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Analysis of photovoltaic systems installed in low-income residences accordingly to the incentives of the Energy Efficiency Program of the National Agency of Electrical Energy of Brazil

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ABSTRACT

Over the years, the energy has been assuming a role that is becoming gradually more and more important in the society. The development of several fields, that impact directly in the life quality of the population, is supported by the energy and the world would probably collapse if there was a sudden absence of it.

However, the energy in the quantities currently used are not easy to generate, transform and distribute. If these processes are not performed correctly, several actives would be compromised, compromising as well the quality of life. Thus, it is presented the importance of having an institution which its only goal is to promote the efficiency of all the processes related to energy, the National Agency of Electrical Energy, in the Brazilian's case.

The job performed by this institution has several fronts. However, one in particular receives more attention than the others in this work, which is the front responsible for the renewable energy sources. These sources have assumed a primordial role in the current scenario that world is passing, due to all the problems related to the environment pollution. The renewable sources can be used to substitute the carbon-based energy fuels and contribute to solve a real threatening that the world is living and that will only increase, in case some strong actions are not performed.

For this reason, this work explores the usage of renewable energy sources, in this case, the distributed generation through photovoltaic systems. The objective is to make a viability analysis to help the decision making of the power distribution companies about if they should invest in this type of project or not, giving the financial incentives of the Energy Efficiency program of the ANEEL.

Besides it, this work took advantage of the possibility of acting in low-income communities. Therefore, besides the possible environmental gains, the social gains were explored as well.

Key-words: Brazilian Energy Efficiency Program, distributed photovoltaic energy, ANEEL.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ACD: Avoided cost of demand

ACE: Avoided cost of energy

ANEEL: Electrical Energy National Agency (of Brazil)

CBR: Cost-benefit ratio

EEP: Energy Efficiency Program

NOR: Net Operation Revenue

PV modules: photovoltaic modules

SUMMARY

1) Introduction

1.1) Context

The Brazilian’s electrical system, in the last years of the past millennium and first years of this millennium, presented some signs of fragility and unreliability, due to the constants shortages that were happening all over the country.

Around the same period, the ANEEL has developed a plan to turn around the electrical energy system and make it more reliable. Thus, they started acting in all the areas that composed it: the generation, transmission and distribution. However, the companies acting in these segments are private institutions, that acquired them through auctions, and the ANEEL as a public agency could only regulated their actions. So, the ANEEL came up with a way to force these companies to invest their own money to the enhancement of their own systems, which actually benefits the electrical system as a whole, including these companies.

In 1999 the ANEEL created the Energy Efficiency Program, the EEP, with the objective to promote the efficient use of the electrical energy, through projects that have the objective to enhance equipment, processes and final uses of energy.

The program forced that a percentage of the Net Operational Revenue of the power distribution companies was used to perform these projects, otherwise these companies would be fined. The ANEEL had identified that the low-income communities were locations that were being neglected and that were affecting negatively the electrical system as a whole. For this reason, it was determined that half of the financial resources obtained through the EEP were directly used at them.

In the first years of program, it was only allowed to invest directly in Energy Efficiency, enhancing the transmission lines or acting directly at the final consumer. However, in 2013 the EEP included the distributed generation coming from renewable energy sources among the possible investments to be performed. Therefore, it was created the possibility to evaluate using the resources of the program to photovoltaic systems, especially for low income communities, where at least half of the collected money must be invested.

Even though it was not released any formal explanation of the reason why the energy sources were included in the EEP, it is possible to infer that it was because of the concernment with the current world's sustainability trends.

Since 1997, with the Kyoto Protocol, it has come to world's attention that the climate and environmental situation was not good, and it was affecting negatively the quality of life around the planet. As many studies point out, the main cause for this is the release of greenhouse gases (GHC) in the atmosphere, which basically happens when there is the transformation of one form of energy based on carbon, like coal or petroleum, to other form of energy.

Since then, this situation has only gotten worse and other events with similar purpose had happened, like the Paris agreement, in 2012. All of them got to the same conclusion, that is necessary to reduce the carbon emissions as much and as fast possible. One of the principal solutions is the substitution of the traditional carbon energy sources for renewable energy sources, because they do not emit GHG in the atmosphere, and those are types of energy sources that can be financed in the EEP.

Finally, with the information above, it is possible to notice that there is the possibility to mix the projects focused on low-income communities and with the renewable energy sources.

1.2) Objective

This work has the purpose to analyze possible typologies of photovoltaic systems for microgeneration and mini-generation to supply the energy demand of low-income families, given incentives of the Energy Efficiency Program of the ANEEL. The analysis will be performed initially by a qualitative study and then by a quantitative one, verifying whether or not each topology could be financed with the financial resources of the program.

1.3) Methodology

It begins explaining the Energy Efficiency Program of the ANEEL, exposing its history and objectives. After that, it is going to be shown how this program has evolved to the point in which it contemplates photovoltaic projects, focused especially for low-income families, which will be properly characterized.

Then, a brief literature review of photovoltaic systems will be done, presenting major characteristics of this energy source, such as the panels, the inverters and some concepts about irradiance.

In the sequence, it will be presented the current ANEEL policies used to regulate the photovoltaic installations used for distributed energy purposes, i.e., the systems used for the micro and mini-generation. It will also be presented some historic of this type of projects is growing in the last years, since the last resolution’s review.

The next step will be to present, characterize and analyze a few typologies of photovoltaic systems, using technical sketches and using the quantitative and qualitative indicators of the ANEEL itself to evaluate them.

Finally, after all this construction, it will be applied to a case study, with a low-income community supplied by one of the largest power distribution companies acting in the Brazil, the EDP São Paulo. Its objective is to calculate the cost benefit ratio of each topology, initially verifying if the topology could be financed in the Energy Efficiency Program and secondly identifying which one would be the best by this quantitative metric.

2) The Energy Efficiency Program (EEP)

The Energy Efficiency Program is one of the many programs and attributions that the Brazilian National Agency of Electrical Energy, the ANEEL, has to manage.

2.1) The National Agency of Electrical Energy

The Brazilian’s Government has a Cabinet, which is currently composed of 22 ministries, each one commanded by a minister. The purpose of the ministries is to assist the President in the exercise of the executive power, each one managing a part of the government portfolio. The ministries have to create, prepare, monitor and evaluate federal programs related to sectors they represent. They decide how to invest the public resources, establishing strategies, policies and priorities. (Brazilian's Government website, 2019)

The ministry responsible for all related energy matters is the Mines and Energy Ministry, which is composed by a few agencies. The agency we are interested in this work is the National Agency of Electrical Energy.

The ANEEL was created in 1997, with the main objective of supplying electrical energy with good quality and at a fair price. The Agency principal attributions are to regulate the energy production, transmission, distribution and commercialization; supervise, directly or indirectly, the energy services provided to the public; establish electrical energy tariffs around Brazil; implement policies and guidelines from the federal government related to energy exploitation; and grant concessions, permits and authorizations of electric power projects and services, by delegation of the Federal Government. (ANEEL, 2019)

Among the several duties and programs that ANEEL is responsible for, one in particular has a strong relevancy to this paper, the Energy Efficiency Program, the EEP (Portuguese for “Programa de Eficiência Energética”). This program was created in the year 1999 and it has the purpose to promote the efficient use of the electrical energy, through projects with the objective to enhance equipment, processes and final uses of energy.

Along the years, a few resolutions were written, detailing and shaping this program better according to each step.

2.2) EEP's Historic

The EEP's historic can be presented through the program's resolutions and manuals, that were published every two or three years, after an evaluation of the program in that period. It had the objective of redefine objectives, aligning actions towards them, and keep the program updated with the current scenario and technologies.

2.2.1) 1999's Resolution

The first EEP resolution, wrote in 1999, had already identified the role that power distribution companies should have in order to achieve the energy efficiency all around the country. This resolution established that these companies should promote projects to reduce the energy waste, focused especially on the final consumer.

In that moment, it had not been yet defined any concrete objectives for the program or even any standard metrics to measure the impact of the projects to be executed.

However, the power distribution should still present to ANEEL yearly reports explaining the motivation, methodologies and the results of the projects done in that period. (ANEEL's Normative Resolution nº 334, 1999)

2.2.2) 2001's Resolution

Starting from this resolution, it was established the obligation that forced the power distribution companies to invest at least 0,50% of their Net Operation Revenue calculated through the ANEEL'S specifications, in projects that promote energy efficiency. These projects, however, should accomplish a few goals and present a good quality, which was measured by the Cost-Benefit ratio indicator, CBR, also created by ANEEL. (ANEEL's Normative Resolution nº 394, 2001)

The Cost-Benefit ratio takes into consideration the annualized costs for the implementation of the projects, that are mainly composed by the cost of equipment, and also annualized benefits, that are composed mainly by the saved energy and avoided cost of energy. In sequence of this paper, it will be presented a better explanation with all the formulas to calculate the CRB of a project.

Also, this resolution mentioned the EEP's Manual, to be published in following year, that would content detailed information about the types of project that could be done in the program, how to calculate the required indicators, how to present the report, among several other possible doubts that the power distribution companies have.

2.2.3) 2005's Resolution

This resolution started with a modification in the value that the power distribution companies should invest in the EEP. It stated that until December 31 of 2005 the companies should invest at least 0,5% of their NOR in energy efficiency, but from January 01 of 2006, this percentage was going to be reduced to at least 0,25%. However, this decision was revoked even before the data it would start, and the 0,5% was maintained. (Brazilian Law nº 9.991, 2000)

This year's version defined better the program goals, the parameters and indicators used to measure their impact, and the fines that should be given to those that did not accomplished them. It was in this resolution that, for the first time, it was stablished the policy that 50% of all the money invested should go to low-income communities.

The CBR's maximum value also changed in this resolution, from 0,85 to 0,80, which actually meant an improvement in the cost benefit ratio, because, for this index, as much as a value is closer to zero, it is better. Also, it was established that the minimum discount rate of the projects should be equal or greater than 12%.

The concept of Public Audiences was also introduced, with the objective of gather suggestions of projects to invest the money obtained and present the respective to public knowledge before its delivery to ANEEL. (ANEEL's Normative Resolution nº 176, 2005)

2.2.4) 2008's Resolution

In comparison with the previous version, this resolution did not have many changes. The most relevant point was the article explaining that, if an energy concessionary did not have enough low-income market to apply 50% of the money collected for these investments, they could ask ANEEL the flexibilization of this obligation. (ANEEL's Normative Resolution nº 300, 2008)

2.2.5) 2013's Resolution

Until the publication of this resolution, in order to invest in energy efficiency in low-income communities, the power distribution companies were focused in perform the simplest actions, like changing the refrigerators or microwaves in people's houses. But, in the richest states of the country, this began to not no-longer be an option, because it was practically exhausted.

Therefore, this resolution allowed the power distribution companies to invest their money in micro generation and mini generation according to some specifications. The micro generation installations should have installed power equal or less than 100 kW; and the mini generation installations should have installed power greater than 100 kW and less than 1 MW. However, in both cases, this energy should come from the following renewable sources: hydro, solar, wind or biomass. For these projects, the CBR's criteria changes slightly, and projects with CBR up to 1,0 are accepted.

Besides it, this resolution was stricter than the previous in general. The articles detailed better the possibilities and obligations about the way the money should be invested. It was created the concept of Public Calls, that should be organized by energy concessionary at least once a year, with the objective to present to ANEEL the proposals of the projects they intended to invest. Also, other parts can participate to these calls and propose projects, such consumers, energy efficiency service companies, efficient energy equipment companies and others and, at the end, the ANEEL chooses the best projects to be executed. (ANEEL's Normative Resolution nº 556, 2013)

The maximum amount of time to invest the money designated to this program is 24 months, considering a monthly basis. This means that the Net Operating Value is calculated each month and if the money of the certain month was not invested 25 months later, the company started to pay fines according to interest rates.

2.2.6) 2018’s Resolution and current situation of the program

The two most recent documents published about the EEP are the 2018’s Resolution and the 2010 Manual. However, the 2018’s resolution did not promote many significant changes in comparison to the previous one.

The percentage of the NOR to be invested in energy efficiency was maintained in 0,5%, but there were plans to change it to 0,25% from the January 01 of 2023. However, this modification was postponed again, now for the third time, as written in the Brazilian Law nº 9.991.

This resolution also maintained the obligatoriness to invest 50% of all the money collected through the EEP in the low-income families and the possibility to invest in distributed energy generation from renewable sources. (ANEEL's Normative Resolution nº 830, 2018)

Even though all these decisions and resolutions may apparent to be somehow of a burden to the power distribution companies, actually they are not it. All these investments are preventing them to have costs to expand the distribution system, to buy or generate more energy or to repair a part of it.

2.3) Public Calls - Selection of projects

As said before in this chapter, every project, before being performed in the

EEP, must pass for a Public Call, which an event organized by the power distribution companies to determine which projects will be done. These events count with the presence of the power distribution companies, final consumers of energy, other companies with businesses related to energy and ANEEL itself.

In these events, all the parts previously named get the opportunity to submit projects they would like to be done, following the eligibility criteria established by the ANEEL, which will be explained in the following pages.

During the execution of the projects, the ANEEL does not have any contact with them. However, at the finish, the Agency evaluates the projects to verify whether or not they have followed the established agreement and if they have reached the established goals. (ANEEL's Public Calls for Power Distribution Companies Practical Guide, 2016)

2.3.1) Public Calls criteria

The Practical Guide of Public Calls for power distribution companies [bibliography], establishes two different criteria. The first, is eligibility criteria and the second, the qualification criteria. First, a project is submitted to the eligibility criteria and then, if it is approved, it goes to the qualification criteria, that has the purpose to rank all the projects. At the end of the process, the best projects that fit in the budget will be selected.

The eligibility criteria contain only one factor, the cost-benefit ratio. The qualification criteria, on the other hand, also contain the cost-benefit ratio, but also several other indicators, because it has to be able to identify which are, in fact, the best projects.

Since this thesis has the objective to analyze typologies of photovoltaic systems installed at low-income residences using the investments of the EEP, in this moment the only concern is to ensure that it is eligible. Therefore, the only criteria that will be explained in detail is the cost-benefit ratio.

2.3.1.1) The cost-benefit ratio

The cost-benefit ratio was created in one of the versions years of the Energy Efficiency Program and it has not change since then. In the first years, the minimum CBR (cost-benefit ratio) that a project should have to be eligible to participate of the EEP was 0,85. However, this value was modified to 0,80, which actually means is more rigorous, because the smaller is the CBR, better is the project. However, for projects regarding stimulated energy sources, which is the case of this thesis, the maximum value of CBR allowed is 1,0.

The CBR has the same formula its creation, in 2002. It can be calculated using the following expressions and values. (ANEEL's Elaboration Manual of PEE, 2002)

$$CBR = \frac{Annualized\ Costs}{Annualized\ Benefits} \qquad (1)$$

The annualized costs are calculated by:

$$AC_{total} = \sum AC_{equipment\ 1} + AC_{equipment\ 2} + \cdots + AC_{equipment\ n} \qquad (2)$$

Which are defined as:

$$AC_{equipment\ n} = CPE_{equipment\ n} \times FRC \qquad (3)$$

And then:

$$CPE_{equip\ n} = CE_{equip\ n} + \left[(CT - CTE) \times \frac{CE_{equip\ n}}{CTE}\right] \qquad (4)$$

$$CRF = \frac{i.(1+i)^n}{(1+i)^n - 1} \qquad (5)$$

Where:

- $CEEP_{quip\ n}$: cost of equipment added of other direct or indirect costs.
- $CE_{equip\ n}$: cost of equipment only.
- CT: total cost of the project.
- CTE: total cost of equipment only.
- CRF: capital recovery factor
- “i” is the interest rate.
- “n” is the equipment’s lifespan.

The annualized benefits are calculated according to the following formulas:

$$Annualized\ benefits = (AE \times ACE) + (RDP \times ACD) \qquad (6)$$

Where:

- AE: avoided energy (MWh/year).
- ACE: avoided cost of energy (R$/MWh)
- RDP: reduction of energy demand in peak hours, from 18h to 22h. (kWh)
- ACD: avoided cost of demand (R$/kW)

Therefore, reducing the annualized costs and increasing the annualized benefits, the CBR’s value decreases and that is the reason why the smallest the CBR is, better is the project from the cost-benefit perspective.

2.3.1.2) Low-income families

Since the objective of this paper is to analyze the technical-economic viability of a photovoltaic installation in low-income residences given the incentives of the EEP, it is important to formally characterize what is a low-income family.

According to the ANEEL, a low-income family is the one that has the per capita income of a maximum of a half minimum salary, which currently is R$ 998,00, therefore R$ 449,00 per capita. Through the energy consumption aspect, the ANEEL states that the low-income families have an average electricity consumption up to 220 kWh on the average in a year. (Brazilian's Government Social Security webpage, 2019)

In order to a family be considered in the low-income condition and eligible to the benefits of it, they must present that their energy consumption in the last 12 months was, on average, below 220 kWh, and the family must already participate of other social assistance program provided by the federal government and listed in the ANEEL's resolution of 2002. (ANEEL, 2002)

To the families that fit these requirements will be provided the benefit of the "social tariff'. The social tariff is a percentual of the actual value of the tariff and it varies according to the consumption. If a family consumes between 0 and 30 kWh, the tariff applied is 65% smaller than its original value. If a family consumes between 31 and 100 kWh, the first 30 kWh will be charged with a discount of 65% and the rest will be charged with a discount of 40% on the tariff. If the family consumption is between 101 and 220 kWh, the first 30 kWh will be charged with a discount of 65% on the tariff, from the 31 to 100 kWh, i.e., 70 kWh, will be charged with a discount of 40% on the tariff, and the rest will be charged with a discount of 10% on the tariff. If the house's consumption is more than 220 kWh, they will have the benefits explained above up to 220 kWh, and they will pay the full price of the tariff for the rest of the consumption.

Consumption parcel [kWh]	***Applied discount***
Up to 30 kWh	65%
From 31 to 100 kWh	40%
From 101 to 220 kWh	10%
Above 220 kWh	0%

Table 1 – Social tariff for low-income families (Source: ANEEL)

2.4) Initial results and projects of the program

In 2015, after 17 years of program, it had received R$ 5,7 billion in investments, it had saved 46 TWh of energy and it had reduced the demand in peak hours by 2,3 GW, with around 4.000 concluded projects. (DE SOUZA BARBOSA, 2017)

Starting from 2013, the ANEEL started to publish the Energy Efficiency magazine, through which it was published objectives, goals, results and projects done by the program. In the first years of the program, it was synonym of exchange or donation of electro domestics, such as refrigerators, because the power distribution companies had to invest half of the money in low-income communities and this was the easiest way of doing it. (ANEEL's Energy Efficiency Magazine, 2013)

Even though it was an important action that brought some significant results, the program could not be just that. By 2013, the residential energy consumption corresponded to less than 4% of the total energy, at the time that the industrial energy consumption corresponded to more than 40%.[11] Therefore, the effort should be better distributed among the various types of projects.

Therefore, in the following years, the ANEEL focused on ways to incentive key projects, especially through the Public Calls stablished in the 2013's EEP Resolution. The Public Calls obligated the energy concessionaries to organize at least once per year an event to present the projects they would like to do and also the projects that other interested parts, such consumers or energy efficiency companies, would like to be done. The Public Calls settled some characteristics that the projects should have for that each Public Call, according to the energetic system needs that ANEEL identified for that moment. At the end of it, according to quantitative criteria, the best projects were chosen. (ANEEL's Energy Efficiency Magazine, 2017) (ANEEL's Public Calls for Power Distribution Companies Practical Guide, 2016)

Other issue that the program had in its first years was lack of knowledge of how to stablish metrics and quantify the impact of the projects, in order to know how the program was performing and also to be able to stablish better goals. Therefore, the ANEEL promoted several editions of the "Training about Measurement and Verification in Energy Efficiency Projects", in partnership with the GIZ, the German Agency for Cooperation and Development, that helped to create a model to measure the impact of all the initiatives and transmit this knowledge to the energy concessionaries. (ANEEL's Energy Efficiency Magazine, 2015)

Since 2013's resolution and the permission to invest in projects of distributed energy, using renewable sources, such solar photovoltaic, the number of this type of project is increasing.

2.4.1) Performed projects and their impact

Along the 20 years of existence of the program, a few projects were done. A few are going to be presented, so it will be possible to understand the dimensions of the program:

2.4.1.1) Refrigerators exchange project

Especially at the beginning of the program, several power distribution companies made projects that basically consisted in exchange old low-efficient refrigerators for new high-efficient ones. As said before, this type of project was done with extremely high frequency because it was one of the easiest ways to invest the money in energy efficiency in low-income families.

