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Integrating Renewable Energy Produced by a Library Building on a University Campus in a Scenario of Collective Self-Consumption

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Abstract: Rising fossil fuel costs and environmental concerns are driving the search for new energy sources, particularly renewable energy. Among these sources, solar photovoltaic (PV) is the most promising in southern European countries, mainly through the use of decentralised PV systems designed to produce electricity close to the point of demand and primarily to meet local energy needs. In an urban scenario, a decentralised energy system usually operates in parallel with the grid, allowing excess power generated to be injected into the grid. Solar carports and rooftop systems are excellent examples of distributed photovoltaic systems, which are far more sustainable than large centralised systems because they do not compete for land use. Despite their operational advantages, these decentralised photovoltaic production plants, which are in most cases financed by specific energy efficiency programs, present challenges in a regulated market where the injection of energy into the electricity grid is restricted by law and support programs. The aim of this work is to integrate two different photovoltaic systems within an academic campus where the only PV source currently available is a solar car park, a solution designed both to provide shaded space for vehicles and to produce energy to be consumed within the facilities. Due to legal restrictions, surplus electricity cannot be sold to the national grid, and solar batteries to store the generated energy are expensive and have a short lifespan. Therefore, since the campus has two different grid connections and a 102.37 kWp PV system, the newly designed system to be installed on the library roof must be calculated to support the installed electricity system during the most critical working hours, determining the specific angle and orientation of the solar panels. On this basis, the energy management of a school campus is fundamental to creating a collective self-consumption system, the basis of a local energy community that can meet energy, environmental, and social objectives.

Keywords: energy efficiency; PV production; energy management; sustainable campuses

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1. Introduction

Growing concerns about climate change and the urgent need to reduce greenhouse gas emissions have led to an increased interest in renewable energy sources on the part of higher education institutions (HEI), with photovoltaic systems (PV) being the most popular renewable energy solution due to their low investment costs, ease of installation, low maintenance requirements, and speed of assembly and the most widely used in southern European countries where solar availability is high. Based on this, the use of PV energy for self-consumption is an investment in promoting sustainable campuses for HEI, as these systems can reduce carbon footprint and energy costs. The solar panels are connected directly to the grid via inverters so that the energy produced can be transferred to the site for in situ self-consumption and, where possible, the surplus can be sold to the national grid. However, there are some situations where the energy surplus cannot be injected into the grid, mainly when PV systems are funded by specific energy efficiency programs or when there is a legal impediment for that imposed by the grid operator. From the point of view of the administrator of the public energy supply network, the injection of active energy is necessary to reduce the pressure on the electricity grid and to reduce CO_2 emissions, both at the scale of the buildings and at the scale of the national electricity grid. However, most of the funding programs that have been mobilised to support the installation costs of the systems stipulate that grid injection is prohibited, resulting in so-called zero-export systems. In practice, a zero-export system means that none of the solar energy produced by the system can be injected to the grid and that excess solar energy is cut off by an electricity injection limiter. The situation is aggravated by the fact that schools and universities have a lower demand for electricity at weekends and on public holidays, so there is a surplus of electricity production that needs to be managed wisely. Based on these constraints, the energy management of an academic campus must define a way to deal with the excess energy production that cannot be injected into the grid, and how to efficiently manage different amounts of energy produced throughout the year with completely different production and consumption profiles.

An academic campus with an average hourly annual consumption of 49.30 kWh in the main building, which houses classrooms and laboratories, and an average hourly annual consumption of 4.24 kWh in the library was used as a case study. This campus manages a self-consumption photovoltaic system, with no energy injection into the public grid, made up of 225 monocrystalline photovoltaic modules (2.12 m × 1.05 m per module) with a peak power of 102.37 kWp, covering a total installed area of 500.85 m^2. The solar panels face west and have an inclination of 10°. Funded by a specific energy efficiency program, it is planned to install a further 30 kWp photovoltaic system on a flat roof of the library building on the campus but with a different electricity supply point from the other campus buildings. In order to optimise the installation, the best orientation for the new PV system will be studied in order to maximise the autonomy of the campus, thereby increasing production during periods of electricity product deficit, such as winter. The energy produced by the PV system varies throughout the year and the storage of energy through the use of batteries is affected by the low durability and reduced useful life of the accumulators.

Therefore, the aim of this study is to discuss how self-consumption systems without grid injection can be complemented, either by energy storage, load management, or the creation of collective self-consumption or, in some cases, an energy community to manage excess electricity production in peak energy production situations, particularly during the summer months in the northern hemisphere. The novelty of this analysis lies in its pragmatic approach to managing surplus photovoltaic energy in environments with strict grid injection regulations. Our contribution is threefold: firstly, we provide an innovative intelligent management model that maximises the use of the solar energy produced, even under regulatory constraints. Secondly, we explore the potential for collective self-consumption within an academic campus with multiple energy delivery points as a strategic step towards energy autonomy. Thirdly, the impact of the orientation and angle of the photovoltaic panels will be assessed, making it possible to increase energy production in winter periods and release surplus production in summer periods. Universities are institutions that should be at the forefront of the energy transition, which is why this debate is of the utmost importance.

This article is structured as follows: Section 2 presents related works on the efficient use of PV energy in higher education institutions. Section 3 details the materials and methods used in this study. Section 4 covers the results and discussion. Finally, Section 5 summarises the conclusions.

2. Literature Review

Universities, as microsystems of society at large and as centres of development and learning, serve as platforms for demonstrating and promoting sustainability. In terms of sustainable energy solutions, solar energy has taken centre stage due to its nature and growth. In a global and national context, there is an urgent need to combat climate change by reducing carbon emissions; therefore, university campuses are excellent living demonstration laboratories by integrating solar energy systems into their infrastructures, thus educating and influencing the academic community who will be the next generation of policy makers, highly skilled professionals, and consumers.

The adoption of innovative research programs aimed at exploring solar technologies, assessing their viability, and optimising their integration into existing energy networks makes it possible to assess in situ performance through instrumentation and verify the real environmental impact. The result of this type of investment is not only a reduction in energy consumption and GHG emissions but also a greater societal impact derived from scientific publications and awareness-raising actions on the potential and challenges of solar energy, guiding political and social decisions and encouraging investment. Particular emphasis will be placed on the integration of PV systems to create energy communities or collective self-consumption in a university campus or similar infrastructure.

Based on this, Araújo et al. (2022), in a university campus with PV energy production, state that optimising the use of renewable energy through organisational measures and strategic planning must be based on assessing the performance of the PV system and its contribution to reducing energy consumption, thus providing insight into energy production patterns and identifying opportunities for optimisation [1]. In addition, it is necessary to define an energy management strategy that schedules energy-intensive activities such as water heating, lighting, and appliance use during optimal PV energy production periods, implement organisational measures to effectively manage the energy from the PV system, and conduct an awareness campaign to promote an energy-saving culture and encourage behavioural changes to reduce energy consumption, develop strategies to utilise surplus PV energy generated during periods of overproduction, explore opportunities to convert surplus energy into renewable energy, explore opportunities to convert surplus energy into other forms such as thermal energy or battery charging, and implement a system for continuous monitoring of energy consumption and PV system performance to identify areas for improvement and adjust energy management strategies accordingly [1].

