Int. J. Renew. Energy Dev. 2024, 13 (6), 1078-1092

Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.cbiore.id

Research Article

Design and evaluation of a standalone electric vehicles charging station for a university campus in Argentina

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Abstract. The increasing popularity of electric vehicles in recent years has led to a growing demand for charging stations. In this context, universities are an ideal setting for their installation, as they have a large number of students, professors, and staff who could benefit from them and, at the same time, it serves as teaching material to raise awareness in the use of renewable energy. This work presents the design and proposal of an electric vehicle charging station for the campus of the Universidad Nacional de Rafaela (UNRaf). The station will be located in an area of the campus where the construction of more buildings and sport facilities is planned. This area will not be connected to the electrical grid and instead, will have an energy storage system to guarantee supply. The station will have the capacity to simultaneously charge 4 bicycles and 2 light electric vehicles, with an average energy demand of 0.786 kWh per hour. Homer Pro software was used for the calculations. The most economically viable option was a 100% renewable solution powered only by solar energy. It is expected to consist of a 15-kW solar system that will produce 22,922 kWh/year and a bank of 30 batteries of 3 kWh plus a single battery of 1 kWh. The installation of the electric vehicle charging station on the UNRaf campus will contribute to promoting the adoption of sustainable transportation, which will help reduce greenhouse gas emissions without using the public power grid.

Keywords: HOMER Pro, Isolated Microgrid, Photovoltaic Panels, Renewable Energies, Solar Energy, Sustainable Development.

Received: 27th May 2024; Revised: 8th July 2024; Accepted: 6th Oct 2024; Available online: 9th Oct 2024

1. Introduction

The transformation of the energy sector is the key to sustainable development. However, in Argentina, this sector mainly depends on fossil fuels such as coal and natural gas. The National Energy Transition Plan to 2030 of Argentina (Subsecretaría de Planeamiento Energético de Argentina, 2023) aims to achieve a 50% share of renewable energies in the country's electricity matrix. To this end, the Argentine government has adopted a series of policies, including a package of laws and programs, such as the Renovar Program (Gobierno de la República Argentina, 2016), the Renewable Energy Trust Fund (Banco Argentino de Desarrollo, 2019), and Law 27,191 on Renewable Energies (Presidencia de la Nación Argentina, 2019). The plan also aims to reduce greenhouse gas (GHG) emissions from the transport sector, one of the main emitters, which have increased in recent years due to the growth of the vehicle fleet and air traffic. According to the report "National Inventory of GHG of the Argentine Republic - Year 2022" (Ministerio de Ambiente y Desarrollo Sostenible, 2022), the transport sector is responsible for 9.9% of total national emissions, which are mainly due to the use of fossil fuels, such as gasoline and diesel. At the local level, in the city of Rafaela, the transport sector is also one of the main responsible for these emissions. In 2018, the transport sector represented 29.13% of the city's total emissions (Instituto Para el Desarrollo Sustentable de Rafaela, 2018), as the result of the large number of internal combustion vehicles that circulate on the city's streets and the population growth. To reverse this situation, it is necessary to reduce GHG emissions from the transport sector. One way to do this is to promote the use of electric vehicles (EV). However, for these vehicles to be a viable option, an adequate charging infrastructure is needed, which mainly uses renewable energy. This transition is an arduous task as it will require charging stations to be as numerous as conventional fuel stations and the energy to supply them will have to come from renewable sources (Nilsson & Nykvist, 2016; Skjølsvold & Ryghaug, 2020). In this context, the Universidad Nacional de Rafaela (UNRaf) wants to make its contribution to the conservation of the planet by using renewable energy within its campus. UNRaf is a recently created educational institution and is in a period of expansion both in terms of the number of students and teaching and its facilities. Regarding the latter, it is worth mentioning that two new buildings are under construction and development that will house classrooms, research centers and administrative offices as well as a football field and sports ground. Due to the unpredictability of construction times and current technical constraints, added to the future objective of becoming independent from the electricity grid with 100% renewable and self-generated energy.

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https://doi.org/10.61435/ijred.2024.60356
ISSN: 2252-4940/© 2024.The Author(s). Published by CBIORE

The first step towards achieving these objectives was the design and evaluation of an electric vehicle charging station (EVCS) based on solar. The sizing of this charging station was specifically designed for the needs of the University and the number of possible solutions and the technical-financial feasibility were analyzed with the HOMER Pro software. Despite the important contributions in previous studies using this type of methodology (Ekren *et al.*, 2021; Oladeji *et al.*, 2021; Nityanshi *et al.*, 2021; Karmaker *et al.*, 2020; Singh *et al.*, 2022; Oladigbolu *et al.*, 2023; Ponnapalli *et al.*, 2023), there are no studies that analyze the isolated microgrid for EVCS in Argentina and especially in the central region of the country, which highlights the significance of the present study. The main objective of this work is to design and evaluate a technically and financially feasible project based on renewable energy for the UNRaf campus. A sensitivity analysis was performed considering different minimum states of charge (SoC) of batteries and different electric loads. In addition, this study also compared the potential costs of satisfying EVCS demands with grid extension.

1.1 Chronological Overview of Electric Vehicles (EVs) in the Argentina Market

The evolution of the EV market in Argentina faces several challenges, shaped by the country's economic status, the limitations of its automotive industry, and its reliance on external markets (Baruj *et al.*, 2021). As a middle-income country with a relatively small domestic market, Argentina has difficulties in transitioning to electric vehicles. The country's geographical distance from regions with high EV demand further complicates its ability to attract investment and technology necessary for this transformation (IEA, 2023). Even though the volume of the EV market is still neglectable, its evolution trend seems to be promising (Statista, 2024), see Fig. 1.

In addition, Argentina is behind the rest of the region in terms of initiatives for the production and use of EVs. However, the current regulatory framework is oriented to address this gap (IDB, 2019). In 2018, the National Government modified the Traffic Law via Executive Order 32/2018 (Boletín Oficial República Argentina, 2018), introducing categories for EVs. The following year, through Executive Order 26/2019 (Argentina, 2019), the government further adapted the regulatory framework by modifying driver's license classifications to include EVs (MOVE, 2019). Nowadays the Congress is analyzing different bills aiming to establish a comprehensive regulatory framework to promote the production, trade, and use of EVs (Baruj *et al.*, 2021). A key step in this direction was taken in October 2021, when the National Government submitted the bill for the Promotion of Sustainable Mobility to Congress. This bill proposes tax benefits for the demand and supply of alternative fuel vehicles, public procurement quotas, and a ban on marketing new Internal Combustion Engine Vehicles starting in 2041. By 2030, the law is expected to attract USD 8.3 billion in investments, create over 20,000 jobs, and save 10.7 million tons of CO2 equivalent (Dulcich *et al.*, 2022).

