Renewable Energy in Urban Low-Income Communities. Case Study of Santa Marta, Rio de Janeiro.

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Energy Engineering and Management

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November 2019

Acknowledgments

I would first like to thank and express my deepest appreciation to my supervisor, Professor Manuel Duarte Pinheiro, for supporting me with his expertise, especially in the formulating of the methodology and the research topic of my Thesis.

I would like to express my deepest gratitude to all the Insolar members, and especially to Henrique Drumond, for all the information and the helpful suggestions shared with me. I feel so grateful to have had the possibility to come in contact with them.

Moreover, I would like to thank my family and all the friends that were closed to me during this period and supported me. In particular, I would like to express my gratitude to my father, who was always present for me with his support and his precious suggestions.

Finally, I would like to give a special thanks to all the students and researchers with who I came in contact during my studies, who helped me with their advice and motivated me.

Resumo

Atualmente, 55% da população mundial vivem em áreas urbanas, estimando-se que vá crescer para 68% até o final de 2050. O desenvolvimento sustentável depende cada vez mais do planeamento e gestão adequada do desenvolvimento urbano, incluindo serviços básicos, como o da eletricidade. Os preços brasileiros da eletricidade estão entre os mais altos da América Latina e demonstraram alta volatilidade nos últimos anos. Na cidade do Rio de Janeiro, Brasil, mais de 22% da população vive em assentamentos informais, áreas superlotadas caracterizadas por moradias de padrão baixo, serviços e infraestruturas precários, habitadas por pessoas pobres. Estas famílias de baixos rendimentos são obrigadas usar grande parte do seu orçamento para pagar o serviço de eletricidade. Este estudo tem como objetivo avaliar, do ponto de vista tecno-económico, o uso de energias renováveis em comunidades urbanas de baixa renda, com foco no estudo de caso de Santa Marta, no Rio de Janeiro. Os resultados mostram que os sistemas solares fotovoltaicos são extremamente competitivos quando comparados com a eletricidade fornecida pela rede elétrica e podem representar uma solução para comunidades de baixos rendimentos, se forem implementados um modelos de negócios e de financiamento adequados.

Palavras-chave: Energia Renovável, Comunidades de baixos rendimentos, Comunidades urbanas, Fotovoltaico, Brasil

Abstract

Nowadays, 55% of the global population lives in urban areas, a ratio that is estimated to grow to 68% by the end of 2050. Sustainable development depends more and more on the adequate management of urban growth, including the successful planning of basic services, such as electricity. In the city of Rio de Janeiro, Brazil, more than 22% of the population lives in informal settlements, overcrowded areas characterized by low standard housing, poor services and infrastructure, inhabited by impoverished people. Brazilian electricity prices are among the highest in Latin America and have shown high volatility in the last years, mainly due to the strong dependence of the electricity sector on hydro sources, which are subject to climate conditions. Without adequate programs, Brazilian low-income families are obliged to compromise their budget to pay the electricity service. In this context, this study aims to assess from a techno-economic point of view, the use of renewable energy technologies in urban low-income communities, focusing on the case study of Santa Marta, in Rio de Janeiro, with the final objective of identifying both competitive and sustainable systems to provide electricity to the community. Results show that solar PV systems are extremely competitive with the electricity supplied by the grid and they could represent a solution for low-income communities thanks to the implementation of adequate business plans and financing methods.

Keywords: Renewable energy, Low-income community, Urban community, PV system, Brazil

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Nomenclature

A	Borrowed Amount
B	Electricity Bill
C	Cost
CF	Cash Flow
CR	Electricity Credits
d_{cea}	Cost of Electricity Availability
EB	Energy Balance
E_g	Energy Gap
E_{gen}	Energy Generated
E_{pv}	Photovoltaic Energy
E_{req}	Required Energy
F_0	Organic Fraction
F_c	Capacity Factor
G	Global irradiance
G	Grant
I	Investment
I_0	Reverse Saturation Current
I_{BG}	Average Produced Biogas
I_d	Diode Current
I_{max}	Optimum Operating Current
I_{pv}	Photoelectric Current
IRR	Internal Rate of Return
I_{sc}	Short Circuit Current
K	Boltzmann's constant
L	Loan Installment
LCOE	Levelized Cost Of Electricity
LCV_{BG}	Biogas Low Calorific Value
m	Ideality Factor
N	Project Lifetime
N_l	Loan Amortization Period
NOCT	Normal Operating Cell Temperature

NPV	Net Present Value
N_s	Solar Cells Number
O&M	Operation and Maintenance
q	Electron charge
Q_{BG}	Biogas Flow
Q_{col}	Collected Biogas Flow
r	Cost of Opportunity
R	Revenues
r_l	Loan Interest Rate
S	Energy Sale
T	Cell Temperature
T	Electricity Tariff
T_{amb}	Ambient Temperature
V	Voltage
V_{max}	Optimum Operating Voltage
V_{oc}	Open Circuit Voltage
V_T	Thermal Voltage
W	Total Waste
W_o	Organic Waste
X	Expired Electricity Credit
β	Electricity Prices Growth
δ	PV Module Power Degradation
η_{col}	Collection Efficiency
η_{con}	Conversion Efficiency
λ	Waste Growth
Υ	Electricity Consumption Growth

Glossary

AC	Alternating Current
ANEEL	Brazilian Electricity Regulatory Agency
BNDES	National Development Bank
BRL	Brazilian Real
COFINS	Social Contribution for Social Security Financing
CONFAZ	National Council of Finance Policy
DC	Direct Current
DG	Distributed Generation
EPE	Energy Research Company
FEAM	Environment State Foundation
GDP	Gross Domestic Product
GHG	Green House Gases
hh	Household
IBGE	Brazilian Institute of Geography and Statistics
ICMS	Tax on Commerce and Services
IDB	Inter-American Development Bank
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
NPV	Net Present Value
PB	Payback
PIS	Employees’ Profit Participation Program
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RN	Normative Resolution
UPP	Pacification Police Unit
USD	United State Dollar
WWP	World Without Poverty
UN DESA	United Nation Department of Economic and Social Affairs

1 Introduction

The world's urbanization is continuously growing; nowadays, 55 % of the world's population lives in urban contexts, a percentage that is estimated to grow to 68% by the end of 2050 (UN DESA, 2018). The actual and future sustainable development is thus extremely linked with adequate planning and management of urban growth; for many cities, it will be challenging to meet the increasing needs of their population, including the one for housing and the one for energy supply.

Latin America is the most urbanized region in the world: about 80% of the region's population lives in cities, and it is predicted that, by 2050, over 90% of the population will be urbanized (Atlantic Council, 2014). 198 cities of Latin-America generate more than 60% of the region's GDP, representing its economic engines. However, in most of the cases, cities' economic development was accompanied by an unplanned and disordered urban growth and, moreover, the additional income did not benefit all the dwellers. As an example, between 2005 and 2012, Brazil has more than doubled its per capita GDP, but the GINI index, which gives a measure of the distribution of income across a country, has improved only slightly, decreasing by 0.4 points (IDB, 2015).

It is believed that informal settlements embody the inequality and the urban poverty that exist in Latin America and it is estimated that about 25% of the urban population live in slums. Informal urban settlements come in all shapes and are referred to with several names including slums, shantytowns or favelas, yet they all imply the same thing: an overcrowded residential urban area featured by low standard housing, poor services and infrastructure, squalor, inhabited by impoverished people (UN-HABITAT, 2017). The appearance of informal settlements is attributable to strong flows of migration to cities by low-income families, alongside with the incapability of cities of meeting the rapid housing need and the inability of the families to pay the price of formal dwellings (IDB, 2015).

Alongside with urban poverty, Latin American cities have to face the problem of violence and insecurity, representing the most violent region of the world (Glebbeek et al., 2016). Moreover, Latin American cities are responsible for 80% of the region's carbon dioxide emissions and climate change is making them even more vulnerable (IDB, 2015).

1.1 Background and Problem

In Rio de Janeiro, Brazil, similarly to the Latin American region's trend, a large part of the population lives in urban slums, also called *favelas*. Most of the favelas consist of public or private land occupied with self-build developed by low-income groups of people, on lands that lack of infrastructures and without following an urban plan. Irregular settlements started appearing at the end of the 19th century in Rio de Janeiro, mainly due to: (1) the abolition of slavery, that resulted in a considerable number of homeless and unemployed people; (2) strong migration flows from rural areas to the city, caused by a reduction of agricultural work and an increase of industrialization; (3) migration flows from other Brazilian regions. In the first thirty years of the 20th century, the favelas started expanding consistently, mainly due to the increment of labour required for the modernization and the expansion of the city; the slums, in fact, tended to develop near the work location. In the following decades, informal settlements continued to expand due to more migratory movements and the expansion of industries. (Magalhães et al., 2003).

Nowadays, informal settlements still exist in large numbers and are spread throughout the city of Rio de Janeiro. According to the most recent census (IBGE, 2013), more than 22% of the population of the city lives in slums. An informal settlement can be characterized for its size, its location, the type of urban site, accessibility, population density and characteristics of the dwelling, including the available services, such as water supply, sanitation system, waste collection and availability of electricity. (IBGE, 2013) evaluated the adequacy of the four services in the Brazilian informal and formal settlements: the results showed that, the percentage of adequacy is always lower in informal ones, highlighting the inequality of services in Brazilian urban areas and the lack of proper basic service in irregular settlements. As regards electricity, 99.7% of the dwellings in informal settlements showed to have access to electric energy. However, the adequacy of this service is estimated at 72.5%.

