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Photovoltaic potential of public buildings in a world Heritage city: The case of San Cristóbal de La Laguna (Canary Islands, Spain)

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A R T I C L E I N F O

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A B S T R A C T

Solar photovoltaic energy is increasingly positioned as an excellent renewable energy source to be implemented in energy communities. However, studies on photovoltaic potential are still required in order to enhance the clean energy transition in energy dependent systems, such as oceanic islands. This work is a study of photovoltaic potential of public building roofs in the World Heritage city of San Cristóbal de La Laguna in Tenerife (Canary Islands). The buildings selected for the study are sports centres, educational centres and civic centres, considering optimum and maximum production scenarios. The results showed the electricity generation capacity of each building, with 8811 and 861 MWh capacity for the maximum and optimum scenarios, respectively. In the optimal scenario, 56% of energy would be generated, of which 31% would be consumed on site, and the remaining 25% would be sent to the grid. The main difference is that in the case of optimal photovoltaic systems, economic profitability criteria take precedence, while in the case of maximum photovoltaic systems, the environmental benefits in terms of CO_2 emissions into the atmosphere increase considerably. In the latter case, CO_2 emissions are reduced by 771%, compared to 75% in the case of optimal photovoltaic systems.

1. Introduction

Self-consumption of electrical energy from photovoltaic (PV) sources consists of producing electrical energy from sunlight by means of the photovoltaic effect used directly by a consumer who is connected to the general electricity grid [1]. In this way, the consumer becomes an energy generator. The main purpose of this photovoltaic generation system is to self-consume solar electric energy at the moment it is being generated, in order to avoid buying energy from the grid, and to reduce the CO_2 emissions associated with the production of imported energy from the grid [2]. Self-consumption involves situations where the photovoltaic generation system can produce more electricity than the consumer needs at a given moment; in this case, energy would be fed back into the grid.

In the self-consumption with surplus mode, the consumer uses the energy from the self-consumption installation when it is needed, and energy can be extracted from the grid at times when the produced energy is not sufficient [3]. When the energy produced from the self-consumption installation is not totally consumed, the remaining energy produced can be injected into the grid. In each billing period, the invoice issued by the supplier will compensate the cost of the energy purchased from the grid with the surplus energy, valued at the average price of the hourly market or at the price agreed with the supplier, applying the applicable taxes [4]. Under no circumstances may the result be negative.

Under the European Green Deal framework, the Spanish Ministry for Ecological Transition aims to promote the creation of energy communities that, through generation of energy on the roofs of public buildings, using photovoltaic panels, provide energy coverage to those areas with the highest rate of energy poverty [5]. The main benefits of energy communities include providing citizens with easy and fair access to local renewable energy resources, facilitating integration of renewable energy into the system, local job creation, and social cohesion and equity [6]. In addition, the Spanish government has created an Energy Roadmap,

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whose target scenario for the year 2030 proposes that 9 GW of self-consumption will be achieved, with 122 GW of renewable generation, of which 39 GW will be photovoltaic [7]. Within the different types of self-consumption, photovoltaic technology is one of the most widely used, mainly due to its economic cost and its ease and possibility of assembly [8]. Photovoltaic solar energy is inexhaustible and its availability is high in the Canary Islands [9]. Moreover, the cost of solar panels is becoming increasingly cheaper, and this trend is expected to continue in the coming years [10].

Under Spanish law, photovoltaic self-consumption initiatives have been promoted by a recent legislation, which regulates the administrative, technical and economic conditions for the self-consumption of electricity [11]. This, together with the fact that module prices have now fallen to as low as 0.2 and 0.3 euros/Wp for self-consumption installations larger than 50 kW, is promoting the creation of energy communities in Spain [12].

Furthermore, according to a 2007 study, the average radiation on the island of Tenerife for the city of Santa Cruz de Tenerife was 2918 kWh/m^2/year [13]. This value has been maintained over the years, however, due to climate change this value is expected to change. Indeed, scientists in the Canary Islands have studied the high photovoltaic potential of the archipelago. However, in a context of climate change and a future rise in temperatures, the way panels work will change, especially for the RCP8.5 scenario [14]. This means that they will be more effective in winter than in summer, as the winters will be warmer but in the summers the temperatures will be too high, lowering the efficiency of the panels [15]. Additionally, solar energy in the Canary Islands has a global horizontal irradiation potential of 1800 equivalent sunshine hours per year (ESH/year), which can be increased to 2250 ESH/year if the photovoltaic panels are placed at a fixed slope angle of 25° [16].

