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## Design of monitoring tool for decision making in buildings with solar energy generation

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### Abstract

The work presented in this article is part of a project that focuses on the field of energy and sustainability and is aligned with the objectives of sustainable development, specifically goal seven, affordable and clean energy, and goal eleven, sustainable cities and communities. The photovoltaic solar installation for self-consumption at the Deusto University's residence hall has been modelled using generation data, consumption data, meteorological data, and installation components. Although the actual installation features an anti-feeding system, the model allows to evaluate potential energy surpluses. To achieve this objective, it has been necessary to collect, transform, and thoroughly clean the data from the solar inverters, as well as store them for later representation. To process, visualize, and analyse data, the web application developed allows users to understand quickly and easily the patterns and trends related to energy consumption through various graphics, providing a clear and accessible visual presentation of the data that helps them make decisions to optimize energy consumption. In addition, an application has been developed that allows to assess whether or not removing the anti-feeding system and modifying the contract with the distribution company may be favourable.

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**Keywords:** Energy efficiency; solar energy generation; consumption models; big data; management application

### Nomenclature

AEMET	Spanish State Meteorological Agency
API	Application Programming Interface
CSV	Comma-separated values
DRH	Deusto Residence Hall
EMT	Electromagnetic Transient

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ETL	Extract Transform Load
LV/MV	Low Voltage/Medium Voltage
PCC	Point of Common Coupling
PV	Photovoltaic
SSE	South-southeast

## 1. Introduction

European Climate Legislation makes achieving the EU's climate target of reducing EU emissions by at least 55% by 2030 a legal obligation. EU countries are working on managing climate neutrality by 2050. One of the main approaches has been the reduction of energy consumption and the search for renewable and non-polluting energy sources. At the national level, and if we analyse data from 2019, in 2020 greenhouse gas emissions produced by electricity generation in Spain were reduced by 14 million tons of CO<sub>2</sub> equivalent compared to the previous year. From the 50 million tons in 2019, it decreased to just over 36 million (taking into account an emission factor of the Spanish electricity system of 0.19 tCO<sub>2</sub> in 2019), but during 2022 there has been a 2.3% increase compared to 2021, stopping the downward trend that existed since 2019 [1].

One of the reasons for this increase is the growing use of electricity generation through combined cycle power plants. In this context, it is necessary to reduce this type of energy generation in order to achieve the objectives set by the EU. Any initiative that contributes to raising awareness among citizens about their consumption habits and helps them consume more efficiently, which does not always mean consuming less, is of vital importance. At this point, photovoltaic solar energy plays an important role. Among renewable energies, solar energy is considered an abundant and available source of energy worldwide, which is why it has gained ground and become an increasingly attractive and viable alternative [2]. Technological advances in the manufacturing of solar panels have led to lower production costs and improved their efficiency. This has made solar energy increasingly competitive in economic terms and more accessible for consumers [3].

In this context, the Aristos Campus Mundus (ACM) project emerges, within which the presented work is framed. The project brings together two universities: the University of Deusto and the Pontifical University of Comillas, committed to socially responsible and sustainable innovation, with the aim of promoting academic, teaching, and research excellence, as well as the full globalization of their university projects [4].

The part of the project presented here has focused on analysing the electricity generation data from the photovoltaic solar plant installed at the University of Deusto's Residence Hall (DRH), modelling electricity generation, and designing and developing a web application that allows analysing the energy behaviour for its further optimization.

Although there are proprietary applications that allow downloading data and visualizing graphs [5][6][7][8], these only present information on electricity generation and not always in a clear manner. The application presented here will read consumption data that, once pre-processed, will be visualized through several dashboards adapted to the needs of the DRH managers, integrating price and weather information into the dashboard.

The following section will explain the materials and methods necessary and Results are explained in Section 3, Results. The article concludes with a section on conclusions and future lines of inquiry.

## 2. Materials and methods

### 2.1. Analysis of the installation

The DRH is a student housing affiliated with the University of Deusto. It is primarily aimed at first-year students who do not live in their usual home during the university term. In this case, it is located on the university campus.