Most of the Brazilian informal settlements have been plagued by electricity issues. In Rio de Janeiro, before many slum areas were pacified through the intervention of Pacification Police Units (UPP), starting from 2008, most of these communities were in the hands of drug lords, who established a strict control on the areas, denying the access to the government. In this time, part of the inhabitants of the favelas used to access the electricity through irregular connection with the grid; the electricity theft – in Brazilian Portuguese, *gato* – was, and is still, a very diffused practice. The steal of electricity has several disadvantages: apart from the economic loss it causes, which is pointed as one of the responsible for the high prices of electricity in Brazil, it also implies several risks to who is involved in this practice, such as electric shock, short circuits, and fires (Lima, 2015). In 2007, it was estimated that in Rio de Janeiro there were more than 200,000 illegal connections (Naudad, 2012). In 2010, electricity theft caused 1 billion BRL loss, while in 2015, the estimated loss due to irregular connection was 850,000 BRL (Mayrink et al., 2016).

Santa Marta is one of the communities belonging to the informal settlements of Rio de Janeiro. After Santa Marta received the first Pacification Unit in 2008, Light, one of the utility companies serving Rio de Janeiro State, started regularizing the access to electricity in the community, by replacing the old electricity network, expanding the system and installing meters for monitoring consumptions. According to (Mayrink, 2016), in 2009, before the regularization, the illegal connections in the community amounted to the 93%, resulting in 93% of the commercial loss for Light (calculated based on unpaid bills and illegal connections), while, in 2015 the irregular connections reduced to almost 0%, resulting in only 5% of economic losses for the company.

On the other side, most of the locals saw their electricity bills increasing greatly during these years, passing from a zero cost service to a paid service. According to (WWP, 2015), the quality of the electricity increased after the regularization process, thanks to the reduction of instability and fires. However, still, many of the locals complain about the existence of several issues related to the service. The connection is not highly reliable and in fact, it is not rare that blackouts occur totally or partially in the community, and the citizens blame the utility company for the slow timeliness offered during these extreme events (IPS, 2018; Rouvenat, 2019). But, most of all, the main concern is the cost of the electricity bills, which absorbs a consistent part of the locals' incomes (B. Carvalho, 2016).

Brazilian electricity prices for consumers, which are subject to the approval of the Brazilian Electricity Regulatory Agency (ANEEL), are among the highest in Latin America. It was estimated that in 2018, the average price reached 0.185 USD/kWh in the residential sector (Enerdata, 2019). Electricity tariffs in Brazil have risen significantly in the past recent years and showed to be very volatile. One of the main reasons that explains the expensiveness and the volatility of the prices is that the Brazilian electricity sector is extremely dependent on hydropower, which actually accounts for more than 64% of the national production (ANEEL, 2019a). Recently (2014-16), due to a severe draught that occurred nationwide, the power sector has been plagued by crises, making the electricity supply less reliable (Hunt et al., 2018).

By analyzing the current electricity prices, it is not difficult to understand that, without adequate policies and programs, low-income families in Brazil are obliged to compromise their budget to pay the electricity service. The use of photovoltaic solar energy and waste to energy technologies could represent a solution.

1.2 Objective

While electricity-related issues are widely recognized in rural areas in developing countries, scholars still have to focus on this problematic situation happening in urban slums. This study aims to contribute to fulfilling this gap existing in the literature, by investigating possible solutions in order to provide more affordable electricity to urban low-income communities.

This study assesses, from a techno-economic point of view, the use of renewable energy systems for urban low-income communities, with the focus on the case study of Santa Marta, in Rio de Janeiro, Brazil. The final objective of this study is to find alternative ways to the electricity from the grid in order to provide a more economical, and at the same time sustainable, service to the low-income community.

Because of the potential of the application, two different technologies are investigated: distributed solar photovoltaic and anaerobic digestion system. Throughout the study, the main focus is kept on the PV system, due to the fact that PV technologies have the potentiality to satisfy completely the electricity demand required by the community, contrary to an anaerobic digestion plant, and that PV systems are more economically viable. In particular, the objective of the PV project focused on finding the business model and the financing mode more adequate for the case study, while the objective of the anaerobic digestion project was limited to assessing its economic viability.

1.3 Approach and Outline

The approach begins with the literature review, which is presented in Chapter 2. Different energy projects targeting low-income communities were reviewed. Also, the electricity sector in Brazil and the regulatory framework for distributed generation systems were investigated, as well as the state of the art of the two proposed technologies.

The study continues with the description of the Santa Marta community case study, presented in Chapter 3. In particular, attention is dedicated to the electricity service; as regards the domestic consumption and the number of clients to serve in the community, many assumptions were taken based on the monthly consumption data between 2010-2018 that were provided by the local utility company. It was assumed that all the households consume the same monthly amount of electricity, which was hypothesized to increase every year. Moreover, the waste system and characterization are described, due to the potential application in energy technologies; data on the amount collected in the community (tons/day) were retrieved from the literature, and it was assumed that it increases every year.

The energy resources available on the territory are also described in Chapter 3. Considering the area's characteristics, hydro and wind resources were excluded from the analysis and thus only solar energy was thoroughly investigated. To conduct the study, data for the location were retrieved from the Photovoltaic Geographical Information System (PVGIS) developed by the European Commission Science Hub: in particular, the hourly solar irradiance (W/m^2) and the air temperature (°C) were obtained for all the available years in the software whose hourly data were complete (2005, 2006, 2007, 2009, 2010, 2011, 2013, 2015). Then, the hourly average values for a year were calculated and were used for the energy assessment.

The approach adopted to conduct the energy assessment of the solar PV technology and the anaerobic digestion plant is described in Chapter 4. The methodology used to for the solar PV modules is the single diode ideal (three parameters) model, as described by (Crispim et al., 2007). The equipment's characteristics were assumed based on the most common brands available in Brazil and the derate factors, which influence the power production, were assumed based on the literature. For the anaerobic digestion plant, the methodology was based on a study conducted for a Brazilian municipality by (R. E. dos Santos et al., 2019).

The methodology adopted for conducting the economic assessment is described in Chapter 5. In order to evaluate the profitability of the two projects, the NPV, the IRR, the payback period and the LCOE were evaluated. As regards the PV system, it was assumed that the whole community participate in the solar project, and the power to install was calculated so to maximize the value of the NPV of the project for a household (and thus for the whole community). The methodology to calculate the cost associated to the electricity bill and the revenues, namely the avoided electricity bill, was based on a study conducted by (Vilaça Gomes et al., 2018) and considering the regulation in force for distributed generation systems in Brazil. A different approach was used for the anaerobic digestion system; in fact, the potential installed power was calculated based on the amount of waste collected in the community and it was assumed that the revenues of the project consist in the electricity sales, based on (R. E. dos Santos, 2019).

Chapter 6 is dedicated to the presentation and discussion of the obtained results.

In Chapter 7, a sensitivity analysis is conducted on the PV project, with the objective of analysing how the economic results (NPV, IRR, PB period, LCOE) change by varying the input parameters.

Finally, Chapter 8 is dedicated to the conclusions and the limits of this study.

2 Literature Review

2.1 Targeting low-income communities

In the context of developing countries and low-income communities, most of the literature on renewable energy focus on the access to electricity through off-grid solutions in rural areas, while, generally, low attention is dedicated to solving electricity issues in urban areas. The aim of this section is to report relevant case studies within the scope of this Thesis, in the context of developing countries and low-income communities, on ways to provide energy.

2.1.1 Energy to low-income communities - a review

Table 2.1 reports the most relevant aspects of some the reviewed case studies.

Table 2.1: Energy to low-income communities, relevant aspects of selected case studies.

