equipment is down, extends its lifespan, and improves the reliability of the system [130], [131]. The uncertainties that exist within the sector of renewable energy provide complex issues that can be effectively addressed via the application of technologies that utilize artificial intelligence and machine learning. AI and ML are helping personnel working in the renewable energy sector to make well-informed decisions, improve system performance, and accelerate the transition toward a sustainable energy future. This is being accomplished through the utilization of data-driven insights,
predictive analytics, and sophisticated optimization techniques.

Examining the utilization of Artificial Intelligence (AI) and Machine Learning (ML) in renewable energy holds significant value for various purposes. It addresses the urgent need for sustainable energy solutions by exploring how AI and machine learning technologies could enhance the effectiveness, reliability, and expandability of renewable energy systems [132]–[134]. Furthermore, this publication illuminates the interdisciplinary nature of this emerging field, connecting renewable energy research with advancements in artificial intelligence and machine learning. Through synthesizing the latest research and emphasizing key patterns and challenges, it educates policymakers, industry stakeholders, and decision-makers on the potential outcomes of implementing AI and ML in renewable energy. A review article serves as a valuable educational tool for students, researchers, and professionals looking to enhance their knowledge of renewable energy and AI/ML applications. In general, writing a review article on this topic helps to expand understanding, inspire creativity, and accelerate the shift toward clean and sustainable energy.

II. MATERIAL AND METHODS

When looking for scholarly articles on the subject for a review, the Boolean search tactics were employed. These tactics use keywords and operators like AND, OR, and NOT to filter search results. A researcher starts by combining keywords linked to artificial intelligence and machine learning with those connected to renewable energy, utilizing “or” to include synonyms or similar phrases to capture a broader range of relevant articles. To ensure a thorough search, they may include related topics or technologies such as deep learning, neural networks, solar, wind, hydropower, or biomass was employed.

For searching particular applications of AI and ML in renewable energy, such as optimization, energy management, forecasting, or grid integration, these phrases were employed. Incorporating terminology associated with particular technologies or applications in the AI, ML, and renewable energy domains, such as smart grids, energy storage, or predictive maintenance, might also be advantageous. To discover the most recent study, the most recent years in their search were included. Combining these tactics allows a researcher to do a comprehensive search that covers all areas of their subject. However, the effectiveness of their search is heavily reliant on the database or digital library being utilized. Each platform has its syntax for Boolean searches; thus, the same was employed on platforms such as IEEE Xplore, Scopus, or Google Scholar. The related papers published in recent years have been growing at a good pace. The relationship between different terms in this domain is depicted in Fig. 2 [135].

III. RESULTS AND DISCUSSION

A. AI and ML Techniques in Renewable Energy Forecasting

1) Solar Power Forecasting:

The radiant energy of the sun is referred to as solar energy [136]. This energy is produced by the thermonuclear fusion of hydrogen gas, which results in massive amounts of electromagnetic energy. There is an average solar radiation intensity of 1367 W/m² on the surface of the planet, and the total global absorption of solar energy is around 1.8 × 1011 MW [137]. This amount of energy that is both ubiquitous and unlimited is more than sufficient to take care of the power requirements of the whole globe [138], [139]. The pursuit of a kind of energy that is both environmentally friendly and
sustainable has quickly become a serious worldwide concern, especially in the world that we live in today [140]. The fast collapse of conventional energy sources such as oil and fossil fuels, together with worldwide environmental issues such as global warming and the increased need for electricity and energy, are the primary factors that have led to the emergence of this crisis [141]. Solar photovoltaic cells are the most widely used and well-established green energy systems [142]–[144], which are employed to meet the growing need for energy on a worldwide scale. This is because solar PV cells are among the many environmentally friendly and renewable energy technologies that are now accessible [145], [146]. In the same way that other energy sources have their flaws, solar photovoltaic cells have their shortcomings and face a great deal of difficulty throughout the integration process [126], [147], [148]. Solar photovoltaic cells, on the other hand, are presently being employed in a tremendous variety of contemporary applications as a result of quick technical developments [149], [150]. Some systems create just a few watts, whereas others generate megawatts of electricity on a daily capacity [151], [152].

In the field of solar energy, the use of machine learning has grown more important since it provides innovative approaches to improvements in output and efficiency [153]. The use of solar energy is becoming more dependable and simpler to incorporate into current power networks as a result of advancements in predictive analytics and panel layout optimization [154], [155]. Machine learning has made significant strides in the field of solar energy, and one of its most important applications is in predictive analytics [156]. The ability of machine learning algorithms to anticipate solar power output with exceptional accuracy is achieved by the study of historical weather patterns, levels of solar radiation, and a variety of environmental factors [157], [158]. The capacity to operate the grid effectively requires this skill, which enables solar energy to be integrated more effectively with other sources of electricity. When it comes to guaranteeing a steady energy supply and lowering dependency on non-renewable energy backups, forecasting is an essential component. This, in turn, encourages the use of solar energy to a greater extent [159]–[161]. A typical work flow of solar power forecasting using ML is depicted in Fig. 3 [162].

