energies

MDPI

Article

Assessing the Potential of Implementing a Solar-Based Distributed Energy System for a University Using the Campus Bus Stops

David Morillón Gálvez [1,†], Iván García Kerdan [2,*,†] and Germán Carmona-Paredes [1]

1 Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico; damg@pumas.iingen.unam.mx (D.M.G.); gcarmonap@iingen.unam.mx (G.C.-P.)
2 Tecnologico de Monterrey, School of Engineering and Sciences, Av. Carlos Lazo 100, Santa Fe, La Loma, Mexico City 01389, Mexico
* Correspondence: i.garciakerdan@tec.mx
† These authors contributed equally to this work.

Abstract: Large educational facilities hold great potential for the implementation of solar-based distributed energy systems. The aim of this paper is to present a prototype and an assessment of a solar-based bus shelter photovoltaic system intended to be implemented at a campus scale that serves as an energy-distributed system. The National Autonomous University of Mexico (UNAM), a campus with an area of 7.3 km^2 and bus stops' roof area availability of around 1100 m^2 was selected as a case study. The proposed system, apart from considering on-site generation, also considers an increase in end-use services such as the installation of television screens for information, charging docks, surveillance cameras, internet service, and lighting. For the assessment, a load facility survey and an estimation of the baseline energy use was conducted based on two demand use conditions, corresponding to 12 and 24 h for different archetypical stations. It was found that the baseline annual energy consumption for all the bus stops represents from 55–111 MWh. In this paper, an initial prototype of a solar-based bus shelter PV system is presented, and an assessment is carried out to understand its potential application at a large scale. The analysis shows that energy use in the retrofitted stations would rise to 167 MWh/year; however, apart from covering on-site demand, the system has the capacity to generate an additional 175 MWh, feeding nearby university buildings. It is calculated that the system could save around 130 t CO_2e annually. The economic analysis shows that the project has a discounted payback (DPB) of almost 9 years and an internal rate of return (IRR) of 5.9%; however, in scenarios where renewable generation and carbon incentives are applied, this improves the project's DPB to 6 years and the IRR to 13%.

Keywords: solar energy; decarbonisation; distributed energy system; energy retrofit; university

check for updates

Citation: Gálvez, D.M.; Kerdan, I.G.; Carmona-Paredes, G. Assessing the Potential of Implementing a Solar-Based Distributed Energy System for a University Using the Campus Bus Stops. *Energies* **2022**, *15*, 3660. https://doi.org/10.3390/en15103660

Academic Editors: Zhengmao Li, Tianyang Zhao, Ke Peng, Jinyu Wang, Zao Tang and Sumedha Sharma

Received: 25 March 2022
Accepted: 13 May 2022
Published: 17 May 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Distributed energy systems (DESs) have become an important energy solution to decentralise the power sector and reduce sectoral carbon emissions. DES have the aim to generate electricity near to where the demand is and can have multiple forms made of a diverse range of generation, storage, and control technologies. The scale of such systems can go from single buildings or premises to a large scale as part of a micro grid.

Several reports have tackled the potential of implementing DESs at a larger scale. A report from Arup and Siemens [1] established the potential of implementing DESs in commercial sites, neighbourhoods, and industrial facilities at a global scale. According to the report, its implementation will result in operational cost reductions up to 28%, with an average return of investment between 3 and 7 years. Furthermore, DESs have the potential to increase electric grid resilience, lower costs in energy balancing, and improve energy security and resilience. The International Energy Agency [2] argues about the importance of the digitalisation of DESs due to their 'invisible' and uncontrollable nature for central operators; thus, the use of novel digital technologies could allow real-time monitoring and managing of the system by users. Additionally, central operators can have access to the system's information and make decisions and influence DES operators based on the provided information. However, digitalisation by itself might not be enough to unlock large-scale implementation of DES, as other issues remain. For instance, a National Renewable Energy Laboratory (NREL) research group [3] provided a technical report about the importance of interconnection in a system with higher levels of distributed energy. The authors pinpointed the importance of technical aspects such as inverters, storage, and distribution system upgrades, as well as cost allocation and cybersecurity. However, more consistent policy and technical frameworks are required to be in place for DESs to be implemented in a robust and risk-free environment.

Hybrid microgrids, integrating both AC and DC, will play a key role in integrating renewable energy resources and technologies. Additionally, such grids will minimise conversion stages, thus reducing energy conversion losses. Kazerani and Tehrani [4] proposed a novel smart city architecture based on hybrid microgrids. The authors concluded that such an approach could lead to higher energy renewable penetration, lower energy prices, and increases in power quality as well as an improvement in the system's reliability, resiliency, and security.

Energy and sustainability measures, including DES projects, have an important opportunity to improve system's reliability, reduce operational costs and, in some cases (dependent on local policies and incentives frameworks), secure steady income through the generation and export of renewable energy.

This paper is organised as follows. First, the most relevant literature on energy studies in universities and DESs is presented. Secondly, the proposed prototype, methodological framework is introduced. In this section, we focus on technical details about the proposed DES system along with an explanation of the preliminary experimentation and data gathering. Additionally, the case study is presented, where current infrastructure to be retrofitted by the prototype is shown. Following this, the results from the energy audit, energy simulation, and a comprehensive techno-economic analysis of a wide scale implementation of the suggested system is presented. This data provides the possibility to discuss necessary incentives to be implemented to make the proposed system a cost-effective solution for large-scale implementation. Finally, conclusions and suggestions for future work are presented.

2. Literature Review

Large, non-residential facilities hold great potential for energy savings as well as DESs due to their size and terrain availability. Before embarking on the implementation of DESs in educational facilities, energy use and environmental aspects need to be understood due to the size and heterogeneity of higher educational premises. Specifically, urban university campuses can be high energy consumers and greenhouse gas (GHG) emitters, either through campus operation or through research activities.

2.1. University Energy Audits

Amaral et al. [5] proposed actions of integral energy sustainability in buildings at the University of Coimbra's main campus. The study highlights the drawbacks from a successful sustainability program implementation and discuss the causes of such results. Through a systematic review, it was possible to identify the most common factors and triggers of failure, classified into four groups: technical, economic, climatic, and behavioural. Within these groups, the main causes include inadequate planning, inadequate systems design, lack of adequate maintenance, low return on investment, failure to consider the local climate, or uncertainty of long-term commitment with sustainable behaviour. Based on these findings, a set of lessons was disseminated for each group, which may be useful for all those who are involved in decision-making, planning, or monitoring of sustainability actions on university campuses, to help anticipate and overcome difficulties in early stages.

To date, there is little research on GHG emission reduction projects at higher education institutions in developing countries. Recently, Yusoff et al. [6] presented the impact of diverse sustainability initiatives applied at the University of Malay, located in Kuala Lumpur, Malaysia. The report presents GHG emission reduction data from campus activities and laboratories. The reduction of emissions was classified according to the Kyoto Protocol in Scope 1, 2, and 3 [7]. Scope 1 of GHG contributes the largest number of activities and produced the main reductions of GHG emissions in electricity consumption (in kg CO_2e/kWh) with a decrease of 90.7% from 2016–2017. The greatest reduction in total annual GHG emissions was found from 2017–2018, with a total of 6590 t $CO_2e/year$. Mohd Zublie et al. [8] provided a feasibility analysis of a roof-based photovoltaic solar energy system of an educational institution in Malaysia. A detailed energy audit was conducted to identify the energy use of the buildings, more specifically, lighting, fans, air conditioning, and equipment. It was estimated that a 5% reduction in energy generation and the energy bill can be achieved based on the installation of photovoltaic solar energy on the roof for self-consumption.