The building shown in Figure 1 a) consists of 3 towers with 10 floors each with a total of 304 rooms, 16 common rooms, 1 computer room, 1 laundry room, 1 gym, 1 industrial kitchen, and its respective dining area. In 2017, a first model was developed to analyse the feasibility of installing photovoltaic solar panels on these buildings [9][10]. These references provide detailed information on consumption profiles. In recent times (year 2023), during the month of

highest consumption (May), the maximum power demand does not exceed 109 kW, daily consumption reaches up to 1.14 MWh, and monthly consumption amounts to 29.58 MWh.

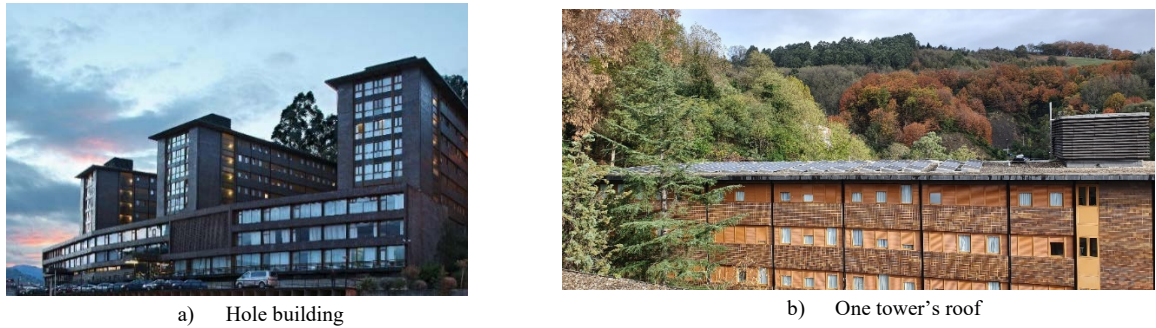


Fig. 1. Images of the DRH building

After a careful study, it was decided to proceed with the installation of solar panels on the roof of the three towers on 21<sup>st</sup> of November 2019. Since then, the university has significantly reduced its carbon footprint.

These panels are located in an elevated position with adequate exposure to the sun, as shown in Figure 1 b). Each set of solar panels is connected to its corresponding inverter, which converts the direct current generated by the panels into alternating current, which is used to supply electricity to each of the three buildings.

Figure 2 shows a schematic of the complete installation. Each building has a generation line with 83 panels, a three-phase inverter, filtering stages, and protection and measurement units. The components of the power system of one of the generation lines, corresponding to the central building, are detailed in the same figure. The current installation requires a three-phase voltage of 220 V, so to adjust the output voltage of the three-phase inverters to 400 V, an autotransformer is used to perform the voltage transformation before connecting to the internal electrical network of the buildings. The installation is completed with a LV/MV transformer up to the point of connection to the public grid (PCC, Point of Common Coupling) located in the electrical room situated in the basement of the central building.

