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Feasibility Assessment of Photovoltaic Systems to Save Energy Consumption in Residential Houses with Electric Vehicles in Chile

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Abstract: Distributed local generation from photovoltaic (PV) systems are gaining more interest, due to reduced component costs, as well as becoming a great solution for the charging of electric vehicles (EV) and the protection of the electrical grid infrastructure. This work aims to size and analyze the economic feasibility of a PV system to support the energy demand presented by the daily charge of an EV, either with or without a battery energy storage system (BESS), for a residential home in Viña del Mar, Chile. Eight different scenarios are dimensioned, with and without BESS, varying the PV installed power according to the surface available on the roof, and the results are supported by using the PVsyst software to determine the energy generated, self-consumption, and the energy both injected and received from the grid. Five different cases are also dimensioned, varying the storage capacity of the BESS, to analyze how profitability varies in each case. The real data on energy consumption, and prices of electricity both injected and received from the grid, were collected from the electricity bills and the distribution company, respectively. The sizing of both the PV panel array and the BESS was performed based on the highest average daily consumption throughout the year. Meteorological data, such as global irradiation and environmental temperature, are obtained from the Explorador Solar platform. Lastly, PV systems with BESS do not achieve profitability; however, for BESS with lower storage capacities, it would be possible to increase its profitability to acceptable ranges. Photovoltaic systems without BESS present better levels of profitability since a lower capital expenditures is required and the payback is shorter. This work contributes to improve the use of solar energy and provides a guide to extend the work to different regions of Chile.

Keywords: residential houses; photovoltaic systems; battery energy storage systems; electric vehicles; PVsyst

Citation: Salles-Mardones, J.; Flores-Maradiaga, A.; Ahmed, M.A. Feasibility Assessment of Photovoltaic Systems to Save Energy Consumption in Residential Houses with Electric Vehicles in Chile. *Sustainability* **2022**, *14*, 5377. https://doi.org/10.3390/su14095377

Academic Editors: Domenico Mazzeo and Luis Hernández-Callejo

Received: 17 March 2022
Accepted: 26 April 2022
Published: 29 April 2022

1. Introduction

There is no doubt that conventional energy sources such as fossil fuels are limited resources with a strong impact on greenhouse gas emissions and the environment. In many countries, most electric generations are still produced from large plants to supply the energy demand [1–3]. In January 2022, the installed generation capacity in Chile corresponded to 57.1% from renewable sources (hydraulic, solar, wind, biomass, and geothermal) while 42.9% from thermal sources (coal, natural gas, and oil). The most significant increase has been in solar photovoltaic and wind technologies, which have increased drastically, increasing from 0.5% in 2011 to 21.6% in 2021 [4,5].

Renewable energies have been gaining more interest since they can be implemented on a smaller scale through distributed generations at a residential level [1,2]. However, the grid integration of electric vehicles (EV) will present a future challenge for the grid infrastructure. This will be due to the mission of supplying the significant increase in energy demand produced by replacing internal combustion vehicles with EVs [6,7]. At the same time, the distribution power system must be redesigned to withstand the electrical stress produced by power peaks presented by the charging of EVs which could cause severe damage to the grid infrastructure by producing power outages or prolonged blackouts. Among the possible solutions for this challenge is the local PV generation [5], which allows to save the energy demand and reduce the costs associated with the redesign and modification of the grid infrastructure. In this way, a series of solutions have been developed to enable end-users to manage their energy consumption at a residential level [3]. This can be done using emerging technologies, such as internet-of-things (IoT), artificial intelligence (AI), and new information and communication technologies (ICT), along with new smart devices that allow monitoring the different states of each appliance [1,2].

The applications of distributed generations at a residential level [8–21], including on-grid or off-grid systems, allow to save energy consumption from the grid, avoid power peaks, reduce energy consumption at critical times, and reduce electricity tariff costs. In the case of Chile, the increase in electromobility is estimated to be imminent due to the policies and trends of reducing polluting gas emissions [7]. For this reason, it is necessary to design solutions that allow meeting this great increase in energy demand and feeding EV charging points, either through EV charging stations or residential chargers. In the latter case, the price of electricity at the residential level is considered a determining economic factor, along with the fines applied when the consumption or power limits established by the electricity distribution company are exceeded. On the other hand, much of the electrical grid infrastructure in the country was not designed and is not prepared to withstand the new operating conditions.

It is not easy to establish the most optimal PV design due to different factors such as consumption level in the house, weather conditions such as global irradiation and local temperature, available surface space which can be on a roof or patio, financial budget, expectations of return on the user's investment, and prices of electricity both coming from and injected into the grid. Table 1 shows a comparison with previous research work for smart home/building with distributed generations including PV, wind turbines, battery energy storage system (BESS), and EVs. Additionally, the acquisition of batteries for PV systems with BESS requires an accurate decision of the user, as a unique dimensioning is necessary at the beginning of the project since later it is not always possible to modify [9]. On the other hand, it also presents a high investment for the initial deployment and the replacement of components of the PV system. In this way, it is necessary to determine the profitability of the design unless it represents an essential need, such as in an off-grid PV system, to protect the grid infrastructure or feed critical equipment.

Table 1. Comparison with previous research work for smart home/building with distributed generations including PV, wind turbines, BESS, and EVs.

Ref.	Location	Photovoltaic System	Battery Storage System	Electric Vehicle	Wind Turbine	Data Collection
[9]	Qatar	Yes	Yes	No	No	Yes
[12]	Ecuador	Yes	No	No	No	No
[13]	Chile	Yes	No	No	No	Yes
[14]	United Kingdom	No	No	No	No	Yes
[15]	Slovenia	Yes	Yes	No	No	No
[16]	United States	Yes	Yes	Yes	No	Yes
[17]	South Korea	Yes	No	Yes	No	Yes
[18]	Sweden	Yes	No	Yes	No	Yes
[19]	Netherlands	Yes	No	Yes	No	Yes
[20]	Spain	Yes	Yes	Yes	Yes	No
[21]	Spain	No	No	Yes	No	No
[22]	Chile	No	Yes	No	Yes	Yes
Current work	Chile	Yes	Yes	Yes	No	Yes

This work aims to design and size a PV system for a smart house, studying the possibility of implementing a BESS to supply the energy consumption of appliances and the charging of an EV. The main contributions are:

- Study the state of the art for energy efficiency at the residential/grid level and compare different case studies for the implementation of PV systems that aim to save the energy consumption of homes/buildings with/without EV charging;
- Collect data from the selected site for the case study, including real energy consumption, meteorological information, solar irradiation, and technical specifications of the selected EV;
- Calculate the capacities of the equipment and its subsystems for the selection of the required technology for the PV system;
- Determine the available surface space required for the installation of the PV system.

2. Related Work

2.1. Smart Homes and Microgrids

The development of smart homes has encouraged the implementation of home energy management systems (HEMS) [10]. Generally, these systems use smart devices, such as appliances, sensors, and bidirectional meters which are capable of monitoring the consumption in real-time, local generation, and variations in the price of energy. The HEMS should be able to make quick decisions that are part of the demand response regarding the energy demand. In a critical situation, the energy distribution company may ask the customer to reduce their energy consumption to alleviate the over demand of the grid, thus avoiding damage to infrastructure or power outages. Another advantage of HEMS is that they can establish interconnections between them. In this way, residents who maintain a local generation system, generally based on renewable energies, can manage their own generated energy, injecting it directly into the grid, marketing it with other residential customers, storing it in batteries or self-consuming it. These processes can be carried out through a HEMS, which allows efficient use of appliances and monitoring of energy consumption through a smart meter. Figure 1 shows a schematic diagram of a HEMS, which manages the energy produced locally from a PV system and the charging and discharging of the BESS and the EV.

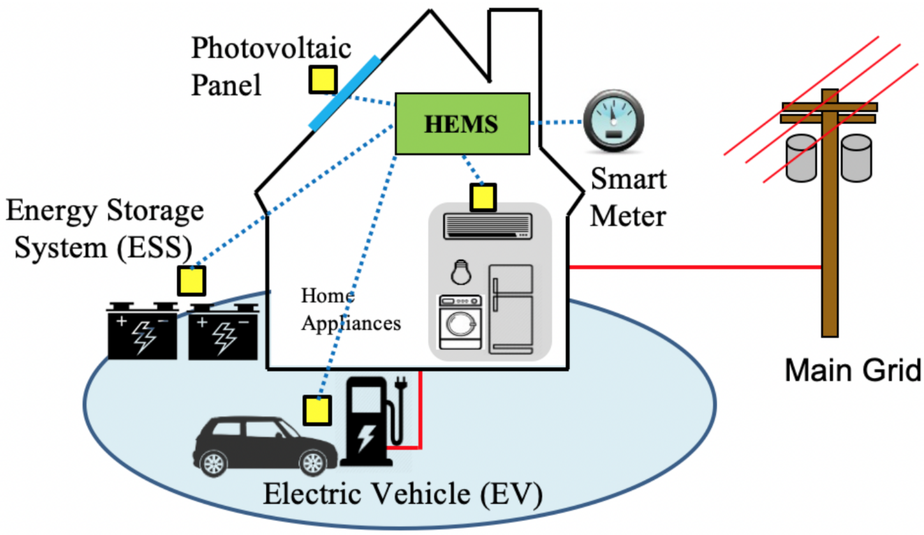

Figure 1. Schematic diagram of a smart home incorporating a HEMS.

2.2. Local Context of Chile

In Chile, renewable energies from PV and wind have been booming during recent years, mainly due to lower investment costs [11], the development in PV panels, batteries, and inverters that are now offering products with greater efficiency and durability, and the favorable meteorological conditions that are established particularly in Chile. The incentives are highlighted by the authorities through subsidy programs, along with the new legal regulations, such as the law of net billing and distributed generation, and the 2050 Energy Policy highlighting the goal of meeting about 60% of Chile's energy generation from renewable sources by 2035.

Five energy megatrends have been projected in Chile, such as the decarbonization of energy generation, including reducing and replacing coal-based generation sources, the increase in residential distributed generation especially based on PV systems or small wind turbines, digital transformation of the grid infrastructure both at the residential/industrial level, energy decentralization of the country, and developing PV projects covering schools, public buildings, and homes in isolated areas. Other aspects include electromobility which presents another fundamental participant in energy development and decontamination. This is due to the fact that 25% of greenhouse gas emissions in Chile corresponds to the transport sector. At the international level, the world powers have planned a series of actions, as in the case of Germany, where the sale of conventional vehicles will be prohibited from 2030, while France and England will do so from 2040. In the case of Norway, the abolition of conventional vehicles by 2025, while India announced that from 2030 sales will correspond exclusively to EVs.