Case	Approach	Main Results	References
Muskegon and Oceana Urban Community, Michigan (USA)	Implementation through a grant of 83 domestic solar systems: PV, hot water, hot air	Investment of 12,000 USD/system. PB period of 5-15 years. Several Social Benefits reported	(Walton, 2014)
Residential Apartment in Akoka, Nigeria. Area with no constant electricity supply	Assessment for an hybrid renewable system: 2kW PV , 0.4 kW gasoline generator and 6 batteries (4 V)	Investment of 5807 USD. PB period less than 5 years.	(Babatunde et al., 2019)
Gobernador Crespo Community, Argentina	Implementation through a grant of an anaerobic digester for heating purposes, of 150m^3 for 4.25 tons/day organic waste	Investment of 117,895 USD. Biogas produced 55 m^3/day. Importance of the collaboration with the locals	(Vögeli et al., 2014)
Jardim Conceição community, São Paulo	Anaerobic digester plant designed for 100 people, with generator of 750 W for electricity pruposes	Investment of 5,888 USD. Requirement of external funding	(Junior et al., 2011)
Jardim Nosso 5 community, Barra Bonita, São Paulo state	Assessment of PV system, 2.1 kW per house	Investment of 4.584 USD/W. Economic viability only with the rise of electricity tariff	(Vale et al., 2017)
Social Housing Programs, Brazil	Assessment of PV system, 0.87-1.52 kW per house	Investment of 3,693-4,986 USD. Economically and environmentally feasible	(Pinto et al., 2016)

The study conducted by (Walton, 2014) on a solar project implemented in a low-income community in Michigan demonstrated that renewable energy systems offer different benefits, besides the economic and the environmental ones. The Muskegon and Oceana Community Action Partnership (MOCAP) in West Michigan, thanks to a grant offered by the Sustainable Energy for Consumers Grants, implemented more projects that involved PV systems, solar domestic hot water and solar hot air systems. MOCAP installed 78 residential units, 22 PV (each of 2.4 kW), 18 solar hot water, 37 solar hot air and 3 larger multi-unit systems for a total of 86 units. The average unit installed price was 12,000 USD with payback periods between five and 15 years. Surveys showed that locals were very satisfied with the installation, and especially with the PV system, whose economic benefits (improvement in utility bills) were more visible according to the users than the benefits brought by the Solar thermal system. Surveys found also that the installations brought other benefits rather than only economic improvements. In particular, the comfort increased, together with social interactions, a sense of environmental stewardship and the general interest associated to the technology. Grown interest was evident by attending programs on renewable energies and taking advantage of other educational opportunities related to the field.

(Babatunde, 2019) investigated on the optimum hybrid renewable energy system for a low-income residential apartment located in Akoka, Nigeria, an area that receive less than 8 hours per day of constant electricity supply. The system was designed through simulations conducted in HOMER software; according to the site's characteristics, photovoltaic panels, wind turbine, gasoline generator and battery bank were investigated. The best results were obtained for a system that involve 2 kW of PV panels, a gasoline generator of 0.4 kW and six batteries (4 V, 1900 Ah), with PV generation accounting for 97% and a monthly power peak of 0.37 kW of the production and the generator for 3% and a monthly power peak of 0.04 kW. Moreover, old equipment in the house was supposed to be retrofitted. The total investment cost resulted to be equivalent to 5807 USD, which include also the energy efficiency retrofitting.

According to (Mangoyana et al., 2011) decentralised bioenergy based systems, besides providing a sustainable form of energy, have the potential to boost local development, create local employment and take action in the climate change mitigation, and therefore they have a high potential for a positive impact in low-income communities. Community-based model involves the participation of the community members in the project, especially at the processing level to benefit from the economic revenues of value added products; the produced commodity is shared among the members to use in other systems or for local marketing.

A community-based success project in a low-income community involved the installation of an anaerobic digester, with a production capacity of 50 m^3/day, in Mbambara district in Uganda, with the scope of providing cooking energy to a local school. The plant was powered through cow dung provided by commercial local farmers. The project was financed mainly by the Australian Development Organisation and the school fees contribution. The project was driven by the need to improve and ensure local energy supply, which was before mainly based on wood, and to promote local development by extending the energy service.

Another example of successful community-based model, even though it didn't involve a low-income community, is the waste to energy project implemented in the village of Juhnde in Germany, where over 70% of the 800 inhabitants participated in a combined heat and power project, using residues from local farms as feedstock for the gas production. The project was mainly financed by the government with a 1.3 million EUR grant, while the participating locals contributed with a 1,500 EUR fee and costs for connecting the distributed heating. The total installed power corresponded 700 kW_{el} and 750 kW_{th}. In general, the project was a success in terms of emissions avoided and community engagement. Moreover, two jobs were created for running and administrating the plant.

The report by (Vögeli, 2014) analysed different case studies of anaerobic digestion systems in developing countries. In 1998 a Solid Waste Treatment Plant was installed in Gobernador Crespo, a community in Santa Fe Province, Argentina, thanks to the funding provided by World Bank. The plant consisted of an anaerobic digester with a volume of 150 m^3 (5.75 m diameter, total height 6 m), designed to treat the organic waste of 5500 inhabitants, for a total of 4,25 ton/day of organic waste; however, in 2008, it was reported that only 12 tons of organic waste were fed into the digester per month. The total investment cost amounted to 117,895 USD, plus it is estimated that 10,000 USD were invested for a modernisation of the plant in 2008. The total biogas production per day is estimated to be 55 m^3/day, and it is used for heating purposes. The authors reported that actually, the plant is not running at its total potentiality, and efforts should be done to increase the weekly feedstock. In fact, for successful community implementation of anaerobic digestion plants, not only the technology needs to be adequate, but people who participate in the project should understand and appreciate the potentiality of the system. Separation of the organic and inorganic waste at the source is an important way of collaborating; workshops and courses on the benefits of the digester plant and on how to segregate the waste can be a powerful tool for a successful operation of the system.

Also according to (Mayer et al., 2019), the key policy to achieve the maximum benefit from waste to energy facilities, is the source segregated collection of waste. In fact, if segregation is realized at the polluter, there are no additional expenses for the sorting of waste. In particular, in low-income areas, the segregation of organic waste produces several advantages; if the organic fraction is directed to biogas plants, the producible energy increases, the environmental impact is reduced and the recovery of nutrients is possible. In order to implement the policy, legal obligations or economic incentives can be involved.

(Junior, 2011) analysed the feasibility of the implementation of a micro anaerobic digestion plant in a low in come community in the outskirts of São Paulo, Jardim Conceição. The community has about 11,000 inhabitants, predominantly low-income families. It was estimated that production of biogas per capita would be 0.12 m^3/week; with such an amount, it would not be possible to use the biogas as a replacement for the liquefied petroleum gas used by the community. For electricity generation purposes, it was estimated that a minimum of 100 people should participate in the project; in this way, a 750 W generator could be installed with an investment cost of 10,970 BRL (corresponding to 5,888 USD in 2011). The author concluded that this investment would be very significant for low-income people, thus requiring external funding support from government or other sources.

(Njoh et al., 2019) reports the case study of the electrification through PV solar of Esaghem, a rural low-income community in Cameroon. Solar power was chosen due to the potentiality of the location. The community consists of 26 residential housing units and a communal hall for a total population of 100-150 people and a total energy requirement of 65.1 kWh/day. The solar PV project cost amounted to 4,600 USD and electrical engineer originals from the community donate their expertise during the design and implementation phases. The villagers also participated in the project and contributed donating the land and the manual labor necessary to complete the installation The author reported that several problems were experienced during the implementation of the project. The main problems were the lack of information of the customer, the vague custom clearance requirements and the lack of skilled technicians at the sub-national level.

Different studies on the potential use of PV system for low-income houses in Brazil exist. The study conducted by (Vale, 2017) assesses the economic viability of PV generation applied to the Brazilian housing program "Minha Casa Minha Vida", which is a federal program to fund housing for Brazilian low-income families in urban and rural areas. The analysis was conducted for the case study of Jardim Nosso 5 residential, a community in the city of Barra Bonita, in São Paulo state, composed of 510 housing unit. The analysis involved a standard PV system for each household of 2.1 kW, with a production equal to 1431 kWh/kW per year. It was estimated that the installed cost was 4.584 USD/W, for a total of 9626.4 USD. Economic results showed that the project could be economically viable only with a considerable rise of the electricity tariff, mainly due to the high investment cost of PV technologies. In particular, with a discount rate of 6.5% and a yearly increase of tariff of 7.0%, the NPV is positive.

(Pinto, 2016) assessed the deployment of PV energy for social housing programs in Brazil, which are funded by the Government. The most common financing plan offered to low-income consumers who wish to acquire a housing unit by means of a social program last 30 years. Different scenarios were analysed and all the results showed that PV systems are an environmentally and economically feasible alternative. In particular, case studies in different regions in Brazil were analysed, and it was estimated that between 868 and 1519 W should be installed so to cover part of the electricity demand, which is estimated to be on average 150 kWh/dwelling per month. The investment cost was estimated to be between 3,693 USD and 4,986 USD. From the dweller point of view, who would have a monthly increase in their financing plan's installment proportional to the installed capacity, the benefits would consist in avoiding electricity bills and, the household cash flow regarding electricity would be positive for all the scenarios investigated. On the other side, the government would benefit by redirecting the cost of generation from the national grid to the solar PV generation

2.1.2 Brazil Example - Insolar

Insolar is a Brazilian start-up founded in 2013 with the main aim of promoting access to affordable solar energy in urban low-income communities. Insolar follows the social business model, where 100% of business profit is reinvested in support of the business' mission (Insolar, 2019).

The social business concept was pioneered by the community development bank Grameen together with its founder Muhammad Yunus. This business model is a hybrid between a common profit-maximizing business and a non-profit organization. Social businesses operate like a regular business enterprise, with products, services, clients, markets, costs, and revenues; the difference relies on the fact that the owners do not have the purpose of making profits for themselves - even though they are entitled to recover their money if wished and surpluses are reinvested in the business itself. Moreover, like a non-profit organization, social businesses are cause-driven, instead of profit-driven; their main objective is to maximize the social value, seeking social benefits such as poverty reduction, social justice, and global sustainability. (Yunus et al., 2010).