Machine learning is very necessary in order to maximize the efficiency of the positioning and orientation of solar panels [163], [164]. By analyzing the patterns of sunshine, the topography, and other geographical aspects, machine learning algorithms are able to provide recommendations for the optimal locations and angles for the deployment of solar panels in order to maximize energy capture [165], [166]. When this process is optimized, not only does it increase the
efficiency of solar farms, but it also ensures that smaller, dispersed installations such as rooftop panels make a significant contribution to the production of electricity [167], [168]. An additional benefit of machine learning is that it assists with the maintenance and operation of solar power plants [169]. It is able to predict equipment faults or detect when solar panels are not performing properly due to dirt accumulation, damage, or other issues. Additionally, it can detect when solar panels are not functioning ideally. Through the use of predictive maintenance skills, issues may be rectified in a proactive manner, hence minimizing the chance of downtime and maximizing the effectiveness and durability of solar energy systems [170]–[172].

The creation of solar cells that are more efficient is another area in which machine-learning techniques aid [173]. The use of machine learning in the examination of vast amounts of data pertaining to the characteristics of materials and the designs of solar cells may reveal patterns and connections that human researchers would overlook, which ultimately leads to breakthroughs in solar cell technology [174], [175]. The results of this research might result in the creation of solar panels that are more efficient in terms of cost, which could hasten the process of solar electricity being more widely used [176]–[178].

In essence, the use of machine learning in solar energy is a major innovation that has the potential to improve the accessibility, efficiency, and integration of renewable energy into our energy systems [179]. It is projected that the use of machine learning technology in solar energy will increase as a result of its improvement, which will result in the creation of more inventive solutions in the field of renewable energy technologies [180], [181]. The following (Table II) is the summary of the use of different ML techniques in the domain of solar energy:

<table>
<thead>
<tr>
<th>Main theme</th>
<th>ML technique</th>
<th>Main outcome</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction of daily solar radiation</td>
<td>Multiple MLs</td>
<td>Artificial neural network (ANN) was superior to other test ML techniques</td>
<td>[182]</td>
</tr>
<tr>
<td>Daily solar radiation mapping</td>
<td>Six ML techniques</td>
<td>Extreme learning machine (ELM) combined with particle swarm optimization provided the best predictions among six test MLs</td>
<td>[183]</td>
</tr>
<tr>
<td>Prediction of daily and monthly solar radiations</td>
<td>ANN, support vector machines (SVM), adaptive neuro-fuzzy inference system (ANFIS), Gaussian process regression (GPR), Multiple linear regression (MLR), Radial basis function (RBF)</td>
<td>With a mean absolute percentage error (MAPE) of 5.1% and a root mean squared error (RMSE) of 0.29, the RBF model was able to predict solar radiation efficiently.</td>
<td>[184]</td>
</tr>
<tr>
<td>Use of Pearson correlation for solar energy forecasting</td>
<td>Random forest (RF), ANN, LR and SVM</td>
<td>ANN was superior with robust predictions</td>
<td>[185]</td>
</tr>
<tr>
<td>Photovoltaic (PV) power forecasting</td>
<td>GPR and SVM</td>
<td>Matern 5/2 GPR was superior in forecasting</td>
<td>[186]</td>
</tr>
<tr>
<td>Site selection and power forecasting using ML</td>
<td>Long short-term memory (LSTM), Gated recurrent unit (GRU), ANN</td>
<td>ML models outperformed conventional approaches by as much as 38% in the site adaptation test.</td>
<td>[187]</td>
</tr>
<tr>
<td>Comparative analysis of ML and conventional approaches for solar radiation and PV power</td>
<td>Maxwell and transportation models, SVM, RF RNN, LSTM, and GRU</td>
<td>The best prediction was by LSTM and GRU.</td>
<td>[188]</td>
</tr>
<tr>
<td>Application of multiple MLs for solar radiation</td>
<td>SVM, LSTM, GPR, ELM, and k-nearest neighbor (KNN)</td>
<td>LSTM and GPR could provide the best prediction results.</td>
<td>[189]</td>
</tr>
</tbody>
</table>

The incorporation of machine learning (ML) into solar energy systems ushered in a new age of efficiency and sustainability in the field of renewable energy [180]. The solar business is overcoming conventional difficulties, maximizing energy output, and improving system maintenance by using the predictive capabilities of machine learning (ML) [191]–[193]. Solar energy can be more successfully incorporated into the global energy mix thanks to the ability of machine learning to evaluate and learn from enormous quantities of data. This will result in a reduction in dependency on fossil fuels and will help mitigate climate change. The role that machine learning technologies play in enhancing the efficiency and dependability of solar energy systems will likely expand as these technologies continue to advance [194], [195]. This holds the promise of a more positive and environmentally friendly future powered by renewable energy [196]–[198].