One of the advantages of incorporating solar panels on the roofs of buildings is that the renewable installation itself is incorporated and its surplus can be passed on to neighbours in the area. Nevertheless, the aesthetic impact of rooftop panels is sometimes seen as undesirable, and some countries have stringent procedures in place before approving permission to install panels [17]. However, in the case of La Laguna in Tenerife, despite being a World Heritage City, the City Council prioritises the Ecological Transition over the design of the roofs, and has launched this study of photovoltaic potential in the city's public buildings, because buildings are responsible for 40% of the world's energy consumption [18].

In addition, due to the World Heritage city conditions, it is easier to incorporate the photovoltaic panels on the roofs, rather than modifying the façades and converting them into solar façades, which would be a much more disruptive task on existing buildings [19].

On the other hand, the progressive decrease in the price of photovoltaic panels over the last decade has allowed solar energy in buildings to position itself as an increasingly economically advantageous option [20]. This makes the installation of panels more affordable for individuals and institutions, reducing the need for public incentives to do so.

1.1. Study area

The Canary Islands are an archipelago in Spain that lies approximately 100 km off the coast of Africa (Fig. 1). It is an outermost European region consisting of eight islands, with a subtropical climate and high tourism [21]. It is precisely the pressure of tourism and the high local population that demands an adequate energy management, to enable the islands to achieve the Ecological Transition required by the current climatic situation [39].

Although one of the islands of the Canary archipelago is leading the way in sustainable energy production, as is the case of the island of El Hierro with its Gorona del Viento Project [22], where a high percentage of the island's energy demand is covered by hydro-wind energy, the rest of the islands are still highly dependent on fossil fuels [38].

This situation, which is exacerbated by the remoteness and insularity of the islands, is a serious obstacle to be overcome when it comes to reducing CO_2 emissions into the atmosphere in the Canary Islands [23]. For this reason, the Canary Islands Government is committed to the creation of energy communities, which serve to promote the production of energy through renewable sources, mainly photovoltaic [5]. These communities could be created in all the cities of the archipelago, with the help of the local administrations. In this article we would like to highlight the example of the city of La Laguna, one of the most populated cities on the island of Tenerife, which is also a World Heritage City [39].

Currently, on the island of Tenerife, the photovoltaic power in self-consumption regime was 2.69MWp in 2019, where the cities of La Laguna and Santa Cruz de Tenerife were the ones that contributed the most to reach this figure [24].

Therefore, this study evaluates the technical and economic feasibility of photovoltaic power plants in 70 public buildings (14 sports centres, 14 educational centres and 42 civic centres) within the municipality of San Cristóbal de La Laguna, Tenerife, for the year 2021. The electrical energy generated by the photovoltaic installations is mainly intended to be self-consumed by the infrastructures of the centres themselves. The document is organised as follows: the Materials and Methods section explains the calculation applied for two different systems, the maximum and the optimum; the Results section analyses the electricity consumption of each of the buildings that form part of the study and compares it with the production of each system, as well as presenting the savings in CO_2 emissions to the atmosphere when using the photovoltaic

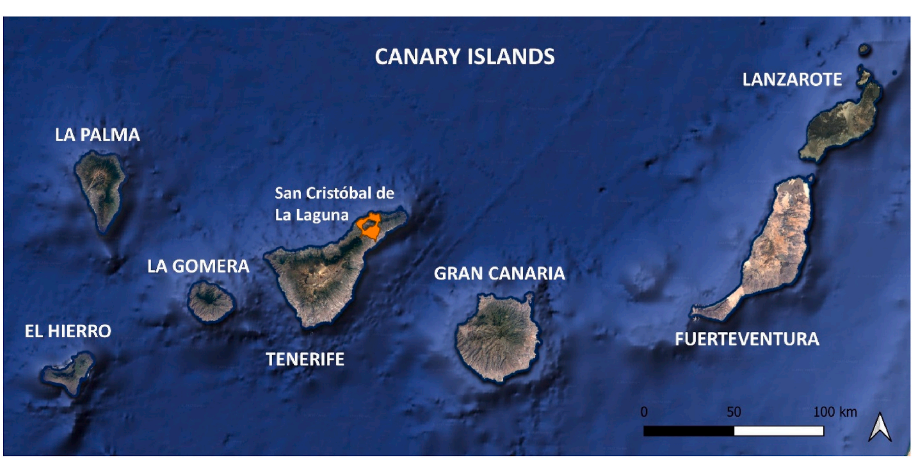

Fig. 1. Canary Islands (Spain). The city of La Laguna (whose coordinates are 28.4853° N 16.3201° W) has been highlighted, as it is the place where this study is focused.

