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Advancements in Bifacial Photovoltaics: A Review of Machine Learning Techniques for Enhanced Performance

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Abstract: Bifacial photovoltaics have gained a lot of popularity in recent years given their ability to utilize scattered and reflected solar radiation from both sides of the panel. Although the price of a Bifacial module is generally higher than conventional mono-photovoltaic panel, it compensates for the higher energy generation per unit area. Even though the potential of Bifacial photovoltaics market is promising, their applications are still limited compared to mono-photovoltaics. However, researchers have been experimenting with Bifacial photovoltaics to exploit their capabilities in different applications and working scenarios, especially with Artificial Intelligence (AI) models. This study will focus on reviewing different Machine Learning (ML) algorithms that have been exploited and modified in order to be used with Bifacial system applications in the last three years of literature. Moreover, most popular ML algorithms are presented and discussed with respect to different Bifacial system parameters. Finally, a conclusion of future prospects and the potential of ML in bifacial photovoltaic industry and applications is presented.

Keywords: Bifacial, Photovoltaics, Machine learning, Renewable energy

Introduction

Green and sustainable power generation plants have become a necessity in almost every country around the world. The most popular and reliable type of renewable energy plants is photovoltaic systems (Renewables, 2018). Solar photovoltaic power plants can be found almost everywhere around the globe. Their efficiency, ease of installation, and reliability made the photovoltaic industry one of the most growing renewable energy industries. In fact, the collective installed photovoltaic systems are expected to reach 1.5 TW of capacity by 2030 (GlobalData, 2019). These numbers might increase with the continuous growth and advancements that we witness in photovoltaics technologies. The average power conversion efficiency of conventional solar photovoltaic panels is hovering over the 20% benchmark in the market (Zheng et al., 2019). However, with the current type of photovoltaics being utilized, the large areas which these systems cover will become a problem in the near future. Therefore, floating photovoltaic plants have become an alternative solution in certain regions with limited land areas (Haas, et.al, 2020; (Scavo et al., 2021).

To compensate for the area problem, a new bifacial solar photovoltaic module was introduced in the market lately. A typical bifacial solar photovoltaic panel consists of two layers of photovoltaic cells, one on the top face,

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like a conventional panel, and one on the back of the panel (Manasrah et al., 2023). The design allows the panel to exploit the solar irradiance from both sides, taking advantage of the scattered and reflected radiation in the process. This feature gives bifacial solar photovoltaic panels up 30% power gain over conventional mono-facial panels with the same panel area (Jang & Lee, 2021). Typically, bifacial photovoltaic systems cost more than conventional ones, however, the price gap is decreasing every year. Nevertheless, researchers have started to experiment with bifacial photovoltaic panels to exploit their capabilities and potential in energy generation. These studies included investigating alternative or modified materials (Yang et al., 2020; Vimala et al., 2023) and formfactors (Choi et al., 2023) with different configurations.

Another type of experimentation with bifacial photovoltaics is the application of Artificial Intelligence (AI) models in such systems. AI technologies provide computational devices that have the ability to receive information, understand it, and respond to it intelligently. Machine Learning (ML) algorithms are considered a subset of AI that can actually improve its responses from experience. These algorithms, namely, can be a powerful tool that is able to detect and predict future events in the performance of bifacial photovoltaic systems. Many recent studies can be found in the literature about this topic, therefore, there is a need to collectively analyze and compare the different approaches in these studies. However, very little research papers have reviewed the different ML algorithms that were investigated with bifacial photovoltaic systems. In this study, a miniature review is presented to summarize the latest advancements in bifacials with ML for the last three years in literature. The goal of this review is to shed light on the most popular ML algorithms that are implemented with such systems and their effect on the performance of bifacials. This study will also discuss the prospects and future of predictive models that are used in bifacial solar photovoltaic applications.

On Bifacial Solar Photovoltaics

The concept of bifacial solar module was first introduced in 1983 (Eguren, 2022) where the technology has been around since the 1960s. However, the technology did not pick up in the market until 2016-2017 (Kopecek & Libal, 2021) when the prices of crystalline silicon (c-Si) wafers dropped dramatically. Figure 1 shows the accumulated power of bifacial systems in the world in the past 10 years. The working principle of a bifacial cell is simple and takes advantage of light passing through it. A typical bifacial cell works just like a mono-facial cell where a portion of the direct sunlight is absorbed and converted into electricity by the cell. However, the bifacial cell also converts reflected and scattered light into electricity from both of its faces in what is known as the albedo effect (Riedel-Lyngskær et al., 2022). Figure 2 illustrates the concept of bifacial and mono-facial panels.