In this case, it is going to be given the example of the project performed by the COELBA, the Electric Company of the Bahia State. They developed a project that consisted in exchanging refrigerators and lamps from low-income families for new and more efficient ones. This substitution was made in partnership with stores at subsided prices. (ANEEL's Energy Efficiency Magazine, 2013)

2.4.1.1.1) Objectives and motivations

The principal motivation of the project was to reduce the energy consume of the low-income families through the exchange of low efficient refrigerators for new a highly efficient ones. With that, it was expected an annually reduction of 1.451,07 MWh and the removal of 325,75 kW of peak demand. The expected cost benefit ratio of this project is 0,558.

According to the IBGE, the Brazilian Institute of Geography and Statistics, the sustainable electricity consume is the one in which the electricity bill corresponds up to 5% of the family income. However, in low-income families these cases practically did not exist.

Another research, made by the COELBA, with 3.700 houses in a low-income community identified that, in average, they consumed from 96 kWh to 139 kWh/month. But, by changing the refrigerators for more efficient ones, there was the opportunity to reduce it to the interval between 81 and 121 kWh/month.

2.4.1.1.2) Procedure and results

The eligible families should apply for this benefit directly at COELBA. Then they would pass for screening phases to verify whether or not they would receive the subside to buy the refrigerators. In case of approval, the person could go to a partner store of COELBA to buy their new refrigerator.

The original price of the refrigerator was R$ 790,00 and they were sold to the consumers at R$ 160,00, which means that R$ 630,00 were subsided by the program.

For this project, the COELBA invested R$ 1.750.000,00 and subsided around 1.500 refrigerators. The saved energy estimated was around 1.000 MWh and the removed peak demand was 250 kW.

2.4.1.2) Photovoltaic system in Pituaçu Football Stadium in Bahia

Pituaçu was the first Stadium in Latin America to be completely supplied by photovoltaic energy and it is a good example of the investment of the EEP program in distributed energy generation. This project, that started in 2009, was used as parameter to other stadiums of the FIFA World Cup of 2014. (ANEEL's Energy Efficiency Magazine, 2013)

2.4.1.2.1) Objectives and motivations

COELBA had basically two reasons to implement the photovoltaic system in that stadium. The first one is that the electricity bills were extremely expensive, around R$ 13.000,00 on average. The second one has a sustainable appeal, because the energy generated from the solar panels is clean.

2.4.1.2.2) Procedure and results

This project costed R$ 5.500.000,00, of which R$ 3.800.000,00 by COELBA, with the money of EEP program, and R$ 1.700.000,00 by the Bahia government. The photovoltaic system consists of 2.302 modules, 52 inverters and differently of house installations, the energy produced by this system cannot be used directly by the stadium, because it is produced at a low-voltage and the stadium's electrical installation is medium-voltage. Therefore, it has pass through a transformer, to be elevated from 220 V to 13,8 kV, and then it can be used.

After three years of operation, it has produced more than 1,7 GWh, which represents almost 600 GWh per year. This energy is more than enough to supply the stadium, and the energy produced in excess is sent to administrative buildings of the government of Bahia. [15]

The electricity bill reduced to R$ 850,00, that represents a percentual reduction of 93,5% and, actually, it is the minimum price for the electricity bill. The power distribution companies charge some fixed costs, such public illumination and availability cost, that cannot be removed even if someone does not use any energy from their grid.

Following the economy of the electricity bills of the stadium, the payback time of the system would be in around 35 years. However, since part of the energy goes to administrative building, this time will be definitely smaller than 35 years.

3) Photovoltaic energy aspects

So far in this thesis, it was presented the Energy Efficiency Program of the ANEEL, which englobes several types of projects and, among them, projects of distributed energy using photovoltaic systems.

This chapter has two objectives: the first is to present a literature review of the history, importance and the main technical aspects of photovoltaic energy; and the second is to present what are the ANEEL's regulations for this type of energy, considering the micro and mini generation.

3.1) Technical aspects

In this section, it will be first explained the source that feeds the photovoltaic energy, i.e., the solar energy. Then, it will be explained which are the components of the photovoltaic system, how it works and the principal operating losses.

3.1.1.) Irradiance and irradiation

The photovoltaic energy works through the energy of the Sun. This energy is transmitted to the Earth through the space, in the form of electromagnetic radiation waves, that have different frequencies and wavelengths. (VILLOZ & LABOURET, 2010) The radiation has three components:

- Direct radiation (Beam radiation):

  It is the radiation received from the Sun in a straight line, without any diffusion by the atmosphere. Its rays parallel to each other and this type of radiation can be concentrated by mirrors, by example.

- Diffuse radiation:

  Consists of light that is scattered by the atmosphere. The diffusion is a phenomenon that scatters parallels beams in several beams that go in any direction. The rays are scattered by clouds, air molecules or dust.

- Albedo:

  It is the part that is reflected by the ground. It depends on the environment and the location. Snow, by example, reflects a massive quantity of light radiation.

The global or the total radiation is the simple sum of all these components. The picture below presents the scheme.

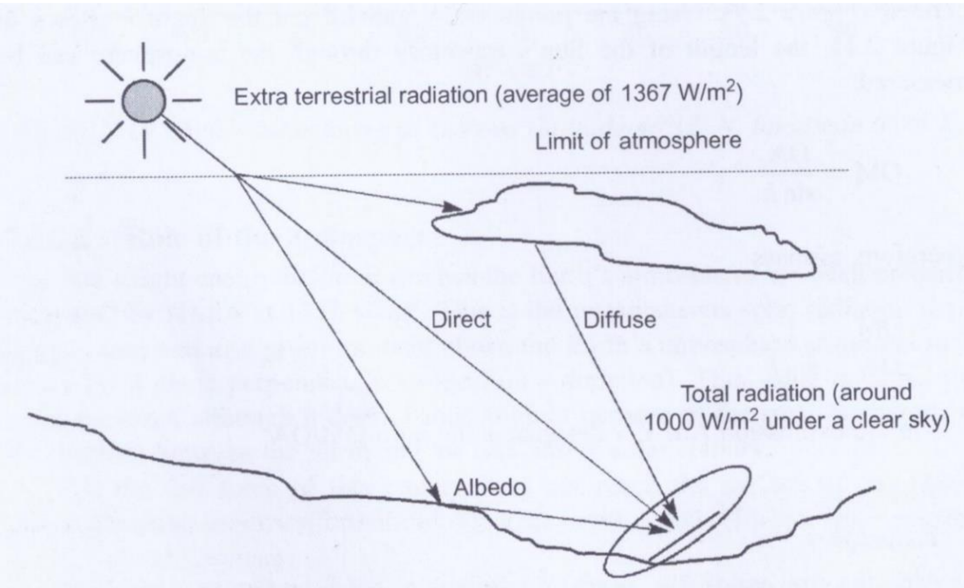

Figure 1 – Components of Solar Radiation on the ground (VILLOZ & LABOURET, 2010)

From these concepts, two important terms were created with the purpose to quantify this energy, the irradiance and the irradiation. The irradiance is the rate at which radiant energy is incident per unit of surface and it is expressed in the unit [W/m²]. The irradiation is the incident energy per unit of surface, which is found by the integration of the irradiance in a certain period time, and it expressed in the unit [J/m²] or [kWh/m²].

The NASA has found that the value of the extraterrestrial radiation just before it reaches the Earth's surface is 1357 W/m², which became the solar constant, given by the letter "G". However, the value of irradiance used as reference on the Earth's surface is 1000 W/m².

The values of irradiation are different according to the geographic position. In general, they are smaller on the extreme north and south, and when coming towards the equator line, the values reach their maximum. Therefore, the geographic place where the photovoltaic system is going to be installed is of extreme importance to the energy production perspective.

3.1.2) Operation of photovoltaic systems

In a simple explanation, when the Sun's beams reach the PV modules, they started the photovoltaic effect, which transforms the Sun's energy into electrical energy in direct current. The PV modules are connected to the inverter, that transforms the direct current into alternating (alternate) current, so it can be used by the electrical equipment.

After that, the electrical connection passes through the fuse box, from where it can go to the electrical equipment of the residence, the batteries (in case they are present in the installation) or directly to the electrical distribution grid, passing through the meter.

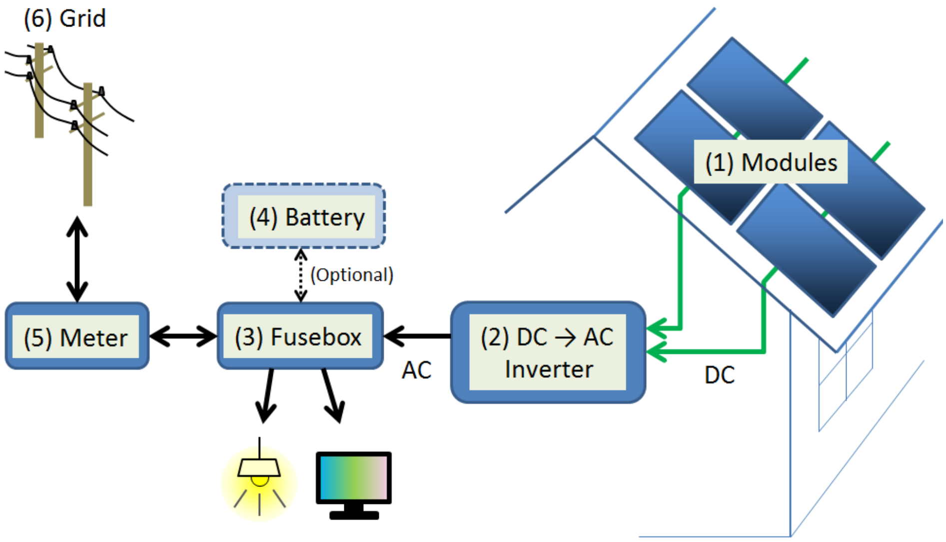

Figure 2 – Scheme of a residential photovoltaic system

3.1.3) Components

As seeing in Figure 2, the main components of a photovoltaic system are the PV modules, the inverter, the fuse box (where the protection systems are installed), the battery and the meter.

In this section, all these components will be properly explained.

3.1.3.1) Photovoltaic modules

The photovoltaic modules are probably the principal component if the photovoltaic systems. It is composed by several photovoltaic cells connected to each other, whose are capable to transform the irradiation that comes from the Sun into electric energy, according to the photovoltaic effect.

This technology was born in the United States in 1954, created by Daryl Chapin, Calvin Fuller and Gerald Pearson. The photovoltaic cells they have created were made of monocrystalline silicon and were the first ones capable to generate enough power to run electrical equipment. These cells had 4% of efficiency at the beginning, but later achiever 11%. (U.S. Department of Energy)

Along the years, other materials were used in the solar cell's production, such the Gallium Arsenide and Cadmium Telluride. However, the Silicon's variations monocrystalline and polycrystalline are still the most used nowadays.

The monocrystalline technology is able to reach efficiency between 15 and 18%, while the polycrystalline technology has a smaller efficiency, between 13 and 15%, but, in the other hand, are cheaper. (VILLALVA, 2015) However, nowadays the technical specifications of manufacturers declare efficiency higher than 20%, for example the SunPower panels, that have efficiency of 22%.

The PV modules present in the market nowadays have, usually, the nominal power from 260 Wp to 330 Wp. The Wp is a unit called "Watt Peak" and expresses the maximum value of power that the module can reach, when it is under the STC (Standard Test Conditions). Also, the life span of the modules is 25 years.

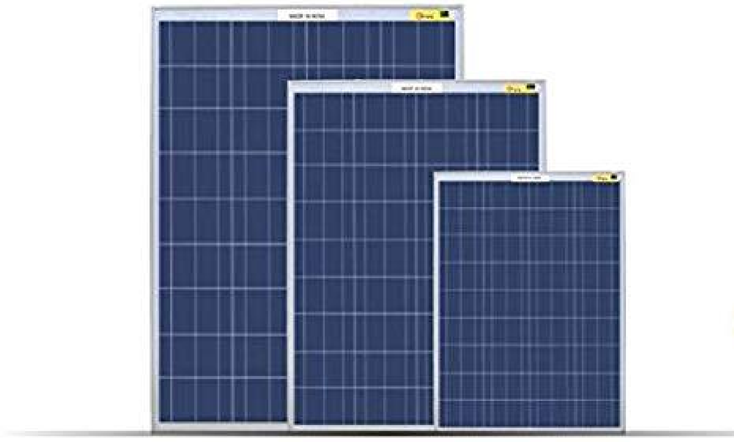

Figure 3 – PV modules

The physical functioning of the PV modules can be performed in a very detailed form, however since this is not the objective of this work, it will be performed in a simpler manner, just as small review. The sun's energy reaches the PV modules with energy enough to surpass the energy gap between the conduction band and the valence band of the atom. Because of that, the electrons start to move from one to the another, creating a recurrent effect among all the solar cells, which is the direct current, that goes to the inverter.

3.1.3.2) Inverter

The inverter is an electrical machine that uses electronic components, such transistors, diodes, capacitors and inductors, to transform direct current in alternate current.

Basically, there are two types, the centralized inverter and the micro-inverter. The centralized inverter collects the direct current coming from all the strings of a photovoltaic system and turn them into one string of alternate current. The micro-inverter is installed on each PV module and make the transformation of direct current into alternate current right there.

Both types use the same principle of operation and there is practically no difference in efficiency. They are composed of transistors, usually by four, in H-bridge configuration. They open according to the reference signal of the voltage, which is in accordance with the Pulse Width Modulation (PWM) technique. However, since this is an application study and it is not the purpose explain in detail how they work, the inverters will be considered as black box, in which from one side enters direct current, and from the other exits alternate current.

Figure 4 – Centralized inverter: Fronius Primo 6.0 kW (Source; Fronius's website)

Figure 5 – Micro inverter ABB (Source: ABB's website)

The centralized inverters are cheaper, considering the kW/R$, than the micro-inverters. However, they are physically big components and for small installation the micro-inverters can be more indicated.

The inverters used in solar power plants can have nominal power in the order of 1 MW to several megawatts. In mini-generation systems, the nominal power is from 100 kW to 1 MW, and in microgeneration systems it is up to 100 kW. The life span of the inverters is from 5 to 10 years.

All of these types come with the MPPT, that is Maximum Power Point Tracking. It is an internal component that regulates the inverter voltage and current, so the inverter can operate always at the highest possible value of power. The Figure 6 below can help to understand this concept.

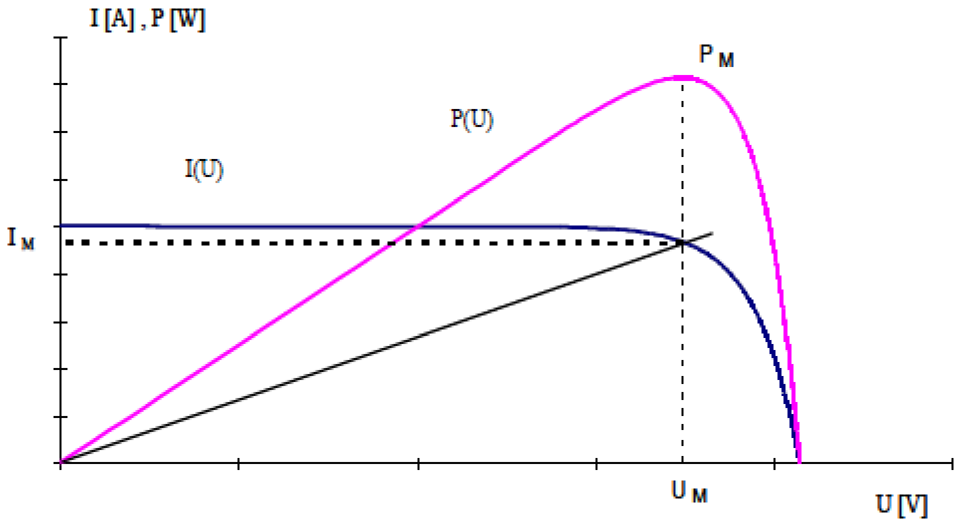

Figure 6 – I-V characteristic curve and correspondent power output (SPERTINO, 2016)

The curve in blue is I-V characteristic of PV modules and the curve in pink is the output power as a function of the voltage. As can be seeing, there is an excellent point between voltage and current in which power achieves the maximum value. The MPPT's role is track this point and maintain the inverter functioning on it so the system can achieve its best performance.

3.1.3.3) Batteries

In the photovoltaic installations, there are some moments in the day when the energy produced by the photovoltaic systems is larger the energy demand of the residence. Therefore, this energy excess has to go somewhere. There are two paths where it can go: the first one is directly to the electric grid and the second is to the batteries to be stored.

It is important to say that the energy that goes to the grid is not lost by the consumer of the residence. It is properly accounted by the meter and then it can be used in moments where the energy demand in the residence is larger than the energy produced by the photovoltaic system.

Therefore, the batteries appear as an option for the people that would like to consume the energy of their own system or to have an insurance for when there is a power blackout, and the electric grid stops working.

The batteries usually have the voltages of 12V, 24V and 48V. They can be made by several types of material, but the one made by acid lead with liquid electrolyte is one of the most used. The life span of batteries is not measured in years, but in cycles of charge and discharge. (VILLALVA, 2015)

3.1.3.4) Energy meters

The energy meter is an equipment that measures the energy flux that passes through them. This equipment is required in every residence supplied with electrical energy and its maintenance and operation is of responsibility of the power distribution company.

In the residences without photovoltaic system, the installed energy meter is unidirectional, thus it measures the energy that comes from the distribution grid to the residence and, at the on each month, the consumer is charged for the amount of energy registered in that period.

In residences that installed the photovoltaic system, the power distribution company must substitute the unidirectional meter for a bidirectional meter, without charging any costs to the consumer. This substitution is required because these residences are small generators of energy and in certain periods of the day, they will inject energy into the grid, which must be accounted, because it affects the value of the electricity bill, according to the ANEEL’s compensation system.

3.1.3.5) Protection systems

The principal protection system present in photovoltaic installations is the surge protection device. It is installed between the electric switchboard and the inverter and is responsible to protect the electric installation against transient surge conditions.

The surge conditions are defined as instants when the voltage of a system reaches very high levels and then, in the next instant, it comes back to normal. This behavior can cause serious problems to the electric installation, which was not designed to support them.

The surge activity can be caused by lightning and utility power anomalies, which elevates the voltage to the highest levels. But they are mainly caused by internal issues of the electric installation, which provokes smaller elevation of voltage, but since they occur more frequently they can also cause damage.

Besides this protection system, there is also the circuit breaker, common to any electric installation. Its functioning is simple, when the current surpasses a certain value, it opens the circuit, preventing the electrical equipment to be damaged.

3.1.4) Shading and temperature losses

All the systems that transform one type of energy into another have losses in the procedure. In the case of photovoltaic system, the two main losses are because of temperature and the shading;

The losses by shading happen when a PV module that is subjected to a shadow caused by an obstacle stops producing energy, even if just one cell is shaded.

The PV modules are composed of several photovoltaic cells connected to each other. Each photovoltaic cell starts to conduct current when there is enough solar energy provided to make the electrons jump from the conduction band to the valence band. With that, it is created a flux of electrons passing through all the cell of the module, then through the wires, until they get to the inverter.

However, if just one cell does not receive enough energy, it will not allow the passage of electrons and the cycle, for that string of cells, is interrupted. The picture below illustrates this effect. (VILLALVA, 2015)

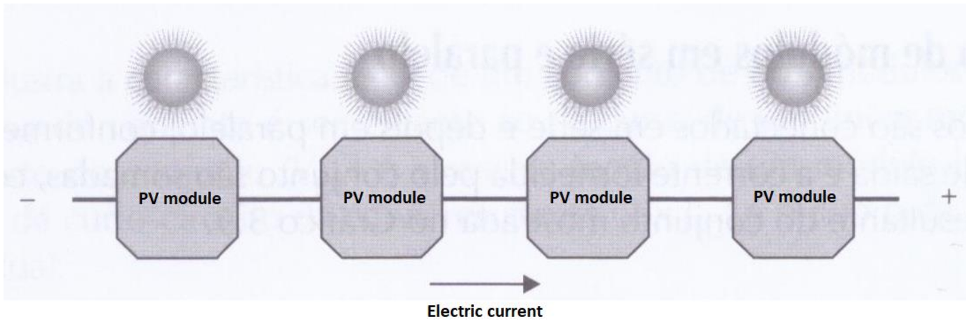

Figure 7 – PV modules in normal functioning (VILLALVA, 2015)

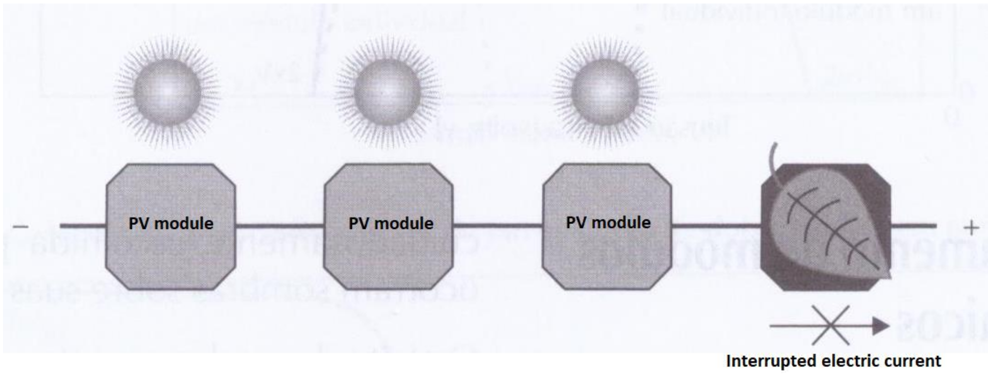

Figure 8 – PV modules with shading in one cell without bypass diode (VILLALVA, 2015)

To minimize this effect, it is possible to add bypass diodes each or more cells, as shown in the picture below (Figure 9). By doing this, it is possible to create an alternate path to electrons to pass avoiding the shaded cell.