installation; finally, the Conclusions section highlights the advantages of both systems and what it means for the Canary Islands archipelago, so dependent on fossil fuels, to opt for renewable energies in environmental terms.

2. Materials and methods

The calculation method used for the assessment of photovoltaic potential consisted of simulating photovoltaic generation with the application developed by Dobontech, called *Dobontech PV Potential Calculator v1.7* [25]. This application calculates the energy, environmental and economic performance of the photovoltaic installation in self-consumption. The application performs the calculations with the consumption load curve of the installation and with the applicable electricity tariffs to each hourly period. The assessment was based on the following tasks: i) Analysis of the roofs available for the installation of photovoltaic modules and adjacent elements that could cause shading in the photovoltaic systems, using computer graphics and orthographic maps, ii) Analysis of the electricity bills of each of the installations, iii) Obtaining the hourly load curve of each of the installations, iv) Analysis of the installable photovoltaic potential in each of the installations, using specific design software, taking into account separations by shadows and limiting construction elements, v) Simulation of photovoltaic generation in self-consumption mode, using simulation software with the data of the hourly load curve and the data of solar radiation and ambient temperature of the area, vi) Determination of the autarchic quota (solar energy self-consumed at the time it is generated), vii) the savings in CO_2 emissions into the atmosphere of each of the proposed installations, and viii) Compilation of the years of construction of each building and the building regulations applied to each of them.

In this article, individual PV self-consumption with surpluses has been analysed, and two scenarios have been proposed.

a) Self-consumption of the maximum PV system: In this case, photovoltaic potential has been analysed, occupying all of the available roofs and spaces with photovoltaic modules, without significant losses due to shading. This case is referred to as the *maximum system.*
b) Self-consumption of the optimal PV system: In this case, the proposed PV system would provide the energy mainly to satisfy the building's daytime consumption, as much as possible, without producing excessive energy surpluses. To this end, the electrical load curve (electricity consumption) of the building and the associated infrastructures have been considered, limiting the surplus energy to no more than 36% of the energy produced annually. In some cases, this means installing very little photovoltaic power, so a minimum of 3kWp of installed power was established. This has been termed the *optimal system.*

The surpluses from this production can also be compensated in the electricity supply bills, sold to the electricity system or shared with other own or third-party infrastructures. The maximum photovoltaic potential has been analysed, occupying the total available roofs and spaces with photovoltaic modules without significant losses due to shading - *maximum system* (Fig. 2). Additionally, the optimum photovoltaic potential has been analysed, minimising the discharge of electrical energy to the grid and maximising the daytime self-consumption of the photovoltaic energy produced - *optimal system* (Fig. 3).

In order to calculate the load curves (Fig. 4), the annual consumption of the available electricity bills and the standardised load curve were used. In this case, three types of curves have been established, according to the type of building analysed: a) Sports Centres: A typical load curve has been assumed for establishments with energy consumption 7 days a week, mainly during the evening-night; b) Educational Centres: The load curve has been obtained from the annual average consumption of schools, compiling load curves from schools, from previous work carried out by Dobontech and c) Civic Centres: A typical load curve has been assumed for establishments with energy consumption 6 days a week, mainly during business hours.

