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Evaluation of the power generation capacity of an installed photovoltaic system

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Abstract

Installations of solar photovoltaic systems are growing as a promising renewable alternative to generate electricity. This paper aims to compare the power generation potential of a photovoltaic solar plant installed in a Vale do Paranhana-Brazil company with the power supplied by the utility. By demonstrating the composition of the electricity tariff currently used by the company, it was possible to perform a subsequent calculation of return on investments. The plant sizing calculation possibly did not take into account the company's consumption data. This factor influences the financial performance expected by investors.

Keywords: photovoltaic plant sizing, photovoltaic power generation, economic viability

1. Introduction

Energy can be defined as the ability to do work or to transfer heat. In human societies, energy originated in the endosomatic form, that is, that arrives through ecological chains. The primary source of energy for these chains is the sun, by illuminating, heating, transferring energy to water, forming clouds and rain, and providing energy to plants through photosynthesis [1].

Energy is one of the basic pillars of mankind's evolution, being as important as water and today as well as information [2].

Renewable energy sources play a key role in the energy, environmental and socioeconomic context [3]. Renewable resources are an important alternative for obtaining energy supplies, both on a smallscale and by considering the larger interconnected systems [4]. The search for alternatives to traditional sources of electric energy opens the way for a new market in the world, and for Brazil in particular [5].

Electrical and thermal energy is very important to the humanity. 87.8% of the electricity is generated at TPPs, where fossil fuel is the source of energy [6]. Unfortunately, fossil fuels are limited. RES allows saving fossil fuels and reducing the burden on the environment [7].

Solar energy is an attractive and environmental clean source to generate electric energy. However, its domestic and intense use is function of several factors, from which the economic issue is the more important [8].

Brazil is a country that has favorable conditions for the generation of photovoltaic solar energy. It presents an estimated growth of approximately 5% per year of the Brazilian energy demand for the period 2010-2019. The average increase in installed power represents an average of 3.3GW each year, inserted in the Brazilian electricity matrix [9].

Solar energy reaches the surface of the earth in the form of sunrays, which can be disposed of in two ways: the first is solar collectors for producing thermal energy, the second is the photoelectric method. The global potential for power generation using the second method reaches 227 GW, thermal energy 435 GW.

Solar energy reaching the surface is 105 thousand TW. If you take only 1% of the energy coming to the surface with an efficiency of 10%, you can get energy in the amount of 105 TW. Given the global growth in electricity demand of 25-30 TW by 2050, the demand for Kazakhstan is 20,000 MW, the solar energy has great potential.

The use of photovoltaic technology to power generated through solar energy is a widely studied alternative in Brazil, and this is because the country has great potential for exploitation of this resource throughout the territory with average irradiation of 1200 and 2400 kWh/m^2/year. [10]

In 2016, micro and distributed electric power generation reached 104.1 GWh with an installed power of 72.4 MW, and the photovoltaic solar source that adds the most significant generation (53.6 GWh) and installed capacity (56.9 MW) [11]. When compared to other sources, the energy from the photovoltaic generation process still represents a minimal share of the overall total, around 0.01%.

According to ANEEL (2005), directly, solar radiation can be: (i) used as a source of thermal energy, for space and fluid heating and mechanical or electrical power generation; and (ii) converted directly into electricity through effects on materials, including thermoelectric and photovoltaic [12].

For the timeframe, it can be considered sufficient for the first solar resource assessments, solar system design, and initial feasibility analysis. In the detailed end-resource assessment project, various standards and instructional installation of appropriate device tasks for on-site resource assessment and measurements for a period of at least one year and hourly solar radiation analysis [13].

The resolution 482/2012 of the National Electricity Agency (ANEEL) imitates conditions for the connection of micro and mini-generation systems to distribution networks, as well as the possibility of creating a power compensation process. Through this, the customer who generates energy can generate credit in periods where its production is higher than its demand. The distributed generation in Brazil became a reality from this document [14].

This paper aims to estimate the amount of electricity generated by a photovoltaic system installed in a company located in the Vale do Paranhana Valle region of Rio Grande do Sul state, in the city of Taquara. The project was executed based on data submitted by the contractor (which for confidentiality reasons will be called (Company B) without a theoretical-scientific review by the contracting company (which for reasons of confidentiality). Confidentiality will be referred to as (Company A) before system implementation.

For the technical validation, the effectiveness and the adequacy of the set installed in (Company A), a theoretical reference was used that considered the solar incidence mapping in Brazil with emphasis on the installation region.