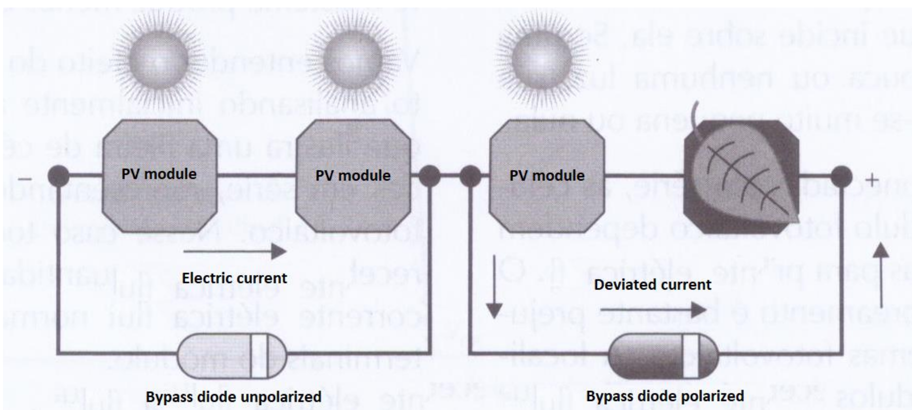

Figure 9 – PV modules with shading in one cell with bypass diode (VILLALVA, 2015)

The temperature losses affect the voltage that the PV modules have in their output terminals and, therefore, they affect the power provided. The lowest is the temperature, the largest will be the outlet voltage. This effect does not affect the electric current, that does not change according with the temperature.

The graphics below explain better this concept. Remembering that the power is voltage multiplied by the current, therefore the maximum values of power are obtained for lower temperatures.

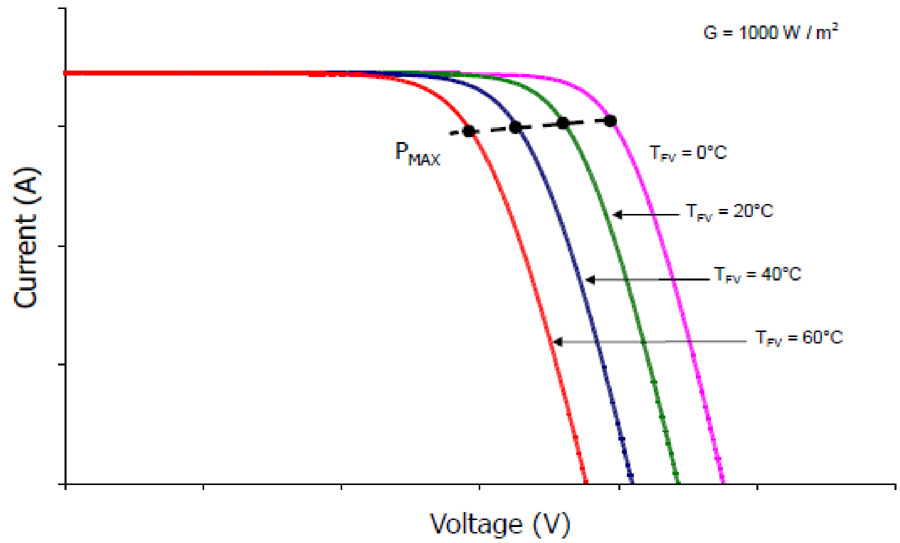

Figure 10 – I-V curve as a function of temperature (SPERTINO, 2016)

3.2) Brazilian's regulation for distributed photovoltaic energy generation

The regulation of photovoltaic energy in Brazil is responsibility of the ANEEL. The first time they have published a material to regulate the photovoltaic energy at distributed level was in 2012, with the resolution 482. Later, in 2015, it was published a revision, called resolution 687, with some small changes.

In the next topics, it will be explained, according to the resolutions 482 and 687, the current scenario of the Brazilian regulations for photovoltaic energy at distributed level.

3.2.1) Installation typologies covered in the resolutions

The resolutions had the purpose to regulate the photovoltaic installation for distributed generation. Therefore, first, it was necessary to define what types of installations are considered as distributed generation.

Distributed generation can be defined as the electrical generation performed by small and grid-connected consumers at their own property. The energy generation can be of any energy resource type, but the most common is the photovoltaic.

According to the resolution 482, the distributed generation can be divided into microgeneration and mini-generation, and the difference between them is only the installed power. The microgeneration has the installed power up to 75 kW and the mini-generation has the installed power between 76 kW and 5 MW.

Besides the installed power, electric installation must be covered in one of the three typologies defined by the ANEEL to be qualified as a distributed generation system.

- **Remote self-consumption**

It is the simplest case of distributed generation. It consists of a house with the energy generation system installed directly on it and it has the only purpose to supply the energy consume of the residence itself. However, if the system is sufficiently big to produce more energy than the residence consumes, the surplus can be sent to another residence connected to electrical grid, as long as it supplied by the same power distribution company and it has the same ownership of the residence that is producing energy.

In most of the cases, it has the installed power smaller or equal to 75 kW, which characterizes it as a micro-generation system.

- **Enterprise with multiple energy consumer units**

This typology is characterized by several consumer units that belong to the same administration, by example a gated community. In this situation, the equipment should be installed in the common area of the community.

The energy consumption of the common areas of the community accounts as an energy consumer unit and the system works mainly to supply it. This means that all the energy generated first is consumed by the common areas and, when there is a surplus, it is sent to the other energy consumer units, which are the houses, equally divided among them all.

- **Cooperatives**

This typology is characterized by the energy generation being performed in a different place than where the energy consumer units are located, as long as they are all supplied by the same power distribution company.

The location where the energy is generated must be represented by a person or a company, which can subscribe other energy consumer units to receive a fraction of the generated energy. The ANEEL does not get into details of how this subscription is going to be compensated and how much of energy goes to each subscriber, but, usually, people pay to receive a fraction of the energy at a lower price than the tariff fees of the power distribution companies.

Therefore, it can be seen as a mini center where energy is produced, very close to the final energy consumers, that sells energy at a lower price than the ones people are forced to pay to power distribution companies.

3.2.2) Energy metering and access to the distribution system

It is responsibility of the power distribution companies to ensure that all the electrical installation with the addition of the energy generation system was performed correctly, according to the ANEEL’s normative.

Once this step is concluded, these companies also have the obligation to meter all the energy that enters and exits the energy consumer units. Therefore, they must change the unidirectional meter, that is only capable to measure the energy that comes from the electrical grid to the residences, for a bidirectional meter, that measures the energy flux in both directions.

The power distribution companies must cover all the expenses of these procedures, being unable to charge anything from the consumers.

3.2.3) Energy compensation system

This system was created because the distributed generation is performed mainly by renewable energy sources. For this reason, there is no control of when they are going to produce energy and, very often, the energy production happens when there is no energy demand in the house.

Therefore, this energy has to somewhere else. One option is using batteries to store the energy to be used later, but this will increase the price of the project.

The other option, which is wildly more used, is the energy compensation system. In this system, the energy that enters and exits the house is measured, and, in a simple explanation, the consumer is charged for the net energy, that is given by the following expression:

$$net\ energy = energy\ injected - energy\ consumed$$

If the net energy is negative, it means that the client has consumed more energy that his photovoltaic system has injected, and he will be charged only for this difference.

In the case the net energy is equal to zero, the client will still pay the availability cost. And if the net energy is positive, it means that the photovoltaic system has injected more energy than the house has consumed. In this last case, even though the client is still charged by the availability cost, the surplus of energy is stored through the credits.

The credits are given in kWh, have until 60 months to be used, and they are used when net energy of a certain month is negative. Therefore, they will compensate months in which the consumption was greater than the generation of energy and reduce the value of the bill up to the availability cost.

4) Topologies of photovoltaic systems

The photovoltaic systems can be installed in some different electrical arrangements. Each arrangement is a different topology, whose is important to be explored, because one of them is going to able to provide the best results for the situation we are verifying.

Keeping in mind this idea, topologies will be presented that are currently authorized by the ANEEL's regulations and other that are not. The motivation to explore the topologies that are not currently authorized is the possibility to find one that suits better for this situation, which could be later include in the ANEEL's regulation.

In total, four topologies are going to be presented in a block diagram format. For all the cases, it will be explained its functioning, qualitative aspects and whether or not the topology is currently authorized by ANEEL.

Before getting into the detail of each one, it is necessary to explain some common concepts that are going to be presented in all of them. There are two optative equipment in all of them, the batteries and one of the meters, called "Meter A", which were drawn with dashed lines. The presence of this equipment does not affect the operation of the system, however they are going to be considered because they can provide some different results, which are worth to be evaluated.

While the Meter A is optional and has the purpose to measure the quantity of energy that is produced by the photovoltaic system, the Meter B is mandatory by the ANEEL's regulation and it has the purpose to measure the quantity of energy that is consumed by the distribution grid and the quantity of energy that is injected to it.

4.1) One residence supplied by PV modules on its own roof using centralized inverter

This topology is the most commonly used in distributed energy generation from photovoltaic systems around the world. It is also the simplest topology, designed to supply only the energy demand of the residence in which it is installed, using the most common and cheapest technology of inverter, the centralized type. The block diagram below schematizes its functioning.

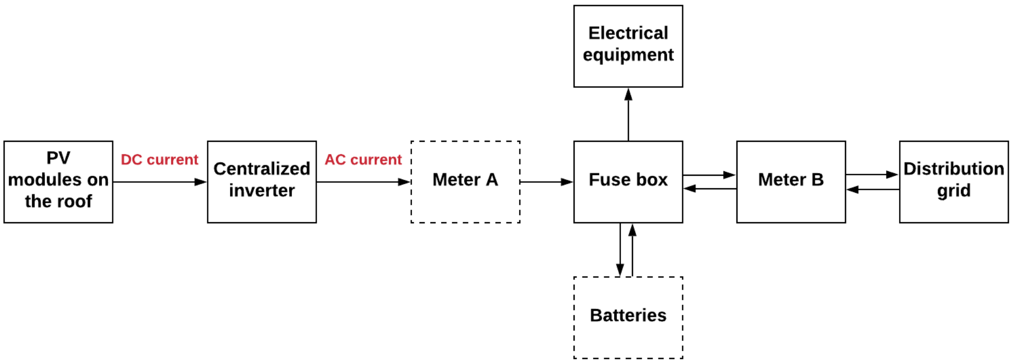

Figure 11 – Topology 1 (Source: the author)

As already explained before, the solar beams reach the PV modules, producing electrical energy in direct current, which goes to the centralized inverter to be transformed into alternate current, passing through the Meter A, that measures the energy produced by the system. From there, it goes to fuse box, from where it can follow three paths.

The energy flow goes to one of them according to a certain preference. The first path to be followed is the electrical equipment, when there is an energy demand coming from them. If there is no energy demand, the energy flow goes to the batteries to be stored. However, if the batteries are completely charged, the energy flow goes to the distribution grid, passing through the meter B, that measures the energy injected to distribution grid.

The energy stored in the batteries will be used when there is an energy demand from the electrical equipment and the photovoltaic system is not producing enough energy to supply it all.

The energy from the distribution grid will be provided to the residence if there is an energy demand coming from it, and neither the photovoltaic system and the batteries have enough energy to supply it all.

From the qualitative perspective, this type of installation is usually very simple and could be finished in two or three days. But, since they are going to be installed in low-income communities, a few problems arise. The roofs where the

PV modules will be installed are usually not in good condition, i.e., they do not provide a stable structure to support the modules, as can be illustrated by Figure 12, that represents how the low-income communities usually are in Brazil.

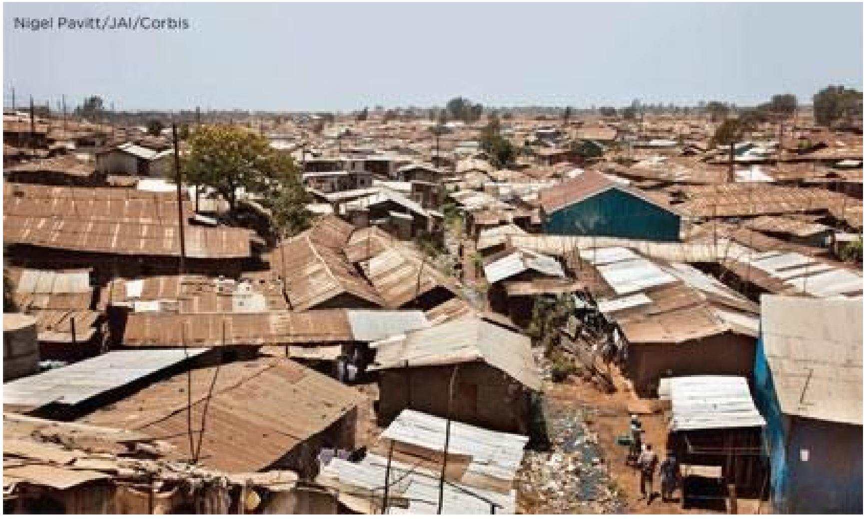

Figure 12 – Low-income community in Brazil

In these conditions, it is harder to install the PV modules, the chances of one or more modules fail due to external factors increase, and the photovoltaic system would produce less energy that its full capacity, which means a reduction in the return of the investment.

The stability of the electrical circuits inside the house could also be a problem, since there is a significant chance that they are not in a regular condition. For this reason, it could be a risk to electrical circuit of the photovoltaic system.

Other problem is the difficulty to access this type of community. The streets are narrow, usually in steep slope, which makes much harder to the installation team enter and perform correctly their job, increasing this type of cost. This will also be an issue for the maintenance of the system.

Finally, the dangerousness and possibility of scam or frauds can be issues as well. It is not the intention of this paper to generalize the people that live in this type of community, but it is a general knowledge that there is a higher incidence of violence in places like this, which could result in the stealing of the equipment, before or after the installation, and could even be a risk to the installation team.

For what concerns the ANEEL's regulation rules for distributed energy generation, this topology respects them all and has no restrictions.

4.2) One residence supplied by PV modules on its own roof using micro-inverter

This topology is very similar to the previous one, the only difference is the inverter, that in this case is micro and, therefore, connected directly on the PV modules. This change does not cause significant changes in the operation of the system and neither in the efficiency.

The substitution of the inverter has mainly two impacts: the first one is the price of the inverter, the micro-inverter being more expensive. The second one, is the practicality that the micro-inverter has in comparison to the centralized, because the centralized inverter needs to be installed inside the house, in an airy and well-conditionate place, and it occupies some space, while the micro-inverter is installed directly on the PV modules and does not occupy any space inside the house.

The following scheme presents its functioning:

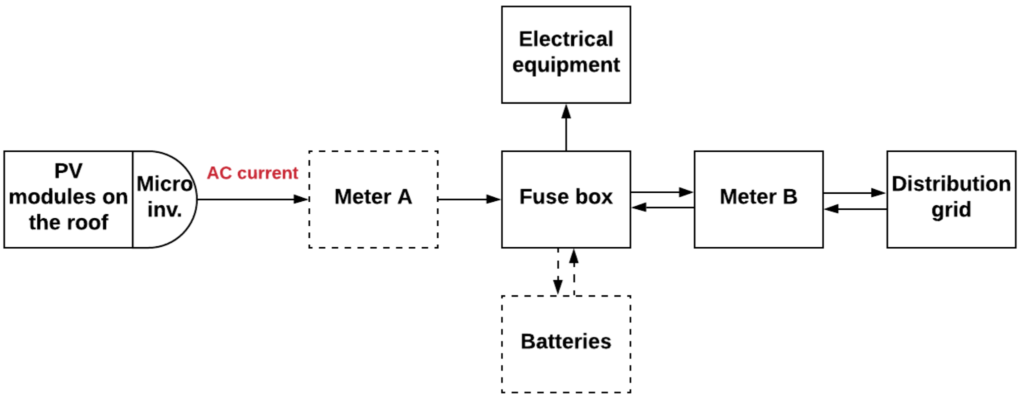

Figure 13 – Topology 2 (Source: the author)

The system's operation and qualitative issues are the same of the previous topology and, for this reason, they were not repeated here. For what concerns

For what concerns the ANEEL's regulation rules for distributed energy generation, this topology respects them all and has no restrictions.

4.3) Two or more residences supplied by PV modules on their own roofs using a common centralized inverter between them all

This topology has the purpose to unify the direct currents that come from the PV modules of all the residences in one centralized inverter and, from there, send the alternate currents to the respective residences. By doing this, the cost of equipment would reduce, because only one inverter would be used.

The functioning of the topology is presented in the scheme below:

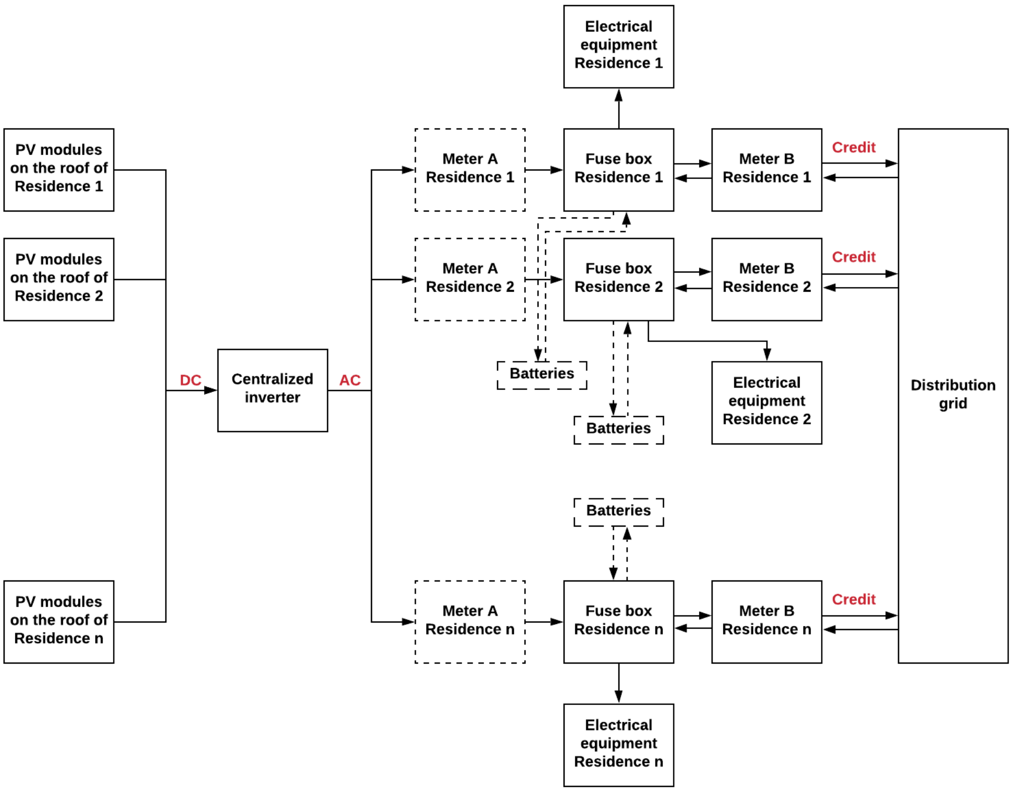

Figure 14 – Topology 3 (Source: the author)

The Sun's beams strike the PV modules installed on the roofs of the residences, generating energy in direct current. In this configuration, all the direct current is unified before it gets to the centralized inverter. For this reason, its nominal power should be greater to support all the current to support it and transform into alternate.

