Influence of wind on the electrical energy production of solar plants

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***Abstract*—In the pursuit of better understanding the various worlds behind solar photovoltaic methods and technologies, researchers rely on incessant investigations with the aim of guaranteeing an effective energy demand response to an ever-growing world population that fights climate change. Solar energy, as a clean source of energy, plays a relevant role in this much desired (r)evolution.**

When talking about photovoltaics, despite the multiple studies on parameters that affect the operation of solar panels, concrete knowledge on this matter is still in an incipient stage and precise data remains dispersed, given the mutability of outer factors beyond technology-related properties, hence the difficulties associated with their exploration. Wind is one of them. Wind loads can affect the temperature of photovoltaic modules, whose efficiency is reduced when higher temperatures are reached. With this in mind, the viability of wind as a natural cooling mechanism for solar plants and its influence on their electrical energy production is studied in this thesis.

Some appropriate results were achieved: depending on the module temperature prediction model used and on the photovoltaic technology in question, solar panels are foreseen to be up to approximately 3% more productive for average wind speeds and up to almost 7% more productive for higher wind speeds. Taking into consideration that wind speed values were collected in the close vicinity of the modules, these results can be proven to be even higher. That being said, this dissertation intends to contribute with accurate insights about wind influence on electrical energy production of solar plants.

***Index Terms*—Wind Flow, Temperature Prediction, Photovoltaic Panel, Output Power, Computational Fluid Dynamics, CAD Models.**

I. INTRODUCTION

Throughout the last years, the urge to reduce the usage of fossil fuels has been arising substantially, putting the conventional energy sources under a lot of pressure. Herewith, the demand for renewable energies is constantly increasing as a consequence of their significance as an alternative to the aforementioned sources. The five major renewable energy resources are wind, hydro, geothermal, biomass and solar. With their never-ending stamp at human scale, they play an imperative role in the ecological footprint, continually giving rise to new projects, new initiatives and also political decisions all over the world, seeking a solid environmental sustainability for the years yet to come [1].

That being said, a much more fruitful use of the renewable resources is crucial for answering the needs of populations and modern societies. In such a way, an ever-developing work has to be carried out by the many renewable related industries in order to improve effectiveness and efficiency. Amongst all the renewables, the usage of solar energy, although its recognized potential, still represents a small portion of the circle graph [2] – a situation expected to change in the upcoming years [3]. With emerging solar PV technologies that show higher efficiencies and less costs, the referred fact is promised to change. With this in mind, as it can be considered that photovoltaics are still in an incipient phase due to their limitations in what concerns efficiency, several researches are on course in order to improve the operation of solar cells, either by, e.g., changing the designs, the structures or the materials, hence amplifying the reliability, spread and range of PV systems.

With this in mind, this dissertation is suggested with the aim of contributing to the growth of solar photovoltaic technology in the sense that a wider knowledge of how external factors affect efficiency and maintenance of solar plants empowers a general perspective of project sizing and forthcoming topics of interest.

Facing many issues to what efficiency is concerned, PV panels are known to have their operation affected by temperature – ambient temperature and module temperature. Accordingly, higher temperatures are known to reduce power output of PV modules, as it will be further explained. High temperatures also represent a problem regarding panels lifetime, since that overheating can lead to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cells. This being the case, several cooling systems have been studied over the years, in order to avoid the issues aforesaid, being that some of them actually achieved relevant results. A consequent factor of these systems is an increase of investment and maintenance costs – a question to get around. Therefore, wind, being a natural and free-of-cost resource, emerges as a possible alternative to them. Nowadays, wind is still neglected when predicting modules temperatures, since that the Standard Approach (SA) – standard method of prediction panels temperatures – does not take wind variables into consideration. This has been proven to be far-fetched and some efforts have been made to change this procedure. With the purpose of improving guidelines for solar photovoltaic practices, distinct researchers have been trying to elaborate panel temperature prediction models that take wind data into account, as it is further shown.

Considering what was previously stated, the work performed and exploited in this thesis aims to identify the variation of modules temperature according to each panel temperature prediction model, to analyze this variation for various PV technologies, to verify the impact of different wind speeds in the variation of modules temperature and to examine how variations of panels temperature impact the output power of each module. All these topics culminate in the study of the viability of wind as a natural cooling mechanism for solar plants.

Solar cells operation depends mainly on the amount of incident light. It is usually measured by a coefficient known as irradiance (or flux density), G, that is a measure of power incident per unit area – its respective units are W/m^2. Being an external factor, it varies depending on several aspects, such as the latitude, season and time of day at a given location. Furthermore, it is affected by other atmospheric conditions like clouds, dust or even relative humidity. Solar cells are known to behave like a diode, whose current flow, I_D, is given by equation (1)

$$I_D = I_S \left(e^{\frac{U_D}{n \cdot U_T}} - 1 \right) \tag{1}$$

Where I_S is the diode reverse saturation current, U_D is the voltage applied across the diode, n is the diode ideality factor and U_T is the thermal voltage, that is equivalent to $\frac{kT}{q}$, in which k is the Boltzmann constant, T is the temperature and q is the electronic charge. As a result, for an ideal case, the current flow in a cell, I_{cell}, is given by equation (2), having in mind that I_{PV} is the current generated by light:

$$I_{\text{cell}} = I_{\text{PV}} - I_D \tag{2}$$

By equation (1) and (2), the final equation for the current flow in a solar cell is:

$$I_{\text{cell}} = I_{\text{PV}} - I_S \left(e^{\frac{U_D}{n \cdot U_T}} - 1 \right) \tag{3}$$

By simple inspection of the previous equation, it can be told that there is a relation of dependency between the current flow, I_{cell}, and the voltage across the diode, U_D.

From a theoretical point of view, it is possible to calculate the value of the Maximum Power Point (MPP) from the I–V curve and P–V curve that characterize a solar cell. These curves represent the relation between current, I_{cell}, and power, P, with voltage, U_D, respectively. For the referred calculation, equation (4) is needed, where C_0 is a constant dependent on the temperature of the solar cell, C_1 is the coefficient of temperature of I_{PV}, ΔT is the difference between the temperature of the cell and the room temperature and, finally, G_{ref} is the reference irradiance (1000 W/m^2).

$$I_{\text{PV}} = \left(C_0 + C_1 \frac{\Delta T}{G_{\text{ref}}} \right) \cdot G \tag{4}$$

The MPP is a point (I, V) that maximizes the area underneath the I–V curve. Therefore, the power of a solar cell and the maximum of its function is required. Given that:

$$P = U \times I = U_D \times I_{\text{cell}} = U_D \left(I_{\text{PV}} - I_S (e^{\frac{U_D}{n \cdot U_T}} - 1) \right) \tag{5}$$

And knowing that $e^{\frac{U_D}{n \cdot U_T}} \gg 1$, it can be said that:

$$P \approx U_D \left(I_{\text{PV}} - I_S \cdot e^{\frac{U_D}{n \cdot U_T}} \right) \tag{6}$$