The objective of the research was achieved with the possibility of evaluating the power generation capacity of the set installed in (Company A) and, with this calculate, how much it meets the company's power demand.

1.1 Solar incidence mapping

Harnessing the economic capacity of using solar energy has its expectations and opportunities dependent on valid information about the available potential and its variability due to natural and anthropogenic factors. There are methods for the determination of solar energy resources: the use of radiometers in conjunction with techniques of interpolation of the collected radiation data; and the use of computational models to determine estimates of incident solar radiation through empirical relationships or the solution of the radiation transfer equation in the atmosphere [15].

In order to catalog a series of satellite data and be a widely used tool for solar energy researchers and entrepreneurs, INPE (National Institute for Space Research) and CCST (Center for Earth System Science) through LABREN (Laboratory of Renewable Energy Resource Modeling and Studies), all government agencies, launched in 2017 the second edition of the Brazilian Solar Energy Atlas [16]. This atlas based on the numerical model for surface solar irradiance evaluation is called BRASIL SR, developed by LABREN itself, where the data are validated by comparing with measured surface values in stations of the SONDA (National Data Organization System) network. Environmental). According to Tiepolo (2015), the BRASIL-SR model uses cloud information extracted from GOES satellite images (geostationary) and climatological data of environmental variables and, thus, shapes the composition of the atmosphere and the radiation processes that occur in it [17].

1.2 Electricity charges.

The object of study for this research is an industrial establishment with purchase of demand (Contracted Demand), whose framework is given in the Conventional tariff structure. This type of service requires a specific contract with the concessionaire, in which a single value of the demand intended by the consumer is agreed. There is an active power demand that must be continuously and continuously made available by the concessionaire at the point of delivery, according to the amount and duration of the supply contract and which must be fully paid.

Although not expressly provided for in Resolution 456, two different demand values are allowed to be contracted, one for the dry period and the other for the wet period. The sum of consumption composes the energy bill of these consumers (at the peak and outside the peak), demand and surpassing.

Still, in relation to the Conventional tariff, the price of electricity is formed by the costs incurred from its generation until the arrival to the consumer, in the electrical outlet. It is also essential to understand that power is a crucial good to which one pays not only for consumption but also for its virtually perennial availability. Thus, it is expected that the price will be sufficient to cover the operating and expansion costs of the entire set that make up the electrical system. These costs should include daily operations and investments made in the network, which aims to eliminate shorter repair times and low failure rates [12].

It is noteworthy that the costs with the acquisition of energy are those resulting from the contracting of amounts of energy through regulated auctions, that is, the energy distributor purchases a certain amount of electricity sufficient to meet its captive market. Energy costs are allocated to the so-called Energy Tariff (ET) and are passed on to consumers without any profit margin.

Costs related to the use of the distribution system included in the Distribution System Use Tariffs are such as capital expenses and the costs of operating and maintaining distribution networks. Costs related to the use of the transmission system and some sector charges collected through the Transmission System Use Tariff.

According to (ANEEL 2005), the concessionaire must bring energy to the consumer, be it an individual or a legal entity, since the electricity company has costs that must be covered by the energy tariff [12]. In general, the electricity bill includes the reimbursement of three distinct costs: Power Generation, Power Transmission or Transmission and Tax Charges [11].

As of Law nº 10848/2004, the amount of power generation purchased by distributors to resell to their consumers determined in public auctions, which is an impediment for distributors to freely buy and energy to be resold without any publicity of the values.

Transporting energy from generation points to the end consumer is a natural monopoly, as competition in this market has no benefit. For this reason, ANEEL works and ensures that the tariffs in this segment are composed only of the possible costs related to the service provided and that there are fair rates.

At these costs, some charges and taxes are not created or instituted by ANEEL, but by legal regulations. Some of these fees only apply to distribution costs, while others embedded in generation and transmission costs.

That is, when the electricity bill reaches the consumer, he pays for the purchase of energy (generator remuneration), transmission (the costs of the transmission company) and distribution (service provided by the distributor), plus charges and taxes determined by Law, which are intended and benefit the Government, Federal, State and Municipal.

The Federal Taxes like the Social Integration Program and the Contribution to Social Security Financing, which are charged by the Union to maintain worker programs and to meet Government social programs.

The State Tax is limited to the tax on the Circulation of Goods and Services, provided for in Article 155 of the Federal Constitution [18]. This Circulation of Goods and

Services tax occurs in transactions related to the circulation of goods and services. The distributor collects the Circulation of Goods and Services tax directly on the invoice and fully transfers it to the State Government.

