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Abstract

In recent years there is the tendency to charge Electric Vehicles (EVs) with clean sources of energy. Due to this tendency, scientific literature focused on problems of locating and sizing Photovoltaic (PV) Charging Stations (CSs). In this paper, we studied the case of the localization and sizing of PV powered CSs in the region of Valle de Aburrá, Colombia, which is the region of the country with the fastest growth of EV adoption. Looking to utilize the largest amount of PV power, we considered level 1 (low-power) PV-grid CSs. The use of other PV charging systems, like level 3 (high-power) charging, would require covering bigger roof areas with PV panels, more than the available on an urban landscape. Considering that this problem takes into account low-power CSs, candidate CS locations are places where people go for extended periods of time, with large roof areas and parking availability. In this problem, the decision variables are the location of the CSs, the amount of charging spots at each selected location, and the size of the PV system. These decisions aim to minimize the added annualized cost of the PV systems, the annualized cost of the charging spots in the selected CSs, and the cost of energy purchased from the grid in a year. For calculating the amount of power that the PV systems are capable of generating, we obtained the typical irradiation curves for each candidate CS location. For solving the studied problem, we propose a Mixed Integer Linear Programming (MILP) formulation.

Keywords: Location Problem, MILP Formulation, Electric Vehicles, Photovoltaic System, Minimize Costs, Photovoltaic Charging Stations, Clean Energy Sources, Photovoltaic Generation, Linear Programming, Energy Demand.

El problema de la localización de estaciones de recarga con sistemas fotovoltaicos: Un caso de estudio.

Resumen

En los últimos años ha surgido la tendencia de cargar los vehículos eléctricos (VE) con fuentes de energía limpias. Como consecuencia la literatura científica se ha interesado por los problemas de localización y dimensionamiento de las Estaciones de Carga Fotovoltaicas (ECF). En este trabajo se estudia el caso de la localización y dimensionamiento de ECFs en la región del Valle de Aburrá, Colombia, la cual es la región del país con mayor crecimiento en la adopción de VE. Con el fin de utilizar la mayor cantidad de energía fotovoltaica, consideramos las ECFs conectadas a la red de nivel 1 (baja potencia). El uso de otros sistemas de recarga fotovoltaica, como el nivel 3 (alta potencia), requeriría cubrir mayores superficies de tejado con paneles fotovoltaicos, más de las disponibles en un paisaje urbano. Teniendo en cuenta que este problema considera las ECFs de baja potencia, las ubicaciones candidatas son lugares a los que la gente acude durante largos periodos de tiempo, con grandes superficies de tejado y disponibilidad de aparcamiento. En este problema, las variables de decisión son la ubicación de las ECFs, la cantidad de puntos de carga en cada ubicación seleccionada y el tamaño del sistema fotovoltaico. Estas decisiones pretenden minimizar el costo agregado anualizado de los sistemas fotovoltaicos, el costo anualizado de los puntos de carga en las ECFs seleccionadas, y el costo de la energía comprada a la red en un año. Para calcular la cantidad de energía que los sistemas fotovoltaicos son capaces de generar, obtuvimos las curvas de irradiación típicas para cada ubicación de las ECFs candidatas. Para resolver el problema estudiado, proponemos una formulación de programación lineal entera mixta (MILP).

Palabras clave: Problema de Localización, Formulación MILP, Vehículos Eléctricos, Sistema Fotovoltaico, Minimizar Costos, Estaciones de Carga Fotovoltaicas, Fuentes de Energía Limpia, Generación Fotovoltaica, Programación Lineal, Demanda Energética.

1. Introduction

Transportation is a big contributor to the production of greenhouse gases due to its dependency on combustion engines. Almost 22% of Europe’s 2017 emissions came from means of transportation through roads (European Environment Agency, 2021). In the US this number goes up to 28% in measurements taken between 1990 and 2018 (United States Environmental Protection Agency, 2021). Therefore, it is necessary to use novel technologies such as Electric Vehicles (EVs). It is also important to ensure that the energy that powers EVs is produced by environmental friendly sources. One alternative that ensures that EVs use clean energies is that some part of the energy used to charge them is generated by Photovoltaic (PV) energy.

Although EVs can be a clean alternative for pollution issues, they have technical limitations. One of the biggest concerns with EVs is their driving range. Because of that limitation, the availability of charging infrastructure becomes a big necessity, mainly in urban areas. The lack of a good implementation regarding these aspects is a significant reason for slowing down the adoption rate of this type of vehicles Quddus (Kabli and Marufuzzaman, 2019; Domínguez-Navarro et al., 2019). Improving the number of Charging Stations (CSs) is proven to encourage customers to buy EVs Amini (Moghaddam and Karabasoglu, 2017). The installation of CSs powered by PV power helps as an incentive to ensure that part of the energy used to power the EVs comes from clean sources.

The joint usage of EVs and PV powered charging systems generates the problem of locating and sizing PV powered CSs in urban environments. In this paper we study a problem of localization and sizing of PV powered CSs in the region of Valle de Aburrá in Colombia. A region with a significant growth on the adoption rate of EVs, and that due to its geography and climate, is prone to environmental issues (El Tiempo, 2021). In this problem we consider the following decisions: where and how many CSs to install, the number of charging spots available in each CS, and the size of the PV system of each CS. Taking into account the condition of being in an urban environment and that available roof areas are limited, we consider level 1 (low-power) CSs, to allow the system to prioritize the use of solar energy. Because of these conditions, the CS locations considered are places where people go for extended periods, large roof areas are available, with many parking spots. These conditions are fulfilled by places like universities, shopping malls, hospitals, and large commercial buildings. As inputs of the problem, we consider the behavior of likely users in terms of locations they go to, the cost of the infrastructure, the maximum tolerable walking distance and the architectural landscape of the city for the case study.