From the inverter, the alternate current can follow its path to any of the residences involved in the installation, passing through the meter A of each one of them, that measures the quantity of energy enters the house coming from the photovoltaic system. The “selected” path will be the one, or the ones, where there is energy demand, and the energy that will go to each residence will be proportional to it.

This means that the if the Residence 1 has an instantaneous demand of 100 kWh, the Residence 2 has an instantaneous demand of 200 kWh and the Residence 3 has no instantaneous demand, the Residence 2 will get most of the benefits of the system in that moment, because it will receive more energy.

For this reason, in this topology it is very important to have the meter A to measure the energy coming from the photovoltaic systems in all the residences. With them, at the end of the month it will be possible to verify exactly how much energy each of the residences consumed and calculate the fairly value of the electricity bills between them all.

After entering the fuse box of the residences, the functioning is pretty similar to the topologies 1 and 2. As said before, it will go to the electrical equipment when there is energy demand, if not, it goes to the batteries and in the case they are completely charged, the energy is injected in the grid, being stored as credits. The credits, given in kWh, can also be a tool to even the bills among all the residences involved.

The energy from the batteries will be consumed when there is energy demand coming from one of the residences and there is not enough energy production to supply it. However, in the configuration presented in the Figure 14, considering only one common battery for all the residences, there is no control of how much energy goes to each one of them. A solution for this problem is very simple: do not use batteries and use just the compensation system.

When there is an energy demand coming from the residences, but there is not enough energy production or energy stored in the batteries to supply it, the energy from the distribution grid will be used to supply it.

From the qualitative perspective, there are the same issues of the previous topologies: the difficulty to install it, the bad quality of the roofs, the unstable electrical circuits of the houses and the dangerousness and the possibility of scams. However, in this topic they would not be described in detail because what concerns us are the different issues that come with this topology.

First, there is the possibility of conflict among the people of the residences that share this same system, once that it is not possible to divide the energy produced in equal shares among them all.

The tools provided by the meter A and the credits of the compensating system can be helpful and fix the situation, but there is the possibility that the people there will not get to an agreement of how to share the energy produced and, consequently, the electricity bills would be an issue. Because if one residence uses more energy from the photovoltaic system than the others, it will use less energy from the distribution grid and thus pay a smaller value of electricity bill than the other, even though they should all get the same benefit. This situation could create problems that could put the system in jeopardy.

The installation will be much more difficult to be performed because it will involve more than one residence. This means that the electrical circuits will be more extensive, passing through difficult areas, increasing the probability of failure.

The location where the centralized inverter will be installed would be an issue as well. It is more recommended to be installed inside the residences, which would require that the residents of one house allow it to be place inside its own residence and occupy some space, while at the same time the people of the other residences would not have to handle this situation and still get all the benefits the system, creating a situation that could develop into a problem.

One possible way out of it could be installing the centralized inverter in a neutral place, like on the roof of the residences, which is possible using inverters that have protection certifications against dust, water, temperature and many other factors. However, since the roofs of these residences is not very strong (Figure 12), there is a significant chance that it would not be able to support it.

For what concerns the ANEEL's regulation rules for distributed energy generation, this topology does not respect them. Actually, it is not precisely a rule for distributed energy generation, but it is a common rule for electrical installations. It is stablished that is not allowed to have an electrical connection among consumers units after the meter B (which is the meter installed in all the residences to the measure the consume).

In this scenario, there is clearly a connection among them, which are all connected to the same centralized inverter. The ANEEL forbids this type of installation precisely for the reason stated before, it is more difficult to measure exactly how much of energy each of the consumers units used, which would implicate in problems of how to each one of charge them. Also, because one residence could steal energy from the other.

However, this solution is potentially less expensive than the previous two, which would increase the cost-benefit ratio and reduce the time of return of investment. In addition, it should be kept in mind that the people in the residences would not pay anything for the photovoltaic system, thus if one receives more or less energy than the other, one would still receive the benefits from it and will pay a smaller value for the electricity at the end of the month. And the power distribution would have accomplished its role of investing in energy efficiency.

4.4) Two or more residences supplied by PV modules on its their roofs using a centralized inverter in one of the residences

This topology is very similar to the previous one, because there is still the purpose to reduce the cost of equipment by using a big centralized inverter for more than one residence. However, this topology proposes a solution that respects the ANEEL's regulations. The following scheme (Figure 15), presents its functioning.

The Sun's beams strike the PV modules that are on the roofs of the residences, whose convert the solar energy into electric energy in direct current. From there, they all go to the centralized inverter that will transform it into alternate current, and here is the difference in comparison to the topology 4.

The alternate current that exits the centralized inverter goes entirely to the one of the residences, passing through the meter A that will measure the quantity of energy produced by the system, and getting to the fuse box.

From the fuse box, the energy can go one of two paths, the electrical equipment of the residence 1 or to the distribution grid. If there is an energy demand coming from the residence, the energy will to the respective electrical equipment, if not, it will go to the distribution grid, to be become credits.

In this topology, it would not make much sense to install batteries on the residence 1, because this topology has the purpose to supply the demand of the other residences with the credits that are injected coming from the residence 1. So, it there is a battery to provide even more energy to the residence 1, probably it would have enough energy to supply the others.

With the stored credits, it would be necessary to create quotes of energy, in percentual, that would go to each of the residences that are involved in the project. This way, all of them would receive the benefits of the photovoltaic system.

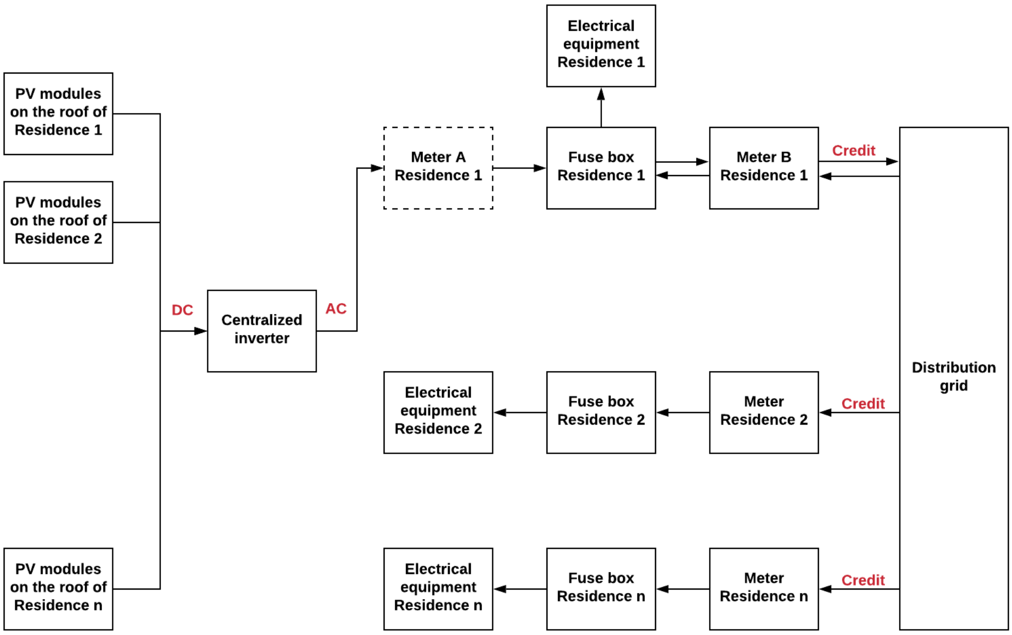

Figure 15 – Topology 4 (Source: the author)

Analyzing the qualitative aspects related to this topology, there is still the issues to install it because of the street conditions and the bad quality of the roofs, this last one that could cause a reduction in the performance, the unstable electrical circuits of the house and the dangerousness and the possibility of scams. All these issues are present practically in all topologies and are better explained in the previous sections 4.1 and 4.2.

Besides them all, there other issues as well. In this configuration, the centralized inverter should be installed inside one of the residences, which could cause a problem to decide which one among the residents of all houses.

Other issue, the same of the topology 3, is the division of energy. This decision can be done by the residents of the houses or even by the power distribution company. However, either way, it is potentially a problem if someone thinks the division is unfair, because the residence 1 consumes energy instantaneously before injecting it to the grid, therefore the quotes cannot be the same to each one of them. A solution for this situation is calculating, on average, how much energy the residence 1 consumes instantaneously and then deduct it from the quote of credits it will receive.

For what concerns the ANEEL's regulation rules for distributed energy, as said before, it respects them all.

4.5) Cooperative of houses supplied by a solar farm using centralized inverters

Having in consideration all the problems of the previous topologies, this was proposed as possible solution.

Practically all the issues presented in the previous topologies were related to the location where the photovoltaic systems would be installed: the bad roofs that do not provide a stable structure for the PV modules; the narrow and bad quality streets that make more complicated to the installation teams to perform their job; the bad quality electrical circuits to which the photovoltaic systems would be installed; the possibility of scams or having the equipment stolen; and the potential problems among the residents because of the photovoltaic systems.

One possible solution is to install the photovoltaic system away from the community, thus acting as a solar farm, and send the energy, using the compensation system, to the cooperative of residences formed by the community. Therefore, at least the problems above would practically be solved. The following scheme presents its functioning:

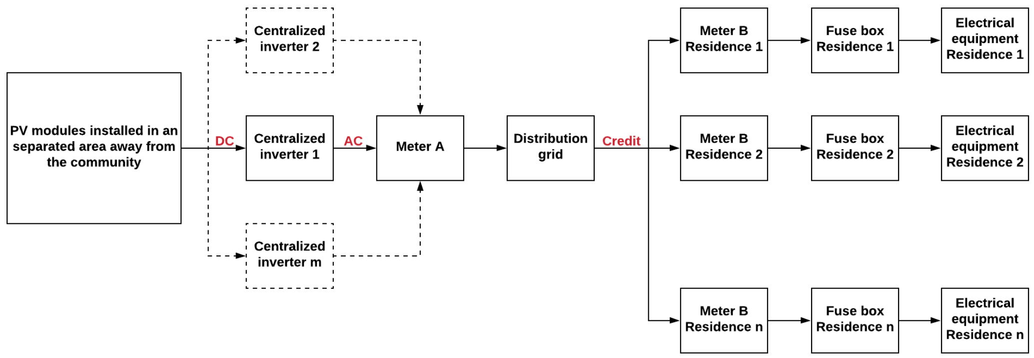

Figure 16 - Topology 5 (Source: the author)

As in the functioning of all photovoltaic systems, the Sun's beams strike the PV modules, inducting the generation of direct current among the panels. The direct current goes to the centralized inverters to be transformed into alternate current. This topology supports one or more centralized inverters, that will have to match the power of the PV modules, for this reason it was used dashed lines for the centralized inverters 2 to m in the Figure 16.

After passing through the centralized inverters, the alternate current goes to distribution grid, passing though the meter A, that measures the amount of energy injected, that is transformed into credits.

These credits will be divided in quotes, given in percentage, and it will be sent to each one of the residences. Thus, the energy flow passes the meter B of each residence, then through the fuse box and, finally, it gets to the electrical equipment.

From the qualitative perspectives, the issues with this topology are different than the previous four cases. The issues in this scenario are not much related to dangerousness, possibility of scams or bad performance of the system. The issues are related to costs.

For this topology work, it will be required a large a space to install the solar farm, with all the PV modules, inverters and other equipment. This place should be as close as possible of the community that is going to be supplied by it, and this land could be acquired or rented, which would increase the CBR of the project.

Since this is considerable big project, it would require constant monitoring and maintenance in order to keep working correctly. In this case, it is possible to think in two ways to handle this situation. The first one, the responsibility for maintenance of the photovoltaic system would be performed by the power distribution company, which would manage the system and cover the costs. However, this situation would increase the CBR, which could make the project impracticable.

The second one is, actually, the manner that the cooperatives currently work under the ANEEL's regulations for distributed energy. In this case, a legal person would manage the photovoltaic system, under some specified rules, to ensure that it will keep working properly and that all the residences will receive energy. However, the problem of the additional cost persists, because this legal person would be a company that should be paid. The difference is that in this case, the community would share this value among them all and pay for a monthly fee. This value should be smaller than the economy they would get with electricity bill, otherwise the residents probably would not want it.

The last issue is one presented before: the division of the energy generated among all the house. However, in this case the solution is much simpler: since the systems are not installed in the people's house, they would not own them and, thus, they could not create a problem and just accept the energy sent to them. The quotes of energy could be equally divided among the all.

For what concerns the ANEEL's regulation rules for distributed energy, this topology respects them all.

5) Case study

In this chapter, the case study will be performed. Thus, the community analyzed will characterized in number of consumers units and electricity demand. Then, the methodology applied to calculate the energy generated by the photovoltaic systems will be presented, followed by the results.

In the sequence, the CBR for each topology will be calculated, in order to verify if they could be financed using the resources of the EEP.

5.1) Characterization of the community

The low-income communities are defined as the set of houses occupied by low-income families. There are many different optics of what is considered a low-income family, but in this case, the regulation of the ANEEL will be used.

As presented in the section 2.3.1.2), the low-income families are those that have the per capita income of half minimum salary (R$ 449,00) and have the maximum energy consumption of 220 kWh/month on average in the last 12 months.

However, the community used in this study is not real, but it is based in a real community. The EDP São Paulo, in the year of 2016, performed a project that installed water heating systems and changed the old and inefficient lamps for new and efficient ones in the houses of a few communities of the São Paulo state using the resources of the EEP. The project was successful and the company, through the intermediation of one of the coordinators of this thesis, Professor André Gimenes, kindly provided the final report and the data they used to perform the project. Thus, the community used in this case study has the same characteristics of this real one.

Among the several quantitative and qualitative characteristics provided by the EDP São Paulo, only two of them are completely essential to perform this study. The first one is the average electricity consumption of the houses in the low-income communities, an information that only the company has, and the second one is the number of houses that are eligible to participate of the program.

The average electricity consumption was calculated using a sampling of 125 residences of a significative universe of more than 30 thousand of the cities of Guarulhos, Itaquaquecetuba, Mogi das Cruzes and Poá, respecting all the guidelines to be considered statistically relevant. The data of each one of the residences is classified and cannot be presented in this thesis. However, to determine the average consumption of a house in a low-income community, first the average consumption of each residences in the past 12 months was calculated, and then the average of all the 125 residences was taken. By doing this procedure, the average electricity consumption found is 142,05 kWh.

The number of residences contemplated with the benefits of the EEP in this project of the EDP São Paulo was around 10 thousand. Thus, in the case study this number will be used, and the total electricity demand to be supplied is equal to 1.420,5 MWh per month.

Other important information is that all the residences were considered having biphasic connection, because even though it is a low-community, the residents use 220V electrical showers, which requires at least the biphasic connection.

However, it is important to keep in mind that the number of residences and the average electricity will change from community to community.

5.2) Equipment selection and costs

The equipment required for a PV system installation are the PV modules, the inverters, the cables, the fixation structures and the protection devices.

The information about the available equipment and respective prices was provided by the company that the author of this thesis currently works, the Solstar Energia Solar Comércio Locação e Serviços, that performs photovoltaic projects and installations mainly for residences and small businesses.

The Solstar buys all its equipment from other company called Sices, that is the main supplier of photovoltaic equipment in Brazil. The price of each component changes slightly from week to week and the data collected from Sices dates the first week of June of 2019.

The selection criteria of the equipment and the other costs are described in the following.

- **PV MODULES:**

The objective is to select the best modules considering the cost-benefit, thus the equipment with best efficiency at the lowest price. A possible way to face this situation is considering the relation between the kilowatt-peak and the price of the PV module (R$/kWp).

The kilowatt-peak is a unit that expresses the power obtained at the output of a PV module when it is exposed at STC conditions of irradiance of 1000 W/m², spectrum AM (Air Mass) 1.5 and cell temperature of 25ºC, and it is the maximum power that the PV module is going to reach.

The kilowatt-peak considers the available area of the PV modules and their efficiency. The following expression will help to understand it.

$$kWp = G \,.\, \eta_{rated} \,.\, Area_{PV} \qquad (7)$$

The G is the irradiance constant, equal to 1000 W/m², which is the value used at the Standard Test Conditions. The rated efficiency the measures the amount the module's capacity to transform the Sun's energy into electrical energy. The PV area is the available area of the PV module capable to perform this work, once the irradiation gives the power as function of the area. So, if the datasheet of a certain module says it has the rated efficiency of 18% and the area of 2 m², the kilowatt-peak is 360 kWp.

All this means that highest values of kWp indicates better module's performance. Considering also the price of the kWp, it is possible to evaluate the cost-benefit ratio through the factor (R$/kWp), in which as small the value is, the better is the cost-benefit.

According to the information provided by the Solstar, the PV module with the smallest R$/kWp was the JA Solar 335W, with the ratio 0,001362 R$/kWp, made of polycrystalline silicon, costing R$ 456,42 and having the life span of 20 years. Its principle characteristics are presented in the following table and the complete datasheet is in the attachment A.

Module	Maximum power [W]	Rated efficiency	Area [m²]	Price [R$/module]	R$/kWp
JAP72S01 - JA Solar	335	17,20%	1,942	456,42	0,00136

Table 2 - Main characteristics of the JA Solar module JAP 72S01 (Adapted from the JA Solar module JAP 72S01 datasheet)

- INVERTERS

In this case study, the inverter selection will depend only on the topology analyzed, considering because its nominal power should match the nominal power of the PV modules, which will change according to the scenarios.

Other factors also affect the inverter selection, such the minimal starting voltage, the maximum voltage that could be applied to its terminals, the position of the strings to be connected at the MPPTs, among many other factors. However, the analysis performed in this thesis is to evaluate the CBR and verify if the projects could be financed by the EEP resources. Thus, the more technical issues were not considered, because they would have little effect on the CBR calculation, and the selection of the inverters for each case was performed considering only to match the output power of the PV modules.

Category	Nominal power [kW]	Manufacturer	Life span	Price per unit [R$]	Topologies
Centralized	1,5	Canadian	15	2.499,00	1
Micro	1,0	AP system	15	3.100,00	2
Centralized	3,0	Canadian	15	3.868,33	3, 4
Centralized	6,0	Canadian	15	5.607,69	3, 4
Centralized	100,0	Canadian	15	6.961,12	5

Table 3 - Inverters (Source: the author)

The datasheet of each inverter is attached in the end of this work, from attachments B to E.

- CABLES (DC AND AC)

The cables can be divided in two parts of the installation: the DC, before the inverter, and the AC, after the inverter. The diameter of the cables is dimensioned according to the nominal current that is going to pass through them. As the value of the current increases, the diameter of the cable will increase as well, otherwise it would reach high temperature and it would be damaged. The table 3, developed by the ABNT (Brazilian Association of Technical Norms), presents the section area of copper cables for different ranges of current. For electrical installations the minimum section area is 2,5 mm².

The material considered for the cables is the copper, because these are the most common types available in the market. The price of the cables is given in R$/meter, depending on the section area and it is listed in the table 4. Therefore, in the analysis of each topology the costs with cables will be different.

Nominal Sections [mm²]	Reference categories											
	A1		A2		B1		B2		C		D	
	Number of charged conductors											
	2	3	2	3	2	3	2	3	2	3	2	3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Copper											
0,5	7	7	7	7	9	8	9	8	10	9	12	10
0,75	9	9	9	9	11	10	11	10	13	11	15	12
1	11	10	11	10	14	12	13	12	15	14	18	15
1,5	14,5	13,5	14	13	17,5	15,5	16,5	15	19,5	17,5	22	18
2,5	19,5	18	18,5	17,5	24	21	23	20	27	24	29	24
4	26	24	25	23	32	28	30	27	36	32	38	31
6	34	31	32	29	41	36	38	34	46	41	47	39
10	46	42	43	39	57	50	52	46	63	57	63	52
16	61	56	57	52	76	68	69	62	85	76	81	67
25	80	73	75	68	101	89	90	80	112	96	104	86
35	99	89	92	83	125	110	111	99	138	119	125	103
50	119	108	110	99	151	134	133	118	168	144	148	122
70	151	136	139	125	192	171	168	149	213	184	183	151
95	182	164	167	150	232	207	201	179	258	223	216	179
120	210	188	192	172	269	239	232	206	299	259	246	203
150	240	216	219	196	309	275	265	236	344	299	278	230
185	273	245	248	223	353	314	300	268	392	341	312	258
240	321	286	291	261	415	370	351	313	461	403	361	297
300	367	328	334	298	477	426	401	358	530	464	408	336
400	438	390	398	355	571	510	477	425	634	557	478	394
500	502	447	456	406	656	587	545	486	729	642	540	445
630	578	514	526	467	758	678	626	559	843	743	614	506
800	669	593	609	540	881	788	723	645	978	865	700	577
1 000	767	679	698	618	1 012	906	827	738	1 125	996	792	652

Table 4 - Nominal section area of copper cables according to electrical current (Source: Norm 5410 from Brazilian Association of Technical Norms)

Section area [mm²]	***Maximum supported current [A]***	***Price per meter [R$]***	***Topologies***
2,5	24	1,24	1, 2, 3
4,00	32	2,42	3, 4

Table 5 – Prices of the cables per section area (Source: the author)

The cables of the DC and AC parts of the circuits will be selected according to the calculations of the current for each topology under the respective considerations and assumptions.