The Municipal Taxes, in turn, refer to the Contribution to Cost of Public Lighting, provided for in article 149-A of the Federal Constitution of 1988, establishing that, among the competencies of the municipalities, according to a specific law approved by the City Council, the billing method and the IPC calculation basis. Therefore, the Municipal Government is responsible for all responsibility for the design, implementation, expansion, operation, and maintenance of public lighting installations. In this case, the concessionaire only collects the general lighting fee that is reversed for the benefit of the municipality.

In this case, the concessionaire only collects the public lighting fee that is reversed for the benefit of the municipality.

From the chart in Figure 1, it can be seen that the value of transmission cost was the fastest growing item in the electricity market since 2001 (125.34%). This increase can be attributed to the high investments made in the primary grid (high voltage) to allow the flow of energy between the various regions of the country, with the aim of increasing the reliability of the national electricity system against the availability of water in the reservoirs of hydroelectric plants. However, it is necessary that this item represents only 5.96% of the value of the electricity bill, and these investments are essential to allow the transfer of energy between regions during periods of low rainfall.

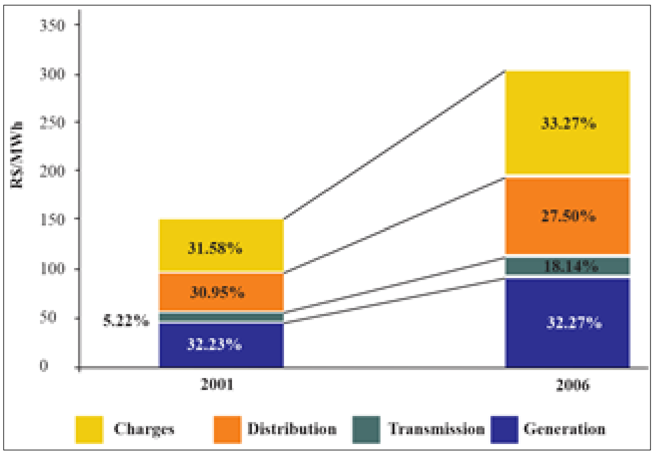


Fig 1: Average Tariff Calculation

The same chart shows that the fastest-growing segment (around 108.11%) was charges and taxes that represent more than 33.27% of the value of the electricity bill, being the item with the most significant impact. Distribution (75.5%) and Energy Purchase (103.94%) had the slowest growth, but still, this increase was higher than the inflation of the period.

1.3 Return on Investment Calculations

Even if all the advantages of photovoltaic solar energy are considered, there is still the doubt that the cost-benefit of investing in a photovoltaic system is not worth it. For this reason, below is a study of the economic gains from the installation of clean and sustainable energy. Some authors, including Lemes Júnior, Rigo and Cherobim (2002) [19], Brigham and Ehrhardt (2012) [20], approach payback as a method of analysis capable of showing the time needed to recover the initial investment. This method considers the value of money over time because it uses a discount rate to verify the exact number of periods in which the project recovers the initial amount invested. Usually, this discount rate used is the minimum attractiveness rate, which is determined by the investor himself as a parameter for the remuneration of his capital [21].

The payback time on solar energy, which is also called payback, represents the time required to recover the installation cost and start making a profit for the owner. For the calculation, it is necessary to survey the total investment cost and divide it by the savings provided monthly, according to Equation 1, Payback Calculation.

Payback (months) = Investment (R$)/Energy Generated (kWh/month) x Rate Amount (1)

The calculation of the return of a photovoltaic solar energy system shall take into account the total investment made and the monthly average generation of the photovoltaic system (energy production in kWh). In Brazil, the payback varies significantly due to solar radiation and tariffs charged, and the higher these values, the lower the system payback. Since the return depends on factors such as the city electricity tariff, the supplier and the size of the system, each case is individually assessed, and the payback may vary significantly.

Another way to understand the benefit of acquiring a photovoltaic power system is by calculating the rate of return on investment. To calculate the annual rate of return, check the ratio between the savings obtained annually through the system and the investment made, according to equation 2 — calculation of Profitability.

Profitability = Economy / Investment (2)

Leveled Energy Cost is a metric for defining the cost of producing energy for a given generation source. Thus it can be used for comparison between different energy sources. All costs of production over the life of the system are also taken into account for this calculation, citing as examples: (i) for the production of energy by a non-renewable energy source such as fossil fuels, this value is defined by the cost of obtaining fuel, maintaining the plant, etc. (ii) in relation to photovoltaic energy, include the costs of materials, design, installation, maintenance, among others, over 25 years of system life (the system will continue to generate after this period). Calculation of Leveled Energy Cost.