According to Guan et al. (2016), the analysis of energy use in a university campus provides valuable insights into energy consumption patterns and can inform energy planning strategies for similar complex infrastructures and urban energy systems based on the energy use profile and energy consumption levels, taking into account seasonal factors that can significantly influence heating energy consumption, with higher variability compared to electricity consumption [2]. The results of the study provide valuable data for energy planning initiatives aimed at optimising energy use in university campuses and urban energy systems, as well as standards and building codes tailored to the specific needs and characteristics of university campuses and urban environments. Overall, the study provides valuable insights into the dynamics of energy use on university campuses and highlights the importance of data-driven approaches to energy planning and management in complex urban environments.

Filho et al. (2019) recommend a comprehensive approach to promote energy efficiency and renewable energy initiatives within universities, based on three different levels: the so-called Level 1 (Macro), where the HEI develops and implements specific energy policies that guide the institution's energy use, efficiency measures, and renewable energy deployment, set clear goals and targets to reduce energy consumption and carbon emissions across the university campus, and invest in energy management systems and technologies to monitor and optimise energy use; Level 2 (meso), where HEIs work with individual faculties to complement university-wide energy plans and tailor initiatives to address the unique energy challenges and opportunities within each faculty; and Level 3 (micro), where HEIs encourage departments to actively engage in energy conservation efforts through initiatives such as installing timers on office equipment and implementing energy-saving practices, as well as providing training and educational resources to department members to raise awareness of energy efficiency and encourage sustainable behaviour [3]. The authors suggest that, by implementing these recommendations and fostering a culture of energy sustainability, universities can significantly reduce their carbon footprint, contribute to cleaner production practices, and demonstrate leadership in addressing climate change.

Underscored by Sustainable Development Goal 7 (SDG 7), a top priority for higher education institutions should be to increase the share of renewable energy sources in the global energy mix [4]. This is critical for mitigating climate change, reducing greenhouse gas emissions, and enhancing energy security. Renewable energy technologies, such as solar, are sustainable alternatives to fossil fuels and contribute to the transition to a low-carbon economy and the achievement of the climate goals outlined in the Paris Agreement [5]. By prioritising increasing the share of renewable energy and improving energy efficiency, higher education institutions can advance their sustainable development agendas.

The study conducted by Horan et al. (2019) provides valuable insights into the potential for deploying decarbonisation technologies on higher education campuses [6]. The authors devise a quantitative approach to assessing the potential for the deployment of decarbonisation technologies by analysing factors such as energy consumption patterns, existing infrastructure, and the feasibility of implementing various decarbonisation technologies. The study also identifies a significant potential for reducing carbon emissions associated with water supply systems. This highlights the importance of considering not only energy-related emissions but also emissions from other sources, such as water infrastructure, in decarbonisation efforts. These findings have the potential to inform strategic planning and decision-making processes aimed at reducing carbon emissions and promoting sustainability in urban environments.

Araújo et al. (2023) state that the creation of local energy communities could increase the use of PV systems by up to 40%, highlighting the benefits of implementing strategic energy consumption patterns and sharing energy resources as measures to increase energy efficiency in higher education institutions [7].

A study by Reis et al. (2019) examines the relationship between load aggregation and the self-consumption rate and profitability of photovoltaic (PV) systems, suggesting that aggregating energy demand from multiple sources can improve the efficiency and economic viability of PV installations [8]. It is important to establish legal mechanisms to facilitate the aggregation of energy demand, storage, and PV generation, including regulatory frameworks and incentives that encourage collaboration between stakeholders and enable the integration of distributed energy resources into the grid. By creating an enabling environment for collaboration and innovation, policymakers can help accelerate the transition to a more sustainable and resilient energy system.

According to research by Roberts et al. (2019), the implementation of a shared photovoltaic (PV) system to aggregate loads in an apartment building can provide significant financial benefits, as it can lead to higher levels of self-consumption and self-sufficiency of solar energy [9]. Residents will be able to use more of the solar energy generated on site, reducing their reliance on grid-supplied electricity. The research suggests that the increased self-consumption and self-sufficiency resulting from the community PV system can have financial benefits. In certain circumstances, such as where there is tariff uncertainty or long-term turnover of residents, the implementation of a shared PV system can provide stability and financial predictability for households. By harnessing solar energy resources and encouraging collaboration within communities, shared PV systems offer a route to a resilient energy environment.

The two-step methodology developed by Mustika et al. decouples billing from asset management at the community level, resulting in potential cost savings and improved operational efficiency [10]. By collectively managing energy resources and optimising consumption patterns, communities can achieve significant cost savings in comparison to individual household actions. The case study presented in the research shows tangible results, with a community of seven houses saving 11.7% on energy bills. Individually, households within the community experienced bill reductions ranging from 11% to 19% compared to a baseline scenario in which each household acts independently. The study provides valuable guidelines for community managers and participants to determine the most appropriate management and energy allocation strategies, which will inform decision-making processes and help optimise the performance of energy communities with collective self-consumption.

The analysis conducted by Frieden et al. (2021) provides valuable insights into the current state of implementation of EU legislation pertaining to collective self-consumption (CSC) and energy communities [11]. It underscores that long-term initiatives such as energy system integration and the reduction of energy poverty remain largely unaddressed by the majority of EU nations. The analysis demonstrates the need for comprehensive and contextually appropriate frameworks to support the successful implementation of CSC schemes and energy communities across Europe. Addressing barriers and ensuring supportive conditions will be crucial to achieving the potential of these initiatives to drive forward the energy transition.

The study conducted by Luz et al. (2021) centres on the techno-economic feasibility of achieving higher renewable energy penetration scenarios in a semi-rural city through diverse collective photovoltaic (PV) arrangements within the Energy Communities (EC) framework [12]. The EC of Reguengos de Monsaraz was modelled using the Calliope modelling framework, combining real electricity demand data with GIS-based rooftop cadastre and weather data. The results indicate that collective agreements contribute to additional PV capacity deployment and a possible modest reduction in the levelized cost of electricity. The study emphasises the importance of local stakeholders using energy modelling tools to inform decision making and identify the most appropriate European set-up. The research underscores the potential of collective PV arrangements within the European Community framework to propel renewable energy deployment at the local level while emphasising the significance of weighing diverse factors and trade-offs in decision-making procedures.