2) Biofuel-based Energy Forecasting

As the principal source of energy, traditional fossil fuels continue to hold a dominant position [199]. Because of the ever-increasing demand and the ever-increasing population of the world, the dwindling stocks of fossil fuels provide a problem for the future supply of these resources [200], [201]. The ever-increasing need for energy may be satisfied by the effective production of biofuel that could be used for transportation means [202], [203]. The problem is further attenuated by the increasing greenhouse gases (GHGs) caused by the use of fossil fuels [199], [204]. Taking a holistic approach to addressing global environmental concerns and advancing sustainable development may be accomplished by analyzing the relationship between the Sustainable Development Goals (SDGs), the achievement of net-zero emissions, the exploration of alternative fuels, and the distinctive contribution of biodiesel [205], [206]. There is a need for several measures to combat climate change, reduce emissions, and ensure that everyone has access to sustainable
energy sources [207], [208]. This interconnection underscores the need for these initiatives [117], [209]–[211].

Goal 7 of the Sustainable Development Goals, which focuses on providing affordable and clean energy, and Goal 13 of the Sustainable Development Goals, which focuses on climate action, offer the foundation for a global transition to renewable energy sources and reducing carbon footprints [212]. Maintaining a balance between the greenhouse gases that are released into the atmosphere and those that are removed from the atmosphere is an essential component of achieving net-zero emissions, which will contribute to a future that is both sustainable and climate-resilient. The investigation of alternative fuels, such as biodiesel, biogas, bioethanol, and furan, is vital in the process of shifting to more sustainable choices that have the potential to successfully reduce emissions from transportation [213]–[216], which is a significant contributor to global greenhouse gas emissions [7], [17], [18].

The practical application of these relationships is shown by biodiesel, which is a sustainable biofuel that may be generated from vegetable oils, animal fats, or recycled cooking grease [219], [220]. In comparison to conventional fossil fuels, this product is not only non-toxic but also biodegradable and produces far less emissions. Making the switch from conventional fuels to biodiesel may be of great assistance to nations in achieving their net-zero objectives, improving energy security, reducing their dependency on imported fuels, and providing support to the local agricultural and recycling industries [221]–[222]. As an additional point of interest, the production and consumption of biodiesel contributes to Sustainable Development Goal 12 (Responsible Consumption and Production) by promoting resource efficiency and reducing waste. SDG 8 is advanced via the creation of job opportunities in the area of renewable energy, while SDG 9 is advanced through the promotion of scientific developments in the production and consumption of biofuels. Both of these goals are advanced through the inclusion into the energy mix [6], [23], [223].

The use of machine learning, a subfield of artificial intelligence, has revolutionized a wide range of sectors via the analysis of enormous amounts of data and the generation of predictions or judgments without the need for explicit programming for specific tasks [224]. The applications of this technology span a broad variety of domains, with the primary emphasis being placed on forecasting engine performance and emission frameworks, in addition to optimization.

When it comes to the performance of engines and the emissions they produce, machine learning algorithms are applied to foresee and improve engine operations in various circumstances. The engine's efficiency, the amount of fuel it uses, and the pollution levels may all be predicted by these algorithms via the analysis of sensor data and historical performance reports [225]–[227]. The literature reveals that engine researchers mainly focused on engine performance metrics like brake thermal efficiency (BTE), brake-specific fuel/energy consumption (BSFC/BSEC), peak cylinder pressure (PCP), and heat release rate (HRR) [228]–[232]. Also, on the emission side oxides of nitrogen (NOx), carbon mono oxide (CO), unburnt hydrocarbons (UHC), and carbon dioxide (CO₂), particulate matter (PM) [233]–[236] were reported. However, these parameters are quite sensitive to changes in engine operating parameters like compression ratio, fuel supply, fuel injection parameters, and engine hardware [237], [238]. The conventional methods of simulation and modeling are time-consuming and tiresome. Also, to support global activities aimed at lowering carbon footprints and tackling climate change, it is vital to place a primary emphasis on the development of engines that are both sustainable and efficient [239]–[241]. The use of machine learning models enables the modeling of a variety of situations, which in turn reveals ideal configurations that conventional experimentation techniques would overlook. Machine learning finds applications in mainly two domains: firstly, the model-prediction of engine performance and emission framework, and secondly in the optimization [242]. Some studies showed the usefulness and applicability of ML in this domain to effectively apply ANN for model and prediction of engine performance and emissions [110], [238], [243]. It could be observed that ANN was mainly used in this domain. Besides this other ML techniques like ANFIS [244], [245], XGBoost [246], GPR [247], Gene expression programming (GEP) [248], [249], SVM, and RF [250], [251] are being applied for model predictions.

