Article **Journal Industrial Engineering**
December 2023, Vol.7 No.19 38-52

Photovoltaic Autonomous Electric Charging Station

Electrolinera Fotovoltaica Autónoma

GARCÍA-CONTRERAS, Cecilia Pamela†*, ONTIVEROS-SÁNCHEZ, Kenneth Arturo and ALVAREZ-MACÍAS, Carlos

Instituto Tecnológico Nacional de México, Instituto Tecnológico de la Laguna.

ID 1st Author: *Cecilia Pamela, García-Contreras* / **ORC ID**: 0000-0003-3056-0896, **CVU CONAHCYT ID**: 1271712

ID 2nd Co-author: *Kenneth, Ontiveros-Sánchez* / **ORC ID**: 0009-0004-1105-7958

ID 3rd Co-author: *Carlos, Alvarez-Macías* / **ORC ID**: 0000-0002-2263-0316, **CVU CONAHCYT ID**: 165872

DOI: 10.35429/JIE.2023.19.7.38.52 Received July 20, 2023; Accepted December 30, 2023

Abstract

Over the past decade, emerging technologies in the automotive sector have evolved with the integration of electric vehicles, providing a sustainable option for consumers. This approach aims to reduce reliance on fossil fuels and extend their extraction and consumption. This study proposes the sizing of an autonomous photovoltaic system to power an electric vehicle charging station, assessing its feasibility and profitability. Given the significance of electric vehicles in the future of transportation, exploring ways to meet their energy needs is crucial in contributing to the reduction of fossil fuels. While the theoretical project proves to be technologically feasible, analyses of areas, components, costs, and return on investment reveal that recovering the initial investment is not economically viable.

Autonomous Photovoltaic System, EV Charging Station, Photovoltaic System Design

Resumen

Durante la última década, las tecnologías emergentes en el sector automotriz han evolucionado con la integración de vehículos eléctricos, ofreciendo una opción sostenible para los consumidores. Este enfoque busca reducir la dependencia de combustibles fósiles y extender su extracción y consumo. Este estudio propone el dimensionamiento de un sistema fotovoltaico autónomo para alimentar una estación de carga de vehículos eléctricos, evaluando su viabilidad y rentabilidad. Dada la importancia de los vehículos eléctricos en el futuro del transporte, es crucial explorar formas de satisfacer sus necesidades energéticas, contribuyendo así a la reducción de combustibles fósiles. Aunque el proyecto teórico demuestra ser factible desde el punto de vista tecnológico, los análisis de Areas, componentes, costos y retorno de inversión revelan que no es económicamente rentable recuperar la inversión inicial.

Sistema Fotovoltaico Autónomo, Electrolinera, Dimensionado

Citation: GARCÍA-CONTRERAS, Cecilia Pamela, ONTIVEROS-SÁNCHEZ, Kenneth Arturo and ALVAREZ-MACÍAS, Carlos. Photovoltaic Autonomous Electric Charging Station. Journal Industrial Engineering. 2023. 7-19: 38-52

* Author's Correspondence (e-mail: ceciliapamela.gc@gmail.com)
† Researcher contributing as first author.

Introduction

In the last decades, it has become common knowledge that the current global energy model, based on fossil fuels, is unsustainable in the long term. The most urgent and immediate reason is the climate change induced by the burning and massive use of fossil fuels, and the second reason (but almost equally urgent) is the impending depletion of fossil fuel reserves with their exhaustive use. With this context in mind, a variety of alternatives have been presented to replace our current energy model. These alternatives are based on the direct or indirect use of renewable energy sources, such as biomass, solar, wind, or tidal energy. The integration of alternative energy sources into a country's energy model, as well as better resource management, is known as sustainable development—a common goal for all countries and their respective companies.

In Mexico, according to data from the Secretary of Energy (SENER) for the year 2020 in the National Energy Balance: Final energy consumption by sector, shown in Figure 1, it is noted that almost 40% of the country's final energy consumption is required by the transportation sector (Final energy consumption by sector, National Energy Balance, 2020).

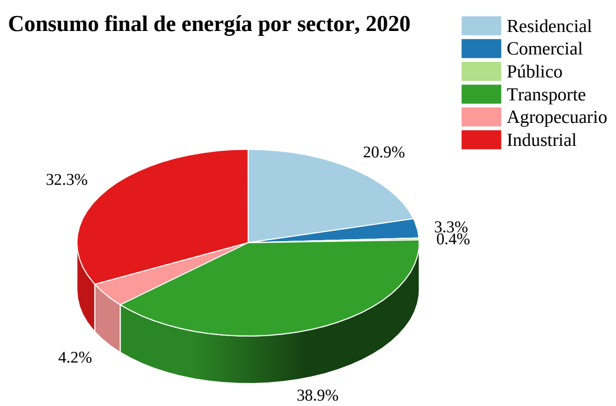

Figure 1 National Energy Balance: Final energy consumption by sector, year 2020
Source of reference: (Final energy consumption by sector, National Energy Balance, 2020)

Due to the high demands for energy and performance expectations, as well as the need to carry their energy source, it is logical to conclude that the transportation sector is the one with the most difficulties in terms of modification and improvement. However, being such an important sector, the transition to a sustainable model is inevitable.

Among the most popular and developed proposals for the transportation sector, specifically for the automotive section, is the so-called electric vehicle (EV).

Generally, all electric vehicles (EVs) have one or more electric motors instead of an internal combustion engine. All EVs use a rechargeable high-capacity battery pack to power the electric motor; this battery must be charged at a specialized charging station or a household outlet. Additionally, electric vehicles must have a controller that will manage the power supplied to the motor, i.e., the vehicle's speed. Electric vehicles that rely solely on rechargeable batteries for operation are called "Battery Electric Vehicles" or BEVs (Electric Vehicle Technology Explained, 2012). Figure 2 shows a basic diagram of a BEV.