- **PROTECTION DEVICES**

The protection devices can also be divided between the DC and AC parts of the installation. The protection devices of the DC are the circuit breaker and the surge protection device, SPD, that must be placed inside a box called string box, which is illustrated in the following picture. The device on red, on the left part of the picture, is the SPD, and on the right there is the circuit breaker.

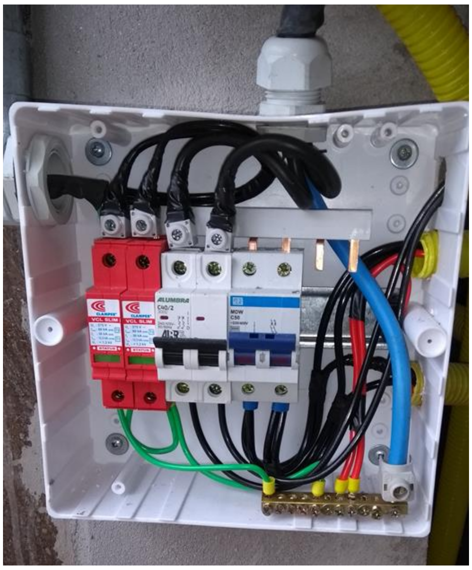

Figure 17 – String Box (Source: Solstar)

The installation of the string box is not mandatory according to the regulation of the power distribution companies, because they already protect their distribution grid with protection on the AC part of the circuit. However, the string box is very important to protect the DC circuit and it is good practice to install it.

The string boxes are sold with the disconnection switch and the SPD inside of them. Even though the dimensioning of one system is different of another, the string boxes for residential installations have practically the same cost, which, according to (Solstar, 2019), is R$ 400,00.

The protection devices of the AC part are the circuit breaker and the SPD, which are installed on the electrical switchboard of the house. The SDP selected is the same for all topologies, because it can withstand a current of 40 kA. The circuit breaker selection depends on the current in which they will operate, which is going to be calculated from topology to topology. The following table presents all the prices, nominal currents and applications of each protection device.

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Device	Nominal current supported [A]	Price per unit	Topologies
AC Circuit breaker	10	10,00	1, 2
AC Circuit breaker	16	12	3, 4
AC Circuit breaker	32	13	3, 4
SPD	40.000	120,00	All

Table 6 - Price of circuit breaker per supported current and SPD cost (Source: Solstar)

- **STRUCTURE AND FIXATION COSTS**

These costs are related to the material required to fixate the PV modules on the roofs. For residential purposes, which is the case of this thesis, the kits are designed and sold for 2 and 4 PV modules. In these kits, all the necessary components required to install the PV modules on the roofs are included, such the fixation rails, the rail’s junctions and the bolts and nuts. The Figure 18 below illustrates these structures, and the table 7 below summarizes its prices.

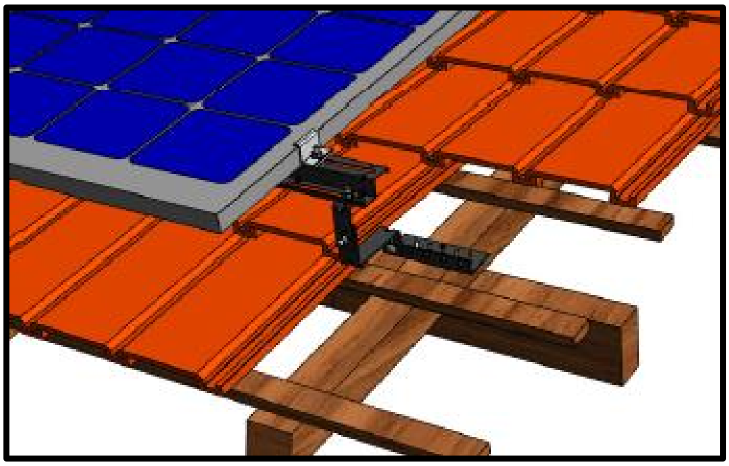

Figure 18 – Structure to support PV modules on rooftops (Source: SPIN Metalúrgica)

Structure type	PV modules	Price per structure [R$]
Rooftop	2	289,00
Rooftop	4	486,00

Table 7 - Costs of fixation structures (Source: Solstar)

- **ENERGY METERS**

After the installation of the photovoltaic systems on the residences, they became small energy generators and will inject energy into the grid. For this reason, it is necessary to substitute the unidirectional meters for bidirectional ones, so it will be possible to measure the energy flow that enters and exits the residences.

The Solstar does not work with energy meters, therefore the company cannot provide this price. So, a price quotation was performed with a Brazilian company called Salfatis, which presented a proposal of R$ 291,00 for a biphasic bidirectional energy meter. Therefore, this is for the energy meter used in the following analysis.

- **LABOR COSTS**

Finally, the last cost is related to the labor of the installation teams. This job can be performed by a team regularly hired by the company or it can be performed by an outsourced service. In this case study, the costs of outsourced services are going to be used.

After a few years acting in the photovoltaic systems installation, the Solstar developed a ratio in R$/kWp of the labor costs related to the installation. The following graphic, kindly provided by the company, presents the values.

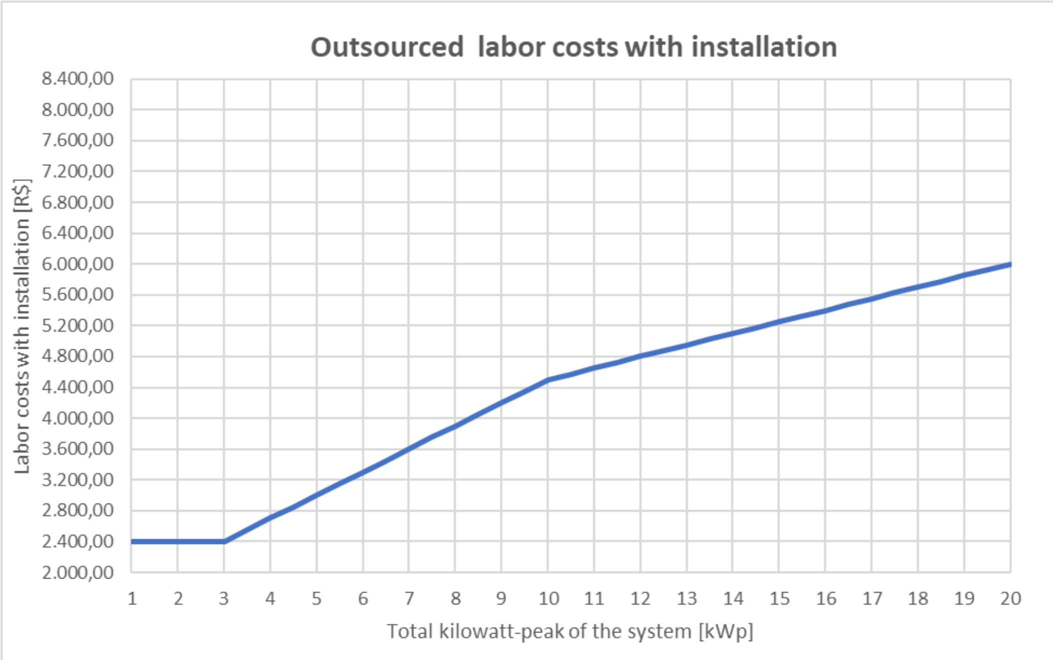

Figure 19 – Outsourced labor costs with installation (Solstar, 2019)

During the analysis of each topology, if the kilowatt-peak of a certain system is greater than 20 kWp, an extrapolation of the graphic above will be done to match the value.

Besides it, the Solstar only performed projects using centralized inverters, thus the graphic above considers only this certain type of installation. However, the installation with microinverters is much easier and fast, therefore, in the topologies that use microinverters, a multiplying factor of 0,9 is going to be applied to the cost obtained through the Figure 19.

Finally, it is important to point out that once again that all these prices and costs were based on the operation of small company collected in a certain date.

5.3) Calculation of the expected production

The calculation of the expected energy production can be performed in simpler or more refined ways. This depends on the data available to make calculus and also the accuracy required.

In this thesis, the following expression was used to calculate the expected production. (SPERTINO, 2016)

$$E_{AC} = H_g \, . S_{PV} \, . \eta_{STC} \, . PR \qquad (8)$$

Where:

E_{AC}: energy productivity;

H_g: global in-plane irradiation (kWh/m²) per day, month or year;

S_{PV}: total area of the PV generator;

η_{STC}: rated efficiency of PV modules (at STC);

PR: performance ratio.

In Brazil, one of the best measurements of the global irradiation is provided by the CRESESB, the Reference Centre of Solar and Eolic Energies. They provide the daily global irradiation of the typical day of each month in the horizontal plane, in the plane with inclination equal to the latitude and the plane with the maximum annual average of several localities in Brazil.

In this case study, the global irradiation adopted was from the city of Guarulhos (geographical coordinates 23,450293º S and 46,524326º W), because it is the one that concentrated the major part of the residences of the EDP São Paulo project. The following table presents all the data:

Angle	***Inclination***	***Daily solar irradiance by the monthly average [kWh/(m².day)]***												
		Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Average***
Horizontal plane	0º N	5,25	5,55	4,79	4,26	3,46	3,25	3,34	4,31	4,31	4,79	5,11	5,71	4,511
Angle equal to latitude	23º N	4,78	5,31	4,93	4,83	4,27	4,22	4,22	5,12	4,58	4,68	4,71	5,10	4,729
Highest annual average	21º N	4,84	5,35	4,94	4,80	4,22	4,15	4,17	5,07	4,58	4,71	4,76	5,17	4,730

Table 8 - Global irradiation for different inclinations in the city of Guarulhos (CRESESB, 2019)

For the topologies with PV modules installed on the roof of the residences will be considered the irradiance of the horizontal plane, because in many cases is not possible to control the azimuth of the panels and the roofs may not be strong enough to support the weight of a structure to tilt the modules. For the topologies with solar farm, it is possible to place the modules in the position where they will receive the highest irradiance, thus with the best azimuth angle and inclination equal to 21º.

The area of the PV generator is the sum of the areas useful to transform the irradiance into electrical energy of all the PV modules in the considered topology.

The rated efficiency of the modules measures their capacity to transform the energy from irradiation of the Sun into electrical energy. As presented in the previous section, the rated efficiency of the selected modules is 17,2%.

Finally, the last factor is the performance ratio. The PR is an indicator used to judge the performance of grid connected PV plants, that ranges from 0 to 1. According to (Khalid, Mitra, Warmuth, & Schacht, 2016), the PR is the proportion of energy that is actually available to be used in the residence or exported to the grid minus the lost due to environmental factors and the energy consumed in the operation process. The PR can be calculated through the following expression:

$$PR = \eta_{deg} \cdot \eta_{tem} \cdot \eta_{soil} \cdot \eta_{net} \cdot \eta_{inv} \cdot \eta_{tran} \cdot \eta_{ppc} \qquad (9)$$

This expression states that the PR can be seen as the product of various loss factors. The η signifies the efficiency of the following factors, in order as in the expression 8: module degradation, temperature, soiling, DC wiring and interconnection losses, inverter losses, transmission losses, and availability and grid connection losses.

So, the PR of a system is quite complex to calculate, once it depends on several factors. However, since the objective of this thesis is not to calculate the exactly value of PR, it is possible to assume a conservative, but real value. According to (Khalid, Mitra, Warmuth, & Schacht, 2016), some studies were conducted to measure the PR in France, Belgium, Taiwan and Germany. The average PR of each locality, respectively, was: 0.76, 0.78, 0.74 and 0.84. In addition, the European PV Guidelines states that a good value of PR ranges between 0.80 and 0.85, and values below 0.75 indicates a problem.

In this case study there are clearly two different places where the modules are going to be placed: the roofs of the residences, which are not are not a very stable and where is not possible to control the azimuth and tilt angles of the PV modules, and the floor of the solar farms, which are very stable and where is possible to control the azimuth and tilt angles of the PV modules to obtain the maximum values of irradiance. Having all this taken into consideration, the PR considered for topologies with PV modules installed on the roof is 0,7, and the PR considered for topologies with PV modules installed on solar farms is 0,85.

As presented in the equation 9, the PR takes into consideration the DC wiring losses, but does not take into consideration the AC wiring losses. In the analysis of the residential topologies, 1 to 4, the AC wiring losses were considered negligible because the circuits are small. For the topology 5, the AC losses are very considerable, but the approach to calculate the CBR is different, so the AC losses will not affect the analysis.

The last point to be taken into consideration is the PV module's life span and how their performance gets worse with the time. According to the attachment A, the life span of the selected PV module is 25 years and its output power decreases linearly from 100% of the nominal power on the first year to 80% of the nominal power on the 25th year. Since the energy production is directly proportional to the output power, the same linear reduction was applied to the expected energy production of the PV modules.

The following tables present the values of the expected production of the selected solar panels placed on the rooftop of the residences, which corresponds to topologies 1 to 4, and the values of the expected production of the selected solar panels placed on the floor of solar farms, which corresponds to topologies 5 and 6.

Period	***Expected production of rooftops installations [kWh]***
January	38,16
February	36,44
March	34,82
April	29,97
May	25,15
June	22,86
July	24,28
August	31,33
September	30,32
October	34,82
November	35,95
December	41,51
First year	***385,62***

Table 9 - Expected production of rooftop installations per selected PV module on the first year (Source: the author)

Year	Expected production [kWh]	Year	Expected production [kWh]	Year	Expected production [kWh]
1	385,62	10	356,70	19	327,78
2	382,41	11	353,49	20	324,57
3	379,20	12	350,27	21	321,35
4	375,98	13	347,06	22	318,14
5	372,77	14	343,85	23	314,93
6	369,56	15	340,63	24	311,71
7	366,34	16	337,42	25	308,50
8	363,13	17	334,21		
9	359,92	18	330,99		

Table 10 - Expected production of rooftop installations per selected PV module over the 25 years life span (Source: the author)

Period	Expected production of solar farms installations
January	42,72
February	42,66
March	43,61
April	41,00
May	37,25
June	35,45
July	36,81
August	44,75
September	39,12
October	41,58
November	40,66
December	45,64
First year	***491,26***

Table 11 - Expected production of solar farm installations per selected PV module on the first year (Source: the author)

Year	Expected production [kWh]	Year	Expected production [kWh]	Year	Expected production [kWh]
1	491,26	10	454,41	19	417,57
2	487,16	11	450,32	20	413,47
3	483,07	12	446,22	21	409,38
4	478,97	13	442,13	22	405,29
5	474,88	14	438,04	23	401,19
6	470,79	15	433,94	24	397,10
7	466,69	16	429,85	25	393,01
8	462,60	17	425,76		
9	458,51	18	421,66		

Table 12 - Expected production of solar farm installations per selected PV module over the 25 years life span (Source: the author)

In the analysis of each topology, the average annual production during the 25 years of life span of the PV modules was considered. Therefore, for PV modules installed on rooftops, the considered annual energy production is 347,06 kWh, and for PV modules installed on solar farms, the considered annual energy production is 442,13 kWh.

5.4) Analysis of each topology

The objective in this section is to calculate the RCB of each topology. From section 2.3.1.1), is obtained by the division of the annualized costs by the annualized benefits. The annualized costs of each topology are calculated depending on the application, price, quantity and life span of all the equipment and labor.

The annualized benefits depend on the avoided energy and on the reduction of the demand. In the cases of photovoltaic systems, there is no reduction of the demand because the people's consuming habits and the electrical equipment used inside the residences are the same as before the project. Therefore, the annualized benefits depend only on the saved energy that the power distribution companies would have to provide to the houses.

The saved energy depends on the number of PV panels installed on each topology, which changes slightly among each one of them. However, the avoided cost of energy, given in R$/MWh, is the same for all topologies. For this reason, this value is calculated in the section 5.4.1), to be used in the analysis of each topology.

However, for the topologies which CBR do not reach the minimum accepted value, a solution will be proposed. The CBR of projects that substitute fluorescent lamps for LED lamps is very low, and it is very common practice among the power distribution companies to make a combined project of lamps something else. Thus, for the topologies that do not reach the accepted value of CBR, a combined project with lamp substitution will be evaluated.

In these situations, besides the avoided energy, there is also the reduction of demand in kW. The reduction of demand also has a coefficient, the avoided cost of demand (R$/kW), that is the same for all topologies and is calculated in the section 5.4.1).

Then, starting from the section 5.4.2), the analysis of each topology is going to be performed, accordingly to the equations presented in the section 2.3.1.1), that come from the ANEEL's manuals.

5.4.1) Avoided cost of energy and avoided cost of demand

The avoided cost of energy can be calculated from the system's perspective or from the consumer's perspective. The ACE calculated from the consumer's perspective is used for stimulated energy sources and the ACE calculated from the system's perspective is used for all the other projects. (ANEEL's Elaboration Manual of PEE, 2010).

The avoided cost of demand is calculated always from the system's perspective. In the following, each one of them is calculated.

- **ACE from the consumer's perspective**

The ACE from the consumer's perspective considers how much the consumer saves per kWh produced by the stimulated energy source. This value will be proportional to amount of energy he no longer uses from the distribution grid, which was charged by the electricity tariff.

Then, it is intuitive to think that the ACE from the consumer's perspective is equal to the electricity tariff, but it is not. When a residence uses the energy instantaneously produced by the photovoltaic system, it does not have the necessity to consume the energy from the grid, therefore it is avoided the cost proportional the electricity tariff.

However, when a residence uses the energy from the distribution grid, that was previously injected by the photovoltaic system, the scenario changes. The tax aliquot of the energy consumed from the grid is greater than the tax aliquot of the energy injected to grid. In simpler words, it means that the value of the energy that the consumer buys from the grid is greater than the value of the energy that the consumer "sells" to the grid.

The Brazilian electricity tariff is divided in two components: the energy tariff and system usage and distribution tariff, both proportional to the kWh. The electricity tariff can be used in two modalities. In the first one, the tariff's value is constant in all the periods of the day. In the second one, it varies according to the moment in which the energy is used, being more expensive in the peak-hours of the system. The majority of Brazilian population uses the first modality, because the second one is relatively new. The following table presents the electricity tariff for the first modality.

Component	***Price [R$/kWh]***
Energy tariff	0,31979
System usage and distribution tariff	0,24174
Total tariff without taxes	0,56153

Table 13 – EDP São Paulo electricity tariff (Source: ANEEL)

From these values, it is necessary to apply the social tariff, in order to verify what is the average electricity tariff of the low-income communities. The methodology used was to verify what portion of the energy consumption of the residences of the community is between 0 and 30 kWh, between 31 and 100 kWh, between 101 and 220 kWh, and the portion greater than 220 kWh. In order to do that, it was used a classified data provided from the EDP São Paulo about its consumers. Even though it is not allowed to present the data of each consumer individually, it is possible to present the present the portion of consumption for each range of value.

Each residence consumed an average of 142,05 kWh/month, which means that the all study group consumed 17.752,75 kWh/month. Analyzing individually the consumption of each residence, the following is obtained.

Portion of the consumption	***Consumption [kWh]***	***Applicable tariff [R$/kWh]***	***Cost [R$]***
Between 0 and 30 kWh	3.712,06	0,19654	729,5506946
Between 31 and 100 kWh	7.238,04	0,33692	2438,626944
Between 101 and 220 kWh	5.087,33	0,50538	2571,021055
Greater than 220 kWh	1.715,32	0,56153	963,204766

Table 14 – Portions of the energy consumption of low-income community (Source: EDP São Paulo)

In order to find the average electricity tariff for the low-residences, we only need to divide the sum of column “Cost” by the sum of column “Consumption”, obtaining 0,37754 R$/kWh. To the value of this tariff is necessary to add the aliquot of taxes, which is given by the table 15.

Tax	*Aliquot [%]*
ICMS	25,00%
PIS	1,05%
COFINS	4,83%
Others	4,41%

Table 15 - Aliquot of taxes (Source: EDP São Paulo)

Then, the value of tariff considering the aliquot of taxes is 0,5835 R$/kWh. However, as said previously in this section, the value of the energy injected does not consider one of the taxes, the ICMS. For this reason, the value of the energy injected is 0,4208 R$/kWh.

