IMPACT OF BIFACIAL PV SYSTEM ON CANARY ISLANDS' ENERGY

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ABSTRACT

This project proposes an investigation motivated by the interest in obtaining a better understanding of the role that the bifacial technology could play in a favorable environment such as the Canarias Islands. In order to develop a scientific knowledge about this technology and to be able to evaluate the functioning of a bifacial system with different configurations that can give important results and show that this type of installations could be fruitful in the near future as already foreseen in the reports of the International Technology Roadmap for Photovoltaic where they predict that will increase their shear in photovoltaics the next years. Bifacial Technology has the advantage of being able to use the back of the module to produce energy using diffuse and albedo radiations. During the project, the mini-modules will be manufactured and characterized, and then placed in out-door structures where measurements will be carried out. In addition, it will try to use the down shifter technique that improves the spectral response thanks to the displacement of wavelengths that are not absorbed by the cells. The main advantage of the bifacial modules is to take advantage of the albedo that reaches its rear side, so that, in this study different configurations will be studied in order to optimize the generation of energy for the specific environmental conditions of the location. It is ambitioned that thanks to this research can be bet on this technology as an alternative and improvement of monofacial PV systems, reaching a higher energy production, estimated between 10%-20%, and be able to be used as an alternative to conventional sources reducing the environmental impact of greenhouse gases.

KEYWORDS:

Bifacial, Solar Cell, PV System, Solar modules

Contenido

1. Background and status

If we consider that the theoretical limit of a crystalline silicon solar cell without concentration is 29.4% [1], the beginnings of this technology were not encouraging, in 1941 when Russell Ohl encountered the photovoltaic effect he only achieved a fraction of the efficiency unit. However, development in the early years was quick (Figure 1). In the 1950s, Bell Laboratories achieved a cell with 6% efficiency using crystalline silicon and doping diffusion at high temperatures. But it wasn't until the 1960s that a reliable standard manufacturing process was established that allowed for approximately 15% efficiency to be achieved [2] [3] (Figure 2a). The greatest efficiency losses of this type of cells came from: i) light reflections on the front side, ii) shading on the front side, iii) resistive losses caused by metal contacts and iv) recombination of carriers on both the bulk and the surface of the silicon [4].

During the 1970s, great progress was made, and it was then that solar cells were launched with efficiencies of around 15%-17% by metallic contact through screen printing. Initially, the cells had an anti-reflective SiO coating that prevented them from absorbing radiation below a certain wavelength, but it was improved with another type of material that also provided a better optical coupling between the cell and the glass. Likewise, it was found that a region with higher rear doping increased the effective concentration of the bulk by slowing down the recombination velocity and was known as the back-surface field (BSF) [3]. Another characteristic of these cells was their texturization of the front face (Figure 2b) that allowed to improve the capacity of light absorption due to the creation of pyramids on the surface by means of an anisotropic chemical attack in such a way that multiple reflections were produced when the light was incident. At this point, it can be considered that a design very similar to the one we have today for silicon solar cells with front metal contacts, an anti-reflective coating, the p-n bond produced by phosphorous diffusion on a p-type substrate, texturization of both sides of the cell, a BSF made of aluminum paste and annealed to form the highly doped region and the rear metal contact was achieved (Figure 3a). Because of the absorption of infrared radiation by Al-BSF, the efficiency of this type of cell is limited to about 20% [5].

Passivation can reduce losses from surface recombination, either by means of a highly doped region, as was the case with BSF, or by depositing a thin layer of silicon oxide or nitride on the surface [6]. This allowed the design of cells known as PESC (Passivated Emitter Solar Cell, Figure 3b) which use a thin layer of oxide that passivates the emitter allowing to minimize recombination between the metal contacts of the cell surface. The back was completely coated with the aluminum alloy to form Al-BSF and also textured for the formation of pyramids to absorb more light. This structure resulted in efficiencies of over 20% [7].

To further improve efficiencies, a structure was developed in which both the emitter and the back of the cells were passivated, called PERC (Passivated Emitter and Rear Cell) and introduced by Martin Green in 1989. In this case, the aluminum was removed from the rear and replaced by a thin layer of thermally formed oxide and evaporated aluminum by contacting the silicon surface locally (by photolithography), thus minimizing the recombination of charge carriers at the rear and increasing internal reflectivity (Figure 4a). In this way, the probability of creating the electron-hole pair increased, the efficiency achieved with this type of structure is 22.8% [5]. This concept of PERC developed into PERL (Passivated Emitter and Rear Locally diffused, Figure 4b) where after the thermal growth of the oxide layer (SiO_2) small laser openings were made where the boron diffusion was performed, being localized locally and achieving that the recombination decreased as well as the contact resistance. In addition, to reduce the reflection on the front face, an anti-reflective layer is created with an inverted pyramid structure that combined with the oxide layer provides a very efficient absorption of light and the efficiency of this type of structure is 24.4% [8].

There are other more advanced structures being researched today that are a kind of intermediate step between conventional and bifacial technology due to their rear configuration. This is the case of IBC (Interdigitated back contact) made by local diffusion of boron at the rear of the cell followed by phosphorus alternating p- and n-type regions (Figure 5a). One of the keys to high efficiencies with this type of structure is that the lifetime of bulk carriers must be long enough for them to reach the contacts [9]. This structure has certain advantages: they have no front contacts, so the problem of shadows caused by losses is eliminated, a greater area of metal is covered at the rear, thus reducing resistive losses, there is less recombination at the front and, as the connection methods for modules are simpler, they are more robust [10]. Another type of structure is the MWT (Metal Wrap Through) which connects the emitter and the back through a metal conductor hole made with laser (Figure 5b). The advantage of this structure is that it reduces shadow losses because of the smaller size of the busbars and fingers, in addition, the fact that it has an emitter region on the rear side means that a greater amount of photocurrent can be produced. This type of structure is suitable for multi-crystalline because the life times of the carriers are shorter [4]. Finally, in the EWT (Emitter Wrap Through) structure, the metal contacts on the front are replaced by conductive holes created by laser (Figure 6). These conductor holes connect the emitter from the front to the rear and will be highly doped and even metallized to reduce resistivity. As with the IBC structure when eliminating the front contacts, the photo-generation will be greater when eliminating shadow losses.