Oyedepo et al. [9] evaluated the economic and environmental impacts of energy saving strategies at Covenant University in Nigeria. The study provides a strategy to conduct an energy audit in 18 buildings aimed at understanding energy use and occupant behaviour; thus, recommendations could be given to reduce energy use. Later, building energy models were developed to test different measures, suggesting that around 80,000 USD could be saved annually alongside the reduction of 500 t $CO_2e/year$.

For Mexico, few studies in educational facilities exist. First, Escobedo [10] presented an analysis and model of electrical energy consumption in university buildings at the National Autonomous University of Mexico based on end uses and architectural parameters, in which the percentage of energy related to lighting was identified. Later, Escobedo et al. [11] proposed scenarios of energy consumption and greenhouse gas emissions reduction, more specifically in assessing different technologies for lighting and water heating.

2.2. DES Studies

The study and application of solar-based systems and DESs has been studied more frequently in the last 15 years. Seidl et al. [12] studied the social acceptance of DESs in Germany, Switzerland, and Austria. Results from a large-scale survey show openness from the population to engage with such systems. An interesting finding is that the population still places large responsibilities for DES installation to governments and utility companies, showing a low willingness to invest from the final users. Wolsink [13] also studied the social acceptance of DESs but with a socio-political focus. The study found that the integration of renewable energy, storage, and demand response require a shift to consumers as coproducers, redefining the concept of electricity from a commercial good to a common good, suggesting that policy should avoid any barrier that could empower final users.

Apart from social studies regarding DESs, most of the literature covers technical and planning issues. Zhou et al. [14] provided an engineering framework to optimally design a DES aiming to obtain an optimal portfolio of technologies and capacities given the energy demand. The framework was applied to China, showing that the recommended design has better performance than the previous centralised systems and the typical district systems found in the case study. Mavromatidis et al. [15] provided a study where uncertainties are identified on energy system models when designing DESs. The author identified renewable energy availability, economic, and environmental aspects of different energy carriers and vectors, techno-economics of technologies, and energy demand as the main uncertainty factors.

Kotsampopoulos et al. [16] proposed a benchmark system for hardware in the loop (HIL) testing incorporating distributed energy resources into a dynamic simulation environment. As a baseline, the authors used the CIGRE European LV distribution networks, as it possesses technical characteristics of an actual utility grid. The authors provided enough detail into the modelling to achieve robust, real-time simulation results. The main outcomes of the study are the precision of practical guidelines and frameworks supporting the implementation of HIL simulations in a laboratory as well as the actual application of the presented framework. Due to the implemented control systems using optimisation techniques, peak shaving, voltage control, and reduction of losses were evaluated.

Falke et al. [17] presented a multi-objective optimisation framework for the planning and operation of DESs in Germany. Apart from considering supply options, the study also considers the implications of investing in energy efficiency measures, providing a robust framework for the design of integrated energy solutions. Perera et al. [18] studied the influence of the urban form on the integration of DESs. The study shows that the urban form has important implications in services, such as heating and cooling, that could influence the design of a DES. Additionally, integration to the grid is also influenced by the form, having implications in the interconnection cost. Therefore, the study shows the importance of doing an energy system analysis and assessment at an urban scale. In this sense, Wu et al. [19] provided a non-linear optimisation model that considers the effects of an urban spatial structure in a DES project. Apart from providing an optimal portfolio of technologies, the model also suggests optimal building mix within the district or neighbourhood.

Moreover, strategies, such as demand response, can improve the overall benefits of DESs. Among non-residential facilities, large educational premises, such as University campuses, could hold the greatest potential due to their large size and low uncertainty in energy demand. Roldán-Blay et al. [20] argued the importance for small and medium facilities to participate in demand response programs and proposed an energy and cost forecasting algorithm to facilitate decision making for these users. The method was applied at the Universitat Politècnica de València. Fonseca et al. [21] provided a systematic review on the potential of implementing hydrogen as a vector in DESs at different scales and buildings or neighbourhood types. The study shows that electrolysers and fuel cells are the most common hydrogen technologies, with larger installed capacities found for the former. On the demand side, it was found that hydrogen holds the greatest potential for storage, with other uses, such as transport, heating, and raw material for the industry, still playing a significant although secondary role in a DES.

Yan et al. [22] studied the optimisation of multiple DESs in a community. The author focused on dispatch energy devices to minimise daily energy costs without hampering energy demand. The author proposed a mixed integer linear programming (MILP) model using the branch and cut method. Li and Zhang [23] used a mathematical model to study the techno-economic and environmental impacts of multiple DESs under two frameworks: centralised and decentralised. In the former, the use of resources and energy management maximises social welfare while, in the latter, the focus is to minimise the cost for each stakeholder involved. The model shows that both frameworks can provide with robust solutions and gains for society as well as stakeholders. However, under a decentralised approach, carbon taxes might decrease internal energy flow and increased system's emissions.

Qiu et al. [24] provides a study analysing the coupling impact of DES interconnection and demand response. For this, the authors developed a MILP energy model able to analyse the flexible management between heating, cooling, steam, and electricity energy demands and obtain an optimal strategy. The model is capable of improving the economic and environmental benefits of DESs.

Rossi et al. [25] studied the environmental and economic implications of a small-scale grid connected to a solar-based system using life cycle analysis. The study's aim was to use mixed integer linear programming (MILP) to optimise the design while considering economic incentives and the capital costs of equipment, such as panels and batteries. From an economic perspective, it is possible to find an installation considering only the PV generation panel. On the other hand, from an environmental perspective, it is possible to find installations based on panels and storage systems. To enhance the economic profitability of such systems, cost reduction of batteries coupled with higher economic incentives are necessary. Iria and Huang [26] investigated the impact of carbon taxes on the installation of PV solar-based systems and battery energy storage systems. The authors used a multi-objective planning optimisation approach to investigate different system's configurations while considering capital and operation costs as well as environmental implications. The results show the advantages of applying a carbon pricing system, as it reduced up to 44% of the case study's carbon footprint and, similarly to the previous study, incentives are necessary for storage technologies to be cost effective.

2.3. Research Gap

As showed in the literature review, on the one hand, most of the studies are based on empirical mathematical models (mostly optimisation models) under uncertainty conditions. On the other hand, more studies considering real-life applications are necessary to understand the full potential of DESs.

Thus, the current study has two main objectives. First, it proposes the design and prototyping of a novel solar-based energy system adapted to existing bus stations' infrastructure on educational premises that would have the potential to serve as generation sites. The proposed system considers a prototype made of a PV solar-based system coupled with a battery bank, power inverters, Wi-Fi routers, efficient lighting, surveillance cameras, and charging ports, providing new services to the university community. Energy audits and irradiation measures are conducted to understand the real site conditions. Secondly, a techno-economic assessment is provided to understand its potential implementation at a campus scale, providing authorities and decision makers with the necessary information. It is expected that the main contribution of this study will be the design of a cost-effective and simple solar-based distributed energy system.