The overall characteristics of the maximum system and the optimal system are shown in Table 1 in terms of installed capacity, PV electricity production, autarchic share, self-consumption share, energy surpluses

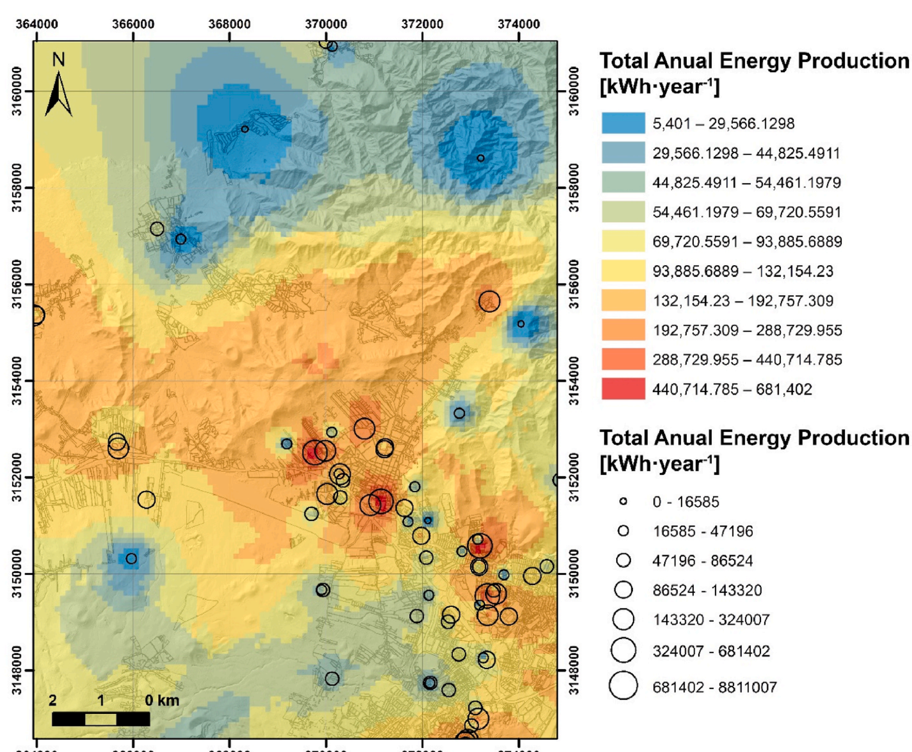

Fig. 2. Photovoltaic production on the roofs of the buildings selected in the study (maximum system) for San Cristóbal de La Laguna (Canary Islands).

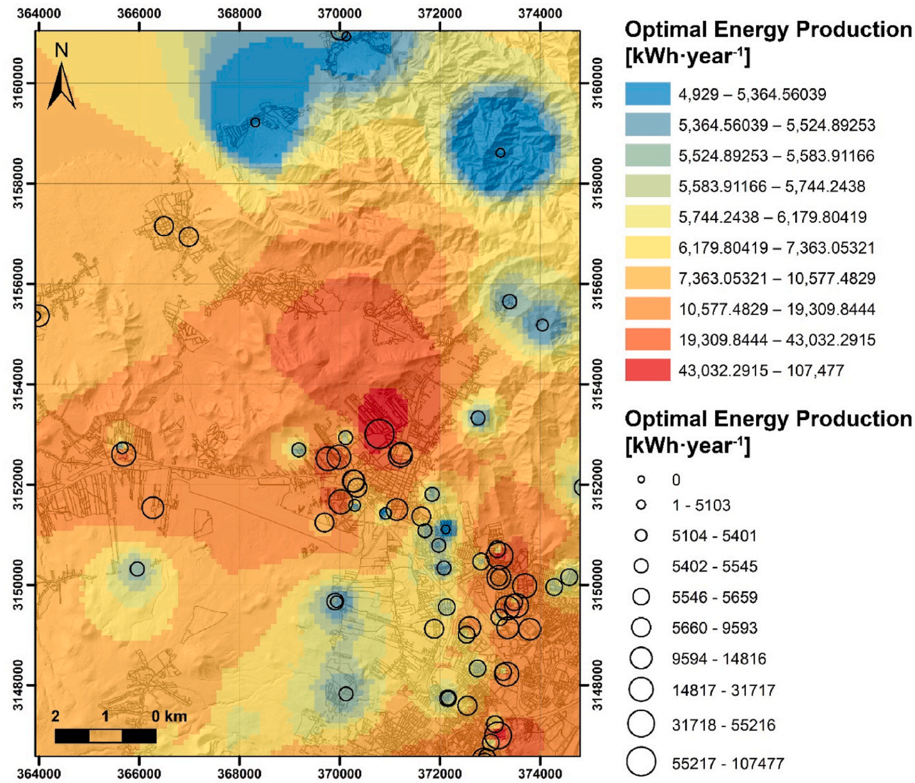

Fig. 3. Photovoltaic production on the roofs of the buildings selected in the study (optimal system) for San Cristóbal de La Laguna (Canary Islands).