Interest in bifacial technology has been growing in recent years even though it was in 1980 that Luque *et al.* [11] described the double-sided solar cell for the first time. In the Figure 7 the evolution of the number of publications on this subject is shown [12]. The great advantage of this type of technology is the ability to convert the light that hits the front and rear of the cell into electricity [13]. Therefore, both diffuse and albedo radiation could be used to increase energy production compared to conventional cells, this can mean up to a 60% increase in radiation collected [14]. The most widely known structure of this technology is PERT (Passivated Emitter and Rear Totally diffused) which is characterized by having both sides diffused (Figure 8a), a slightly doped BSF that reduces recombination on the back side and a doped opposite sign on the front side of the contacts that minimizes the effect of the contact resistors thus increasing the efficiency of the cell [15]. For this type of structure, the use of n-type substrate is preferable due to the longer diffusion lengths of the minority carriers [16] and does not suffer light-induced degradation (LID) [17]. For the N-PERT structure, efficiencies of 21.3% have been reported [18]. The most promising structure today is HIT (Heterojunction with Intrinsic Thin-layer) which has increased its efficiency year by year to a maximum of 26.33% [19]. The structure is based on a thin layer of amorphous silicon deposited on both sides of the crystalline silicon that can passivate the free bonds of the substrate, thus increasing efficiency (Figure 8b). Furthermore, since the manufacturing process does not exceed 200ºC, it avoids degrading the bulk material properties. Another of its characteristics is that it absorbs a greater number of wavelengths with respect to other single-union cells and that the temperature coefficients are better, thus increasing the open circuit voltage [19]. However, it has several drawbacks that decrease efficiency such as the recombination of carriers, the shading effect of electrodes and problems with light absorption [20].

2. Assumptions and objectives

This research is motivated by the interest in obtaining a better understanding of the role that bifacial technology could play in a favorable environment such as the Canary Islands. The assumptions (climatic conditions) of this research suggest that the production of energy from optimally configured bifacial systems could provide economic benefits to an isolated system that is highly dependent on primary energy sources despite having climatic conditions to encourage greater penetration of renewables, photovoltaics. Bifacial technology will gain market share in the coming years as seen in the latest report of the International Technology Roadmap for Photovoltaic [21]. In addition, different studies (Table 1) corroborate that the production of energy with bifacial systems surpasses, under the same environmental conditions, monofacial systems.

2.1. General objectives

The general objective of this research is to develop a scientific knowledge about bifacial photovoltaic technology in the Canary Islands through the evaluation of a system of bifacial modules with different configurations.

A high priority for the European Commission [22] is to achieve a transition to a climate-neutral economy that modernizes and supports economic growth by contributing to job creation within the Union. The H2020 programme is the instrument used to boost research and innovation activities to encourage advances, discoveries and firsts worldwide. To achieve these objectives, the EU has relied on expert groups which have identified several priorities to be followed up in the Strategic Energy Technology Plan [23]. This project aims to achieve priorities 1 and 2 of this plan within photovoltaic technology, in particular:

- Within crystalline silicon technology to achieve module efficiencies above 20% by 2020 and 35% by 2035 compared to 2015 values.
- Improve the quality of life and sustainability by increasing the life span of the modules to 30 years (with 80% of the initial power) in 2020 and up to 35 years in 2025, while minimizing the impact on the life cycle through the use of recyclable module components.

At a national level, this research is part of the RETOS programme, one of the eight major challenges facing Spanish society within the Spanish Science and Technology Strategy: "Safe, sustainable and clean energy". The aim of this proposal is to achieve greater energy production for the Canary Islands' electricity system from a renewable source such as solar energy.

Both priorities are perfectly in alignment and addressed in this project, as its final objective is to reduce the LCOE of photovoltaics and to position it in the market by competing with other electricity generation technologies.

2.2. Specific objectives

The specific objectives of the proposed research are:

- Develop a method of characterization of bifacial modules.
- Design a test bench for field measurements.
- To measure and study under what circumstances a two-facial module system can generate more energy than a mono-facial one.
- Learn about the impact of down shifter technology on bifacial modules.

3. Bifacial photovoltaic system

When the bifacial cells are mounted in modules with a glass-to-glass enclosure, an estimated energy gain, compared to the single-facial modules, is around 10%-30% depending on the mounting conditions [14][24] which we will discuss later. It is estimated that the glass to glass encapsulation will reduce costs due to the increased reliability and durability of the module, as it does not have (the cells) metal rear part does not absorb infrared radiation (IR) thus decreasing the temperature coefficients [14][25]-[27]. Therefore, by producing more energy and having longer lifetimes, they can reduce the LCOE (Levelized Cost Of Electricity), which compares unit costs over the economic lifetime of different technologies, for bifacial photovoltaic modules even though they can be somewhat more expensive to manufacture [25][28]. This could be a premature reading of the benefits that bifacial modules can provide, a more detailed study of the combined effect of the incidence of light on both sides and its consequences is needed so that this technology can finally be accepted in the market in a stable way [29].

The optimal design of a photovoltaic plant with bifacial modules is very different from the current ones for monofacial technology [28], are more complex because they depend to a large extent on the location where they are installed and their configuration [30]. In order to be able to compare both technologies, the Bifacial Gain (BG) has been defined as the ratio between the yields (Eq. 1), so that it is given as a percentage of the higher the yield of the Bifacial with respect to the monofacial. This parameter is not a property of the module as it depends on the environment in which it is installed (direct and diffuse irradiance, albedo, clearness index...) and the conditions in which it is mounted (inclination, height or module separation), therefore, each PV system needs an individual [28] and specific evaluation.

3.1. Environmental parameters

One of the factors that make bifacial technology have a higher BG is the diffuse component of radiation. It has been proven that in those places where there is a greater diffuse component, the performance of the bifacial modules will be better than that of the monofacial modules [31] due to the extra absorption of diffuse radiation at the rear of the module [25]. A parameter that gives an idea of this diffuse component is the so-called clearness index, K_T, the relationship between terrestrial radiation on a horizontal surface and extraterrestrial radiation, which in turn is related to the fraction of diffuse radiation as compared to the global fraction as quantified by Liu and Jordan with their model (Eq. 2) [32]. Sun *et al.* [25] were able to demonstrate in their work how the BG decreases with the increase of KT, so that places with low KT have higher BG. On average, in the Canary Islands there is a clarity index of 0.6 [33], which means that 30% of the global radiation will be diffuse, then in principle, the installation of bifacial modules would make sense in this location.