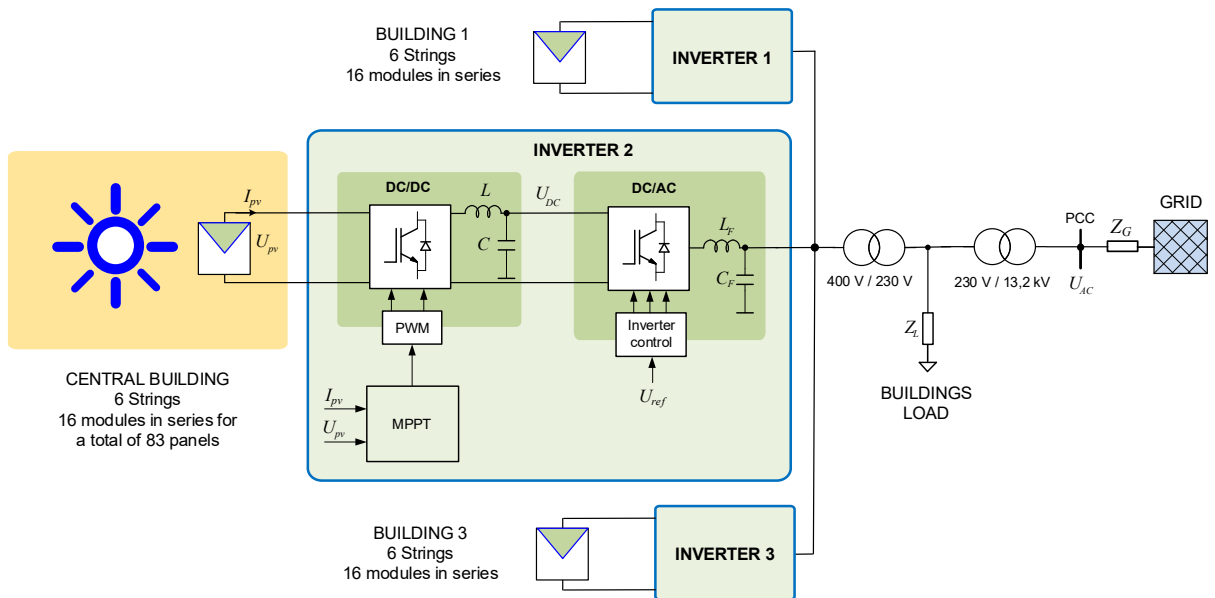


Fig. 2. Diagram of the photovoltaic installation at the DRH

The inverters in each building are interconnected to share the generated energy (Figure 3). This maximises the utilisation of available solar energy, with similar electricity generation across the three lines, efficiently distributed according to the energy needs of each building. It's important to note that, unlike the energy generated by the solar panels shared among the DRH buildings, the energy consumed from the conventional electrical grid varies according to each building's needs, where each one may consume more or less energy.

Furthermore, it's important to mention that the sizing of the solar installation was done in such a way that there would be no energy surplus that could be fed back into the grid or go to waste. As it is a self-consumption installation without surplus, an anti-feeding system is necessary to ensure that any unused and produced energy is not injected into the grid. Therefore, only the amount of energy needed at that moment is generated, and if there is the potential to generate more energy than is consumed, the inverters adjust the operating point of the generation systems to obtain only the energy that will be consumed.

This measure has been taken to ensure efficient and sustainable management of the energy generated by the solar panels, avoiding waste and unnecessary overproduction. In this way, solar energy is used responsibly, ensuring that the generated energy is maximally utilised to meet the energy needs of the residence hall [11].



Fig. 3. Inverters of the photovoltaic installation at the DRH

## 2.2. Data sources

The data of the solar installation, both solar generation and consumption of the DRH, have been taken from the Ingecon Sun Monitor, of Ingeteam [12]. It has its own application to monitor, and control photovoltaic solar energy systems (PV), that allows monitor various parameters of a PV system, such as DC voltage and current, AC voltage and current, instantaneous power, and generated energy.

Meteorological data was provided by the State Meteorological Agency of Spain (AEMET) [13] from its records of hourly irradiance and temperature at the Loiu station, on an Excel sheet.

## 2.3. Implementation considerations

The commercial application does not gather all the necessary information for decision-making, as it is also necessary to access consumption information, electricity prices, and meteorological data, among others. The application presented is capable of collecting and representing much more detailed and precise data than the previous one, allowing users to make informed decisions about the use and optimisation of the installation.

The extraction of data from the solar installation was carried out through a CSV file obtained from Ingecon Sun Monitor, offline. This file contains data from the commissioning of the installation to the moment it is downloaded.

Regarding the data, extraction, cleaning, and transformation were carried out using an ETL process, the decision-making and cleaning procedure was manual, and decisions were made in agreement with experts in the field. It was

found that many data points did not add value, others were redundant, and some were poorly structured, so it was necessary to determine which data was useful to continue.

From all available data, the columns of "phase," "dateTime," "totalGridConsumption (W)," "totalConsumption (W)," "pvGeneration (W)," and "selfConsumptionRatio" were selected.