For solving the studied problem, we use a Mixed Integer Linear Program (MILP) formulation capable of obtaining optimal solutions at relatively low computation times for the case study of the Valle de Aburrá region. Although this model is built for a specific case and region, it can be replicated in any urban area just by gathering few pieces of data. Additionally, we ran sensitivity analyses to know which were the most sensible variables.

The remainder of this paper is organized as follow: section 2, is a review of pertinent literature about solar power, EVs. and solutions that involve both; section 3, is an explanation of how PV powered EV charging works; section 4, is a formal description of the problem and the MILP formulation; section 5, is the description of the case study in detail and the computational experiments that we executed; section 6, is the results discussion and finally, section 7 concludes the paper.

2. Literature review

The studied problem focuses on three decisions, where to locate CSs, the size of the PV system that selected candidates should have, and the management of the energy required for charging. Thus the literature review focuses in problems that consider these decisions.

In the literature some investigators studied the problem of localization and sizing of CSs with distributed generation. Bhatti, et al. (2016) ran a review of the technological status of EVs with PV as source of power.The authors conclude that PV powered solutions combined with a connection to the grid are flexible and interruption-less. The authors also state that energy management systems, highly relay on optimization algorithms. Although there are many problems of PV powered CSs localization and sizing, up next, we will review problems where the aim is to minimize the cost of infrastructure plus the cost of purchasing energy because they are similar to our objective function. We will now introduce problems that integrate these conditions. In Amini, Moghaddam and Karabasoglu (2017) the study concludes that the charging rate is one of the influential factors of parking lot demand. Focusing on the economic side of EV charging Mozafar, Moradi and Amini (2017) considers the stochastic nature of Renewable Energy Sources (RES) formulating a multi-objective optimization problem that aims to reduce the charging costs, having the location of RES and EV CSs as the optimization variables. Ugirumurera and Haas (2017) plan an entire green EV charging system minimizing the investment in the PV system. Wang, et al. (2019) use a multi-objective planning model to determine the location and size of EV CSs, RES, and distribution network expansion schemes to minimize the total investment and maximize the charging service capability. Quddus, Kabli and Marufuzzaman (2019) goal is to minimize the overall cost of the network electricity concerning existing CSs. Short-term expected decisions include renewable energy use and grid power usage. Long-term decisions imply station expansion decisions, showing that decisions do not have to be over existing infrastructure, but can take into count future decisions.

A problem that is similar to ours is the propose by Ji, et al. (2020). Although their objective is to maximize the profit of a system of CSs aided by PV energy (instead of minimizing the total cost like our case), they include similar decisions and constraints. They aim to decide the location of CSs aided by PV energy. They consider as a restriction that EV owners have a maximum acceptable walking distance. Also, all the expected EVs demand must be served, and if solar energy is not enough, grid available energy can be used as a source of power. The main difference with our problem is that their objective function maximizes the profit of selling the energy to EV owners, while we aim to reduce the total cost of the charging system and its operation. Also, the input parameters are different, they choose their candidate CS locations by using heat maps made by tracking currently used EVs, while we propose analyzing the available architectural landscape of the region and surveying the behavior of present EV owners and possible buyers of EVs.

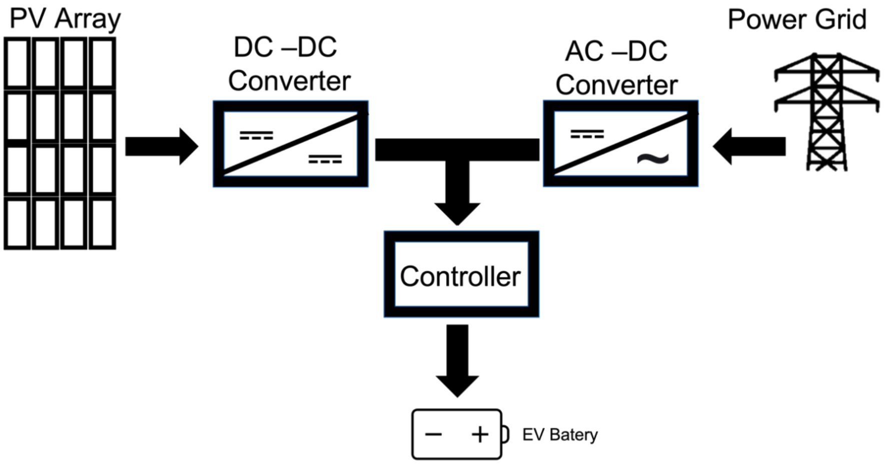
3. PV Charging stations

Looking to facilitate the understanding of the problem, in this section, we are going to describe the components of PV powered CSs and how they work.

PV-grid CSs can get power from both the PV system and the power grid (Bhatti, et al., 2016). A typical PV-grid charging system has three main components: the first component is a DC-DC power converter with a MPPT (maximum power point tracking), this last item is used for extracting the maximum available power from the PV array according to the conditions it is working at; the second component is an AC-DC converter connected to the grid inlet, converting the AC power from the grid to the DC required by the EV; the third component is a controller that decides between different charging operations. The charging operations are charging only with PV energy, charging by PV power and grid power combined, charging only with grid power.

This element is always prioritizing the use PV power. All the charging operations must ensure that the supply of energy is adequate for a level 1 (low power) connection with 11 kW of power. Therefore, for the second operation (combine), the power taken from the grid is the result of what is needed by the EV (11 kW) minus the complete PV power generated. For our case we do not consider Energy Storage System, this meaning we do not use storage batteries for the stations. Batteries for EVs are charged using Direct Current (DC) so that is why the input of the battery is in DC in every case. Figure 1 shows a simplified scheme of the system.