The diffuse nature of the radiation will mitigate an effect known as self-shading [34] which also depends on the location (latitude), the albedo, the relationship between the radiation reflected by a surface it is incident upon and the installation. Self-shading occurs when part of the ground does not receive direct radiation due to the shadow produced by the module itself, so that the unshaded part of the ground contributes direct radiation to the albedo [26] while the shaded part contributes diffuse radiation. The effect of the latitude has an impact on the shadows produced by the modules, for a given inclination of the modules it is necessary to have latitudes below 30º the solar path will be closer to the zenith at midday, producing less extended shadows than for latitudes above 30º [27]. Therefore, production is higher near the equator and decreases with latitude. In the case of the Canary Islands, the latitude is 28º-29º, remaining within the range of latitudes where the production of this type of technology is optimal. The conditions of the surface where the modules are installed will give different albedos. In the Canary Islands the typical value of a land covered with vegetation is 0.25 which corresponds to a BG of 10%. However, albedo can be modified by developing more effective reflective grounds that could increase this BG to 20% [25].

3.2. Configuration parameters

The BG of the bifacial modules increases as we move away from the optimal angle (both inclination and orientation) with respect to the monofacial modules, in addition, there is a better performance of the bifacial modules due to the extra radiation at the rear [35]. This energy gain will be greater for isolated modules or small installations than for large ones [36] where shading between different rows of modules must be taken into account, with the BG falling to 5%-15% as a result of overestimated rear irradiances compared to modules located in the center of the installation [37]. For the design of a photovoltaic plant, three fundamental parameters or aspects must be considered:

- String height

The shading of the modules limits reflection on the ground by reducing the energy captured. By increasing the installation height of the modules, this effect can be reduced, i.e. installations at higher heights reduce shade and the benefit is that the reflection on the floor can be used [25][38]. There is a limit where the reduction of shading losses is negligible, and this is an important value in order to minimize installation costs (Figure 9). Increasing the height of the modules by a certain amount reduces the operating temperature through better ventilation, also increasing the efficiency of the module and extending its service life, even though it may lead to an increase in installation costs. For installations above 1 m above the ground, a BG of up to 30% can be achieved [25].

- Module spacing

For latitudes near the Equator, optimum performance in monofacial modules is given for a distance between rows of 0.25 m but would make installation and maintenance difficult. To perform these operations normally, the minimum distance between rows must be at least 2 m. Another problem related to the distance between rows has to do with by-pass diodes, for small distances these diodes will limit production for a period throughout the day due to shading [27].

- Angle of inclination and orientation of modules

In general, the angles of inclination in bifacial photovoltaic plants will be greater than those used in monofacial installations in order to collect more reflected energy from the ground [37]. With the increase of the diffuse content of the global radiation, the short-circuit current gain of the bifacial module compared to the monofacial module is higher [39]. Vertically installed (BV) and East-West oriented (EO) bifacial modules can produce more energy than installed monofacial modules with an optimal angle of inclination regardless of location [27], this increased production would occur in the early morning and late afternoon hours (Figure 10), in the last case, it would coincide with a peak demand without having to store energy. Advantages such as saving land, operating as a sound barrier on roads and being less likely to be covered by snow or dust [26] are incentives to install bifacial photovoltaic modules vertically. On the other hand, the optimum slope depends on the albedo and the installation height, it has been proven that this optimum slope increases with the albedo for all heights [38]. A photovoltaic plant with optimally inclined modules (BOT) can produce more energy depending on the location. Appelbaum *et al.*[31] compared BV and BOT in Tel Aviv, Israel, concluding that BOT produced 32% more energy than BV for the same environmental conditions but this is a general result because of other factors influencing BG. Regarding the orientations, for the BV they orient East-West to receive the same amount of radiation on both sides and because the shadows are less elongated [27] while for the BOT the orientation will be South-North. These two orientations are true except in the Arctic and Antarctic regions where there is no dependence on the azimuth due to polar days [25].

3.3. Solar tracking

The energy produced by photovoltaic systems depends on the amount of solar energy it is capable of collecting and tracking the solar path can be used to increase it. The tracking systems ideally allow the modules to accurately target the position of the Sun and compensate for daily changes in altitude and seasonal latitude as well as the change in the azimuth angle of the Sun. Because of the slow movement of the Sun, a stable control system without oscillations is necessary and for this purpose the main tool would be the use of tracking axes with optimized mobile devices and an appropriate control system [40].

The tracking systems can be classified into two groups: single-axis or double-axis. In both cases, increases in electricity generation are observed on both clear and cloudy days and are economically viable. These systems provide energy gains of between zero and 100% compared to fixed and optimally configured systems, obviously that gain depends on the season, climate and location [41].

Single-axis systems increase annual energy production compared to fixed systems by 12%-30% [42] while in double-axis systems it is between 10%-40% [43]. Double-axis systems have a 3%-5% higher output than single-axis systems and are more efficient and economically viable in the case of large plants because environmental conditions affect them to a lesser extent. Huang *et al*.[44] confirmed that double-axis systems produce more energy than single-axis systems, but for their installation he assumed that the energy gain should exceed the costs of equipment and consumption of all moving parts, as well as maintenance and operating costs.

3.4. A key factor: a reliable characterization method

Currently, the installed capacity of bifacial systems worldwide is negligible, the lack of reliable data is one of the reasons why new investors do not end up deciding to invest in this type of installation [45]. In addition, there is a need for a standardized characterization method to help improve confidence in the technology. For monofacial devices, the Standard Test Conditions are well defined and accepted by the scientific community and the market, however, there is currently no standard for bifacial technology [46] although the standardization process officially started in 2015 led by IEC [47]. This standardization process takes into account different environments and conditions for measurement.