Argentina's traditional automotive industry saw a 30% contraction in total vehicle production between 2012 and 2022. The domestic companies have increasingly focused on producing standard, low-complexity components, limiting the industry's capacity to innovate and adapt to the demands of the EV market. This reduction in productive and technological capabilities presents a major obstacle to the country's ability to undertake a large-scale transition to electric vehicles. Moreover, Argentina's automotive industry is heavily oriented towards the foreign market, with Brazil being the primary destination for its exports, accounting for 65% of the total in 2022. However, the slower pace of transport electrification in Brazil, coupled with the significant role of biofuels in the region, limits Argentina's ability to scale up EV production. The lack of demand for electric vehicles in both local and external markets makes it difficult for Argentine subsidiaries of multinational corporations to secure investments for EV development (Rubio *et al.*, 2024). Despite these challenges, there are still opportunities for Argentina to activate the local market and to carve out a niche in the global EV market (de Luca *et al.*, 2024). Focusing on specific segments, such as electric buses or utility vehicles,

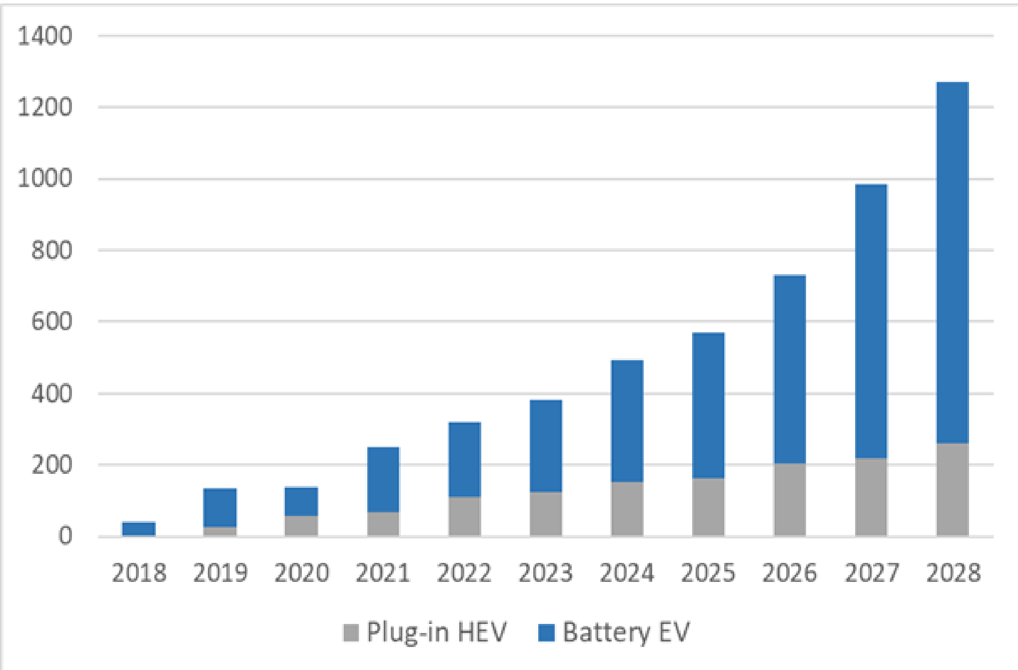

Fig. 1 EV unit sales registered up to 2023 and forecast up to 2028. Source: Statista, 2024.

could allow Argentina to leverage its existing capabilities while gradually building the necessary infrastructure and technological expertise. However, this will require targeted government support, strategic partnerships, and a clear vision for the future of the automotive industry (Slaifstein & Nicchi, 2023).

1.2 Geographical Overview of Charging Stations Development Globally

In many countries, EV charging stations are scarce and widely spaced apart. This scarcity of public chargers limits the adoption of electric vehicles. While EV charging infrastructure is being established in several countries, the necessary number of stations has not been achieved in most places, except in certain regions (Ritchie, 2023). As global EV charging networks expand, the demand for electric vehicles is anticipated to grow. However, these charging networks are still underdeveloped in the majority of countries (Mastoi *et al.*, 2022).

North America is the leader in infrastructure and innovative technologies, particularly the United States. It has been a global leader in the adoption of electric vehicles and the development of charging infrastructure. This leadership is evident in the extensive network of fast-charging stations, as well as the use of renewable energy sources, which not only enhances sustainability but also reduces long-term operational costs, to power these stations (Brown *et al.*, 2024). The United States has seen a proliferation of charging stations, especially in urban areas and along major travel routes, such as Tesla's Supercharger network (Li, 2024). Additionally, the country has made significant progress in standardizing charging technologies, which has facilitated interoperability between different providers and improved the user experience. In Canada, although the density of charging stations is lower, the country has adopted a similar approach regarding the integration of renewable energies. The diversity of charging options available is highlighted, from public stations in urban areas to fast-charging stations on highways. In addition, the installation of residential chargers has been promoted to facilitate the charging of electric vehicles at home (Etukudo *et al.*, 2024).

Europe is another region that has experienced rapid growth in electric vehicle charging infrastructure, largely driven by favorable government policies and a strong commitment to sustainability (Mastoi *et al.*, 2022). The study by Corti *et al.* (2024) highlights that Europe is not only investing in charging stations for cars but also in infrastructure for micro mobility vehicles, such as electric scooters and bicycles. This diversification is crucial in densely populated cities, where micromobility plays a key role in reducing congestion and pollution. Countries like Norway, the Netherlands, and Germany lead in charging station density per capita. In Norway, particularly, the benefits of deploying EVs are significant thanks to the fact that virtually all electricity in the country is produced by renewable sources, mostly hydropower (Falchetta *et al.*, 2022). Moreover, in Southern Europe, in countries like Spain and Italy, solar energy has become a key source for charging stations (Lanz *et al.*, 2022).