Figure 1. Scheme of a CS



4. Problem formulation and model

Let be a set of destinations. For each destination we know the expected demand expressed in EVs that need to be charged per day. Let be a set of candidate CS locations. For each candidate CS location we know the available roof area , the annualized cost of purchasing and installing a square meter of solar panel , the annualized cost of purchasing and installing of a charging spot , the maximum number of available parking locations , and the cost of the electric energy purchased from the grid (expressed in $/kWh). Let be the distance between a destination and a candidate CS location . The parameter represents the maximum distance an EV owner is willing to walk between his destination and his assigned CS location. The parameter represents the power required by a charging spot to charge an EV. Let be a set of moments during the day . The parameter represents the time interval between moments. Let be the the power generated by a square meter of PV system during a moment in the candidate CS location . The parameter represents the number of days in a year.

In this problem, the objective function minimizes the annualized total cost of the system. This total cost includes the annualized cost of installing all the necessary charging spots, plus the annualized cost of installing the required area of solar panels, plus the annual value of the required energy from the grid. A feasible solution of this problem must ensure that the following restrictions are respected: the number of charging spots and thus the number of assigned EV in a selected CS location must be less than or equal to the available parking spots in the selected CS location . The size of the PV system of a selected CS location must be less than the available roof area in that CS location . All the EVs that need to be charged must be served. The distance between a selected CS for an EV owner and the demand centroid must be less than . In this point it is worth noting that the time of charging an EV is constant because they will charge during the whole daytime. We remark that for this problem level 1 (low power) CSs are used, thus charging times are long. EVs owners are considered to be working in the meantime.

This problem is modeled as a MILP formulation. In this model we use the following decision variables: Variable is the amount of charging spots that will be installed in the CS location . Variable represents the number of square meters of solar panels installed in the CS location . Variable is the amount of energy purchase from the grid at the CS location . Variable is equal to 1 if at least one EV owner with a destination is assigned to a candidate CS location , 0 otherwise. Variable is the number of EVs with a destination are assigned to the CS location . Finally, Variable is the amount of power required from the grid in a CS location during moment .

$\text{Min } Z=\sum_{j\in M} f_j\, x_j + \sum_{j\in M} c_j\, y_j + \sum_{j\in M} g_j\, e_j$	(Equation 1)
$\sum_{j\in M} v_{ij} = r_i$	(Equation 2)
$\sum_{i\in N} v_{ij} \leq x_j$	(Equation 3)
$x_j \leq q_j$	(Equation 4)
$w_{ij} \leq x_j$	(Equation 5)
$v_{ij} \leq w_{ij}\, r_i$	(Equation 6)
$d_{ij}\, w_{ij} \leq D_{max}$	(Equation 7)
$u_{jt} \geq hx_j - p_{tj}\, y_j$	(Equation 8)
$e_j=\sum_{t\in T} u_{jt}\ \Delta s$	(Equation 9)
$v_{ij}\in Z^{+}\ \forall i\in N,\forall j\in M$	(Equation 10)
$x_j\in Z^{+}\ \forall i\in N$	(Equation 11)
$y_j \geq 0\ \forall i\in N$	(Equation 12)
$e_j \geq 0\ \forall i\in N$	(Equation 13)
$v_j \geq 0 \forall j\in M,\forall t\in T$	(Equation 14)
$w_{ij}\in\backslash\{0,1\backslash\}\ \forall i\in N,\forall j\in M$	(Equation 15)

5. Case study

The region of Valle de Aburrá is an area in Colombia composed of 11 municipalities that are home to approximately 3.5 million people (Medellín Cómo Vamos, 2020). The geographical and climate conditions of the region, along with the activities related to industries and transportation, have generated several contamination issues (Bedoya and Martinez, 2009). This scenario has motivated the creation of different projects of sustainable mobility, mainly EVs. Valle de Aburrá is the region with the highest adoption rate of EVs in Colombia (RUNT, 2019). Due to that expected high demand, government entities are working towards generating the appropriate infrastructure to support the adoption of EVs. Many researchers have discussed the challenges that EVs adoption mean to electrical systems, problems like transmission lines overload, voltage drop in some sensitive networks, and the uncertainty in the demand. In this context, arises the necessity to solve the problem explained in this paper.

For this case of study, we had some considerations. As we mentioned before we used level 1 (low power) CSs. Candidate CS locations are in shopping malls, universities, and hospitals, so we consider that people will stay for long periods, 12 hours in our case. All costs and values are given for a 1-year period. All equipment that had to be depreciated was depreciated in a 10-year horizon.

5.1. Candidate parking lot locations

Due to the nature of the use of slow CSs, the necessity that EVs stay for long periods of time, and that large roof areas will be used to install PV systems, the first step of the process was to define possible locations for candidate CS. Due to the lack of free space and high prices for land in the region, we made the following considerations to put together the set of candidates CS locations:

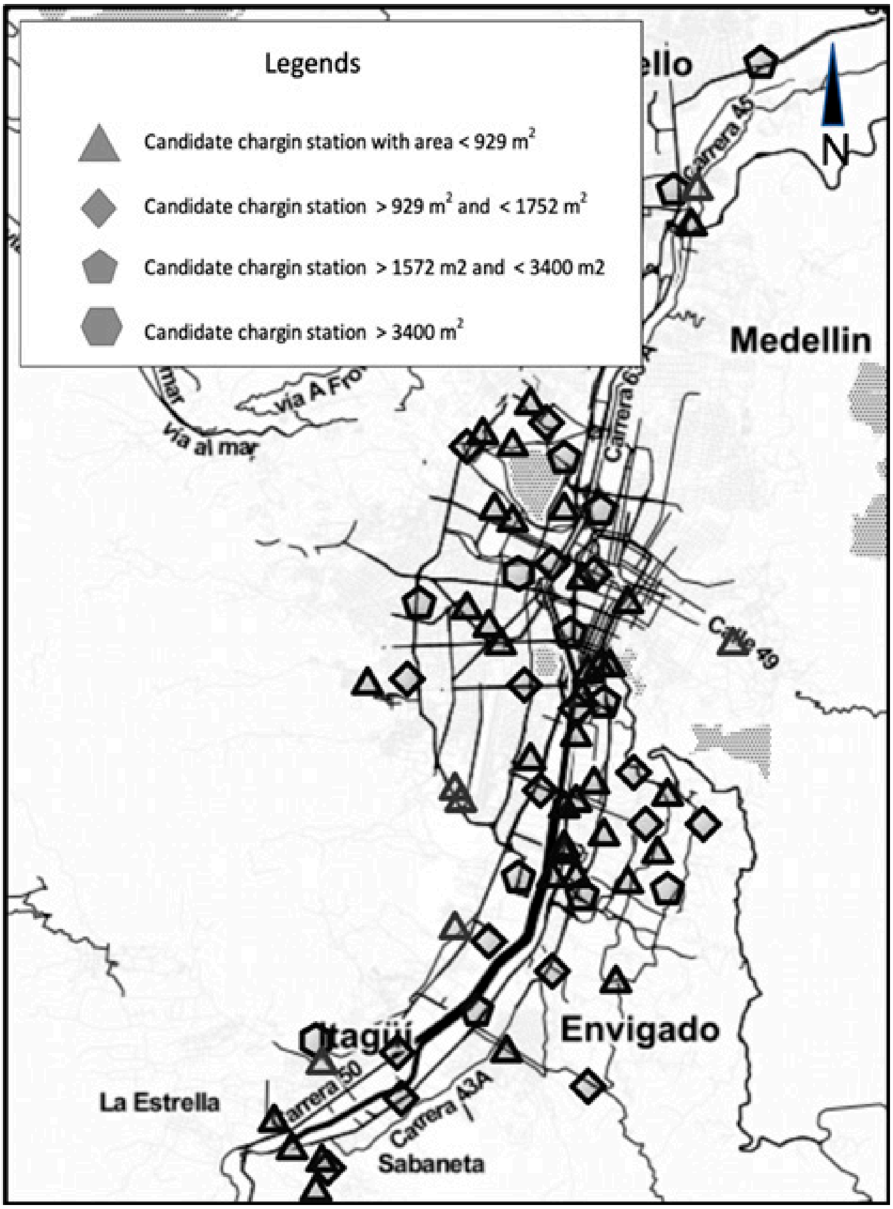
- Public access places were prioritized, for example shopping malls, universities, and hospitals. Parking spots had to already be available, therefore parking lots would not have to be constructed.
- Considering that existing structures will sustain PV systems, an that this will add an additional load to the structure, buildings that follow the newest seismic construction code are able to handle the

new demands. Colombia has a construction code that regulates the seismic and structural design of structures, and it was updated in 2010. So, for assuring the capability of structures for bearing this new load we defined two criteria. One was choosing buildings constructed after 2010. The other, in case we needed to choose an older building it had to have higher structural design requirements, this was the case for shopping malls, universities, and hospitals Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2010).

- Shading of nearby structures or trees would cause problems to electricity generation. That is the reason why the candidate CS locations had to be the tallest structure in the proximity.

Following these considerations, a pan over the area of interest was run using Google Earth® (Google, 2020a) looking for considerable roof areas. Using the Timelapse tool of the software the approximated date of construction was defined. The result is a set of 72 possible CS locations that are spread over the area of study, and all of them follow the 3 considerations mention before. For each candidate, the following information was gathered: type of use, coordinates, and constructed area. Figure 2 shows the location of the candidate CSs.