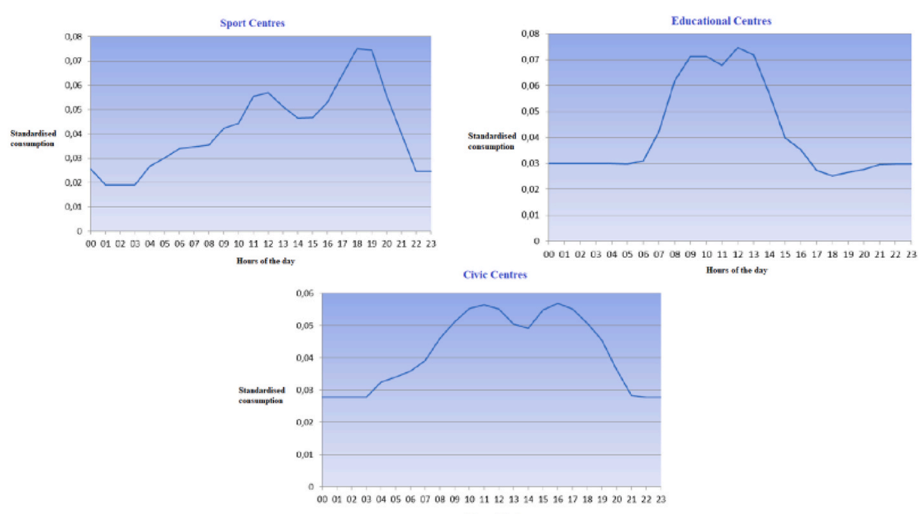

Fig. 4. Normalised average annual load curves for the centres studied.

Table 1
Overall characteristics of maximum and optimal photovoltaic systems.

Facility	Maximum system	Optimal system
Total Installed Photovoltaic Capacity	4926 kWp	478 kWp
Solar Production	8811 MWh	861 MWh
Total Autarchic Quota	58,00%	42,00%
Total Self-consumption Quota	771,00%	75,00%
Energy surpluses	93,00%	44,00%
Avoided CO_2 emissions to the atmosphere per *year*	6836 Tm CO_2	691 Tm CO_2

and CO_2 emissions not released to the atmosphere on an annual basis.

In order to be able to evaluate the photovoltaic potential at each location, the meteorological data of these locations must be known, in particular the solar radiation and ambient temperature data. To obtain this meteorological data, the *PV Performance Tool"* of *PVGIS* (Photovoltaic Geographical Information System) was used [26]. The meteorological database used within this tool was PVGIS-SARAH. This database consists of a 0.05° × 0.05° grid and has been obtained using the CM SAF algorithm for Africa. This database contains data from 2005 to 2016. To determine the base year of meteorological data to be used, the TMY (Typical Meteorological Year) was also downloaded from the same tool for the period 2005–2016 in *San Cristóbal de La Laguna*, in a location without significant shadowing effects due to adjacent orography and in which horizon contour shading has been disabled.

The TMY data are only available for global horizontal radiation, and it is not possible to obtain the TMY radiation for different inclinations and orientations in the tool [27]. Since, in this study, it was interesting to obtain solar radiation data for the different inclinations and orientations of the photovoltaic modules to be installed at each location, we proceeded to calculate the year that is closest to the TMY from the set of data available from 2005 to 2016. The year that was closest in the different locations was 2005. Therefore, the hourly data for 2005 was used as the base meteorological year for all locations throughout the study.

Also, for the study, crystalline silicon photovoltaic modules of 380 Wp each and with module dimensions of 1.776 m $\times$ 1.052 m have been utilized. These dimensions have been considered because they are the standards frequently used by manufacturers of 120-cell crystalline silicon modules (half cell). The 380Wp output is also high performance within this standard format. For PV inverters, a European inverter efficiency of 97% with Maximum Power Point Tracking (MPPT) has been considered [28]. The remaining parameters used in the PV production calculations are as follows: i) Dirt losses: 2.00%, ii) DC wiring losses: 1.50% and iii) AC wiring losses: 1.50% [29].

