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COMPARISON OF ELECTRICAL ENERGY PRODUCTION USING TWO SOLAR IRRADIATION MODELS OF BIPV

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Abstract – Amid growing needs for sustainable buildings and renewable energies, this paper presents a comparison between two different approaches of solar irradiation models for the production of electrical energy from photovoltaic (PV) panels. This project aims to evaluate the electrical energy produced from the sustainable building ADREAM, located in LAAS-CNRS, Toulouse. Initially, the Energy Simulation Software Pleiades+Comfie (P+C) was employed for the global Dynamic Thermal Modeling of the building. Thus, the P+C software served as a reliable tool for the modeling of the electrical production from the installed PV panels. In order to estimate the performance of this model, its accuracy was compared to that of an optimized solar irradiation model (Matlab), built from literature references. A description of the ADREAM building is provided, along with the methodology of the two simulations. The simulated results of PV energy production were compared to measured data. Finally, the two results were evaluated for the purpose of determining the most optimized modeling strategy.

Keywords – Sustainable Building, BIPV Models, Pleiades+Comfie, Optimized Solar Irradiation Model, PV Energy Production

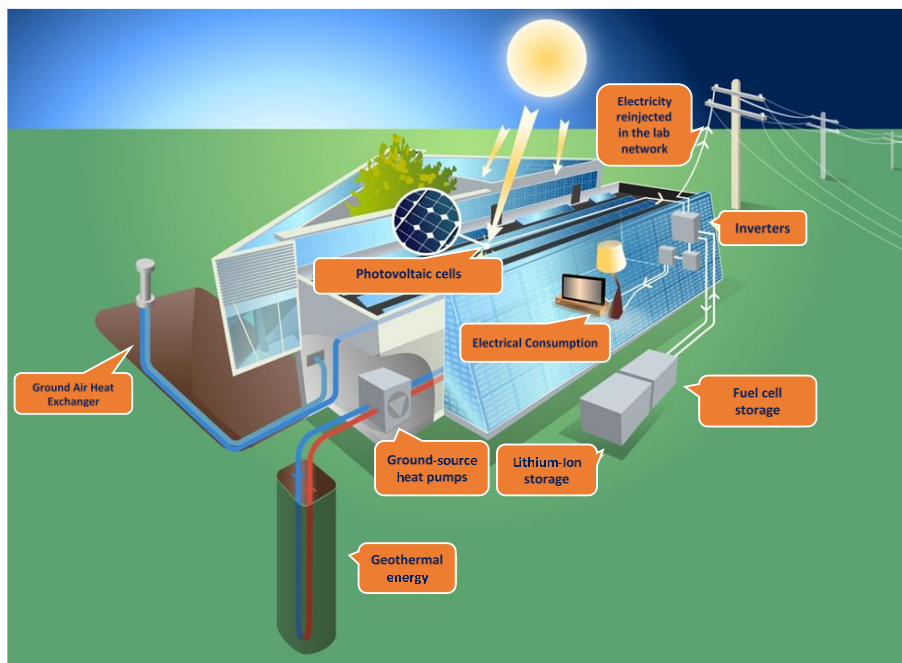


Figure 1 : Energy sources and systems installed at the building ADREAM

1. INTRODUCTION

As buildings are responsible for about 40% of the global energy consumption, they represent one of the primary targets of world policies that aim to reduce energy consumptions. The final objective is the achievement of energy savings in the order of 25% by 2030 [1]. The concept of a net Zero Energy Building (ZEB) was defined in the scientific literature by 2006, but it had not been concretely translated into laws and norms, until the National Renewable Energy Laboratory (NREL) proposed some preliminary definitions in 2006 [2]. In 2009, Aalborg University expanded this concept with a state of the art synthesis of ZEB definitions [3]. Recent demonstrators tried to achieve a zero net energy consumption target over one-year-cycles. These demonstrations implied that the energy demand for heating and electrical consumption must be minimized. The reduced demand should be completely met by its own annual production of renewable energy [4, 5]. Among the different renewable energy sources, such as the solar irradiation, the wind, the biomass, etc., solar energy has a high potential of exploitability due its wide availability.

Technological and structural drawbacks limit the development of this type of buildings. The main difficulty lies on the accurate evaluation of consumption (energy meters) and their impact on environment (CO₂ emissions). The reliability of renewable sources is another major issue, as well as the insufficient knowledge of adapting their usage to building integrated systems (limited space, problematic thermal effects, high costs, and system complexity). In 2015, the International Energy Agency edited a report about different energy performance metrics and their evolution between 2000 and 2012 based on two scenarios of consumption and greenhouse emission reduction by 2025 [6].