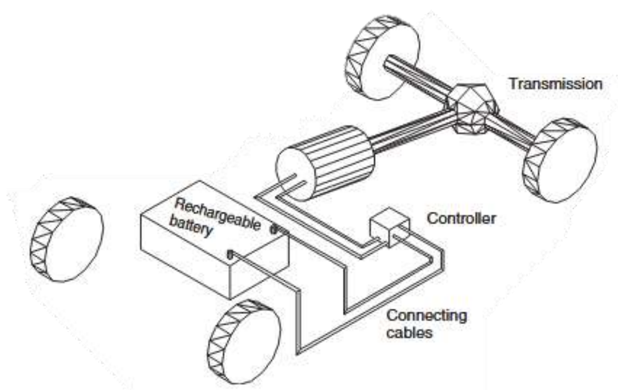

Figure 2 Battery-powered electric vehicle
Source of reference: (Electric Vehicule Technology Explained, 2012)

Rechargeable batteries are typically located underneath the center of the chassis, with more mass at the rear for better safety and weight distribution in the vehicle. A design challenge is that batteries usually account for about 40% of the weight in an electric vehicle (EV), whereas in a fossil fuel-based car, the engine, cooling system, and support systems only make up 25% to 30% of the car's weight (depending on the size of the gas tank), (Ultimate guide for Electrics Cars, 38-43, 2020).

These rechargeable batteries do not have a definitive charging time that can be applied universally to all electric cars on the market. However, we know that three aspects affect their charging:

– Charging point power
– Battery capacity
– Maximum car charging power

In cases where the maximum power and charging point power differ, the lower power will determine the waiting time. Battery capacity determines the charging time and how often the process should be repeated (Electric Vehicule Technology Explained, 2012).

On the other hand, the average lifespan of batteries is estimated to be around 3000 full charge cycles. Therefore, if we consider daily charging and discharging, we find that the battery lasts just over 8 years. This may seem like a relatively short time, especially for the primary energy source of a car (which is typically seen as a long-term investment). However, this is considering the worst-case scenario, as the usual recommendation is that electric vehicle batteries never fully discharge, just as no one would let their internal combustion car run completely out of fuel.

Currently, there are different types of batteries available for use in EVs, including lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, lithium-ion with cathode (LiFePO4), and lithium polymer (J. Larminie, 2012). For comparative purposes, these batteries, along with some important specifications, are presented in Table 1.

Battery	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Lifespan (charge-discharge cycles)
Lead-Acid	30-40	75	500-800
Nickel-Cadmium (NiCd)	40-60	80	1500-200
Nickel-Metal Hydride (NiMh)	30-80	150	300-500
Lithium-Ion	100-250	150	400-1200
Lithium-Ion with Cathode	90-100	250	2000
Lithium Polymer (LiPo)	300	300	1000

Table 1 Comparison of commercially available batteries
Source of reference: (Electric Vehicule Technology Explained, 2012)
*These data are only guidelines, as battery performance depends significantly on usage (appropriate or not)

While battery technology continues to advance, and the future trend is for prices to gradually decrease, batteries are still relatively expensive and not fully adapted for trips of more than 200 km per charge. Fortunately, in an urban environment and for the average use of a car, over 90% of trips do not exceed 200 km (How Green are Electric or Hydrogen-Powered Cars?, 2016).

Generally, lithium-ion batteries (one of the most commonly used types of batteries for electric cars) undergo an aging and wear process over their lifespan due to physical and chemical reasons. The following guidelines help maintain batteries in a reliable long-term state and preserve the highest possible capacity and autonomy:

– For short trips in daily use, it is advisable to charge the high-voltage battery to a maximum of 80% on average.

– For parking periods exceeding 12 hours, it is recommended to park the vehicle with a state between a minimum of 30% and a maximum of 80%.

– For charging the battery to 100%, it is preferable to set the timer on the charging manager and start driving immediately after the charge is complete.

On the other hand, the charging infrastructure or charging station is a facility that provides electricity for recharging the batteries of electric vehicles (EVs), including plug-in hybrid vehicles. Charging stations used as fast electricity dispensers typically have a battery fast-charging time of no more than ten minutes, and both these and domestic stations must be directly connected to a power source (usually the electrical grid) (The Electric Vehicle and its Interaction with the Electrical Grid, 2010).

Currently, each car brand or manufacturer usually has its own connector for charging the desired vehicle. In other words, a charging station for a specific electric car cannot be directly connected to a car from a different brand, as there are different inputs for different brands or manufacturers.

In the future, it is intended that charging station formats and their connection to cars will be limited and consolidated to a single standard protocol to keep prices lower (Ultimate Guide for Electric Cars, 38-43, 2020). Currently, the standard protocol with the most opportunities to consolidate is IEC 62196, developed by the International Electrotechnical Commission (IEC), which allows charging stations described in Table 2.

Name	Supply (kW)	Voltage (V)	Current (A)	Phase
CHAdeMO "Charge de move"	62.5	500	125	DC
VDE-AR-E 2623-2-2	43.5	400	63	3 fases
SAE J1772-2009	16.8	240	70	1 fase
Serie Libera	22	400	32	3 fases

Table 2 Charging station systems developed from the international standard IEC 629196
Source of reference: (El vehiculo electrico y su interacción con la red eléctrica, 2010)

While they may seem few, the future goal is for only one type of universal connector to exist. The estimated trend is that CHAdeMO and Tesla charging stations (not included in Table 1.3 due to limited available information) will be the final contenders, but it is still too early to definitively state which of the two will win the competition (Ultimate Guide for Electric Cars, 38-43, 2020). On the other hand, the charging stations described in Table 1.3 still do not fully meet the commonly accepted definition of "fast charging systems" by the industry, as they require more than 10 minutes for an average user to recharge during a mid-journey stop. Meanwhile, the Tesla Supercharger, by Tesla Motors, can supply up to 120 kW and achieve an 80% battery recharge time in 5-10 minutes (The Electric Vehicle and its Interaction with the Electrical Grid, 2010). For security and copyright reasons, official information on the operation method and exact demand for Tesla Superchargers is scarce.

In all European countries, the electric vehicle charging infrastructure is very advanced. Spain, in particular, has 11,517 out of 224,237 publicly accessible charging points available in Europe, with 71,079 registered electric vehicles by the end of 2021 (Annual Evolution of the Total Number of Electric Vehicle Registrations in Spain between 2013 and 2021, 2022).