When a module is in a real location it will be illuminated on both sides simultaneously, considering also that the intensity on the back side will be lower, therefore it would be advisable to carry out the measurements under double illumination, since other factors come into play that are not taken into account with monofacial technology. In case of not having a solar simulator that allows double illumination and in order to illuminate both sides of the cell simultaneously and also to reduce the intensity of the irradiance on the front side, a prototype called Bifacial Cell Tester (BTC) was designed and built at CENER. This is a vertical sample holder positioned perpendicular to the surface with two mirrors symmetrically positioned at 45° (Figure 11a). The mounting bracket includes the necessary means for connecting the cell on both sides and a reference cell for measuring the irradiance after reflection in the mirror. In order to measure with different albedo coefficients, meshes can be placed at the back of the cell to reduce the intensity and to simulate different albedos. As can be seen in Figure 11b, the light is sent perpendicularly to the surface and then also perpendicular to the cell after reflection in the mirrors [48]. This means that the I-V curve can be measured under double illumination and the bifacial efficiency for different types of albedo, the short-circuit current, the fill factor and the open circuit voltage can also be obtained. The problem with this method is that the metal meshes used only reduce the intensity of the incident light without changing the light distribution [29].

However, there is another possibility to carry out the characterization based on the characteristic parameters of the front and rear faces, for which Singh *et al.* [49] proposed a series of equations (Eq. 3-5) to obtain the bifacial efficiency of a cell from these parameters, which he called 1.x efficiency. This parameter does not allow comparing the performance between monofacial and bifacial modules as the calculation of the bifacial efficiency takes into account the incident light on both sides of the cell. To make this comparison, the gain-efficiency product is defined (Eq. 6).

4. Concept test

The project also includes a test concept for existing and developing technology in monofacial modules known as "down shifting" (DS) [50]. This technique improves the external quantum efficiency (EQE) in the ultraviolet (UV) range (Figure 12) of photovoltaic cells. The concept can be applied to existing commercial cells using different materials by depositing a thin layer either above the glass or between the two glasses used in the encapsulation (Figure 13). This improvement in the spectral response of the cell is typically in the range of 300nm-500nm and is expected to have a triple effect on the modules:

i. Absorbing photons at wavelengths where the module is not effective, converting them into electron-hollow pairs.
ii. Converting these photons to the wavelength range of the visible where they are effective.
iii. To protect the module against UV radiation.

In addition, these layers are completely transparent in the visible range so that they do not affect the performance of the photovoltaic modules at all other wavelengths.

5. Competitive groups

The competing groups currently researching this technology have been reviewed. The most important projects and groups are summarized in the following paragraph:

i. Bifacial PV Project [51]: Sandia National Laboratories, National Renewable Energy Laboratories and University of Iowa work together to understand how bifacial systems perform.
ii. MOSBIT [52]: where the Fraunhofer Institute for Solar Energy Systems together with Solar World try to develop a characterization methodology for modules and bifacial systems.
iii. HERCULES Project [53]: this is a project that brings together many institutions including research centres, universities and different companies, including the Fraunhofer Institute for Solar Energy Systems, the French National Solar Energy Institute on the international scene and the Polytechnic University of Barcelona at national level. To achieve their goals of developing highly efficient module technologies, cost reduction and increased module durability, they rely on three cell technologies: PERT, IBC and HIT.
iv. Silicon Competence Centre (SiCC) [54]: where material properties are investigated to improve the efficiency of biface cells and to transfer laboratory manufacturing processes to industry.

6. Methodology

The project activities will have a duration of three years, with clearly defined tasks and milestones per year. Four tasks can be differentiated during the duration of the project from the study of bifacial technologies, manufacturing and installation of the test benches, field measurements and the dissemination of the results obtained, not only at the end of the project but also during the project where two deliverables will be made. In the schedule (Table 2) you are shown in section the activities to be carried out are summarized. A detailed analysis of these is presented below.

During the first year, an in-depth analysis of the state of the art of the different technologies of bifacial cells (T.1.1) will be carried out, which will last approximately 9 months and will culminate in a report containing the most relevant results found in the bibliographic search (H1). Following this analysis, it will be decided which technology is the most suitable for the field study and manufacturers will be sought who can supply the needs of the project (T.1.2) so that it is expected that during the last quarter of 2019 and the first quarter of 2020 the necessary cells will be available for the characterisation of these cells (T.1.3). The characterization will consist of several tests that will be carried out in the laboratories of the National Center for Renewable Energies (CENER), from measuring spectral response, thermography, electroluminescence and characteristic I-V to know the characteristic electrical parameters of the bifacial cells. To obtain the I-V feature on both sides, it must be possible to temporarily and completely eliminate the contribution of the front or rear side of the device during measurement. To achieve this, it will be necessary to develop tools that allow the modification of the non-irradiated background of the measurement equipment since it has been demonstrated that the use of a conductive and reflective surface for measurement overestimates the efficiency of the cell by more than 2%, and the use of this type of surface for measuring bifacial cells is not recommended [55]. Therefore, to be considered as good, the background irradiation on the unexposed side must be below 3 W/m2 at least 2 points [56]. The International Electrotechnical Commission (IEC) defines bifaciality as the ratio between the I-V characteristic of the rear and front under STC conditions (1000 W/m^2, 25ºC and AM: 1.5) unless otherwise specified, so that the bifaciality coefficients are defined by Eq. 9.

After the characterization of the cells, the mini-modules will be manufactured, consisting of a single cell with dimensions of 156mm x 156mm mono or multicrystalline, which will be decided after the initial analysis. The encapsulation will have a double glass layout, one of which will have a low iron content, ethylene vinyl acetate (EVA) will be used as the encapsulant, followed by solar cells, a new EVA film and finally glass, so that it will have greater durability as it will have less degradation and will be the most suitable for high temperature and humidity conditions. The frame of the mini-modules will be made of anodized aluminum and, finally, the connection boxes will have 4 pins and a connector attached to a data acquisition board so that parameters such as current, voltage, radiation and cell temperature can be monitored. Special attention must be paid to the place where these junction boxes are placed, as they cannot go in the usual place in the rear part, so that a special design is intended to place them in the frames and prevent them from leaking.