In order to achieve the objective of an autonomous or positive energy building, the choice of the renewable sources depends on the availability of local energy resources. In this context, solar irradiation provides several suitable uses (solar heating, natural lighting, photovoltaic energy production). Since 1999, demonstrations of Building-Integrated Photovoltaics (BIPV) appear as a ZEB solution [7, 8].

The building ADREAM of LAAS-CNRS was designed as a BIPV research platform for the development of ZEB metrics. This paper provides the description of the ADREAM building (Section 2), two different modeling approaches for simulating the PV energy production (Sections 3 and 4), the results and comparisons of their accuracies (Section 5), and finally, a conclusion and perspectives on BIPV modeling (Section 6).

2. THE ADREAM BUILDING

The ADREAM building (French acronym for Embedded Reconfigurable Dynamic Autonomous and Mobile Architectures) was inaugurated in 2012 [8]. Comprising a large surface of BIPV systems, it can be used as an experimental platform to validate numerous concepts on Smart Grids, micro-grids, as well as on

Ambient Physical Cyber Systems. Figure 2 provides an aerial view of the building ADREAM, showing the totality of its BIPV surface.



Figure 2: Aerial view of the ADREAM building

Today, ADREAM is entirely monitored through a large sensor network which includes a meteorological station. The acquisition of four years of production and consumption data allows the extensive examination of the building's functioning, as well as its ongoing optimization. This process relies on a large amount of data (thermal, electrical, air quality, comfort, lighting, etc.) being stored every day in the platform's database through 6500 sensors. Figure 3 shows the measured data for PV energy production for the year 2014 with a sampling period of an hour.

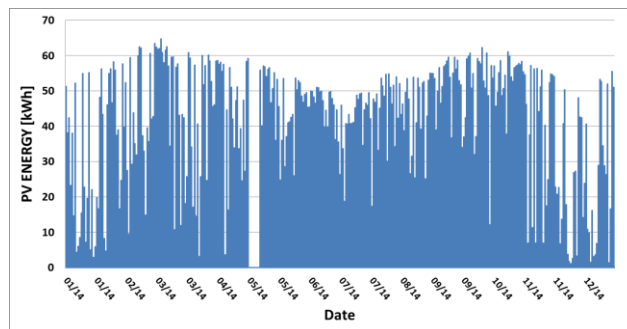


Figure 3: ADREAM's measured PV Energy Production (2014)

Recent scientific studies on the building are based on the concept of New Generation Energy Networks. The related domains include power electronics, data processing, security functioning, and automation. The resolution of the associated challenges demands the understanding of the different behaviors of connected systems in an electrical network, such as photovoltaic panels and inverters, through complete model elaboration and analysis. Each type of energy source (thermal or electrical) present in the building can be studied through a modular monitoring infrastructure. Additionally, the emulation of different consumption profiles (e.g. lighting, electronic equipment, data servers) coupled to human usages is possible.

Finally, a modeling approach to energy management and optimization for the totality of the systems, integrating all the entities of production and consumption has been initiated.

3. PV ENERGY PRODUCTION USING THE SOLAR IRRADIATION MODEL OF PLEIADES+COMFIE

3.1. DYNAMIC THERMAL MODEL OF ADREAM

As a response to the growing needs for energy optimization projects, an initial modeling phase of the building ADREAM was carried out by the software Pleiades + Comfie (P+C) [9]. P+C is a widely used thermal simulation program developed at the Ecole des Mines in Paris and supplied by the company Izuba. As indicated by Peuportier [10, 11, 12], P+C can be considered as a precise simulation tool for the generation of temperature evolution and energetic needs profiles, as well as for the study of their sensibility to main thermal parameters. The choice of the software for was based on: a) the consistent development of the software through frequent updates which involve additional parametrization options, b) experience of use, and c) a “user-friendly” interface.

The main entry parameters involved in the modeling process of ADREAM with the P+C program employed the thermal characteristics of its structure, the scenarios of usage, the systems’ characteristics and a complete weather file. This file was based on the data extracted by the meteorological station installed on the roof of the building and it was the main input for the thermal modeling, as well as for the PV energy production simulation. The different components of this file are: the exterior temperature (C°), the global horizontal irradiance (W/m²), the direct horizontal irradiance (W/m²), the diffuse horizontal irradiance (W/m²), the relative humidity (%), and the wind speed (m/s).