Then, by deriving the power in function of the voltage, equation (7), it is possible to calculate the MPP, since it is the point where the prior derivative is null.

$$\frac{dP}{dU_D} = 0 = I_{\text{PV}} - I_S \cdot e^{\frac{U_D}{n \cdot U_T}} \left(1 + \frac{U_D}{n \cdot U_T} \right) \tag{7}$$

The short circuit, I_{SC}, is the point of maximum current that a solar cell achieves – it corresponds to $U_D = 0$ –, whereas the open circuit voltage, V_{OC}, is the point of maximum voltage of a solar cell – it corresponds to $I_{\text{cell}} = 0$. This being said, two-equations that contribute to the understanding of solar cells operation are the short-circuit current variation with irradiance, equation (8), and the open-circuit voltage variation with the relation $\frac{I_{\text{SC}}}{I_S}$, equation (9).

$$I_{\text{SC}} = I_{\text{SC}_{\text{ref}}} \cdot \frac{G}{G_{\text{ref}}} \tag{8}$$

$$V_{\text{OC}} = n \cdot U_T \cdot ln \left(\frac{I_{\text{SC}}}{I_S} + 1 \right) \tag{9}$$

Where $I_{\text{SC}_{\text{ref}}}$ is the reference short-circuit current [4].

For a constant temperature, when the irradiance increases, the currents increase considerably, which means that I_{SC} will be much higher. On the other, the open-circuit voltage has only a slight increase. This can be proved theoretically by inspection of equations (8) and (9). For a constant irradiance, I_{SC} remains approximately constant with an increase of temperature, having an unnoticeable elevation. Differently, the respective I_{VOC} value decreases greatly with an increase of temperature, which can be induced by examination of the equations mentioned above.

II. Related Work

A brief analysis of the chosen literature is shown in order to present relevant related studies to the work that is going to be shown thereafter. Several important research findings will serve as a foundation to the calculations carried out in the last phase of this research.

In 2003, Tamizhmani et al. [5], based on IEEE PAR 1479 "Recommended Practice for the Evaluation of Photovoltaic Module Energy Production", proposed a method to predict power/energy production as a function of ambient temperature, T_a, wind speed (W_{speed}), wind direction (W_{dir}), total irradiance and relative humidity. They first developed a model based on the 5 inputs already mentioned and then tested another one based on 3 inputs only: ambient temperature, wind speed and global irradiance. They evaluated the two models by using a Neural Network from MATLAB Toolbox and explained that the 3 input model is more reliable due to lower related errors, as the errors in the measurement accuracy of wind direction and humidity may have a stronger influence than the two parameters themselves on the coefficient values; this phenomenon can be verified by their simulations, where several factors where compared, reaching a final conclusion: there is a simple linear relationship between the module temperature and the ambient conditions that can be simulated empirically by equation (10), where the respective units are °C for T_{a}, W/m^2 for irradiance and m/s for wind speed.

$$T_{\text{m}} = 0.943 \cdot T_{\text{a}} + 0.028 \cdot G - 1.528 \cdot W_{\text{speed}} + 4.3 \quad (10)$$

This equation was formulated with the objective of fitting to all the different technologies under study and it is here classified as the **Tamizhmani** model.

In 2011, Ruscheweyh et al. [6] approached the effect of wind loads on solar plants placed on rooftops. They stated that there are some parameters that influence wind loads, such as the angle of the module to the horizontal plane, the distance of the module rows to each other, the position of the module in the module field, the gaps between the module's respective gap to the ground, the supporting system and many others. One of their main concerns was a phenomenon called the leading edge vortex – when there is a wind flow directed towards the building corner. In their research, they simulated the effect of wind in a wind tunnel by generating a wind profile, testing their model with a boundary layer for a free field. Between a lot of concepts-description and further simulations, they came to the conclusion that all the results had the same tendency once the modules at the rim of the module field present the maximum wind load. This last-mentioned is reduced gradually when moving towards the rear field, which shows a significantly reduced load, due to the wind shadow effect.

In 2013, Schwingshackl et al. [7] compared the accuracy of different models that include and do not include wind data to predict PV cell temperature, assuming that the temperature of the model is the same as the cells' [8], they studied the cooling effect of wind on PV cell temperature for different cell technologies installed at a PV test facility in Bolzano, Italy, taking into consideration the module temperature as a function of solar irradiance, ambient temperature and wind, as shown in the prediction models below. Schwingshackl et al. performed in-situ measurements, using sensors installed at a weather station placed next to the PV plant for obtaining the meteorological parameters. The PV cells temperature was recorded at the back of the modules. In addition to these measurements, they also used wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF). Regarding the cell temperature prediction, eight models were used. The ones introduced here are the models pertinent to the work developed in this thesis. As a consequence of their importance, their names are displayed in bold. All of these models relate the cells (therefore, the module) temperature with the incoming irradiance and relevant meteorological parameters.

The first model is the aforementioned **Standard Approach**, (11), that is also known as the NOCT formula, in which the cell temperature is given by:

$$T_c = T_a + \frac{G}{G_{\text{NOCT}}} \cdot (T_{\text{NOCT}} - T_{\text{a,NOCT}}) \quad (11)$$

Where G is the in-plane irradiance, T_{NOCT} is the nominal operating cell temperature, a factor whose value depends on the PV technology. G_{NOCT} and $T_{\text{a,NOCT}}$ are parameterized values: 800 W/m^2 and 20°C, respectively. Although the full description of Nominal Operation Cell Temperature (NOCT) can be found in [9], it is important to know that it considers a wind speed of 1 m/s. The SA was the reference model used by Schwingshackl et al. and it is the model that will be used later as a reference when performing comparisons.

The second and third models are advanced models proposed by Skoplaki et al. [10], here called **Skoplaki 1** and **Skoplaki 2**, respectively. As follows, they take wind data into account and both of them rely on (12).

$$T_c = T_a + \frac{G}{G_{\text{NOCT}}} \cdot (T_{\text{NOCT}} - T_{\text{a,NOCT}}) \cdot \frac{h_{\text{w,NOCT}}}{h_w} \cdot \left[1 - \frac{\eta_{\text{STC}}}{\tau \cdot \alpha}(1 - \beta_{\text{STC}} T_{\text{STC}})\right] \quad (12)$$

Being h_w the wind convection coefficient, $h_{w,\text{NOCT}}$ the wind convection coefficient at NOCT conditions (where $W_{\text{speed}} = 1\text{m/s}$), η_{STC} is the efficiency of the module at STC, τ is the transmittance and α is the absorptance – their product is assumed to be equal to 0.9 [11] –, β_{STC} is the temperature coefficient of maximum power of the module and T_{STC} is the temperature at STC conditions, 25°C. What differs between the two last-mentioned models is the parameterization of $h_w(v)$. Skoplaki 1 uses the parameterization developed by Skoplaki et al., as demonstrated by (13) and Skoplaki 2 refers to the parameterization suggested by Armstrong et al. [12], given by (14).

$$h_w = 5.7 + 2.8 W_{\text{speed}} \quad (13)$$

$$h_w = 8.3 + 2.2 W_{\text{speed}} \quad (14)$$

The wind speed is the local wind speed measured close to the module.