3. Methodology

3.1. Case Study

The National Autonomous University of Mexico (UNAM) main campus was considered in a case study. The campus is in the southern part of Mexico City and has been catalogued as a UNESCO Heritage Site. The campus is home to around 130,000 students and staff. The total energy consumption in 2018 is shown in Table 1 and will be considered as the baseline. Although there is data availability for 2019 and 2020, these years are not representative due to the COVID-19 pandemic. To validate the trend, the consumption corresponding to the year 2011 is also considered.

Table 1. Total energy consumption at CU-UNAM (Source: Escobedo et al. [11] and UNAM).

Year	Energy Consumption in UNAM [GWh/Year]
2011	81.3
2018 *	83.3
2020	61.2

* Baseline.

According to Escobedo et al. [11], by energy share, lighting represents 32.6%, refrigeration 16.4%, special equipment 14.9%, computing 5.2%, air conditioning 4.3%, miscellaneous 3.8%, power 2.2%, heating 0.4%, and others 20.2% (Escobedo, 2014). Greenhouse gas (GHG) emissions associated with energy consumption reached 49.6 Mt CO_2e, which represents 0.01% of national emissions and 0.1% of emissions from Mexico City alone. In 2018, GHG emissions increased to 50.8 Mt CO_2e.

The university has its own regulated transportation system; therefore, both maintenance of buses as well as stations are a responsibility of the university. The system is made of 12 routes and 170 stops. Figure 1 shows the map of the entire system and the exact location of the bus stations. What is not indicated in the energy consumption values (Table 1) is whether the energy demand of the bus stations is included; nevertheless, it is assumed for this study that they have been included, in order to be able to compare the benefits of the solar station distributed energy system at a university level.

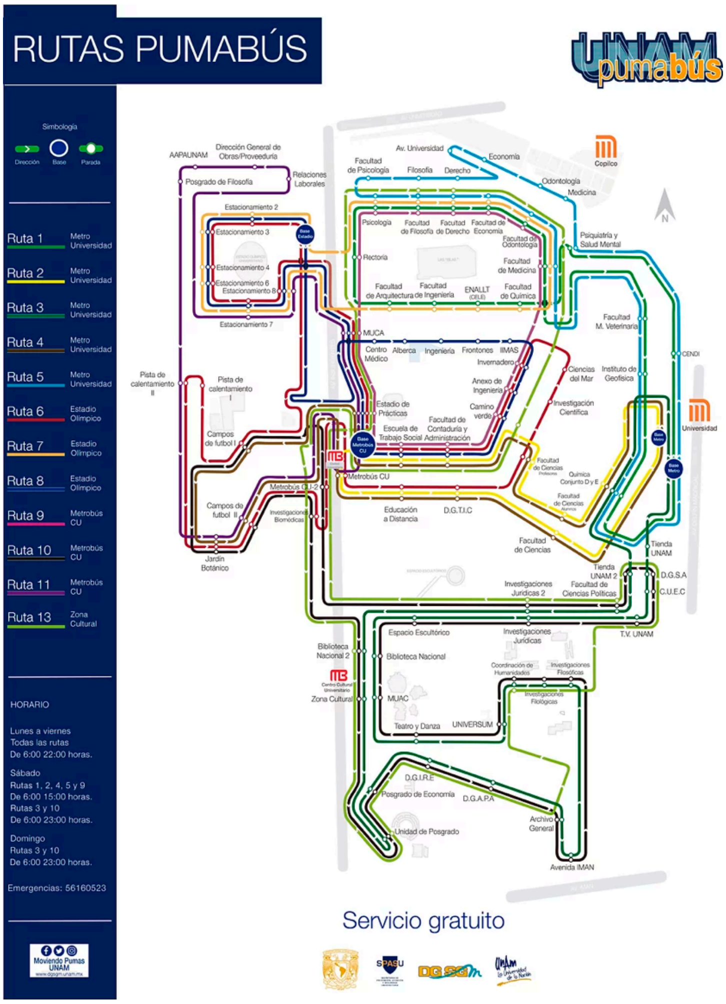

Figure 1. UNAM transport system routes and stations. Source: https://www.dgsgm.unam.mx/pumabus (accessed on the 15 January 2022).

3.2. Bus Stations Energy Survey

As information was lacking about energy demand from bus stations, an energy audit was carried out on a campus level. The procedure to carry out a diagnosis required several activities that range from a visit to the facilities to the delivery and presentation of the energy diagnosis report to those responsible for the energy management of the facility. The main activities for the elaboration of the diagnosis were the following:

- Tour of the facilities'
- Gathering of information on electricity bills;
- Gathering of basic information about the installation;
- Carrying out data collection of energy consuming equipment;
- Analysing the data;
- Identifying potential energy savings;
- Preparing the energy diagnosis report.

From the data survey carried out on the campus, 67 stations of the 170 stations were found to have the potential to install a solar-based system, mainly due to having a roof with no shading obstructions. Originally, these roofs have been designed for solar and rain protection. From this analysis, 7 different archetypical bus stations have been identified (Table 2) and a total roof area of 1532 m^2 was found, 1100 m^2 of which is available for PV systems.

Table 2. Archetypical bus stations on the campus.

Archetype	Area (m^2)	Amount	Lighting Fixture	Photo
A	10	15	T3	
B	50	10	T5	
C	66	7	T5	
D	3	35	LED	
E	16	5	LED	
F	105	1	T5	
G	130	1	LED	

After collecting information on the installed capacity of equipment at station level (mostly lighting fixtures and power outlets) and to account for energy consumption, we assumed two energy-use scenarios, considering the hours of service of the lighting in the stations (12 h or 24 h). From the audit, it was noticed that some stations have the lighting fixtures on for the entire day, while others only operate from 6 p.m. to 6 a.m. With these assumptions, an energy demand range was obtained. Table 3 shows aggregated data per archetype station as well as the total energy demand of the analysed bus stations.

Table 3. Energy demand scenarios for the campus bus stations.

Archetype Station	Energy Use [kWh/Year] 12 h Use	24 h Use
1	7096	14,191
2	14,191	28,382
3	13,245	26,490
4	11,651	23,302
5	1664	3329
6	6623	13,245
7	999	1997
Total	55,469	110,936

The related CO_2 emissions were determined, using the methodology established in the Intergovernmental Panel of Experts on Climate Change (IPCC [27]) Section 2, associated with the use of electrical energy and the generation of emissions:

$$E_{CO_2(IPCC)} = \sum_i C_i * PC_i * FE_{CO_2,i} \tag{1}$$

where

E_{CO_2} = Total carbon dioxide emission [t]
i = Type of fuel [Natural gas, Diesel, Coal]
C = Annual fuel consumption [m^3 or t]
PC = Calorific power of fuel [MJ/m^3 or MJ/t]
FE = CO_2 emission factor [t/MJ or kg/MJ] = 0.457 kgCO_2/kWh.