The sector advocates for a minimum network of 70,000 publicly accessible charging points by 2023, 120,000 by 2025, and 340,000 by 2030 (Fast Charging Points in Spain for Electric Cars: Where They Are and What Price They Offer, 2022). Installation and charging companies in Spain support these ideas and have plans such as Iberdrola's Smart Mobility Plan, which aims to have a fast charging station every 50 km to enable travel throughout the country with autonomy (Nuno, 2010).

In contrast, Mexico only has 2,100 charging points (it is not specified in the figures if these are public or private). This is despite reports that 2021 was a "good year for the commercialization of electric vehicles in Mexico" (Electric Cars Exist, but No Plugs: The Dilemma of the Automotive Sector in Mexico, 2022). It is a common idea that one of the main reasons why only 1 in every 20 cars sold in the country is "green" is the limited accessibility to charging or a lack of charging stations in Mexico (Electric Cars Exist, but No Plugs: The Dilemma of the Automotive Sector in Mexico, 2022).

Despite bureaucratic barriers and misinformation, access to charging stations is a problem that the country will have to face sooner or later, as electric cars will be the only option for personal transportation in the not-so-distant future. This is considering that countries like France and Japan have already set a deadline for the commercialization of internal combustion cars—sooner or later, countries worldwide will have to adopt similar measures, including Mexico (Charging Stations: The Great Business Stalled by the Electrical Counter-Reform, 2021). Pure Battery Electric Vehicles (BEVs) are commonly charged from the electrical grid overnight at the owner's residence, provided they have their charging station or an adapter to plug directly into the grid outlets.

The energy from the grid is generated from a combination of sources; major generators use nuclear, coal, and gas energy. In some places, power production in the electrical grid may also come from renewable sources such as hydro, wind, and solar (Ultimate Guide for Electric Cars, 38-43, 2020). However, it's essential to remember that a fast-charging supply requires an industrial-type electrical service, as it demands large amounts of energy in a very short time (10 minutes or less).

The required power from the grid when charging a car with this type of service can go up to 210 kW. If we consider a charging station similar to current gas stations, with multiple simultaneous fast-charging points, the station might demand power peaks on the order of megawatts—which, if the electrical grid is not prepared, can cause voltage drops or outages during busy hours when several vehicles decide to charge simultaneously (The Electric Vehicle and its Interaction with the Electrical Grid, 2010).

For this reason, we believe that installing this charging station can be more beneficial if connected to an autonomous solar photovoltaic system, which stores energy from the photovoltaic panels when demand is low and releases/supplies it once demand is high. As the name implies, it would be a system off the electrical grid so that, if megawatts of energy were demanded at once and these could potentially cause an imbalance in the electrical grid, the electrical grid would not be affected because it is not connected to the system. For an autonomous system, various factors, mainly geographical and climatological, must be considered to adequately size the type and quantity of equipment (modules, batteries, cables, controller, protection, etc.) to meet the energy demand required by the user. Additionally, it must adhere to pre-established values and standards for safe sizing and installation.

The objective of this work is to conduct a case study for the locality of Torreón, Coahuila, and verify, theoretically, if it would be possible to install a fast-charging station for electric vehicles powered by an autonomous solar photovoltaic system.

Methodology

Currently, there are many options in the market for sizing software for photovoltaic installations, such as PVsyst, RETScreen, or HOMER (economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case Study of Spain, 2018). However, these programs are not the only option for sizing a photovoltaic system. To size the system traditionally, we will have to consider each part together and go back or change some parameter or device if it turns out to be cumbersome later.

We start with the batteries, first obtaining the capacity required by the battery in Ampere-hours, with Equation 1.

$$Ah\ en\ batteries\ s = \frac{Required\ Energy\ (Wh)}{Battery\ Bank\ Voltage \times \%\ Discharge \times 0.77} \quad (1)$$

It is recommended not to discharge the battery beyond 50% to have a longer lifespan without sacrificing too many hours of use (Style, 2012). With this data, a battery model and a connection scheme are chosen to meet the discharge demand. Then we must size the battery charge and, therefore, the supply it must have, taking into account the peak solar hours of the region (PSH). This with Equations 2 and 3.

$$Load = Battery\ Bank\ Voltage * \%\ charge * capacity \quad (2)$$

$$Supply = \frac{Battery\ Bank\ Capacity * \% charge}{PSH} \quad (3)$$

In a correct sizing, after sizing the batteries (with the help of Equation 1 and having a clear understanding of the energy required by the system), we move on to size the charge controller.

The work of the charge controller/regulator is key in the system because its optimal operation ensures battery protection. It is essential to ensure that the controller corresponds to the system voltage (12V/24V/48V), and the maximum current of the regulator is greater than the maximum current that the modules can generate in short circuit (Style, 2012). If, when sizing the solar modules to be used, this condition is not met, the modules or the controller must be changed (Macías, Topic 4 - Elements of Autonomous Systems, 2022). With this in mind, we will use Equation 4 to size the ideal controller's maximum current, and based on that data, look for a controller in the market that matches or exceeds this requirement.

$$Maximum\ controller\ current = \frac{(Solar\ Photovoltaic\ Power)}{(Battery\ Bank\ Voltage)} \quad (4)$$

Additionally, we need to know how much current the controller should allow to pass to charge the batteries, using the same discharge percentage used in Equation 1, along with the PSH. This minimum controller current is calculated with Equation 5.

$$Controller\ Current = \frac{Battery\ Bank\ Capacity(Ah) \times \%\ discharge}{PSH} \quad (5)$$

ISSN 2523-0344

Once a model available on the market is selected, we need to know the power that the controller can withstand with Equation 6. This is necessary because it gives us a range or limit for sizing modules.

$$P_{MPPT} = I_{\max} \times V_{bat} \qquad (6)$$

The modules are the engines or generators of energy in an autonomous photovoltaic system, converting solar energy into electrical energy via the photoelectric effect (Un sistema fotovoltaico autónomos, 2012). So we must have a clear idea of the required energy generation from the modules, with Equation 7.