Leveled Energy Cost = Investment (R$)/Total Energy Generated (kWh) (3)

This metric allows us to understand a photovoltaic system as a large energy package, for which it will be paid a certain amount and will give it a certain amount of energy. Note that the value obtained by the Leveled Energy Cost is in reais per kWh generated, whereas it can be directly compared to the value of the energy tariff that is paid by the consumer. Thus, it appears that investing in a photovoltaic system has an economic return for the company, and is clean and renewable energy, although there are many doubts and questions about the high value to be spent.

2. Materials and Methods

This case study included data collected directly from the industry called (Company A), through electricity bills, technical data from photovoltaic panels imported directly for system installation and documents of devices installed in the solution sold by (Company B).

Subsequently, technical analyzes of the system proposed by the supplier were performed, with power generation calculations based on information collected from the company itself, namely: a) Location of the facility; b) Solar radiation in place according to the location of the building; c) Design data of the installed system; d) Power of solar panels; e) Yield of solar panels; f) Inverter power; g) Yield of the inverters; h) Energy consumption by (Company A). To locate the system installation point, we used the Google Maps application where latitude and longitude data were reached at the following coordinates: 29 ° 41'23.5 "S and 50 ° 48'51.2" W (-29.68986111 S and -50.81422222 W, in decimal form). These data were located in the horizontal global solar irradiation table of the Brazilian Solar Energy Atlas. In this search, the coordinates considered were latitude -29, 700500 and longitude -50, 849000, which were the closest references presented in the database. The results gave rise to the graph explicit in Figure 2.

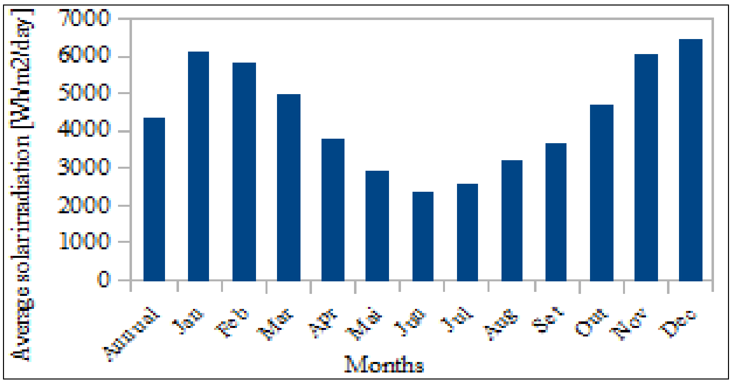


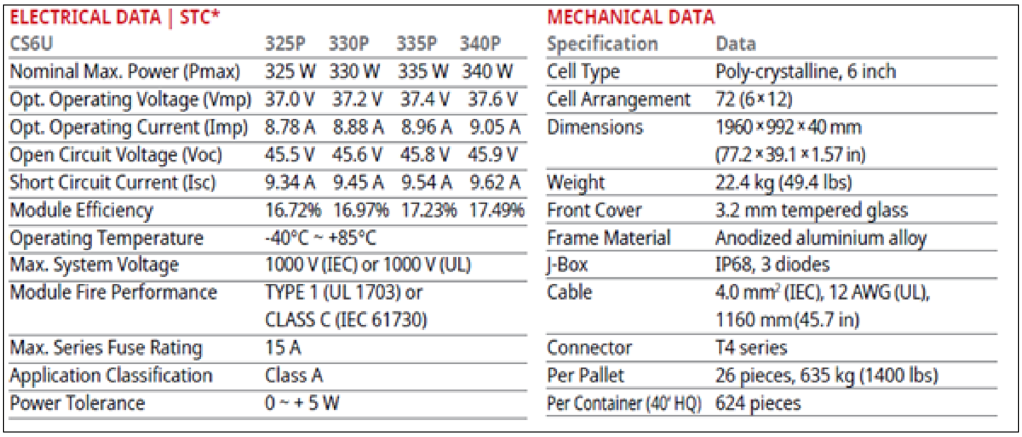
Fig 2: Graph of global horizontal solar irradiation at plant installation point

3. Results and Discussions

The system data installed in (Company A) follows the information in Table 1.

Table 1: Installed Plant Technical Data (Company B).