3. Materials and Methods

3.1. Case Study

The case study under analysis is a campus of a higher education institution (HEI) in the northwest region of Portugal, consisting of a group of buildings designed for teaching, research, and other academic activities, as well as a library building designed to support all scholarly work and practices. The whole campus is connected to the grid with two power supply points: the first one serves two academic buildings, the pedagogical complex, a four-storey classroom block with laboratories, auditorium, and amphitheatre, and administrative services, and a two-storey workshop building with a design laboratory, carpentry workshop, and several technical areas. Both buildings are occupied during term time by more than 2500 students and nearly 200 staff members who support all teaching and research activities. On the other hand, the second supply point serves two additional buildings: the library, consisting of a reading room, study rooms, offices, and 4 large workrooms, and a sustainability laboratory equipped with a wide range of technical equipment for research in energy efficiency, renewable energy, water efficiency, and environmental technologies, as well as indoor air quality.

The pedagogical complex and the workshop building were recently renovated to improve energy efficiency, which included thermal insulation of the facade, replacement of window frames, and the adoption of shading devices in the glazed openings to the south, east, and west, as well as the installation of new high-efficiency boilers for heating, and an air conditioning system was installed on the roof of the school auditorium. All lighting systems were upgraded to LED technology and a new carport-type photovoltaic system with a peak power of 102.8 kW was installed on the campus, connected to the first supply point, i.e., serving both the pedagogical complex and the workshop building.

The campus library is currently undergoing a retrofit process to improve the building's energy performance, including a number of energy efficiency measures, such as the implementation of LED technology for lighting, the replacement of a gas boiler with a high-efficiency unit, the installation of a closed-loop control system, and the supply and installation of a 30 kWp rooftop photovoltaic system. The integration of all campus buildings into the national grid is shown in Figure 1.

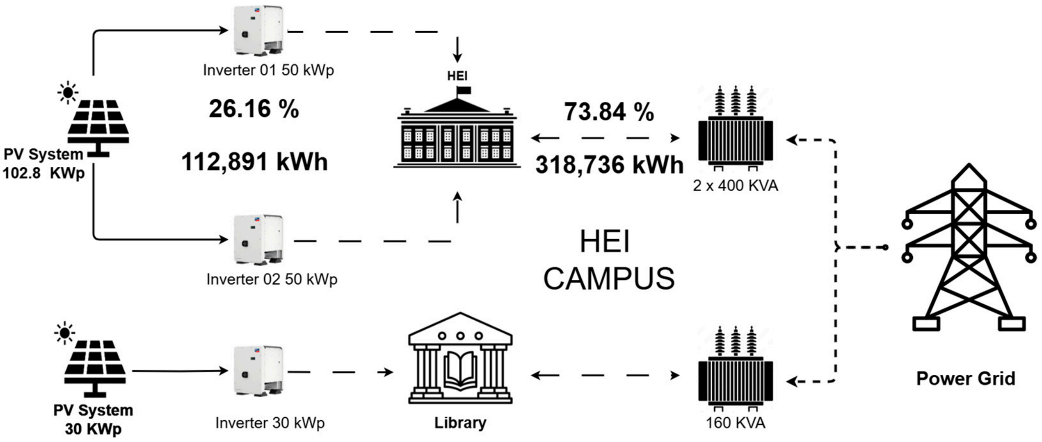

Figure 1. Simplified scheme for integrating all campus buildings into the grid.

3.2. Data Collection and Processing

The data used for the analysis were obtained from three different sources:

1. To estimate the production of the installed PV system, the Photovoltaic Geographical Information System (PVGIS) platform was used [13].
2. Production data were obtained by directly accessing the SMA Solar Technology AG platform, which allows data to be calculated with a 15 min interval [14].
3. Consumption data were obtained from the load diagram of the Portuguese energy distributor E-REDES [15].

Based on the mentioned sources, the results were obtained using the algorithm shown in Figure 2.

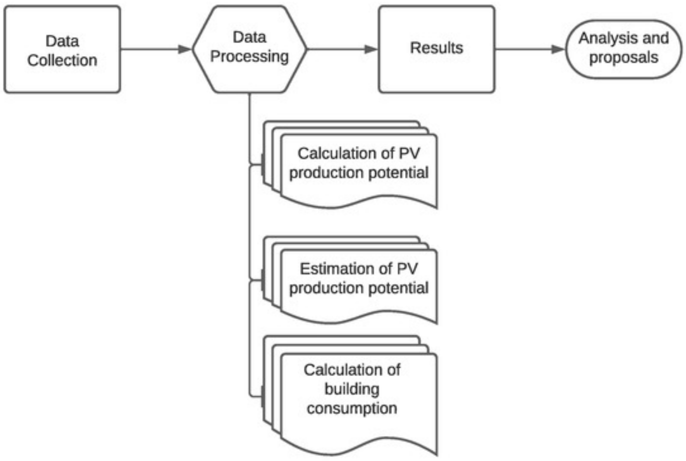

Figure 2. The study's methodology algorithm.

3.3. Energy Sharing

European legislation recognises the importance of community energy initiatives as a means of empowering local communities, promoting the use of renewable energy, and contributing to the transition to a more sustainable energy system. These initiatives typically involve various forms of collective ownership, participation, and benefit sharing, including Renewable Energy Communities (RECs), which are defined as legal entities, such as co-operatives, associations, or local authorities, established to produce, consume, or supply renewable energy while ensuring democratic decision making and benefit sharing among members. The EU Renewable Energy Directive (RED II) [16] provides a framework for the recognition and support of RECs in EU member states, Citizen Energy Communities (CECs), which are similar to RECs but with a stronger emphasis on individual citizen participation, promote active citizen participation in the energy transition, and are supported by EU legislation, including the RED II, to be member-owned energy co-operatives engaged in various energy-related activities, including renewable energy production, energy efficiency projects, and energy supply, operating on a nonprofit basis and prioritising the interests of their members and the local community [16]. EU legislation, such as RED II, recognises the role of energy co-operatives in promoting the use of renewable energy, as well as Local Energy Communities (LECs), which encompass a wider range of community energy initiatives that involve collaboration between local stakeholders, including citizens, businesses, local authorities, and energy service providers, with the aim of optimising energy use, promoting the integration of renewable energy, and enhancing energy resilience at the local level. EU legislation, including RED II and the Clean Energy for All Europeans package [17], supports the development of LECs as key drivers of the energy transition (Figure 3).

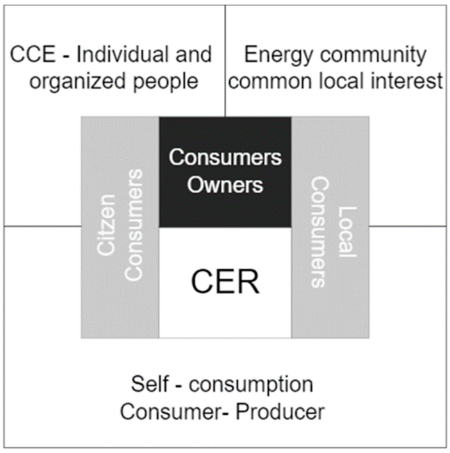

Figure 3. Community energy initiatives scheme.

