



EXPERIMENTAL ANALYSIS AND INNOVATION STRATEGIES FOR BIFACIAL PHOTOVOLTAIC MODULES

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As the third largest renewable energy source at present, solar photovoltaic (PV) technology has become a significant player in the global energy industry [1]. New solar module designs are emerging as photovoltaic technology advances. Bifacial PV modules are one of them that have attracted much interest in recent times [2,3]. Bifacial designs have the unique feature of generating power from both the front and back surfaces, which can result in higher power generation than traditional monofacial modules. The amount of irradiation received at the back surface is the main factor affecting the performance of bifacial modules. Direct irradiance, ground reflected irradiance, structure reflected irradiance, and diffuse sky irradiance make up the total irradiance at the back side of the module [4]. Figure 1 shows the elements of solar irradiance that falls on a bifacial PV module.

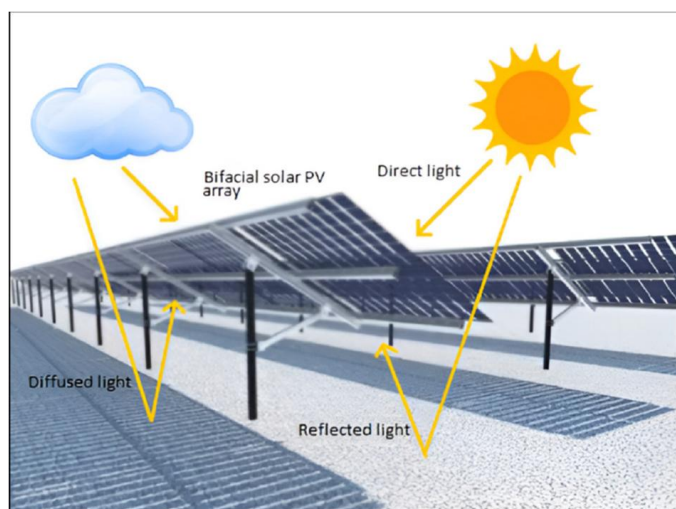


Figure-1. Components of solar radiation incident on a bifacial solar photovoltaic module [5].

The view factor, a purely geometric measure that represents the ratio of the radiant flux leaving the emitting surface to the flux reaching the receiving surface, is an essential element affecting the rear surface irradiance of bifacial photovoltaic (PV) modules [4]. The amount of reflected radiation received by the rear side of a solar module depends on the view factor between it and the ground. However, this irradiance can be strongly affected by ground surface irregularities such as shadows from the module or surrounding objects [6,7]. View factors for shaded and unshaded ground areas must be calculated independently to properly



account for selfshadowing effects. Ground reflectivity, sometimes referred to as albedo, is another important factor affecting the performance of bifacial PV [8]. Higher power yields are achieved with higher albedo values because they increase the rear surface irradiance [9]. The global market share of bifacial solar PV systems is expected to grow significantly, reaching 40% by 2028 and possibly dominating the market (90%) by 2033, according to the International Technology Roadmap for Photovoltaics (ITRPV) [10]. It is clear that the popularity of bifacial solar PV systems has been increasing over time, especially in recent decades. In 2019, the market share of bifacial solar PV systems increased by approximately 15%, and by 2022, it is expected to more than double [11]. This trend highlights the importance of understanding the factors that maximize the efficiency of bifacial PV systems. The market share of bifacial solar cells by year is presented in Fig. 2.

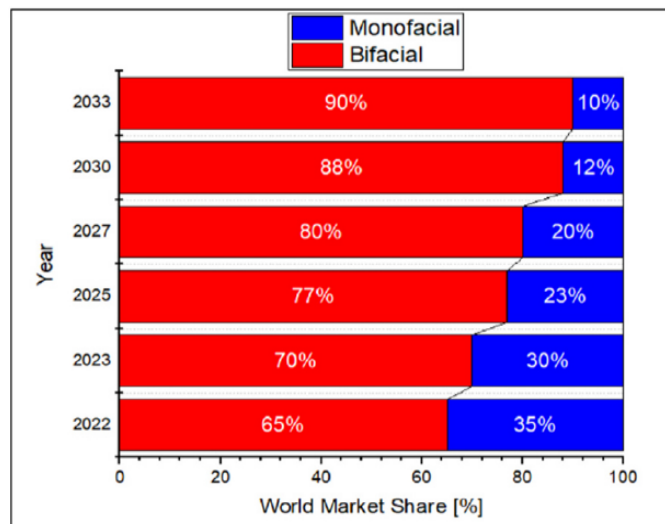


Figure-2. Market share of bifacial solar cell technology by year [10].

Research into bifacial PV systems uses a wide range of experimental setups to determine performance under real-world conditions under a variety of parameters. Rooftop installations, such as the four ~1 kW prototypes on the GAIA building in Barcelona or the 18-module, 6.8 kW installation on the IIT Kharagpur campus, are often used to evaluate performance in urban or building-integrated environments. Ground-mounted systems are also common, often equipped with adjustable frames to systematically change tilt angles and heights [11, 13, 14, 15]. A growing area of research is innovative integrated systems, including bifacial PV Trombe walls with reversible louvers, designed for combined power generation and thermal management in buildings. Bifacial photovoltaic thermal (BPV/T) systems are also being developed to simultaneously harvest electrical and thermal energy, optimizing overall energy use. Vertical arrays, particularly those oriented east-west, have attracted considerable attention due to their unique



diurnal power profiles and demonstrated benefits in reducing pollution, particularly in desert climates [14, 15]. To isolate specific variables and improve data reliability, experiments often include controlled ground surfaces. This includes the use of white painted roofs or patches of ground to maximize albedo, or the strategic placement of tracking reflective mirrors to significantly increase irradiance on vertical modules. Some arrays also use “dummy” panels surrounding the test modules to simulate larger array conditions and minimize unintended edge effects, thereby ensuring the collection of more representative data [12, 16].

BPV systems consistently show higher energy yields than single-sided systems. Vertical BPV modules can produce up to 1.4 times more energy than vertical single-sided modules [17]. When using reflective glazing, energy production can increase by up to 57% per day and up to 51% per year [18]. Overall, increasing roof albedo by 0.1 can increase BPV energy production by 4.55% [20]. From an economic perspective, BPV systems offer significantly shorter payback periods despite higher initial costs (e.g. 7.07 years for BPV/T, 11.89 years for PV [19]; 4 years 10 months for 1 MW BPV, 6 years 5 months for single-sided [21]). They show higher cost-effectiveness (e.g. 460% higher return over 20 years compared to PV [19]; cost-effectiveness index 1.6 vs. 1.4 [21]). Among the optimal parameters, the tilt angle varies with season and location (e.g. 49° in November for Baghdad [22]). The optimal tilt for BPV may be around 22° [21]. There are optimal heights (e.g. 120 cm in Baghdad [22]; 1.5 m for an 8 kW system in India [21]). Higher heights reduce self-shading and increase reflected light capture [22]. An east-west vertical azimuth angle can give two daily peaks and perform as well as single-sided systems with optimal tilt [17].

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