Therefore, in order to find the ACE from the consumer’s perspective is necessary to make a weight average of these two values. A study performed by the ANEEL found that 38,92% of the energy generated by the system is consumed instantaneously and the other 61,08% (ANEEL's Regulamentory Impact Analysis Report, 2018). By doing the calculation, the value of the ACE from the consumer’s perspective is 0,4841 R$/kWh. This percentual were considered for one house with the photovoltaic system installation, therefore this value is valid for topologies 1, 2 and 3.

However, the topology 4 was designed to have the photovoltaic system installed in one residence, injecting energy into the grid to be used by the other residences. Thus, for this topology, the ACE_{cons} assumes a different value. For the topology’s 4 project with two residences, the amount of energy consumed instantaneously is half of the regular case, i.e., 19,46%, and the other 80,54% is consumed indirectly. Thus, the ACE_{cons} for the topology 4 with two residences is 0,4525 R$/kWh.

In the topology 4 with four residences, the amount of energy consumed instantaneously is one quarter of the regular case, i.e., 9,73%, and the other 90,27% is consumed indirectly. Thus, the ACE_{cons} for the topology 4 with four residences is 0,4367 R$/kWh.

In the topology 5, there is no instantaneous consumption of energy. Therefore, the ACE_{cons} is 0,4208 R$/kWh.

- **ACE from the system's perspective**

The ACE from the system's perspective is calculated by the following expression:

$$ACE_{sys} = \frac{ET_{ph}.ELC_{ph} + ET_{rh}.ELC_{rh}}{ELC_{ph} + ELC_{rh}} \quad (10)$$

Where:

- ET_{ph}: energy tariff of the power distribution company at peak-hours.
- ET_{rh}: energy tariff of the power distribution company at regular-hours.
- ELC_{ph}: energy loss coefficient at peak-hours.
- ELC_{rh}: energy loss coefficient at regular-hours.

As it is possible to see, in this case it is used the second methodology of for the electricity tariff, which takes into consideration the moment in which the energy is consumed. The energy tariff values are the ones currently used by the EDP São Paulo and energy loss coefficients are provided by the ANEEL. The following table summarizes all these values and also the calculated of the ACE, which was used in all topologies to calculate the annualized benefits.

	Value	*Unit*
ET_{ph}	0,39555	R$/kWh
ET_{rh}	0,15273	R$/kWh
h_p	765	hour
h_r	7.995	hour
LC	0,75	Adimensional
RDC_{rh}	0,5929	Adimensional
ACE_{sys}	0,2778	R$/kWh

Table 16 – Avoided cost of energy from the system's perspective (Source: the EDP São Paulo)

- **ACD**

The avoided cost of demand is calculated by the following expression:

$$ACD = \left(SUDT_{ph} \,.\, h_p \,.\, LF\right) + \left(SUDT_{rh} \,.\, h_r \,.\, LF \,.\, RDC_{rh}\right) \qquad (11)$$

Where:

- $SUDT_{ph}$: system usage and distribution tariff of the power distribution company at peak-hours.
- $SUDT_{rh}$: system usage and distribution tariff of the power distribution company at regular-hours.
- $h_{p:}$ number of peak hours in a year.
- $h_{r:}$ number of regular hours in a year.
- LC: average load factor of the electrical system of the power distribution company.
- RDC_{rh}: reduction of demand constant in regular hours.

The following table summarizes all these values:

	Value	*Unit*
$SUDT_{ph}$	0,39555	R$/kWh
$SUDT_{rh}$	0,15273	R$/kWh
h_p	765	hour
h_r	7.995	hour
LC	0,75	Adimensional
RDC_{rh}	0,5929	Adimensional
ACD	769,93	R$/kW

Table 17 – Avoided cost of demand (Source: EDP São Paulo)

The system usage and distribution tariffs were provided by the EDP São Paulo, the number of hours in peak hour and regular hours follow the Brazilian nomenclature, the load factor was provided and the reduction of demand constant in regular hours were provided by the EDP São Paulo as well.

5.4.2) Analysis of the topology 1

The first topology, defined in the section 4.1), consists in one photovoltaic system installed in each residence using centralized inverter. The first step of the analysis is to calculate the number of PV modules installed in each residence. In order to do that, the average annual consumption of one residence was divided by the average annual energy production of one PV module over its life time, presented in section 5.3). By doing that, the number of PV panels found was 4,91. Even though this number is much closer to 5 than it is 4, the number of PV modules adopted is 4, because this topology does not consider a possible surplus of energy in reach residence.

The peak power obtained with 4 PV modules of the selected type, that has 335 Wp, gives a total of 1,34 kWp for the all system. The inverter with closest value of power has 1,5 kW, presented in table 3. (Attachment B).

Usually, for systems with only 4 PV modules, the connection in series is adopted. For this reason, the nominal direct current is equal to the nominal current of the PV module, which is 9,35 A, presented in the attachment A. The cable with the smallest section area cable to support this current is the one with 2,5 mm², according to tables 4 and 5. For what concerns the protection devices of the DC part, one string box is going to be used in each installation, as properly explained in the section 5.2).

The alternate current is calculated dividing the maximum power enabled by the inverter by the operation voltage of the residence. So, in this case, the AC obtained is 6,09 A. Thus, it is possible to use the same cable of 2,5 mm² of the DC part of the circuit. The protection devices selected to be installed in the AC part of the circuit are the circuit breaker of 10 A of nominal current and the SPD of 40 kA. The length of cables considered was 100 meters, divided in 50 meters for the DC circuit and 50 meters for the AC circuit.

The fixation and structure considered is the one for 4 PV modules placed on the rooftop, according to table 7. The energy meter is the same for all topologies, as explained in the previous section. And finally, according to the Figure 19, the labor costs for a system of 1,34 kWp is R$ 2.400,00.

The following table summarizes all this information and the calculus of the annualized benefits.

Annualized costs - Topology 1									
Component	**Category**	**Quantity per project**	**Total quantity**	**Price per unit [R$]**	**Life span [years]**	**CRF**	**CE equip [R$]**	**CPE equip [R$]**	**AC equip [R$]**
PV modules	Equipment	4	40.000	456,42	25	0,094	18.256.800,00	34.429.511,23	3.225.314,58
Inverter	Equipment	1	10.000	2.499,00	15	0,117	24.990.000,00	47.127.288,77	5.505.859,70
Cables	Others	100	1.000.000	1,24			1.240.000,00		0,00
String box	Others	1	10.000	400,00			4.000.000,00		0,00
SPD	Others	1	10.000	120,00			1.200.000,00		0,00
Circuit breaker	Others	1	10.000	10,00			100.000,00		0,00
Structure	Others	1	10.000	486,00			4.860.000,00		0,00
Energy meter	Others	1	10.000	291,00			2.910.000,00		0,00
Labor costs	Installation	1	10.000	2.400,00			24.000.000,00		0,00
Total							81.556.800,00	81.556.800,00	**8.731.174,28**

Table 18 - Annualized costs of Topology 1 (Source: the author)

The cable's quantity per project is given in meters and so its price per unit. The labor costs quantity per project is given by installation, considering that each residence represents one installation, and 10 thousand installations were considered, one for each residence of the community.

From the table 18 above, it is possible to notice that all the costs of the project were proportionally included in the cost of equipment and then annualized over the life span of each equipment. Finally, the annualized cost of the topology found was R$ 8.731.174,28.

The annualized benefits are multiplying the total energy production provided by the PV modules by the ACE from the consumer's perspective, which presented in the table 19.

Annualized benefits - Topology 1	
Energy production of 1 PV module [kWh/year]	347,06
Total energy production [kWh/year]	13.882.446,90
ACE_{cons} [R$/kWh]	0,4841
Annualized benefits [R$]	**6.720.492,54**

Table 19 - Annualized benefits of Topology 1 (Source: the author)

The CBR is given by the division of the annualized costs by the annualized benefits. Therefore, in this case, the RCB calculated is 1,30. This value is greater than the maximum accepted value, which is 1,0 and, for this reason, the project of this topology could not be financed using the financial resources of the EEP. For this reason, it was performed the analysis combining the photovoltaic system to substitution of lamps.

5.4.2.1) Analysis of the topology 1 with substitution of lamps

In the lamp substitution projects performed previously by the EDP São Paulo, the RCB found was around 0,11, which is way smaller than the maximum accepted value of RCB required by the ANEEL to finance the EEP projects. The analysis performed in this section was based in the methodology and information collected by a project the EDP São Paulo performed in the same low-income community presented in the section 5.1).

The first step is to quantify how many lamps would be substituted. According to the project performed by the EDP São Paulo, on average the low-income communities have 1,5 lamps in the living room, 2 lamps in the bedrooms, 1 lamp in the bathroom and 1,5 lamps in the kitchen. The most common type of lamp found was fluorescent with nominal power of 45 W, considering also the reactor.

According to the EDP São Paulo, each one of the lamps works for 1.460 hour per year, but each one presents a different factor of coincidence of peak-hours. This factor expresses the amount time that each lamp is working during the peak hours of the electrical system and it is indispensable in order to calculate the reduction of demand in peak hours. These values are presented in the table 20 below.

Current system					
	Living room	***Bedroom***	***Bathroom***	***Kitchen***	***Total***
Nominal power (lamp + reactor) [W]	45	45	45	45	
Total quantity	10.000	20.000	10.000	10.000	50.000
Installed power [kW]	450	900	450	450	2.250
Opertion time [hours]	1.460	1.460	1.460	1.460	
Coincidence in peak hours factor	0,5	0,2	0,2	0,4	
Energy consumed [MWh/year]	657	1.314	657	657	3.285
Average demand on peak hours [kW]	225	180	90	180	675

Table 20 - Characteristics of the current illumination system of the community (Source: the author)

The proposed lamp to substitute the current one is made of LED, it has the nominal power of 10 W and the considered price was R$ 9,50, taking the average price of a few retail stores, and its life span is 17 years. The following table summarizes the characteristics of the proposed illumination system considering the substitution of the lamps.

Proposed system					
	Living room	***Bedroom***	***Bathroom***	***Kitchen***	***Total***
Nominal power (lamp + reactor) [W]	10	10	10	10	
Total quantity	10.000	20.000	10.000	10.000	50.000
Installed power [kW]	100	200	100	100	500
Opertion time [hours]	1.460	1.460	1.460	1.460	
Coincidence in peak hours factor	0,5	0,2	0,2	0,4	
Energy consumed [MWh/year]	146	292	146	146	730
Average demand on peak hours [kW]	50	40	20	40	150

Table 21 - Characteristics of the proposed illumination system of the community (Source: the author)

Therefore, it is possible to verify that the reduction of demand in peak hours from the current system to the proposed one is 682,5 kW, and that the energy saved using the proposed system instead of the current system is 3.066 MWh/year. Considering the values of ACD and ACE_{sys}, which are 769,93 R$/kW and 0,2778 R$/kWh respectively, it is possible to calculate the annualized benefits of the lamps using the equation 6, obtaining R$ 1.377.211,30.

To the value of the annualized benefits of the lamps is added the annualized benefits of the photovoltaic system of the topology 1, which are R$ 6.513.644,09, as presented in table 19, totalizing the annual benefits of R$ 7.890.855,39.

In order to calculate the annualized costs of the system, the same methodology as the one performed in the previous section was used. It was added the cost of lamps, but the labor costs remained the same as before, because the marginal cost to substitute a few lamps when the installation team is already there is practically zero. The annualized costs are presented in the table 22.

The CBR for this situation, found by the division of the annualized costs by the annualized benefits, is 1,07. The maximum value of CBR is no longer 1,0, it is 0,8 instead, because only projects of stimulated energy sources could go up 1,0. Therefore, the effects of adding lamps in the projects were reduced, because previously the distance between the CBR found and the accepted value was 0,30, and now, in the alternative project adding the lamps, the distance between the CBR found and the accepted value is 0,27, almost the same.

Annualized costs - Topology 1 with substitution of lamps									
Component	*Category*	*Quantity per project*	*Total quantity*	*Price per unit [R$]*	*Life span [years]*	*CRF*	*CE equip [R$]*	*CPE equip [R$]*	*AC equip [R$]*
PV modules	Equipment	4	40.000	456,42	25	0,094	18.256.800,00	34.219.125,14	3.205.605,86
Inverter	Equipment	1	10.000	2.499,00	15	0,117	24.990.000,00	46.839.311,22	5.472.215,42
Cables	Others	100	1.000.000	1,24			1.240.000,00		0,00
String box	Others	1	10.000	400,00			4.000.000,00		0,00
SPD	Others	1	10.000	120,00			1.200.000,00		0,00
Circuit breaker	Others	1	10.000	10,00			100.000,00		0,00
Structure	Others	1	10.000	486,00			4.860.000,00		0,00
Energy meter	Others	1	10.000	291,00			2.910.000,00		0,00
Labor costs	Installation	1	10.000	2.400,00			24.000.000,00		0,00
Lamps	Equipment	6	60.000	9,50	17	0,110	570.000,00	1.068.363,64	117.124,10
Total							82.126.800,00	82.126.800,00	8.794.945,38

Table 22 – Annualized costs of Topology 1 considering the substitution of lamps (Source: the author)

5.4.3) Analysis of the topology 2

The topology 2 was defined in the section 4.2) and consists in one photovoltaic system installed in each residence using microinverters. This topology is practically equal to the topology 1, changing only the centralized inverter for microinverters.

To define the number of PV modules used, the same procedure used for topology 1 was adopted. The annual energy consumption of one residence was divided by the annual energy production of 1 PV module under rooftop conditions, which gives 4,91 PV modules. Therefore, just like in the topology 1, the number of PV modules adopted per residence is 4, because this topology was not designed to have any surplus of energy.

The microinverters selected were the ones with the lowest R$/kW, which characteristics are presented in table 3. This microinverter can support up to 4 PV modules and has a peak output power of 1 kW. Thus, in this topology, each 2 PV modules were connected to one microinverter. (Attachment C).

Since the direct current is transformed into alternate current directly on the PV modules, there is no necessity of having a string box and the amount of cables used in the DC part of the installation can be considered negligible.

However, for the AC part of the circuit is necessary to calculate the nominal current. As done in the topology 1, it was considered that the 4 PV modules were connected in series. Thus, the nominal alternate current of this topology is given by the division of the maximum power, 1,34 kW, by the voltage of the residence, 220 V, which gives the same AC of the topology, 6,09 A. Therefore, the same circuit breaker and cable's section area were selected, considering also that the required length of cables is 100 meters per residence.

The fixation and structure considered is the one for 4 PV modules placed on the rooftop, according to table 7. The energy meter is the same for all topologies, as explained in the section 5.2).

For what concerns the labor costs, the system has a peak-power of 1,34 kWp, which, according to the Figure 19, would mean a cost of R$ 2.400,00. However, as properly explained in the section 5.2), subsection "Labor costs", the labor costs of microinverters are smaller because they are easier to install. Thus, the multiplying factor is applied to the value found in the Figure 19, for the given conditions. So, the labor costs considered are R$ 2.140,00.

The following table summarizes all this information and the calculus of the annualized benefits.

Annualized costs - Topology 2									
Component	***Category***	***Quantity per project***	***Total quantity***	***Price per unit [R$]***	***Life span [years]***	***CRF***	***CE equip [R$]***	***CPE equip [R$]***	***AC equip [R$]***
PV modules	Equipment	4	40.000	456,42	25	0,094	18.256.800,00	26.794.341,15	2.510.061,16
Inverter	Equipment	2	20.000	2.499,00	15	0,117	49.980.000,00	73.352.458,85	8.569.734,39
Cables	Others	100	1.000.000	1,24			1.240.000,00		0,00
String box	Others	0	0	400,00			0,00		0,00
SPD	Others	1	10.000	120,00			1.200.000,00		0,00
Circuit breaker	Others	1	10.000	10,00			100.000,00		0,00
Structure	Others	1	10.000	486,00			4.860.000,00		0,00
Energy meter	Others	1	10.000	291,00			2.910.000,00		0,00
Labor costs	Installation	1	10.000	2.160,00			21.600.000,00		0,00
Total							100.146.800,00	100.146.800,00	**11.079.795,55**

Table 23 - Annualized costs of Topology 2 (Source: the author)

In comparison to the topology 1, it is possible to notice that the labor costs have reduced, and the string box costs became zero. However, the inverter costs have increased significantly and the total annualized cost of the topology 2 is greater than the annualized cost of the topology 1.

Since the quantity of PV modules is the same as the topology 1 and they will operate at the same conditions, the annualized benefits of the topology 2 are exactly equal to the annualized benefits of topology 1, as presented by the following table.

Annualized benefits - Topology 2	
Energy production of 1 PV module [kWh/year]	347,06
Total energy production [kWh/year]	13.882.446,90
ACE_{cons} [R$/kWh]	0,4841
Annualized benefits [R$]	**6.720.492,54**

Table 24 - Annualized benefits of Topology 2 (Source: the author)

The CBR is calculated dividing the annualized costs by the annualized benefits. Thus, for the topology 2, the calculated CBR is 1,65. Since this value is greater than the maximum accepted value, which is 0,8, this topology cannot be financed using the financial resources of the EEP.

For this topology, the alternative project of adding lamps will not be performed, because the CBR found for the photovoltaic system of this topology is greater than the one found for the topology 1. Thus, since adding lamps to the topology 1 did not work, it would not word for topology 2 as well.

5.4.4) Analysis of the topology 3

The topology 3 was defined in the section 4.3) and involves more than one residence in one project. It consists in placing the PV modules on the rooftops of each one of the residences and use a larger centralized inverter, because it would reduce costs.

Therefore, the quantity of PV modules and the centralized inverter used depends on the number of residences per project. So, two scenarios were considered: a project with 2 residences and other with 4 residences.

5.4.4.1) Analysis of the topology 3 with two residences per project

The average annual energy consumption of two residences is 3.408,48 kWh. The average annual energy production of the selected PV module during its life span is 347,06 kWh. Thus, the quantity of PV modules required to supply energy for the two residences would be 9,82. However, in the same way as happened in the topologies 1 and 2, this topology was not designed to have any surplus of energy as well. So, for each project was considered 9 PV modules.

The selected PV module has 0,335 kWp, so the total project has 3,015 kWp. The centralized inverter with closest nominal power to match this value is the one with 3 kW that, according to table 3, costs R$ 3.868,33 per unit (Attachment B). Even though the peak power of the PV modules being slightly greater than the inverter's nominal the power, it will not affect the system's operation because the difference is so small it can be considered negligible.

In order to calculate the direct current, it is necessary to define the PV modules configuration. Since the total number of PV modules is even, it is not possible to have an odd number of strings. However, the selected inverter can support up to 550 V of DC input voltage and each PV module has a voltage of 46,7 V. Therefore, it is possible to place them in the series configuration.

Thus, the nominal current is the same of the topologies 1 and 2, which is 9,35 A. For this reason, the section area of the selected cable of the DC part of the circuit is 2,5 mm², as explained in the Figure 4. Because there is only one inverter, there is the necessity of only string box.

For what concerns the AC part of the circuit, the alternate current is calculated dividing the nominal power of the inverter, 3,0 kW, by the operation voltage of the residence, 220 V. By doing this, the alternate current is 13,64 A. Thus, the circuit breaker selected supports up to 16 A, it costs R$ 12,00 per unit, as presented in table 5, and one unit was considered for each one of the two residences. The SPD is the same for all the topologies, that supports currents up to 40 kA and costs R$ 120,00, and one unit was considered for each one of the residences as well.

Still considering the AC part of the circuit, the cable with section area of 2,5 mm² was selected because it has the minimum section area required by Brazilian Association Technical Norms, that can support a current up to 24 A. Also, it was considered that each residence required 100 meters length of cable, half on the DC part and half on the AC part. So, since every two residences form a project, 200 meters were required per project.

The fixation and structure costs must support 9 PV modules. However, as presented in the table 7, there is not a possible combination that supports exactly this number. So, two structures of 4 PV modules and one structure of 2 PV modules were selected, with total cost of R$ 1.261,00.

Each residence requires one energy meter, because the energy can be injected by any of them, so it is 2 per project. Finally, the labor costs of a 3,0 kWp residential installation, according to Figure 19, is R$ 2.400,00 per project.

Since every two residences makes one project and there are 10 thousand residences, the total number of projects of this topology is 5 thousand. The following table presents the annualized costs.