Once the mini-modules have been obtained, they will be characterized by a structure that will be manufactured in CENER (T.2.1), thus beginning the activities of the second annuity and concluding with the second milestone (H2). This task will overlap with T.1.4 for approximately 3 months, as the test bench that will be used to characterize the mini-modules will be necessary for the characterization. This task will be carried out in two phases in order to obtain the parameters of each of the faces independently (front and rear) and the bifaciality parameters of the mini-modules themselves. Important issue in the first case is to have a non-reflective background, in addition to being able to use openings to limit the irradiance to the area of study (Figure 15). For the second case, the structure manufactured in CENER will be necessary to measure the mini-modules individually. The mounting is shown in Figure 11, it is a vertical sample holder located perpendicular to the surface with two mirrors symmetrically positioned at 45º. The holder includes the necessary means to connect the mini-module and includes a reference cell for measuring the irradiance after reflection in the mirror. In order to be able to carry out measurements with different albedo coefficients, it is suggested to place some meshes that reduce the intensity in the rear part, being able to simulate different albedos. The light is sent perpendicular to the surface and then perpendicular to the mini-module after reflection on the mirrors. The other structures manufactured for the field test benches will also be carried out in CENER and will be in total 2, in each of them up to 8 mini-modules can be installed and it will be possible to modify the height from 0.5 m to 1.25 m approximately. The structures will have the possibility of modifying the azimuth angle (orientation) and inclination to be able to configure the mini-modules in different ways, allowing them to be placed up to a vertical position (90º inclination). One of the benches will have a dual-axis tracking system that allows tracking the sun's trajectory using a sensor or in an automated manner, the latter being less accurate. In addition, in order to carry out a study of how albedo affects production, it will be possible to install a more reflective floor, either by means of paint or material that can be used on the base of these benches. With the installation of these structures (T.2.2) at the site where the measures will be carried out, the second task would be completed and the third milestone (H3) of the project would be reached.

In the fourth quarter of the second year, outdoor measurements would begin, for which a data acquisition system giving the values of open circuit voltage and short-circuit current (I-V characteristic) for all mini-modules at one-minute intervals would be required so that they are recorded and can be sent to a server, thus allowing real-time monitoring (T.3.1). During the year the measurements last, the fixed test bench will be used for measurements with different configurations (inclination and orientation), in order to know which would be the most suitable, although it should be taken into account that the radiations will not be the same in the months in which each one of them is located. Parallel to the measurement and data acquisition, a simulation will be carried out for the elaboration of a model to calculate the performance of the bifacial mini-modules (T.3.2) of the installed system that will require meteorological and location data to be able to carry out optical, thermal and electrical models. The task will conclude with the compression and analysis of the data (H4) obtained during the year from the measurements made (T.3.3), the extraction of conclusions and recommendations for the installation of this technology in the Canary Islands. These results are intended to be disseminated in specialized International Congresses that appear in the schedule as deliverables (E1, E2) that complete the dissemination task (T.4).

Given the duration of the project, the tasks and milestones of the 2020 and 2021 annuities may be modified depending on the results and conclusions drawn during the previous tasks.

7. Conclusions

In this work, a review of cell technology has been carried out, from the discovery of the photovoltaic effect to the bifacial cells we know today, and the ideal conditions for the installation of this technology have been studied. The importance of this type of cell lies in being able to absorb radiation from both sides in order to obtain greater efficiency. With respect to which conditions are the best, an analysis has been carried out, both environmental (diffuse radiation, albedo...) and geographical (latitude) as well as photovoltaic system configuration (height, separation between modules and inclination) for which this type of technology would be beneficial in an environment such as the Canary Islands. This technology is not yet mature and has not yet been introduced into the market, mainly due to the lack of a standardization system that provides investors with security so that they can bet on it. The low installation capacity worldwide does not allow reliable data to be obtained from a technology whose configuration is very different from the monofacial systems known today. There are different research groups of this technology around the world and with the same objective this project is proposed for Spain and, specifically, for the Canary Islands.