$$Required\ Generation = Battery\ Bank\ Voltage * supply \qquad (7)$$

The five electrical parameters (Open Circuit Voltage, Maximum Power Voltage, Short Circuit Current, Maximum Power Current, and Maximum Power) of a panel are already measured by the manufacturer and given in its datasheet, along with the characteristic curve they create. However, this curve can be affected by temperature or irradiance parameters. In a correct sizing, these changes in voltage must be anticipated according to the temperatures of the area; remembering that the recorded high and low temperatures have a corresponding correction factor, which can be found in NOM-001-SEDE-2018, and are calculated with Equations 8 and 9, respectively

$$V_{max} = V_{OC} * Correction\ Factor\ (low\ temp.) \qquad (8)$$

$$V_{min} = V_{PM} * Correction\ Factor\ (high\ temp.) \qquad (9)$$

Meanwhile, the short-circuit current can increase if there is irradiance greater than 1000 W/in which the module is tested, so we use Equation 10 to cover that variation.

$$I_{max} = I_{SC} * 1.25 \qquad (10)$$

This will change the characteristic curve of the module to match what is actually produced in the area where we plan to install it. If the chosen controller is an MPPT, these peaks and variations won't matter as much because this device is designed to always seek the best performance from the panel (Macías, Tema 4- Elementos de sistemas autonomos, 2022).

The different electrical parameters of the module will help us choose the most suitable modules for our system. However, before choosing in the market, we must use Equation 11 to obtain the total power that the modules must have, taking into account the PSH.

$$P_{FV}(W_p) = \frac{Required\ Energy\ (Wh)}{PSH\ (h) \times 0.77} \qquad (11)$$

After choosing the module to use and the arrangement in which they will be connected, we use Equation 12 to obtain the maximum current delivered by the module to the controller. This data will serve to check that the selected controller will withstand the energy provided by the photovoltaic array.

$$I_{max,mod} = \frac{P_{\mathrm{module}} \times \#\ panels}{Battery\ Bank\ Voltage} \qquad (12)$$

Once all the parts of the DC autonomous photovoltaic system are measured, we can add the element to switch from direct current to alternating current: an inverter. Inverters, as the name suggests, are responsible for converting direct current to alternating current, transforming it from low voltage to a higher voltage. This process, logically, involves losses of around 10-15%, with efficiencies between 85-90% (Macías, Tema 4- Elementos de sistemas autonomos, 2022).

The inverter, when connected to products in the market that are regulated by law, has recommendations for sizing. These recommendations, given in the Official Mexican Standard, state: "[For] currents of the photovoltaic source circuit, the maximum current must be calculated by [...] the sum of the short-circuit current of the modules in parallel, multiplied by 125 percent" (NOM-001-SEDE-2018). This calculation is reflected in Equation 13, with 125 percent squared to provide greater protection.

$$P_{inversor} = \sum Equipment\ Power \times 1.25^2 \qquad (13)$$

Once an inverter that fits the power required by the system and complies with NOM safety measures is obtained and chosen, we can find out the current demanded by the inverter with Equation 14. The current demanded by the inverter is essential data for the operation of the autonomous system, as it tells us if our system supplies the proposed load or if we need to resize any part of the system.

$$Demand = I_{max,inv} = \frac{P_{inv}}{V_{bat}} \quad (14)$$

Finally, for the wiring, various factors that can affect the gauge to choose must be taken into account; mainly the required ampacity (with its corresponding adjustment factors), whose formula is described in Equation 15, and the voltage drop, whose corresponding formula is found in Equation 16.

$$Adjusted\ Required\ Ampacity = \frac{\sum I_{SC-parallel} \times 1.25^2}{F_T \times F_C} \quad (15)$$

$$e_T = \frac{2 \times distance \times I_{MP}}{V_{MP}} \times R \quad (16)$$

As with any equation, it is important to keep the units of the data consistent. Otherwise, the result would be incorrect. Additionally, adjustment factors F_1 and F_2 can be obtained from the tables of NOM-001-SEDE-2018 when certain data about the locality in question is available (such as maximum and average temperatures).

Results

Location of the System for the Case Study

The present case study will be conducted for the city of Torreón, Coahuila, Mexico (latitude 25°37' N and longitude 103°23'). This city is characterized by high levels of solar radiation and mostly clear skies, meaning that the solar radiation reaching a solar panel is high. It is an area where the installation of photovoltaic systems is popular. In fact, the brightest period of the year lasts for 3.3 months, from April 3 to July 14, with an average daily incident energy exceeding 7.2 kWh/m2. The brightest month of the year in Torreón is May, with an average of 7.8 kWh, while the darkest is December, with an average of 4.1 kWh (El clima y tiempo promedio en todo el año en Torreón, México, 2021). The solar resource and the expected growth in EV purchases in the area make it a good zone to study the feasibility of an autonomous PV-BESS solar system.

Additionally, we consulted other data for the study location:

- T_{max}=44°C
- T_{min}= -4°C
- $T_{average}$= 22.7 °C

Using Google Earth and the CONAGUA extension, we reviewed data from the nearest meteorological station. In this case, the closest one is at "Presa Coyote" and has data from 1981-2010. We observed that the highest temperature reached was 44°C, recorded in 1996, while the minimum temperature was -4°C, recorded in 1998. These data are highlighted in Figure 3.

Figure 1 Screenshot of the Google Earth program with the CONAGUA informatics extension, showing data taken from 1981-2010 in Torreón, Coahuila.
Source of reference: (Servicio Meteorológico Nacional, 1981-2010)

From the page https://power.larc.nasa.gov/data-access-viewer/ developed by NASA, we obtained an Excel file shown in Figure 4 for the specific location (coordinates highlighted in green). This file has the average peak solar hour of the region when the solar system is tilted according to latitude. From the data for each month, we took the lowest one, corresponding to December (highlighted in yellow).

We get the data for the city, PSH=5.38 hours.

Figure 4 Screenshot, Excel file describing the PSH of Torreón, Coahuila
Source of reference: (20-year Meteorological and Solar Monthly & Annual Climatologies, 2001-2020)

ISSN 2523-0344

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Study of the load for the system

The charging rate varies among different EV models on the market, depending largely on the charge acceptance rate of the vehicle's battery. This rate is controlled by the energy management system of the batteries in each car.