Installed Plant Data	
Total Installed Power (kWp)	300
Total Plant Area (m²)	1,652
Nº of Arrangements	59
Nº of Plates per Arrangement	18
Photovoltaic Plant Modules	1,062
Considered Peak Power (kW)	6.4
Modules Peak Power (kWp)	345
Inverter Peak Power (kWp)	50
Total Quantity of Inverters	6



ELECTRICAL DATA | STC*

CS6U	325P	330P	335P	340P
Nominal Max. Power (Pmax)	325 W	330 W	335 W	340 W
Opt. Operating Voltage (Vmp)	37.0 V	37.2 V	37.4 V	37.6 V
Opt. Operating Current (Imp)	8.78 A	8.88 A	8.96 A	9.05 A
Open Circuit Voltage (Voc)	45.5 V	45.6 V	45.8 V	45.9 V
Short Circuit Current (Isc)	9.34 A	9.45 A	9.54 A	9.62 A
Module Efficiency	16.72%	16.97%	17.23%	17.49%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC) or 1000 V (UL)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	15 A			
Application Classification	Class A			
Power Tolerance	0 ~ + 5 W			

MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 6 inch
Cell Arrangement	72 (6 × 12)
Dimensions	1960 × 992 × 40 mm (77.2 × 39.1 × 1.57 in)
Weight	22.4 kg (49.4 lbs)
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP68, 3 diodes
Cable	4.0 mm² (IEC), 12 AWG (UL), 1160 mm (45.7 in)
Connector	T4 series
Per Pallet	26 pieces, 635 kg (1400 lbs)
Per Container (40' HQ)	624 pieces

Fig 3: Installed Solar Plate Technical Data (Adapted from Installed Plate Technical Data Sheet 2018).

Knowing that these boards are in 59 arrangements of 18 pieces each, totaling 1,062, the system's peak power, which is 300 kW, is sufficiently covered by the sum of the board power, which totals 350.46 kW. Calculation from Equation 4. The estimate of the total control of the solar array.

Total Solar Plate Set Power (kW) = Number of Cards (Pk) X Maximum Solar Card Power (kW) (4)

Another finding is that the peak power of the system is limited by the sum of the maximum potentials of the 6 ABB TRIO-50.0-TL-OUTD inverters, which manage a maximum power of 50 kW each, totaling 300 kW. According to data in Table 2, they are constrained by a weighted efficiency of 98%.

Table 2: Technical Data of the Installed Plant. (Company B).

Operating performance	TRIO-50.0-TL-OUTTD	TRIO-60.0-TL-OUTTD-480
Maximum Efficiency (ŋmax)	98,30%	98,50%
Weighted Efficiency (EURO)	98,00%	98,00%

According to Junior (2004), the energy that can be produced through a power plant can be represented by equation 5 [XX]. Calculation of the energy produced by the photovoltaic system [22].

Eg (kWh) = P (kW) X HSP (hours) x ŋcc / ca (percentage) (5)

Eg = energy produced by the system;

P = nominal power of the photovoltaic system;

HSP = number of Full Daily Sun Hours at an intensity of 1,000 W/m², which is equivalent to the total daily energy incident on the generator plate surface in kW/m², in hours;

ŋcc/ca = DC to AC drive efficiency.

Applying the formula to the known data and using the solar radiation values raised in the methodology, it is possible to estimate the energy generated in each month, according to Table 3. In this calculation, the energy variation caused by the change in ambient temperature was waived. In the case of solar panels, they are 0.41% for each degree Celsius (º C).

Table 3: Plant Energy Production Data.

	Days	Power. (kW)	Average Irr. (kWh/m²d)	Inverter Yield (%)	Energy (kWh)
Jan	31	300	6.21	0.98	56,634.40
Feb	28	300	5.72	0.98	47,045.88
Mar	31	300	4.79	0.98	43,619.60
Apr	30	300	3.80	0.98	33,551.28
Mai	31	300	2.84	0.98	25,901.99
Jun	30	300	2.34	0.98	20,594.70
Jul	31	300	2.55	0.98	23,213.36
Aug	31	300	3.23	0.98	29,474.68
Set	30	300	3.61	0.98	31,840.20
Out	31	300	4.65	0.98	42,407.44
Nov	30	300	6.13	0.98	54,057.78
Dec	31	300	6.53	0.98	59,514.42
Total Annual					467,855.72

Consumption data for "Company A" was taken from the energy bill based on the measurements taken by the utility following the information in Table 4, setting an average annual utilization of 49,890.50 kWh.

Table 4: Consumption Data for (Company A).