2.3. *Configuration of PV System*

There are a variety of different configurations of PV systems, which differ either according to the type of building, installed PV power, meteorological data, whether or not they include a BESS, and if they are interconnected to the grid or isolated from it. Tables 2 and 3 summarize the cases studied.

Table 2. Summary of Studied Cases of Implementation of PV System Installations.

Ref. No.	Contribution	Specifications (A: Generation System, B: Consumption Parameters, C: EV Parameters)
[9]	Dimensioning of BESS based on monitored data on consumption and experimental data of PV generation for households with different consumption profiles	(A) Simulated PV system power: 5 and 20 kW
[12]	PV system design for a house from simulated local data of global radiation, consumption, generation, and injection into the grid, using PVsyst software	(A) PV power required: 1.4 kWp, Generation: 1519.3 kWh/year (B) Daily consumption: 17.8 kWh/day, Injection into the grid: 1398.3 MWh/year
[13]	Economic feasibility evaluation of a PV system for a university library, using a survey to estimate consumption, and the simulation of local generation using data from Solar Explorer	(A) PV panel power: 250 Wp, PV panel efficiency: 18–22%, PV panel dimensions: 1.64×0.99 m^2 (B) Daily consumption: 150–450 kWh/day, Monthly consumption: 2000–10,000 kWh/month, Total area: 1368 m^2
[14]	Data collection and monitoring of active power for 2 years, both of the total consumption and of the most demanding appliances in a residential neighborhood	(B) N° monitored houses: 21
[15]	PV system on site installation in a house, data collection and monitoring of active power, consumption, generation and BESS state of charge	(A) Installed PV power: 6.72 kWp, Useful storage capacity: 6.6 kWh
[16]	PV system on site installation, data collection and monitoring, both consumption, PV generation and state of charge of the BESS and EV, for a ZEH	(A) PV installed power: 2.5 kWp, BESS storage capacity: 10 kWh, Surface area: 210 ft^2 (B) Power consumption: 750–2000 W (C) Model: Toyota Prius, Battery model: Lithium-ion 5 kWh

Table 2. *Cont.*

Ref. No.	Contribution	Specifications (A: Generation System, B: Consumption Parameters, C: EV Parameters)
[17]	Algorithm to optimize the EVs charging for the staff of a shopping center	(A) Simulations: 50 kW PV system generation was simulated from a 3 kW PV system of a school. Consumption was simulated based on real data from a utility company of South Korea (C) 12 identical EVs, Battery capacity: 24 kWh, Power chargers: 1–7.7 kW
[19]	Simulation of the behavior of consumption curves from four different energy management algorithms for a smart microgrid composed by an office, internet servers, three homes, and two EVs	(A) PV installed power: 31 kWp (B) Injection into the microgrid: 2.0–12.4 MWh/year (C) EV Model: - Tesla Model S, Battery capacity: 85 kWh, Charger power: 22 kW, Consumption: 0.233 kWh/km - Nissan Leaf, Battery capacity: 24 kWh, Charger power: 6.6 kW, Consumption: 0.211 kWh/km
[20]	Algorithm modeling of EV charging demand and hybrid PV-wind generation in a charging station	(A) Multiple cases: PV installation area: 0–1875 m^2, Storage capacity: 0–500 kWh, N° wind turbines: 1–4, Wind turbine power: 1–3 kW (B) Power consumption from the grid: 0–300 kW (C) N° EV chargers: 1–10, EV charger power: 50 kW, Battery capacity: - Electric bike: 3.6 kWh, Small car: 16 kWh, Large car: 25 kWh, Van: 63 kWh

Table 3. Summary of studied cases of implementation of PV system installations.

Ref. No.	Contribution	Specifications (A: Generation System, B: Consumption Parameters, C: EV Parameters)
[21]	Standardized charging methodologies for EVs with different battery capacities	(C) Domestic SAE standard: Voltage: 120–240 Vac, Maximum current (AC): 12–16 A, Charger power: 1.4–1.9 kW, PHEV charging time: 7 h (0–100% battery charge), BEV charge time: 17 h (20–100% battery charge), Installation cost: 500–800 USD (C) IEC domestic standard: Voltage: 230–450 Vac, Maximum current (AC): 16 A, Charger power: 3.7–11 kW
[22]	Evaluation of the economic feasibility of the implementation of a small wind turbine with BESS in a house isolated from the grid	(A) Wind turbine power: 6 kW, N° batteries: 4, Battery capacity: 200 Ah, N° inverter/charger: 2, Nominal power inverter/charger: 3000 W (B) Installed power: 5202 W, Daily consumption: 28.4 kWh/day, House total area: 52 m^2

2.3.1. PV System Interconnected to the Grid

Figure 2 shows the configuration of a PV system interconnected with the grid. The system allows to supply the residential load and/or inject the surplus energy generated into the grid. On the other hand, when the generation is not enough, the energy from the grid is used as a backup.

In Ref. [12], on-grid PV system was presented for a case study at the residential level in Ecuador, in which the results of global radiation, generated energy, and the energy injected into the grid were simulated using PVsyst software, in order to size the installed PV power necessary to supply the energy demand of a standard house. Finally, the obtained results indicated that the system requires an installed PV power of 1.4 kWp.

In Ref. [13], the work presented a case study for PV implementation in the library of the Technical University Federico Santa María, Concepción, Chile. In order to obtain an estimated data on the daily and monthly consumption, a survey was conducted to the staff in order to determine the daily hours usage of each appliance. The local global radiation was obtained through the Solar Explorer online platform. Finally, the economic indicators were obtained, such as net present value (NPV), internal rate or return (IRR) and payback, which indicates that the project is profitable.

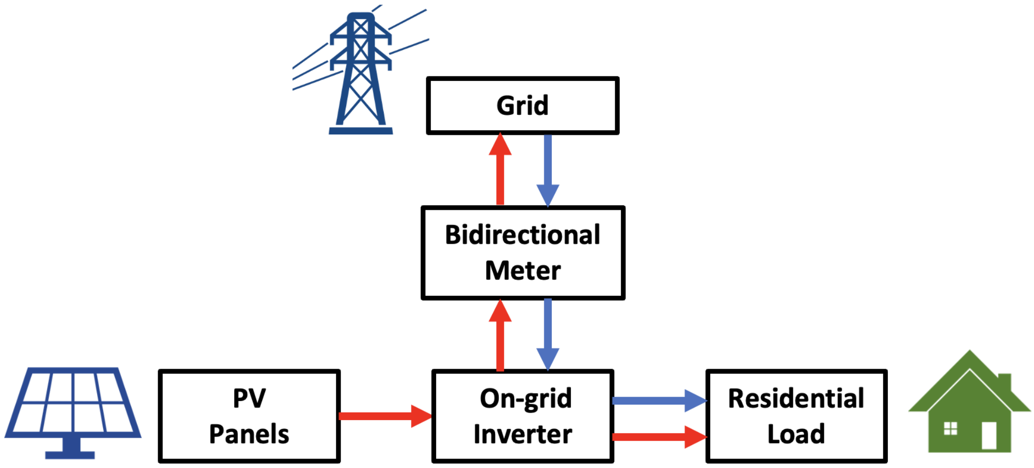

Figure 2. Schematic diagram of a PV system interconnected to the grid. Flows in red correspond to local generation, while flows in blue correspond to energy coming from the grid.

On the other hand, to achieve a more reliable estimation for the energy consumption, there are other more accurate methodologies. In this direction, in Ref. [14], a case study related to the collection of energy consumption data for the residential sector was implemented in the United Kingdom. For a period of 2 years, 21 households with different occupants were monitored. Measurements of the active power were measured every 8 s, either for the total home consumption or from appliances in particular that present the highest consumption using sensors installed in the sockets of the home.

2.3.2. PV System with BESS

Figure 3 shows a schematic diagram of a PV system with a BESS. The main objective of BESS is to store the surplus energy of the local generation for later self-consume when the demand exceeds the generations. In other scenarios, the BESS are also charged from the grid when it is economically convenient and then self-consumes the stored energy when the price of grid electricity reaches high costs.

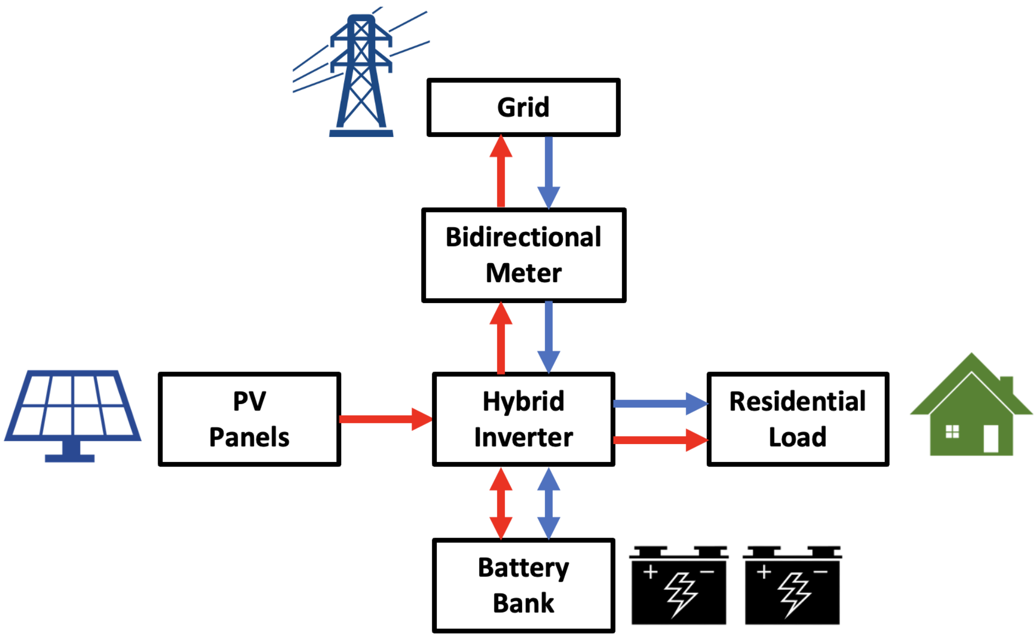

Figure 3. Schematic diagram of a PV system with BESS interconnected to the grid. Flows in red correspond to local generation, while flows in blue correspond to energy coming from the grid.