The fourth model was developed by Koehl et al. [13], but makes use of an empirical model advanced by Faimann [14]. In this way, Koehl et al. specify the values of the U_0 and U_1 constants for different PV cell technologies, which are used in (15) – equation that describes the **Koehl** model.

$$T_c = T_a + \frac{G}{U_0 + U_1 \cdot W_{\text{speed}}} \quad (15)$$

In an attempt to suggest an evolved prediction model, Mattei et al. [15] proposed one that says the PV cell temperature follows the subsequent equation, (16):

$$T_c = \frac{U_{\text{PV}} T_a + G \cdot [\tau \cdot \alpha - \eta_{\text{STC}}(1 - \beta_{\text{STC}} T_{\text{STC}})]}{U_{\text{PV}} + \beta_{\text{STC}} \cdot \eta_{\text{STC}} \cdot G} \quad (16)$$

Where U_{PV} is the heat exchange coefficient for the face of the module. Since they refer two possible parameterizations for this variable, this implies the existence of two models: **Mattei 1** and **Mattei 2**, following the procedure described for the Skoplaki models. In the first one (17), U_{PV} is reported such as:

$$U_{\text{PV}} = 26.6 + 2.3 W_{\text{speed}} \quad (17)$$

In Mattei 2 (18), it is given as:

$$U_{\text{PV}} = 24.1 + 2.9W_{\text{speed}} \tag{18}$$

Similarly to (13) and (14), W_{speed} is the wind speed measured close to the module.

Finally, a model proposed by Kurtz et al. [16] that does not consider parameters associated with each PV technology. This being said, the **Kurtz** model (19) proposes a correlation between cell temperature, ambient temperature, irradiance and wind speed given by:

$$T_c = T_a + G \cdot e^{-3.473-0.0594W_{\text{speed}}} \tag{19}$$

Likewise the previous models, this one includes the local wind speed as a variable.

After comparing all the data obtained, Schwingshackl et al. stated that for p-Si cells, models Mattei 1 and Mattei 2 are the most accurate. When it comes to CdTe, they report that the SA and Kurtz model achieve the best results, indicating that it happens "probably because those PV modules have a higher thermal inertia than the silicon PV technologies" [7, p. 6]. Nevertheless, they make it pretty clear that since all PV technologies have different characteristics thus different behaviors, when estimating the temperature of the modules (taking wind data into account), it would be fallacious to select a generalized approach.

In 2016, Amajama et al. [17] studied the impact of wind on the output of a photovoltaic panel (mono-crystalline cell type), experimentally. The results were analyzed by computing the output current and the output voltage versus wind speed at nearly constant air temperature, air pressure, relative humidity and solar illuminance/intensity. Along with that, the relation between wind speed and solar illumination/intensity was tested, maintaining also the aforesaid parameters nearly constant. That being said, they state that wind speed, having an effect on radio waves propagation, aids it if the wind is flowing in parallel to the signal, but acts in the adverse way if it is tangential or anti-parallel, impairing the propagation of the radio waves. Moreover, they pointed out the similarity between these waves and electromagnetic radiations, that share comparable properties.

With the formerly mentioned in mind and following the data analysis, they attained two advantageous (A, B) and two disadvantageous (C, D) situations, respecting the performance of the PV module in function of the wind: (A) when wind is towards the front of an observer (or panel) with the sun some distance away in front; (B) when wind is towards the back of the observer (or panel) and the sun is behind; (C) when wind's direction is towards the back of an observer (or panel) and the sun is some distance in front of the observer (or panel); (D) when the sun is some distance behind the observer (or panel) and the wind direction is towards the front of the observer (or panel). To sum up, in this last study, it was evidenced that, under the same conditions, when the molecular particles of the wind are in phase with the direction of the solar photonic particles, solar illuminance/intensity is favoured, thus unfavoured when out of phase. Consequently, the same phenomenon occurs in relation to the output of a photovoltaic panel [17].

III. Methodologies

The methodologies used are explained throughout this section. They refer to by what means the thematic introduced before was developed. Between all the new-era softwares and available information, a major concern relies on how to gather trusted sources and achieve tangible and authentic results by simulation methods and calculations. Accordingly, following the equations that represent the operation of solar cells, it is imperative to estimate how wind and its mutable characteristics affect them and how it is revealed on the overall performance of the system. With the previously mentioned in mind, the equations already explained serve as a foundation to all of the remaining work.

As this dissertation is focused on the effect of wind (velocity and shadowing) on energy generation of solar plants – by studying the changes in temperature of solar cells according to the technologies and designs used –, the temperature values of the different modules had to be known. Having said that, the tools that allowed the acquisition of those values were the cell temperature prediction models mentioned previously, whose names are displayed in bold – Standard Approach, Skoplaki 1, Skoplaki 2, Koehl, Mattei 1, Mattei 2, Kurtz and Tamizhmani. As pointed out before, the **reference model** is the Standard Approach. Although the NOCT formula implies a wind speed of 1 m/s, it doesn't take accurate wind data into account – despite wind's known volatility – and, notwithstanding its flaws, it is an industry standard method for calculating cells' temperature. Therefore, it becomes mandatory to cement fundamental notions when forecasting the power variation due to wind loads by consequent cell temperature fluctuations in solar plants. With this, temperature and resultant power deviations between all the models suggested were analyzed in order to understand how different PV technologies behave upon different prediction models and different wind speeds. This work was applied to all the modules present in the geometry detailed afterwards so as to investigate the effect of wind shadowing between PV arrays.

In order to perform complex engineering computations, a model of each of the intended PV geometries had to be created by scratch. For this task, a Computer-Aided Design (CAD) software is needed and the chosen softwares were FreeCAD and Fusion 360. The first one was used to create the solar PV geometries and the later-mentioned ensured the design of the wind tunnels. When it comes to Computational Fluid Dynamics (CFD), which is "a science that, with the help of digital computers, produces quantitative predictions of fluid-flow phenomena based on the conservation laws (conservation of mass, momentum, and energy) governing fluid motion" [18, p. 421], the software that allowed its concretion was Autodesk CFD – a CFD simulation software that engineers can use to predict how liquids and gases will perform when applied to some CAD geometry.

Once acquired the wind speed values by means of CFD, Microsoft Excel was the designated software to compute the calculations of the temperature (and associated peak power variation) for every single module, according to each 1) model, 2) solar cell technology and 3) wind speed value.