The emission factor (*EF*) associated with the use of electrical energy that is directly associated with the electrical matrix of each country will present different values for each region. Considering that Mexico City's emission factor [28] total GHG emissions were calculated in the range between 25.3–50.7 t CO_2e and that the average lifetime of the prototype is 15 years and compared to the expected GHG reduction in the Mexican power system due to NDC [29], the life cycle emissions reduction was found between 326–654 t CO_2e (average = 490 t CO_2e) (Figure 2).

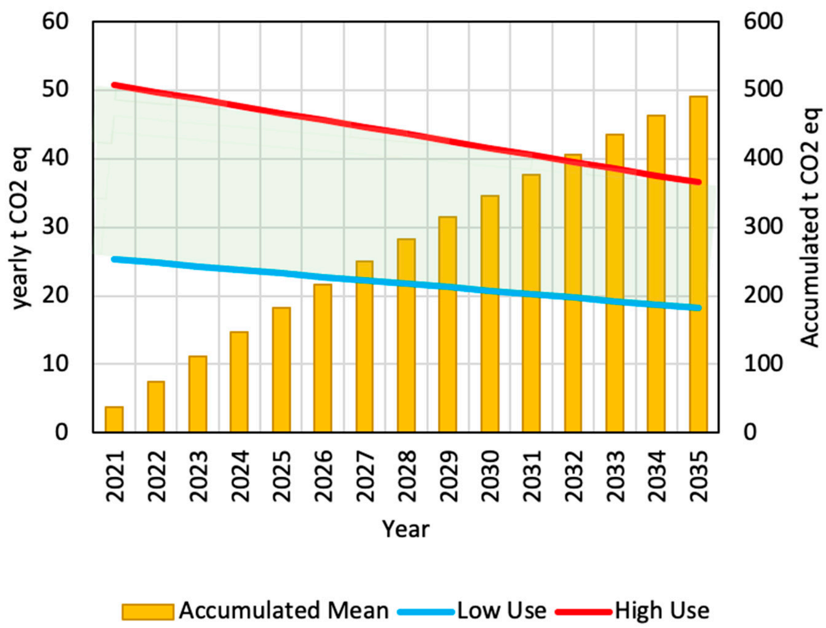

Figure 2. System's life cycle carbon emissions reduction potential.

3.3. Solar Irradiation and Prototype Solar Bus Station

3.3.1. Solar Irradiation Measurement

The project has also considered the design, construction, and testing of a prototype solar-based station. Prior to the testing, solar radiation was measured and evaluated for a 6 month-period in order to have actual on-site data. Figure 3 shows the low-cost solar station designed for this purpose.

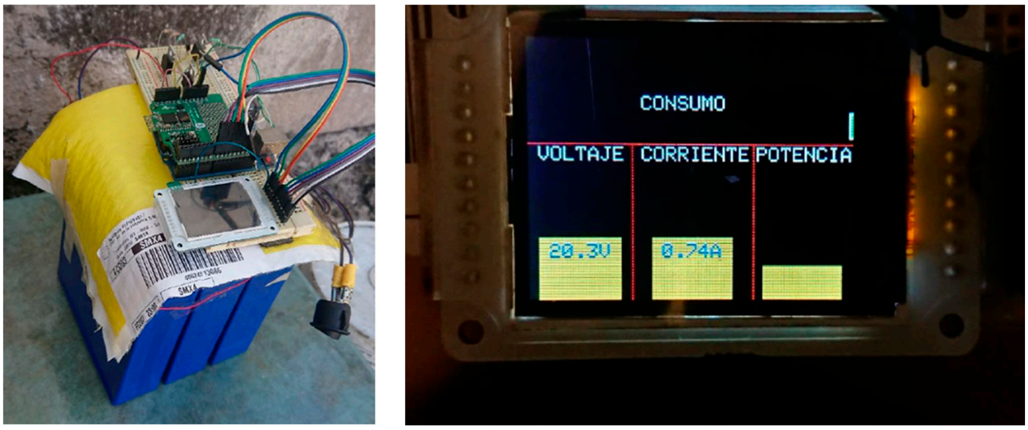

Figure 3. Low−cost solar station for on-campus irradiation measurement.

Figure 4 shows the actual measurement made by the station in a single day.

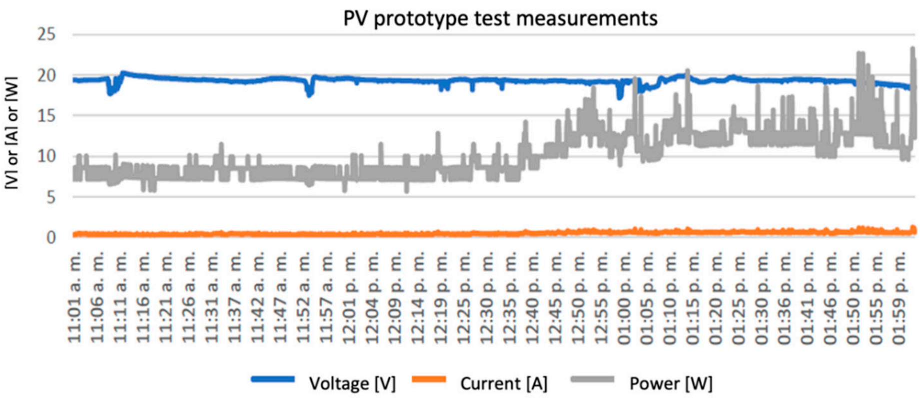

Figure 4. Voltage, current, and power measurements from the prototype solar-based system (measurements taken 21 February 2021).

3.3.2. Solar Station System Prototype

A first an effort was made to create a prototype that could be tuned and tested. This prototype, with the different services that will be provided (lighting, charging docks, cameras, etc.), has already been considered to obtain an energy demand as realistic as possible. Figure 5 shows the schematic of such a prototype.

The proposed arrangement is made of an array of six monocrystalline photovoltaic modules of 260 W (1.6 kWp), connected in parallel in order to add the nominal current delivered by each of them and be able to charge the 12 V battery through the charge controller, to which 24 V can be connected at the input for charging the batteries. The system has been arranged with a diode to avoid currents in the opposite direction when some or all of them are occluded by shadows. Immediately at the output of the array, a charge controller has been connected to control the current and voltage with which the battery bank with a capacity of 6 kWh is charged. According to manufacturer data, the overall conversion efficiency of the arrangement is about 20%.