In Ref. [15], the work implemented an on-grid PV system with BESS at the residential level. It was pointed out that the energy flows come from the local generation or the grid, which can supply the home consumption or recharge the BESS that can be used more efficiently later. In this scenario, a PV system of 6.72 kWp was installed with a BESS capacity of 6.6 kWh. In this way, most PV generation was produced from 10:00 AM to 5:00 PM, while energy consumption reached its peak at the end of the day around 11:00 PM.

In Ref. [9], a study carried out in Qatar which aims to size a BESS based on different values of installed PV systems, which covered various homes with different consumption profiles. The main purpose of storing surplus local generation within this study was to avoid energy flows to the grid, which can cause problems of instability. The rooftop installations were preferred due to limited space availability. The exceptional high rates for horizontal global irradiation make PV installations profitable. Finally, due to the high temperatures in summer, there was a high dependence on air conditioning which corresponds to about half of the energy demand at that time of year. The horizontal global irradiance data were collected at the solar experiment facility of Hamad Bin Khalifa University, where energy consumption monitoring data was also obtained from four different households with different occupant profiles. The study indicated that there are high levels of energy consumption in the residential area, however, the profile was largely determined by the size and type of the air conditioning system, the number of occupants, antiquity of the house, annual economic income, as well as the clients who present electricity tariffs that were subsidized by the state.

2.3.3. PV System with BESS for EV Charging

In Ref. [16], the authors highlighted that in the United States most of the EV residential chargers have a power of 6 kW. Along with this, it is also considered the power consumption of the home, which for a normal home usually varies between 2250 to 6250 W, while for a Zero-Energy House (ZEHs) where all the consumption comes from the same local generation, this varies in the range of 750 to 2000 W. In this way, a ZEH home was considered with a PV system with an installed power of 2.5 kWp. In addition, a BESS was installed, along with the addition of the energy consumption of a Toyota Prius hybrid EV. The calculation of the energy consumption of the EV was calculated by means of a trip of 11 miles during approximately 2.25 h, thus reaching a consumption close to 3000 Wh at the end of the trip. Figure 4 shows a schematic diagram of a PV system configuration to support a residential load and EV charging.

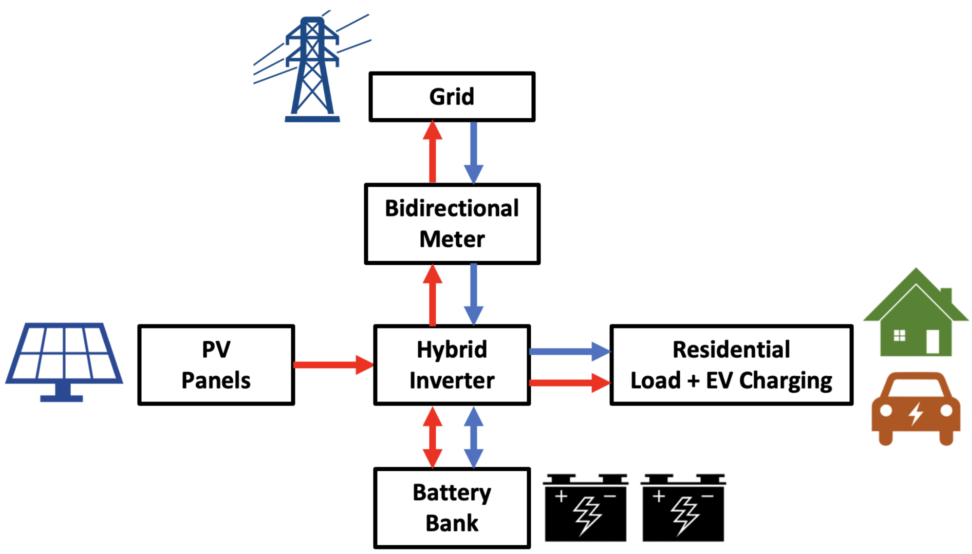

Figure 4. Schematic diagram of a PV system with BESS to support residential load and EV charging. Flows in red correspond to local generation, while flows in blue correspond to energy coming from the grid.

2.3.4. PV System without BESS for EV Charging

Due to the high investment cost and the unattractive economic results that arise when including BESS, in various case studies it is decided to implement a smart charging system making the most of the solar resource by charging EVs through a smart schedule. Figure 5 shows this configuration that consists of a PV system interconnected to the grid without considering BESS, in which the energy management system is in charge of seeking the most optimal decisions both at an economic level, as well as to protect the grid infrastructure.

In Ref. [17], a PV system was implemented in a commercial building in South Korea, which seeks to increase energy efficiency through smart charging methods for EVs that allow maximum use the resources. An algorithm was developed to predict the PV generation and the level of energy consumption according to weather conditions, and on the other hand, to schedule the most optimal time to recharge the EVs. To simulate the PV generation, a 50 kW PV system was assumed for the commercial building, and PV generation data from a school that housed a 3 kW PV system was used. On the other hand, to simulate the energy consumption, actual consumption data from a South Korean utility company was used. Additionally, 12 identical EVs were considered for the charging center with power chargers between 1 and 7.7 kW. Additionally, the variable price of electricity were considered, both for periods of high and low demand, respectively.

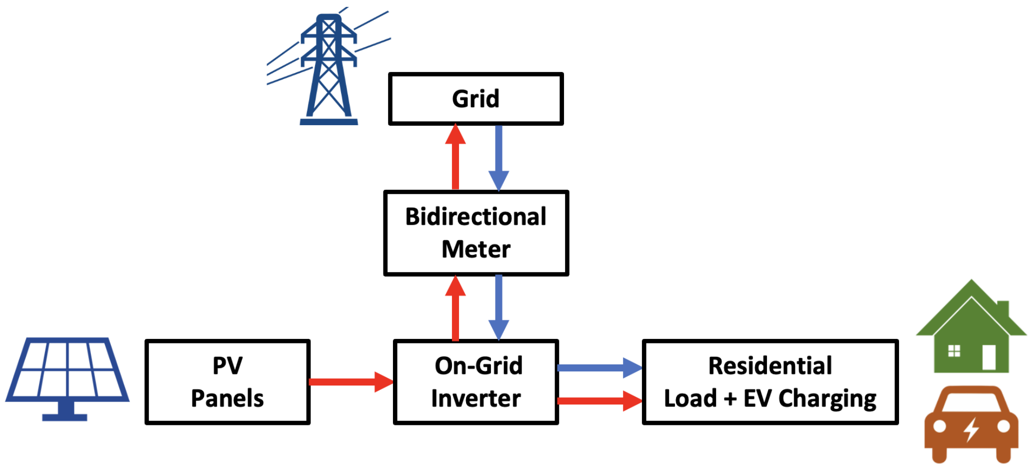

Figure 5. Schematic diagram of a PV system without BESS to support residential load and EV charging. Flows in red correspond to local generation, while flows in blue correspond to energy coming from the grid.

In Ref. [18], similar configuration was studied at the grid level in Sweden. The behavior of the daily load curve of the grid, the average PV generation curve, and the power curve demanded by the charging of EVs were studied. Two consumption peaks were at 8:00 AM and 7:00 PM. The study concluded that the incorporation of the power demand from EVs charging to the grid base load presented a significant increase in power maximum demanded. However, the incorporation PV generation generates a significant drop in the maximum power demanded and allows saving much of the energy consumption.

In Ref. [19], the work considered the implementation of an energy management system through different algorithms for a microgrid located in the Netherlands. This microgrid was made up of a 31 kWp PV system, non-controllable loads such as an office, internet servers and three homes, and controllable loads corresponding to two EVs. A simulation was carried out of operation of the microgrid where algorithms managed to reduce the maximum power demand through charging patterns by reducing the power of the EV charger required. Other algorithms aimed to store the surplus in the EVs batteries, to later use them as self-consumption or inject them into the microgrid thus reducing energy consumption.

2.3.5. Hybrid PV-Wind System with BESS for EV Charging Station

Figure 6 shows a schematic diagram of a hybrid PV-wind system to charging EVs at charging station centers which have a large installed power based on high power chargers which cause significant stress on the grid infrastructure. As a result, certain charging stations choose to save the peak power and consumption through local PV and wind generation along with the implementation of BESS.

In Ref. [20], a hybrid PV-wind system with BESS configuration was implemented where mathematical models were developed to simulate the EVs charging demand and generation from renewable energies such as wind and PV. The developed models allow the analysis of dimensioning the generation system as well as the economic feasibility for a charging station investment. The study indicated that the energy demand depends directly on the capacity and initial state of charge for the EV battery before charging.

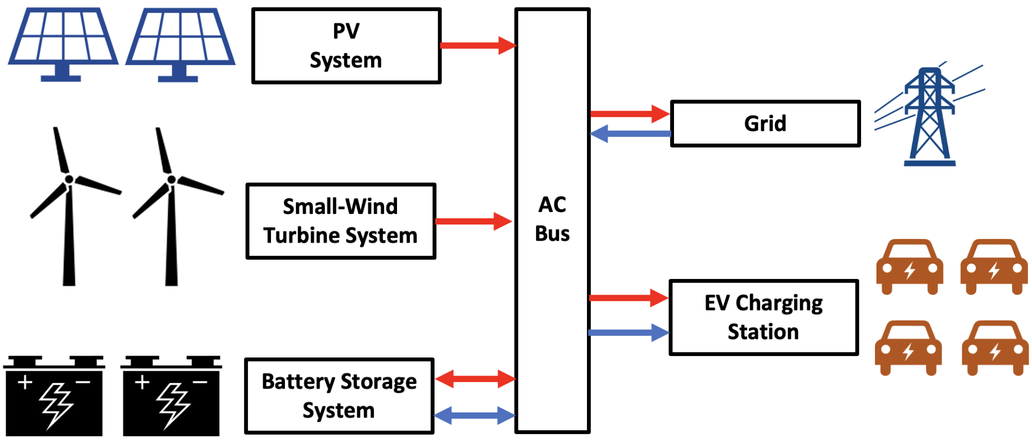

Figure 6. Schematic diagram of a hybrid PV-wind system with BESS to support EV charging station. Flows in red correspond to local generation, while flows in blue correspond to energy coming from the grid.