For example, the 2020 model, Porsche Taycan, which was the best-selling model in Mexico in 2021, limits its charging rate to 50 kW for fast charging. With this rate, the charging station can recharge the Taycan's battery from 10% to 80% state of charge (SoC) in 30 minutes (Charging high-voltage battery, 2020). Additionally, we must take into account that, unlike a gasoline charging station, the charging rate (from the charging station to the vehicle's battery) is not constant over time. For physical and chemical reasons, the charging speed decreases as the charge level approaches 100% (Charging high-voltage battery, 2020).

For example, when the SoC is below 30% at the start of charging, the recharge rate is about 0.72 kWh per minute. However, when the SoC reaches 80%, the recharge rate decreases to 0.16 kWh per minute, which is less than half of the energy rate required for charging at the beginning of the process (economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case Study of Spain, 2018).

Fast charging stations have a hysteresis effect when the battery reaches a point close to full charge, so a fast charging station can only charge up to 80% of the battery's SoC. Current fast charging stations have a nominal output power of 50 kW and charge the vehicle's battery with direct current (DC) taken from a three-phase electrical grid (Electric Vehicle and Its Interaction with the Electrical Grid, 2010).

In this study, we will consider an EV with a 60 kWh battery, a one-hour fast charging process, and a Terra 54HV UL charging station. This charging station has an approximate price of EUR £25,500, which, as of May 20, is equivalent to MXN $538,535.58.

We calculate the charging power for the autonomous system taking into account the input data requested by the charging station, obtaining Table 3 showing the power factor data and the nominal input power from the corresponding data sheet.

Electrical Specifications	Terra 54HV
Maximum output power	50 kW continuos
AC input voltage	480Y/ 277 VAC+/- 10% (60 Hz)
AC input connection	3 fases: L1, L2, L3, GND (no neutral)
Nominal input current and nominal input power	64 A, 54 kVA
Recommended upstream breakers	A
Power Factor	>0.96
THD	Comp. IEEE 519; 5%
Short circuit rating	65 kA; 10 kA optional
DC output voltage	CCS-1: 200-920 VDC
DC output current	125 A
Efficiency	95%

Table 1 Electrical Specifications of Terra54HV Charging Station, ABB
Source of reference: (Terra 54HVL UL , 2021) $P = 54000\, VA \times 0.96 = 51{,}840\, VA$

We obtain that the charging station requires 51.84 kW of power in one hour.

Sizing of Autonomous System

To continue with the sizing, we will consider that, in a day, two electric cars will be charged with a single charging station. Therefore, the consumption hours are set at 2h. The energy required by the batteries is:

$$Required\ Energy = \sum Power\ of\ charges * consuption\ hours = 51.84\ kW \times 2h = 103.68\ kWh$$

From this, we size the batteries. First, we size the discharge:

$$Ah\ Batteries = \frac{103{,}680\ Wh}{48V \times 0.5 \times 0.77} = 5610.38\ Ah$$

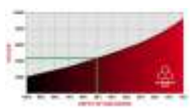
Specifications		
Brand	Rolls	
Modelo	2 OS 33P	
Medidas	0.392m×0.211m×0.63m	
Area	0.0694m2	
Battery Type	Deep cycle, flooded	
Cost per Unit	MXN $17,451.15 USD $876	
Total Required Batteries	72	
Required Area	4.9968 m^2	
Total Cost	MXN $1,256,482.8 USD $63,072	
Life Cycles vs. Charge Deepness	4000 life cycles = 50% discharge	

Table 4 Specifications of Rolls battery, 2 OS 33 P
Sources of reference: (Rolls, 2022)

To supply sufficient voltage and amperage with this Battery Types, we obtain the scheme shown in Figure 4.

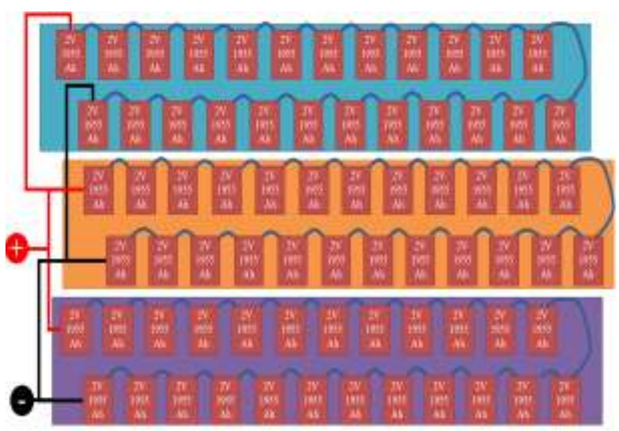


Figure 4 2V battery scheme to reach 48V and 5610 Ah

This scheme includes:

- 24 batteriesconnected in series= 48 V/1955 Ah
- 3 parallels= 48V/5865 Ah

The battery charging is calculated as follows:

$$Charge = 48V \times 0.5 \times 1955\ Ah = 46920\ Wh$$

We continue with the sizing of the controller, first calculating the necessary supply that the controller must support, at a minimum, considering the peak solar hours in the area:

$$Supply = \frac{1955\ Ah \times 0.5}{5\ h} = 195.5\ A$$

Taking into account the supply parameter, we look for an MPPT regulator/controller that exceeds this current. Since it is such a large amperage, we will connect multiple controllers in parallel to support the required amount. The chosen model from the market is shown in Table 5.

Specifications		
Brand	VICTRON	
Model	Regulador SmartSolar MPPT RS 450V 200A Victron	
Dimensions	0.487m×0.434m×0.146m	
Battery Voltage	48V	
Maximum input voltaje	450V	
Maximum charging current	200[a]	
Number of units required	2	
Cost per Unit	MXN $43,958.26 EUR £2,085.96	
Total Cost	MXN $87,916.52 EUR £4171.92	

Table 5 Specifications of the SmartSolar MPPT RS 450V 200A Victron regulator
Source of reference: (VICTRON, 2019)

$$P_{controller\ allowed} = Battery\ bank\ voltage \times Controller\ amperage$$

$$P_{controller\ allowed} = 48V \times 400A = 19200W$$

Next, we will size the photovoltaic modules and their arrangement. First, we need to know the energy generation required by the system:

$$Generation\ req = Battery\ bank\ voltage \times Supply$$

$$Generation\ req = 48V \times 195.5A = 9384W$$

Parameters for the modules:

- $9384W < P_{máx} < 19200W$
- $195.5A < I_{SC} < 400A$
- $48V < V_{Pmáx} < 450V$

Considering the above parameters, the selected model with specifications is described in Table 6.