As this investigation intends to propose a general perspective on how wind affects the performance of solar plants, it was required that the CFD simulations were based on suitable and concrete data, such as realistic atmospheric conditions and characteristic values, for instance, the parameters of solar cells, dimensions of the PV modules and the support system designs. In what wind speeds are concerned, as there are multiple sources of meteorological information, it was taken into account data made available by Instituto Português do Mar e da Atmosfera (IPMA) and Meteored. After analyzing the maximum and average wind speed values for the Lisbon district throughout the year 2020, two final values were established: W_{avg} = 4.06 m/s – Average Average Wind Speed – and W_{max} = 17.55 m/s – Average Maximum Wind Speed.

Since that all module temperature prediction models consider T_a and G – ambient temperature and irradiance, respectively – and that NOCT conditions require $G_{\text{NOCT}} = 800\,\text{W/m}^2$ and $T_{a,\text{NOCT}} = 20\,°\text{C}$, the values chosen for the in-plane irradiance and ambient temperature are the same as the NOCT ones so that $G = G_{\text{NOCT}} = 800\,\text{W/m}^2$ and $T_a = T_{a,\text{NOCT}} = 20\,°\text{C}$.

Given that there are many PV cells technologies, it is imperative to simulate the most convenient ones. With this purpose, p-Si, CdTe and CIGS technologies were the ones selected. Being that different technologies behave differently due to their intrinsic characteristics and, as beforesaid, aiming to the most accurate real-life simulation results, three distinct solar panels datasheets were collected – one for each technology. These datasheets can be found in [19], [20] and [21], respectively. Their main characteristics (that are fundamental for the calculations) are expressed in table I.

TABLE I
MAIN PARAMETERS FOR EACH SOLAR CELL TECHNOLOGY.

Parameter		Technology		
		p-Si	CdTe	CIGS
Efficiency (%)	η	15.6	17.0	13.9
Temp. Coef. of P_{mpp} (%/°C)	β_{STC}	-0.39	-0.28	-0.31
NOCT (°C)	T_{NOCT}	45	45	47
Koehl Coefficient 0	U_0	30.02	23.37	22.19
Koehl Coefficient 1	U_1	6.28	5.44	4.09

Before proceeding to the computational simulations, a CAD geometry of the PV arrays had to be created having in mind its real dimensions. Understanding that each company produces PV modules of distinct sizes, it wouldn't be adequate to simulate different geometries and then compare the results obtained, given that the design of each structure influences the aerodynamics hence the wind speeds around solar panels, which would lead to misleading results. For this reason, only one geometry was considered, having in mind that the Temperature Coefficient of P_{mpp}, β_{STC}, and the remaining parameters accounted in every cell temperature prediction model are technology/material-specific and their value isn't dictated by module's dimension. The dimensions used for constructing the CAD models were 1645 x 992 x 35 mm, that correspond to the p-Si panels. That being said, two geometries were created, as seen in figures 1 and 2 – arrays of three and nine panels, respectively, in two parallel rows, distancing 2140 mm from each other.

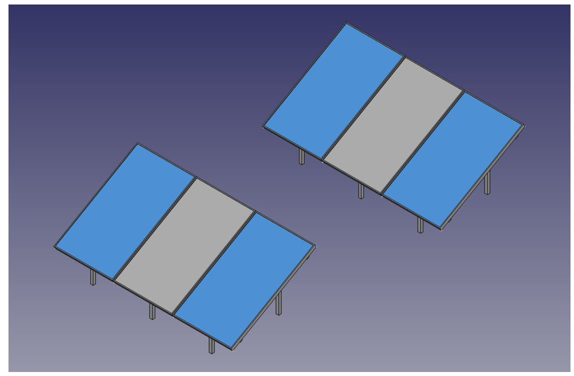

Fig. 1. Two rows of arrays (3 by 2).

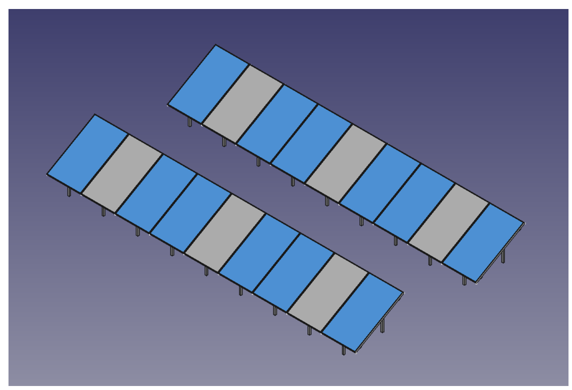

Fig. 2. Two rows of arrays (9 by 2).

For the purpose of studying wind flow around the panels, CFD simulations demand that the geometries created have to be inside a wind tunnel. Assuming h as the total height of the CAD model, w its total width and l its total length, tunnels were created respecting the following rules proposed by Autodesk, the company that developed Autodesk CFD [22]: $3h <$ tunnel height $< 4h$ – model sitting on the floor (z = 0); $5w <$ tunnel width $< 7w$ – model in the center; tunnel length from the front (inlet) to the object = $2l$ (in the direction of flow); tunnel length from the object to the back (outlet) = $4l$ (in the direction of flow).

Before running simulations, the geometries created had to go trough a process called meshing, which is the process of dividing a CAD model into multiple small cells (mathematically defined shapes) that can be used to discretize a domain in order to simplify a geometry's complexity and to whom the governing equations are applied when solving simulations.

The final step before proceeding to simulations was to setup the solver. It was where fluid material properties, boundaries and the flow physics model were defined. As a thermal analysis wasn't performed, the materials assigned to the rows of PV panels were neglected – the geometry was only defined as a solid. However, the fluid inside the wind tunnel must be air, obviously. Wind tunnel structure does not present any requirement in what concerns materials; in spite of that, it inevitably needed boundaries designation, which is a process based on imputing physical conditions to the boundaries of the flow domain – the so-called boundary conditions. They are inherent to the wind model applied to the wind tunnel, that is detailed right away. That being said, the boundary conditions set were: inlet – velocity type, with magnitudes of W_{max} and W_{avg} (steady-state); outlet – pressure type, equal to zero (steady-state); top and sides – slip/symmetry type. Once the front of the PV geometry is facing the inlet, wind flow is parallel to planes xOy and yOz and perpendicular to xOz.

Finally, with the understanding that wind is a fluid flow, when simulation the wind influence on photovoltaic panels, it was decided to neglect its laminar phase, since it is well known that the laminar phase of a flow (smooth path with no disruption between adjacent paths) is much smaller than its turbulent one (chaotic path that comprises eddies, swirls and flow instabilities) in the type of problem studied here. Thereby, a turbulent flow k-epsilon (which is the default turbulence model in Autodesk CFD) was applied as an external flow in the longitudinal direction of the wind tunnel, at the inlet. The standard $k - \epsilon$ model was chosen by virtue of its characteristics: it gives accurate predictions on distribution of speed around CAD geometries [23] and it is a general purpose model (the most used) that performs well for a large number of applications. The $k - \epsilon$ model is part of the Reynolds-Average Navier Stokes (RANS) family of turbulence models and both letters that name it (k and ϵ) refer to two transport equations that are solved upon its usage: turbulent kinetic energy – energy in turbulence – and turbulent dissipation rate – rate of dissipation of turbulent kinetic energy –, respectively.