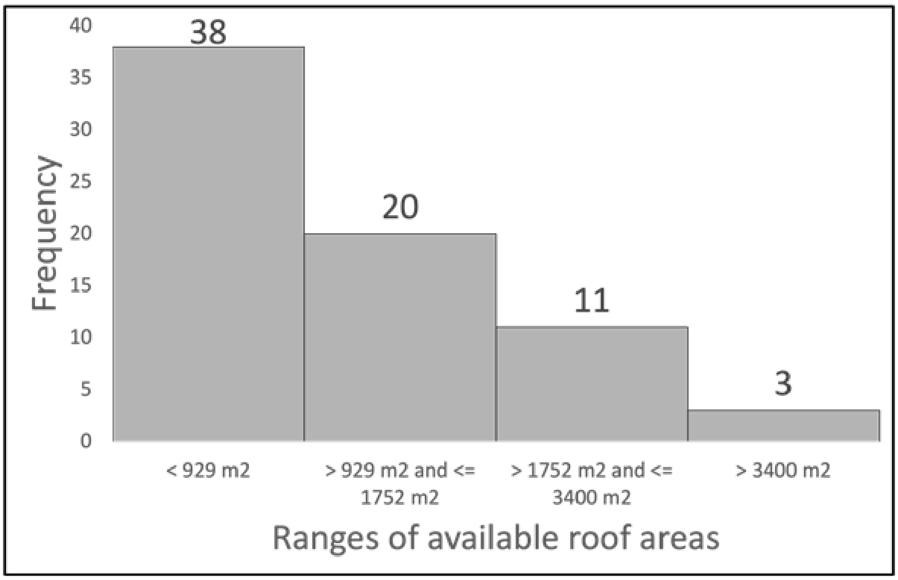
Figure 2. Location of candidate CSs



5.2. Solar power capacity

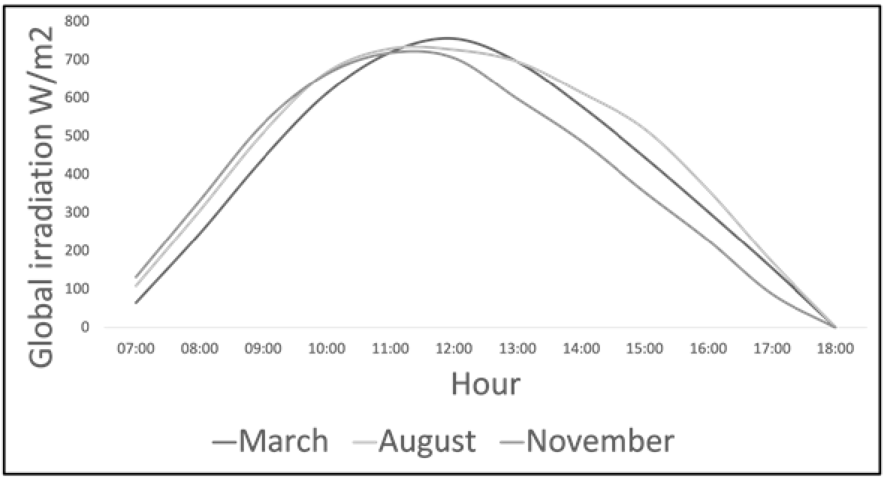
After defining the set of candidate CS locations, for each one of them we need to define the maximum power generation capacity of the roof with the use of PV-Watt® (National Renewable Energy Laboratory, 2020). Also, with the tool PVGIS® (European Commission's Science and Knowledge Service, 2020), we obtained the irradiance for each hour of the day. With both tools, it was possible to define hour by hour how much power could be generated by a square meter of solar panels on each location. In Figure 3 we show the classification that we used to identify the 72 candidate CSs according to the available roof area. This area is the one that defines the maximum capacity of the PV system. We can see that most candidate CSs have areas with less than 929 m^2 and that large CSs with more than 3400 m^2 are not frequent. This is because of the distribution of buildings in the region of the case study.

Figure 3. Classification of candidate CSs according to roof area



It is important to note that that information changes from day to day due to the climate conditions. Colombia is a country located near the Equator, so it has no seasons, but is in the Intertropical Convergence Zone (ITCZ). Under typical circumstances there are two wet seasons and two dry seasons in a year. As mentioned on the formulation of the problem, one of the parameters needed is the power generated by a square meter of PV system during an instant of the day for moment at candidate CS location . To perform our calculations, we needed to choose the data from an irradiation profile, we decided to choose the irradiation profile of a typical March day for each candidate CS location. March is a transition month between a dry and a wet season, so for conservative calculations that would result in the average conditions. Figure 4 shows the comparison of the irradiance profile for an specific candidate CS for the months of August, that is the month with higher irradiation, November that is the month with lower irradiation, and March that was the month used.

Figure 4. Irradiation profiles for a candidate CS



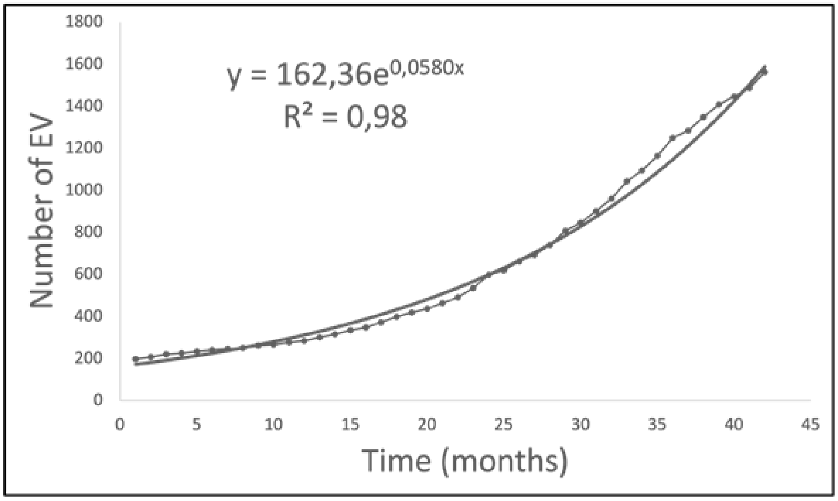
5.3. *Demand calculation*

The set of possible destinations taken into count for this study was put together by identifying the neighborhoods that EV owners would frequent the most. To determine how the demand was distributed we ran two processes. First, a survey and second a forecast.

We did two surveys that asked EV owners and possible EV buyers about their typical destinations. The surveys were made to get an idea of typical destinations that needed to be considered in the formulation. We designed two Qualtrics® (Qualtrics,2020) digital surveys. One to know the behavior of EV owners. The other survey was conducted for possible EV buyers. We obtained 151 responses. 8 EV owners answered, and 77 possible EV buyers were identified, the rest of responses did not achieve the requirements for being considered possible EV buyers. Information that was useful for us included the neighborhoods that EV owners and possible EV buyers frequent the most. We aggregated the responses of each neighborhood that was identify and located it into a single point. We picked the coordinates of this point visually to be as close as possible to the center of the irregular shape of the neighborhood, this point receive the name of demand centroid. Also, from the actual EV owners that answered the survey, we identified their behavior towards charging in public stations. They charge their EV in an average of 2 days per week on public CSs, meaning that a typical charging day would require to service 2/7 of the total number of EVs in the region. To determine the magnitude of a demand centroid, the number was calculated proportionally to the percentage of people that had that neighborhood as a destination. Then we multiplied that proportion by the total amount of EVs that is estimated to be circulating on the region, getting that way the distribution of the demand for the formulation.