Asia, particularly China, has seen an explosion in the adoption of electric vehicles and the construction of charging stations. China is the world's largest electric vehicle market, and the government has made significant investments in charging infrastructure to support this growth. China's focus has been on creating massive urban charging networks, especially in cities like Beijing, Shanghai, and Guangzhou. These cities boast thousands of charging stations, many of which are integrated into residential and commercial complexes (Ji & Huang, 2018). However, Asia also faces unique challenges. Das (2024) highlights that coastal cities in Bangladesh have great potential for integrating hybrid charging stations that use both solar and wind energy. These stations can help mitigate challenges related to energy availability and grid stability in the region. In India, for instance, the development of charging stations has been slower due to the limited availability of electricity and the lack of standardization in charging technology. Charging stations in India are beginning to integrate renewable energy sources, such as solar, to overcome these challenges. However, the widespread adoption of electric vehicles still faces obstacles due to poor electrical infrastructure and high temperatures, which can affect both batteries and charging stations (Tarei *et al.*, 2021). Japan, another key player in the Asian market, has made significant strides in integrating charging stations and the implementation of emission standards. Japan has adopted a "rapid charging" approach, with stations that allow a vehicle to be charged in less than 30 minutes. This approach is particularly important in a country where space is limited and efficiency is key. Additionally, Japan has been a pioneer in the standardization of charging technologies, such as the CHAdeMO system, which has been adopted by several countries outside of Asia (Mastoi *et al.*, 2022). Latin America and Africa lag behind in terms of charging infrastructure development compared to other regions. However, some countries are beginning to make notable progress. In Latin America, countries like Brazil, Chile, and Colombia are leading in the adoption of electric vehicles and the development of charging stations. However, public policies, subsidies, and coordination between different agents (public administrators, regulators, energy suppliers, operators, and EV users) are crucial to accelerate EV adoption in the region (Bitencourt *et al.*, 2023). Africa, on the other hand, faces more significant challenges due to the absence of clear policies and regulations, the high purchase price of EVs, poor electricity networks, and the scarcity of public e-charging stations. However, there are ongoing initiatives in countries like South Africa and Kenya to develop charging stations that use renewable energy, particularly solar. These initiatives align with efforts to improve overall electrical infrastructure and promote sustainability on the continent (Gicha *et al.*, 2024).

2. Methodology

2.1 Design and optimization of EVCS

The Hybrid Optimization Model for Electrical Renewable HOMER Pro® simulation tool widely used and tested in different scenarios was used in the present analysis (Arabzadeh Saheli *et al.*, 2019; Çetinbaş *et al.*, 2019; Shezan, 2019; Kasaeian *et al.*, 2020; Koffi *et al.*, 2022; Diyoke *et al.*, 2023; Khamharnphol *et al.*, 2023; Oueslati *et al.*, 2023). The required input data was: the load profile, meteorological resources, economic constraints and specifications of the system components (the software provides instructions with characteristics and prices). This data is used to provide a list of feasible systems ranked by lowest total Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). The data loaded by default with a discount rate of 8%, an inflation rate of 0% and a project life horizon of 25 years were used as assumptions for an initial study. Furthermore, the modeling and optimization of different hybrid energy systems from the literature were previously studied in terms of various techno-economic and environmental parameters. The financial

Table 1
Economic-financial formulas used by HOMER Pro.

Net Present Cost (NPC)	NPC is defined as the present value of the system's total cost throughout the project lifetime, minus the total revenue's current value during the project lifetime $$NPC = \frac{C_{ann}}{CRF}$$ where: C_{ann} is total annualized cost (i.e., the sum of the annualized costs of each system component), and CRF is capital recovery factor calculated from the following equation: $$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}$$ where: i is annual interest rate or real discount rate (%), which is used to convert between one-time costs and annualized costs in percentage, and N is Project lifetime (year). The annual interest rate is calculated by: $$i = \frac{i' - f}{1 - f}$$ where: *i'* is the nominal discount rate (%), which represents the rate at which one can borrow money, and *f* is the expected inflation rate over the project life (%).
Levelized cost of energy (LCOE)	The levelized cost of energy is the average cost per kWh of useful electrical energy produced by the system. $$LCOE = \left(\frac{C_{ann,tot}}{Energy\ Served}\right)$$ where: $C_{ann,tot}$ is total annual cost [USD/year] and $Energy\ Served$ is total served electrical load [kWh/year].
Initial Capital	The initial capital cost of a component is the total installed cost of that component at the beginning of the project. $$C_{ca} = \sum_{k=1}^{K} Cc_k$$ where: Cc_k is the cost of component k.
Operating Cost	The operating cost is the annualized value of all costs and revenues other than initial capital costs. $$C_{operating} = C_{ann,tot} - C_{ann,cap}$$ where: $C_{ann,tot}$ is the total annualized cost [USD/yr] and $C_{ann,cap}$ is the total annualized capital cost [USD/yr].
O&M Costs of de System	It is the sum of the operation and maintenance costs of all components. $$C_{O\&M} = \sum_{k=1}^{K} C_{O\&M_k}$$ where: $C_{O\&M_k}$ is the operation cost of component k.

and technical indicators and formulas used by HOMER Pro are expressed in the following tables, for more details and equations refer to the software's webpage (HOMER Pro, 2006): This software also gives the possibility to analyze how it can affect numerous input variables in the systems. The sensitivity parameters considered in this work involve minimum SoC and different load situations.

Grid extension cost is defined as the cost per km of the user's distance to the nearest access point to the central grid. Effect of distance from grid and the optimal breakeven distance are commonly calculated using HOMER Pro. The price per kilometer, an input variable used to break-even point calculation, is typically assumed to have a linear relationship proportional to project length. However, this assumption may not hold true for short distances. To address this limitation, a detailed analysis of capital costs was performed.

2.2 EVCS Case Study Location

This work considers powering a charging station designed for UNRaf staff and students. The campus is located in the city of Rafaela (-31.271 S, -61.511 W), a place corresponding to the Castellanos department, province of Santa Fe (Argentina) (Fig. 2). The city is located on the Pampas plain, at an altitude of 100 meters above sea level. Although there are currently no limitations for access to electrical energy service, by reason of an expansion of the property as previously mentioned, the western part of the campus (marked with the red rectangle) will not have access to the electrical grid in the next 10 years. Therefore, it is desired that the provision be independent and

Table 2
Technical formulas HOMER Pro.

Solar irradiance calculation equation	$G = Go(1 + \alpha\, cos(\theta))(1 - \beta T)$ where: G is the solar irradiance at the PV panel location, G_o is the extraterrestrial solar irradiance, α is the atmospheric loss coefficient, θ is the solar zenith angle, β is the temperature coefficient, and T is the panel temperature.
Electrical power output of the PV panel	$P_{PV} = AG\eta_{PV}P_R$ where: A is the panel area, G is the solar irradiance, η_{PV} is the panel efficiency, and P_R is the performance ratio (accounts for losses due to shading, dirt, and other factors).
Wind power calculation equation	$P_{WT} = \frac{1}{2}\rho_{air}AV_{wind}^3$ where: P_{WT} is the power available in the wind, ρ_{air} is the air density, A is the effective swept area of the rotor, and V_{wind} is the wind speed.
Battery capacity required	$C_{battery} = \frac{E_{demand}}{(V_{battery}\eta_{battery}DOD)}$ where: DOD is the depth of discharge, $V_{battery}$ is the battery voltage, and $n_{battery}$ is the battery efficiency.

Fig. 2 Location of the UNRaf Campus in the city of Rafaela (blue rectangle) and projected area for the creation of more buildings and sports field (red rectangle). Location within the province of Santa Fe (Argentina) upper left. Source: Google Maps.

environmentally friendly, without generating harmful emissions (Grupo Banco Mundial, 2022).