In March 2023, an update of this directive was approved, taking another step towards European independence from fossil fuels with the Renewable Energy Directive III (RED III) [18]. It was agreed to increase the target for renewable energy production to 42.5% by 2030 to reach 45%, the figure proposed by the European Commission, reaffirming the EU's determination to achieve energy independence. It also defines the simplification of licensing procedures for renewable energy projects under the new legislation, recognising renewable energy as a priority public interest. Member states will create special "go-to areas" for renewable energy, with particularly fast and simple approval procedures in areas with high renewable energy potential and low environmental risks. The agreement also sets a renewable energy consumption target of 49% for buildings by 2030. However, the process of transposition into national legislation is incomplete and there are countries where there has not even been legal definition of RECs and CECs like Germany. In some cases, the definitions that have been established do not meet all the criteria set out in the Directives, leaving room for the concept to be distorted. For example, in the case of Luxembourg and Hungary, the established definition does not refer to the obligation to ensure an open and voluntary membership of the community. In fact, no country meets all the requirements identified by the European Commission as necessary to create a favourable and non-discriminatory context for the implementation of RECs.

In Portugal, the legal regime resulting from the partial implementation of REDII was published in 2019, defining what renewable energy communities are, which can include natural or legal persons, public or private, including small and medium-sized enterprises, as well as local authorities [19]. The Portuguese law allows municipalities and other entities to become producers, to store and share energy locally, and to develop municipal or even inter-municipal policies in this area. More recently, Decree-Law No. 15/2022 [20] establishes the organisation and operation of the National Electricity System, which also transposes Directive (EU) 2019/944 [21]. In addition, Decree-Law No. 30-A/2022 [22] approves exceptional measures to simplify procedures for the production of energy from renewable sources, and Decree-Law No. 72/2022 [23] amends the exceptional measures for the implementation of projects and initiatives for the production and storage of energy from renewable sources. According to the published legislation, it is assumed that consumers can assume the role of "prosumers", i.e., agents who, in addition to consuming, have the capacity to produce energy locally and manage their consumption profile under certain conditions. It should be noted that the implementation of energy communities in the European Union, a few years after the publication of the new Renewable Energy Directive, is well below its potential. To accelerate the spread of the concept on a large scale, it will be necessary to invest in information and dissemination, in supporting municipalities as the main promoters and facilitators, and in implementing a facilitating framework, namely through incentive mechanisms that consider the specificities of this type of initiative.

According to the law, a self-consumer is defined as a final consumer who produces electricity from renewable energy sources on his premises to meet his own needs and who can also store and sell the excess electricity produced. Collective self-consumption refers to the case where two or more final consumers located in the same building or group of buildings act together as self-consumers. Based on this, a university campus has strong potential to operate as a collective energy self-consumer; a university campus can not only reduce its environmental footprint and energy costs but also serve as a living laboratory for research, education, and innovation in sustainable energy practices. Collaboration with students, faculty, staff, and external stakeholders is essential to realising the full potential of campus-wide energy initiatives.

4. Results and Discussion

4.1. Framework

Section 4 analyses the impact of aggregating two separate PV systems installed on an academic campus into a collective self-consumption system and evaluates the potential benefits in terms of increased overall yield, primarily by increasing energy production, diversifying resources through redundancy and resilience to fluctuations in energy production, optimising energy consumption by more closely matching energy production to consumption patterns within the collective self-consumption group, reducing reliance on grid electricity to achieve economies of scale in maintenance and operating costs, and fostering collaboration and community engagement. The aggregation of PV systems into a collective self-consumption system will contribute to grid stability and reliability.

Based on this strategy, the structure of this section is as follows: in Section 4.2, through data consumption and production analysis, the hourly energy balance for the pedagogical complex building through the year was designed; in Section 4.3, with historical data both of 2019 and 2023, it shaped an hourly energy consumption for each month designed for the library building. Still in this section, a production forecast was carried out for a 30 kWp PV system, with increasing installation angles, in order to evaluate the impact of the tilt of the PV panels on the energy efficiency both in the summer and winter season. In Section 4.4, the monthly energy autonomy of both buildings has been evaluated separately, considering that, in the Pedagogical Complex building, real data are available both in terms of energy consumption and production. For the library building, the average consumption data for the years 2019 and 2023 were considered and then the autonomy of the system was calculated by implementing a series of numerical simulations carried out by varying the inclination of the PV panels. Finally, in Section 4.5, the energy autonomy of the whole campus was evaluated based on the real consumption data for both buildings, including the real energy production for the installed PV system for different installation angles, using specific software for energy simulation, and in the Section 4.6 the energy management for the campus is highlighted.

4.2. Energy Consumption and Production in the Pedagogical Complex Building

Figure 4 represents, on an hourly basis, the average consumption of the building per month to evaluate the impact of the photovoltaic system on the energy consumption of the building. The energy shown is divided into two parts: the energy supplied to the grid and the energy supplied by the 102.08 kWp photovoltaic system, both obtained based on the energy consumption data, considering that the system does not allow grid injection. Since PV energy injection into the grid is not allowed, the actual scenario represents the energy balance corresponding to the total grid energy consumption for the pedagogical complex building subtracted from the power production of the PV system. The data on building grid energy consumption refer to the period before 2023, when the overall infrastructure was not designed to allow for the integration of PV energy into the grid system.