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10. Appendix

10.1. Figures

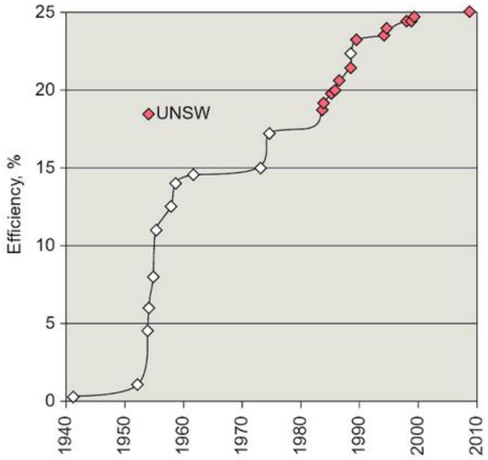

Figure 1. Evolution of efficiency in the laboratory of silicon solar cells

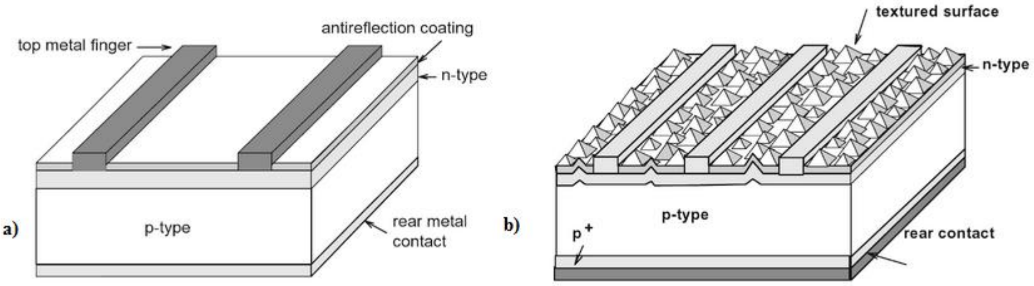

Figure 2. a) Solar cell design from the 1960s b) Textured solar cell

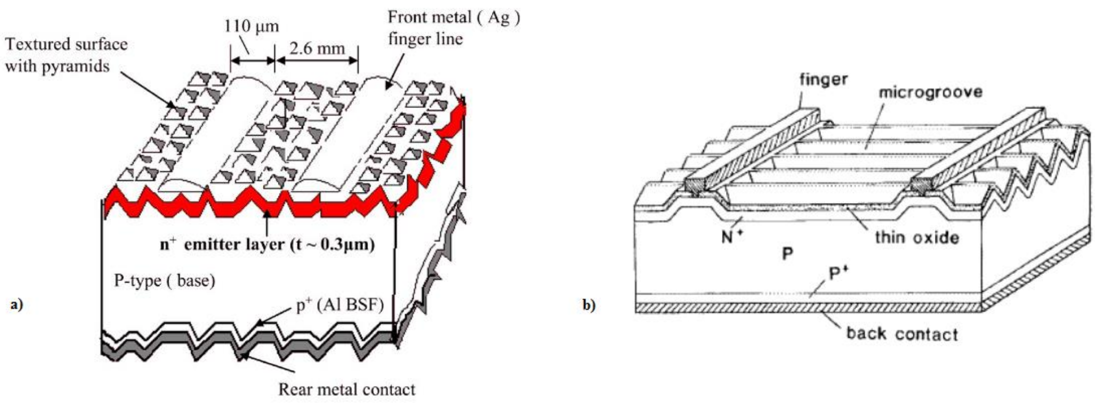

Figure 3.a) Solar cell with Al-BSF structure b) Solar cell with PESC structure

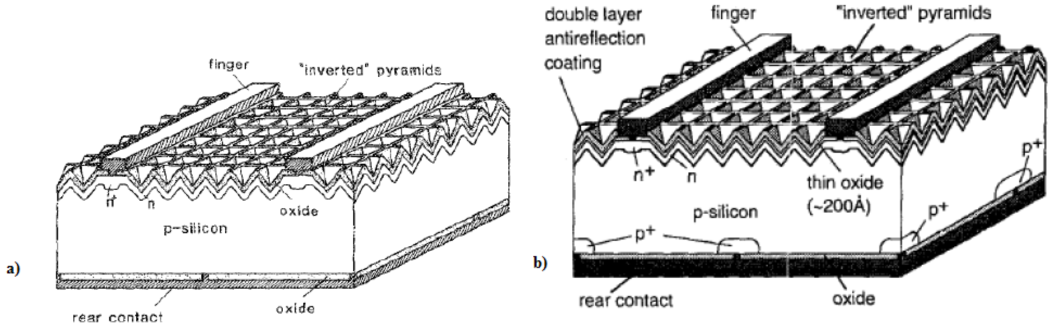

Figure 4. a) Solar cell with PERC structure b) Solar cell with PERL structure

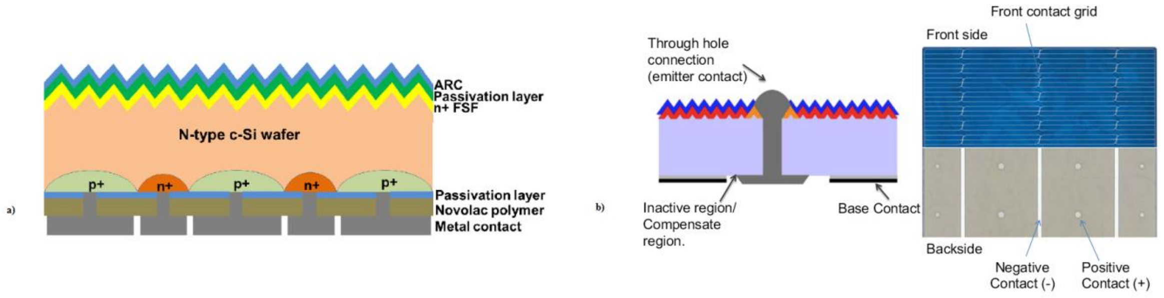

Figure 5. a) Solar cell with IBC structure b) Solar cell with MWT structure

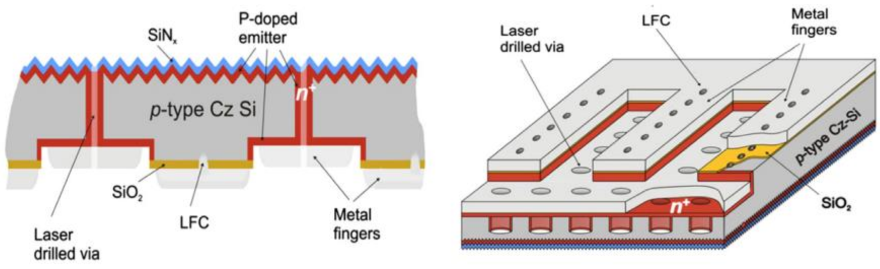

Figure 6. Solar cell with EWT structure

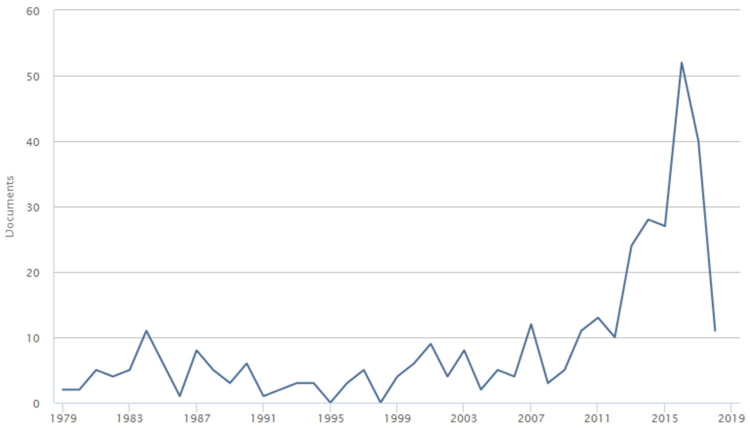

Figure 7. Number of scientific publications on bifacial technology from 1978 to May 2018, totaling 413 documents.