The Brazilian start-up Insolar works in collaboration with low-income communities to install photovoltaic systems, with the scope of reducing the residents' electric energy bills and empowering the community, besides taking action for the environment. Santa Marta, in Rio de Janeiro, is the first community that collaborated with Insolar. They together designated the site locations that first would have received the installation of the solar systems, selecting the places from which the community benefits the most, such as institutions and small entrepreneurs. Community places involved nurseries, the residents' association, the local cable car, sports centers, and others, for a total of 200 solar modules installed. (Insolar, 2019).

The first community projects were sponsored through a grant obtained from a donor, with the expectation that, once the residents, both of Santa Marta and from other communities, would have seen the long-term benefits, they would have chosen to invest themselves, with the right financing system in place (Watts, 2016). Insolar currently has expanded its social business to 15 urban low-income communities and works in order to guarantee that the locals can acquire the system without compromise their budgets; the start-up, in fact, collaborates with financial institutions so that the residents are offered credits to purchase the technology and pay back in affordable monthly installments (Solar Impulse Foundation, 2019).

Also, pursuing a holistic and collaborative approach, Insolar helps to create a network of collaboration and partnerships between the community and third parties, such as financing institutions, NGOs, business entities, privates, technical experts; through this network, the locals have more possibilities to access the market and entrepreneurial opportunities. Insolar, through various collaborations, organizes workshops, interviews and training sessions so to engage the community and allow the residents to participate actively in the project. In fact, the installations in the community of Santa Marta were performed by a group of residents, who were first trained in basics electricity, safety, working in heights and PV installations.

In general, the whole projects gave positive results in terms of empowering the community: besides bringing economic advantages to the beneficiaries of the technology installation, more of the trained residents were motivated to start their own business activities, found a quality job, or return to study.

The main key factors of the social business are illustrated in Figure 2.1.

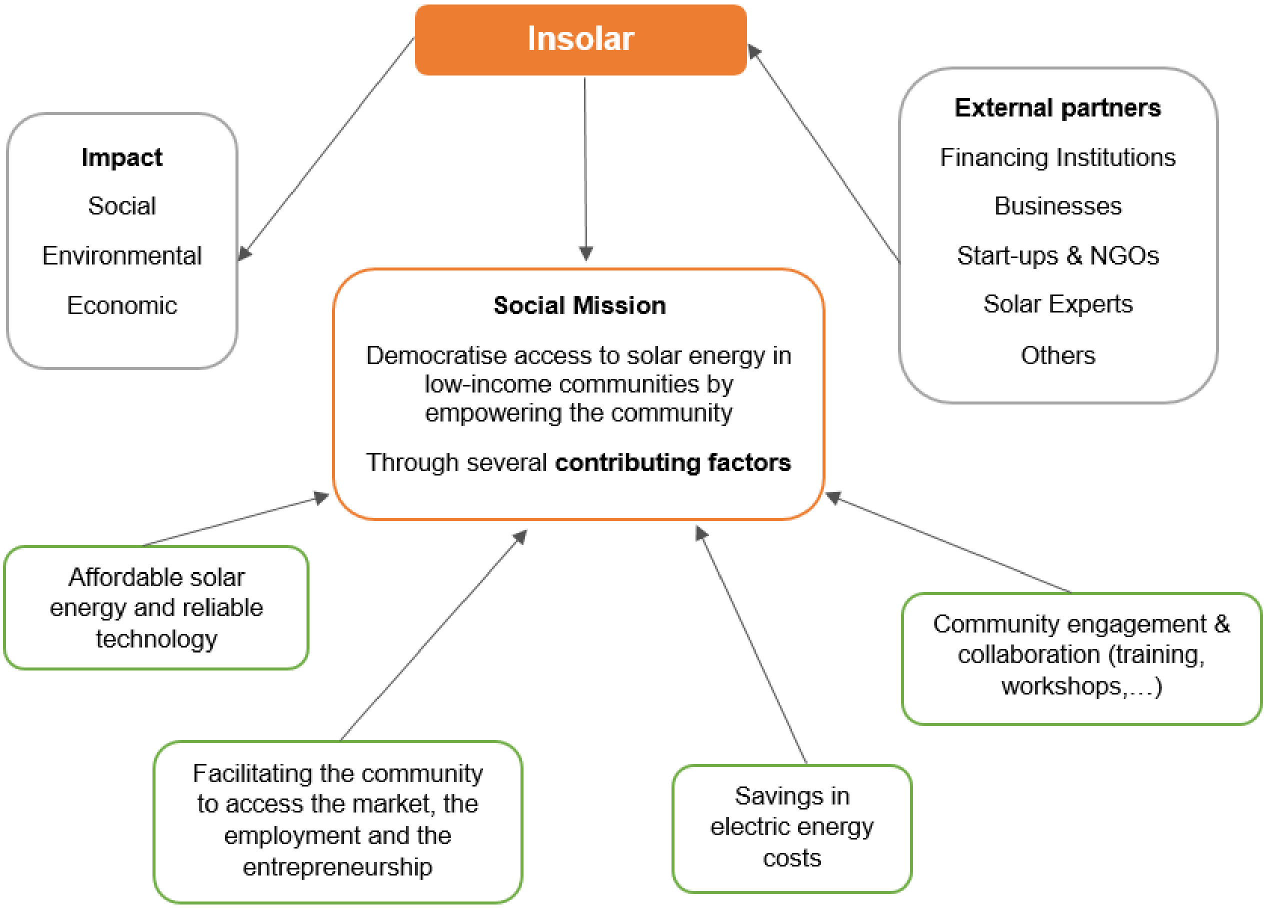

Figure 2.1: Insolar social business plan.

2.2 Electricity Sector in Brazil

2.2.1 National Electricity Production and Consumption

The Brazilian electricity sector is the largest in South America, counting a total installed capacity of 167,163 MW in 2019. Moreover, it is forecasted that during the next years a capacity of 23,302 MW will be added (ANEEL, 2019a).

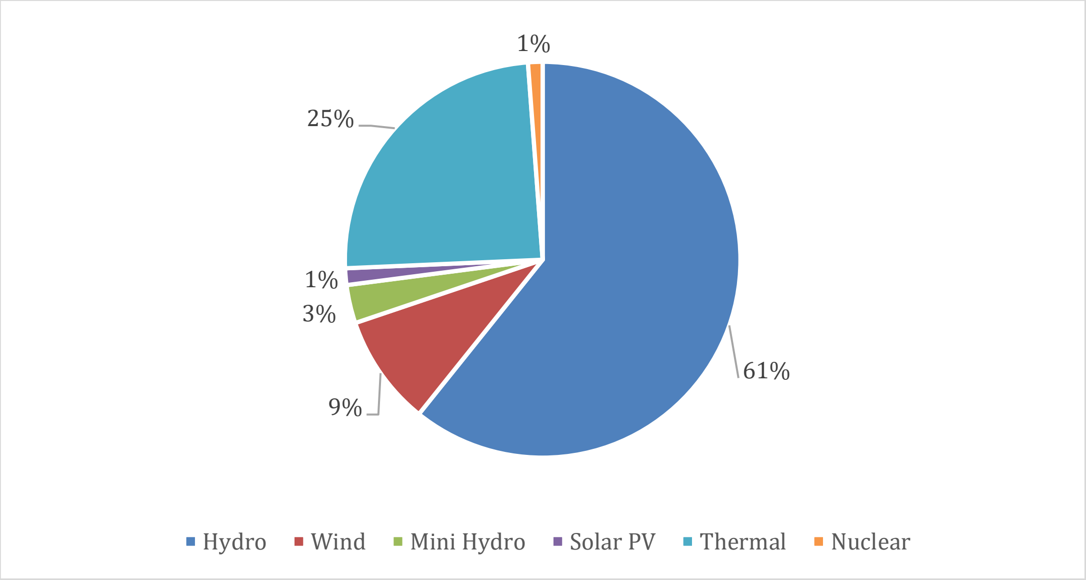

Figure 2.2: Electricity Matrix in Brazil. Source: (ANEEL, 2019a).

Figure 2.2 shows the electricity matrix in Brazil. Currently, most of the electricity production comes from Hydro generation, which accounts for the 64% of the total generation and makes Brazil a country with great renewable production. On the other hand, due to the extreme dependence from hydro resources, the Brazilian power sector has been plagued several times by crises associated with climatic conditions, with a frequency of 10-15 years (Hunt, 2018). The most recent crises took place in 2014 and 2015, caused by several draughts that occurred nationwide. Other renewable resources, like wind and solar, have increased gradually during the last years, reaching respectively the 9.06% and 1.36% of the total share. In particular, as regards solar energy, Brazil shows a huge potential, having a large geographic area with favourable irradiance conditions, but at the same time, the country presented different barriers to the massive introduction of this technology in the recent years, such as: the high cost of initial investment, the dependence on external financing for purchase the system, the reliance on imports of solar technologies from China, the lack of adequate policies (Garlet et al., 2019). However, nowadays solar PV technologies are becoming more competitive in Brazil and in the next years, 94 PV projects will be realized, for a capacity of 3.9 MW (ANEEL, 2019a).

In 2017 the total electricity consumption in Brazil amounted to 526.2 TWh, while the national production was about 624.3 TWh (EPE, 2018). However, it is forecasted that the electricity consumption will grow at a rate of 5% per year until 2023, much faster than the global average growth (Corrêa Da Silva et al., 2016). Due to the strong dependency on hydroelectricity, in order to guarantee a reliable supply, it will be necessary to diversify the electricity generation mix.