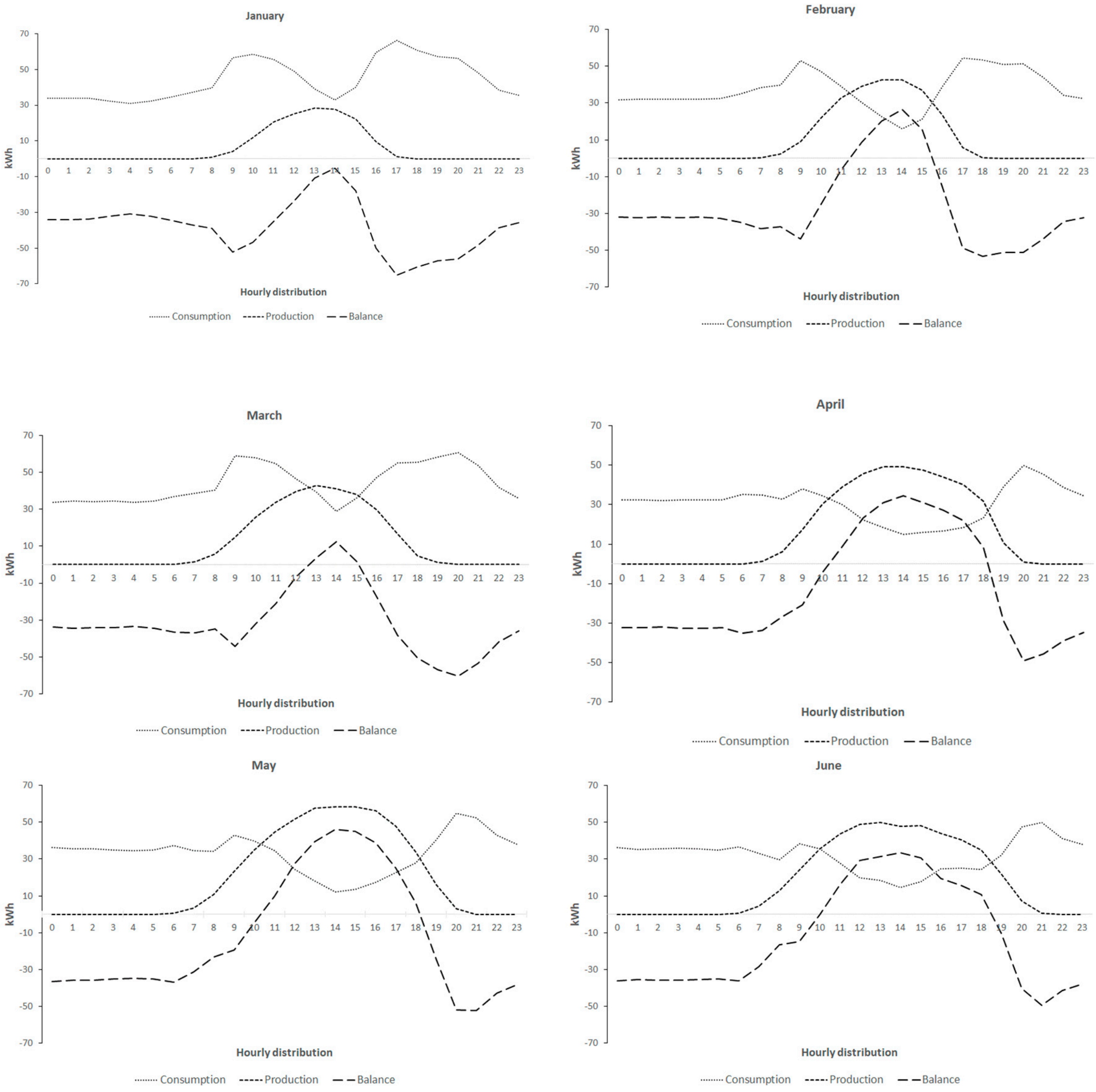

Figure 4. *Cont.*

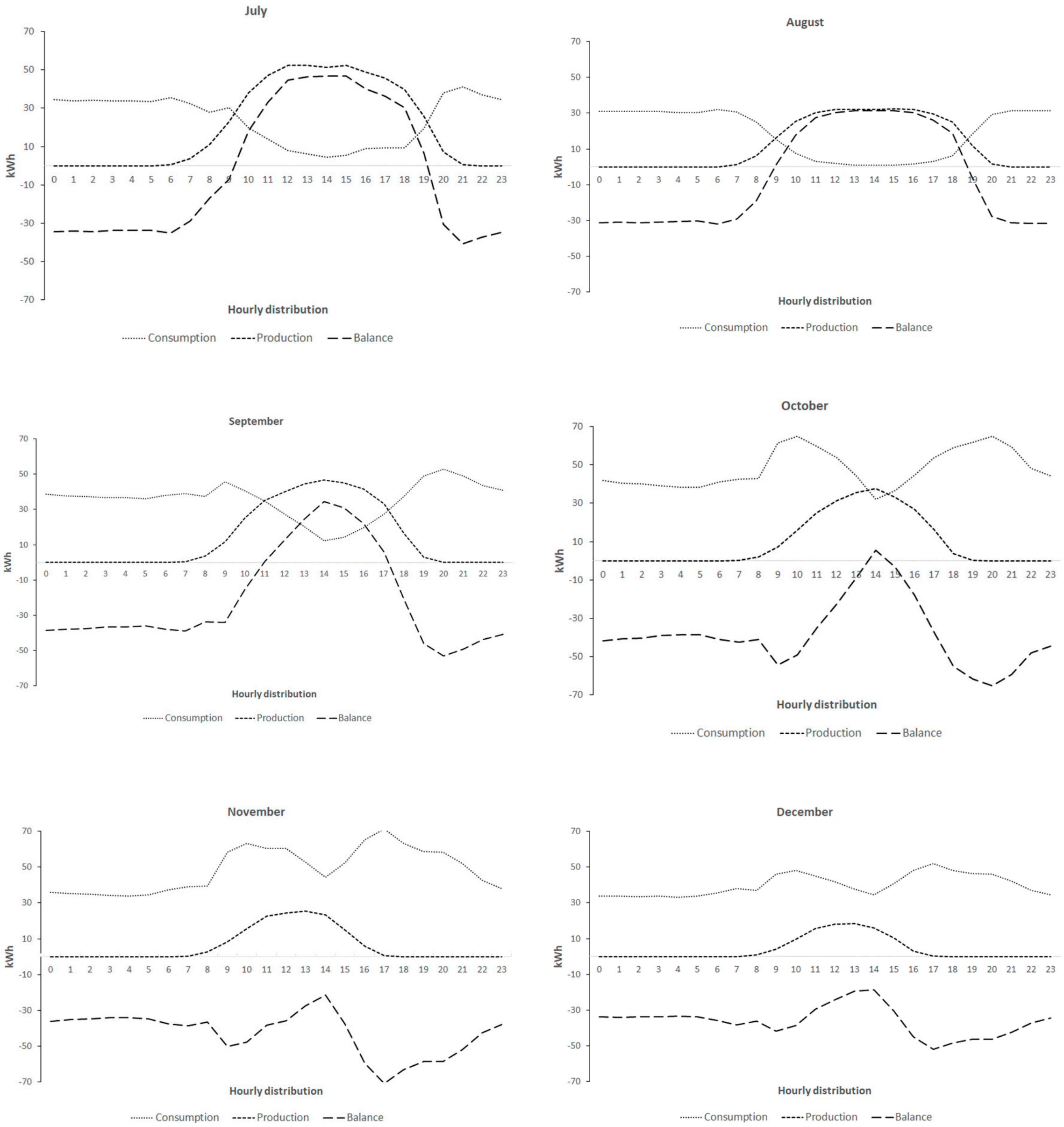

Figure 4. Monthly consumption of electricity in pedagogical complex for the year 2023.

The analysis of Figure 4 allows it to be concluded that, for all the periods from November to January, the grid energy consumption exceeded the PV energy production. In the remaining months, it is quite clear that the PV energy production exceeded the grid consumption for some daily periods, this situation being more evident between April and August. The annual energy balance shows the positive impact of the photovoltaic system on the overall energy consumption of the building.

4.3. Energy Consumption and Production in the Library Building

Figure 5 shows the average hourly consumption (C) of the library building, considering the data collected for the years 2019 and 2023, before and after the pandemic crisis. In the same graphs, the predicted production of a 30 kWp PV system funded by a special energy efficiency program and designed to be installed on the building's flat roof using PVGIS software (version 5.2) was plotted, considering a range of different panel angles and orientations. PVGIS-SARAH2 radiation database was applied for simulation, which includes an average production forecast between 2005 and 2020. According to a preliminary simulation considering a set of parameters recommended by the software (14% of losses, latitude of 41.695 °N and longitude of −8.848 °E, and elevation of 4 m), a scenario with an optimised panel slope of 36° and azimuth of 5° was taken as a base reference for further simulations. Based on this scenario, a set of additional simulations considering an increment of 10° on the panel slope was implemented.