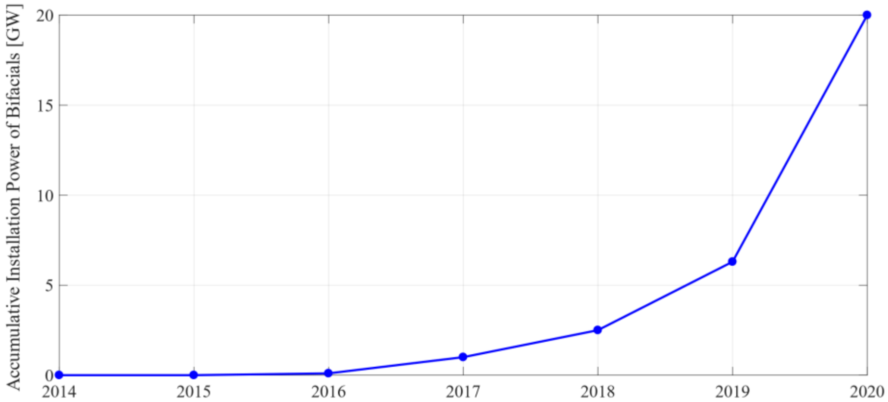

Figure 1. Accumulated power of bifacial systems in the world (Kopecek & Libal, 2021).

While mono-facial module systems can be installed in a “fixed” mode, facing one direction (Manasrah et al., 2021), or in a “tracking” mode, bifacial photovoltaic systems can be installed vertically, horizontally, or on a slant (facing either South, or North) if the system is in a “fixed” mode. However, bifacial systems can also be installed in “tracking” mode to maximize the generated power gain. Figure 3 shows the output power of fixed and tracking bifacial system setups against the time of the day.

A bifacial power gain is the amount of extra energy generated from the backside of a bifacial module which is always a fraction of the conventional energy generated from the front side (Gu et al., 2020) which is referred to as “bifacial ratio”. Power gains in bifacial modules can reach up to 30% of the maximum rated power if it was a mono-facial module with the same size and number of cells. Therefore, it is safe to assume that a bifacial system can generate up to 30% more power than a mono-facial system within the same covered area and modules size.

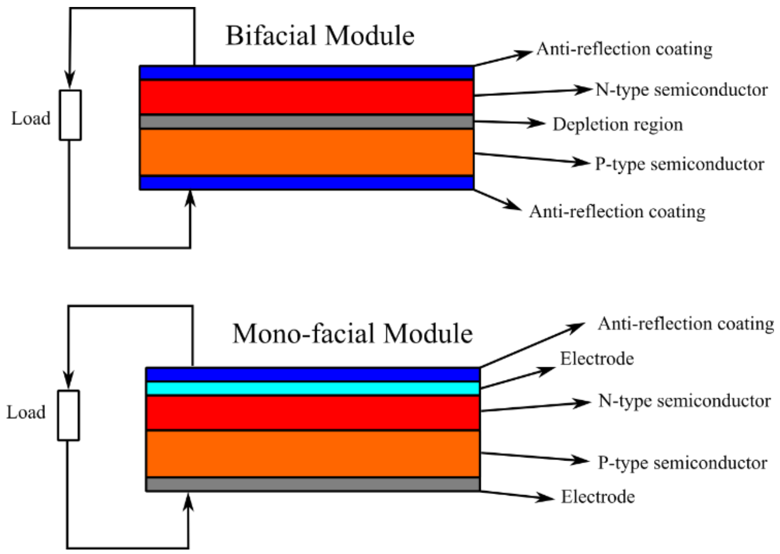

Figure 2. Working principle of mono-facial and bifacial cells (Gu et.al., 2020).