MongoDB and the Mongoose library were used to create the database. Node.js and Express.js were used for developing server-side applications. FastAPI was used as the development framework, and React was used for the client-side. Regarding the integration of external data sources, the decision was made to use the application programming interface (API) provided by the AEMET for weather data, as it provided the most complete and accurate information for the project's specific needs. The API provided by the Spanish Electric Grid (ESIOS REE) was used to obtain the electrical data.

### 3. Results

#### 3.1. Development of the model

The EMT (Electromagnetic Transient) simulation model of the PV solar installation at the DRH, was developed in MATLAB/Simulink/SimscapeElectric. It allows obtaining energy generation curves based on climatological data and real building consumption [14][15]. The model has been validated with real registers of generation and consumption of the installation obtained from the inverters' telemetry and the supplying electric company's meter, from December 2019 to May 2023.

Based on the electrical plans and the documentation of the components, the block model of the photovoltaic installation was implemented, consisting of 3 lines, one per building, with 83 panels on each roof, each with 400 Wp, made of polycrystalline silicon cells and all arranged in the same South-South-East (SSE) orientation. Therefore, electrical energy is generated with a peak power of the photovoltaic field of 99.6 kWp and 99 kW nominal at inverter output, which will be used for self-consumption without surpluses. The buildings' roofs are gable roofs in the Southwest-Northeast (SW-NE) axis with a 3° slope.

The configuration of each of the three lines consists of 6 strings of 16 modules in series, reaching 83 modules per inverter. The coupling of the produced energy to the distribution grid will be carried out by 3 inverters with a nominal power of 33 kW. Each inverter has an input DC conversion stage to ensure 600 V<sub>DC</sub> input and a LCL filtering stage in the connection to the building's distribution grid. Connection to the Medium Voltage grid of 13.2 kV has been considered through a step-up transformer.

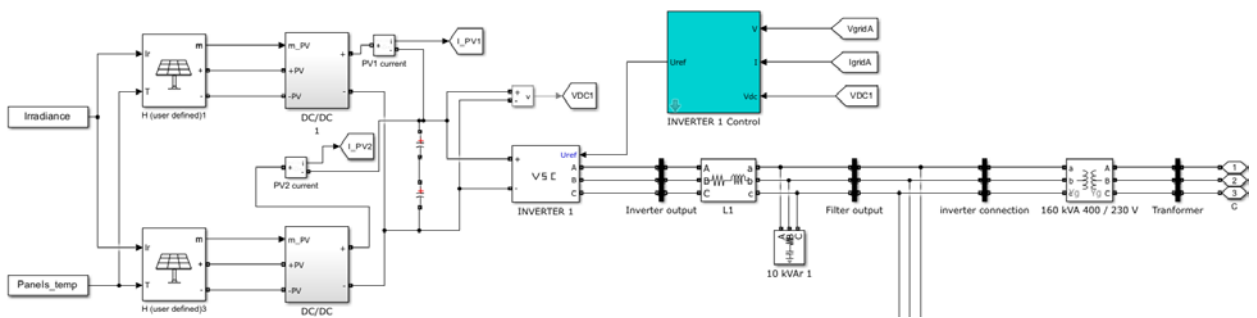


Fig. 4. Model of one of the PV generation lines

Figure 4 shows the block implementation of one of the PV generation lines. This model requires as input the irradiance data on the panels and their temperature. Irradiance is a key parameter in the design and operation of photovoltaic systems, referring to the power per unit area received from the sun, measured in watts per square meter (W/m<sup>2</sup>). The input meteorological data is provided by AEMET based on its records at the Loiu station (4.62 km away from the PV installation location). It consists of Excel files of hourly irradiance and temperature data.

A model of load was also addressed to simulate the consumption of the installation as accurately as possible. This model takes as input the real consumption curve of the installation obtained from the telemetry of the inverters and

the meter of the supplying electric company, with the added challenge of synchronizing it in phase with the generation model and the proposed grid model.