At this point, it is worth noting that the pyranometer of the ADREAM rooftop provides only the global horizontal irradiance. Therefore, its decomposition into direct and diffuse irradiance was estimated through the exploitation of the Type16c modelling block of the TRNSYS software. Effectively, this block contains models developed by Hay and Davies [13], Perez [14], Reindl [15], which, according to the software developers, estimate the diffuse fraction of the hourly horizontal solar radiation data.

Figure 4 shows the 3D model of the building in the P+C environment. The details of this project are provided in [16], along with its calibration process, and its energetic analysis. For the purpose of the current project, the same validated model was employed as a basis for the simulation of the PV energy production.

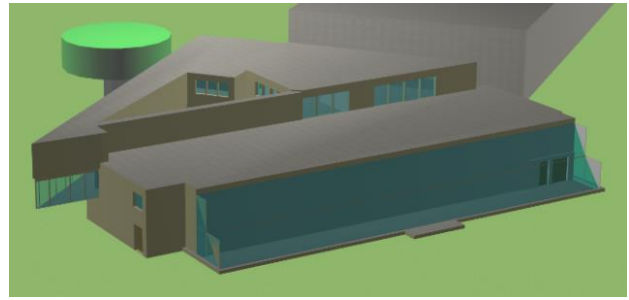


Figure 4 : ADREAM 3D model in the P+C environment

3.2. PV SYSTEMS MODELING

The input of the P+C simulation comprised the main weather file and the technical characteristics of the PV panels installed in the various parts of the ADREAM building. As explained in Section 3.1, the TRNSYS data processing produced a complete weather file that could sufficiently provide all the required input values for a full-year simulation. On the other hand, the technical documentation supplied by the PV manufacturers provided the necessary information for their modeling in the P+C platform. Table 1 summarizes the PV panels’ information entered in P+C before launching the simulation of their corresponding electrical production.

Table 1 : List of ADREAM's PV systems

Placement (Angle)	PV Module (η)	Power (kWp)	Inverters (η)
Accessible Roof (45°)	TE2200 250Wc (15.9%)	17.2	4 × 2.5kW TENESOL (94.6%)
			1 × 5kW TENESOL (94.6%)
			1 × 3.3kW TENESOL (94.8%)
Cladding (90°)	TE2200 250Wc (15.9%)	13.4	2 × 6kW SMA (95.3%)
			1 × 2.1kW SMA (95.2%)
Inaccessible Roof (10°)	TE2200 250Wc (15.9%)	24	3 × 5kW TENESOL (94.6%)
			3 × 2.5kW TENESOL (94.6%)
Facade (60°)	Double or Triple glazing PV cells (14.3%)	38	6 × 5kW SMA (95.3%)
			3 × 2.1kW SMA (95.2%)

The electrical energy production of ADREAM’s PV panels as simulated by P+C is based on the total efficiency of the PV systems (PV cell + Inverter + Network Losses), as well as on their corresponding inclinations. The result of the simulated electrical production is provided in Section 5. Figure 5 presents the P+C simulated PV energy production for the year 2014.

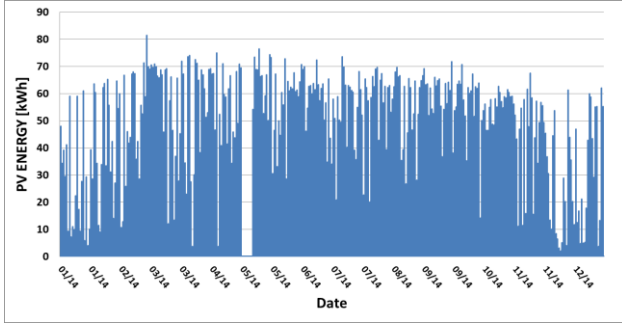


Figure 5: Simulated PV Energy Production with P+C (ADREAM, 2014)

4. PV ENERGY PRODUCTION USING AN OPTIMIZED SOLAR IRRADIATION MODEL

In order to estimate the PV energy production for the building ADREAM, an optimized solar irradiation model was used. This model was developed through Matlab in LAAS-CNRS, Toulouse based on previous PhD research [17] and models from the literature [18, 19, 20, 21, 22].