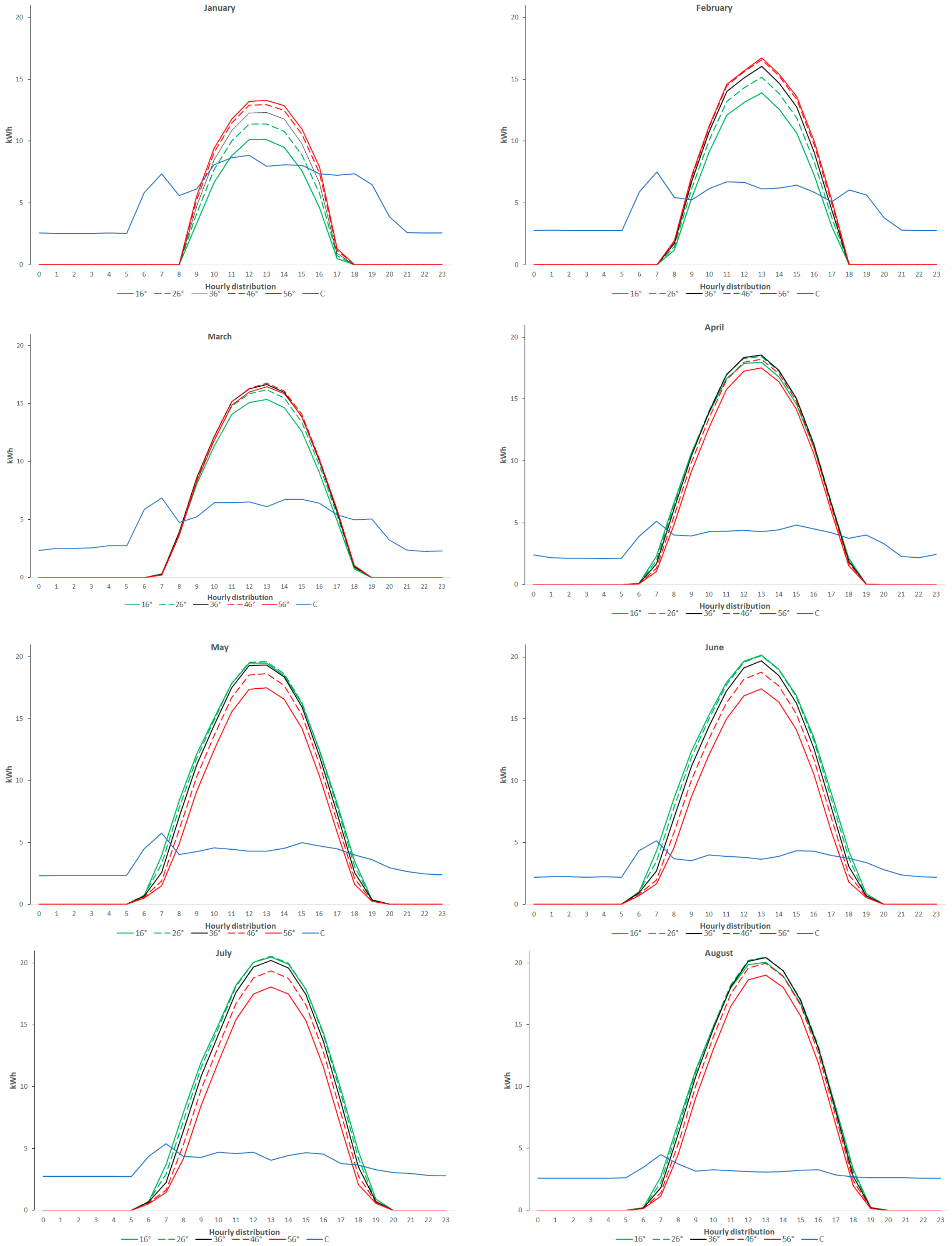

Figure 5. *Cont.*

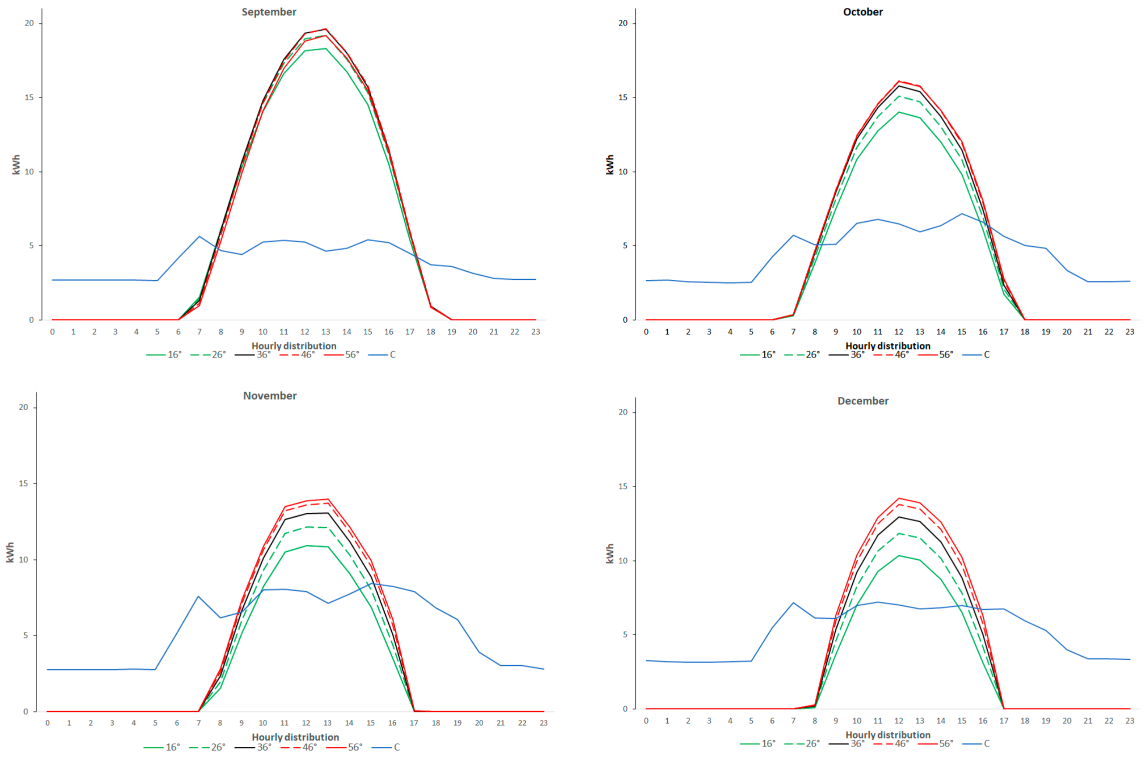

Figure 5. Monthly consumption of electricity in the library building for the year 2023.