2.3 Electric Load and Operation Strategy

Initially, the target load profile was evaluated to determine the size of the charging station. Fig. 3 illustrates the estimated daily, monthly, and annual load profiles, considering an average demand where the lowest load time is at 8:00 am with 0.28 kW and the highest load time is at 6:00 pm with 5.11 kW (Fig. 3 top left). The Seasonal Profile figure shows the variability between different months with peak loads ranging from 6.68 to 8.62 kW. In addition, it can be seen that the load profile remains constant throughout the year, showing its highest supply between 6:00

Table 3
Applied load of the different EVs

Type	Power load (kW)	Quantity	Power Sum (kW)
Bike	0.28	4	1.12
Tricycle	0.72	1	0.72
Car	4.96	1	4.96

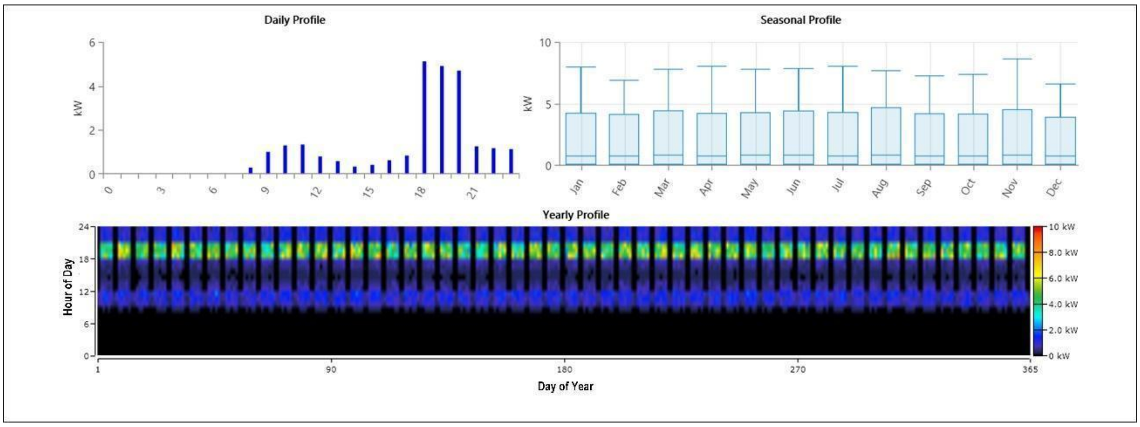

Fig. 3 User load profiles estimated by HOMER Pro.

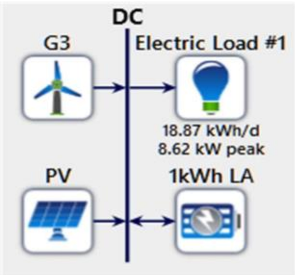

Fig. 4 Scheme of the proposed isolated microgrid.

pm and 8:00 pm, which coincides with greater attendance of students.

These values were calculated based on an isolated charging station for the vehicles detailed in Table 3. The daily demand profile was estimated according to the University's opening hours from 8:00 am to 12:00 am. The charging station will not be in operation at night when the University is closed (Bansal *et al*., 2020). It was considered that the car and tricycle owned by the university are used for maintenance tasks and are charged only once a day in different shifts, so that one of them is always available and that their charge is consumed during the day. The necessary load during weekends was also considered, averaging its values and considering a half day of 4 hours from 8:00 am to 12:00 pm (profile not shown).

The power load given in this Table for each vehicle is based on the manufacturer recommendations aimed to ensure the batteries lifetime. For each case, taking into account the battery capacity and the charging time provided by the manufacturer it can be determined the mean power load which is listed in this Table.

The power flow diagram of the proposed charging station is shown in Fig. 4. It is an off-grid system driven by direct current that consists of wind turbines (WT), solar panels (PV) and energy storage. The software will evaluate and recommend the best system: hybrid, solar PV, or wind turbine. The technical and economical specifications of each component are tabulated in Table 4 and are those configured by default in the software. This Table shows the main characteristics of each system for a rated size that can be scaled. The technical and economical values in the Table are given for a 1 kW PV System, a 3 kW Wind Turbine and a 1 kWh capacity Battery Storage.

Table 4
Technical and economic definitions for the components of the proposed system.

Component	Producer	Specifications	Costs
Photovoltaic Panels (PV)	Generic	Panel rated power: 1kW. Derating factor: 80% Lifetime = 25 years	Capital (USD): 2.500 Operation (USD/year): 10 Replacement (USD): 2.500
Wind Turbine (WT)	Generic	Rated power: 3 kW Hub height: 18 m Lifetime = 20 years	Capital (USD): 18.000 Operation (USD/year): 180 Replacement (USD): 18.000
Battery Storage	Generic	Lead Acid Nominal voltage: 12 Nominal capacity (KWh): 1 Nominal capacity (Ah): 83.4 Capacity ratio: 0.403 Rate constant (1/h): 0.827 Roundtrip efficiency: 80% Maximum charge current (A): 16.7 Maximum discharge current (A): 24.3 Maximum charge rate (A/Ah): 1 Minimum State of Charge: 40%	Capital (USD): 300 Operation (USD/year): 10 Replacement (USD): 300

2.4 Renewable Energies in EVCS

Rafaela has a temperate climate, with an annual average rainfall of 951 millimeters. Temperatures range from an average of 18 to 6 °C in winter and from 31 to 18 °C in summer. The region has 2,500 hours of sunshine per year. In terms of wind energy, it is estimated that its winds have a speed of around 5 m/s but are not constant during the day. According to the NASA Prediction of Worldwide Energy Resource database obtained from HOMER, Rafaela has average values of solar irradiance, ambient temperature and wind speed of 4.85 kWh/m$^2\cdot$day, 19 °C and 6.08 m/s, respectively (Bellini *et al.*, 2005; Tang *et al.*, 2021). Figure 5 shows weather information on solar irradiance, temperatures and wind speeds.

Fig. (5a) shows the monthly average of solar radiation in the city of Rafaela. It also includes the clearness index, which is the ratio between the measured GHI (Global Horizontal Irradiance) and the solar radiation that would be received under clear sky conditions. The clearness index indicates the extent to which atmospheric conditions affect the solar radiation reaching the surface (Jiang, 2009). The highest clearness index is in January and is 0.578 and the lowest in June is 0.503. On average it remains practically constant throughout the year and this allows us to predict with accuracy the weather conditions of the later periods. As can be seen, the months with the highest solar radiation are January, February, November and December. According to the seasons of the year in Argentina, the month of January corresponds to summer and the educational institution keeps its doors closed for students but not for plant and research personnel. Additionally, the months of February and December correspond to exam dates and the end of the university academic year, respectively, therefore, there is no significant attendance of students at the institution. In addition, the months between March and September show a decrease in solar radiation due to the Autumn and Winter seasons where there are fewer hours of sunshine per day, there is greater cloudiness or seasonal variations in solar angles affect to a greater extent (Schetinger *et al.*, 2020).