Finally, in a block for measurement and signal comparison, all the records that can be obtained from the model simulations were incorporated, including various graphs comparing power generated by the model and recorded by the inverter, power generated, power consumed from the grid, and power consumed from the grid, or comparison graphs of daily, monthly, or annual generated energy. Of course, all model records can be exported as data files.

Figure 5 shows the complete model of the self-consumption installation with its four main blocks.

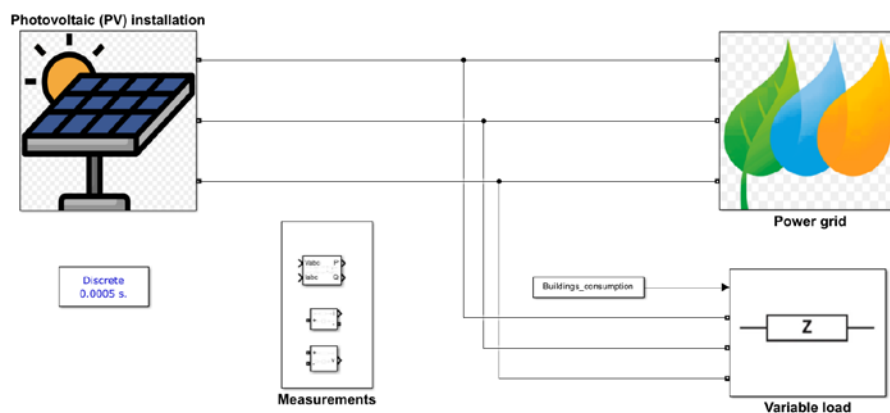


Fig. 5. MATLAB/Simulink model of the self-consumption photovoltaic installation

Regarding the validation of the model, the first phase involved checking the proper integration of real consumption data into the model through a comparative analysis between this real consumption, instantaneous power in W, and the records obtained from simulated consumption in the variable load block.

Next, the results of the model regarding energy generation were validated. The model considers an operation mode without surplus limitation and, therefore, with the possibility of occasional energy injection into the grid. The operation mode of the real installation, based on surplus-free generation and, therefore, with an anti-feeding mechanism programmed into the inverters, will be implemented in a future extension of the model. Additionally, following the guidelines set in the installation execution project, overall power losses of 14% are considered (wiring efficiency, errors in maximum power point tracking, inverter efficiency, and shading).

For the validation of the energy generation model, records from the available history were used in which the anti-feeding system had not been activated, meaning those time periods when the building's consumption had always been higher than the energy generated by the PV installation.

Based on the meteorological data provided by AEMET and the installation's consumption obtained from the telemetry of the inverters and the meter of the supplying electric company, a comparison between simulated generation (in blue) and real generation recorded by the inverter (in orange) was obtained, as shown in Figure 6.

Once again, simulation results are presented for January 10, 2023. The total daily generation, including system losses mainly associated with shading, reaches 167.07 kWh simulated for this study day compared to the 168.21 kWh real generation obtained from the inverter telemetry.

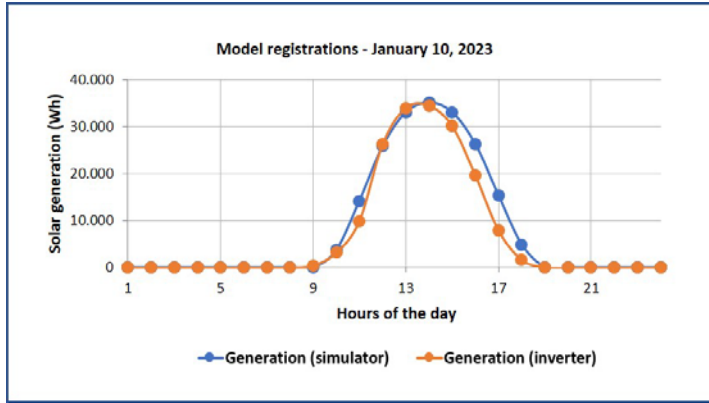


Fig. 6. Comparison of simulated generation versus actual generation recorded by the inverters