The results show that, regardless of the increase in tilt of the solar panels, the average value of PV production is correlated with the number of hours of sunlight: in December and January, there is an average production of 32%; in November, 33%; in February, 38%; in October, 39%; in March, 41%; in September, 43%; in April, 44%; in May and August, 46%; and, finally, in June and July, 47%. As expected, PV production is higher in the summer months. Regarding the variation in the value of the tilt of the solar panels, an independent analysis of the results shows that there is a higher production in the winter months (September to March), corresponding to tilt angles of 46° and 56°. In the summer months (April to August), the inclinations with the highest production are those with an inclination of 16° and 26°.

4.4. Energy Autonomy Analysis for Both Buildings

4.4.1. Pedagogical Complex Building

Based on both the total energy consumption of the pedagogical complex and the electricity production of the PV system, the hourly energy autonomy can be determined according to the graph in Figure 6. The graph shows the percentage of the total energy over a 24 h period that is guaranteed by the installed PV system, always considering that grid injection is not allowed and, therefore, the autonomy cannot exceed 100%. To calculate the autonomy of the installation, the total photovoltaic production and energy consumption over a 24 h period were considered. The calculation of energy consumption considered the fact that classes take place both during the day and at night and that the cleaning service starts at 6 a.m., requiring the use of lighting systems. From the point of view of air conditioning energy consumption, the winter months were considered, given the mild climate during the summer period. All these variables have a direct impact on the autonomy of the system. In systems without grid injection, it is possible to establish a correlation between photovoltaic production and existing energy consumption. In this way, the autonomy is higher in the summer months due to the lower existing energy consumption, determined by the low level of school activity that ends in mid-June. Between October and March, the autonomy of the system is less than 20%; in April, 28%; in May and June, 30%; in July, 38%; in August, 39%; and in September, 23%. To improve the autonomy of the system, the teaching activities should be adapted to the period of photovoltaic production and the cleaning services should operate within this period.

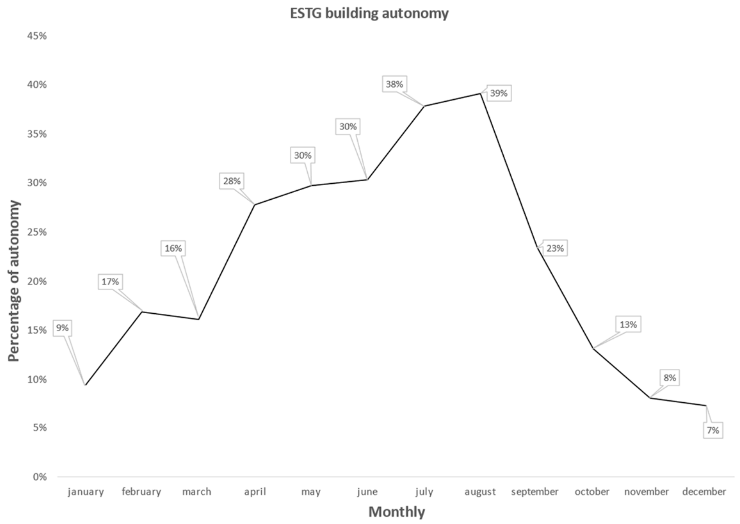

Figure 6. Annual energy autonomy for the Pedagogical Complex Building.

4.4.2. Library Building

As mentioned above, a scenario with an optimised panel slope of 36° and an azimuth of 5° was used as a base reference for further simulations for the library building. Based on this, additional simulations were performed considering tilt angles ranging from 06° to 86°. Since we are talking about systems without grid injection, production will be very close to consumption during the summer school vacations. When PV production exceeds consumption, the inverter adjusts production to avoid grid injection. With this system, it is possible to increase PV production during the winter when school classes are at their peak (Table 1).

Table 1. Average monthly values for the autonomy of the library building considering growing PV slope installation (kWh).

Month	06°	16°	26°	36°	46°	56°	66°	76°	86°
January	3.36	3.07	2.91	2.83	2.77	2.75	2.74	2.74	2.75
February	2.58	2.51	2.46	2.43	2.40	2.39	2.39	2.39	2.40
March	2.07	2.03	2.00	2.00	2.00	2.01	2.02	2.04	2.09
April	1.47	1.48	1.50	1.52	1.54	1.56	1.58	1.63	1.70
May	1.35	1.41	1.46	1.51	1.56	1.61	1.65	1.76	1.87
June	1.17	1.23	1.28	1.34	1.40	1.45	1.50	1.59	1.69
July	1.44	1.50	1.54	1.57	1.63	1.68	1.77	1.84	1.98
August	1.38	1.40	1.42	1.44	1.47	1.50	1.53	1.59	1.65
September	1.76	1.76	1.76	1.77	1.78	1.79	1.80	1.83	1.89
October	2.24	2.16	2.11	2.08	2.07	2.06	2.07	2.08	2.10
November	3.35	3.14	3.00	2.91	2.88	2.85	2.84	2.84	2.85
December	3.41	3.19	3.08	3.01	2.96	2.93	2.91	2.91	2.91
Average	2.13	2.07	2.04	2.03	2.04	2.05	2.07	2.10	2.16

Table 1 shows the mean monthly figures for the energy autonomy of the library building considering the overall energy consumption and the PV electricity production to all sets of increasing panel slopes. The results' analysis shows the best performance for an installed panel with slopes of 26°, 36°, and 46° (Figure 7).

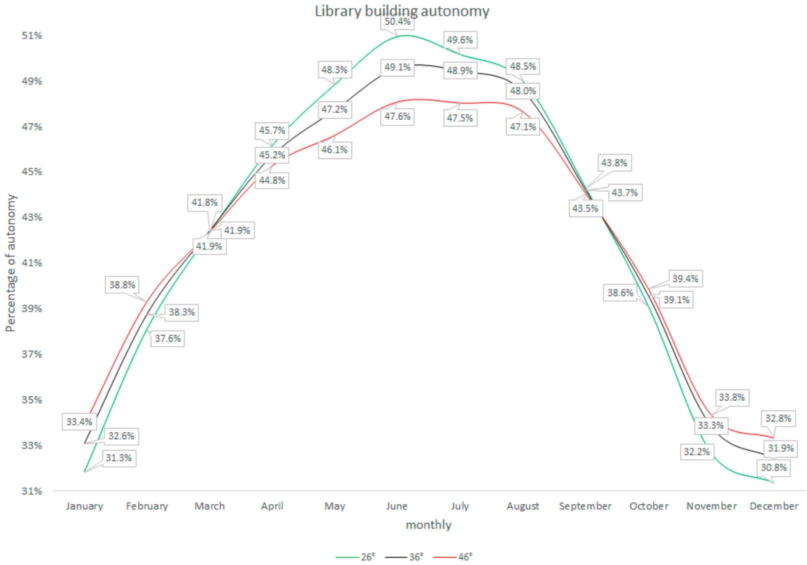

Figure 7. Library building autonomy for PV slopes of 26°, 36°, and 46°.