2.2.2 The Brazilian Legislative Framework for DG

In 2019, the total installed capacity of distributed micro and mini-generation exceeded the value of 1 GW in Brazil. Solar PV is the main source for DG, counting more than 870 MW of installed capacity, followed by micro and mini hydroelectric plants. According to ANEEL, this result was achieved thanks to the policies implemented in the last years. (ANEEL, 2019b).

This section discusses the main legislation in force in Brazil in relation to the distributed generation.

2.2.2.1 Normative Resolution 482

The Normative Resolution 482 (RN482), firstly introduced in 2012 by the Brazilian National Agency of Electric Energy (ANEEL), addressed for the first time in Brazil the topic of the penetration of small renewable power plants to the distribution network with the purpose of boosting them. The RN482 introduced the Net Metering scheme, according to which the system owner can inject into the grid network the surplus of energy receiving in exchange energy in the form of credits that can be used over the next 60 months; in this way, the grid acts the role of storing energy for the user and the system's profit relies on avoiding all or part of the electricity supply cost (Pillot et al., 2018; Vilaça Gomes, 2018). In 2015, ANEEL introduced some modifies to the RN482 through Normative Resolution 687. The RN687 allows the "shared generation", characterized by the union of more consumers, inside the same concession area, through consortiums or cooperatives (ANEEL, 2015b). Thus, the users can share the benefits of one solar distributed generation system, dividing the energy produced and the credits among their selves.

2.2.2.2 Normative Resolution 414

The Normative Resolution 414 (RN414) establishes the cost of electricity availability, which indicates the amount that has to be paid by the users to the distribution company in order to guarantee the electricity supply even if it is not used. In case of consumers with low-voltage connections (below 2.3 kV), the cost of electricity availability per month is equivalent to the consumption of: (1) 30 kWh if the grid connection is monophasic or biphasic with two conductors; (2) 50 kWh if it is biphasic with three conductors; (3) 100 kWh if it is three-phase (ANEEL, 2010). It is therefore essential to bear in mind this financial compensation while sizing the distributed energy system in order to do not oversize it.

2.2.2.3 Agreement ICMS 16

The Agreement 16 about the tax on commerce and services (ICMS), first approved under the National Council of Finance Policy (CONFAZ) in April 2015, states the tax exemption for operations related to the circulation of electric energy that are subject to the compensation scheme as described by the Normative Resolution 482 introduced by ANEEL (CONFAZ, 2018). Agreement 16 is currently in force in almost all the Brazilian Federal Units, among them the state of Rio de Janeiro. The ICMS exemption is applied to the quantity that corresponds to the sum of the electric energy injected into the grid plus the active energy credits produced in the consumer unit or in another consumer unit belonging to the same owner. The benefits apply only to the compensation of electric energy produced by micro or mini distributed generators, whose installed power is, respectively, less than or equal to 75 kW and more than 75 kW and less than or equal to 1 MW. The ICMS exemption doesn't apply to the cost of electricity availability and to any other value covered by the distribution company.

The same exemptions apply to the social contribution for social security financing (COFINS) and the employees' profit participation program (PIS) (Rosas Luna et al., 2019).

2.3 State of the Art of the Technologies

This section presents an overview of the two technologies investigated in this Thesis: the grid-connected PV system and the anaerobic digestion system. Regarding distributed generation PV systems, the main related business models are introduced.

2.3.1 Grid-connected PV Power System

Distributed photovoltaic power systems can be mainly differentiated in off-grid installations and grid-tie installations. In grid-connected configurations, the PV system is directly connected to the grid through a special inverter, whose main function is to transform the direct current (DC) generated by the PV modules into alternating current (AC), which can be supplied to conventional electrical devices. Grid interconnected PV system allows to have more effective utilization of the generated power, but at the same time they require more sophisticated inverter systems when compared with off-grid installations; the inverter must operate in phase with the grid, synchronizing the frequencies of the produced energy with the one provided by the grid. This is the main reason for which the grid-tie inverters have higher costs when compared to off-grid inverters. (Dantas et al., 2018).

A grid-tie configuration can be also equipped with battery back-up systems, in order to create a system that is not dependent on the grid, especially during outages and emergency situations. In fact, if a power outage due to the utility grid occurs, grid tie-systems with no batteries would not provide electricity to the users, even with having solar panels connected, because their reliance is based on the connectivity to the grid and the generation unit cannot disconnect from it (Eltawil et al., 2010). Nevertheless, battery back-up systems increase considerably the investment cost, and they will not be investigated further in this study.

Figure 2.3 illustrates a basic scheme of a grid-connected PV array without battery back-up system. The connection with the utility network can be realized through a circuit breaker on a distribution panel, or through a service tap localized between the distribution panel and the utility meter (Tobnaghi, 2016). In a grid-connected installation, when the power produced by the PV based system is lower than the local loads' consumption, the difference is supplied by the grid, while, if the production is higher than the consumption, the difference is injected into the grid, assuming that the local interconnection rules permit.

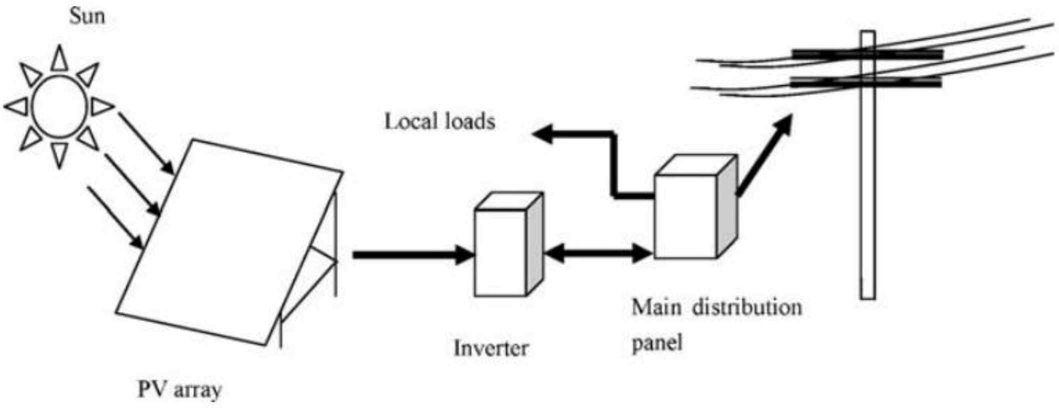

Figure 2.3: Grid-connected PV system. Source: (Eltawil, 2010).

2.3.1.1 Business Models and Financing Methods

This section discusses the main business models and financing methods adopted for distributed residential solar generation systems in Brazil; in fact, especially in the case of low-income markets, adequate business models and financing methods play a key role to guarantee the feasibility and the affordability of the project.

As regards business models, three main types were encountered:

- *Customer-owned model.*

  In this configuration, the owner of the PV system is the owner of the dwelling on which the power system is installed; the aim of the project is to satisfy the self-consumption, granted credits whenever the production exceeds the consumption (Zhang, 2016). The installation of the systems is generally done by a third party, who might or might not take care of the performance and maintenance. The main disadvantage of this model is the relatively high upfront cost, due to the fact that investment costs of PV systems increase with the decreasing of the power installed, namely, the more the users, the less the initial cost.

- *Third-party ownership model.*

  In this model, the solar system is owned by a third party, generally a company, who is responsible for all the logistics related to the project: the third party takes care of the installation, the maintenance, the engineering as well as of the whole investment and the other O&M costs (Mehmedova, 2016). The solar energy is offered as a service to the consumers by the PV system owner, either through a solar lease agreement, by which the customers pay a monthly rent to the company independently from the actual solar generation, or either through a solar power purchasing agreement, by which the customers pay the solar energy according to the generation per kWh (Soysal, 2017). Through third-party ownership models, the users have the great advantage of avoiding the investment and O&M costs of the project.

- *Community-Shared Model and Solar Cooperative*

  In the community-shared model, multiple individual customers share the ownership of a solar system connected with the utility grid. The customers purchase a part of the generation and receive proportional credits on their electricity bill (Zhang, 2016). This model is featured by several advantages, such as (1) reaching the cost efficiency thanks to the larger scale of the project, and (2) overcoming the site barriers that some households have, such as the home orientation, the shading or the inadequacy of the roof structure of supporting such a system. Solar cooperatives fall within the community-shared model, with the main difference that the co-owners generally participate in the management of the projects (Soysal, 2017).

Regarding the financing of PV distributed projects, three main ways exist: self-financing mode, external financing mode, or a combination of the two:

- *Self-Financing Mode*

  The self-financing mode implies that the owners of the system finance the project using their own income, without relying on external sources such as lenders or investors. It is a model that is widely adopted and it can include cash purchase, or home equity loans and line of credits (Zhang, 2016). Generally, the self-financing mode implies the lowest total cost, as there are no external interest rates or other kinds of transactions due to external financing. However, at the same time, it is likely that most of the households, especially in low-income communities, cannot bear the upfront cost related to a residential PV system, making this financing mode prohibitive, or even if they own enough savings to cover the whole initial costs, they might be reluctant in investing such an amount in a project whose economic benefits are more evident in the long-term, rather than in the short one.