In Ref. [21], a series of standards for EVs charging were indicated in order to protect the grid from overdemand and prolong the useful life of these batteries. The charging methods can be unidirectional (the energy goes from the grid to the EV), bidirectional (the EV can be charged from the grid and return the energy to the home or to the grid when economically convenient), smart charging (where it is recharged in order to protect the grid from overconsumption), and uncontrolled (when there are no grid monitoring systems or recharging schedules).

2.3.6. Off-Grid PV or Small Wind Turbine System with BESS

Figure 7 shows an off-grid configuration which corresponds to the implementation of PV systems or small wind turbines with BESS. This configuration is usually found in rural areas without access to electricity.

In Ref. [22], the implementation of a small wind turbine was dimensioned for a house located on Santa María Island, Chile. For the estimation of energy consumption, a survey was made of all the devices with the highest consumption and daily hours of use. As it is not always possible to supply all the devices on certain occasions, the devices were classified by priority for the user. In this way, the installed power of the home was close to 5.2 kW, so for safety reasons and future increases in demand, a small wind turbine with a nominal power of 6 kW was considered. Regarding the BESS, a 9.6 kWh energy storage capacity were considered.

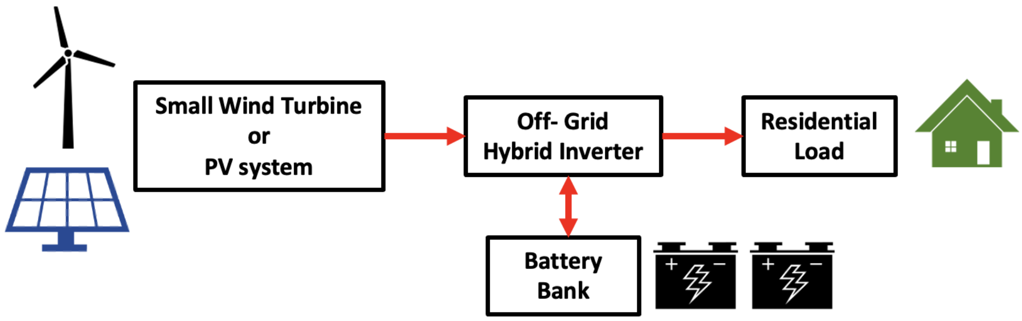

Figure 7. Schematic diagram of a small turbine wind or PV system isolated from the grid with BESS. Flows in red correspond to local generation, while flows in blue correspond to energy coming from the grid.

3. Data Collection

To carry out the PV system dimensioning, necessary data were collected, such as the energy consumption of the home, local meteorological data, and electricity rates of the power distribution system in the sector.

3.1. Meteorological Information

The home of this case study is located in the city of Viña del Mar, Chile. The latitude, longitude and height above sea level correspond to 33.03° South, 71.32° West and 16 m above sea level, respectively. The meteorological data were obtained from the Solar Explorer online platform that allows analyzing the renewable resources available within the geography of Chile [23]. Based on the data obtained, Figure 8 shows the average levels of the global hourly radiation incident on the inclined plane with an angle of inclination equivalent to the latitude of the place for each month of the year. Additionally, it can be seen that the most critical months with lower global radiation correspond to June and July. Figure 9 shows the average values obtained of the hourly ambient temperature for each month of the year.

Hour/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	3	0	0	0	0	0	0	0	0	1	12	14
7	44	22	6	0	0	0	0	0	10	75	98	82
8	193	168	150	133	61	5	6	106	175	244	269	247
9	366	331	315	299	225	214	218	280	351	424	451	432
10	561	511	474	443	336	348	361	423	511	594	624	614
11	747	702	664	578	430	442	463	544	634	730	790	782
12	883	845	774	662	492	489	489	597	728	843	894	905
13	961	932	826	717	521	523	514	618	746	867	919	951
14	946	929	830	702	507	495	520	589	700	812	870	920
15	847	854	760	622	465	449	456	519	601	687	749	810
16	690	703	612	484	338	339	350	415	458	514	562	631
17	471	477	401	293	241	214	267	241	266	299	343	408
18	235	237	188	86	1	0	4	65	112	123	131	182
19	31	24	4	0	0	0	0	0	0	1	17	29
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

Figure 8. Average incident global radiation W/m^2, in the plane with an inclination equal to the latitude of 33° S.

Hour/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	15	15	14	12	11	9	9	9	10	11	12	13
1	15	15	14	12	10	9	8	9	10	10	11	13
2	15	14	13	11	10	9	8	9	9	10	11	12
3	14	14	13	11	10	8	8	8	9	9	11	12
4	14	14	12	11	10	8	7	8	8	9	10	12
5	14	14	12	10	9	8	7	8	8	9	10	12
6	14	14	12	10	9	8	7	7	8	8	10	12
7	15	14	13	10	9	8	7	7	8	9	11	13
8	16	16	14	11	10	8	7	8	9	11	12	14
9	17	17	15	13	11	9	9	10	11	13	14	16
10	18	18	17	15	13	11	11	12	13	14	16	17
11	20	20	18	16	14	13	13	14	15	16	18	18
12	21	21	20	18	16	15	14	15	16	17	19	20
13	22	22	21	19	17	16	15	16	17	18	20	21
14	23	23	22	20	17	16	16	17	17	19	20	22
15	24	24	22	20	17	16	16	16	17	19	20	22
16	23	23	22	19	17	15	15	16	17	18	20	22
17	23	23	21	18	15	14	14	15	16	17	19	21
18	22	22	20	17	14	12	12	13	14	16	18	20
19	20	20	18	15	13	12	11	12	13	14	16	18
20	19	18	17	14	12	11	11	11	12	13	14	16
21	17	17	16	14	12	11	10	11	11	12	13	15
22	17	17	15	13	11	10	10	10	11	12	13	14
23	16	16	15	12	11	10	9	10	10	11	12	14

Figure 9. Average distribution of the hourly temperature in the place for each month of the year in °C.

3.2. Home Power Consumption Information

Actual energy consumption information for the home was available from the monthly electricity bills during the period between October 2018 and June 2021. In this way, the historical averages of daily consumption were obtained for each month of the year. On the other hand, the energy demand that the charging of a Nissan Leaf e+ EV would present is simulated. Because the consumption of the EV will depend on many factors, such as the speed at which it circulates, environmental conditions, type of route, traffic jams, among others, a simple estimation of consumption is made based on the technical parameters indicated by the manufacturer (see Table 4) [24].

It was considered a residential EV charger, which can charge the EV with the energy required for a journey of 11 km in one hour of charging. This assumption is because the case study is located in an urban sector of the city. For this reason, it is assumed that for each day, the members of the family drive a maximum of 22 km per day during the year, in order to maintain a EV load margin.

For the dimensioning, the most critical situation was considered, and where the maximum estimated daily distance will always be driven. Thus, in order to charge the EV with the energy equivalent to the 22 km, there is a need to use EV charger for a period of 2 h a day. Therefore, with these assumptions, the daily consumption of the EV charger would be equal to 4.6 kWh/day to satisfy daily trips. It should be noted that the full charging of the EV was not considered, thus avoiding over consumption from the grid and reducing the required dimensioning of the PV system. Subsequently, the total average daily consumption of the household is estimated for each month. For this, household consumption is added to the energy consumption of the EV charge. From Figure 10, it is possible to see that there is a higher consumption during the winter months. The most critical month is July mainly due to the use of electric heating devices in the house.

Table 4. Electric vehicle parameters.

Parameters	Description
Model	Nissan Leaf e+
Actual battery capacity	62 kWh
Charging mode (home)	Wall plug 2.3 kW (230 V/10 A), Full charge time: 28 h 45 min, Charge speed: 11 km/h

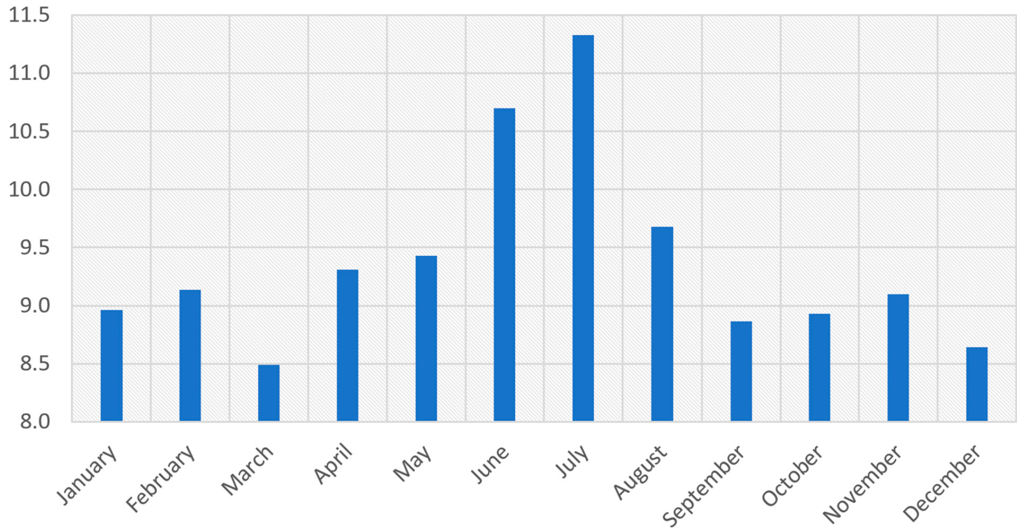

Figure 10. Average total daily energy consumption in kWh/day.

3.3. Grid Information

The home is located within an urbanized area of the city, and where there is electricity supply from the distribution company. The price of the energy injected into the grid corresponds to the charge for energy of around 88 CLP/kWh. The price of the energy from grid is approximately double since the charges included other fees associated with the transport of electricity, reaching a price of around 163 CLP/kWh.

4. PV System Dimensioning

The calculation is divided into steps for the dimensioning of the main components of a PV system interconnected to the grid (with or without a BESS). The configurations of the schematic diagrams are given in Figures 4 and 5.

4.1. PV Array Dimensioning

For the dimensioning, a 410 Wp PV panel was selected [25]. Table 5 shows the main parameters of the PV panels.

Table 5. PV panel parameters.