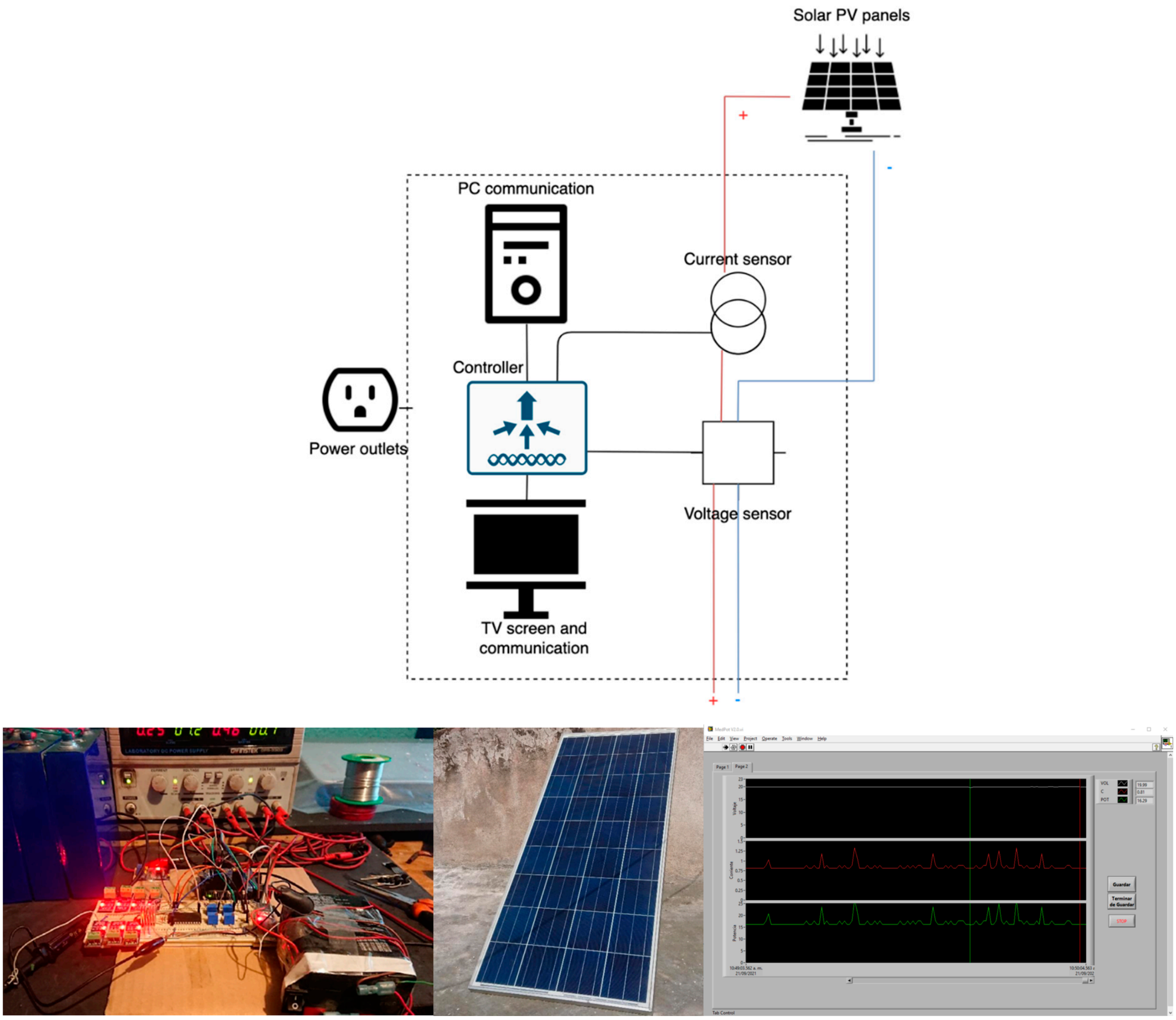

Figure 5. Diagram (**top**) and first implementation of the proposed system: electronic design, PV panel and LabView controller (**bottom**).

The panels' positions are fixed, with an inclination corresponding to the latitude of the placement (19°20′01″ N), aiming to obtain the maximum potential at that point. Perturb & observe (P&O) is used as a maximum power point tracking (MPPT) algorithm. In this method, the instantaneous values of voltage and current in the module $V(n)$, $I(n)$ are used to measure the power, given by:

$$P(n) = V(n) * I(n) \tag{2}$$

Power output at time n is compared with the previous step $(n-1)$. $(\Delta P = P(n) - P(n-1))$. Positive ΔP variations mean that the disturbance in ΔV contributes to increasing power, so the next ΔV update will be carried out with the same sign. Once the MPP is found, the next update will drive a negative ΔP, so the disturbance is reversed. The selection of this algorithm is due to its simplicity and robustness.

4. Results

4.1. Simulation Results (Prototype)

PVSyst software was used to model the proposed system energy performance by introducing the dimensioning of the roof stations where the solar panels will be placed. This accounts to around 12 m^2 or 1.6 kWp.

Figure 6 shows the prototype behaviour of the output power of the inverter and the voltage against the current of the parallel-connected array, as we aimed to increase the value of the current, expecting it to be six times greater than the nominal current, which is 8 A and a voltage of 30 V. From the graph of voltage vs. current, we can see that having our system between a temperature range of 60 °C and 20 °C can achieve variations between 5.0% and 22.2% of the nominal voltage of our system and at a temperature of −10 °C we can reach the maximum voltage that it could deliver.

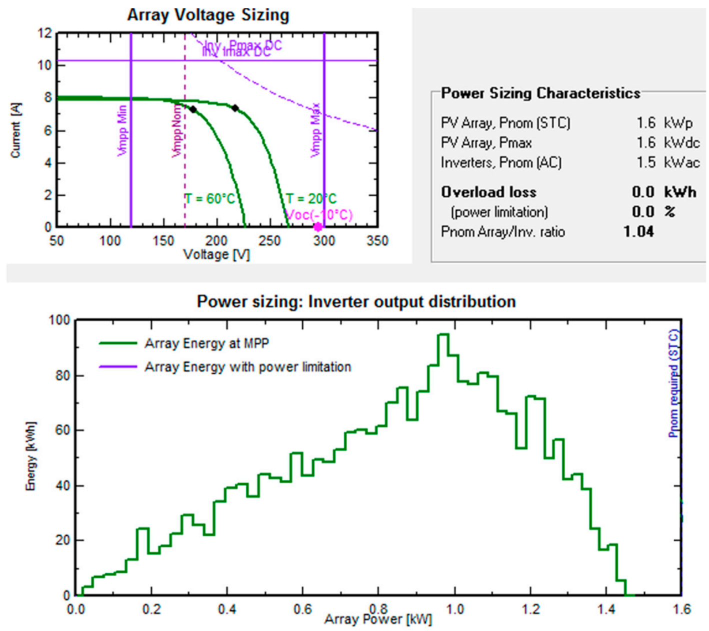

Figure 6. Prototype response curves (voltage and power sizing).

Figure 7 shows the distribution of the energy supplied to the network according to daily insolation on campus. The area with the highest concentration is between radiation levels of 5 and 7 kWh/m^2, which represent between 5 and 8 kWh supplied to the network or consumed locally per day.

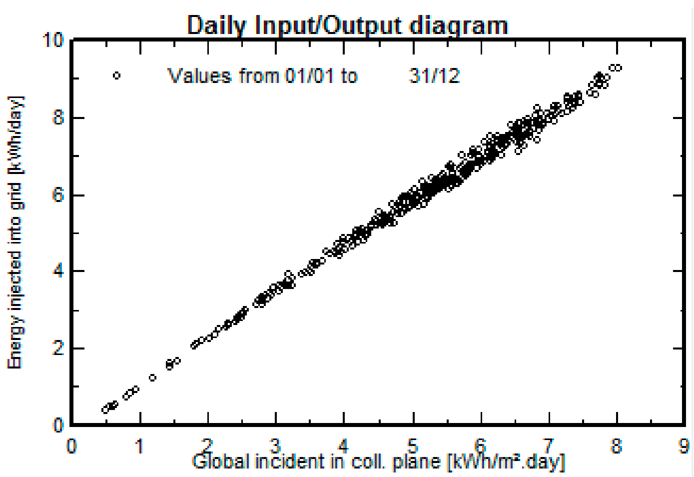

Figure 7. Correlation between energy injected into the grid according to daily insolation levels.