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Specifications		
Brand	CanadianSolar	
Module	HiKU7, CS7N-670MS	
Type	Monocristalino	
Efficiency	21.6%	
Maximum Rated Power (Pmax)	670 W	
Maximum rated voltage (Vmp)	38.7 V	
Maximum rated power current (Imp)	17.32 A	
Open Circuit voltage (VOC)	45.8 V	
Short-circuit current (ISC)	18.44 A	
# modules required	15	
Dimensions	2.384m×1.303m×0.035m	
Required Area	3.106 m^2	
Price per unit	MXN $4,272.48 USD $214.5	
Total	MXN $64,087.2 USD $3,217.5	

Table 6 Specifications of the HiKU7, CS7N-670MS solar panel

Source of reference: (CanadianSolar, 2022)

An arrangement in parallel and one in series must be made to cover the energy, voltage, and amperage demands of the system:

– 13 parallels:
– 10 parallels: $I_{máx,mod} = 10 \times 18.55A = 185.5\ A$
– 3 parallels: $I_{máx,mod} = 3 \times 18.55A = 55.65\ A$
– Suma: 241.15 A

– 3 strings/serie: $V_{máx,mod} = 3 \times 45.8V = 137.4\ V$

– Power of 15 paneles: $P_{máx} = 670W \times 15 = 10{,}050\ W$

The amperage that the module provides to the batteries is:

$$Module\ current\ to\ batteries = \frac{P_{máx}}{V_{bat}} = \frac{10{,}050W}{48V} = 209.37A$$

Figure 5 shows the installation scheme, including the connection of the battery scheme, along with the controllers and the specified photovoltaic array.

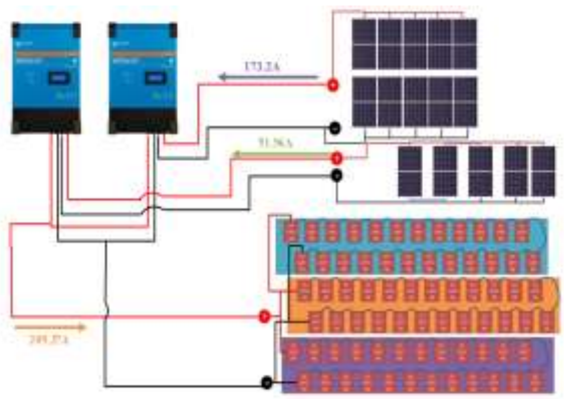

Figure 5 Autonomous Photovoltaic System Scheme, including photovoltaic array, controllers, and battery scheme

Before continuing with the sizing of the inverter and system wiring, we must consider that temperatures and irradiance in the area can change the output values of the panels, so we must consider the changes in the characteristic curve and the output values that this implies.

Consulting NOM-001-SEDE-2018, Chapter 6, we obtain the following correction values for voltages, according to the extreme temperature data obtained earlier:

– -4°C=1.12
– 44°C=0.8120

The tables from which these factors were extracted are shown in Figure 7.

Figure 7 Tables of correction factors for voltages, indicating the obtained values
Source of reference: (NOM-001-SEDE-2018)

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NOM-001-SEDE-2018, Chapter 6, Article 690, Section 8, Subsection a, indicates:

"For currents of the photovoltaic source circuit: The maximum current must be calculated by one of the following methods (NOM-001-SEDE-2018):

1. The sum of the short-circuit current of the modules in parallel, multiplied by 125 percent.
2. For photovoltaic systems with a generation capacity of 100 kW or more, a documented photovoltaic system design using a standard industry method and developed by an electrical engineer will be allowed. The calculation of the maximum current value will be based on the average of three hours of the highest current resulting from the simulation of local irradiation of a photovoltaic array, taking into account orientation and elevation."

We then obtain:

– $V_{máx} = V_{OC} \times Correction\ Factor = 45.8V \times 1.12 = 51.296V$
– $V_{min} = V_{mp} \times Correction\ Factor = 38.7V \times 0.8120 = 31.42V$
– $I_{máx} = I_{SC} \times 1.25 = 18.55 \times 1.25 = 23.18A$

These corrections result in a correction of the original I-V curve of the module, obtaining a graph similar to the one presented in Figure 8, where we see the possible voltage and current surpluses, as well as the possible voltage decrease at high temperatures.

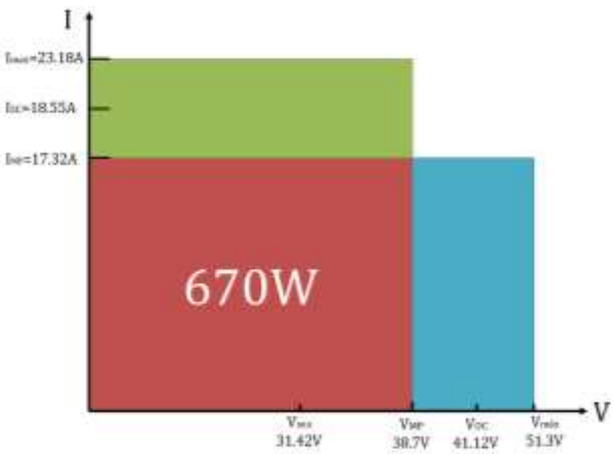

Figure 8 Modified I-V curve with temperature and safety factors for voltage and current, respectively

Finally, the photovoltaic system supplies the following amount of Ampere-hours per day, and we can determine if it satisfies the demand of the batteries.

$$Ah\ per\ day = Current_{controller} \times PSH = 222.5A \times 5 = 1112.5\ Ah$$

$$V_{bat} \times Ah\ per\ day = 48V \times 1112.5Ah = 53400Wh$$

$$53400Wh > 46920Wh$$

Continuing, we obtain the current that the controller would be supplying to the batteries to recharge them. This data will help us size the cables.

$$Current_{controller} = \frac{\text{Photovoltaic poer}}{\text{Battery bank voltage}} = \frac{10{,}050\ W}{48\ V} = 209.375\ A$$

The next part of the sizing is the direct current to alternating current inverter since the charging station is designed with AC power.