IV. Experimental Evaluation

Wind flow around the PV arrays was analyzed for each geometry, taking into consideration the two aforementioned wind velocities at the inlet: W_{avg} = 4.06 m/s and W_{max} = 17.55 m/s. In order to extract valuable information about turbulent flow behavior, a vertical plane – parallel to yOz and perpendicular to xOz – was applied to the wind tunnel, for each geometry and for each inlet wind speed. This generated a cross section inside the tunnel's volume, where it can be observed the wind flow pattern. With the purpose of obtaining a general wind flow distribution around the whole geometries, a rectangular grid of points was defined at the inlet. Each of these points generates a path across the tunnel for the corresponding wind element point, creating a continuous line.

In what the first CAD model is concerned (3 by 2 geometry), its simulations results for W_{avg} are shown in figure 3 and figure 4. For the first one, the vertical plane is aligned with the central module of both rows, given that they are parallel (x and z coordinates are equal). For the later one, the plane is aligned with the tip module of each array. The left side scale indicates the velocity magnitude in cm/s, starting in 0 cm/s and ending in 514.366 cm/s for all the figures that refer to this wind speed value. It was observed that the wind

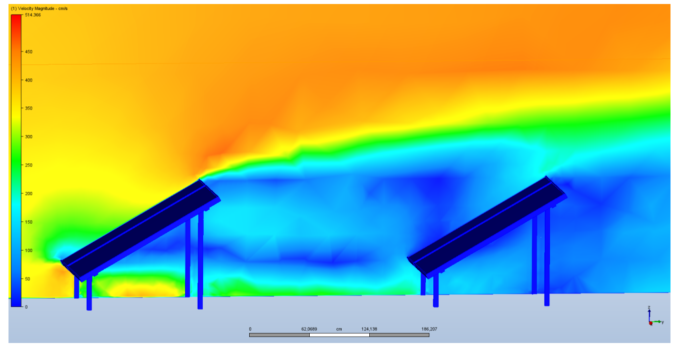

Fig. 3. Wind flow for a vertical panel aligned with central module of the 3 by 2 geometry – W_{avg}.

shadow phenomenon introduced earlier occurs, which implies a decrease in wind speed right after the first array, thus leading to a lower wind intensity for the second row. When inspecting the wind behavior close to the front PV module, it was possible to verify that wind has higher speed magnitudes in the upper portion of its face. Although this also happens to the equivalent panel of the second row, the magnitudes are much different, which will cause disparities between temperatures of the modules.

It can be said that despite the fact that turbulent flows are not likely to be perfectly predictable, there is approximately a symmetry of wind flow distribution thus wind speed distribution from the middle of each row to each of its extremities. Consequently, there is no need to show wind flow simulations for both of them. By examination of the cross section that

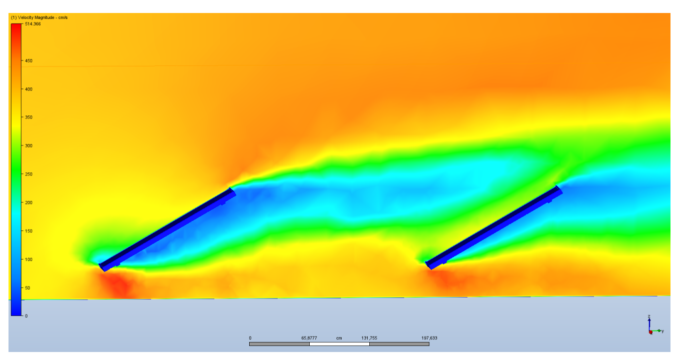

Fig. 4. Wind flow for a vertical plane aligned with tip module of the 3 by 2 geometry – W_{avg}.

represents wind flow for the surroundings of the tip modules of each row, it was seen that the wind shadow effect is attenuated, hence the rear panel presents higher speed values near its face if compared to the central module. At the same time, it is clear that wind has a not so different behavior for all the front row modules when compared to the rear set.

Figure 5, which is also a side view that allows the perception of wind movement along the wind tunnel when crossing the whole PV structure, made evident the appearance of swirls that differ from the common motion of the fluid, as they are represented mostly by blue lines after each array. These swirls are the so-called eddies in fluid mechanics. Their energy is successively transferred from large eddies to smaller ones until it is dissipated [24]. This figure confirms wind shadowing between rows of panels by two factors: reduction of lines density and mitigation of wind speed.

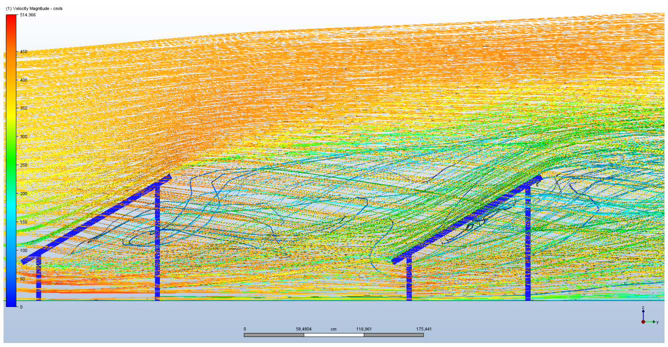

Fig. 5. Side view of wind flow for the 3 by 2 geometry – W_{avg}.

The same procedure was repeated for W_{max}, where similar results were obtained proportionally, i.e., the wind behavior was verified as identical, but wind speeds presented higher magnitudes and turbulent events were enhanced.

Next, wind velocity values were collected for a very close vicinity of the panels' faces. These values are shown in table II, in which the parcel *Ratio* indicates the ratio between the wind speed collected and the inlet speed value. Note: numbering of panels is done from left to right and it starts in the left tip panel of the first row.

TABLE II
WIND SPEED FOR EACH PANEL (3 BY 2 GEOMETRY).

	W_{avg}		W_{max}	
	Speed (m/s)	**Ratio**	**Speed (m/s)**	**Ratio**
Panel 1	2.7700	0.6823	12.3322	0.703
Panel 2	2.5737	0.6339	11.4047	0.650
Panel 3	2.7617	0.6802	12.2184	0.696
Panel 4	2.6932	0.6634	12.1172	0.690
Panel 5	1.3441	0.3311	5.9081	0.337
Panel 6	2.6806	0.6602	12-0584	0.687

By comparison of the values for both wind speed values, their similarity in what the ratio is concerned is truly evident. There is a significant decrease of wind speed for the central module of the second row (panel 5) but the effective difference between panel 1 and 4 and between 3 and 6 is almost unnoticeable; although the distribution of wind speed may not be so alike, the average wind speed values are.

The 3 by 2 geometry presents a reduced complexity when compared to the geometry covered in this subsection. Although it can represent a real-life situation in such a manner that the simulations results detailed before are a very coherent starting point for what can be expected for other arrangements, the most common designs found in solar plants are clearly more similar to this second one. This being said, each of the tasks performed for the simpler CAD model were replicated to the 9 by 2 geometry.