- *External Financing*

  External financing may happen in different ways, whose characteristics might vary a lot according to the borrower's nature, whether it is represented by a business identity or a private customer. External financing can include: loans, public and governmental financings, crowd-funding financings, business angels, grant funds from donors, etc. (Mina et al., 2013).

2.3.2 Anaerobic Digestion Technology

Anaerobic digestion is a biological process that involves the bacterial breakdown of organic matters in the absence of oxygen. Through this process, a gas, called also biogas, mainly composed of methane and carbon dioxide, is produced. Three main steps characterize the anaerobic digestion: (1) decomposition of organic matter by bacteria into smaller molecules, such as sugar; (2) conversion of the matter into organic acids; (3) conversion of the organic acids into gas. Depending on the organic feedstock and the technology design, the biogas is composed typically by 55-75% of methane. Typical feedstock for anaerobic digester is: livestock manure, wet organic waste, sewage sludge. (Rogoff et al., 2011).

The biogas can be later used for the production of electricity, through an adequate engine, for the production of electricity and heat through combined heat and power system, or as a transport fuel. In Figure 2.4 it is possible to see a scheme of a typical anaerobic digestion plant and the possible end-use of the biogas and the bypass products.

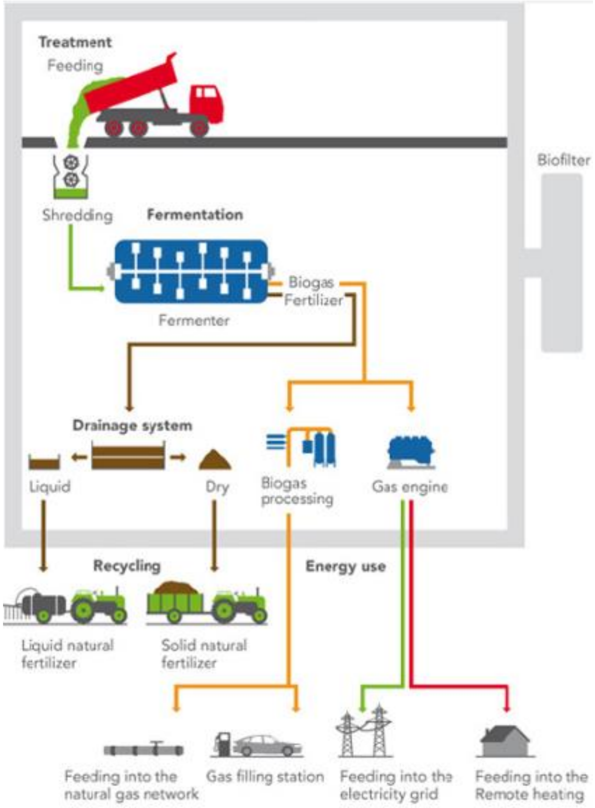

Figure 2.4: Anaerobic digestion system scheme. Source: (Li et al., 2011; R. E. dos Santos, 2019).

According to (Kalyani et al., 2014), the main advantages of anaerobic digestion systems, compared with other waste to energy technologies, are: (1) closed system (anaerobic digester) that enables to trap the gas produced efficiently; (2) control of GHG emissions and positive environmental gains; (3) no bad odors or visible pollution produced; (4) no social resistance; (5) compact design, few land area required. On the other hand, the main disadvantages are: (1) only suitable for waste containing high amounts of organic matters; (2) high investment cost; (3) requiring accurate waste segregation.

3 Case Study: Santa Marta Community

3.1 Location and Brief History

The community of Santa Marta is located on the Dona Marta hill, in the Botafogo neighbourhood, in the South Zone of the city of Rio de Janeiro, Brazil. According to the most recent census conducted in 2010 by the Brazilian Institute of Geography and Statistics (IBGE, 2013), Santa Marta has a total population of 3908 inhabitants, 1176 households, and a total occupied area of 53706 m^2. However, according to many other unofficial sources, the total population and the number of households would be much higher (F. Carvalho et al., 2012). Figure 3.1 shows the location of Rio de Janeiro in the state of Brazil, while Figure 3.2 illustrates the location of Santa Marta in the city of Rio de Janeiro. Figure 3.3 shows the satellite view of the Santa Marta area.

Figure 3.1: Location of Santa Marta in Brazil. Scale: 1 : 454^10^6. Source:(Google Maps, 2019c)

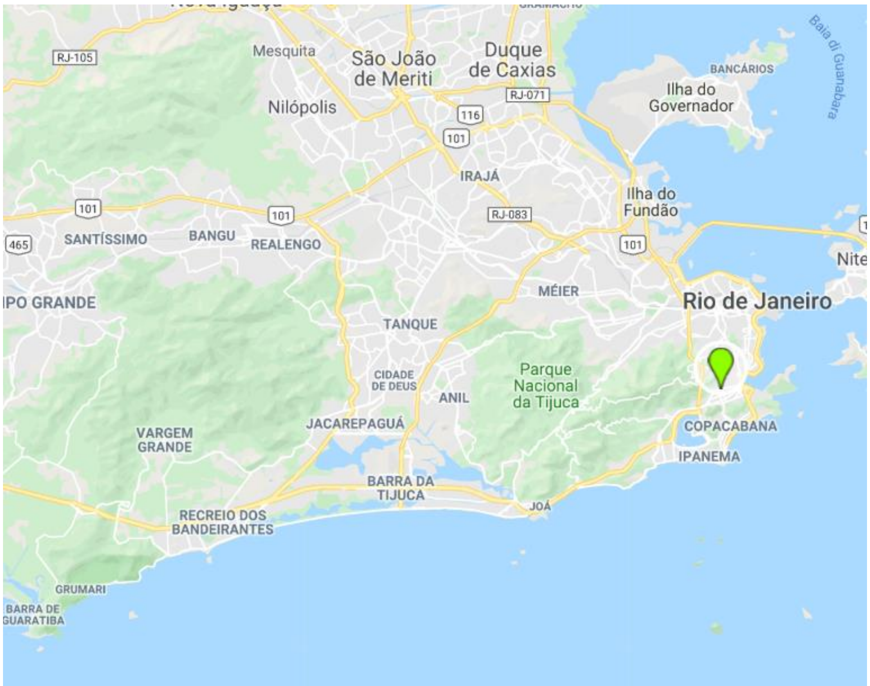

Figure 3.2: Location of Santa Marta in the city of Rio de Janeiro. Scale: 1 : 3.33 ^10^{6}. Source:(Google Maps, 2019d)

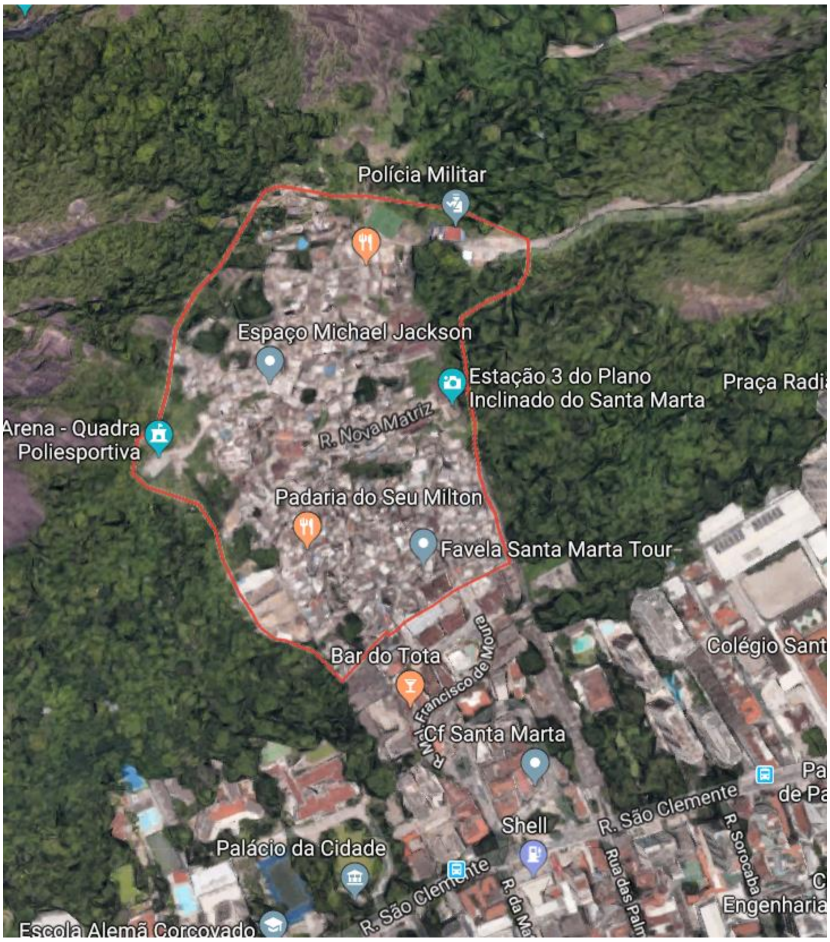

Figure 3.3: Satellite view of the community. Borders are marked in red colour. Scale: 1 : 5,555. Source: (Google Maps, 2019b).