Energy Consumption at (Company A)			
Month/year	Peak (kWh)	Out Peak (kWh)	Total Consump. (kWh)
Jun	572.0	41,810.0	42,382.0
Jul	484.0	33,322,0	33,806.0
Aug	632.0	43,761.0	44,393.0
Set	876.0	52,531.0	53,407.0
Out	2,314.0	57,040.0	59,354.0
Nov	4,688.0	69,050.0	73,738.0
Dec	4,069.0	62,284.0	66,353.0
Jan	2,666.0	47,039.0	49,705.0
Feb	1,090.0	45,840.0	46,930.0
Mar	896.0	48,262.0	49,158.0
Apr	917.0	39,423.0	40,340.0
Mai	1,426.0	50,981.0	52,407.0
Total Annual			611,973.0

The averages of (Company A) consumption and the Company's energy production estimate are explicitly shown in the graph in Figure 4. Considering total annual use from June 2017 to May 2018 (611,973.00 kWh) versus the estimated energy to be generated over 12 months (467,855.72 kWh), it is observed that the plant will meet around 76% of the total used.

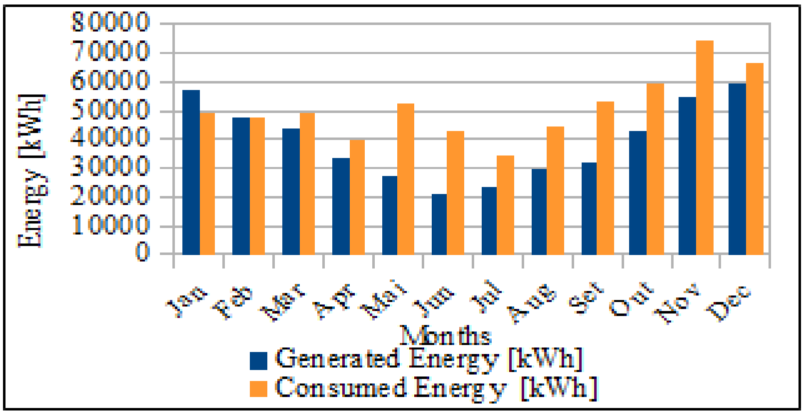


Fig 4: Forecast Graph of Generated Energy *x* Consumed Energy.

The averages of (Company A) consumption and the Company's energy production estimate are explicitly shown in the graph in Figure 4. Considering total annual consumption from June 2017 to May 2018 (611,973.0 kWh) versus the estimated energy to be generated over 12 months (467,855.72 kWh), it is observed that the plant will meet around 76% of the total used.

4. Conclusion

The conclusions reached are that the plant sizing calculation did not take into account the consumption of (Company A). In conversation with managers expecting to understand how this calculation was not performed before the system installation, it is believed that the source of the difference was that observation was made only about the peak power already recorded in the company, which in previous measurements rotated around 305 kW on average as per Figure 5.

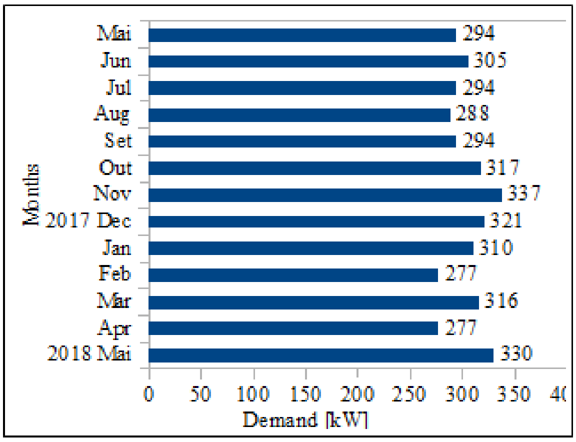


Fig 5: Power Demand Data for (Company A).

This information led those who made the decision about the size of the plant to believe that covering the average power would be meeting the demand but obstructed the view on the concept of energy consumed. Applying three more arrangements and their converters on the plant could achieve the total production required.

The discussion about the calculation of return on investment was suppressed from the present work due to lack of data release of the total amount invested in installing the system but is duly based on the theoretical framework for later application.

Another opportunity for improvement would be the more advanced analysis of the energy generated by the diffuse solar irradiation on the solar plates, which were disregarded in the calculation. Finally it was found that the expectation by the managers to have the company's electricity bill practically zero in the following months will most likely not be met due to the myopic design of the plant and due to the disregard of the supply of demand for installed power that will follow being charged and offered by the utility.

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