On the other hand, optimization is a prominent application field that focuses on using machine learning to enhance processes and systems in various industries. In many industries, including manufacturing, logistics, and energy distribution, machine learning algorithms are particularly adept at evaluating complex information to identify the most efficient routes, production schedules, and distribution management techniques [242]–[252]. We can save costs and decrease our environmental impact if we optimize our performance. The use of machine learning to improve diesel engines that are fuelled by biodiesel includes predictive modeling, optimization of fuel injection, modeling of combustion, fault detection, and optimum control techniques [253], [254]. As an example, machine learning algorithms scrutinize biodiesel blends' compositions, the engine's state, and environmental elements to anticipate performance and emissions. Through the use of sophisticated models that mimic combustion in a variety of settings, they fine-tune the timing and pressure of fuel injection to maximize combustion efficiency. When it comes to defect detection, machine learning enables the rapid identification of abnormalities, which in turn facilitates the fast repair of infrastructure. Continuous optimization of engine settings is performed to improve fuel economy and lower emissions via the use of optimum control systems [255]. Machine learning enhances the performance of biodiesel engines, which results in these engines being more environmentally friendly and efficient than conventional diesel engines.

Even though the biofuel business has the potential to make a substantial contribution to the development of sustainable energy solutions, it is often confronted with several challenges that prevent its expansion and general adoption [256], [257]. The dispute that is usually referred to as the “food versus fuel” debate is a serious topic since it involves the struggle for agricultural land and water resources between biofuel production and food production [258]. There is a possibility that this rivalry may lead to a rise in the cost of food and will inspire concerns about food security, especially in regions with a scarcity of agricultural resources.
Furthermore, biofuels' consequences on the ecosystem are a complicated topic. Even though they could reduce greenhouse gas emissions in contrast to fossil fuels, the benefits can be nullified by the carbon footprint associated with changes in land use, farming, and the manufacturing of biofuels [259], [260]. Deforestation and a reduction in biodiversity are two consequences that might result from the transformation of land for the cultivation of biofuel crops under certain circumstances [261]–[263].

There is one additional challenge to take into consideration, and that is the financial viability of biofuels [264][265]. Biofuels typically depend on government subsidies and policy support to compete with conventional fuels. As a result of fluctuations in oil prices, the cost-competitiveness of biofuels might be affected, which can result in unclear market prospects [266]–[268]. In addition, the biofuel industry requires significant advancements in both technology and infrastructure to improve efficiency and reduce costs [269], [270]. This includes the production of biofuels from non-food sources such as agricultural waste and algae, as well as the establishment of the necessary distribution and retailing networks to make biofuels accessible to consumers [271], [272]. Last but not least, it is essential to consider the social and ethical issues, such as the impact that widespread biofuel production has on the communities located nearby, the rights of landowners, and the development of rural areas. To successfully address these difficulties, it is essential to adopt a holistic strategy that considers the economic, environmental, and social elements of the production and use of biofuels. In this way, it will be possible to guarantee that the expansion of the biofuel business plays a positive part in the global move toward energy systems that are both sustainable and environmentally friendly [273]. A typical flow chart showing the application of intelligent approaches in this domain is depicted in Fig. 4 [274].

![Flow chart showing the application of intelligent approaches in the biofuel domain](image)

The biofuel sector has a wide variety of challenges, and machine learning offers several intriguing opportunities to address and overcome these challenges. Through data analysis and predictive modeling, machine learning has the potential to enhance the efficiency, sustainability, and economic viability of the production and consumption of biofuels. Here are some of the ways that machine learning might be beneficial to the biofuel industry:

- Large amounts of agricultural data, including weather patterns, soil conditions, and crop health, may be examined with the use of machine learning algorithms to anticipate and improve crop yields, notably for the production of biofuels [275]. By optimizing this process, we can solve the argument over the "food versus fuel" issue by increasing the efficiency of the production of biofuel crops. Consequently, this might result in the creation of greater output with less amount of land, thus protecting more area for the production of food.

- Through the use of machine learning models, one may improve their understanding of the complex biochemical processes that are involved in the synthesis of biofuels [276]. Due to the fact that these models are able to forecast the most efficient processing methods and ideal conditions for converting biomass into biofuels, they are able to reduce the amount of energy that is used and the amount of waste that is produced throughout the manufacturing process [277].
manufacture of biofuels has the potential to have a smaller carbon footprint and fewer negative impacts on the environment if artificial intelligence is used to optimize these methods.

- By using machine learning, the process of developing advanced biofuels from non-food sources such as agricultural residue, algae, and cellulosic materials may be accelerated, resulting in much faster advancement. The most advantageous feedstocks and growing techniques may be identified by machine learning algorithms via the examination of genetic data and growth circumstances. This helps to improve sustainability and reduce the amount of rivalry with food production [278].

- It is possible to develop accurate projections for biofuel demand, pricing, and competitiveness by using machine learning algorithms to undertake an analysis of market patterns, oil prices, and policy influences. To improve the economic viability of biofuels, this research may be of assistance to biofuel producers and investors in making choices that are well-informed, getting finance, and reacting to changing market circumstances [279].

- For biofuels to be widely used, it is necessary to ensure that they are distributed effectively from production facilities to end-users. Machine learning has the potential to improve logistics and supply chain operations, resulting in reduced transportation costs and emissions. Additionally, it will ensure that biofuels are delivered to high-demand markets in an efficient manner [280].