3. Results and discussion

In analysing the electricity consumption of the different facilities, it can be seen that the annual energy consumption is very biased. Among the different types of facilities, educational centres and some sports centres have the highest consumption, in contrast to the vast majority of civic centres, which have low annual consumption values. In the case of the latter, the low consumption is due to the effect that COVID-19 has had on this type of facility, the vast majority of which are temporarily closed (Fig. 5).

The proposed photovoltaic installations have a total installed capacity of 4909.98 kWp in the case of maximum systems or 478.42 kWp in the case of optimal systems (Table 2), resulting in a solar energy production of 8811 MWh and 861 MWh respectively. A decrease in CO_2 emissions also occurs, which can be seen in Fig. 6.

Overall, of the total energy consumed, 95% is produced by the photovoltaic systems in the case of the maximum system, where 7% of the energy is consumed in the installations themselves at the time the solar energy is generated, and the remaining 88% is solar energy injected into the grid. In the case of the optimal system, the percentage of energy produced by the photovoltaic systems drops to 56%, with 31% of the energy being consumed in the installations themselves at the time the solar energy is generated, and the remaining 25% being solar energy injected into the grid.

Due to its World Heritage status and the consequent increase in tourism and local population, the city of La Laguna has been concerned for years about its ecological transition and its commitment to sustainability (Santamarta et al., 2022).

A study was performed in the Canary Islands on the photovoltaic potential capable of being generated in the archipelago [30]. This study is based on calculating the amount of roofs available and, through a series of scenarios based on the surface area actually available, and on the basis of reduction in space due to multiple factors. The scenario was chosen in which 39.1 km^2 of space is available to include photovoltaic energy. With this surface area, a large part of the archipelago's electricity demand could be covered.

The main motivation for promoting the creation of energy communities in the Canary Islands is, precisely, insularity. The insularity and the lack of development of renewable energies in the Canary Islands means that the Islands' dependence on fossil fuels is very high [9]. Hence the importance of promoting the production of renewable energies for the Ecological Transition, by increasing independence and ensuring supply [31]. It is important to highlight that political power must be involved in and promote these initiatives, as one of the main barriers that energy communities may face is the lack of political support [32], which can hinder these projects and, therefore, the sustainable development of the community.

Furthermore, although on this occasion the study has been conducted for photovoltaic installation because of all the advantages mentioned above, it should be noted that energy communities can benefit from any renewable production. In the case of the Canary Islands, it would be interesting to explore self-generation through geothermal energy [33]. Similar studies on geothermal polygeneration have been carried out in Italy, specifically in Naples, giving very good results in this respect [34].

When considering energy sufficiency on the islands, an issue that is becoming increasingly important in the Canary Islands, various energy sources can be considered. In the case of the island of El Hierro, there is a study [35] that shows the viability of the hydro-wind energy system, which saves 98.7 GWhp/y, followed by photovoltaic energy, which saves 16.8 GWhp/y on the island.

Moreover, this new energy paradigm on the islands is positioned as an employment niche. Specifically, a recent study undertaken on an

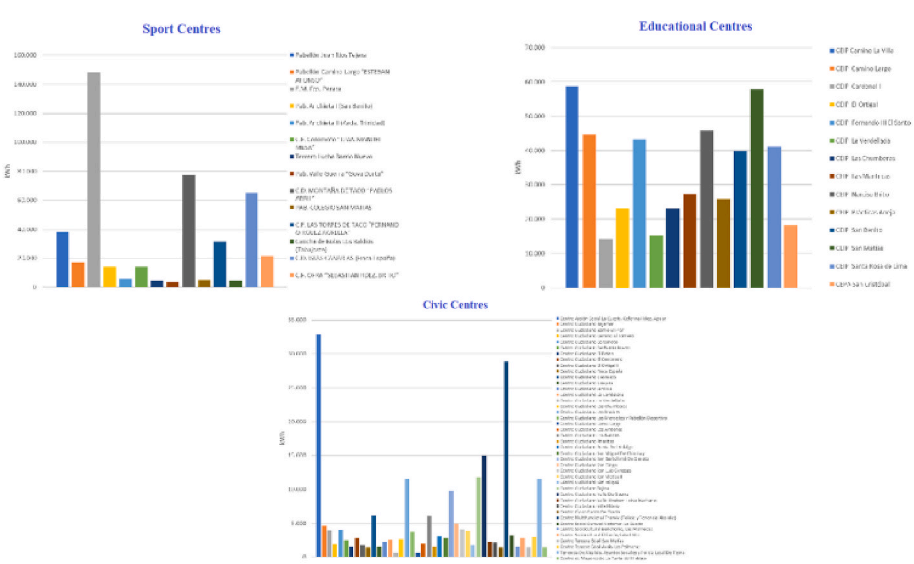

Fig. 5. Annual energy consumed in each type of installation studied.