Parameters	Description
Model	Ulica Solar UL-410M-144
Nominal power	410 Wp
Nominal efficiency	20.18%
Effective PV area	1.815 mm^2

An inclination of 33.03° is assumed for the PV panels. Subsequently, the theoretical power of the PV panel is obtained from the data of the global radiation incident on the inclined plane and the parameters of the PV panel (see Equation (1)) [26]:

$$P_{tp} = RG_{inc} \cdot E_p \cdot A_{fp} \tag{1}$$

where P_{tp} is the instantaneous theoretical power of the PV panel (W), RG_{inc} is the incident global radiation on the inclined plane equal to the latitude (W/m^2), E_p is the PV panel nominal efficiency, and A_{fp} is the effective PV area of the panel (m^2). Then, the theoretical energy generated by the PV panel during each hour of the day is determined as given below (see Equation (2)) [26]:

$$E_{tp} = P_{tp} \cdot T_r \tag{2}$$

where E_{tp} is the theoretical energy generated by the PV panel at a given time of day (Wh) and T_r is the time interval of 1 h in which the corresponding incident global radiation level exists. In this way, the daily theoretical energy generated by each PV panel is given below (see Equation (3)) [26].

$$E_{tdp} = \sum_{h=0}^{23} E_{tp} \tag{3}$$

where E_{tdp} is the theoretical daily energy generated by the PV panel (Wh/day). Energy losses were considered, such as the thermal losses of the PV panel defined based on the instantaneous temperature of the PV cell, instantaneous environmental temperature and technical parameters of the PV panel that are provided by the manufacturer. In this way, the thermal loss factor is calculated as (see Equation (4)) [26]:

$$U = U_c + U_v \cdot Vel_v \tag{4}$$

where U is the thermal loss factor ($W/m^2 \cdot \Delta T$), U_c is the thermal loss constant (W/m^2T), U_v is the wind proportional factor ($W{*}s/m^3 \cdot \Delta T$), and Vel_v is the local wind speed (m/s). In [27], it is recommended to use a thermal loss factor becomes a constant equal to 29 $W/m^2 \cdot \Delta T$, thus, no local wind speed data is required. Then, the temperature of the PV module is calculated at each hour of the day (see Equation (5)) [26]:

$$T_{cel} = T_{amb} + \frac{1}{U} \cdot \alpha \cdot RG_{inc} \cdot (1 - E_p) \tag{5}$$

where T_{cel} is PV cell instantaneous temperature (°C), T_{amb} is local instantaneous ambient temperature in (°C) and α is fraction between the radiation absorbed and the radiation reflected by the PV panel (in [27], it is recommended to use 0.9). Subsequently, the hourly thermal loss of power during each hour of the day is obtained from Equation (6) as as given below [26]:

$$P_{tpi} = Coef_T \cdot (T_{cel} - Tnom_{cel}) \cdot P_{tp} \tag{6}$$

where P_{tpi} is hourly power loss due to thermal loss in the PV panel (W), $Coef_T$ is power loss coefficient of the PV panel due to the instantaneous temperature variation of the cell with respect to the nominal temperature of the cell (%/°C) and $Tnom_{cel}$ is nominal operating temperature of the PV cell (under NOCT conditions). Subsequently, the daily effective power generated by a PV module during July, after considering thermal losses, is obtained from Equation (7) as given below:

$$P_{ehp} = P_{tp} - P_{tpi} \tag{7}$$

where P_{ehp} is hourly effective power of the PV panel (W). In this way, it is possible to obtain that the loss of power due to thermal effects in the panel acquires a positive value throughout the day, due to the fact that the instantaneous temperature of the cell is lower than the nominal operating temperature of the panel for much of the day. So, the lower the temperature of the module, the greater its generation. On the other hand, low instantaneous temperature values of the cell are obtained due to the low local ambient temperatures during the month of July which corresponds to midwinter. Other types of losses were considered with the Loss Factor method Equation (8), which considers n factors, which allow a prior estimation of the losses [28,29].

$$F_{per} = \prod_{i=1}^{n} f_i \tag{8}$$

In this way, a loss factor of 0.698 is obtained, with the values assumed in Table 6 [29]. Then, effective energy generated by each PV panel can be calculated Equation (9) as given below [28,29]:

$$E_{ehp} = P_{ehp} \cdot T_{pe} \cdot F_{per} \tag{9}$$

where E_{ehp} is hourly effective energy generated by each PV panel (Wh) and T_{pe} is the time interval of 1 h in which the calculated effective power of each panel acts on average. Finally, the daily effective energy generated by each PV panel is given below (see Equation (10)) [26]:

$$E_{edp} = \sum_{h=0}^{23} E_{ehp} \tag{10}$$

where E_{edp} is daily effective energy generated by each PV panel (Wh).

Table 6. Energy loss factors.

Energy Loss Factor	Estimation	Description
PV panel power tolerance	1	Manufacturer indicates 0/+5 W, so in the worst case there would be no power loss in the module
Inverter efficiency	0.88	
PV panel error	0.98	Losses caused by small differences in the parameters between installed PV panels [30]
Losses in diodes and connection terminals	0.995	
Direct current ohmic losses	0.98	
Altern current ohmic losses	0.99	
PV panel soiling	0.95	Mainly due to dust, bird droppings, among others
System unavailability	0.98	Either due to PV system component failures or maintenance stops
External shades	0.9	

Finally, the number of PV panels required is determined with Equation (11) as given below [26]:

$$N_{pf} = \frac{C_{dt}}{E_{edp}} \tag{11}$$

where N_{pf} is the number of PV panels needed to supply all consumption in the most critical month and C_{dt} is total average daily consumption in kWh/day. Thus, the installation of 12 PV panels is required, reaching an installed power of 4.92 kWp.

4.2. Inverter Dimensioning

For the PV system interconnected to the grid and with BESS, a hybrid inverter were considered, while for the configuration without BESS it could be considered a normal inverter. In order to size the power of the inverter, it is recommended to be slightly higher than the installed PV power of the system, since in this way the inverter would always work within its operating range and the losses due to overload would be avoided. Finally, the power of the inverter is determined from Equation (12) as given below [31]:

$$Pnom_{inv} = \frac{P_{sf}}{E_{inv} \cdot N_{inv}} \tag{12}$$

where $Pnom_{inv}$ is inverter nominal output power in AC (kW), P_{sf} is PV system installed power under STC (kW), E_{inv} is estimated nominal efficiency of the inverter and N_{inv} is number of inverters to use [26,29].

In this way, a 5.5 kW inverter were considered. It is possible to use other inverter powers, as long as it is previously verified that the open circuit voltage and the short circuit current of the PV array are within the ranges parameters of the selected inverter. Thus avoiding overvoltages that can cause damage to the equipment [29]. Table 7 shows the parameters of the selected hybrid inverter [32].

Table 7. Hybrid inverter parameters.

Parameters	Description
Model	Voltronic Power InfiniSolar E 5.5 KW
Nominal Power	5500 W
Bank battery voltage	48 Vdc

4.3. Battery Bank Dimensioning

The battery bank can be dimensioned based on different objectives, either as energy backup, reduction in power peaks or perform energy management that allows obtaining economic benefits. However, for this case study, it was carried out based on the days of autonomy required to supply the energy consumption during this period. In this way, the minimum capacity required of the battery bank is calculated with Equation (13) as given below [26]:

$$\mathrm{Creq_{bb}} = \frac{\mathrm{N_{da}} \cdot \mathrm{F_s} \cdot \mathrm{C_{dt}}}{\mathrm{V_{bb}} \cdot \mathrm{Dod}} \tag{13}$$

where $\mathrm{Creq_{bb}}$ is the minimum required capacity of the battery bank (Ah), $\mathrm{N_{da}}$ is desired number of autonomy days, $\mathrm{F_s}$ is safety factor which is considered in cases where critical equipment is present or in homes isolated from the grid, $\mathrm{C_{dt}}$ is total average daily consumption in (kWh/day), $\mathrm{V_{bb}}$ is battery bank voltage (V) which is determined by the parameters of the selected inverter, and Dod is maximum depth of discharge of the battery bank.

In this work, 1 day of autonomy was considered, so that the battery bank must be able to store at least the energy equivalent to the daily consumption in the month of July. On the other hand, the safety factor in this case is considered equal to 1, since the battery bank does not turn out to be a critical component since the home is interconnected to the grid. Furthermore, the voltage of the battery bank is defined by the parameters of the selected inverter. Finally, the depth of discharge is assumed to be 45%, which corresponds to a conservative value that allows a longer useful life for the batteries and reduces the costs associated with their replacement. A battery with a nominal voltage of 8 V and a capacity of 568 Ah is chosen for a total discharge rate of 20 h. The battery bank is capable of supplying a daily energy demand of 12.27 kWh (sighly greater than the average daily consumption of 11.33 kWh during July) for 20 h a day (see parameters in Table 8). With the assumed depth of discharge, the useful life of the batteries according to the manufacturer is close to 4800 cycles, which is equivalent to a useful life of 13.15 years, assuming that there is a charge/discharge cycle during each day [33].

Table 8. Battery parameters.

Parameters	Description
Model	Rolls Flooded Deep Cycle Battery 8 CS 17P
Nominal voltage	8 V
Nominal capacity C20 (discharge in 20 h)	568 Ah

4.4. Other Components

Other components were dimensioned based on the technical regulations that apply in Chile [34–37], such as the electrical wiring for AC and DC circuits, the electrical piping, and the electrical protections, both for DC and AC circuits, such as thermomagnetic switches, differential protectors, fuses, connection to ground, among others.

5. Results

Figure 11 shows the annual and average daily generation by the PV system along the project's life. The PV panels power degradation rate of 0.7% per year were considered, which directly affects the generation.

In this work, there is no information about the real consumption profile of the home, therefore, it was necessary to assume an average daily energy consumption profile during each month of the year from 2022 to 2046, based on the actual monthly values collected.

However, in the case of a PV system with BESS, it is assumed that there is a HEMS that allows supplying most of the demand from self-consumption, which allows storing the surpluses generated for later use. On the other hand, it is only possible to obtain economic savings by injecting energy into the grid, according to Chilean Net Billing and Distributed Generation regulations. In this way, it is only possible to reduce the billing of the electricity rate to zero.

Regarding the economic analysis, the useful life of the PV system components is approximately 25 years except for the batteries that must be replaced every 13.15 years. In addition, the value added tax (VAT) of 19% is considered in the acquisition of the components and an investor discount rate of 10%. The price of electricity from the grid is equal to 165 CLP/kWh and an injection price equal to 88 CLP/kWh.

With respect to CAPEX, this is calculated based on the price of the components of the PV system, as well as the assembly equipment and the payment of certified installers, which are estimated to be 10% to 15% of the initial investment. Regarding OPEX, PV systems generally have very low operating costs which correspond mainly to maintenance work. However, on this occasion they are not estimated within the financial balance.