For the different slopes studied, an annual energy autonomy of 2.03 kWh for a slope of 36° and an energy autonomy of 2.04 kW for a slope of 26 and 46° stand out. The values obtained are very similar, but the annual analysis allows us to see how the system performs in the winter and summer months. If we analyse this system only for the library building, the 46° inclination is the best situation because it increases the production in the months with the highest energy consumption, which are the winter months.

Since grid injection is not allowed, the focus is on selecting the most effective panel tilt to increase the overall energy performance by increasing the building autonomy. Based on the implemented simulation, the adoption of a 46° tilt angle increases the PV production and thus increases the building autonomy of the library.

4.5. Overall Energy Autonomy of the Campus

Based on the partial analysis for both the pedagogical complex and the library buildings, this section evaluates the overall campus energy consumption and PV production. For the energy consumption side, the annual grid energy consumption for each building is summed up and, for the PV production side, the 102 kWp carport system is analysed together with the 30 kWp system planned to be installed on the flat roof of the library building. It should be noted that in neither case can the autonomy be higher than 100%, since it is a system without grid injection. Based on this, in Table 2 the average monthly values for the autonomy of the campus considering growing PV slope installation are shown.

Table 2. Average monthly values for the autonomy of the campus considering growing PV slope installation (kWh).

Month	06°	16°	26°	36°	46°	56°	66°	76°	86°
January	41.28	40.80	40.41	40.11	39.89	39.76	39.73	39.79	39.94
February	31.84	31.59	31.39	31.27	31.19	31.15	31.15	31.19	31.29
March	33.33	33.15	33.03	32.96	32.95	33.00	33.11	33.28	33.51
April	22.13	22.13	22.15	22.19	22.25	22.32	22.41	22.50	22.60
May	23.01	23.07	23.13	23.22	23.34	23.45	23.58	23.71	23.94
June	20.90	20.99	21.09	21.19	21.32	21.45	21.58	21.71	21.84
July	18.98	19.04	19.10	19.19	19.31	19.42	19.54	19.66	19.78
August	17.59	17.62	17.65	17.69	17.74	17.79	17.84	17.89	17.93
September	27.65	27.59	27.55	27.55	27.59	27.66	27.76	27.90	28.06
October	39.76	39.38	39.09	38.94	38.87	38.86	38.93	39.07	39.32
November	45.69	45.22	44.83	44.54	44.33	44.22	44.21	44.29	44.47
December	39.31	38.79	38.36	38.02	37.76	37.61	37.55	37.59	37.72
Average	30.12	29.95	29.82	29.74	29.71	29.73	29.78	29.88	30.03

In Figure 8, the curves of autonomy of the pedagogical complex building and the entire campus autonomy are represented, considering the PV panel slopes that offer the higher annual performance (26°, 36°, and 46°).

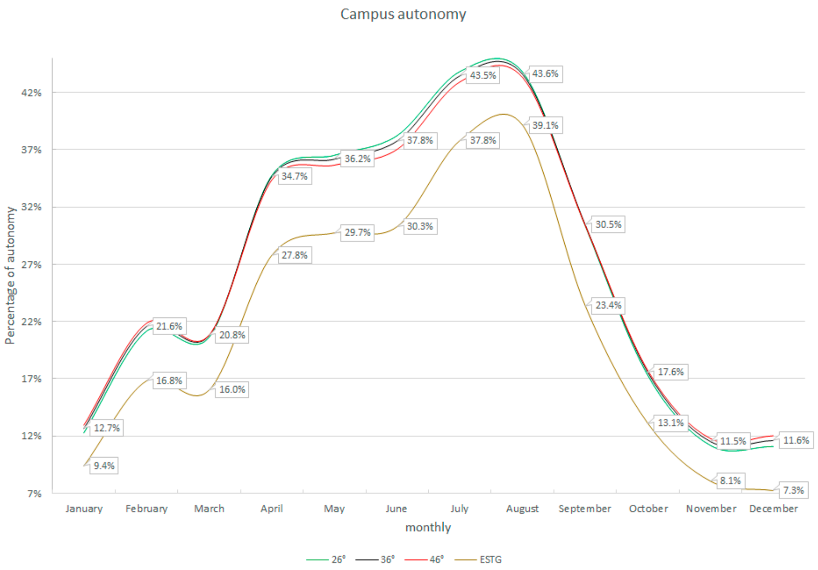

Figure 8. Campus overall autonomy.

According to Figure 8, it can be concluded that the newly designed 30 kWp PV system, when integrated with the existing infrastructure, can bring out an increased autonomy for the campus. Based on this, it is clear that PV systems without grid injection are excellent examples of collective self-consumption as initially advanced. As previously shown, this installation can increase PV production during the winter period, when most needed, since, in summer, PV production exceeds consumption for most of the time and the inverter adjusts the total energy production to avoid grid injection.

4.6. *Energy Management for the Campus*

In order to adapt the energy consumption of the campus to the two PV production systems, it is essential to define a strategy to adapt the lighting consumption between 6 and 8 a.m., when cleaning services are in operation for both buildings.

In the Educational Complex building, it is proposed to install motion detectors in the different corridors, which are large areas that sometimes do not need to be turned on all the time. In the library building, it is proposed to change the lighting system to LED technology. In all the simulations considered, consumption values were included throughout the 24 h of the day for both buildings. Since these are off-grid systems, energy storage devices could be an advantage.

5. Conclusions

An academic campus with an installed photovoltaic (PV) carport system and a new rooftop PV system yet to be installed has a zero-injection goal due to regulatory restrictions. Therefore, the new PV system should be designed to avoid feeding excess power back into the grid. To implement the analysis, a detailed understanding of the hourly consumption patterns including data collection and peak demand forecasting was implemented for both the pedagogical complex building and the library. The new PV system was sized based on consumption using production forecasting using solar irradiance data for the campus location considering seasonal variations. Since the system to be installed has zero injection, it was possible to calculate that the annual autonomy forecast both for the library building and the entire campus show a variation of less than 1% for panel installation slope varying from 16° to 66°. This study allows the conclusion that, considering the diversity of consumption throughout the academic year, PV panel tilt can play an important role in PV sizing to increase campus autonomy. The autonomy of the campus can be further improved if there is a load management system implementation, mainly by applying an automatic control device for lighting systems and promoting changes in cleaning service schedules, allocated from 6 to 8 a.m. The use of demand-side management strategy to shift energy consumption to periods of high PV production is fundamental, mainly by scheduling high-consumption activities during peak production hours. In addition, the installation of a battery storage system to handle small surpluses and provide backup during low production periods is an option, along with the use of smart controls to manage when equipment operates to match PV production peaks. For a zero-injection photovoltaic system, the goal is to closely match the PV production with the site's consumption on an hourly basis. Detailed hourly consumption data, accurate production forecasting, demand-side management, and possibly energy storage are all critical components to achieving this goal. In short, the energy management of a school campus is fundamental to the creation of a collective self-consumption system, the basis of a local energy community that can meet energy, environmental, and social objectives.

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