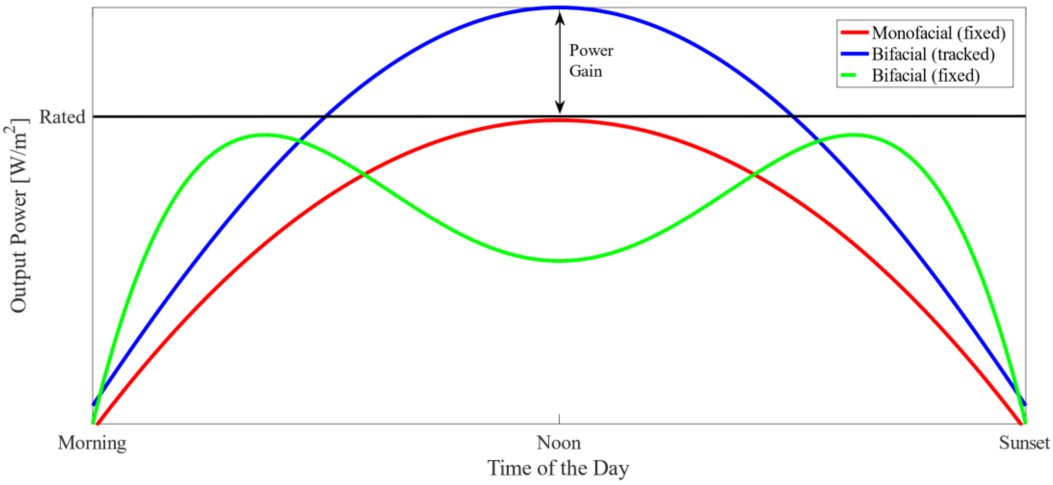

Figure 3. Output power of two bifacial setups (Kopecek & Libal, 2018).
[Curves not based on experiments data]

Of course, when talking about reflected sunlight, it is assumed that the bifacial system should be well above the ground. Increasing the height of the system could increase the installation cost. However, there is a simple approach to determining the optimal height of a bifacial system above the ground which is called in the industry as the "normalized height" (Raina et al., 2022). This will be the ratio between the width of the system and its actual height above the ground. As the system gets larger (i.e., width of the system), its height above the ground should be increased as well to maintain a normalized height. Hence, the reflected irradiance remains the same no matter how large the system is.

On Machine Learning (ML)

There is no doubt that AI and ML products have bloomed in the last decade. The technology entered almost every field of the industry from smartphones (Masoud et al., 2019) through business (Masoud et al., 2021) and communication networks (Jannoud et al., 2021), all the way to even water disinfection technologies (Bashayreh et al., 2021), e-commerce (Loukili et al., 2023), healthcare (Alanazi, 2022), and manufacturing (Kumar et al., 2023). However, there is a common misconception about the differences between AI and ML. Artificial intelligence (AI) is a broad field that refers to the technologies used to build machines that are able to mimic the human intelligence (i.e., receive, understand, and respond). On the other hand, Machine Learning (ML) is a subset of AI that gives the system the ability to learn and improve with time and experience. The learning process depends on many algorithms that are used to analyze input data. In other words, ML is considered to be the application of AI that allows a system to learn and improve.

Machine learning (ML) can be divided into three main branches: supervised learning, unsupervised learning, and reinforcement learning. Each branch has many algorithms that can be implemented in the forms of mathematical formulas that can be trained. For instance, supervised learning consists of algorithms that deal with input-output data samples called pairs. These pairs need to be “labeled” by a human supervisor, hence the name. This labeling process could be time-consuming or complex if we are dealing with large sets of data (Jaskie et al., 2021). The predicted results are then compared to the labeled pair and the error is used as feedback to improve the prediction based on the mathematical model. Unsupervised learning, on the other hand, does not require data labeling in the process. Instead, the generated models learn on their own to discover patterns in the data structure (Alloghani, et al., 2020). Clustering and reducing data dimensionality are very common examples of this type. In reinforcement learning, ML algorithms provide an “agent” from data that performs an “action” based on the state received from the environment. If the action of the agent is not accurate, it gets a “punishment” in a reward shaping process. This technique is designed to encourage or discourage agents to take more accurate decisions or not repeating previous ones, respectively. Figure 4 shows all three main types of ML with a few examples from each of them.