Year	PV panel production guarantee (%)	Jan kWh/day	Feb kWh/day	Mar kWh/day	Apr kWh/day	May kWh/day	Jun kWh/day	Jul kWh/day	Aug kWh/day	Sep kWh/day	Oct kWh/day	Nov kWh/day	Dic kWh/day	Annual generation kWh/year
1	97.0	21.15	20.43	18.42	15.64	11.49	11.22	11.64	13.92	16.60	19.27	20.68	21.38	6132.17
2	96.3	21.01	20.29	18.29	15.54	11.42	11.14	11.56	13.83	16.49	19.14	20.54	21.23	6090.03
3	95.7	20.86	20.15	18.16	15.43	11.34	11.07	11.48	13.73	16.37	19.01	20.40	21.08	6047.88
4	95.0	20.72	20.01	18.04	15.32	11.26	10.99	11.40	13.63	16.26	18.88	20.25	20.94	6005.74
5	94.3	20.57	19.87	17.91	15.21	11.18	10.91	11.32	13.54	16.14	18.74	20.11	20.79	5963.59
6	93.7	20.43	19.73	17.79	15.11	11.10	10.84	11.24	13.44	16.03	18.61	19.97	20.64	5921.45
7	93.0	20.28	19.59	17.66	15.00	11.02	10.76	11.16	13.35	15.92	18.48	19.83	20.50	5879.30
8	92.3	20.14	19.45	17.53	14.89	10.94	10.68	11.08	13.25	15.80	18.35	19.69	20.35	5837.16
9	91.7	19.99	19.31	17.41	14.78	10.86	10.60	11.00	13.16	15.69	18.21	19.54	20.20	5795.01
10	91.0	19.84	19.17	17.28	14.68	10.78	10.53	10.92	13.06	15.57	18.08	19.40	20.06	5752.86
11	90.3	19.70	19.03	17.15	14.57	10.70	10.45	10.84	12.96	15.46	17.95	19.26	19.91	5710.72
12	89.7	19.55	18.89	17.03	14.46	10.63	10.37	10.76	12.87	15.35	17.82	19.12	19.76	5668.57
13	89.0	19.41	18.75	16.90	14.35	10.55	10.30	10.68	12.77	15.23	17.68	18.98	19.61	5626.43
14	88.3	19.26	18.61	16.77	14.25	10.47	10.22	10.60	12.68	15.12	17.55	18.83	19.47	5584.28
15	87.7	19.12	18.47	16.65	14.14	10.39	10.14	10.52	12.58	15.00	17.42	18.69	19.32	5542.14
16	87.0	18.97	18.33	16.52	14.03	10.31	10.06	10.44	12.49	14.89	17.29	18.55	19.17	5499.99
17	86.3	18.83	18.19	16.39	13.92	10.23	9.99	10.36	12.39	14.77	17.15	18.41	19.03	5457.85
18	85.7	18.68	18.05	16.27	13.82	10.15	9.91	10.28	12.30	14.66	17.02	18.26	18.88	5415.70
19	85.0	18.54	17.91	16.14	13.71	10.07	9.83	10.20	12.20	14.55	16.89	18.12	18.73	5373.56
20	84.3	18.39	17.77	16.01	13.60	9.99	9.76	10.12	12.10	14.43	16.76	17.98	18.59	5331.41
21	83.7	18.25	17.62	15.89	13.49	9.91	9.68	10.04	12.01	14.32	16.62	17.84	18.44	5289.26
22	83.0	18.10	17.48	15.76	13.39	9.84	9.60	9.96	11.91	14.20	16.49	17.70	18.29	5247.12
23	82.3	17.95	17.34	15.63	13.28	9.76	9.52	9.88	11.82	14.09	16.36	17.55	18.15	5204.97
24	81.7	17.81	17.20	15.51	13.17	9.68	9.45	9.80	11.72	13.98	16.23	17.41	18.00	5162.83
25	81.0	17.66	17.06	15.38	13.06	9.60	9.37	9.72	11.63	13.86	16.09	17.27	17.85	5120.68

Figure 11. Projection of the daily generation of each month and the annual generation for 25 years by the PV system considering the degradation of the PV panels.

5.1. Results of PV System with BESS

Figure 12 shows the energy management through the years of operation including self consumption and injected to/from grid. The BESS allows the energy demand to be supplied entirely from PV generation, while the surpluses are injected into the grid. Additionally, from year 6, energy from the grid begins to be seen during the month of July, which is due to the decrease in PV generation due to the degradation of the panels. Therefore, it is not possible to supply the entire energy demand of the home.

Table 9 shows that the acquisition cost of the BESS represents about 40% of the total cost of the initial investment. From the economic evaluation, on the one hand, the annual billing of CLP$565.059 is reduced to zero during the first five years of operation, because the energy from the grid is replaced by self-consumption, and that the reimbursement of surpluses is null because the billing of the electricity tariffs is zero in this period. In addition, there is the reinvestment corresponding to the replacement of the batteries in the year 2034 (which corresponds to year 13 of operation) equivalent to CLP$4.230.222. Finally, the annual savings generated by the system are obtained, which will correspond to the reduction in the billing of the electricity generated by self-consumption and the reimbursement of the injected surpluses.

The economic indicators such as the null Payback, a negative IRR of −0.59% and a negative NPV of CLP$−6.804.372 indicates that the project is not profitable.

Operation year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Self-consumption kWh/year	3425	3425	3425	3425	3424	3422	3419	3416	3412	3407	3402	3397	3392	3388	3383	3378	3373	3368	3364	3359	3354	3349	3345	3340	3335
Injected to grid kWh/year	2708	2665	2623	2581	2539	2500	2460	2421	2383	2346	2309	2271	2234	2197	2159	2122	2085	2047	2010	1973	1935	1898	1860	1823	1786
From the grid kWh/year	0	0	0	0	0	3	5	8	13	18	23	27	32	37	42	47	51	56	61	66	71	75	80	85	90

Figure 12. Energy management with BESS.

Table 9. CAPEX calculation for the installation of the PV system with BESS.

Component	Quantity	Unitary Price without VAT (CLP)	Total Price (CLP)
PV panel	12	$96.720	$1.160.040
Hybrid inverter	1	$1.150.000	$1.150.000
Battery	6	$705.037	$4.230.222
Wiring and Electrical piping	–	$151.243	$151.243
Electrical proteccions	–	–	$506.612
Assembly cost	–	–	$719.872
Installation	–	–	$1.079.807
		CAPEX without VAT	$8.998.395
		CAPEX plus VAT	$10.708.091

5.2. Results of PV System without BESS

Figure 13 shows the energy management through the years of operation including self consumption and injected to/from grid. It is observed that, unlike the case with storage, for the first year of operation, self-consumption is lower by approximately 45%, because there is no way to store surpluses when the generation is greater than energy consumption. On the other hand, the injection of surpluses into the grid increases by 70% compared to the previous case.

Table 10 shows the CAPEX for a PV system without the incorporation of a BESS. The implementation of the PV system allows self-consumption equivalent to CLP$253.064 per year for the first year of operation. In comparison, an amount equivalent to CLP$311.995 would have to be paid for energy from the grid. Now, the injection of surpluses into the grid would generate a refund of CLP$405.652 for the first year. However, as mentioned earlier, the reimbursement of surpluses cannot be greater than the price of the electricity rate.

The economic indicators such as a Payback of 7.5 years, an IRR of 12.65% and a positive NPV of CLP$890.354 indicates that the project is profitable for the selected discount rate.

Operation year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Self-consumption kWh/year	1534	1533	1532	1532	1531	1531	1530	1529	1529	1528	1527	1527	1526	1525	1525	1524	1523	1522	1521	1520	1519	1519	1518	1517	1516
Injected to grid kWh/year	4598	4557	4515	4474	4432	4391	4349	4308	4266	4225	4183	4142	4100	4059	4018	3976	3935	3894	3852	3811	3770	3729	3687	3646	3605
From the grid kWh/year	1891	1892	1892	1893	1893	1894	1895	1895	1896	1897	1897	1898	1899	1899	1900	1901	1902	1902	1903	1904	1905	1906	1907	1908	1909

Figure 13. Energy management without BESS.

Table 10. CAPEX calculation for the installation of the PV system without BESS.

Component	Quantity	Unitary Price without VAT (CLP)	Total Price (CLP)
PV panel	12	$96.720	$1.160.040
Inverter	1	$1.150.000	$1.150.000
Wiring and Electrical piping	–	$140.743	$140.743
Electrical protections	–	–	$398.170
Assembly cost	–	–	$284.955
Installation	–	–	$427.433
		CAPEX without VAT	$3.561.941
		CAPEX plus VAT	$4.238.710

5.3. Simulation Results of PVsyst

The same cases from the previous section were simulated using PVsyst software for PV systems with and without BESS. From Solar Explorar, hourly databases on global horizontal irradiation and ambient temperature were imported for the selected location. Additionally, from the PVGIS website, the solar chart of the place from which the solar elevation angle and the azimuthal angle were obtained for each hour of the day and for different dates of the year, considering the topographic shadows produced by the local relief. The inclination angle of the panels was set equal to the latitude at 33.03°, while the orientation was set towards to North.

Regarding energy consumption, the average daily values for each month of the year were entered. Since no particular consumption profile is defined, the software assumes a constant load power during each hour of the day. The same dimensioning calculated in the previous sections was entered into the software, simulating the same system components by entering their technical parameters. The storage objective was set as self-consumption, being able to supply the energy demand during a day of autonomy. A depth of discharge of 45% was defined, establishing the maximum and minimum charge limit at 90% and 45%, respectively, in order to avoid overcharging and overdischarging from the batteries and thus prolong their useful life.

Thermal losses in the PV array were considered, assuming that the panels are under free air circulation in the open and a radiation absorption coefficient of 0.9, ohmic losses of the continuous and alternating circuit in 2% and 1%, respectively. Module mismatch losses at 2%, losses due to dirt at 5%, panel reflection losses as a default value indicated by the software, panel degradation losses at 0.67% annual, and losses due to system unavailability at 2%. Additionally, in the case with BESS, the software simulates losses in the battery bank based on the manufacturer's instructions.

Energy management was assumed differently in each of the cases. In the case with BESS, the PV energy surpluses are stored to later be self-consumed in the home. In the event that the batteries reach a maximum charge point, the resulting PV surplus is injected into the grid. Finally, if the PV generation or the energy stored at a certain moment of time is not enough to supply the energy consumption, then energy is obtained from the grid.