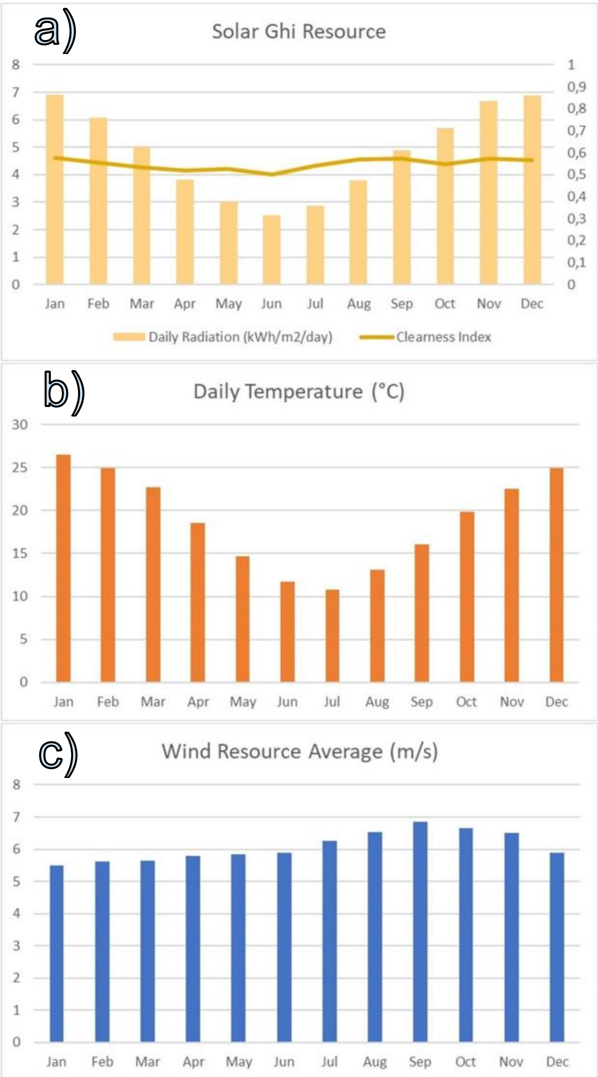

Fig. 5 Weather information retrieved from NASA Prediction of Worldwide Energy Resource database. **a)** The monthly average solar global horizontal irradiance in Rafaela. **b)** Average daily temperature vs. month, last 30 years. **c)** Monthly average wind speed at Rafaela.

As shown in Fig. (5b), the temperature range between the highest temperature of 26.55 °C (January) and the lowest of 10.77 °C (July) is 15.78 °C, with an annual average monthly temperature of 18.88 °C. This moderate temperature range benefits solar energy generation, it allows solar cells to cool at night and heat up during the day. Too high a temperature range can have a negative effect on the efficiency of solar cells (Sun *et al.*, 2022).

Fig. (5c) shows the average wind speed for the city of Rafaela. The dataset provides valuable information on long-term historical wind speed patterns, allowing for accurate assessments of wind energy resources. In the city of Rafaela, the average wind speed is generally measured at a specific height, known as the anemometer height (in this work 10 m was selected). The chosen height is fundamental, since the wind speed increases with height due to the reduction of surface friction, according to the boundary layer theory of fluid mechanics and the lower number of obstructions (Stull, 2012). As can be seen, the lowest value in the wind average occurs in the month of January, while the other months show an average value greater than 5.5 m/s, with September standing out due to the change of season, where the winds are more intense. It is worth mentioning that the annual average wind speed is 6.08 m/s.

3. Results and Discussion

A list of 586 feasible combinations of the elements proposed in Fig. 4 were evaluated using HOMER Pro Software. The optimal conditions were reached according to the Net Present Cost (NPC) and the levelized cost of energy (LCOE). The optimal economic and technical results of the components of the different charging station models are shown in Table 5 and Table 6 respectively. The combination of PV with battery storage is economically the best system architecture for the charging station, with an NPC of USD 99,355. It is clear that it had the lowest energy cost, LCOE of 1.12 USD/kWh, as well as lower operation and maintenance costs, and a lower initial investment capital. The solution composed of photovoltaic panels, wind turbines and batteries (PV-WT-Batteries) is also comparable, achieving an LCOE of 1.21 USD/kWh and an NPC of USD 107,721. A short compilation of similar studies using renewable sources is shown in Table 7. Although the LCOE of this work is higher, there is a precedent of a similar standalone project that also has a high cost of energy. Abdelbaki *et al.* (2019) analyzed different systems to supply energy to an isolated population in the Argentine Patagonia and obtained for a system powered only by solar panels the highest NPC, and energy costs of 2.70 USD/kWh, emphasizing the importance of considering

Table 5
Main economic indicators optimized by HOMER Pro

System Design	NPC (USD)	LCOE (USD/kWh)	Initial Capital (USD)	Operating Cost (USD/yr)	O&M Costs of de System (USD/yr)
PV-Battery	99355	1.12	64804	2673	1060
PV-WT-Battery	107721	1.21	69050	2991	1185
WT-Battery	131698	1.48	82800	3782	1500

Table 6
Optimal size and technical performance of the systems optimized by HOMER Pro

System Design	PV* (kW)	WT* (Qty.)	Batteries (Qty.)	System Energy Production (kWh/yr)	Clipped Energy (%)	Unmet Load (%)	Unmet Load (kWh/yr)
PV-Batt	15		91	22922	65.1	0.0868	5.98
PV-WT-Batt	9.5	1	91	21587	64	0	0
WT-Batt		3	96	21213	63.9	0.0716	4.93

*PV: Photovoltaic Panel
*WT: Wind Turbine

greater energy diversification and having multiple storage systems.

This proposal is aligned with the real needs of the National University of Rafaela and its community. This is relevant in developing countries, where socioeconomic and technological conditions can differ significantly from those of more advanced nations (Ebenezer *et al.*, 2021). In the province of Santa Fe, public universities pay a subsidized differential rate for public entities, in which the final cost per kWh ranges between USD 0.075-0.10. This means that the price of energy is not a relevant factor to take into account and that any sustainable generation alternative is less profitable. This gap between renewable energy prices and the subsidized price of energy, which mostly comes from non-renewable sources, is currently hindering the transition to clean energy (Hafez & Bhattacharya, 2017; Mardones & García, 2020).