Annualized costs - Topology 3 for two residences									
Component	***Category***	***Quantity per project***	***Total quantity***	***Price per unit [R$]***	***Life span [years]***	***CRF***	***CE equip [R$]***	***CPE equip [R$]***	***AC equip [R$]***
PV modules	Equipment	9	45.000	456,42	25	0,094	20.538.900,00	33.813.294,35	3.167.588,13
Inverter	Equipment	1	5.000	3.868,33	15	0,117	19.341.650,00	31.842.255,65	3.720.116,24
Cables	Others	200	1.000.000	1,24			1.240.000,00		0,00
String box	Others	1	5.000	400,00			2.000.000,00		0,00
SPD	Others	2	10.000	120,00			1.200.000,00		0,00
Circuit breaker	Others	2	10.000	12,00			120.000,00		0,00
Structure	Others	1	5.000	1.261,00			6.305.000,00		0,00
Energy meter	Others	2	10.000	291,00			2.910.000,00		0,00
Labor costs	Installation	1	5.000	2.400,00			12.000.000,00		0,00
Total							65.655.550,00	65.655.550,00	6.887.704,37

Table 25 - Annualized cost of Topology 3 for two residences (Source: the author)

The annualized benefits were calculated taking into consideration the energy production of the PV modules and the ACE_{cons}. The values are presented in the following table.

Annualized benefits - Topology 3 for two residences	
Energy production of 1 PV module [kWh/year]	347,06
Total energy production [kWh/year]	15.617.700,00
ACE_{cons} [R$/kWh]	0,4841
Annualized benefits [R$]	7.560.528,57

Table 26 - Annualized benefits of Topology 3 for two residences (Source: the author)

The CBR can be find dividing the annualized costs by the annualized benefits and for this topology, the CBR found is 0,91. Because this value smaller than 1,0, this project could be financed using the financial resources of the EEP.

5.4.4.2) Analysis of the topology 3 with four residences per project

Other configuration evaluated is the one with four residences per project. The average annual energy consumption of the four residences together is 6.816,96 kWh. Since each selected PV module produces 347,06 kWh per year under the rooftop conditions, it would be required 19,64 PV modules per projects. However, since the topology was not designed to have any surplus of energy, 19 PV modules were considered.

The total power of these PV modules is 6,37 kWp. The inverter selected should have the nominal power slightly greater than this value, because it would be able to operate at the maximum value that the PV modules can provide and is the least expensive solution.

However, the available options on the Brazilian market are the inverter of 6 kW, that costs R$ 5.607,69, and the inverter of 8,2 kW, that costs R$ 6.691,12, as presented in table 3. For this reason, the 6 kW is still the best solution, considering also that the inverts can operate well with a little overload. Therefore, the inverter selected is the one of nominal power of 6 kW. (Attachment D).

Since there is only one inverter, there is the necessity of only one string box. In order to define the direct current of the system to select which cable to use, it is necessary to choose the PV module's configuration. Since 19 is a prime number, it is only possible to place them in a series configuration, which is supported by the selected inverter. So, since there is only one string, the direct current is the equal to nominal current of each PV module, which is 9,35 A. In the same way as all the previous topologies, the cable with the minimal section area that can support this current and it is allowed by the Brazilian Association of Technical Norms is the one with 2,5 mm².

For what concerns the AC part of the circuit, the alternate current is calculated dividing the inverter's nominal power, 6,0 kW, by the operating voltage of the residence, which is 220 V, obtaining 27,27 A. The cable with minimum section area capable to support this current is the one with 4 mm², according to table 4, that costs R$ 2,42 per meter (tables 4 and 5). The total cable's length considered is still 100 meters per residence, being 50 meters on the DC part and 50 meters on the AC part.

The protection devices of the AC part of circuit are the SPD, that can support up to 40 kA, and the circuit breaker of 32 A, that are installed on the electrical switchboard of one of the four residences.

The fixation and structure costs must support 19 PV modules. However, as presented in the table 7, there is not a possible combination that supports exactly this number. So, five structures of 4 PV modules were selected, considering that space is not a problem, and one of the residences could place two structures.

Because the surplus of energy could be injected from any of the residences, it is required to change all four energy meters. The labor costs of a system with 6,37 kWp, according to the Figure 19, are R$ 3.400,00.

Finally, since every four residences makes one project and there are 10 thousand residences, the total number of projects of this topology is 2,5 thousand. The following table presents the annualized costs.

Annualized costs - Topology 3 for four residences									
Component	***Category***	***Quantity per project***	***Total quantity***	***Price per unit [R$]***	***Life span [years]***	***CRF***	***CE equip [R$]***	***CPE equip [R$]***	***AC equip [R$]***
PV modules	Equipment	19	47.500	456,42	25	0,094	21.679.950,00	34.824.862,11	3.262.350,56
Inverter	Equipment	1	2.500	5.607,69	15	0,117	14.019.225,00	22.519.312,89	2.630.921,08
Cables [2,5 mm²]	Others	200	500.000	1,24			620.000,00		0,00
Cables [4,0 mm²]	Others	200	500.000	2,42			1.210.000,00		0,00
String box	Others	1	2.500	400,00			1.000.000,00		0,00
SPD	Others	4	10.000	120,00			1.200.000,00		0,00
Circuit breaker	Others	4	10.000	13,00			130.000,00		0,00
Structure	Others	1	2.500	2.430,00			6.075.000,00		0,00
Energy meter	Others	4	10.000	291,00			2.910.000,00		0,00
Labor costs	Installation	1	2.500	3.400,00			8.500.000,00		0,00
Total							57.344.175,00	57.344.175,00	5.893.271,64

Table 27 - Annualized costs of Topology 3 for four residences (Source: the author)

The annualized benefits were calculated taking into consideration the energy production of the PV modules and the ACE_{cons}. The values are presented in the following table.

Annualized benefits - Topology 3 for four residences	
Energy production of 1 PV module [kWh/year]	347,06
Total energy production [kWh/year]	16.485.350,00
ACE_{cons} [R$/kWh]	0,4841
Annualized benefits [R$]	7.980.557,94

Table 28 - Annualized benefits of Topology 3 for four residences (Source: the author)

The CBR can be find dividing the annualized costs by the annualized benefits and for this topology, the CBR found is 0,74. Because this value smaller than 1,0, this project could be financed using the financial resources of the EEP.

However, as properly explained on section 4.3), the ANEEL and the power distribution companies do not allow any electrical connection among the residences after the energy meter, which is present in this topology. Therefore, even though it passes the CBR rule, it cannot be implemented by current regulations.

This topology was analyzed in order to verify if there was a possible configuration of photovoltaic system able to be financed with the financial resources of the EEP. Since it has passed the eligibility criteria, a modification of the current regulations could be evaluated in order to include this topology of project among the accepted ones.

5.4.5) Analysis of the topology 4

The topology 4 was defined in the section 4.4) and it is a variation of the topology 3 that is allowed by the ANEEL and the power distribution companies. It consists in using the rooftops of more than one residence and one centralized inverter, because the relation kW/R$ is smaller than installing one centralized inverter per residence, and, differently than topology 3, the energy produced by the photovoltaic system enters only through one residence. Then, the energy injected into distribution grid is transformed into credits, which can be used by the other residences.

In the same way as done in the topology 3, two analysis are going to be performed: one consisting in two residences per project and other consisting in four residences per project.

5.4.5.1) Analysis of the topology 4 with two residences per project

The definition of the equipment used in each project of this topology is practically the same of the topology 3 for two residences, presented in the section 5.4.4.1).

The number of PV modules required to produce the energy consumption of two residences is 9,82. However, this topology was not designed to have any surplus of energy, so 9 PV modules were considered per project.

Since the number of PV modules is the same of the topology 3 for two residences, the selected inverter is the same. Therefore, the inverter used has the peak power of 3 kW and costs R$ 3.868,33.

The direct current and alternate current are the same of the topology 3 for two residences. For this reason, the same string box, AC protection devices and cables were used. The only difference is that the length of cables used in installation are smaller, because the it is performed in only one residence. So, 100 meters was considered per project, 50 meters on the DC part of the circuit and 50 meters on the AC part of the circuit, both with section area of 2,5 mm². Other point in having the energy production being injected in only one residence is that it is required only one energy meter per project.

The costs with structure, fixation and labor are the same of the topology 3 for two residences, because they have the same characteristics concerning these points. The annualized costs are presented in the following table.

Annualized costs - Topology 4 for two residences									
Component	***Category***	***Quantity per project***	***Total quantity***	***Price per unit [R$]***	***Life span [years]***	***CRF***	***CE equip [R$]***	***CPE equip [R$]***	***AC equip [R$]***
PV modules	Equipment	9	45.000	456,42	25	0,094	20.538.900,00	32.404.740,77	3.035.636,55
Inverter	Equipment	1	5.000	3.868,33	15	0,117	19.341.650,00	30.515.809,23	3.565.148,11
Cables	Others	100	500.000	1,24			620.000,00		0,00
String box	Others	1	5.000	400,00			2.000.000,00		0,00
SPD	Others	1	5.000	120,00			600.000,00		0,00
Circuit breaker	Others	1	5.000	12,00			60.000,00		0,00
Structure	Others	1	5.000	1.261,00			6.305.000,00		0,00
Energy meter	Others	1	5.000	291,00			1.455.000,00		0,00
Labor costs	Installation	1	5.000	2.400,00			12.000.000,00		0,00
Total							62.920.550,00	62.920.550,00	6.600.784,66

Table 29 - Annualized costs of Topology 4 for two residences (Source: the author)

The annualized benefits were calculated taking into consideration the energy production of the PV modules and the ACE_{cons}. As properly explained in the section 5.4.1), subsection ACE from the consumer's perspective, the ACE_{cons} for the topology 4 for two residences is 0,4525 R$/kWh. The following table summarizes the results obtained.

Annualized benefits - Topology 4 for two residences	
Energy production of 1 PV module [kWh/year]	347,06
Total energy production [kWh/year]	15.617.700,00
ACE_{cons} [R$/kWh]	0,4525
Annualized benefits [R$]	7.067.009,25

Table 30 - Annualized benefits of Topology 4 for two residences (Source: the author)

The CBR was found dividing the annualized costs by the annualized benefits, obtaining the value of 0,93. This value is smaller than 1,0 and the characteristics of this system are allowed by the current regulation. Therefore, this system can be financed using the financial resources of the EEP.

5.4.5.2) Analysis of the topology 4 with four residences per project

The definition of the equipment used in each project of this topology is practically the same of the topology 3 for four residences, presented in the section 5.4.4.2).

The number of PV modules required to produce the energy consumption of four residences is 19,64. However, since this topology was not designed to have any surplus of energy, 19 PV modules were considered per project.

The peak power of these PV modules combined is 6,37 kWp. In the Brazilian market the inverters of 6 kW and 8,2 are available, but the one with 6 kW is more adequate for this topology, because is less expensive and, since the overload is small, it can deliver practically the same performance. (Attachment D).

The direct current and alternate current are the same of the topology 3 for four residences. For this reason, the same string box, AC protection devices and cables were used. The difference is that since project is installed in only one residence instead of four, it requires one fourth of the length, i.e., 100 meters per project, 50 meters on the DC part and 50 meters on the AC part. The section area of the cables of the DC part is 2,5 mm² and the section area of the cables of the

AC part is 4,0 mm². Other point in having the energy production being injected in only one residence is that it is required only one energy meter per project.

The costs with structure, fixation and labor are the same of the topology 3 for two residences, because they have the same characteristics concerning these points. The annualized costs are presented in the following table.

Annualized costs - Topology 4 for four residences									
Component	***Category***	***Quantity per project***	***Total quantity***	***Price per unit [R$]***	***Life span [years]***	***CRF***	***CE equip [R$]***	***CPE equip [R$]***	***AC equip [R$]***
PV modules	Equipment	19	47.500	456,42	25	0,094	21.679.950,00	32.060.149,13	3.003.355,63
Inverter	Equipment	1	2.500	5.607,69	15	0,117	14.019.225,00	20.731.525,87	2.422.054,73
Cables [2,5 mm²]	Others	50	125.000	1,24			155.000,00		0,00
Cables [4,0 mm²]	Others	50	125.000	2,42			302.500,00		0,00
String box	Others	1	2.500	400,00			1.000.000,00		0,00
SPD	Others	1	2.500	120,00			300.000,00		0,00
Circuit breaker	Others	1	2.500	13,00			32.500,00		0,00
Structure	Others	1	2.500	2.430,00			6.075.000,00		0,00
Energy meter	Others	1	2.500	291,00			727.500,00		0,00
Labor costs	Installation	1	2.500	3.400,00			8.500.000,00		0,00
Total							52.791.675,00	52.791.675,00	5.425.410,36

Table 31 - Annualized costs of Topology 4 for four residences (Source: the author)

The annualized benefits were calculated taking into consideration the energy production of the PV modules and the ACE_{cons}. As properly explained in the section 5.4.1), subsection ACE from the consumer's perspective, the ACE_{cons} for the topology 4 for four residences is 0,4367 R$/kWh. The following table summarizes the results obtained.

Annualized benefits - Topology 4 for four residences	
Energy production of 1 PV module [kWh/year]	347,06
Total energy production [kWh/year]	16.485.350,00
ACE_{cons} [R$/kWh]	0,4367
Annualized benefits [R$]	7.199.152,35

Table 32 - Annualized benefits of Topology 4 for four residences (Source: the author)

The CBR is calculated dividing the annualized costs by the annualized benefits, finding the value of 0,75 for this case. Since this value is smaller than 1,0 and the characteristics of this system are allowed by the current regulation, it could be financed using the financial resources of the EEP.

5.4.6) Analysis of the topology 5

The topology 5 was defined in section 4.5) and it consists in a solar farm placed in a location away from the community, which will generate energy to send to the houses through the distribution grid. The purpose of this topology is to reduce the value of the R$/kW installed, using the gain of scale on the price of the equipment and the increment of the efficiency of the system.

The approach to calculate the annualized costs is quite different for this topology. Differently of the previous topologies, in which the selection of the inverter was made to match the nominal power of the PV modules per project, the selected inverter in this case is the one with the greatest nominal power available in the Brazilian market. This inverter, according to table 3, is projected by the ABB, it costs R$ 65.890,00 and it has the nominal power of 100 kW.

The next step is to find how many PV modules is possible to connect to one inverter, and then calculate how many combinations of inverter and modules is required to provide the energy needed by the community.

According to the attachment E, the maximum input voltage of this inverter is 1.000 V and, according to attachment A, the Voc of each PV module is 46,7. For this reason, is possible to place 21 PV modules per string. Thus, each string has the nominal power of 7,035 kWp, which means that 15 strings have a combined power of 105,5 kW, representing an inverter overload of only 5%, which does not affect much the energy production. So, each inverter supports 315 PV modules.

The expected energy production of one PV module under the solar farm conditions is 442,13 kWh/year, as presented in section 5.3). So, the energy production of 315 PV modules connected to one inverter is 139.271,19 kWh/year. Considering that the annual energy demand of the community is 17.046,00 MWh/year, it is required 122 combinations of inverters and PV modules, totalizing 122 inverters and 38.430 PV modules. Therefore, since the peak-power of each PV module is 0,335 kWp, the installed power of this solar farm is 12,874 MWp.

In the analysis of the previous topologies, from this point started the dimensioning of cables, protection devices, structures and others. However, the technical aspects of a solar farm are much more complex. It would be required to dimensioning the primary cabin, several transformers, disconnect switches and circuit breakers of elevated complexity, among other issues.

For these reasons, the approach adopted was different. In the last energy auction performed in Brazil, 29 photovoltaic plants were sold by the total of R$ 4,2 billions, combining for the installed power of 1.032 MWp. Thus, the ratio R$/kWp practiced for solar farms in the Brazilian energy market is 4.067,64 R$/kWp, according to the (ANEEL's press release, 2018). However, the price practiced by the companies at the auctions certainly includes a profit margin, that increases the total value of the project.

This analysis just takes into consideration the cost to perform the project, without any profits, because it uses the financial resources of the EEP. One manner to estimate what is the profit margin is verifying a company that works in the same sector. Therefore, using the company in which the author works as reference (Solstar, 2019), its profit margin is of around 25%. So, a conservative assumption would be assuming a profit margin of 15% for the auctioned solar farms, obtaining 3.457,49 R$/kWp.

As previous calculated, the peak-power of this topology is 12,874 MWp. So, multiplying it by the factor R$/kWp, it is obtained that the total cost of this solar is R$ 44.511.939,97. The next is table the costs of equipment, i.e., the PV modules and inverters, and annualize the other costs in their life time.

Annualized costs - Topology 5								
Component	***Category***	***Total quantity***	***Price per unit [R$]***	***Life span [years]***	***CRF***	***CE equip [R$]***	***CPE equip [R$]***	***AC equip [R$]***
PV modules	Equipment	38.430	456,42	25	0,094	17.540.220,60	30.523.293,83	2.859.384,90
Inverter	Equipment	122	65.890,00	15	0,117	8.038.580,00	13.988.646,15	1.634.287,16
Other						18.933.139,37		0,00
Total						44.511.939,97	44.511.939,97	4.493.672,06

Table 33 - Annualized costs of Topology 5 (Source: the author)

The annualized benefits were calculated taking into consideration the energy production of the PV modules and the ACE_{cons}. As properly explained in the section 5.4.1), subsection ACE from the consumer's perspective, the ACE_{cons} for the topology 5 is 0,4208 R$/kWh. The following table summarizes the results obtained.

Annualized benefits - Topology 5	
Energy production of 1 PV module [kWh/year]	442,13
Total energy production [kWh/year]	16.991.084,93
ACE [R$/kWh]	0,4208
Annualized benefits [R$]	7.149.848,54

Table 34 - Annualized benefits Topology 5 (Source: the author)

The CBR is found dividing the annualized costs by the annualized benefits. Thus, in this case, the value found is 0,63. Since this value is smaller than 1,0, which is the maximum value allowed by the ANEEL, this topology could be financed using the financial resources of the EEP.

5.5) Evaluation and comparison of results

First, it is necessary to have in mind that the objective was not to perform a technical analysis, but a potential analysis, in order to evaluate if the topologies presented could be financed in the EEP. Thus, the analyzes performed had a level of detail enough to understand the order of magnitude of each component and the CBR found is not a definitive number. However, the assumptions taken for the analysis were conservative, which means that it is more likely that the CBR's calculate are greater in the comparison with the CBR's values that would be obtained if the projects were actually performed.

The CBR found for each topology is presented in the following table.

Topology	*Inverter's nominal power*	*Application*	*CBR*	*Eligibility criteria*
1	1,5	Residential	1,30	Did not passed
1 with lamp substitution	1,5	Residential	1,07	Did not passed
2	1,0	Residential	1,65	Did not passed
3 for two residences	3,0	Residential	0,91	Passed
3 for four residences	6,0	Residential	0,74	Passed
4 for two residences	3,0	Residential	0,93	Passed
4 for four residences	6,0	Residential	0,75	Passed
5	100,0	Solar farm	0,63	Passed

Table 35 - CBR results (Source: the author)

From the five topologies analyzed, three of them match the eligibility criteria of the EEP and could be financed through the program. Even though the topologies 1 and 2 are the simplest ones and most commonly used in the market nowadays, the did not match the eligibility criteria.

However, the other topologies did match the criteria, because, as expected, using the gain of scale of the inverters, it is possible to reduce the ratio R$/kW and make the project more economic. This is can be seen in the table 35, in which according to the increment of the size of the inverter adopted, the CBR decreases.

Even though the topology 3 matches the eligibility criteria, it could not be financed because it does not respect all the regulation of the power distribution companies. This topology was proposed to explore possibilities beyond the regulations. However, the topology has practically the same operation and can be financed because it also matches the eligibility criteria. Thus, there is not the necessity to investigate if there was the possibility to include the topology 3 in the power distribution company's regulation.

The topology 5, that has the smallest RCB, takes in advantage other point besides the gain of scale. Since it is a solar farm, the project would provide the best possible conditions to the PV modules to produce the maximum amount of energy possible. Therefore, this topology has the gain in energy efficiency as well, which reduces even more the RCB.

Thus, the viable options according to the analysis previous performed are the topologies 4 and 5. After matching the eligibility criteria, the qualitative aspects, properly explained in the chapter 4, should be verified in other to determine which one would be best for which situation.

However, the choice would be between having several residential systems installed directly in the communities, where it might have problems to install the system, the constant possibility of scams or having the equipment stole, and the difficulty to perform maintenance, which would reduce the system's efficiency. Or having a solar farm whose management would be performed by the power distribution company indefinitely or by a third part to be selected, which may lead to a bureaucracy and very exhausting process.

Finally, it is important to once again note that the costs used to perform the analyzes were obtained by the purchase values that a small company acting in the sector kindly provided to perform this thesis. Thus, in cases of bigger companies, such the power distribution companies, buying equipment in a big scale, the costs would probably decrease sharply.