4.2. Energy Use and DES Assessment

After the initial tests were made and the extra equipment loads were simulated, the loads and the total energy requirement for a single prototype solar station were determined and are shown in Table 4. The audit also demonstrated that 6 h of artificial lighting (6 p.m.–12 p.m.) is enough to provide a secure and safe environment, reducing inefficiencies throughout the entire system.

Table 4. Service and energy requirements of the solar station.

Component	Power [W]	Daily Operational Hours [h]	Energy Consumption [Wh]
Elevated CCTV camera	10	24	240
Single Channel Video Encoder	5	24	120
Internal CCTV camera	5	24	120
Modem	5	18	90
Antenna	5	18	90
LED lighting	60	6	360
USB ports (x6)	60	8	480
TV (information)	100	24	2400
Total	250	-	3900

Considering that the entire available roof area will be installed with PV panels, it is estimated that the system's installed capacity will reach 191 kWp. Together with the irradiation measurements obtained (Section 3.3.1), an annual panel generation output (PVOUT) of around 1788 kWh/KWp was determined. The estimated monthly values for energy generation are presented in Table 5.

Table 5. Monthly solar radiation and power generation from the solar-based system.

Month	Average Radiation [kWh/m^2]	System Generation [kWh]
January	4.86	23,508
February	4.44	19,413
March	6.61	31,971
April	6.89	32,240
May	6.42	31,031
June	5.72	26,780
July	6.47	31,299
August	9.22	44,599
September	5.81	27,170
October	4.81	23,240
November	4.97	23,270
December	4.89	27,583

As mentioned, if the system is implemented at the campus scale, a rise in energy demand due to the new services is expected; however, the energy savings that the university will achieve by using the solar-based DES will offset the demand and provide extra savings. These outputs are presented in Table 6.

Table 6. Annual energy savings scenarios in CU-UNAM with solar stations.

Actual Stations Energy Use		Retrofitted Stations Energy Use [kWh]	Retrofitted Stations Solar Energy Generation [kWh]
12 h [kWh]	24 h [kWh]		
55,468	110,937	167,170	342,104

As it can be seen, the new stations represent up to a 3-fold increase in energy demand but with a surplus in energy generation. Table 7 shows the monthly surplus energy that the system can provide to the university network, with a consideration of the energy consumption and the difference with generation.

Table 7. Aggregated monthly energy consumption of the refurbished stations and surplus energy generation.

Month	Stations Energy Demand [kWh]	Surplus Energy [kWh]
January	14,198	9310
February	12,824	6589
March	14,198	17,773
April	13,740	18,500
May	14,198	16,833
June	13,740	13,040
July	14,198	17,101
August	14,198	30,401
September	13,740	13,430
October	14,198	9042
November	13,740	9530
December	14,198	13,385

The system can inject 174,934 kWh into the grid every year. Overall, the system represents an annual emissions reduction of around 130 t CO_2 depending on the use. Overall, the mitigation that could be achieved with the system is 0.04% of the total university emissions; nevertheless, it would be a first step and it provides a system that can be expandable to other facilities trying to achieve a net zero energy campus by 2050.

4.3. Economic Analysis

To demonstrate the financial viability of the proposed system, a discounted cash flow analysis under different scenarios was used. It was determined that the capital cost of the 191 kWp solar-based system is around US$ 210,100. Firstly, two different scenarios were analysed, one without any incentives and another one with incentives due to renewable energy generation (0.01 US$/kWh). For the price of electricity, the average price per kWh for the country is 0.083 US$/kWh. Both scenarios consider a discounted factor of 4% and an annual electricity price rise of 5%.

Without incentives, it has been calculated that the project's NPV (10 years) is around US$ 28,867 and the IRR is 5.95%, with a discounted payback of 9 years. Considering a small incentive for renewable generation, the NPV improves to US$ 57,139, with an IRR of 8.26% and a discounted payback of just below 8 years (Figure 8).

In terms of emissions, the project saves around 130 tCO_2e per year. Additionally, two carbon price scenarios were considered based on IEA forecasts [30]: a pessimistic scenario assuming that the carbon price goes from 24 to 30 US$/$tCO_2e$ between 2022 and 2032, and an optimistic one assuming it goes from 39 to 100 US$/$tCO_2e$ in the same timeframe. A low carbon price will improve the project's NPV to US$ 86,126 and IRR to 10.5%, while an optimistic scenario would achieve an NPV of US$ 125,032 and an IRR of 13%, reducing the project's payback to just over 6 years (Figure 9).

Results show that a DES has the capacity to be implemented at the campus scale under the right conditions. The emergence of new technologies such as PV panels, storage, and distribution systems, coupled with a higher global demand for this equipment, should allow the reduction of capital-cost-making projects more financially viable. Additionally, novel financial models, incentives, and ownership models need to be implemented to remove the financial burden from the end user. Currently, for solar incentives in Mexico, there are tax incentives for all buyers of solar panels, and according to the ISR Law Article 32 section XXVI, it is possible to deduct 100% of the initial investment in a single fiscal year, benefiting the taxpayer with up to 30% savings on the purchase of a solar-based system. However, an emissions trading system still needs to be implemented, considering the maximum limits of emissions that each industry will be able to generate. So, large-scale clean energy projects, such as the one presented in this study, will be able to sell their carbon certificates and reduce by halfway through the payback period.