Despite the higher cost of electricity generated by the technologies analyzed, it is crucial to consider the significant reduction in CO_2 emissions per kWh that these technologies achieve compared to traditional power plants (Filote *et al.*, 2020). Argentina's commitment to the Paris Agreement and the introduction of the carbon tax in 2018, starting at USD 10 per ton of CO2e and currently reduced to USD 6 per ton due to economic instability, further underscore the importance of considering environmental impact in energy decisions (Chiacchiera *et al.*, 2023). Although this carbon tax value may not seem significant at present, it could become more relevant if the current subsidy policy is withdrawn. The optimal system consists of a 15 kW PV system with a bank of 91 kW battery bank (main features of devices are described in Table 4 from which 22,922 kWh/yr are produced annually. The Clipped Energy or excess electricity is 65.1%, and very similar in the other similar systems analyzed, this high value negatively affects the profitability of the projects. To avoid the loss of this energy, it would be convenient to consider it for use in an irrigation system, office heating or for lighting that sector of the campus.

The unsatisfied load fraction within the systems refers to the total unsatisfied demand over the total annual electrical demand. It can be seen that the three solutions present a very low percentage of unsatisfied level, as shown in Table 6. The highest unsatisfied load can be attributed to seasonal variations during the months of May-June, which can decrease energy generation during those specific months and, together with fluctuations in the demand profile, could contribute to the unsatisfied load.

3.1 Photovoltaic Panels

The photovoltaic system is expected to generate 22,922 kWh/year, with a capacity factor of 17.4% and 4,374 work hours per year. Fig. (6a) shows the variation of the output power of the photovoltaic panels throughout the year during the day. Apparently, the panels start generating at 8 in the morning, between 8 and 11 in the morning they produce approximately 6.4 kW. Subsequently, between 11:00 a.m. and approximately 3:00 p.m., between 13-16 kW is produced. Finally, between 3:00 p.m. and 6:00 p.m. it produces approximately 6.4 kW. As can be seen, production varies slightly depending on the months of the year, it is negatively influenced in the winter months.

3.2 Batteries

As can be seen in Fig. (6b), the state of charge (SoC) of the battery bank remains constant throughout the year, at a percentage between 80% and 100%. In fact, 35.47% of the time the batteries remain between 98-100% charged. Furthermore, it can be observed that the months where the highest consumption or discharge of the battery bank occurs corresponds to the months of May and August where the SoC can decrease to 40%.

It can also be seen that on an average day the battery bank has a SoC between 70% and 80%, from 6:00 p.m. to 8:00 a.m. the next day. This is because it is used between 6:00 p.m. and

Table 7
Literature summary of stand-alone EVCS designs

Optimal System	References	Country	NPC (USD)	COE (USD/kWh)
PV-Battery	Oladigbolu *et al.* (2023)	Arabia Saudi	255,997	0.152
PV-Battery	Filote *et al.* (2020)	Romania	128,167	0.85
Diesel-PV-Battery	Hafez *et al.* (2016)	Canada	835,000	0.551
WT-PV-Battery	Ekren *et al.* (2021)	Turkey	697,704	0.064
PV-Hydrogen-Battery	Shaikh *et al.* (2022)	Pakistan	11,065	0.0014
WT-PV-Diesel-Battery	Boddapati *et al.* (2022)	Denmark	531,072	0.351
Biogas Gen-PV-Battery	Karmaker *et al.* (2020)	Bangladesh	56,202	0.1302
Biogas Gen-PV-Battery	Singh *et al.* (2022)	India	68,202	0.1902
Wind-CPV-FC-Bio-Gen-Battery	Al Wahedi & Bicer (2022)	Qatar	2.53M	0.285
PV-Wind-Battery	Li *et al.* (2022)	China	831,540	0.294
PV-Battery	Apribowo *et al.* (2021)	Indonesia	52472.84	0.15

*PV: Photovoltaic Panel
*WT: Wind Turbine
*CPV: Concentrated Photovoltaic Thermal

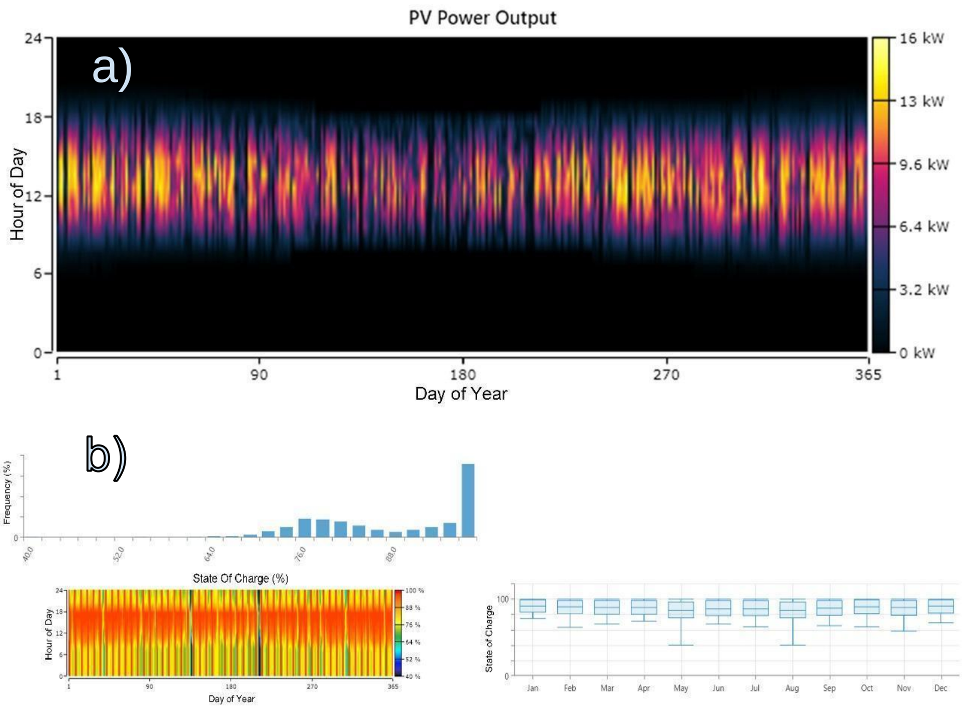

Fig. 6 Power generation scenario shown by HOMER Pro **a)** Output power of photovoltaic panels during the day throughout the year. **b)** State of charge (SoC) of the battery bank projected in one year, based on days.

12:00 p.m. during demand hours and where generation falls, then it is maintained with that state of charge until the next day when it is recharged. Furthermore, it is examined that on weekends, the SoC corresponds to approximately 100% (orange-red color).

3.3 Sensitivity Analysis

A sensitivity analysis was carried out for different Minimum State of Charge, modifying their % SoC between 10, 20, 30, 40 and different estimated load situations of 18.1; 18.9; 19.6 and a maximum load of 22.4 kWh/d. In the following Fig.