First, we need to know the maximum Ah that the controller will be able to supply to the inverter:

$$Inverter\ Ah = Controller\ amperage \times HSP = 400A \times 5h = 2000Ah$$

The next part of the sizing is the direct current to alternating current inverter since the charging station is designed with AC power.

First, we need to know the maximum Ah that the controller will be able to supply to the inverter:

$$P_{inverter} = \sum Equipment\ Power * 1.56 = 51{,}840 \times 1.56 = 80{,}870W$$

Specifications	
Brand	Growatt
Model	MAX 80KTL3-LV
Dimensions	0.86m×0.6m×0.3m
Input	104,000 W/1100V
Output	80,000W/400V trifásico
Frequency	50Hz/60Hz
Cost	MXN $96,811.48 EUR £4,584.17

Table 7 Specifications inverter Growatt, MAX 80KTL3-LV
Source of reference: (Growatt, 2018)

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We calculate the current demand of the inverter with:

$$Demand = \frac{Max.\text{inverter power}}{V_{bat.}} = \frac{104{,}000W}{48V} = 2166.67A$$

The current that the inverter can demand, once the load is applied, is covered by the maximum values of the inverter. Now, we will analyze the best wiring for this installation. The required ampacity of the conductors, with respect to the photovoltaic modules used, is obtained by multiplying the short-circuit current of all modules in parallel by a safety factor of 125% squared. Additionally, two additional factors are considered to modify the required ampacity and, therefore, will change the required gauge in our installation.

These factors are correction within the conduit/channeling (if there are more than two cables in the conduit, there will be losses) and the temperature factor since the wiring is made of a conductor that the ambient temperature can affect. Then we get the following equation:

$$Adjusted\ required\ ampacity = \frac{\sum I_{sc-Parallel} \times 1.25^2}{F_T \times F_C}$$

The piping for the wiring must be separated from the ground by 10cm, and according to NOM-001-SEDE-2018, Table 310-15(b)(3)(c), shown in Figure 9, "Adjustments to ambient temperature for circular conduits exposed to sunlight," we add 17°C to the maximum temperature of the area to then find the temperature adjustment factor.

Distancia por encima del techo hasta la base del tubo conduit milímetros	Sumador de temperatura °C
De 0 hasta 13	33
Más de 13 hasta 90	22
Más de 90 hasta 300	17
Más de 300 hasta 900	14

Figure 9 Table of adjustments to ambient temperature for circular conduits exposed to sunlight on or above roofs
Source of reference: (NOM-001-SEDE-2018)

$$Total\ Temperature = 44°C + 17°C = 61°C$$

With this data, we consult NOM-001-SEDE-2018, Table 310-15(b) (2)(a), "Correction Factors based on an ambient temperature of 30°C," shown in Figure 10.

Para temperaturas ambiente distintas de 30 °C, multiplique las anteriores ampacidades permisibles por el factor correspondiente de los que se indican a continuación:			
Temperatura ambiente (°C)	Rango de temperatura del conductor		
	60 °C	75 °C	90 °C
10 o menos	1.29	1.20	1.15
11-15	1.22	1.15	1.12
16-20	1.15	1.11	1.08
21-25	1.08	1.05	1.04
26-30	1.00	1.00	1.00
31-35	0.91	0.94	0.96
36-40	0.82	0.88	0.91
41-45	0.71	0.82	0.87
46-50	0.58	0.75	0.82
51-55	0.41	0.67	0.76
56-60	-	0.58	0.71
61-65	-	0.47	0.65

Figure 10 Correction factors based on an ambient temperature of 30°C
Source of reference: (NOM-001-SEDE-2018)

We obtain that the value of the first Correction Factor is 0.47. Additionally, we will consider that, in the system, each conduit will have a maximum of 2 cables (positive and negative), along with the ground cable. This results in the Conduit Correction Factor as 1. So, with this data, we can obtain the value of the adjusted required ampacity and, consequently, determine the gauge of the cable required.

$$Adjusted\ required\ ampacity = \frac{241.5A \times 1.25^2}{0.47 \times 1} = 801.7A$$

Based on NOM, specifically on Table 310-15(b)(17), "Permissible ampacities of individual insulated conductors for voltages up to and including 2000 volts outdoors based on an ambient temperature of 30°C," shown in Figure 11, we choose an AWG800 gauge to support the required ampacity.

Figure 11 Permissible ampacities of individual insulated conductors for voltages up to and including 2000 volts outdoors based on an ambient temperature of 30°C
Source of reference: (NOM-001-SEDE-2018)

The resistivity of the AWG 800 cable is 0.0377 Ω/km (NOM-001-SEDE-2018), so to determine if this gauge is sufficient for the load and distance, we use the following formula:

$$e_T = \frac{2 \times distance \times I_{MP}}{V_{MP}} \times R$$

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Assuming 50 m of wiring, we get:

$$e_T = \frac{2\times 0.05km\times 17.32A}{39.7V} \times 0.0377\ \frac{\Omega}{km} = 1.64 \times 10^{-4}$$

$$e_T = 0.164\% < 3\%$$

The voltage drop is less than 3%, so the gauge is suitable for the intended distance, as well as for the voltage and ampacity it needs to transmit.

Specifications	
Brand	RNEDA
Gauge	800AWG
Required quantity	50m
Price per meter	MXN $500
Total	MXN $25,000

Table 8 Specifications, cable 800AWG
Source of reference: (RNEDA, 2019)

For the sizing of the thermal-magnetic switch, we must take into account the current that the inverter will be supplying at its output, and, therefore, to the charging station.

$$\frac{P_{inverter}}{V_{bat}} = \frac{80{,}870W}{48V} = 1684.8A \text{ c}$$

In the market, we look for a thermal-magnetic switch that fits this parameter or exceeds it.

Specifications	
Brand	PowerPact
Model	PowerTag , RLF36250U44A
Capacity	600V 2500ª
Price	MXN $58,000

Table 9 Specifications of the PowerPact thermal-magnetic switch
Source of reference: (PowerPact, 2020)

Finally, we reach the sizing of connectors. MC4 connectors will be used, as they comply with article 690-33 of NOM-001-SEDE-2018, Plugs and connectors. MC4 connectors are the most commonly used in the market; the quantity of connectors depends on the number of panels to connect.