- Machine learning algorithms are able to evaluate the environmental consequences of biofuels over their whole lifespan. These effects include but are not limited to changes in land usage, water consumption, and emissions of greenhouse gases [281].

By addressing these difficulties, machine learning improves the efficiency and long-term viability of the biofuel business and contributes to the sector's growth and integration into the global energy environment. With the ongoing development of machine learning technologies, it is anticipated that their influence on the biofuel business will increase dramatically, ultimately resulting in the creation of more environmentally friendly and economically viable biofuel solutions. Table III lists the summary of the application of different ML techniques in the domain of solar energy:

<table>
<thead>
<tr>
<th>Main theme</th>
<th>ML technique</th>
<th>Main outcome</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction of biodiesel characteristics and fatty acid profile</td>
<td>LR, RF, XGBoost, and SVM</td>
<td>Using a machine learning framework to forecast biodiesel fuel properties based on its fatty acid composition</td>
<td>[282]</td>
</tr>
<tr>
<td>Predictive modeling of biodiesel production</td>
<td>RF and AdaBoost</td>
<td>AdaBoost was efficient in the optimization of process parameters</td>
<td>[283]</td>
</tr>
<tr>
<td>Model forecasting of engine operation</td>
<td>ANN and response surface methodology</td>
<td>The study uncovered that ANN-RSM is a valuable hybrid technique for model-prediction.</td>
<td>[284]</td>
</tr>
<tr>
<td>Evaluation and forecasting to determine biodiesel purity</td>
<td>Alternating model tree, RF, MLP-ANN, and least median square</td>
<td>Results reveal that the AMT stands out as the top forecasting technique.</td>
<td>[285]</td>
</tr>
<tr>
<td>Forecasting of biodiesel production</td>
<td>Bayesian-optimized SVR and ANN</td>
<td>Hybrid SVR approach outperformed the other approach</td>
<td>[286]</td>
</tr>
<tr>
<td>Model-prediction of engine performance</td>
<td>ANN</td>
<td>The hybrid approach could accurately predict the engine performance</td>
<td>[287]</td>
</tr>
<tr>
<td>The modeling forecasting of biofuel-powered engine</td>
<td>ANN-Generic algorithm – RSM</td>
<td>A triple-blended biofuel-powered engine performance could be modeled with more than 90% accuracy.</td>
<td>[288]</td>
</tr>
<tr>
<td>Emission and performance prediction of engine running on biofuel blends</td>
<td>ANN-RSM</td>
<td>It was observed that RSM could optimize, and ANN could accurately predict the biofuel-powered engine.</td>
<td>[289]</td>
</tr>
</tbody>
</table>

Using machine learning (ML) in the biofuel industry is a significant step toward creating an energy environment that is more environmentally friendly and efficient. Artificial intelligence (ML) provides exciting solutions for tackling issues in the biofuel business because of its capacity to evaluate big datasets, forecast results, and enhance procedures. Machine learning is vital for the economic and environmental success of biofuel production since it allows for the optimization of crop yields, the enhancement of production procedures, and the development of new feedstocks. In addition, machine learning makes it possible to do market research, optimize supply chain operations, and evaluate environmental impact, which provides stakeholders along the biofuel value chain with helpful information [290]. As the need for renewable energy continues to rise, the role that machine learning plays in fostering innovation and speeding the adoption of biofuels is becoming more critical.

To unlock the full possibilities of machine learning in the biofuel business, academics, industry participants, and policymakers will need to collaborate to overcome technological, economic, and regulatory constraints. Biofuels that have been enhanced via ML-based optimization and innovation might make a big contribution to the transition to a more sustainable energy future [291], [292]. This is because considerable focus has been placed on addressing difficulties, which has led to breakthroughs in machine learning technology.

3) Biomass Energy Forecasting

A comprehensive approach to combating climate change and achieving sustainable development goals may be accomplished by investigating the relationship between biomass usage, the pursuit of net-zero emissions, the generation of renewable energy, and the reduction of
Biochar can potentially increase soil fertility and carbon sequestration properties \cite{311}, \cite{312}. Similarly, CCS systems are two ways in which biomass energy systems may function as carbon sinks in addition to their ability to reduce direct greenhouse gas emissions \cite{259}. Biochar, for example, is a stable form of carbon that is produced by the pyrolysis of biomass. When applied as a soil supplement, biochar can potentially increase soil fertility and carbon sequestration properties \cite{311}, \cite{312}. Similarly, CCS systems can sequester carbon dioxide (CO\textsubscript{2}) emissions from biomass power plants or bioenergy facilities beneath the ground, effectively removing carbon from the atmosphere \cite{313}, \cite{314}. In addition, biomass energy is compatible with other renewable energy sources, such as solar and wind power, and it provides reliable electricity production, which contributes to the maintenance of grid stability and the fulfillment of shifting energy needs \cite{212}. Because power plants that use biomass can quickly modify their output to complement intermittent renewable sources, they are able to provide a consistent energy supply and reduce the need for backup power from fossil fuels \cite{315}, \cite{316}. Additionally, sustainable land management techniques are included in the relationship between the use of biomass and the reduction of greenhouse gas emissions \cite{317}, \cite{318}. This connection extends beyond the production of electricity. For the purpose of increasing biomass production, improving carbon sequestration, and promoting biodiversity conservation, the implementation of agroforestry, reforestation, and afforestation initiatives might be beneficial. The production of biomass in conjunction with environmentally responsible land management methods is an approach that plays a significant part in bolstering the resilience of ecosystems and aiding attempts to adapt to climate change \cite{319}, \cite{320}.