Starting by the analysis of simulations related to W_{avg}, a vertical plane was applied to the wind tunnel, as it can be seen in figure 6, generating a cross section along the PV structure and the tunnel. This figure depicts the wind flow for the area represented by the plane. The scale displayed in the left side of the figures that illustrate the average average wind speed at the inlet indicates the velocity magnitude, starting in 0 cm/s and goes up to 645.984 cm/s. As it was done for the previous geometry, the plane is aligned with the central module of the 9 by 2 geometry. Once again, the wind shadow effect can be observed due to the much lower wind speed verified for the surroundings of the rear module.

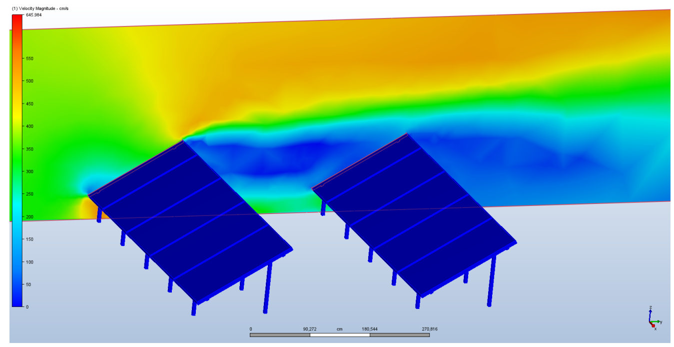

Fig. 6. Wind flow for a vertical panel aligned with central module of the 9 by 2 geometry – W_{avg}.

Figure 7 shows wind flow when the vertical plane is aligned with the tip modules. By its inspection, it was possible to confirm that just like with the preceding geometry, wind shadowing effect is almost null for the modules at the extremities.

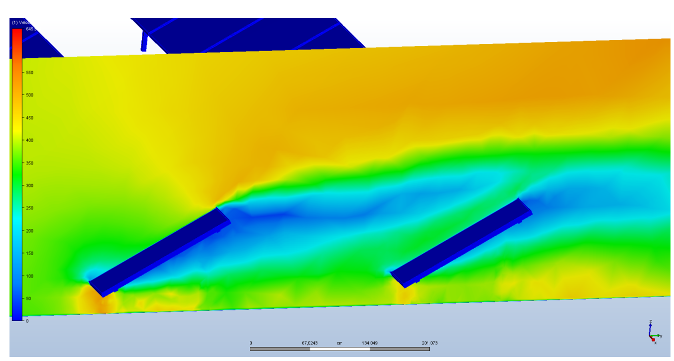

Fig. 7. Wind flow for a vertical panel aligned with tip module of the 9 by 2 geometry – W_{avg}.

Wind velocity values were also collected for this geometry respecting to each of the velocities at the inlet, W_{avg} and W_{max}. These values are exhibited in table III. By its inspection, it was noticed an abrupt difference between the wind speeds registered for the tip modules of the rear row (panels 18 and 10) and the remaining, as expected. There is a clear difference between both scenarios: for a lower velocity at the inlet, the ratios observed for the tip panels of each row (1 and 10, 9 and 18) decrease substantially from the front to the rear row, but for a higher wind velocity at the inlet, the wind shadow effect is reduced for the tip panels, which leads to a similar ratio when comparing wind speed for panel 1 with 10 and panel 9 with 18 for this velocity – relations that are closer to what was verified for the first geometry.

TABLE III
WIND SPEED FOR EACH PANEL (9 BY 2 GEOMETRY).

W_{avg}					
Panel	**Speed (m/s)**	**Ratio**	**Panel**	**Speed (m/s)**	**Ratio**
Panel 1	2.8307	0.6972	Panel 10	2.0932	0.5156
Panel 2	2.5662	0.6321	Panel 11	0.8621	0.2123
Panel 3	2.4935	0.6142	Panel 12	0.7557	0.1861
Panel 4	2.4389	0.6007	Panel 13	0.7445	0.1834
Panel 5	2.4498	0.6034	Panel 14	0.7180	0.1769
Panel 6	2.4767	0.6100	Panel 15	0.7561	0.1862
Panel 7	2.5241	0.6217	Panel 16	0.7959	0.1960
Panel 8	2.5407	0.6258	Panel 17	0.8583	0.2114
Panel 9	2.7356	0.6738	Panel 18	2.1541	0.5306
W_{max}					
Panel	**Speed (m/s)**	**Ratio**	**Panel**	**Speed (m/s)**	**Ratio**
Panel 1	13.2141	0.7529	Panel 10	12.3679	0.7047
Panel 2	11.965	0.6818	Panel 11	3.4115	0.1944
Panel 3	11.5708	0.6593	Panel 12	2.6822	0.1528
Panel 4	11.4064	0.6499	Panel 13	2.8797	0.1641
Panel 5	11.4009	0.6496	Panel 14	2.8360	0.1616
Panel 6	11.4496	0.6524	Panel 15	2.9946	0.1706
Panel 7	11.6691	0.6691	Panel 16	2.8800	0.1641
Panel 8	11.9045	0.6783	Panel 17	3.2980	0.1879
Panel 9	13.0969	0.7463	Panel 18	12.2337	0.6971

Temperature predictions were only performed for the second geometry (9 by 2), which depicts a more common case in solar plants. In addition to that, due to the similarities verified for wind flow for both of the geometries under study, it would be almost redundant to calculate the temperatures for each geometry. That being so, the calculations for the 9 by 2 geometry were done according to the following: module temperature forecast according to each prediction model; for each prediction model, each PV Having said that, table IV shows the values of temperature (in °C) predicted by each model, taking into account each PV technology and the two distinct wind speed values used in CFD simulations, $W_{avg} = 4.06$ m/s and $W_{max} = 17.55$ m/s. Each of the values displayed refers to a single average temperature value for each set of 18 panels. As it was aforesaid, it is important to mention that models Skoplaki 1, Skoplaki 2, Koehl, Mattei 1 and Mattei 2 take into consideration technology-relative parameters, whereas Kurtz and Tamizhmani do not. This is the reason why the temperatures are the same for the same values of wind speed, disregarding technologies.

TABLE IV
VALUES OF TEMPERATURE IN °C FOR EACH SET OF 18 PV PANELS.