For the forecast, we gathered the data of the number of EVs that were sold until the date of the study to estimate the possible growth in the number of EVs in a 2-year horizon. For estimating the growth in EVs sales, we gathered data from the monthly reports of the association of car dealers Asociación Nacional de Mobilidad Sostenible (2020) and the national traders federation FENALCO (2020). From the reports it was possible to know the behavior of the sales since 2010 in the country and detailed by region from 2017. Considering the uncertainty in the future of EVs sales we used an Exponential Accumulated Growth fitting forecasting method in which we made an exponential regression to the graph of total EVs vs time, obtaining an value of 0.98. Figure 5 shows the growth of the amount of EVs in the region since 2017, the line in the background is the graph of the equation obtained through the regression. According to this forecast in 2 years a total of 5750 EVs would be on the streets of the region.

Figure 5. Number of EVs in the region since 2017



With the gathered information it was possible to define that 41 demand centroids needed to be served with magnitudes of EVs demand ranging from 271 in the biggest one to 19 EVs in the 26 smaller ones. In Figure 6 we show the location of demand centroids that need to be served. Figure 7 describes the frequency of the magnitude of the 41 demand centroids. We can see that most of the demand centroids will have a demand of 19 EVs each day, meanwhile higher values for demand centroids are not frequent but will impose a great load on the system, the largest demand centroid is 14 times larger than the mode.

Figure 6. Location of demand centroids

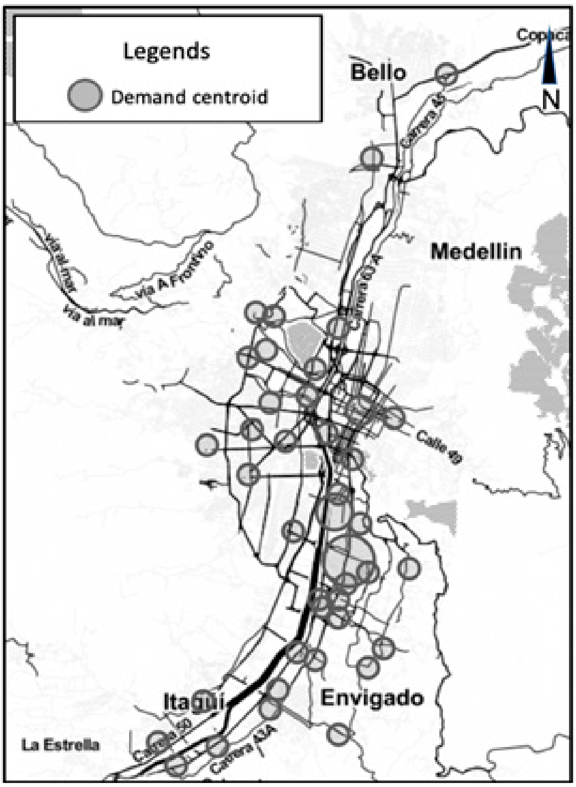
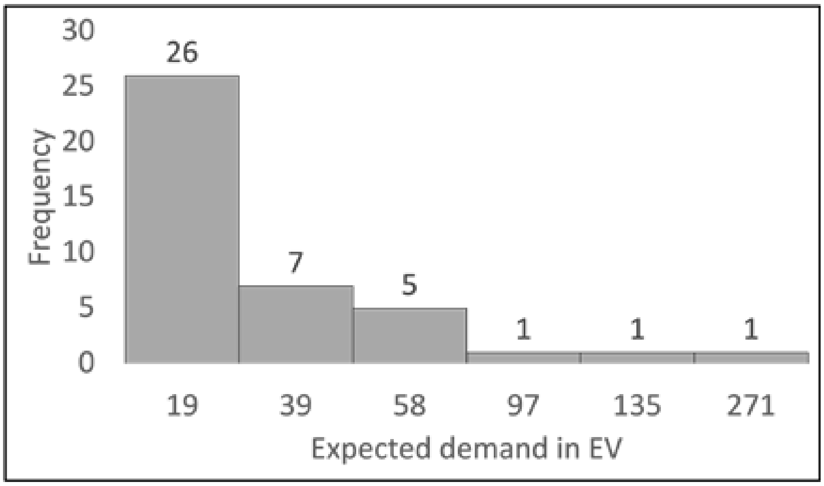


Figure 7. Demand distribution across centroids



5.4. Cost of PV installation and energy from the grid

The costs involved in solving the case study are for a candidate CS location , the annualized cost of purchasing and installing a square meter of solar panel , the annualized cost of purchasing and installing a charging spot , and the cost of the electricity that is purchased to the grid . In our case these costs are specific for the Valle de Aburrá region. The cost of PV systems and charging spots are direct investment costs, these are annualized as mentioned before.

For calculating these costs, both equipment types were depreciated at a rate of 10% per year, being that value the cost of property. For PV systems the price per square meter of installed panel was obtained using the quotation tool of Emergente (2020), a company that works in the area, the resulting cost is $16.52 per square meter per year. For a single charging spot cost, we used the price of residential 11 kW power CSs that are sold in the market, the price was $110.10 per CS per year. The cost of energy from the grid varies according to the location and the prices are defined by the utility company, for each candidate spot we gathered the cost of a kWh.

6. Results

For the case study, we built a base scenario for the problem based on data we gathered. In this section, we present such scenario, evaluate its solution, and perform some sensitivity analyses. The MILP formulation was implemented and solved using OR tools MILP solver Google (2020b) on Python 3.8.2 Van Rossum (2020). Experiments were run on a computing cluster with an Intel Core i5 processor (with 2 cores at 1.4 GHz) and 4 GB of RAM running on macOS Big Sur - 64 bits.