Therefore, it is vital to carefully examine sustainability criteria to fully harness the potential of biomass in terms of achieving net-zero emissions and mitigating greenhouse gas emissions \cite{321}. When it comes to producing sustainable biomass, it is of the utmost importance to prioritize preserving the environment, preserving biodiversity, and the promotion of social fairness. This should be done without disrupting food production or the natural ecosystems. When it comes to ensuring the responsible sourcing and exploitation of biomass, it is essential to establish certification programs that are open and transparent, robust regulatory frameworks, and the participation of stakeholders \cite{322}–\cite{324}.

The use of biomass, the pursuit of net-zero emissions, the implementation of renewable energy, and the reduction of greenhouse gas emissions constitute a holistic strategy for combating climate change and furthering sustainable development \cite{325}. Exploring biomass energy systems may provide a flexible and sustainable energy source that plays a vital part in reducing greenhouse gas emissions, assisting in the transition towards a low-carbon economy, and enhancing the resilience of ecosystems \cite{326}, \cite{327}. Through the strategic usage of biomass in a way that is both sustainable and integrated, communities have the opportunity to achieve ambitious climate targets while simultaneously fostering economic growth, energy stability, and environmental conservation \cite{328}, \cite{329}.

Even though biomass energy has the potential to be a source of renewable energy, the industry faces several severe hurdles that prevent it from being widely adopted and from being scalable \cite{330}, \cite{331}. One of the most significant challenges is the rivalry for biomass resources that exists between other industries, such as the production of food and the preservation of land \cite{332}, \cite{333}. The "food versus fuel" debate is sparked when agricultural land formerly used for food production is diverted to produce energy crops \cite{294}, \cite{334}. This raises concerns about food security, changes in land usage, and deforestation. It is necessary to engage in careful land-use planning and sustainable management methods to avoid unfavorable impacts on the environment and society and achieve a balance between biomass production for energy and other essential requirements \cite{335}–\cite{337}.

The variable nature of biomass feedstocks and their accessibility is another challenge the biomass energy business must contend with \cite{338}. The availability of biomass is affected by seasonal variables, weather conditions, and agricultural cycles, in contrast to fossil fuels, which can be collected and stored for lengthy periods \cite{339}. Because of this fluctuation, there are uncertainties in the supply chains of biomass, which ultimately affects the reliability and cost-efficiency of the generation of biomass energy. When it comes to the logistics and transportation of biomass feedstock, issues arise, especially in rural and distant places that have little or inadequate infrastructure \cite{340}, \cite{341}.

In addition, the widespread adoption of biomass energy systems is hampered by difficulties of technological and technical character. Combustion, gasification, and anaerobic digestion are examples of technologies that may be used to convert biomass \cite{342}–\cite{343}. These technologies need
sophisticated machinery and complex procedures, which can be costly to set up. Because the use of either inefficient or obsolete technologies may impede the economic viability of biomass energy projects, efficiency and scalability are two of the most important elements to consider. The inclusion of biomass energy into existing energy systems and grids involves some technological challenges, particularly around grid stability, energy storage, and system flexibility [344], [345]. This is especially true when biomass is exploited in conjunction with intermittent renewable energy sources such as solar and wind power.

Addressing the issue of environmental sustainability continues to be a big concern for business that deals with biomass energy [346], [347]. However, inappropriate ways of producing and using biomass may lead to undesirable environmental impacts such as deforestation, soil degradation, and the loss of biodiversity. This is even though biomass has the potential to reduce greenhouse gas emissions in contrast to fossil fuels [348]. The implementation of stringent sustainability standards, the performance of lifecycle assessments, and the establishment of regulatory frameworks to guarantee the responsible sourcing, production, and utilization of biomass feedstocks are all necessary steps to take to ensure that the environmental benefits of biomass energy are balanced with its potential environmental drawbacks.

Several factors play a key role in determining the growth and development of the biomass energy industry, including economic and regulatory problems. There are several factors that might present obstacles to the development of biomass energy projects and investments, including policy frameworks, government backing, and changes in the energy market [349], [350]. Additionally, the lack of financial incentives and market strategies to capitalize on the environmental and social benefits of biomass energy adds to the complexity of its economic viability and attraction to investors. This is because there are no market methods to profit from these benefits [351], [352].