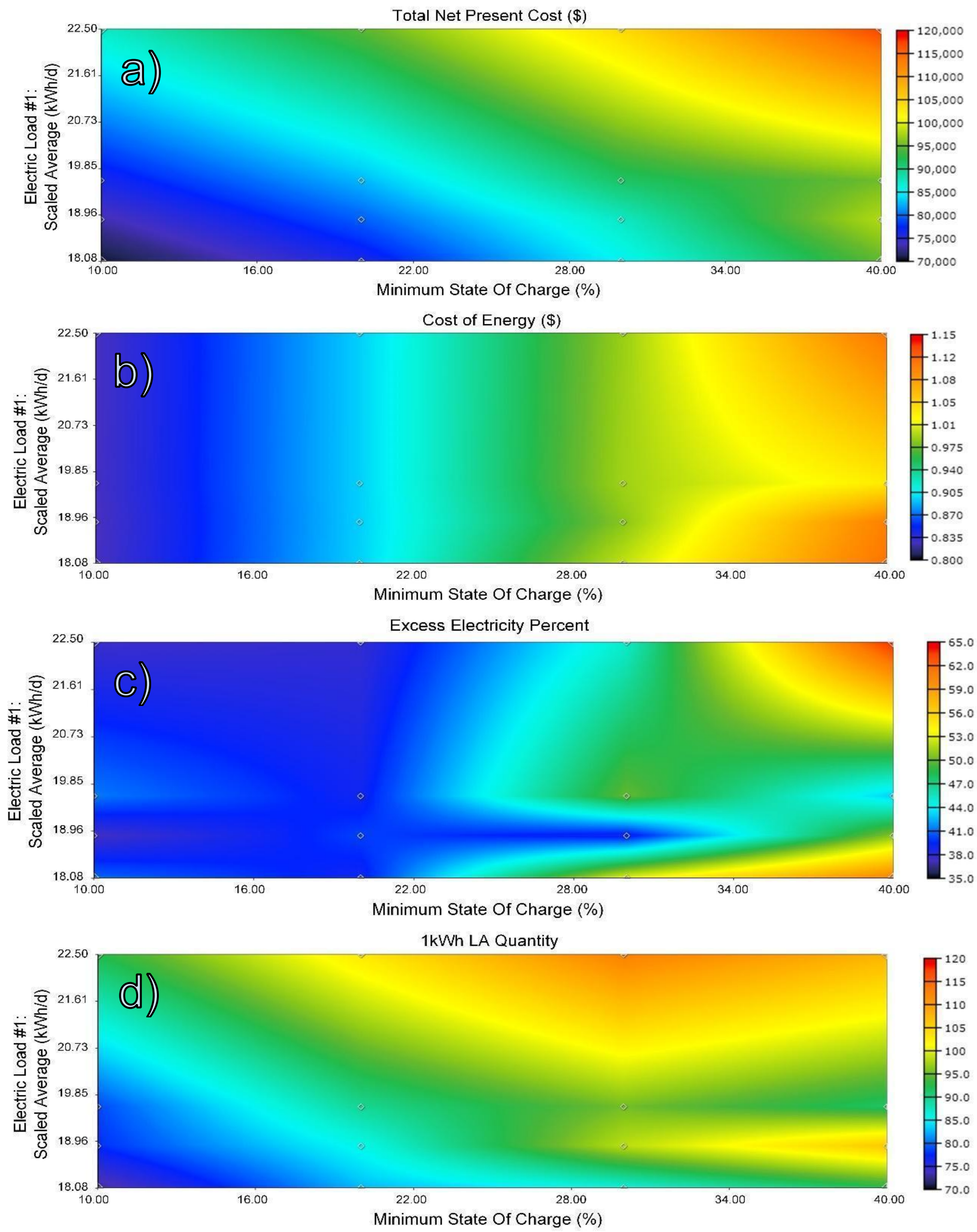

Fig. 7 Sensitivity analysis displayed by HOMER Pro. **a)** Surface graph of the NPC varying the Minimum state of charge (%) and the Electric Load (kW). **b)** Surface graph of the cost of energy in dollars varying the Minimum state of charge (%) and the Electric Load (kW). **c)** Surface plot of excess electricity varying Minimum State of Charge (%) and Electric Load (kW). **d)** Surface graph of the number of 1 kW storage batteries required varying the Minimum state of charge (%) and the Electric Load (kW).

7, it can be seen the influence of the minimum percentage of battery storage and the different charging conditions on: NPC, cost of energy, excess energy produced and number of batteries needed. In Fig. 7a it can be noted that the lower the SoC and the lower the required load, the NPC is always lower. The surface map shows in dark blue the lowest NPC, which is observed to be around USD 70,000. It is highlighted that NPC could also be reduced by considering a capacity shortage greater than zero and incorporating a non-renewable source (Lal & Raturi, 2012), such as a diesel generator, but this is not the objective of this project. In the same way, the cost of energy is reduced, obtaining prices below the dollar between 0.8 and 0.9 for minimum SoC between 20-30% (Fig. 7b). It can also be seen in Fig. 7c) that up to approximately 20% of minimum load the lowest excess energy is produced in percentage terms, between 35 and 42% (blue range), being that in the system calculated by default (40 % load) an excess of 63% occurred. Finally, Fig. 7d) shows how the necessary number of batteries is reduced by reducing their minimum charge.

In summary, increasing the SoC leads to higher NPC values, energy costs, excess electricity produced, and number of batteries. It is worth mentioning that the minimum state of charge of the battery system (SoC_{min}) is the relative state of charge below which the storage system is never depleted, since, to avoid permanent damage to rechargeable storage batteries most are not fully discharged. Normally, the percentage range of 30 to 50 is selected for the SoCmin, thus avoiding excessive discharge that could damage them (Lambert *et al.*, 2006; Oladigbolu *et al.,* 2020). The impact of these factors will drive

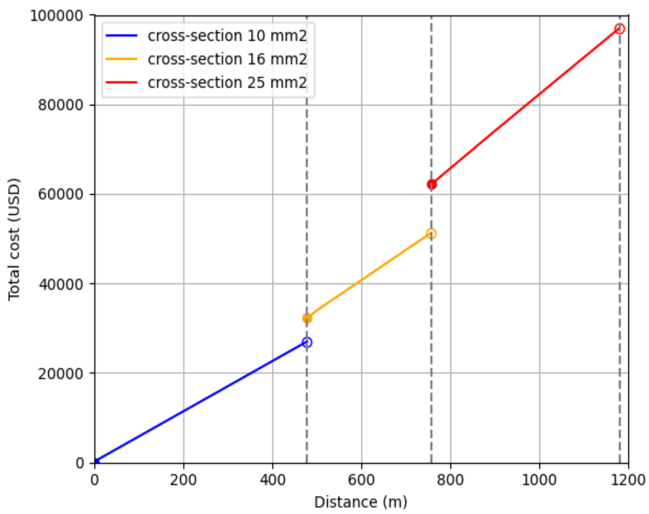

Fig. 8 Total cost vs Distance, conductor diameter.

decision-making to support planning in line with the university's strategic objectives.