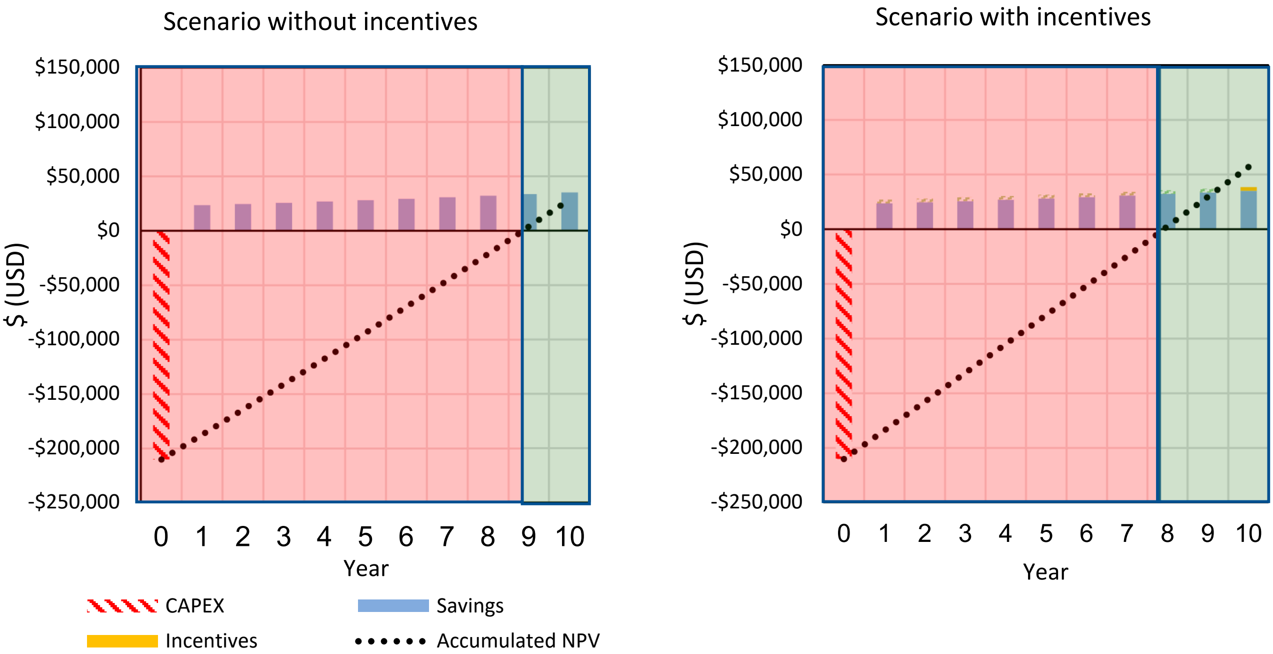

Figure 8. Cost−benefit scenarios for a project without (**left**) and with incentives (**right**) for renewable energy generation.

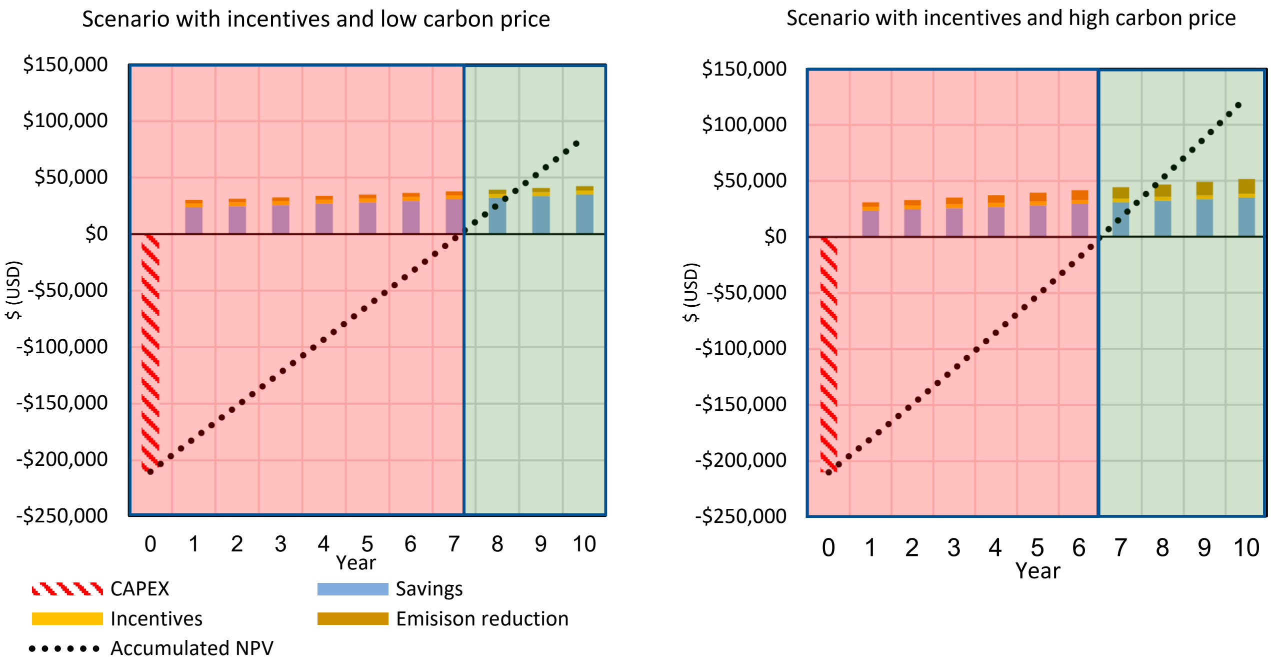

Figure 9. Cost−benefit scenarios for a project with incentives and an additional carbon incentive for low price scenario (**left**) and high−price scenario (**right**).

5. Conclusions

DESs in urban settings, especially large educational campuses, hold a great potential for building sector decarbonisation. This study has presented the design, testing, and assessment of a novel solar-based bus shelter prototype to be implemented on bus stations' roof areas equivalent to 1100 m^2 on a Mexican University campus. The system, apart from improving the experience of students and staff due to an increase in energy services, also has the capability of becoming an energy plus system by proving renewable energy to the campus grid. The assessment of the potential for its implementation was based on wide-scale site survey. An important result from the survey was understanding the energy demand of stations as well as providing us with an archetypal classification of the different bus stations and an understanding of the potential that each design holds in the wider DES. The survey also allowed the research team to identify current stations' operational problems, such as inefficient use of lighting, providing us with actions and recommendations for facility managers to minimise its impact as well as maximise the project's techno-economic potential when the new design is implemented.

Among the benefits highlighted in the project are the increase in services at the bus stations, such as TV news, charging docks, surveillance cameras, internet service, and lighting. Although this could represent a 3-fold increase in energy demand, with the available roof area, the system is comprised of a 191 kWp system, which in turn offsets the demand for the new energy services while being able to provide an extra 175 MWh to the university network. This represents a reduction of 130 t CO_2e, equivalent to a decrease of 0.04% in total emissions from energy use on campus. Nevertheless, the economic analysis shows that, for the system to be implemented and have more chances to succeed, there is a need of renewable generation and carbon reduction incentives to achieve a project with a relatively low payback time (<6 years).

For future work, the prototype is expected to be fabricated so that its suits every single archetype, while testing different solar and control technologies that would allow the system to increase generation values and improve its cost-effectiveness. Additionally, different storage subsystem configurations will be investigated to understand their technical and economic impact on project. Finally, the detailed analysis of the DES interconnection with the campus grid is needed as transmission losses and control methods for its minimisation need to be considered in further detail.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15103660/s1, Supplementary: Solar radiation measurements.

Author Contributions: Conceptualization, D.M.G. and G.C.-P.; methodology, D.M.G., I.G.K. and G.C.-P.; validation, D.M.G., I.G.K. and G.C.-P.; formal analysis, D.M.G., I.G.K. and G.C.-P.; investigation, D.M.G., I.G.K. and G.C.-P.; resources, D.M.G.; data curation, I.G.K. and G.C.-P.; writing—original draft preparation, D.M.G. and I.G.K.; writing—review and editing, I.G.K.; visualization, I.G.K.; supervision, D.M.G.; project administration, D.M.G.; funding acquisition, D.M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by DGAPA UNAM through a PAPIIT project with grant number 32-IT100120 and the APC was funded by Tecnologico de Monterrey Grants for Scientific Papers Publication.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data can be found as Supplementary File.