Finally, in Figure 7, the simulation result is presented concerning energy generation and consumption for the first half of January 2023. It can be observed that the real energy generation recorded by the installation's measuring equipment does not match in some cases with the simulated energy generation. Precisely on those days, the anti-feeding system had been activated in the real installation to limit the generated energy to the installation's consumption. This circumstance can be verified by analysing how the building's consumption, during these periods at the beginning of the month with very little activity in the DRH, matches the generation obtained from the inverter telemetry. In reality, on those days, the generator has the capacity to generate above the energy demand of the buildings, which is what limits the anti-feeding system. The model allows working without this limitation, considering surplus energy, and therefore to explore other grid connection alternatives considering different bill-saving modalities is possible. During the second week of January, with the return of students to the residence hall after the Christmas holiday period, it is clearly noticeable how the buildings' consumption spikes, and solar generation must rely on the power grid to meet the demand of the loads.

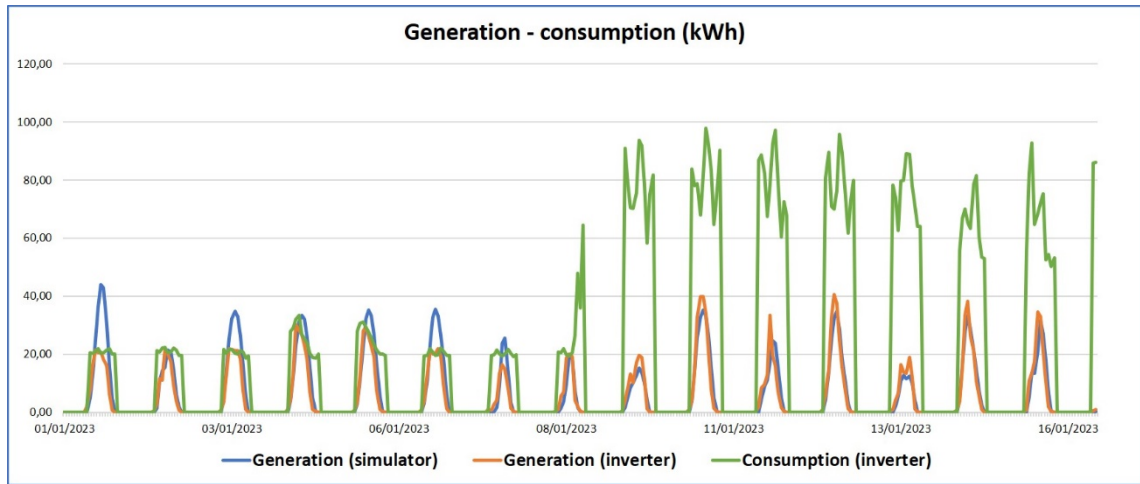


Fig. 7. Simulation results for energy generation and consumption over half a month

### 3.2. Development of the visualization platform

The application for the visualization of real data includes a set of dashboards for analysing various aspects of energy consumption [16][17]. The dashboard presented in Figure 8 shows a summary of the main data from the web

application. This main window displays four panels at the top, one for each of the variables collected from the solar panel inverter data, which are: generated energy, consumed energy, total consumption in MWh, and the average self-consumption percentage.