In order to effectively address these difficulties, a complete approach is required, one that incorporates technical improvements, regulatory support, the participation of stakeholders, and sustainable management practices [353]. By overcoming these challenges, the biomass energy industry has the potential to have a stronger influence in the fight against climate change, the enhancement of energy security, and the promotion of sustainable development [354]. Machine learning offers promising solutions for overcoming the many challenges that the biomass energy business faces, to enhance its efficiency, environmental friendliness, and viability from a financial standpoint [355], [356]. Machine learning may help handle these difficulties in a number of different ways, including the following:

- **Improving the Management of Biomass Resources:** Machine learning algorithms are able to analyze a wide variety of data sources, including satellite imaging, climate data, and soil information, in order to improve the management of biomass resources [357]. An improvement in decision-making about land usage, crop selection, and harvest schedules may be supported by machine learning [358]–[360]. This can be accomplished via the study of biomass availability, growth patterns, and quality. The goal is to increase biomass output while simultaneously reducing environmental damage [361].

- **Improving the Logistics of the Biomass Supply Chain:** Machine learning has the potential to improve the logistics of the biomass supply chain by predicting demand, optimizing routes, and scheduling operations in an efficient manner. In the end, machine learning algorithms have the potential to improve inventory management, reduce transportation costs, and reduce the amount of biomass that is lost during storage and transit. This will eventually lead to an increase in the efficiency of the generation of biomass energy [322], [362].

- **Improving the Processes of Biomass Conversion:** Machine learning has the potential to improve the efficiency and functionality of several technologies that are used for the conversion of biomass [363]. These technologies include combustion, gasification, and analytical digestion. Machine learning algorithms may improve operating parameters, discover abnormalities, and anticipate equipment problems by analyzing process data and sensor readings [364], [365]. This eventually results in a reduction in downtime and an increase in energy output. It is also possible for machine learning to assist in the development of technologies for the conversion of biomass by accelerating the identification of materials, the optimization of processes, and the enhancement of designs [366], [367].

- **Support for environmental sustainability:** With the use of machine learning, environmental sustainability may be supported. Machine learning can assist in the prediction of environmental consequences, the optimization of land use, and the assistance of regulatory compliance for sustainable biomass production and consumption methods [368], [369]. Machine learning algorithms can analyze the environmental effects of biomass energy projects by conducting an analysis of environmental data and simulating ecosystem dynamics [370], [371]. The planning of land use and the formulation of policies may both benefit from this knowledge. In addition, machine learning may be of assistance in the monitoring and protection of ecosystems, providing support for projects that aim to preserve sustainable biomass production while also being responsible to society and the environment [372].

- **Providing Assistance with Market Analysis and Policy Development:** Machine learning can analyze market patterns, assess the consequences of policies, and provide assistance with decision-making about investments in biomass energy and formulation of policies [373], [374]. Machine learning algorithms can identify market opportunities, estimate energy demand, and assess the economic viability of biomass energy projects. This is accomplished by studying market data, customer preferences, and regulatory frameworks. Furthermore, machine learning may be used to aid in policy analysis and scenario modeling [375], [376]. This can provide policymakers with insights into the possible implications of different policy interventions and assist in developing effective strategies for increasing the use of biomass energy.

A summary of different ML techniques used for biomass energy is listed in Table IV.
In general, machine learning offers a variety of opportunities to solve difficulties that are often encountered in the biomass energy business. These include the enhancement of resource management, supply chain logistics, conversion processes, and environmental sustainability. Through the use of machine learning technology, the biomass energy business has the potential to uncover novel opportunities for progress, efficiency, and environmental friendliness, so contributing to the transition towards a more sustainable and strong energy landscape [12], [14].

B. Future Perspectives and Challenges

An investigation into the use of machine learning (ML) techniques in the area of renewable energy indicates a future that is both complicated and exciting, with a variety of views and obstacles. To successfully navigate the route towards renewable energy systems that are more efficient, reliable, and sustainable, boosted by machine learning technologies, it is essential to have a solid understanding of these dynamics.

1) Future perspectives

Recent Developments in Algorithms for ML: The development of machine learning in the field of renewable energy is contingent on developing sophisticated algorithms built expressly for the unique characteristics of renewable energy systems. Deep learning architectures, reinforcement learning approaches, and hybrid models are being investigated to improve the management of complex and nonlinear interactions in energy data [48], [387].

Real-time predictive analytics: In the case of renewable energy systems, the improvement will be made possible via the use of machine learning technology, which will increase the accuracy of energy production, demand, and grid operations forecasting [12], [388]. The management of energy, the stability of the grid, and the inclusion of variable renewable energy sources like solar and wind power into existing power systems will all be improved as a result of this [389], [390].

Autonomous energy system: It is anticipated that energy systems will evolve to be self-sufficient and driven by machine learning. These systems will be able to optimize themselves, adapt to changing conditions, and continue to be robust in the face of environmental shifts, variations in energy consumption, and market volatility. The purpose of these systems is to improve the efficiency of energy production, distribution, and consumption, with the eventual goal of fostering enhanced energy independence and sustainability [391], [392].