On the other hand, in the case without BESS, the generated surpluses cannot be stored and injected directly into the grid.

Regarding the simulation results, the projected generation is obtained for 25 years of operation in each case. Figure 14 shows the PV system with BESS, where the PV system generates 6.8 MWh per year, in which 45% per year is self-consumed at home, 39% is injected into the grid and 16% corresponds to energy losses. On the other hand, the home's energy consumption is 3.4 MWh per year, in which only 11.5% is supplied from the grid, thanks to the implementation of the BESS. It can also be seen that during the months of April and June, a significant amount of energy can be seen from the grid together with energy injected into it, so in these cases the capacity of the BESS was not sufficient to store all the surpluses and be used as self-consumption later. A similar case occurs during May and July, where there is energy to and from the grid. However, in this case, even if all the surpluses were stored, energy would still be present from the grid since the latter is higher than the injected one.

Figure 15 shows the PV system without BESS. There is the same PV generation as in the previous case of which only 19.6% per year is self-consumed at home, 75.4% is injected into the grid, and 5% corresponds to energy losses. This is a lower percentage than the previous case since losses at the level of the BESS are avoided. On the other hand, this is the same energy consumption of the home of which 61% per year is supplied from the grid, and where in the winter months the highest values are seen.

Finally, the economic results are obtained considering a discount rate of 10%, a horizon of 25 years, a price of electricity from the grid of 0.208 USD/kWh, and an injection price to the network of 0.111 USD/kWh. For the case with BESS, a NPV of −9189 USD was obtained. It is concluded that the project is not profitable for the selected discount rate, while it is not possible to obtain a payback within the project horizon. Unlike the results obtained in calculation report, the NPV obtained for this case was close to −8571 USD, which differs from that obtained in the PVsyst software. The difference in the results is largely due to the consideration of additional losses considered by the PVsyst software such as those generated in the BESS, together with the difference in the meteorological data used. Similarly, in the case without BESS where a NPV of USD 2532 is obtained for which the project turns out to be profitable, while a payback of 10.3 years is achieved which turns out to be attractive in relation to the useful life of the project system components.

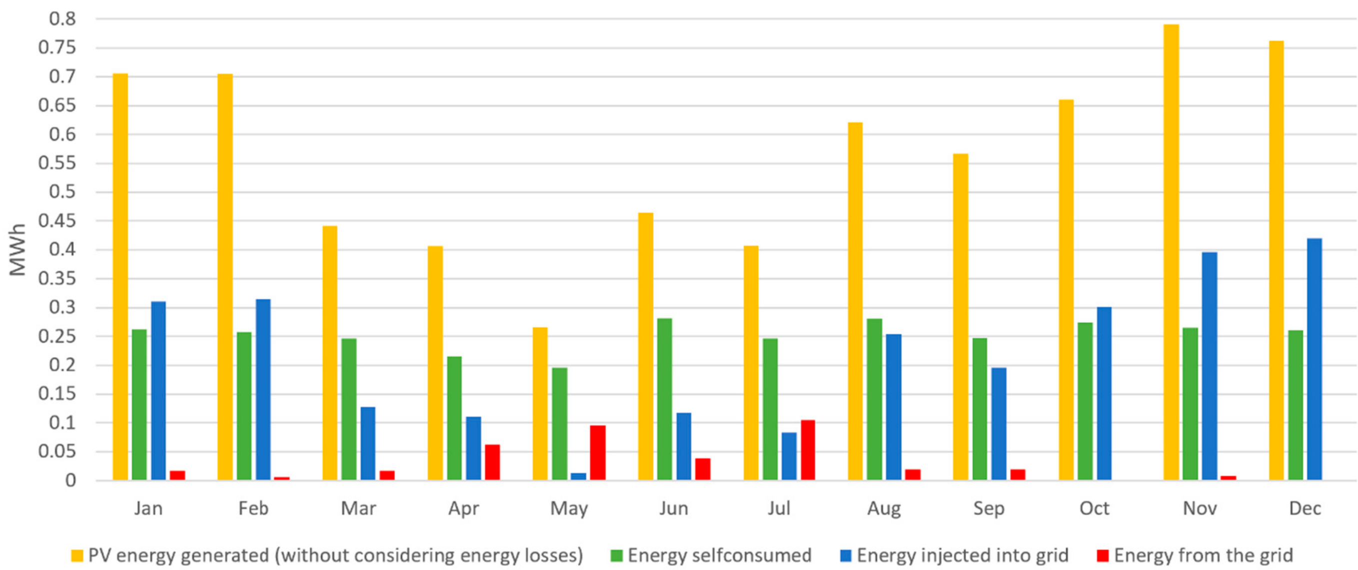

Figure 14. Energy management for PV system with BESS.

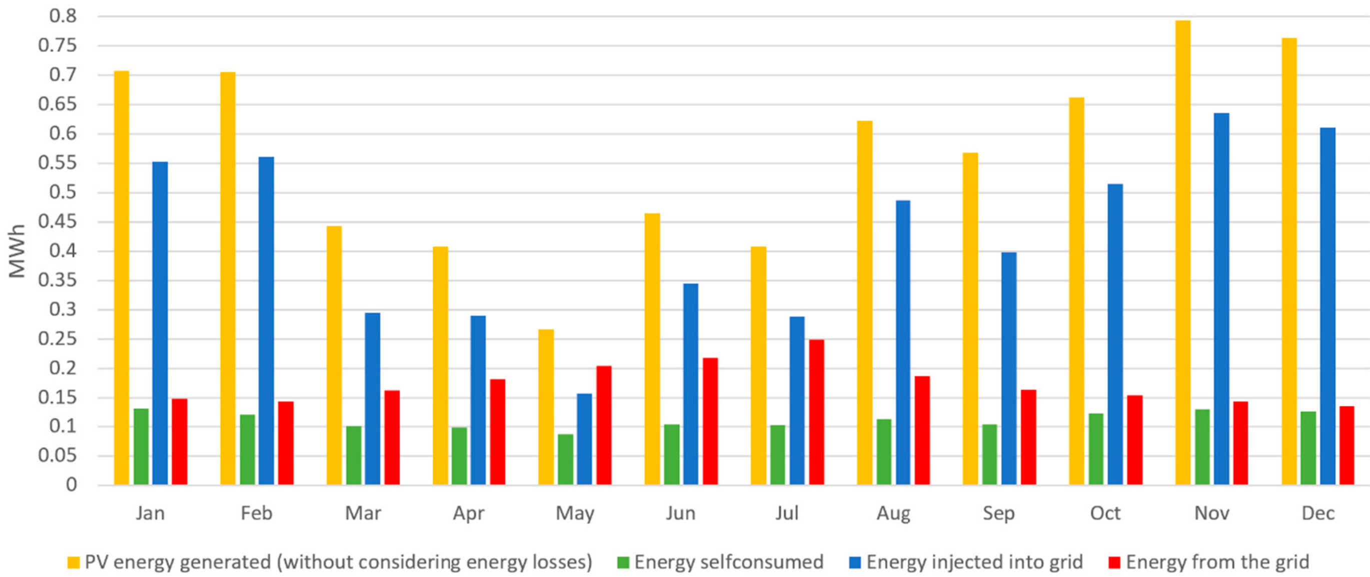

Figure 15. Energy management for PV system without BESS.

5.4. Results of Different Sizing Based on the Available Surface

A major problem that usually arises in the dimensioning of residential PV systems is the availability of surface for the installation.

In this work, eight different scenarios are developed, both with or without BESS, based on the surface occupation of a roof with a assumed slope of 30°. Table 11 shows the economic indicators corresponding to each scenario considering the surplus injection limitation.

Table 11. Economic results for the eight scenarios depending on the available roof surface, considering the established limitation.

Configuration Type	PV Panels	Required Surface (m^2)	CAPEX (CLP$)	NPV (CLP$)	IRR (%)	Payback (Years)
PV+BESS	4	from 9	8.229.260	−6.384.060	−4.8	No payback
PV+BESS	8	from 17	9.143.939	−5.270.035	0.4	23.9
PV+BESS	12	from 25	10.708.091	−6.804.372	−0.6	No Payback
PV+BESS	16	from 34	11.724.407	−7.820.688	−1.3	No Payback
PV	4	from 9	1.859.335	612.966	14.2	6.7
PV	8	from 17	2.782.648	1.358.395	16.2	5.9
PV	12	from 25	4.238.710	890.354	12.7	7.5
PV	16	from 34	5.333.011	−203.947	9.5	9.4

For the cases with BESS, it is concluded that:

- None of the scenarios turns out to be profitable for the discount rate considered. This is mainly due to the high initial investment cost that the acquisition of the BESS presents;
- For the scenarios of 4, 12 and 16 panels, the projects are not profitable and the investment would not recover within the time interval;
- For the 8 panels scenario, a payback is achieved within the project horizon, however, a discount rate of at most 0.4% would be needed for the project to be profitable, which turns out to be very below the normally used range of 5 to 10%.

For the cases without BESS, it is concluded that:

- The cases of 4, 8 and 12 panels are profitable, while the case of 16 panels does not meet the expected profitability for the selected discount rate;
- The most favorable case is 8 PV panels. It is observed that sizing on a smaller scale in relation to sizing based on the energy consumption results in greater profitability. This

is mainly due to the fact that, compared to the cases of 12 and 16 panels, a lower initial investment is required, and at the same time a greater fraction of the energy generated is selfconsumed. This allows greater savings to be achieved due to the cost of electricity investment and a smaller amount of surpluses are also generated which are valued at a lower price than selfconsumed energy. On the other hand, compared to the case of 4 PV panels, in the latter case, based on selfconsumption and the injection of surpluses, it is not possible to reduce the electricity rate to zero, so the greatest possible economic savings are not obtained. In the case of 8 panels, despite requiring a greater initial investment, there is a greater generation, achieving greater self-consumption (for example, in the case of 4 panels, for the first year self-consumption is of 1338 kWh/year, while in the case of 8 panels it amounts to 1493 kWh/year), which allows greater annual economic savings and recover the investment in a shorter period of time;

- The decrease in profitability from the case of 8 PV panels to 16 PV panels is because there is a selfconsumption limit for PV energy, which is defined based on the same energy consumption of the home. Therefore, by installing a greater number of panels, a greater investment is required, and at the same time the annual economic savings will be capped at the amount equivalent to the annual electricity rates to be paid, corresponding to CLP$565.059 (see Table 12).