Table 2
Hired Power, Photovoltaic Power and Saving Annual CO_2 emissions at each location.

			Maximum System	Optimal system	Savings Annual CO_2 emissions ($kgCO_2$/year)
Type of facility	Facility	Hired Power (kW)	Photov. Power (kWp)	Photov. Power (kWp)	
Sport Centres	Pabellón Juan Ríos Tejera	9	336.70	15.20	493,376
	Pabellón Camino Largo	13.15	70.68	6.84	93,345
	E.M. Fco. Peraza	200	132.24	59.28	202,656
	Pabellón Anchieta I	13.15	138.32	5.70	185,614
	Pabellón Anchieta II	13.15	138.32	3.04	185,721
	C.F. Coromoto	42.24	31.16	5.32	43,497
	Terrero Lucha Barrio Nuevo	13.15	77.52	3.04	103,81
	Pabellón Valle Guerra	13.86	167.20	3.04	205,441
	C.D. Montaña de Taco	48.32	129.20	31.16	178,123
	Pabellón Colegio San Matías	7.80	126.54	3.04	167,172
	C.F. Las Torres de Taco	58	65.74	12.16	92,174
	Cancha de Bolas Los Baldíos	3.94	40.66	3.04	54,951
	C.D. Finca España	68	392.16	26.60	528,768
	C.F. Ofra	75	76	8.36	104,522
Educational Centres	Camino La Villa	36.70	104.50	17.48	142,935
	Camino Largo	30	80.18	12.92	111,217
	Cardonal I	19.10	35.72	4.18	48,437
	El Ortigal I	26.30	57.76	6.84	74,165
	Fernando III El Santo	25	222.30	12.54	367,64
	La Verdellada	3.80	57.76	4.18	79,195
	Las Chumberas	38	62.70	4.18	87,676
	Las Manetcas	3.30	116.28	7.60	151,078
	Narciso Brito	30	184.68	14.44	251,429
	Prácticas Aneja	30	286.14	7.60	525,831
	San Benito	40	131.48	11.40	180,426
	San Matías	35	179.74	16.72	249,873
	Santa Rosa de Lima	30	134.90	12.16	145,625
	San Cristóbal	10.6	22.80	5.70	31,178
Civic Centres	La Cuesta	69	12.16	12.16	17,259
	Bajamar	7.61	4.56	3.04	5861
	El Pilar	5.70	14.44	3.04	20,557
	El Tornero	5.50	13.30	3.04	18,728
	Coromoto	5.30	38.76	3.04	53,188
	Barrio Nuevo	11.95	19	3.04	24,958
	El Batán	7.89	6.84	3.04	8606
	El Centenero	7.90	28.12	3.04	39,684
	El Ortigal II	5.75	12.54	3.04	17,75
	Finca España	7.80	19.76	3.04	28,124
	Guamasa	5.70	53.20	3.04	70,067
	Guajara	9.20	8.74	3.04	33,96
	Jardina	1.20	3.04	3.04	4191
	La Candelaria	11.50	54.34	3.04	77,833
	La Verdellada	6.16	9.88	3.04	12,870
	Las Chumberas	8.31	36.48	3.04	58,139
	Las Madres	10.50	42.94	4.56	57,624
	Las Mercedes	5.50	121.60	3.04	169,068
	Lomo Largo	3	17.48	3.04	24,300
	Los Andenes	13.10	28.12	3.04	38,776
	Los Baldíos	5.50	39.52	3.04	27,612
	Piteritas	9.20	16.72	3.04	23,787
	Punta del Hidalgo	17.32	13.30	3.04	16,721
	San Miguel de Chimisay	23.60	45.22	3.04	61,757
	San Bartolomé de Geneto	13.10	29.64	3.80	41,630
	San Diego	13.94	25.08	3.04	35,464
	San Luis Gonzaga	13.30	29.26	3.04	40,681
	San Matías II	7.80	53.96	3.04	64,913
	San Roque	5.50	26.22	3.04	32,624
	Tejina	45	11.40	4.94	14,605
	Valle de Guerra	32	66.12	6.46	81,523
	Valle Jiménez	7.80	28.12	3.04	40,018
	Villa Hilaria	10.52	30.02	3.04	41,869
	Barrio de Gracia	11.50	37.62	3.04	52,359
	Multifuncional Tranvía	124	51.30	11.40	73,555
	Vistamar	13.86	28.50	3.04	40,756
	Benchomo	10.35	15.20	3.04	21,060
	El Rocío	9.20	33.82	3.04	48,297
	San Matías	4.40	39.90	3.04	57,001
	Las Palmeras	9.58	24.70	3.04	35,434
	Tenencia de Alcaldía	7.80	36.10	4.94	45,940
	Centro de Mayores. La Punta	13.86	53.58	3.04	67,143
Total		**1554.26**	**4909.98**	**478.72**	**6,836,344**