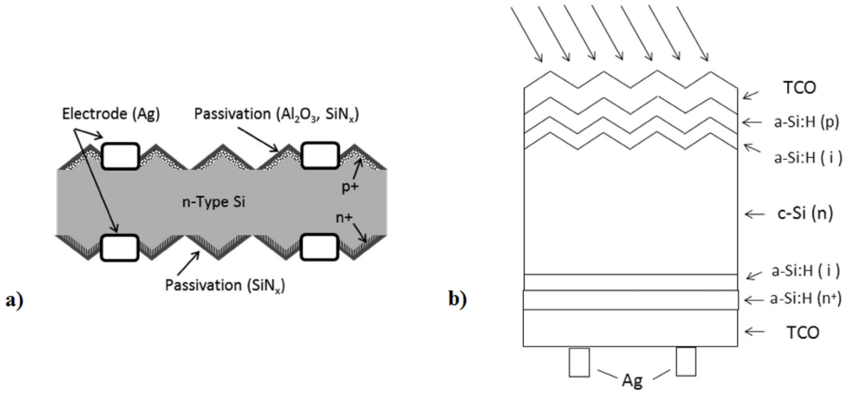

Figure 8. Solar cell with structure a) n-PERT b) bifacial HIT

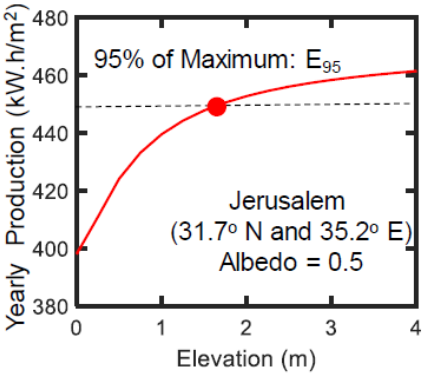

Figure 9. Optimally oriented and inclined annual electricity production for bi-facial modules depending on the height in Jerusalem [25]

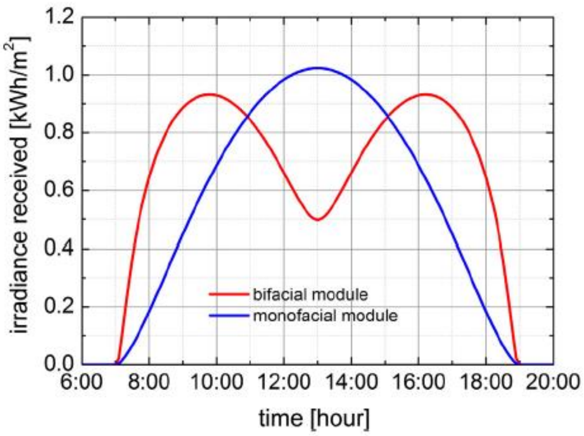

Figure 10. Simulation of the radiation received by a vertically installed bifacial module and a bifacial module with optimal inclination for a certain day in Singapore. The radiation received by the bifacial is 8.54 kWh while for single-facial it is 7.38 [26]

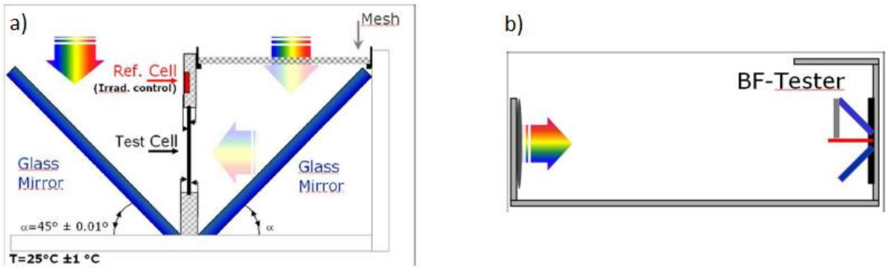

Figure 11. a) BCT diagram and b) Illumination diagram [48]

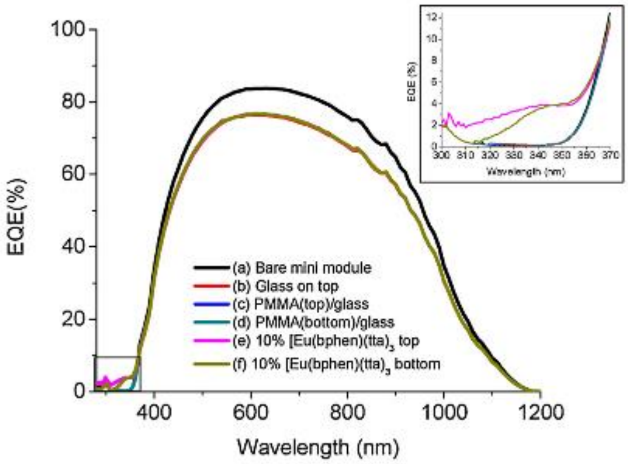

Figure 12. Spectral response for different mini-modules with DS technique applied [50]

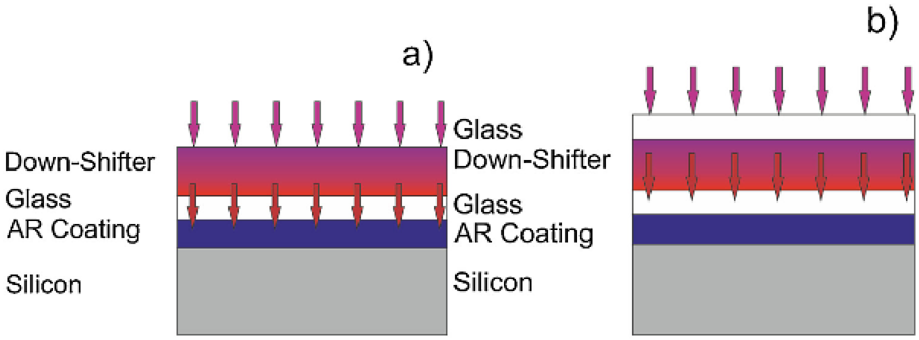

Figure 13. Possible locations of layer a) just below the glass b) on both sides of the glass [50]

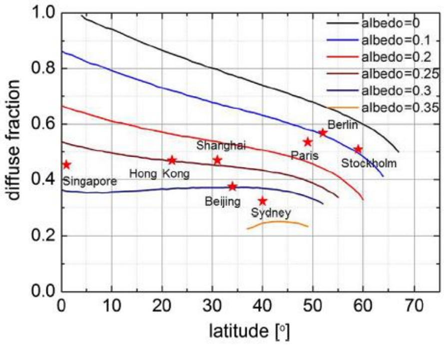

Figure 14. Diffuse radiation fraction from which vertically installed modules receive 1% more energy than monofacial modules optimally inclined, calculated as a function of latitude and for different albedo coefficients [26]

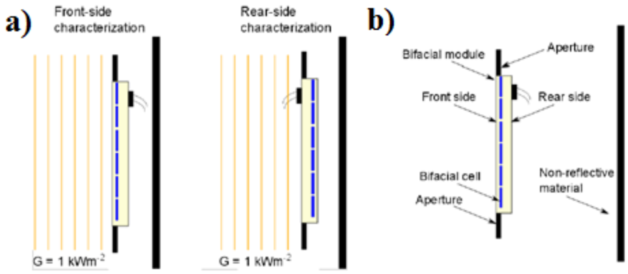

Figure 15. Measurement of the I-V characteristic of a bifacial module [56]