Table 12. Average economic results for the cases without BESS.

PV Panels	CAPEX (CLP$)	Annual Tariff without PV System (CLP$)	Average Annual Selfconsumption Savings (CLP$)	Average Annual Surplus Injection Savings (CLP$)	Total Annual Savings (CLP$)	Payback (CLP$)
4	1.859.335	565.059	215.587	50.185	265.771	6.7
8	2.782.648	565.059	244.263	200.298	444.561	5.9
12	4.238.710	565.059	251.708	313.351	565.059	7.5
16	5.333.011	565.059	255.847	309.212	565.059	9.4

Because the low profitability obtained from PV systems with BESS at the residential level, it is likely that no investor will be interested, and the grid infrastructure could not be protected. This is due to the high initial investment cost, as well as to the established limitation of the maximum reduction to zero of the electricity rate in Chile. Due to this, the economic results of the previous cases are analyzed, but without considering this limitation, allowing a total monetary reimbursement of the surplus energy injected (see Table 13).

Table 13. Economic results for the eight scenarios depending on the available roof surface, without the established limitation.

Configuration Type	PV Panels	Required Surface (m^2)	CAPEX (CLP$)	NPV (CLP$)	IRR(%)	Payback (Years)
PV+BESS	4	from 9	8.229.260	−6.384.060	−4.8	No payback
PV+BESS	8	from 17	9.143.939	−5.104.013	0.7	23.5
PV+BESS	12	from 25	10.708.091	−4.900.371	2.7	19.4
PV+BESS	16	from 34	11.724.407	−4.351.490	4.3	16.9
PV	4	from 9	1.859.335	612.966	14.2	6.7
PV	8	from 17	2.782.648	1.358.395	16.2	5.9
PV	12	from 25	4.238.710	1.485.347	14.5	6.5
PV	16	from 34	5.333.011	1.960.930	14.7	6.4

In this way, with the new results, it can be observed for the cases with BESS that:

- With the exception of the case with 4 PV panels, the IRR increases for all the projects because there is a greater economic reimbursement due to the injection of surpluses. In the case of 4 panels, this does not happen because the total annual savings fail to reduce the electricity rate to zero, so the limitation in this scenario does not affect the results;

- Unlike the case with limitation, now the scenario with 16 panels turns out to have the highest IRR, because the highest level of surplus is generated, and therefore greater economic savings;
- Neither case is profitable at the selected discount rate;
- There is a direct relationship between the number of PV panels and the profitability of the project. Therefore, for PV systems with a number of panels greater than 16, it is projected that an IRR would be obtained within the range between 5% and 10%, allowing these projects to be profitable;

On the other hand, for the cases without BESS, it is concluded that:

- Cases with 4 and 8 panels, the total annual savings fail to reduce the annual electricity rate to zero. Therefore, the limitation does not affect the results in these cases;
- Despite the increase in the profitability of cases with 12 and 16 panels, the case with 8 panels is still the optimal;
- The cases of 12 and 16 panels are less profitable than the case with 8 panels, because the reimbursement of surpluses cannot compensate for the increase in CAPEX required in those cases.

5.5. Economic Results According to Storage Capacity of the Battery Bank

The economic results were obtained for the base case of a 4.92 kW PV system with 12 installed panels of 410 W, but this time varying the storage potential of the BESS for lower capacities, in order to reduce the initial investment costs. Five different cases were studied, which are summarized in Table 14, presenting different storage capacities, aimed at supplying certain critical loads within the home, or with the intention of charging the electric vehicle for daily trips. In all cases, deep cycle batteries from the manufacturer Rolls, a maximum depth of discharge of 45% and a maximum total discharge time of 20 h (C20) were considered.

Table 14. BESS description and storage potential for each studied case.

Case	N° Batteries	Nominal Voltage (V)	Capacity C20 (Ah)	Storage Potential (kWh)
1	6	8	568	12.3
2	4	12	371	8
3	4	12	210	4.5
4	4	12	155	3.3
5	4	12	85	1.8

The economic results obtained are summarized in Table 15, where it can be seen that as a BESS with less storage potential is installed, then the project will increase its profitability. However, despite the drastic drop in paybacks, together with the increase in the IRR, in none of the cases the expected rate of return of 10% is obtained.

Table 15. Economic results obtained for each case.

Case	CAPEX	NPV (CLP$)	IRR (%)	Payback (Years)
1	10.708.091	−6.804.372	−0.6	No payback
2	8.503.352	−4.170.300	2.4	19.9
3	5.680.272	−2.197.107	4.2	16.1
4	5.374.967	−1.003.456	7.4	10.7
5	4.954.677	−616.922	8.3	10.1

It should also be noted that by reducing the storage potential, there is a greater risk of overloading the grid infrastructure, so that, in future work these possible economic losses could be considered in the study.

6. Discussion

It is concluded that the cases with BESS do not reach the expected profitability for any of the cases studied. While, for systems without BESS, its profitability increases when the installed power is less than the power obtained in a dimensioning based on the energy consumption, because there is a greater fraction of self-consumption of the PV generation, together with the fact that a lower initial investment is required. Furthermore, there is a limitation in the economic savings that can be obtained, which is determined by the amounts of the electricity bills, as well as the legal limits imposed on the reimbursements of the injected surpluses which can only reduce the electricity rate to zero.

For this reason, the previous cases were analyzed considering a total reimbursement of all energy injections into the grid, eliminating the legal limitation on reimbursements, thus obtaining an increase in profitability when installed a PV system with a higher installed power, because the maximum economic savings are achieved through self-consumption, and in addition, extra income is being received from of injection reimbursements. In this way, it would be possible to obtain profitable projects for systems with BESS if this legal limitation were not present.

Subsequently, the PVsyst software is used to simulate the energy management during the first year of operation for each of the two sizing based on energy consumption. In this way, it is concluded that a BESS will allow a large part of the surplus to be stored, thus avoiding energy from the grid, avoiding over consumption from it, and protecting grid infrastructure. However, as future work, it would be interesting to study if it is possible that a large storage capacity is not essential to protect the grid infrastructure if a HEMS is applied, so the BESS can be dimensioned with smaller capacities and thus reduce the investment costs. On the other hand, it should be noted that the software consider a greater number of factors that influence PV generation, such as variations in meteorological data, where the software creates synthetic data from probabilistic methods, or by considering the variations in generation from the efficiency curves of each PV system component.

In this work, the main objective of dimensioning the PV systems was to save the energy consumption for the home and the daily charging of the EV. However, the same EV battery could be used as a kind of alternative battery bank. Nevertheless, the PV system dimensioned is not designed to fully charge the EV battery, since in this way a large number of panels would be needed, which would possibly not fit the space available within a typical home in Chile. Additionally, it is necessary to consider the degradation of EV batteries due to frequent use, which could lead to a high replacement cost. Depending on the needs of the residents, the EV could be fully charged from the grid, and in this way it could be used in emergencies or as a backup for critical equipment within the home. Future work could realize the economic feasibility of using the EV as a storage source instead of investing in a battery bank.

7. Conclusions

Small scale distributed generation systems will be a fundamental element in smart cities which are currently in constant development. This work presented a feasibility study for sizing PV systems, with and without BESS, in order to support the house energy consumption and provide economic savings for residents. It is concluded that PV systems with BESS do not turn out to be profitable, due to the high investment cost that the acquisition of a BESS presents, and which corresponds to about 40% of the initial investment for the base case study of 12 PV panels. On the other hand, there is a drastic difference between investment cost of each case. The CAPEX when incorporating a BESS increases by 442%, 328%, 252% and 219%, for 4, 8, 12 and 16 PV panels, respectively, compared with PV systems without BESS, assuming a storage capacity of 12.3 kWh. When sizing a BESS with a lower storage capacity, profitability tends to increase; however, the estimated discount rate of 10% is not achieved. This is mainly due to a lower initial investment being required, together with lower replacement costs for the batteries. However, in cases of lower storage capacity, an acceptable rate of return is achieved, considering the context in which there is an urgent need to power critical equipment or help reduce stress on the grid infrastructure or charge the EV with local generation. Finally, even though a higher capacity BESS allows a higher level of self-consumption, together with less energy from the grid, this effect does not compensate for the high investment cost required by a higher capacity bank.

On the other hand, PV systems without BESS turn out to be highly profitable, with an IRR of 16.2% and a payback of 5.9 years for a PV system with a nominal installed power of 4.92 kW. However, as there is no BESS to store surplus energy for later charging of the EV, the implementation of an HEMS is essential within the home, along with the implementation of a smart EV charging schedule which must schedule charging times within the time range of higher PV generation in order to reduce consumption from the grid. Furthermore, the most optimal sizing from the economic aspect will always require a lower number of PV panels than the sizing based on the energy consumption of the home, corresponding to 12 PV panels in this study case. In this way, a PV system of 8 panels without BESS turns out to be, from an economic point of view, the most optimal dimensioning of all those studied regardless of whether or not there is a limitation on the reimbursement of the injected surpluses.

The present work leaves open much research. On the one hand, despite the null profitability of the systems with BESS, the economic losses that could cause damage to the grid infrastructure or its cost of redesign were not considered. Thus, if a balance were made between the losses generated and the additional investment that the implementation of a BESS requires, it would be interesting to discover if this type of system is ultimately profitable. On the other hand, a great solution to improve the profitability of the PV system is the energy transactions between consumers. Energy transactions are generally carried out within smart energy microgrids, allowing a resident who has a PV system in their home to market their own generated energy by selling it on an energy market at a price greater than the grid price. The interested consumers in buying this energy can obtain it at a lower price than the grid price. However, in Chile, there are still legal obstacles regarding the sale of energy between residents.

Author Contributions: Conceptualization, J.S.-M., A.F.-M. and M.A.A.; methodology, J.S.-M., A.F.-M. and M.A.A.; software, J.S.-M.; validation, J.S.-M., A.F.-M. and M.A.A.; writing—original draft preparation, J.S.-M., A.F.-M. and M.A.A.; writing—review and editing, J.S.-M., A.F.-M. and M.A.A.; supervision, A.F.-M. and M.A.A.; project administration, M.A.A.; funding acquisition, M.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Agencia Nacional de Investigación y Desarrollo (ANID) through the Proyecto Fondecyt de Iniciación en Investigación 2020 under Project ID11200178.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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