Technology	**poly-Si**		**CdTe**		**CIGS**	
Wind speed	W_{avg}	W_{max}	W_{avg}	W_{max}	W_{avg}	W_{max}
SA	45		45		47	
Skoplaki 1	36.81	27.44	36.56	27.33	38.69	28.27
Skoplaki 2	37.70	29.30	37.44	29.16	39.67	30.34
Koehl	39.63	31.01	44.53	33.36	47.38	35.90
Mattei 1	39.64	33.73	39.22	33.44	40.02	34.01
Mattei 2	40.67	33.34	40.22	33.06	41.06	33.61
Kurtz	42.30	35.51	42.30	35.50	42.30	35.51
Tamizhmani	42.78	32.55	42.78	32.55	42.78	32.55

Remembering that the Standard Approach is the reference model, which does not account with wind data (it just has an implicit wind velocity of 1 m/s associated), the variation of the temperatures predicted by the models that take wind data into account compared with the standard model is very significant: the maximum absolute variation (worst case) between the results predicted by the complex models is 8.1822 °C, but it is increased to 18.7338 °C when compared with the SA – this type of discrepancy is much more common throughout all the comparisons between the other models with the Standard Approach than with one another. By inspection of table IV, it is visible that the Skoplaki models predict lower temperatures than the other models for every technology; the Koehl model is the one that exhibits higher variations with the various technologies; the Mattei models present very similar temperatures across all the technologies and the results they generated are identical between both models, never showing a variation of more than 1.037 °C; the Kurtz and Tamizhmani models predicted close temperatures between them for W_{avg}, but differ for higher wind speeds. One interesting case that deviates from all the others is the prediction performed by the Koehl model for the CIGS technology at W_{avg}, which is slightly higher than the value expected by the NOCT formula.

It was noticed that the predicted temperatures are always lower for W_{max} in contrast to W_{avg}, which clarifies the influence that wind has as a cooling mechanism for solar photovoltaic modules. The higher the speed, the lower the temperature predicted according to the module temperature prediction models. These variations in temperature can make all the difference in the output power of the panels, since high temperatures reduce modules efficiency.

Taking into consideration the temperatures predicted in the previous section, the corresponding output power variations were calculated. Knowing that the SA is the reference model, it can be assumed that its predictions correspond to the temperatures commonly expected and these temperatures correspond to a certain power output variation. Being that all the temperatures predicted by the different models are lower than the ones foreseen by the NOCT formula, except for the case mentioned above, the values displayed in table V are the difference between the temperatures predicted by the models that take wind data into account and the values anticipated by the Standard Approach multiplied by the temperature coefficient of P_{mpp}. Given that β_{STC} units are %/°C, the results obtained are in percentage.

TABLE V
OUTPUT POWER VARIATION IN PERCENTAGE (%) FOR EACH SET OF 18 PV PANELS.

Technology	**poly-Si**		**CdTe**		**CIGS**	
Wind speed	$W_{\mathbf{avg}}$	$W_{\mathbf{max}}$	$W_{\mathbf{avg}}$	$W_{\mathbf{max}}$	$W_{\mathbf{avg}}$	$W_{\mathbf{max}}$
Skoplaki 1	3.19	6.85	2.36	4.95	2.58	5.81
Skoplaki 2	2.85	6.12	2.12	4.43	2.27	5.16
Koehl	2.09	5.45	0.13	3.26	-1.20	3.44
Mattei 1	2.09	4.40	1.62	3.24	2.16	4.03
Mattei 2	1.69	4.55	1.34	3.34	1.84	4.15
Kurtz	1.05	3.70	0.76	2.66	1.46	3.56
Tamizhmani	0.87	4.86	0.62	3.49	1.31	4.48

The interpretation of table V is that wind speed (W_{avg} or W_{max}) has an influence such that its flow increases/decreases output power in $x\%$ when compared with the output power variation normally expected by the SA, in which wind is not taken into consideration.

The analysis of this table is analogous to the one performed for table IV, since one is the consequence of the other. This being said, for the highest variations of temperatures match the highest variations of output power. As it was estimated, the Koehl model predicts an overheating of the panels, decreasing their output power in 1.20% for the CIGS technology when there is a wind speed of 4.06 m/s at the inlet of the wind tunnel. Given that the Skoplaki models showed the biggest decreases of temperatures by wind action, they obviously point to the most beneficial output power variations. Although Kurtz and Tamizhmani models do not take technology-dependent variables, the output power calculations related to them do, which ends the similarities between results for distinct technologies.

V. CONCLUSIONS

This dissertation was developed with the main purpose of studying the influence of wind in energy generation of solar plants. To accomplish this task, several parameters were analyzed, which culminated in the decision of giving preference to the investigation of how wind could perform as a natural cooling mechanism for solar photovoltaic modules in solar plants look-alike arrangements of PV arrays. Delving into the several methods one could use to examine the interaction between wind flow and modules temperature, it was decided to follow empirical models that predict panels temperature according to various wind speeds and technology-based parameters (for most of them). Given that individual technologies present intrinsic properties, the temperatures that would be foreseen would tend to vary from technology to technology. The understanding of this fact led to the choice of three technologies in vogue worldwide (by distinct factors). Due to the fact that it wouldn't be plausible to compare wind flow around geometries of different sizes, it was assumed that all three had exactly the same proportions, but with different parameters that would characterize each of them; since the variables used in the temperature prediction models are technology-related, dimensions could be neglected.

That being said, a Computational Fluid Dynamics analysis of the wind flow around PV geometries was done with the intention of collecting data on wind speeds close to the solar photovoltaic panels. It was observed that for the direction of wind studied, the front rows of photovoltaic arrays always show higher wind velocity magnitudes, which are similar to the ones registered for the tip panels of the rear rows; the occurrence of wind shadowing between rows of panels imply lower wind speeds for most back panels. The referred data were used in the calculations related to the modules temperature predictions that were subsequently crucial to the output power variation results calculated for each scenario. To execute this assignment, it was imperative to use factual wind information that was gathered from reliable sources, thus empowering simulations of concrete circumstances, mimetizing a real-life approach.

The results achieved expose that higher wind speeds are directly related to decreases in modules temperature: for the average wind speeds verified for Lisbon in the year of 2020, variations of output power reached 3.19 percentage points, which expresses a very significant amount of electrical energy production when talking about solar plants. For the highest wind velocities, a maximum variation of 6.85 percentage points in power output was registered. Despite the fact that these last are not the most common values for wind velocities, they are always recorded at some moment, hence their relevance in this research.

One decisive factor that has to be taken into account is that the results attained are highly dependent on the values of wind speeds collected through simulations, on the parameters found in solar panels datasheets and, finally, on the accuracy of the temperature prediction modules employed. To what the wind speeds collected are concerned, the abrupt differences of velocity around the panels influence the calculations made in a critical way. In order to interpret the calculations results displayed in this dissertation correctly, it must be foreknown that the wind speed value collected for each solar photovoltaic panel involve an area right after the surface of the PV panels, where wind speeds have lower magnitudes. This procedure leads to lower temperatures variation and lower output power variations. With this in mind, it can be said that the results here achieved allude to the worst case (although its just-proven benefits), from an electrical engineering perspective.

Taking into consideration the results obtained, it can be said that, in fact, wind works as a natural cooling mechanism for solar panels, thereby improving their productivity, which can lead to significant benefits respecting electrical energy production in solar plants. Nevertheless, several other factors that are correlated with wind loads must be investigated and should not be neglected when thinking about wind influence on solar plants.