Acknowledgments: The authors acknowledge the support from Instituto de Ingeniería at the Universidad Nacional Autónoma de México. The authors also want to acknowledge the work from UNAM undergraduate student Alejandro David Crespo Lopez for his work in data collection and analysis.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. ARUP. *Distributed Energy Systems. Flexible and Efficient Power for the New Energy Era*; Research Report; ARUP: London, UK, 2016.
2. IEA. *Distributed Energy Resources for Net Zero: An Asset or a Hassle to the Electricity Grid?* Commentaries; IEA: Paris, France, 2021.
3. Horowitz, K.; Peterson, Z.; Coddington, M.; Ding, F.; Sigrin, B.; Saleem, D.; Baldwin, S.; Lydic, B.; Stanfield, S.; Enbar, N.; et al. *An Overview of Distributed Energy Resource (DER) Interconnection: Current Practices and Emerging Solutions*; NREL/TP-6A20-72102; Laboratory NRE: Golden, CO, USA, 2019.
4. Kazerani, M.; Tehrani, K. Grid of Hybrid AC/DC Microgrids: A New Paradigm for Smart City of Tomorrow. In Proceedings of the 2020 IEEE 15th International Conference of System of Systems Engineering (SoSE), Budapest, Hungary, 2–4 June 2020; pp. 175–180.

5. Amaral, A.R.; Rodrigues, E.; Gaspar, A.R.; Gomes, Á. Lessons from unsuccessful energy and buildings sustainability actions in university campus operations. *J. Clean. Prod.* **2021**, *297*, 126665. [CrossRef]
6. Yusoff, S.; Abu Bakar, A.; Rahmat Fakri, M.F.; Ahmad, A.Z. Sustainability initiative for a Malaysian university campus: Living laboratories and the reduction of greenhouse gas emissions. *Environ. Dev. Sustain.* **2021**, *23*, 14046–14067. [CrossRef]
7. UNFCCC. Kyoto Protocol to the United Nations Framework Convention on Climate Change. In Proceedings of the United Nations Framework Convention on Climate Change, Kyoto, Japan, 11 December 1997.
8. Mohd Zublie, M.F.; Hasanuzzaman, M.; Rahim, N.A. Feasibility Analysis of Solar Power Generation System for Office Building in Academic Institution. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1127*, 012039. [CrossRef]
9. Oyedepo, S.O.; Anifowose, E.G.; Obembe, E.O.; Dirisu, J.O.; Khanmohamadi, S.; Kilanko, O.; Babalola, P.O.; Ohunakin, O.S.; Leramo, R.O.; Olawole, O.C. Assessment of Economic and Environmental Impacts of Energy Conservation Strategies in a University Campus. In *Green Energy: Solar Energy, Photovoltaics, and Smart Cities*; Wiley: Hoboken, NJ, USA, 2020; pp. 441–468.
10. Escobedo, A. *Análisis y Modelación del Consumo de Energía Eléctrica en Edificios Universitarios con Base a Usos Finales y Parámetros Arquitectónicos*; UNAM: Mexico City, Mexico, 2009.
11. Escobedo, A.; Briceño, S.; Juárez, H.; Castillo, D.; Imaz, M.; Sheinbaum, C. Energy consumption and GHG emission scenarios of a university campus in Mexico. *Energy Sustain. Dev.* **2014**, *18*, 49–57. [CrossRef]
12. Seidl, R.; von Wirth, T.; Krütli, P. Social acceptance of distributed energy systems in Swiss, German, and Austrian energy transitions. *Energy Res. Soc. Sci.* **2019**, *54*, 117–128. [CrossRef]
13. Wolsink, M. Distributed energy systems as common goods: Socio-political acceptance of renewables in intelligent microgrids. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109841. [CrossRef]
14. Zhou, Z.; Liu, P.; Li, Z.; Ni, W. An engineering approach to the optimal design of distributed energy systems in China. *Appl. Therm. Eng.* **2013**, *53*, 387–396. [CrossRef]
15. Mavromatidis, G.; Orehounig, K.; Carmeliet, J. A review of uncertainty characterisation approaches for the optimal design of distributed energy systems. *Renew. Sustain. Energy Rev.* **2018**, *88*, 258–277. [CrossRef]
16. Kotsampopoulos, P.; Lagos, D.; Hatziargyriou, N.; Faruque, M.O.; Lauss, G.; Nzimako, O.; Forsyth, P.; Steurer, M.; Ponci, F.; Monti, A.; et al. A Benchmark System for Hardware-in-the-Loop Testing of Distributed Energy Resources. *IEEE Power Energy Technol. Syst. J.* **2018**, *53*, 94–103. [CrossRef]
17. Falke, T.; Krengel, S.; Meinerzhagen, A.-K.; Schnettler, A. Multi-objective optimization and simulation model for the design of distributed energy systems. *Appl. Energy* **2016**, *184*, 1508–1516. [CrossRef]
18. Perera, A.T.D.; Coccolo, S.; Scartezzini, J.-L. The influence of urban form on the grid integration of renewable energy technologies and distributed energy systems. *Sci. Rep.* **2019**, *9*, 17756. [CrossRef] [PubMed]
19. Wu, Q.; Ren, H.; Gao, W.; Weng, P.; Ren, J. Coupling optimization of urban spatial structure and neighborhood-scale distributed energy systems. *Energy* **2018**, *144*, 472–481. [CrossRef]
20. Roldán-Blay, C.; Escrivá-Escrivá, G.; Roldán-Porta, C. Improving the benefits of demand response participation in facilities with distributed energy resources. *Energy* **2019**, *169*, 710–718. [CrossRef]
21. Fonseca, J.D.; Camargo, M.; Commenge, J.-M.; Falk, L.; Gil, I.D. Trends in design of distributed energy systems using hydrogen as energy vector: A systematic literature review. *Int. J. Hydrogen Energy* **2019**, *44*, 9486–9504. [CrossRef]
22. Yan, B.; Somma, M.D.; Luh, P.B.; Graditi, G. Operation Optimization of Multiple Distributed Energy Systems in an Energy Community. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–6.
23. Li, L.; Zhang, S. Techno-economic and environmental assessment of multiple distributed energy systems coordination under centralized and decentralized framework. *Sustain. Cities Soc.* **2021**, *72*, 103076. [CrossRef]
24. Qiu, R.; Liao, Q.; Yan, J.; Yan, Y.; Guo, Z.; Liang, Y.; Zhang, H. The coupling impact of subsystem interconnection and demand response on the distributed energy systems: A case study of the composite community in China. *Energy* **2021**, *228*, 120588. [CrossRef]
25. Rossi, F.; Heleno, M.; Basosi, R.; Sinicropi, A. Environmental and economic optima of solar home systems design: A combined LCA and LCC approach. *Sci. Total Environ.* **2020**, *744*, 140569. [CrossRef] [PubMed]
26. Iria, J.; Huang, Q. Optimal Sizing of PV-Battery Systems in Buildings Considering Carbon Pricing. In Proceedings of the 2021 31st Australasian Universities Power Engineering Conference (AUPEC), Perth, Australia, 26–30 September 2021.
27. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories*; Prepared by the National Greenhouse Gas Inventories Programme; IGES: Tokyo, Japan, 2006.
28. Climate_Transparency. *Brown to Green: The G20 Transition towards a Low-Carbon Economy*; Climate Transparency: Berlin, Germany, 2017.
29. SENER. *Prospectiva del Sector Eléctrico (PRODESEN) 2016–2030*; SENER: Mexico City, Mexico, 2016.
30. IEA. *Carbon Pricing Can Help Put Clean Energy at the Heart of Stimulus Packages*; Commentaries; International Energy Agency: Paris, France, 2020.