In consequence of this point and the point discussed in the beginning of this section, where it is explained that the assumptions taken in the analyzes were conservatives, there is the possibility that the topologies 1 and 2 would match the maximum value CBR as well.

6) Conclusion

The Energy Efficiency Program created by the ANEEL has the purpose to improve the quality of Brazilian’s Electrical system, acting in the generation, transmission and the consumption segments, by forcing the power distribution companies to invest their own money in the enhancement projects.

One of the fronts of the EEP is the stimulation of the use of renewable energy sources, implemented in the program in 2013, which are encouraged more than the other projects, by allowing them to have a worse cost benefit ratio. Besides it, the EEP forces that half of the money should be applied to low-income communities, because these are the places that require more attention.

From the power distribution’s perspective, this is a very interesting type of project, because they usually have defaults among the electricity bills in low-income communities, which could be fixed if the electricity bills would reduce sharply. From the consumer’s perspective, they would receive energy without any costs and, since their electricity bills would reduce, they would have an economic relieve and probable increase in their life’s quality. There is also the environmental perspective that would be benefit, because of the usage of a renewable source of energy, especially in a moment when the sustainability is very serious concern.

However, projects involving stimulated energy sources are being regularly performed by the power distributions companies. The reasons probably are that they are habituated to perform simpler projects, such substitution of lamps inefficient lamps for new and efficient ones, and that there is some uncertainty of whether or not the stimulated energy source’s projects are viable according the ANEEL’s EEP rules.

Therefore, this thesis has entered to perform this role and verify the viability of projects involving stimulated energy sources focused for low-income communities.

In order to do that, five main topologies of photovoltaic projects were proposed, with a few variations and considering also configurations that are not currently allowed by the ANEEL’s regulations, in order to exhaust all the possibilities.

Combining information provided by the power distribution company EDP São Paulo and an installation company of photovoltaic systems Solstar, the study performed in this thesis validates the possibility of having photovoltaic system's projects for low-income communities financed by the ANEEL's Energy Efficiency Program.

The analysis was conduct in order to verify the potential of this type of project, verifying technical and economic aspects of each topology, using a conservative approach to calculate the cost-benefit ratio. Even though, the results found are very optimistic.

Three of the five topologies could be financed in the EEP and the other two have results very close to the minimum eligibility criteria. As expected, there is a gain of scale by using inverters with highest nominal power, as it is possible to see in the table 35, in which the nominal power of inverters is inversely proportional to the CBR. There is also the gain in efficiency for the solar farm, once the all project and structure were designed to extract the maximum of the solar energy. But, in addition, it is necessary to highlight that even the topologies 1 and 2 could match the eligibility criteria.

The cost's information used was provided by a small installation company, that buys its equipment in small quantity and have low bargain power. If a power distribution company decides to perform the project, they would have to acquire the equipment in large quantity and, since they are big companies, they would have a great bargain power, that could reduce the costs up to the point in which the topologies 1 and 2 would match the eligibility criteria.

These results can lead a power distribution company to start the analysis to perform a project with the same characteristics, once there is enough evidence to prove they can be financed in the EEP and because they promote other goods to the company, the society and the environment.

In the further analyzes, the points that require more attention are those related to the qualitative issues, initially discussed in the chapter 4), but that were not properly quantified, because this thesis restricted its analysis only to the viability matters.

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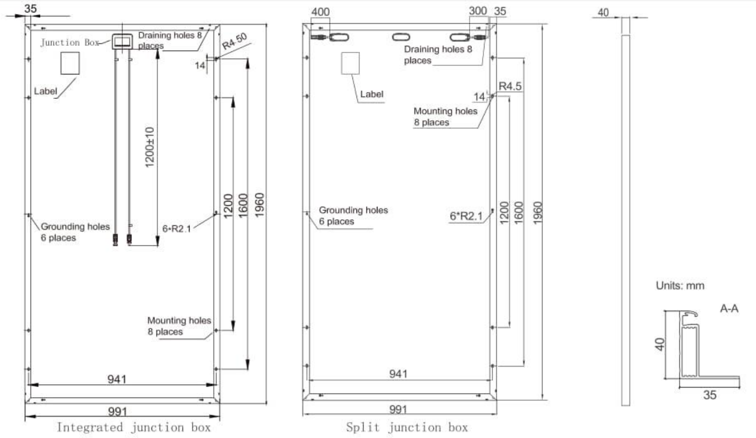
ATTACHMENT A

JA SOLAR

JAP72S01 315-335/SC Series

MECHANICAL DIAGRAMS



Remark: customized frame color and cable length available upon request

SPECIFICATIONS

Cell	Poly
Weight	22.5kg±3%
Dimensions	1960mm×991mm×40mm
Cable Cross Section Size	4mm²
No. of cells	72(6x12)
Connector	PV-ZH202B PV-KST4-EV02/xy, PV-KBT4-EV02/xy QC4.10-35/45 TL-Cable01S-F UTXCFA4AM, UTXCMA4AM
Country of Manufacturer	China/Vietnam

ELECTRICAL PARAMETERS AT STC

TYPE	JAP72S01 -315/SC	JAP72S01 -320/SC	JAP72S01 -325/SC	JAP72S01 -330/SC	JAP72S01 -335/SC
Rated Maximum Power(Pmax) [W]	315	320	325	330	335
Open Circuit Voltage(Voc) [V]	45.85	46.12	46.38	46.40	46.70
Maximum Power Voltage(Vmp) [V]	37.09	37.28	37.39	37.65	37.83
Short Circuit Current(Isc) [A]	9.01	9.09	9.17	9.28	9.35
Maximum Power Current(Imp) [A]	8.49	8.58	8.69	8.77	8.87
Module Efficiency [%]	16.2	16.5	16.7	17.0	17.2
Power Tolerance	0~+5W				
Temperature Coefficient of Isc(α_Isc)	+0.058%/℃				
Temperature Coefficient of Voc(β_Voc)	-0.330%/℃				
Temperature Coefficient of Pmax(γ_Pmp)	-0.400%/℃				
STC	Irradiance 1000W/m², cell temperature 25℃, AM1.5G				

Remark: Electrical data in this catalog do not refer to a single module and they are not part of the offer.They only serve for comparison among different module types.

ELECTRICAL PARAMETERS AT NOCT

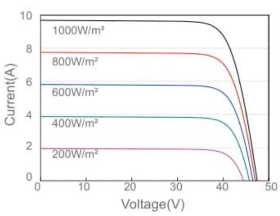
TYPE	JAP72S01 -315/SC	JAP72S01 -320/SC	JAP72S01 -325/SC	JAP72S01 -330/SC	JAP72S01 -335/SC
Rated Max Power(Pmax) [W]	233	237	241	244	248
Open Circuit Voltage(Voc) [V]	42.84	43.04	43.24	43.41	43.63
Max Power Voltage(Vmp) [V]	34.45	34.64	34.82	35.03	35.21
Short Circuit Current(Isc) [A]	7.23	7.29	7.35	7.40	7.46
Max Power Current(Imp) [A]	6.77	6.84	6.91	6.97	7.04
NOCT	Irradiance 800W/m², ambient temperature 20℃, wind speed 1m/s, AM1.5G				

OPERATING CONDITIONS

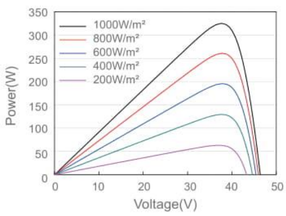
Maximum System Voltage	1500V DC(IEC)
Operating Temperature	-40℃~+85℃
Maximum Series Fuse	20A
Maximum Static Load,Front	3600Pa, 1.5
Maximum Static Load,Back	1600Pa,1.5
NOCT	45±2℃
Application Class	Class A

CHARACTERISTICS

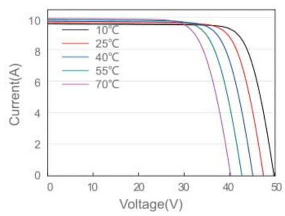
Current-Voltage Curve JAP72S01-325/SC



Power-Voltage Curve JAP72S01-325/SC



Current-Voltage Curve JAP72S01-325/SC



Premium Cells, Premium Modules

Version No. : Global_EN_20180920A

ATTACHMENT B

TECHNICAL DATA		
MODEL NAME	CSI-1.5K-TL	CSI-3K-TL
DC INPUT		
Max. Recommanded PV Power(STC)	1900W	3400W
Max. DC Input Voltage	450V	550V
Start Voltage	80V	
DC Voltage Range	70-450V	70-550V
MPP Work Voltage Range/ Nominal Voltage	70-450V/250V	70-550V/360V
Full Load DC Voltage Range	175-400V	250-500V
Max. Input Current	10A	13A
Max. Input Current per String	10A	13A
Number of MPP Trackers /Strings per MPPT	1/1	1/2
AC OUTPUT		
Rated AC Output Power	1600W	3000W
Max. AC Output Power	1650W	3000W
Max. Output Current	7.8A	14.3A
AC Nominal Voltage; Range	220,230,240Vac; 180-280Vac	
AC Grid Frequency; Range	50,60Hz; ±5 Hz	
Power Factor	1	
THDI	<3%	
AC connection	Single Phase	
EFFICIENCY		
Max. Efficiency	97%	
CEC Efficiency	96.5%	
MPPT Efficiency	99.5%	
PROTECTION		
DC Reverse Polarity Protection	Yes	
DC Switch Rating for Each MPPT	Yes	
Output Over Current Protection	Yes	
Output Over Voltage Protection-Varistor	Yes	
Ground Fault Monitoring	Yes	
Grid Monitoring	Yes	
Integrated All-Pole Sensitive Leakage Current Monitoring Unit	Yes	
GENERAL DATA		
Dimensions(W/H/D)	271x267x142mm	271x320x142mm
Weight	6.1Kg	8.8Kg
Operating Temperature Range	−25°C ~ +60°C with derating above 45°C	
Noise Emission (Typical)	≤25 dB(A)	
Altitude	2000m without derating	
Self-Consumption Night	<0.5 W	
Topology	Transformerless	
Cooling Concept	Natural	
Environmental Protection Rating	IP 65	
Relative Humidity	100%	
FEATURES		
DC Connection	H4	
AC Connection	Connector	
Display	LCD	
Interfaces: RS232/ RF/ Wi-Fi/ Ethernet	Yes/Optional/Optional/Optional	
Warranty: 5 Years / 10 Years	Yes/Optional	
CERTIFICATES AND APPROVALS		
CE; VDE 0126-1-1; IEC 62109; G83; AS4777; AS/NZS 3100; INMETRO		

Caution: For professional use only. Please read safety and installation instructions before using the product.

ATTACHMENT C

Microinversor APsystems YC1000-3-220 - Datasheet

Modelo	YC1000-3-220
Dados de Entrada (DC)	
Faixa de Tensão MPPT	16V-55V
Faixa de Tensão de Operação	16V-55V
Tensão Máxima de Entrada	60V
Tensão de Partida	22V
Corrente Máxima de Entrada	14.8A×4
Dados de Saída (AC)	
Trifásico	127V/ 220V
Potência Contínua Máxima de Saída	900W
Potência de Pico de Saída	1000W
Corrente Nominal de Saída	2.36A x 3
Tensão Nominal de Saída	127V x 3
Faixa de Tensão de Saída Padrão / Extendida	101.6V-139.7V*/ 82V-152V
Frequência Nominal de Saída	60Hz
Faixa de Frequência de Saída Padrão / Extendida	57.5Hz-62Hz*/ 55.1Hz-64.9Hz
Fator de Potência	>0.99
Distorção Harmônica Total	<3%
Eficiência	
Eficiência de Pico	95%
CEC Eficiência ponderada	94.5%
Eficiência Nominal MPPT	99.5%
Consumo de Potência Noturna	300
Mechanical Data	
Faixa de Temperatura de Operação Ambiente	-40°F até +149°F (-40°C até +65°C)
Faixa de Temperatura de Armazenamento	-40°F até +185°F (-40°C até +85°C)
Dimensões (L x A x P)	259mm x 242mm x36mm (10.2" x 9.5" x1.4")
Peso	3.8kg (8.4lb)
Corrente AC Máxima do Barramento	20A
Classificação do Gabinete	IP67
Ventilação	Convecção natural – Sem Ventilador

ATTACHMENT D

TECHNICAL DATA FRONIUS PRIMO 3.8-1 TO 8.2-1

INPUT DATA	PRIMO 3.8-1	PRIMO 5.0-1	PRIMO 6.0-1	PRIMO 7.6-1	PRIMO 8.2-1
Max. permitted PV power (kWp)	5.7 kW	7.5 kW	9.0 kW	11.4 kW	12.3 kW
Max. usable input current (MPPT 1/MPPT 2)	18 A / 18 A	18 A / 18 A	18 A / 18 A	18 A / 18 A	18 A / 18 A
Total max. DC current	36 A				
Max. admissible input current (MPPT 1/MPPT 2)	27 A				
Operating voltage range	80 V - 1,000 V				
Max. input voltage	1,000 V				
Nominal input voltage	410 V	420 V	420 V	420 V	420 V
Admissible conductor size DC	AWG 14 - AWG 6				
MPP voltage range	200 - 800 V	240 - 800 V	240 - 800 V	250 - 800 V	270 - 800 V
Number of MPPT	2				

OUTPUT DATA		PRIMO 3.8-1	PRIMO 5.0-1	PRIMO 6.0-1	PRIMO 7.6-1	PRIMO 8.2-1
Max. output power	240 V	3,800 W	5,000 W	6,000 W	7,600 W	8,200 W
	208 V	3,800 W	5,000 W	6,000 W	7,600 W	7,900 W
Max. output fault current / Duration	240 V	584 A Peak / 154 ms	584 A Peak / 154 ms	584 A Peak / 154 ms	584 A Peak / 154 ms	584 A Peak / 154 ms
Max. continuous output current	240 V	15.8 A	20.8 A	25.0 A	31.7 A	34.2 A
	208 V	18.3 A	24.0 A	28.8 A	36.5 A	38.0 A
Recommended OCPD/AC breaker size	240 V	20 A	30 A	35 A	40 A	45 A
	208 V	25 A	30 A	40 A	50 A	50 A
Max. efficiency (Lite version)		97.9 %				
CEC efficiency (Lite version)	240 V	95.5 %	96.5 %	96.5 %	97.0 %	97.0 %
Admissible conductor size AC		AWG 14 - AWG 6				
Grid connection		208 / 240 V				
Frequency		60 Hz				
Total harmonic distortion		< 5.0 %				
Power factor (cos $\varphi_{ac,r}$)		0.85 - 1 ind./cap				

TECHNICAL DATA FRONIUS PRIMO 10.0-1 TO 15.0-1

INPUT DATA	PRIMO 10.0-1	PRIMO 11.4-1	PRIMO 12.5-1	PRIMO 15.0-1
Max. permitted PV power (kWp)	15.00 kW	17.10 kW	18.75 kW	22.50 kW
Max. usable input current (MPPT 1/MPPT 2)	33.0 A / 18.0 A			
Total max. DC current	51 A			
Max. admissible input current (MPPT 1/MPPT 2)	49.5 A / 27.0 A			
Operating voltage range	80 V - 1,000 V			
Max. input voltage	1,000 V			
Nominal input voltage	655 V	660 V	665 V	680 V
Admissible conductor size DC	AWG 14 - AWG 6 copper direct, AWG 6 aluminum direct, AWG 4 - AWG 2 copper or aluminum with optional input combiner			
MPP Voltage Range	220 - 800 V	240 - 800 V	260 - 800 V	320 - 800 V
Number of MPPT	2			

OUTPUT DATA		PRIMO 10.0-1	PRIMO 11.4-1	PRIMO 12.5-1	PRIMO 15.0-1
Max. output power	240 V	9,995 W	11,400 W	12,500 W	15,000 W
	208 V	9,995 W	11,400 W	12,500 W	13,750 W
Max. output fault current / Duration	240 V	916 A Peak / 6.46 ms	916 A Peak / 6.46 ms	916 A Peak / 6.46 ms	916 A Peak / 6.46 ms
Max. continuous output current	240 V	41.6 A	47.5 A	52.1 A	62.5 A
	208 V	48.1 A	54.8 A	60.1 A	66.1 A
Recommended OCPD/AC breaker size	240 V	60 A	60 A	70 A	80 A
	208 V	60 A	70 A	80 A	90 A
Max. efficiency (Lite version)		97.9 %			
CEC efficiency (Live version)	240 V	96.5 %	96.5 %	96.5 %	97.0 %
Admissible conductor size AC		AWG 10 - AWG 2 copper (solid / stranded / fine stranded) , AWG 6 - AWG 2 copper (solid / stranded)			
Grid connection		208 / 240 V			
Frequency		60 Hz			
Total harmonic distortion		< 2.5 %			
Power factor (cos $\varphi_{ac,r}$)		0-1 ind./cap.			

December 12, 2016

Fronius Canada Ltd. / 2875 Argentia Road, Units 3 - 6 / Mississauga, ON L5N 8G6 / www.fronius.ca / 905-288-2100

ATTACHMENT E

ABB string inverters

PVS-100/120-TL
100 to 120 kW

Technical data and types

Type code	PVS-100-TL	PVS-120-TL
Input side		
Absolute maximum DC input voltage ($V_{max,abs}$)	1000V	
Start-up DC input voltage (V_{start})	420V (400…500 V)	
Operating DC input voltage range (V_{dcmin}…V_{dcmax})	360…1000 V	
Rated DC input voltage (V_{dcr})	620V	720V
Rated DC input power (P_{dcr})	102 000W	123 000W
Number of independent MPPT	6	
MPPT input DC voltage range at ($V_{MPPTmin}$…$V_{MPPTmax}$) at P_{acr}	480…850V	570…850V
Maximum DC input power for each MPPT ($P_{MPPT,max}$)	17500 W [480V≤V_{MPPT}≤850V	20500 W [570V≤V_{MPPT}≤850V
Maximum DC input current for each MPPT (I_{dcmax})	36 A	
Maximum input short circuit current (I_{scmax}) for each MPPT	50 A [1)]	
Number of DC input pairs for each MPPT	4	
DC connection type	PV quick fit connector [2)]	
Input protection		
Reverse polarity protection	Yes, from limited current source	
Input over voltage protection for each MPPT - replaceable surge arrester	Type II with monitoring only for SX and SX2 versions; Type I+II with monitoring only for SY and SY2 versions	
Photovoltaic array isolation control	as per IEC62109	
DC switch rating for each MPPT	50 A / 1000 V	
Fuse rating (versions with fuses)	15 A / 1000 V [3)]	
String current monitoring	SX2, SY2: (24ch) Individual string current monitoring; SX, SY: (6ch) Input current monitoring per MPPT	
Output side		
AC Grid connection type	Three phase 3W+PE or 4W+PE	
Rated AC power (P_{acr} @cosϕ=1)	100 000 W	120 000 W
Maximum AC output power (P_{acmax} @cosϕ=1)	100 000 W	120 000 W
Maximum apparent power (S_{max})	100 000 VA	120 000 VA
Rated AC grid voltage ($V_{ac,r}$)	400 V	480 V
AC voltage range	320...480 V [4)]	384...576 [3)]
Maximum AC output current ($I_{ac,max}$)	145 A	
Rated output frequency (f_r)	50 Hz / 60 Hz	
Output frequency range (f_{min}…f_{max})	45…55 Hz / 55…65 Hz [5)]	
Nominal power factor and adjustable range	> 0.995, 0…1 inductive/capacitive with maximum S_{max}	
Total current harmonic distortion	< 3%	
Maximum AC cable	185mm2 Aluminum and copper	
AC connection type	Provided bar for lug connections M10, single core cable glands 4xM40 and M25, multi core cable gland M63 as option	
Output protection		
Anti-islanding protection	According to local standard	
Maximum external AC overcurrent protection	225 A	
Output overvoltage protection - replaceable surge protection device	Type 2 with monitoring	
Operating performance		
Maximum efficiency (η_{max})	98.4%	98.9%
Weighted efficiency (EURO)	98.2%	98.6%
Communication		
Embedded communication interfaces	1x RS485, 2x Ethernet (RJ45), WLAN (IEEE802.11 b/g/n @ 2,4 GHz)	
User interface	4 LEDs, Web User Interface	
Communication protocol	Modbus RTU/TCP (Sunspec compliant)	
Commissioning tool	Web User Interface, Mobile APP/APP for plant level	
Remote monitoring services	Aurora Vision® monitoring portal	
Advanced features	Embedded logging, direct telemetry data transferring to ABB cloud	
Environmental		
Ambient temperature range	-25...+60°C /-13...140°F with derating above 40°C / 104 °F	