6.1. Base scenario

Considering the parameters explained in section 5, we solved the case for the Valle de Aburrá region. The run time for solving the base problem was about 5 seconds, plus 5 seconds creating a map that indicates where each demand centroid is located, if a candidate CS location is used or not, and how each demand centroid is serviced. The results the formulation gives are:

- If the problem has a solution or not.
- The total cost of the required investment (USD/year).
- Number of charging spots needed in each selected candidate CS (units).
- Installed square meters of solar panels in each selected candidate CS (m^2).
- Produced solar energy in each selected candidate CS (kWh).
- Used energy from the grid in each selected candidate CS (kWh).
- A matrix that indicates how a demand centroid is serviced by selected CS locations (units).
- The area used for PV system vs the available area in each selected candidate CS (m^2).

The optimal solution for this scenario states that out of 72 candidates CSs, 66 were selected. Out of the available roof area for the selected CSs, 98.07% is used for the installation of the PV system. The average walking distance for an EV owner is 0.69 km. In Figure 8 we can see the histogram of the distances EV owners are required to walk. The energy management according to its source is 21.15% is produced by the PV system, and 78.85% is from the grid. From the total cost of the system, the cost of installing the PV system is 11.61%, the reminder 83.39% is the cost of purchasing energy from the grid.

Figure 8. Histogram of distance walk by EV owners in optimal solution

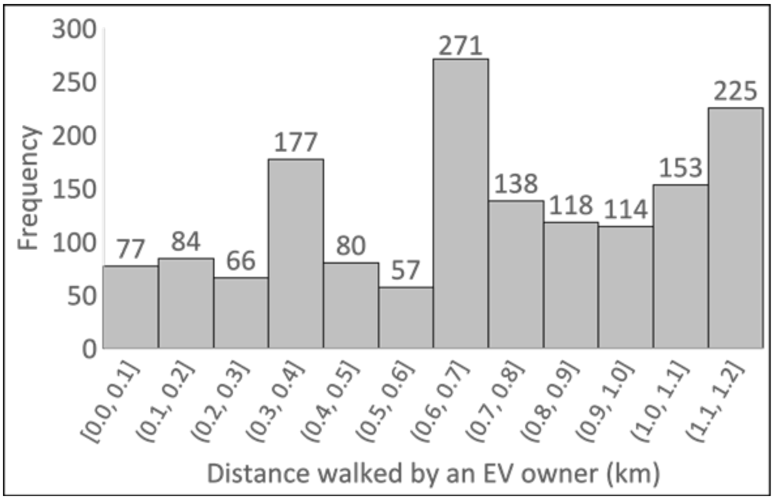


Figure 9 shows an extract of the graphical solution for the base scenario that the formulation can create. It shows the portion of the map that includes the demand centroids with the higher magnitudes. The lines between demand centroids and selected CS locations indicate the number of EV owners assigned. Figure 10 allows us to see the histogram of the percentage of use of available locations for charging spots vs the number of charging spots that solution assigns to the selected CSs. Analyzing the result, we found that 56.60% of the total demand is serviced by the 15 selected CSs with a percentage of use between 84% and 100%. This result indicates that the solution tends to use as much as possible of good located candidate CSs, and the reminder is spread up between less ideal candidate CSs.

Figure 9. Graphical solution for highest demand centroids

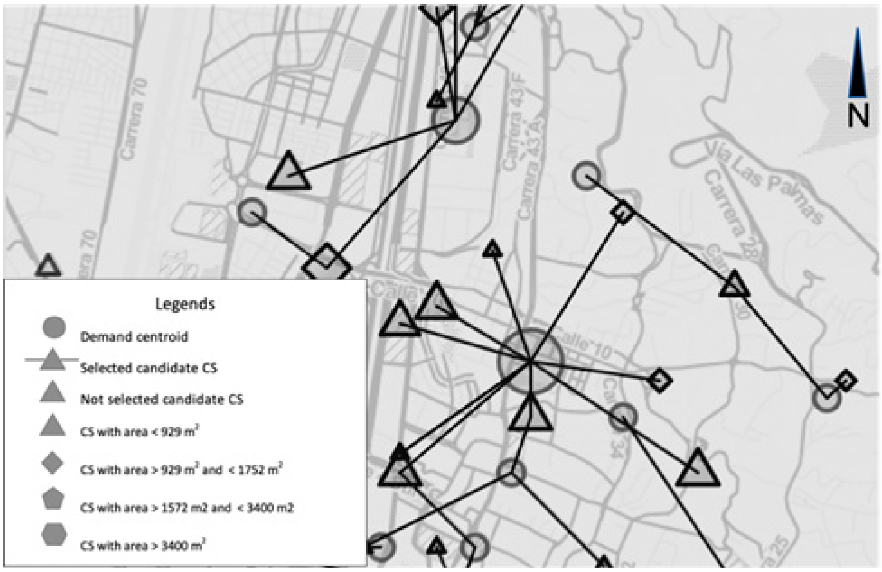
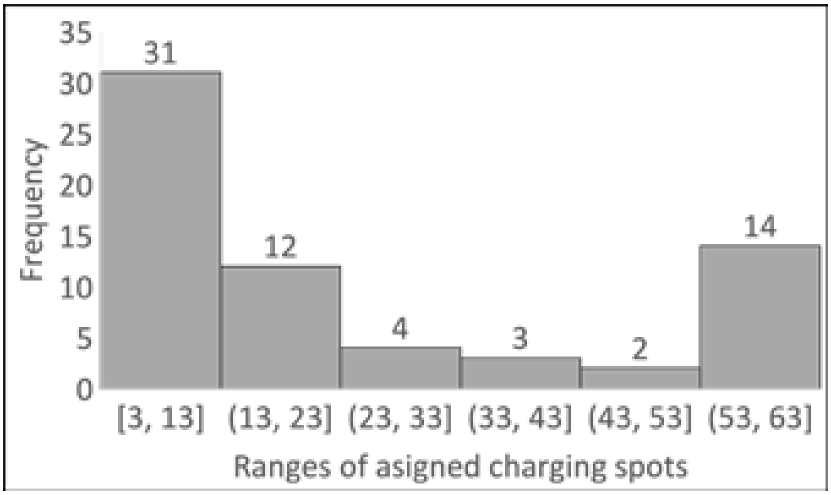


Figure 10. Histogram of installed charging spots in selected CSs



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6.2. Sensibility Analyses

After solving the base scenario, we performed some sensitivity analyses varying certain parameters. Table 1 indicates the different scenarios that we ran, the total cost of the solution, and the number of selected CSs for that variation. Table 2 shows the variation in the percentage of the price that is invested in the charging spots vs the PV systems vs the price of electricity purchased to the grid in each variation. Table 3 presents the behavior of the available roof area vs the used roof area. Table 4 indicates the variation in energy source, this means, what percentage of electricity is generated by the PV systems against how much energy is purchased from the grid.