Figure 3.3 shows the satellite view of the Santa Marta area. The community's boundaries are sharply delimited, and mainly for this reason, no significant increment of the population was recorded in recent years. In particular, the territory is delimited (F. Carvalho, 2012):

- On the South-West side by a wall built in 2009 with the aim of separating the *favela* from the territory of the City Palace and of protective the native vegetation. This fact caused many discontent among the community's inhabitants.
- On the Eastside by the cable car railway, which was inaugurated in 2008 by the government.
- On the Southside by the beginning of asphalt roads.

The spatial distribution of the favela is organized accordingly to the geography of the hill on which it stands. The lower part, which is the easiest to access from the city, is where the most valuable and stable houses are located and where there is the greatest demographic concentration; in this area the alleys and the streets are narrower and darker, thus contributing in the creation of an unhealthy environment. On the other side, while moving upfront, the favela became less and less densely populated and the buildings more and more unstable (Barbosa, 2016).

The birth of the Santa Marta community dates back to the late 20', when the first wooden houses were built on the hill mainly by the workers who came to participate to the construction works for the St. Ignatius College, a private Catholic school founded by the Society of Jesus and located in the Botafogo district. The population of Santa Marta began to increase significantly in the following decades, following the intensive real estate growth in the South Zone of the city, which required cheap labour for the civil works. It the census of 1950, 1632 inhabitants were already registered in the community. (Barbosa, 2016). Between 1982 and 1986, the wooden dwellings were transformed into brick dwellings, by the inhabitants themselves. In this period, the Government was still absent in the area and, for decades, the community was in the hands of drug lords. In December 2008, the community was brought under the control of the Police, with the installation of the first Pacification Police Unit (UPP) of the city of Rio de Janeiro, which established relationships with the government, social associations, and NGOs. After the pacification, many public services were introduced in the community such as: infrastructure projects, garbage collection, street lighting, post office. (WWP, 2015).

3.2 Electricity Service

The Santa Marta community is supplied by the utility company Light. Before the pacification of the favela (December 2008), irregular connections to the grid were quite diffused, implying payment default for the company, but also risks and unreliable power supply for the users. After the pacification, Light started the regularization of the electricity access process; in the early times, the utility company took actions with the aim of reducing illegal connection and promoting sustainable access to electricity by launching different programs such as the Social Tariff for Energy and the Recicla Light Program. In 2015, Light stated that illegal connections disappeared, and 100% of the households were connected to the grid (Mayrink, 2016).

However, in the past recent years, many of the inhabitants have been complaining about the electricity service. According to the locals, the tariffs prices are very high compared to the medium salary, and sometimes the bill doesn’t reflect the actual consumption. Moreover, the connection is not highly reliable: it is not rare that blackouts occur totally or partially in the community and the citizens blame the utility company for the slow service offered during these extreme events. (IPS, 2018; RioOnWatch, 2014).

3.2.1 Electricity Tariffs

Table 3.1 illustrates the electricity tariff for residential use in force from April 2019 in the municipalities supplied by the utility company Light (Light, 2019b).

Table 3.1: Low voltage tariff in USD/kWh for residential use, updated to August 2019. Source: (Light, 2019b).

Tariff with PIS/COFINS and ICMS				**Homologated Tariff by ANEEL without taxes**	**Tariff with PIS/COFINS without ICMS**
Up to 50 kWh	From 51 to 300 kWh	From 301 to 450 kWh	More than 450 kWh		
(no ICMS)	(ICMS 18%)	(ICMS 31%)	(ICMS 30%)		
0.162163	0.199985	0.240493	0.236802	0.154348	0.162163

Moreover, in 2015, (ANEEL, 2015a) introduced the tariff flag system. The system has three modalities: green, yellow and red and they indicate whether there is an increment of the final price of electricity, based on the electricity generation conditions. The green flag indicates favourable conditions and no increments are applied; with the yellow flag, the tariff increase of 0.015 BRL per consumed kWh; the red flag level 1 implies an increment of 0.040 BRL per kWh, while the red flag level 2 corresponds to an increment of 0.060 BRL per kWh.

To promote more affordable electricity access, Light provides the Social Tariff of Electric Energy, which is a special tariff that consists of a discount granted by the Brazilian Government on the electricity tariff (Light, 2019c). The discount varies within the range of 10% - 65%, according to the following conditions:

- First 30 kWh/month consumed => 65% discount
- From 30 kWh to 100 kWh/month => 40% discount
- From 100 kWh to 220 kWh/month => 10% discount
- More than 220 kWh/month => No discount.

The people who can benefit from the social tariff fall into the categories set out below:

- Families registered in the Single Registry for Social Programs of the Federal Government with a monthly income per capita less than or equal to half of the national minimum wage; or
- Who receives the Continuous Benefit of Social Assistance; or
- Families registered in the Single Registry with a monthly income up to three times the minimum wage, of which a member has a disease or disability, whose treatment or medical procedure requires the continuous use of an electrical device.

It is likely that some of the households in Santa Marta have access to the Social Tariff. Nevertheless, according to a study conducted in the low-income community of Babilonia in Rio de Janeiro (Moon, 2018), the Social Tariff doesn't work properly mainly because the requirements to get access to it are very restricted and it is not easy to register to obtain it. Considering that the study-case of Santa Marta shares many similarities with the one of Babilonia, it is probable that the same issues exist in Santa Marta.

3.2.2 Electricity Consumption

Table 3.2 reports the average values for the monthly electricity consumption per household in Santa Marta between 2010 and 2018. The data of the average monthly electricity consumption (kWh) per customer in the community and of the monthly number of clients over the period 2010-2018 were provided by (Light, 2019a).

Table 3.2: Average monthly electricity consumption per household in Santa Marta over the period 2010-2018. Source: (Light, 2019a).

Monthly electricity consumption (kWh)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
142	147	153	132	128	117	112	111	109	123	126	128

Figure 3.4 illustrates how the average monthly consumption per household varies throughout the year. The maximum consumption is reached in March while the minimum one occurs during the month of September. In general, the consumption registers an increasing trend during the period that goes from October to March, while the trend is decreasing over the period that goes from April to September. This trend can be related to the weather and climate conditions that characterize the city of Rio de Janeiro. The summer season – December to March – is hot and humid, with average high temperatures that climb to 30 °C in the hottest months of January and February. The winter period is warm and drier, and the coldest month is July, with the lowest average temperature of the year around 18.3 °C. Both autumn and spring have mild temperatures and are wetter than winters but drier than summers (Weather Atlas, 2019). The highest electricity consumption during summer periods is likely to be attributable to the usage of cooling systems, which can come in the form of air conditioners, in better-equipped houses, or in the form of fans.

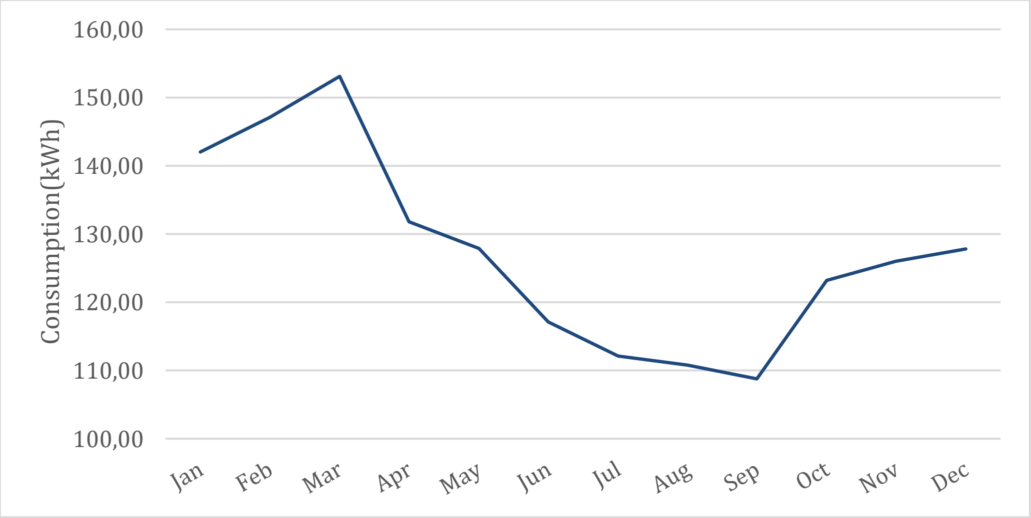

Figure 3.4: Average monthly electricity consumption per household in Santa Marta over the period 2010-2018.

Table 3.3 reports the whole consumption of the community over the period and the yearly average number of clients. In order to conduct the energy assessment, it was first deemed necessary to analyze critically the yearly energy demand trend of the community over the last 8 years.

Table 3.3: Yearly electricity consumption of the whole Santa Marta Community and the average number of clients. Source: (Light, 2019a).