To the extent of the reliances explained for the final results herein presented, this thesis cannot be considered a dogma for projects with the same technologies here studied or for every scenario, but it is manifested as a general approach that certainly contributes with a strong insight on how wind influences the electrical energy production in solar plants through its cooling effects.

VI. Future Work

Throughout the analysis of the experimental results, it was proven that wind can privilege the electrical energy production in solar plants by reducing the temperatures of the photovoltaic modules, thus preventing lower panels efficiencies. Nevertheless, it opens several possible paths for improvements in the future and this is what is discussed in this final section.

The first recommendation has to be the experimental (in-situ) validation of the results calculated by the different module temperature prediction models for the area of Lisbon, concerning irradiances of 800 W/m^2 and ambient temperatures of 20°C to then compare them with the values obtained in this dissertation for the various technologies. Moreover, an investigation that verifies the relationship between wind speeds, pressure influence and dust deposition on solar panels would be of great value, given that these three factors are not independent from each other.

Furthermore, it would be interesting to study how wind affects the output power of circular solar plants (or others designs), whose arrangements of PV arrays are completely distinct from the type of geometries here presented, consequently implying dissimilar wind flows. Also, different wind directions or non-constant irradiances (taking the sun movement into consideration, for example) may contribute to a deeper understanding of the relation between wind and irradiance and its significance when choosing the best site for the construction of a solar plant.

Lastly, an additional research that can be allied to the work developed in this thesis is suggested: an approach on how wind can work as a cooling mechanism on electric cables of solar plants, given that their overheating reduces the output power, too. This could reinforce the pertinence of using wind as a natural cooling system in solar plants.

All these few ideas may help in the pursue and consolidation of knowledge around the unthinkable number of factors that affect solar plants performance, beyond solar photovoltaic technology-related idiosyncrasies.

References

[1] European Comission. 2020 Climate & Energy Package. https://ec.europa.eu/clima/policies/strategies/2020_en, 2020. Online; accessed 14 May 2020.

[2] Associação Portuguesa de Energias Renováveis. Balanço da produção de eletricidade de portugal continental (abril de 2020). https://www.apren.pt/pt/energias-renovaveis/producao, 2020. Online; accessed 16 May 2020.

[3] International Energy Agency. Renewables 2019. https://www.iea.org/reports/renewables-2019, 2019. Online; accessed 14 May 2020.

[4] Arno H M Smets, Klaus Jäger, Olindo Isabella, René ACMM van Swaaij, and Miro Zeman. *Solar Cell Parameters and Equivalent Circuit*. TU Delft, 2016.

[5] Govindasamy Tamizhmani, Liang Ji, Yingtang Tang, Luis Petacci, and Carl Osterwald. Photovoltaic module thermal/wind performance : Long-term monitoring and model development for energy rating. *NCPV and Solar Program Review Meeting*, pages 936–939, 2003.

[6] Hans Ruscheweyh and Reiner Windhövel. Wind loads at solar and photovoltaic modules for large plants. *Proceedings of the 13th International Conference on Wind Engineering*, 2011.

[7] C. Schwingshackl, M. Petitta, J. E. Wagner, G. Belluardo, D. Moser, M. Castelli, M. Zebisch, and A. Tetzlaff. Wind effect on PV module temperature: Analysis of different techniques for an accurate estimation. *Energy Procedia*, 40:77–86, 2013.

[8] L. W. Florschuetz. Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. *Solar Energy*, 22(4):361–366, 1979.

[9] T. Markvart. *Solar Electricity*. John Wiley & Sons Ltd., Chichester, 2 edition, 2000.

[10] E. Skoplaki and J. A. Palyvos. Operating temperature of photovoltaic modules: A survey of pertinent correlations. *Renewable Energy*, 34(1):23–29, 2009.

[11] John A. Duffie and William A. Beckman. *Solar Engineering of Thermal Processes*, volume 3. WILEY, 4 edition, 2013.

[12] S. Armstrong and W. G. Hurley. A thermal model for photovoltaic panels under varying atmospheric conditions. *Applied Thermal Engineering*, 30(11-12):1488–1495, 2010.

[13] Michael Koehl, Markus Heck, Stefan Wiesmeier, and Jochen Wirth. Modeling of the nominal operating cell temperature based on outdoor weathering. *Solar Energy Materials and Solar Cells*, 95(7):1638–1646, 2011.

[14] David Faiman. Assessing the Outdoor Operating Temperature of Photovoltaic Modules. *Wiley InterScience*, 16:307–315, 2008.

[15] M. Mattei, G. Notton, C. Cristofari, M. Muselli, and P. Poggi. Calculation of the polycrystalline PV module temperature using a simple method of energy balance. *Renewable Energy*, 31(4):553–567, 2006.

[16] S Kurtz, D Miller, M Kempe, N Bosco, K Whitefield, Miasole J Wohlgemuth, N Dhere, and T Zgonena. Evaluation of High-Temperature Exposure of Photovoltaic Modules: Preprint. *Nrel*, pages 2399–2404, 2009.

[17] Joseph Amajama, Julie C. Ogbulezie, Nsed A. Akonjom, and Victor C. Onuabuchi. Impact of wind on the output of photovoltaic panel and solar illuminance/intensity. *International Journal of Engineering Research and General Science*, 4(5), 2016.

[18] Howard H Hu. Chapter 10 - Computational Fluid Dynamics. In Pijush K Kundu, Ira M Cohen, and David R Dowling, editors, *Fluid Mechanics (Fifth Edition)*, pages 421–472. Academic Press, Boston, 5 edition, 2012.

[19] BYD. 156.57p - series - 4bb. https://sg.byd.com/wp-content/uploads/2017/10/combine-4-1.pdf. Online; accessed 23 April 2021.

[20] First Solar. First solar series 4 pv module. https://www.firstsolar.com/en-Emea/-/media/First-Solar/Technical-Documents/Series-4-Datasheets/Series-4V3-Module-Datasheet.ashx. Online; accessed 23 April 2021.

[21] Solar Frontier. Product data sheet sf170-s. https://www.solar-frontier.com/eng/solutions/products/pdf/datesheat_170.pdf. Online; accessed 23 April 2021.

[22] Autodesk. Wind tunnel. https://knowledge.autodesk.com/search-result/caas/CloudHelp/cloudhelp/ENU/FlowDesign/files/GUID-9B85F4A0-5072-454D-8710-CCFF26507BE9-htm.html. Online; accessed 2 June 2021.

[23] G. Gun Gun Ramdlan, Ahmad Indra Siswantara, Budiarso, Asyari Daryus, and Hariyotejo Pujowidodo. Turbulence model and validation of air flow in wind tunnel. *International Journal of Technology*, 7(8):1362–1371, 2016.

[24] Inc. Encyclopaedia Britannica. Eddy. https://www.britannica.com/science/eddy-fluid-mechanics. Online; accessed 17 June 2021.