It is clear is that solar power is not enough to charge all EVs in any case. Using energy from the grid is always necessary. This situation is caused by the lack of enough roof area, because if we look at the variations the algorithm tends to use as much solar energy as it can, it only changes that decision completely if the price of the PV systems is more than tripled in variation cj-200. Also, we can confirm this by analyzing that when the percentage of demand is set to a lower number, the use of PV energy tends to grow. Looking at cost percentages, we can see that the greatest amount of investment is in what needs to be paid for energy purchased to the grid. It is clear that PV energy is cheaper.

Table 1. Monetary Results

Scenario name	Variation	cj	fj	Demand	Total price (USD)	Candidates
Base	None	$16.52	$110.10	1560	$12,319,320	66
fj-800	fj	$16.52	$220.21	1560	$12,491,082	66
fj-2000	fj	$16.52	$550.52	1560	$13,006,365	66
fj-5000	fj	$16.52	$1,376.29	1560	$14,294,572	66
cj-80	cj	$22.02	$110.10	1560	$12,736,473	66
cj-100	cj	$27.53	$110.10	1560	$13,148,449	63
cj-150	cj	$41.29	$110.10	1560	$13,946,964	44
cj-159	cj	$43.77	$110.10	1560	$13,959,629	39
cj-200	cj	$55.05	$110.10	1560	$13,959,865	36

Scenario name	Variation	cj	fj	Demand	Total price (USD)	Candidates
dem-0.75	Demand	$16.52	$110.10	1174	$8,789,323	66
dem-0.5	Demand	$16.52	$110.10	783	$5,625,076	66
dem-0.25	Demand	$16.52	$110.10	391	$2,538,664	59

Table 2. Monetary results composition

Scenario name	Variation	Charging spots % price	PV system % price	Grid power %
Base	None	1.40%	10.21%	88.39%
fj-800	fj	2.76%	10.07%	87.17%
fj-2000	fj	6.63%	9.67%	83.70%
fj-5000	fj	15.08%	8.80%	76.13%
cj-80	cj	1.35%	13.04%	85.61%
cj-100	cj	1.31%	14.54%	84.15%
cj-150	cj	1.24%	3.00%	95.77%
cj-159	cj	1.24%	1.05%	97.71%
cj-200	cj	1.24%	0.00%	98.76%
dem-0.75	Demand	1.47%	13.80%	84.73%
dem-0.5	Demand	1.53%	19.99%	78.48%
dem-0.25	Demand	1.70%	32.91%	65.40%

Table 3. Area installation

Scenario name	Variation	Available area	Installed area	Remaining area	Remaining %
Base	None	77642	76141	1501	1.93%
fj-800	fj	77642	76141	1501	1.93%
fj-2000	fj	77642	76141	1501	1.93%
fj-5000	fj	77642	76140	1502	1.93%
cj-80	cj	77642	75412	2230	2.87%

Scenario name	Variation	Available area	Installed area	Remaining area	Remaining %
cj-100	cj	73383	69435	3948	5.38%
cj-150	cj	48040	10126	37914	78.92%
cj-159	cj	44972	3359	41613	92.53%
cj-200	cj	44347	0	44347	100.00%
dem-0.75	Demand	77642	73447	4195	5.40%
dem-0.5	Demand	77642	68070	9572	12.33%
dem-0.25	Demand	67601	50580	17021	25.18%

Table 4. Energy source percentage

Scenario name	Variation	Solar energy %	Grid energy %
Base	None	21.15%	78.85%
fj-800	fj	21.15%	78.85%
fj-2000	fj	21.15%	78.85%
fj-5000	fj	21.15%	78.85%
cj-80	cj	21.05%	78.95%
cj-100	cj	19.50%	80.50%
cj-150	cj	3.06%	96.94%
cj-159	cj	1.05%	98.95%
cj-200	cj	0.00%	100.00%
dem-0.75	Demand	27.27%	72.73%
dem-0.5	Demand	36.91%	63.09%
dem-0.25	Demand	52.87%	47.13%

7. Conclusions

In this paper, we designed a MILP formulation to propose the optimal distribution of PV-grid CSs, minimizing the total cost of installation and operation, using the already built architectural landscape of the region. We solved the case study. The merit of the solution method is that part of the required information comes from surveying current EV owners and possible EV buyers, acquiring that way insights into how PV-grid CSs may be located in the future. We can conclude that:

Deciding to use PV-grid level 1 (low-power) CSs was the right decision because the amount of electricity needed cannot be exclusively supplied by PV power. It is important to notice that PV power consumption is prioritized due to its lower price.

The value of installing PV systems per square meter greatly affects the outcome.

The limitation of available roof areas for PV systems causes the solution to use more grid electricity.

The speed of the program allows to analyze larger sets of information and can be used again to get a more refined answer.

The significance of the study is that it aims to decrease the impact that a possible high sales rate of EVs may have on the electric grid by using PV power and helping the owners of these EV to contribute to the environment by using clean energies.

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