10.2. Equations

$$BG(\%) = \frac{(Y_b - Y_m)}{Y_m} \times 100$$

Eq. 1. Bifacial gain

Y ≡ energy efficiency of the modules

$$K_d = \frac{H_d}{H} = 1.39 - 4.03 \cdot K_T + 5.53 \cdot K_T^2 - 3.11 \cdot K_T^3$$

Eq. 2. Diffuse vs. global radiation fraction

Hd ≡ Diffuse radiation on horizontal plane

H ≡ Global radiation on horizontal plane
KT ≡ Clearness Index

$$\eta_{1.x} = \frac{(I_{sc-f+I_{sc-r}}) \cdot V_{oc-bi} \cdot FF_{bi}}{A_{cell} \cdot (1+x) \cdot G_{STC}}$$

Eq. 3. Definition of 1.x.efficiency

$$V_{oc-bi} = V_{oc-f} \cdot \frac{ln\left(R_{Isc} \cdot \frac{I_{SC-f}}{I_0}\right)}{ln\left(\frac{I_{sc-f}}{I_0}\right)}$$

Eq. 4. Bifacial open circuit voltage

I_0 ≡ Saturation current in a diode model

$$FF_{bi} = FF_f \cdot \left[R_{Isc} - (R_{Isc} - 1) \cdot \frac{pFF}{FF_f}\right]$$

Eq. 5. Bifacial Fill Factor

pFF ≡ fill factor considering that there are no resistive losses

$$GEP = g \cdot \eta_{1.x}$$

Eq. 6. Definiton of gain effiency product

$$\varphi_{Isc} = \frac{I_{sc,rear}}{I_{sc,front}}$$

Eq. 7. Bifaciality coefficient of short-circuit current

$$\varphi_{Voc} = \frac{V_{oc,rear}}{V_{oc,front}}$$

Eq. 8. Bifaciality coefficient of open circuit voltage

$$\varphi_{Pmax} = \frac{P_{max,rear}}{P_{max,front}}$$

Eq. 9. Bifaciality coefficient of maximum power

10.3. Tables

Location (Type)	**Latitude**	**Facing**	**Tracking**	**elevation (m)**	**tilt angle (º)**	**albedo coefficent**	**Bifaciality**	**BG (%)**	**Ref.**
El Gouna, Egypt (Sim)	27.38	South	No	1.5	25	0.2	0.91	13.46	
						0.5		33.85	
		East-West		0.5	90	0.2		-14.88	
					90	0.5		-5.99	
Konstanz, Germany (Sim)	47.65	South	No	1.5	37	0.2	0.91	15.98	
						0.5		35.73	
		East-West		0.5	90	0.2		-4.52	
					90	0.5		15.77	
Kasese, Uganda (Sim)	0.17	East-West	No		90	0.2		1.53	
					90	0.5		21.91	
			One axis		90	0.2		40.1	
					90	0.5		62.2	
Amsterdan, Netherlands (Sim)	52.37	East-West	No	0.5	90	0.2	0.96	10.4	
						0.5		29.5	
Doha, Qatar (Sim)	25.28	East-West	No	0.5	90	0.2	0.96	-5.6	
						0.5		17.2	
Cairo, Egypt (Sim)	30.04	South	No	0	35	0.2	0.8	10.6	
				0.5	32			12.9	
				2	31			13.8	
				0	42	0.5		24.3	
				0.5	34			28.8	
				2	32			30.6	
Oslo, Norway (Sim)	59.91	South	No	0	55	0.2	0.8	15.4	
				0.5	54			15.5	
				2	54			15.5	
				0	58	0.5		28.1	
				0.5	57			28.3	
				2	56			28.3	
Hokkaido, Japan (Exp)	43.06	South	No	0.5	35	0.2	0.95	25.7	
						0.5		13	
Alburquerque, USA (Exp)	35.08	South	No	1.08	15	0.55	0.9	30.2	
		West			15			36.7	
		South		1.03	30	0.25		14.6	
		South		0.89	90			32.2	
Golden (Exp)		South	No	1.02	30	0.2	0.6	8.6	
Paris, France (Exp)	48.86	South	No	0.4	30	0.2	0.9	18.4	
						0.35		28.2	

Table 1. Different experimental studies (Exp) or simulations (Sim) in different locations and installation conditions.

Task	**Description**	**2019**				**2020**				**2021**			
		1	2	3	4	1	2	3	4	1	2	3	4
T.1	**SELECTION AND PROCUREMENT OF BIFACIAL MINI-MODULES**	🟧	🟧	🟧	🟧	🟧	🟧						
T.1.1	Study of the state of the art of bifacial structures on the market	▨	▨	▨	**H1**								
T.1.2	Selection and purchase of the bifacial technology to be used					▨							
T.1.3	Characterization of bifacial cells					▨							
T.1.4	Manufacture and characterization of mini-modules						**H2**						
T.2	**MODULES AND STRUCTURES OF THE FV SYSTEM**						🟧	**H3**					
T.2.1	Selection and purchase of outdoor measuring equipment						▨	▨					
T.2.2	Installation and commissioning of measuring equipment							▨					
T.3	**OUTDOOR MEASUREMENTS AND SIMULATIONS**								🟧	🟧	🟧	🟧	🟧
T.3.1	Field measurement with different system configurations								▨	▨	▨	▨	
T.3.2	Development of behaviour models: simulation and comparison									▨	▨	▨	
T.3.3	Data processing and analysis										▨	▨	**H4**
T.4	**DISSEMINATION AND EXPLOITATION OF RESULTS**					🟧	**E1**	🟧	🟧	🟧	🟧	🟧	**E2**

H1	Decision on the technology and configuration to be used
H2	Obtaining and characterizing mini-modules with the selected technology
H3	Functional installation of the measuring system outdoors
H4	Conclusions on the improvement of bifacial technology in the Canary Islands
E1, E2	Presentation of results at specialized international congresses

Table 2. Schedule for the implementation of the project