Integrated approach: Decentralized intelligence and decision-making inside renewable energy systems will be made possible via the process of connecting machine learning algorithms with Internet of Things sensors and edge computing technologies. Real-time monitoring, control, and optimization of energy assets at the local level will be made possible as a result of this, which will result in improving energy efficiency and grid resilience [393], [394].

Collaboration: In the future, research will emphasize interdisciplinary cooperation among experts in renewable energy, data scientists, and domain specialists to develop complete solutions for the difficulties that are found at the intersection of energy, the environment, and society. Moreover, enhancing the awareness of understanding of the importance of environmental protection is very important [395]. Through collaborative efforts, we will be able to develop cutting-edge machine-learning applications that will have a substantial influence on the field of renewable energy.

2) Challenges

Quality and availability of data: Quantity and quality of the data that is accessible is one of the problems that must be overcome [396]. When it comes to using machine learning for renewable energy, one of the most significant challenges is the need for a large quantity of diverse data to properly train machine learning models [397]. It is very necessary to have access to data sets that are dependable, comprehensive, and representative to construct machine learning models that are accurate and robust for applications using renewable energy [398], [399].

Understanding and Clarity: To establish trustworthy relationships with stakeholders and win their support,
machine learning models that are used in renewable energy systems need to be simple to understand and straightforward to comprehend. It will be vital to improve the understandability of machine learning models and explain the decision-making methods associated with them in order to ensure that they are widely accepted in energy planning, policy-making, and operational procedures [400], [401].

Scalability and Generalization: To be effective, machine learning algorithms need to be able to scale up and generalize over a wide range of geographical locations, climates, and renewable energy technologies. As a prerequisite for their use in real-world renewable energy systems, the development of machine learning solutions that are capable of scaling and adapting to a wide range of settings and data sources is essential.

Energy efficiency: When it comes to machine learning algorithms and computer infrastructure, the consumption of energy may be a major worry because of the environmental and economic ramifications it has, especially when it is used on a big scale [402]. For the purpose of minimizing the impact that machine learning technologies have on the environment, it is vital to develop energy-efficient machine learning algorithms and hardware accelerators, as well as to fine-tune computing resources for applications that include renewable energy [403], [404].

Ethical issues: Take into account the following about the ethical and social impacts: Concerns surrounding privacy, prejudice, fairness, and accountability are raised when policy-making, and operational procedures [400], [401].

To address these forthcoming opportunities and challenges, it is necessary for academics, policymakers, industry stakeholders, and members of civil society to work together. This will allow them to capitalize on the revolutionary influence that machine learning can have in driving renewable energy toward a more sustainable and equitable future ahead. By overcoming these challenges and making the most of the opportunities presented by machine learning, we will be able to accelerate the transition to a more sustainable energy environment that is driven by advancements in renewable energy [407].

IV. CONCLUSION

It is concluded that the use of AI and ML in the field of renewable energy, especially in biomass, biofuels, engines, and solar power, has the potential to substantially transform the energy industry. A significant amount of progress has been made in boosting efficiency, dependability, and sustainability in a variety of industries via the combination of artificial intelligence and machine learning technologies with renewable energy sources. When it comes to biomass and biofuels, developments in artificial intelligence and machine learning algorithms have significantly improved approaches to managing biomass resources, optimizing feedstock, and the generation of biofuels. Using data-driven insights and predictive analytics, researchers and industry stakeholders can improve the efficiency of the biofuel supply chain. This includes the growth and harvesting of crops, as well as the conversion of biomass and the synthesis of fuel. The optimization of this process not only increases the economic viability of biofuel production but also reduces the negative impacts on the environment and accelerates the transition toward a low-carbon economy.

In addition, using artificial intelligence and machine learning in both engines and combustion systems has led to considerable improvements in engine performance, emissions reductions, and fuel economy improvements. These advancements have a significant potential to enhance the sustainability of transportation and power production, which will eventually contribute to the worldwide measures being undertaken to battle climate change and reduce harmful levels of air pollution. Artificial intelligence and machine learning are valuable tools within the solar energy sector, particularly in enhancing the efficiency and reliability of solar photovoltaic (PV) systems. Machine learning algorithms can analyze vast amounts of solar data, including irradiance levels, weather patterns, and system performance indicators, to improve the design, operation, and maintenance of photovoltaic (PV) systems. This optimization aims to optimize energy output, decrease downtime, and boost overall system efficiency. As a result, the cost-effectiveness and accessibility of solar energy will be increased.

As we look to the future, it will be essential to continue research and innovation in artificial intelligence and machine learning for renewable energy to overcome the challenges that still exist and uncover new opportunities. To put these achievements into practice in a realistic manner and accelerate the global transition toward a sustainable energy future powered by renewable sources, it is vital to collaborate with academics, industrial partners, and policymakers. By using artificial intelligence and machine learning, we can build a more sustainable energy ecology for the generations who will come after us.

REFERENCES