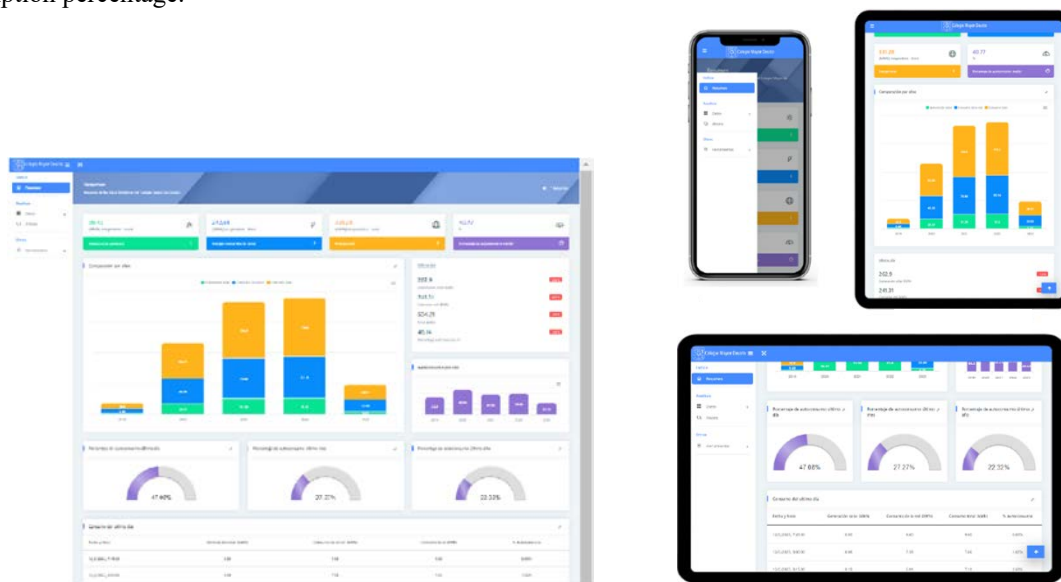


Fig.8. Image of the summary dashboard and its different devices [18]

The developed application shows the variables of generation, consumption, total consumption in kWh, and self-consumption percentage for each building are displayed, and also displays the savings and total expenditure generated with the solar panels from their commissioning until today [18]. There is also an overall dashboard which displays detailed information through graphs with all the variables managed by the web application, both from the solar panels and from external data sources, from which the most relevant conclusions can be drawn.

From the information analysed from the graphs obtained from the different dashboards, the following conclusions have been drawn:

1. There is an increase in consumption from 2021 to 2022. The self-consumption percentage also increases, but it still does not represent half of the total consumption at any time, so there are still many improvement actions that can be considered to optimize it.
  2. Regarding the buildings, it can be observed that Building 2 (central) consumes the most, and concerning the other two buildings, Building 3 consumes more than Building 1. Due to this, it would be interesting to investigate why these differences occur.
  3. Since the solar installation was put into operation until now, there has been savings compared to the expenditure incurred, although both the price and consumption have increased. This suggests that it will increasingly become more profitable to have this type of installation.
  4. From the analysis of the holiday period, it is evident that during the summer, self-consumption does not reach 100%, which can inform the decision to increase the number of solar panels. Additionally, there are several instances in which energy is wasted and it could have been produced and used later.
  5. The months with the highest consumption are January and March, followed by February, May, October, and December. The causes could be analysed, and several improvement actions could be proposed to reduce consumption in those months.
  6. It can also be observed that the generation increases and decreases throughout the day in a bell-shaped curve, resembling a Gaussian distribution, but consumption does not follow the same pattern. Therefore, it could be considered storing the extra energy produced during the day and using it during these peak demand hours.
- There are more graphs besides those shown here that can help justify decisions related to the installation [18].

#### 4. Conclusions and future work

This article has presented a comprehensive solution for modelling electricity generation, management, and optimization in a campus environment with solar energy generation. This solution integrates data from different sources, allowing all relevant information to be visualized in a single dashboard. From the development of the project, some preliminary conclusions can be drawn, leading to actions to modify consumption habits, thus making more efficient use of the facilities by minimizing consumption from the conventional power grid.

Furthermore, this dashboard is scalable and can be extrapolated to other similar installations in urban environments. Although the project has been successfully completed, there are still opportunities to expand the application. In this regard, a short-term improvement would be to deploy and host the application on its own domain to make it more accessible and user-friendly for the residence hall administrators. Additionally, there is potential to add new functionalities to the application in the future, such as including real-time data from the solar panel inverters or more data from other sources.

Moreover, although the main advantage of having a model that allows simulating the installation without an anti-feeding system is to evaluate the surplus of the installation, as future work, a controller can be developed for the inverter of the model equivalent to the controller of the installation's inverter, to emulate its behaviour.

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