4.1. DESIGN OF SOLAR IRRADIATION MODEL

For the development of an optimized solar irradiation model, a good understanding of the composition of solar radiation on a terrestrial surface is necessary. Direct radiation (S), diffuse radiation (D) and reflected radiation (R) add together to form the global radiation (G) on a surface as given in equation (1).

$$G = S + D + R \quad (1)$$

For the estimation of the global irradiance on an inclined surface such as a PV panel, it is necessary to estimate each of these components for the given inclination 'i' as shown in equation (2).

$$G_i = S_i + D_i + R_i \quad (2)$$

The reflected part can be neglected based on the surrounding environment and the direct part (S , S_i) can be determined through basic geometric calculations. However, the estimation of the diffuse component of the global irradiance on a given inclined surface is the determining and more complex part of a solar irradiation model. Many attempts to model D and D_i have been carried out in literature. The works of Temps and Coulson [18], and Klutcher [19] study the horizontal diffuse irradiance while Skarveith [20], Orgrill and Hollands [21], and Erbs [22] study the diffuse irradiance on a surface of given inclination. These existing models have been compared and combined into an optimized and calibrated solar irradiation model. The details of the complete model are not the main topic of this paper; however, Figure 6 shows an overview of its structure.

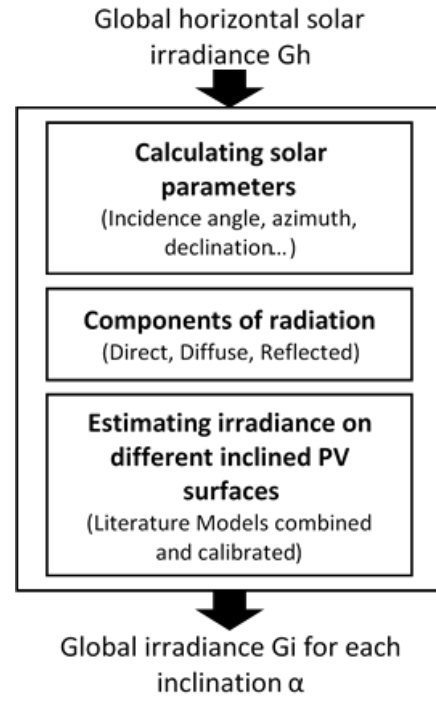


Figure 6: Simplified diagram of the solar irradiation model

Using this optimized model and global horizontal solar irradiance data from a pyranometer integrated in the ADREAM building, we can estimate the global irradiance on each inclined photovoltaic surface for every minute of the year. This estimated data will be used to calculate the total PV power and total PV energy production of the platform.

4.2. PV ENERGY PRODUCTION

Various PV systems are integrated in the ADREAM building. Each system is composed of a specific string of PV panels tilted at a given angle, connected to a single inverter as shown in Section 3.2, Table 1. Using equation (3), the electrical production of each individual PV system can be calculated, as the specific efficiencies of each subsystem are known.

$$P_{sys_i}(w) = PV_{surface_i}(m^2) * G_{i_{\alpha i}} \left(\frac{w}{m^2} \right) * \eta_{PV_i} * \eta_{INV_i} * (1 - MM_{loss}) * (1 - OHM_{loss}) \quad (3)$$

Where:

P_{sys_i} : Electrical power produced by the system 'i' [W]

$PV_{surface_i}$: Total PV surface in the string 'i' [m²]

$G_{i_{\alpha i}}$: Global inclined irradiance arriving on a surface at angle α [W/m²]

η_{PV_i} : Efficiency of the PV panel technology used in string 'i'

η_{INV_i} : Efficiency of the inverter connected to string 'i'

MM_{loss} : Mismatch losses [%]

OHM_{loss} : Ohmic losses [%]

The total PV power for the whole building is calculated by adding the power of all the PV systems.

$$P_{pvtotal}(w) = \sum_i P_{sys_i} \quad (4)$$

The final goal of this type of model is to estimate the annual PV energy production in order to study the impact of BIPV in ZEBs as seen in the introduction of this paper. As the input data from the buildings sensors has a period of one minute, the annual energy consumption can be calculated by integrating the total PV power $P_{pvtotal}$ over the examined time period. The results of the simulation are presented in Figure 7.

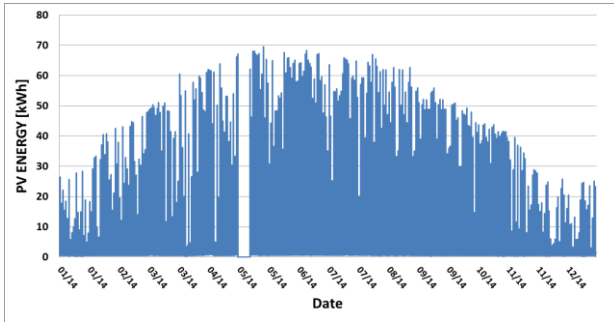


Figure 7: Simulated PV Energy Production with Matlab (ADREAM, 2014)

A comparison between these simulation results with the measured data as well as with the P+C results is provided in Section 5.