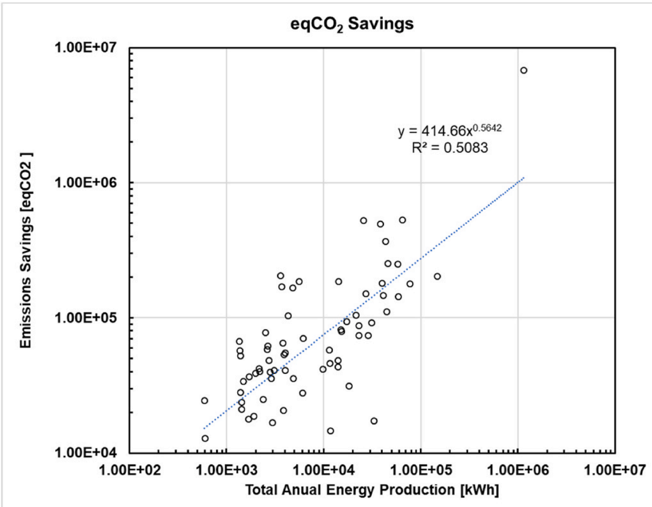

Fig. 6. Savings in CO_2 emissions linked to photovoltaic production. The higher the photovoltaic production, the greater the emission savings.

island in Croatia indicates that approximately 18 new jobs are created per year for 1 MW of installed PV [36]. In addition, permanent local jobs can be generated, in tasks linked to maintenance, in this case 0.3 per MW of installed PV, according to Dorotic et al.

Another study linked to energy communities highlights the importance of involving the local community, scientists as well as companies in the whole process, in order to achieve greater success in the implementation of these measures in the long term, and to facilitate their replicability in other areas [37].

4. Conclusions

In both optimal and maximum PV systems, the environmental benefits are very attractive. Likewise, savings in CO_2 emissions into the atmosphere are greater in the case of maximum photovoltaic systems than in the case of optimal photovoltaic systems (CO_2 emissions into the atmosphere are reduced by 771% in the first case compared to 75% in the case of optimal photovoltaic systems). In other words, the maximum system is a sink for CO_2 emissions from the point of view of energy consumption (it saves more CO_2 than it produces).

With regard to the energy produced, if we focus on the optimal system, which is more realistic and less productive than the maximum, we would still have a scenario where approximately 30% of the energy generated would be consumed by the installations studied and 25% would be returned to the grid. Therefore, it is worth betting on this type of system that allows sustainable development of the communities, especially in those areas as dependent on the exterior as the Canary Islands archipelago. On the other hand, although economic data is not presented in this article, an economic estimate was made for both systems. It is noteworthy that the maximum system has an initial investment 15 times higher than the optimum system, and has a payback period 1.6 times longer. However, for both systems, the amount of money saved annually is equivalent to the initial investment required.

Finally, the study can be complemented by feasibility studies on geothermal energy, which can be easily implemented in volcanic areas, allowing the Canary Islands to become energy independent.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Author contributions

Conceptualization, Juan C. Santamarta; methodology, Noelia Cruz-Pérez, Juan C. Santamarta, Alejandro García-Gil; software, Alejandro García-Gil; validation, Rubén Fuentes Beltrán; investigation, Noelia Cruz-Pérez, Jesica Rodríguez-Martín; resources, Rubén Fuentes Beltrán; writing—original draft preparation, Noelia Cruz-Pérez, Jesica Rodríguez-Martín. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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