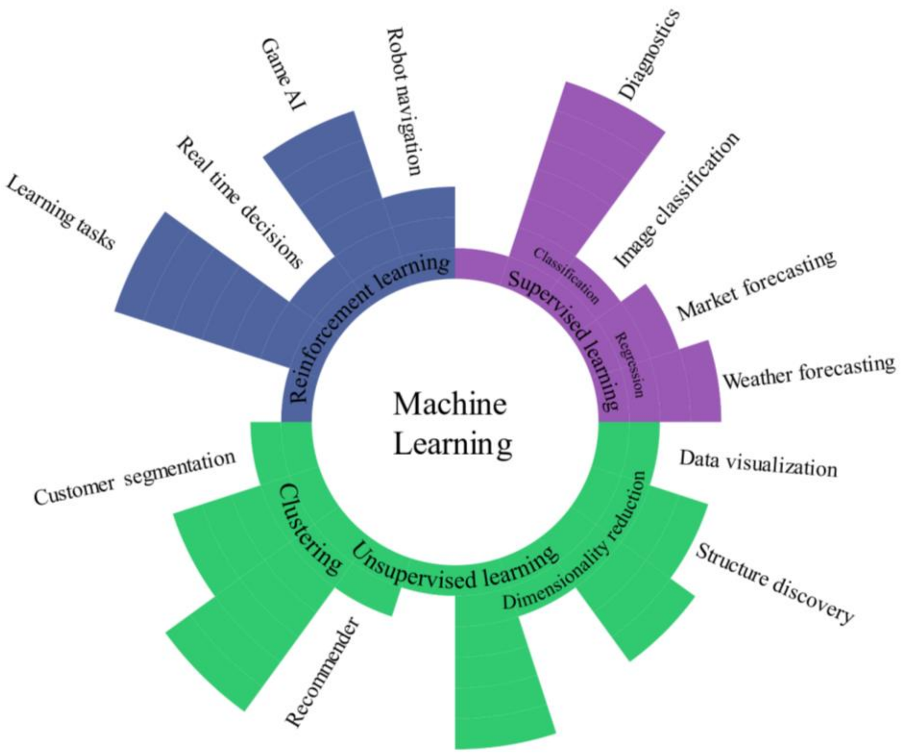

Figure 4. Machine learning types with examples (Sarker, 2021).

Advancements in Bifacial Photovoltaics with ML

Many ML algorithms were implemented with bifacial photovoltaic system, mainly for performance predictions and economical purposes. This miniature review discusses studies that investigated different ML algorithms with bifacials in the last three years. Many prediction models have been developed for bifacials recently to study their performance and energy production. For example, a previous study implemented a type of recurrent neural networks (RNN) to predict the output power of bifacial systems (Yunqiao &Yan, 2023). The study utilized real data from power stations and used many weather parameters like wind speed, temperature, clouds, irradiance, and ground type. Results showed that the predictive model depends on the weather characteristics which were heavily dependent on the accuracy of weather stations. Another study implemented Artificial Neural Networks (ANN) to forecast the generated energy from bifacial systems (Ghenai et al., 2022). Results showed that ANN accurately predicted improvements in power generation with the increase of surface albedo with R values of more than 99%. Real-time decomposition method was also used to calculate the performance ratio of bifacials with reliable and accurate results (Dobos et al., 2021). A more recent study deployed an autoencoder convolutional neural network model with mean absolute error and data filter layers (Manasrah et al., 2023) to predict the performance of bifacial modules under partial shading. Results showed accuracies of 91% in predicting and locating shades.

Machine learning techniques were also utilized to predict optimal tracking angles for bifacial systems (Tsuchida, et al., 2022). Deep reinforcement learning was deployed to learn in real time with the tracking system. The features of the model included global irradiance, generated power, time, and tilt angle. The results showed that the proposed model achieved up to 9% more electricity yield with high albedo. A similar approach was implemented in an older study where convolutional neural networks CNN model was used in a solar tracking system (Carballo, 2019). Adaptive real-time tracking was also used with bifacial systems (Sun et al., 2024). Improvements in energy production were presented up to 7.5% compared to conventional tracking algorithms. Table 1 summarizes the previously mentioned studies.

Table 1. Summary of previous ML studies on bifacial systems.

Last name	Year	Approach	Purpose	Results
Yunqiao	2023	RNN	Power prediction	Accuracy depends on weather data.
Ghenai	2022	ANN	Power prediction	R=99%.
Dobos	2021	Real-time decomposition	Performance ratio	Reliable accuracy in real data performance.
Manasrah	2023	Autoencoder CNN	Anomaly and shade detection	91% accuracy in detecting and locating shade.
Tsuchida	2022	Deep reinforcement learning	Tracking	9% improvement in power.
Sun	2024	ARTT	Tracking	Up to 32% improvement over conventional tracking.

By taking a deeper look at the literature, only very few research papers have investigated machine learning algorithms with bifacial systems specifically. Nevertheless, there has been an exponential increase in publications on bifacial technology (Gu et al., 2020). However, many studies presented similar machine learning methods on conventional mono-facial photovoltaics (Tina et al., 2021). This raises a question of whether there is an actual potential of bifacial photovoltaic systems in the near future on the market. Even though bifacial systems can be an interesting technology to investigate with ML models, the topic is still not very popular among scholars even with real experimental data. Perhaps the performance gain of bifacials over conventional systems is enough in a way that does not necessarily require complex algorithms for improvement purposes. However, machine learning algorithms are taking over real-world applications in almost every research field as discussed earlier. Therefore, there is much room for model development especially in the applications of bifacial systems.

Conclusion

In this paper, a miniature review is conducted on the deployment of different machine learning algorithms with bifacial photovoltaic systems. The technology of bifacial solar modules has been developing rapidly and getting less expensive with time. The paper reviewed different machine learning algorithms that were used to improve the performance or generated power of bifacials. Many of the previously presented studies relied on real experimental data to predict performances. However, even though bifacials have been around for years now, applying machine learning models on such systems is still not that popular. The most rational reason could be that bifacial systems (either fixed or tracked) are already superior over conventional mono-facial ones. Hence, there is much potential for development in this area especially for bifacial photovoltaic applications.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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