3.4 Grid extension costs

The grid extension is projected with the connection point in the current main panel of the UNRaf, which already has an available output to connect the EVCS planned. The network in question consists of a Single-Phase Low Voltage Line, supplied by the local electric energy distributor (Empresa Provincial de la Energía de Santa Fe), with a nominal voltage of 220 V and a frequency of 50 Hz. In addition, a power factor (cos φ) of 0.85 is considered due to the reactive loads of the Charging Station.

The conductor cross-section is calculated based on the Maximum Simultaneous Demand Power, which in this case study is around 6.80 kW. According to Ohm's Law, the maximum current in this case would be 36.36 Amps. With this information, the conductor cross-section is determined according to its permissible current, which is provided by different catalogs of the conductor brands available in the market. The cost of the network extension depends on its length and, therefore, on the conductor cross-section. Since, for a given conductor length, the voltage drop may reach the 5% allowed according to the Electrotechnical Association of Argentina (AEA), it is necessary to use conductors of larger cross-sections to guarantee that the final voltage is within acceptable parameters, even when smaller sections that support the maximum current are used (Fig. 8).

Therefore, a 10 mm^2 1.1 kV underground Cross-Linked Polyethylene (XLPE) conductor can be used for lengths of up to 478 meters; for lengths greater than this and up to 757 meters, a 16 mm^2 conductor will be required; and for lengths greater than this and up to 1180 meters, a 25 mm^2 conductor will be required. Assuming these requirements, the capital cost (also mentioned "Total Cost" in Fig. 8 calculated to extend the grid amounts to USD 25265. It is important to note that, as evidenced in the graph, the voltage drop is a limiting factor for single-phase electrical networks, so in the case of longer network extensions, the transition to a medium voltage electrical network system should be considered, which in Argentina is usually 7620 V for single-phase lines. For that reason, calculating a breakeven point using an average cost USD kW/km might not be accurate in this system.

3.5 Environmental Feasibility

None of these systems produce greenhouse gases and therefore have a sustainable environmental standard. However, one point to consider is the recycling and/or final disposal of spent batteries and other peripheral elements, which will require an additional calculation of the environmental footprint (Kumar *et al.*, 2022). Taking into account that emission factor obtained for Argentina in 2023 was 0.429 $kgCO_2$/kWh (Estadística del Informe Síntesis del MEM, n.d.), powering the proposed system using only the electricity grid would generate 9,833 kg/yr of CO2.

3.6 Socioeconomic Aspects of the EVCS Proposal

Generally, the typical concerns about the use of this type of energy are safety and the negative impact on the environment (Akita *et al.*, 2020), which are minimized in this proposal. In addition, the installation of the panels is planned on the private property of the University, taking advantage of the roofs of the facilities, thus avoiding the phenomenon known as (NIMBY) not-in-my-backyard (Dear, 1992). In line with the proposal, Michel *et al.* (2015) conducted a survey to evaluate the acceptance of several potential sites for photovoltaic installations, resulting in industrial sites and modern buildings being considered the most suitable for these projects. Additionally, the construction of sustainability must have education as its central axis, educational institutions can be key in the adoption of knowledge and skills about renewable energies. Integrating them into teaching, research and extension promotes sustainable culture, providing students with tools to understand their importance and incorporate them into their daily lives (Ferreira *et al.*, 2020). Although the acquisition of EV is being encouraged, the market is still incipient in Latin America, to this consideration must be added the practically non-existent charging infrastructure, which is reduced to less than 10 stations throughout Argentina, some of them experimental. Promoting electromobility as an environmental strategy to reduce emissions from the transport sector is not an easy task in Argentina (Isla *et al.*, 2023), due to the extensive presence of alternative non-renewable fuels. An example of this, there is the popularized use of compressed natural gas (CNG) which is very competitive in cost and is a great disincentive to hybrid or electric vehicle technology. According to Quirós-

Tortos *et al.* (2019), who analyzed the situation of 17 Latin American countries, Argentina has the most expensive acquisition cost and is the one that needs the greatest incentive to make EV as profitable as internal combustion vehicles (IC). However, the country has made notable progress in the use of renewable energy (Gismondi, 2023; Wainberg, 2023) and, globally, according to forecasts from various energy and statistical organizations, such as BP, OPEC, IEA, IRENA and Bloomberg NEF, it is estimated that electric vehicles will continue to be competitive in the market, even despite low oil prices (Kasputin & Grushevenko, 2020). Another important point to highlight is the current socio-economic situation of the country, of increasing poverty and vulnerability, which can negatively influence the achievement of this type of project (Risso, 2024).

4. Conclusions

This study focuses on the innovative design of an isolated microgrid for an electric vehicle charging station on the UNRaf campus, a significant development in the central region of Argentina, especially in a context where charging infrastructure for electric vehicles is practically non-existent. The station, designed to meet the specific charging needs of the campus, including 4 bicycles, 1 tricycle, and 1 four-wheeler, also provides power access to an area under construction. Through a comprehensive technical, economic, and environmental analysis using HOMER Pro, the study evaluated three scenarios—solar panels, wind turbines, and a combination of both—concluding that a 15-kW solar panel system with a 91 kWh lead-acid battery bank was the most cost-effective, with a LCOE of 1.12 USD/kWh and an initial capital cost of USD 64,804. The sensitivity analysis optimized the design by considering various states of battery charge and electrical demands, while also comparing the proposed off-grid system to a network extension, which proved to be 2.5 times more economical. Nevertheless, the recommended system's reliance on 100% renewable energy contributes significantly to reducing greenhouse gas emissions, aligning with global sustainability goals and Argentina's commitments under the Paris Agreement. In conclusion, this project not only offers a model for other regions in Argentina and Latin America but also underscores the need for broader research into integrating diverse renewable energy sources, such as biomass, to enhance system resilience. For the successful promotion of electromobility, it is essential to address local constraints, including socio-economic conditions and regulatory frameworks, while also implementing supportive public policies and fostering collaboration between universities, governments, and the private sector. Continuous monitoring and evaluation will be vital in adapting the system to future challenges and providing valuable insights for the ongoing development of sustainable energy solutions.

Acknowledgments

This work was carried out thanks to the financing granted by the National Council for Scientific and Technical Research (CONICET) and by the Rafaela Research and Transfer Center (CIT). The authors appreciate the collaboration of Mr. Franco Roldán.

Author Contributions: J.P.C.: Conceptualization, software, formal analysis, writing—original draft, editing, project administration, E.L.V.; formal analysis, writing—original draft, review, validation, editing, visualization, L.I.S.; supervision, methodology, writing—review, formal analysis, validation, resources, E.E.D.; writing—review and formal analysis, C.R.R.; supervision, review, validation, formal analysis. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received financial support from Universidad Nacional de Rafaela (UNRaf).

Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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