Specifications	
Brand	Autosolar
Precio per pair	MXN $124.05
Required Pairs	15 pares (30 conectores en total)
Total Price	MXN $1860.75

Table 10 Specifications of MC4 connectors
Source of reference: (Autosolar, 2022)

Finally, the total costs of each element, as well as the complete installation, are shown in Table 11.

	Costs
Charging Station	$ 538,535.58
Batteries	$ 1,256,482.80
Controller	$ 87,916.52
Modules	$ 64,087.20
Inverter	$ 96,811.48
Wiring	$ 25,000.00
Switch	$ 58,000.00
Connectors	$ 1,860.75
Total	$ 2,128,694.33
Total + Labor (10%)	**$ 2,341,563.76**

Table 11 Costs of the installation of an autonomous photovoltaic system for a fast charging station

The final installation scheme is shown in Figure 3.3.15, already showing the connections of the battery system with the controllers and the inverter, as well as the power supply from the solar panel systems to the controllers. We also observe how the inverter is connected to the load, in this case, the Terra 54HV UL charging station, and is protected by the thermal-magnetic switch.

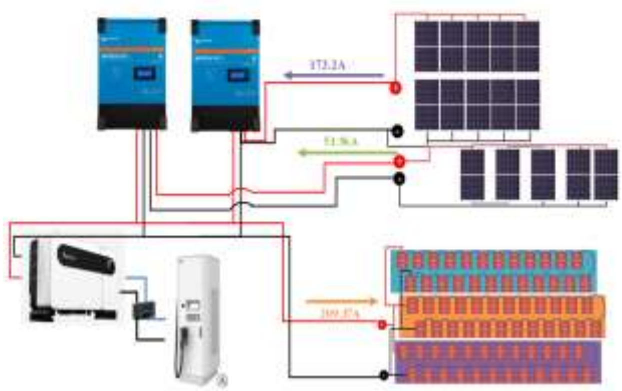

Figure 12 Final scheme of autonomous photovoltaic system installation

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Return on Investment, Autonomous System

The return on investment is an economic analysis to determine if the necessary investment for the autonomous system can be recovered or if, on the contrary, it would be just a luxury and a lost investment. This return on investment can be calculated assuming that we will sell the energy at the local marginal price established by CENACE. We must remember that the local marginal price varies according to demand and the time of day, so we obtained an average of the daily consumption of the corresponding node to Torreón, Coahuila, in April 2022. First, we obtained the Node key, being 05TRR-115, as shown in Figure 13.

Figure 13 Screenshot of the document "Catálogo NodosP Sistema Eléctrico v2022"
Source of Reference: (CENACE, 2020)

With the node key, values of the local marginal price (PML) for the node and each hour of the day from April 16 to April 30, 2022, were extracted from the document "PrecioMargLocales SIN MTR Abr02 v2022," also obtained from CENACE. Using these data, the graph shown in Figure 14 was generated.

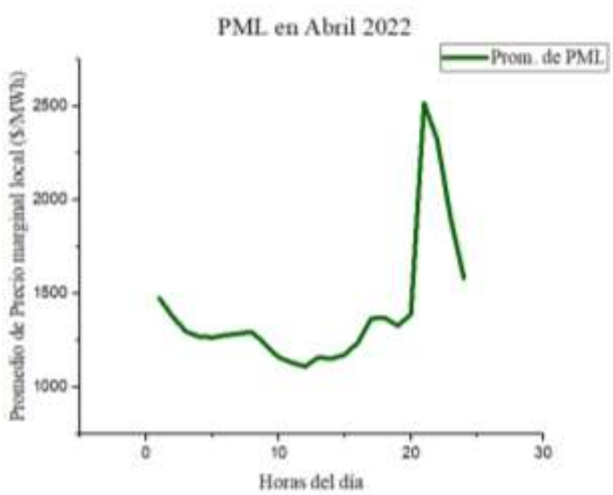

Figure 14 Average Local Marginal Price for node 05TRR-115, from April 16 to 30, 2022
Reference Source: (CENACE, 2020)

From these data, we find that the daily average PML is MXN$1403/MWh. This value will be used to calculate the return on investment.

For the calculation, let's consider that the fast charging of a single electric vehicle (EV) is approximately 52 kWh, which is equivalent to 0.052 MWh. Thus, the potential profit for each EV fast charge would be:

$$1403\ \frac{MXN\$}{MWh} \times 0.052\ MWh = MXN\$72.9 \approx MXN\$73$$

If we consider the most optimistic scenario of 2 charges per day, we obtain a daily income of MXN$146. If we extrapolate this income over 365 days to calculate the annual revenue, we get:

$$MXN\$146 \times 365\ days = MXN\$53{,}290/year$$

Therefore, for the return on investment, we will calculate how many years it will take to recover the initial investment:

$$\frac{MXN\$\ 2{,}341{,}563.76}{MXN\$53{,}290/year} \approx 44\ years$$

In the most optimistic scenario, it would take us approximately 44 years to recover the initial investment, without taking into account the maintenance that the installation would require. Furthermore, this timeframe significantly exceeds the lifespan of batteries (estimated at 13 years in good conditions) and the useful life of photovoltaic modules and the inverter (around 25 years) (L. Santiago, 2018).

Acknowledgements

We express our deep gratitude to the Instituto Tecnológico de la Laguna for their invaluable support in providing us with their facilities, enabling the effective conduct of our research and writing.

Financing

This work has been funded by CONACYT [CVU 1271712].

Conclusions

In this study, an energy and economic sizing was carried out for the case of a standalone photovoltaic system in the locality of Torreón, Coahuila, Mexico. The main objective of the work was achieved: theoretically, it was determined that it is possible to install a fast-charging station powered by photovoltaic energy in the region.

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However, it would not be a financially viable project in any aspect, as the lifespan of the components is much shorter than the time needed to cover the initial installation expenses of the system. Consequently, it is concluded that, if this project were to be implemented, the initial investment would never be recovered.

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