5. SIMULATION RESULTS

The electrical energy produced by the PV installation of the ADREAM building was simulated through the use of the two models described in Sections 3 and 4. Figure 8 presents the annual simulated PV production for each model compared to the measured data for the year 2014.

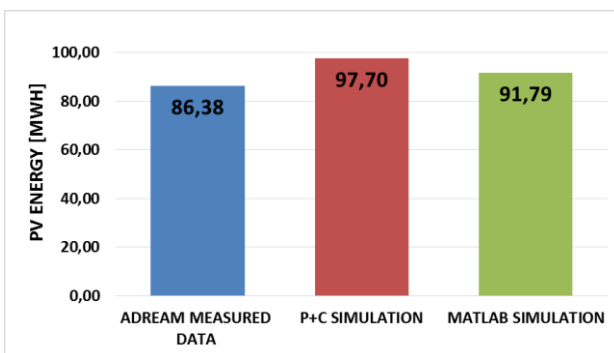


Figure 8: Annual Electrical Energy Production from ADREAM's PV Systems (2014)

As it can be observed, the P+C simulation overestimates the annual PV energy production by 11.32MWh (13.1% relative error), while the Matlab simulation overestimates it by 5.41MWh (6.2% relative error).

Figure 9 depicts the monthly simulated PV production for each model compared to the measured data.

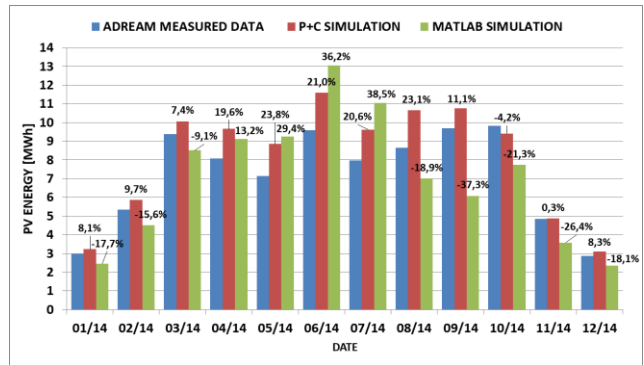


Figure 9: Monthly Electrical Energy Production from ADREAM's PV Systems and Relative Errors for each model (2014)

As it can be observed, the P+C simulation consistently overestimates the PV energy production over eleven months by an average of 13.9% compared to measured data. It is also notable that this overestimation is more significant during the summer months (19.9% on average for April-September), while it is less remarkable during the rest of the months (6.8% on average for November-March). On the other hand, the Matlab simulation tends to underestimate the PV energy production over eight months (-20.6% on average for August-March), while highly overestimating it during four months (29.3% on average for April-July).

According to the examination of the data and the simulated results, it can be deduced that the P+C simulation is more accurate than the Matlab simulation on a monthly basis. That is, the monthly P+C energy production deviates less from the measured data than the Matlab energy production for ten months of the year. However, while P+C is evidently a valuable tool for short term energy production estimations, the Matlab simulation is more reliable when it comes to the yearly energy production estimation, even though it produces a higher monthly deviation from the measured data. This fact implies that the latter modeling approach is more appropriate for responding to the standards of a ZEB assessment [4, 5].

6. CONCLUSION AND PERSPECTIVES

In the context of ZEB research, two different types of modeling approaches for estimating the energy production of the BIPV systems of the ADREAM building were produced and analyzed. The ADREAM platform was employed due to its capacity to provide precise BIPV data over significant periods of time. As deduced in Section 5, a P+C simulation of the BIPV systems is an accurate tool for monthly energy production estimations, whereas a Matlab simulation, based on an optimized solar irradiation model, provides a more reliable yearly energy production estimation. As a matter of fact, the most relevant aspect of a ZEB is its production to consumption balance over one-year-cycles. Thus, this work contributes to the development of ZEBs through the precise modeling and optimization of BIPV systems.

The work on the presented models forms the basis for uncovering and examining further perspectives. Pleiades + Comfie can be used as an inclusive tool for combining the modeling of energy production and consumption and providing a complete energetic assessment. On the other hand, the Matlab model can be subject to further optimization since it produces significantly deviated simulation results on a monthly basis.

Finally, an overall improvement of this project's methodology should include a cross-examination of measured and simulated data over additional years for a more thorough insight on the optimization of BIPV systems.

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