Yearly Electricity Consumption (MWh) and Clients										
Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	Average

Clients	1594	1591	1616	1614	1631	1641	1644	1645	1638	1624
MWh	1934	2415	2644	2878	3119	2991	2459	2176	1707	2480

From Figure 3.5 it clearly emerges the discontinuous growth trend that characterizes the total demand. The trend of consumption grew rapidly from 2010 to 2011 (24.9 %), while it showed a linear increase (around 9 % every year) from 2011 until 2014 when it reached the maximum peak. From 2014 to 2015 the consumption slightly decreased (-4.1%), while it dramatically reduced during the period 2015-18. This decreasing trend is in contrast with the general forecast applicable to fast-developing countries as Brazil, according to which there will be an increment of the electricity consumption per capita, in relation to the economic growth and to the increment of the community prosperity. According to the World Bank, electric energy use grows more rapidly in low and middle-income communities (The World Bank, 2014), and there should be no exceptions for the case of Santa Marta.

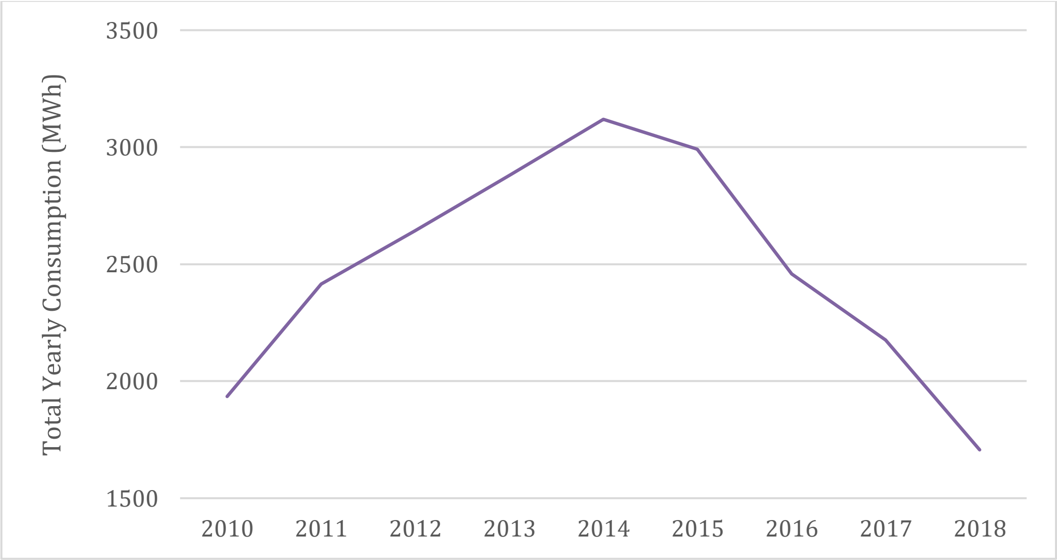

Figure 3.5: Electricity consumption in Santa Marta over the years 2010-2018. Source: (Light, 2019a).

In order to understand the drastic decrease in the consumption that occurred during the years 2015-18, it is possible to relate to the electricity production in Brazil over the same period. The International Energy Agency provides access to official data related to electric power generation in Brazil from 1971 to 2016 (International Energy Agency, 2018). Figure 3.6 illustrates the electricity generation in Brazil from 2010 to 2016. It is possible to notice how the trend of the generation is similar to the trend of the consumption in Santa Marta over the same period: the generation showed a linear increase from 2011 until 2014, year in which it reached its maximum peak. After 2014, it decreased, similarly to the trend of the demand. This decrease can be attributed to the crisis that plagued the Brazilian power sector in 2014 and 2015, caused by the draught that occurred nationwide and related to the strong dependency on the hydropower sector (Hunt, 2018).

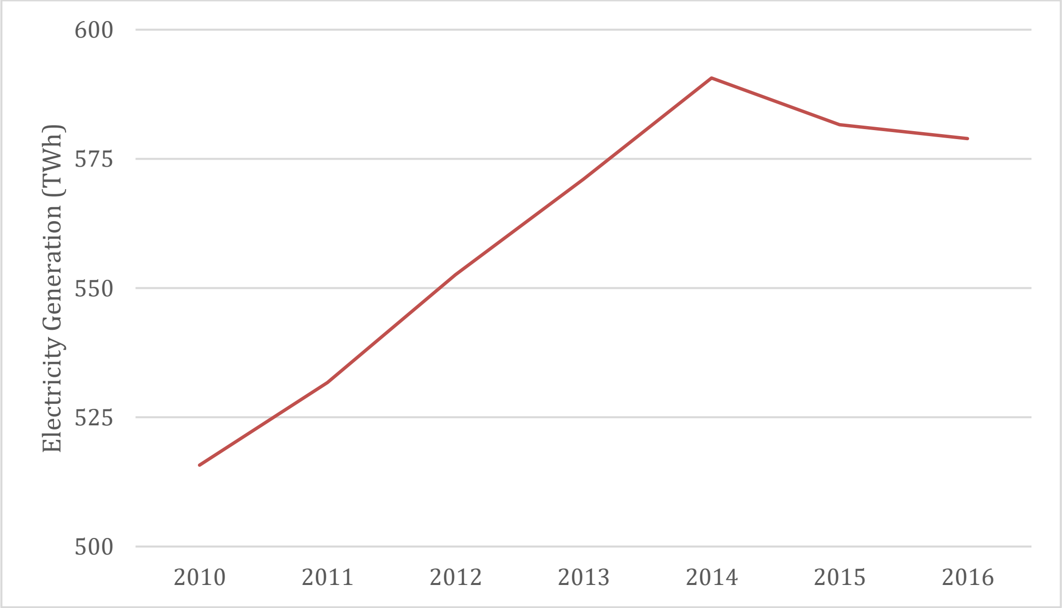

Figure 3.6: Electricity generation (TWh) in Brazil over the years 2010-16. Adapted from: (International Energy Agency, 2018).

3.3 Waste System

In this section the waste system is described due to its potential applications in waste to energy technologies.

The waste collection in the community of Santa Marta is managed by the *Companhia Municipal de Limpeza Urbana* (Comlurb) – Municipal Urban Cleaning Company – which is the main sanitation company operating in the waste collection, the final waste disposal, and the urban cleaning procedures in the city of Rio de Janeiro (Prefeitura da Cidade do Rio de Janeiro, 2009). In Santa Marta, Comlurb disposes of a team composed of 10 sanitation workers, who every day perform the sweeping service as well as the manual garbage collection from the two available collection points. Routinely, specific workers perform the cleaning of the hillsides by using the rappelling technique. Comlurb laments the presence of irregular disposals off schedule; its operators are thus trying to raise awareness among the inhabitants through different campaigns (Comlurb, 2019).

Although Comlurb provides a full waste collection service, the quality of the services provided in high-populated areas in irregular settlements is not at the same level as in formal neighbourhoods. This is partly due to the difficult access to these areas with standard waste collection vehicles, as many of the favelas - as in the case of Santa Marta - are located on forested hills in the city, and often the alleys inside the communities are too narrow to allow the passage of any kind of vehicle (Climate & Clean Air Coalition, 2017).

According to (Watanabe, 2015), while walking through the favela of Santa Marta it is possible to encounter a fair amount of garbage, open-air sewages, insects, and rats. In the author's opinion, the critical waste situation is not only attributable to the waste management company but mainly to the inhabitants' behaviour. In 2014, the inhabitants themselves launched the campaign *"Eu quero um Santa Marta limpo!"* - "I want a clean Santa Marta!" – whose main aim was to change the attitude of the community in relation to waste management practices, as well as to require improvements in the collection procedure (Schmitt, 2014). Seminars and workshops were the main tools used by this program to reach the inhabitants' behaviour. However, as appointed by (Comlurb, 2019), nowadays the waste issue still persists in Santa Marta.

The lack of correct waste management has a huge impact on the health of the society, the environment, and the economy. Inadequate – or absent – solid waste collection is proven to negatively affect human health. According to (Catapreta et al., 1999), children who are frequently exposed to the presence of uncollected waste, have 40% higher probabilities of contracting diarrheal, parasitic and dermatological diseases than not-exposed children. Moreover, many other health and environmental risks may occur when the waste contaminates the soil, the air, and the water.

3.3.1 Waste's characterization

Due to the inhabitants' lifestyle, the high rate of tourism, various street markets, over 50% of the total waste stream produced by the city of Rio de Janeiro is organic (Climate & Clean Air Coalition, 2017). Some of this organic matter is treated in designed compost facilities, but still the majority is disposed in landfills. According to (Comlurb, 2019), the waste collected in Santa Marta is not separated from the garbage collected in other areas. In 2012, Comlurb declared that the total daily amount produced in the favela was equal to 8 tons, thus corresponding to a yearly value of 2920 tons (V. Santos et al., 2012). Table 3.4 reports the gravimetric composition of the waste of the city of Rio de Janeiro for the year 2008-2011; it is here assumed that the urban waste in Santa Marta has the same gravimetric characteristics.

Table 3.4: Gravimetric composition (%) of urban waste in Rio de Janeiro. Years 2008-11. Source: (V. Santos, 2012).

Waste Gravimetric Composition (%)				
	2008	2009	2010	2011
Paper	15.96	16.08	16.46	16.84
Plastic	18.58	20.31	19.11	19.29
Glass	2.79	2.84	2.96	3.19
Organic Material	56.21	53.63	55.02	52.68
Others	6.46	7.14	6.45	8.00
Total	100	100	100	100

It is possible to observe in Table 3.4 that the organic fraction amounted to 52.68 % in 2011; according to a more recent source (Prefeitura da Cidade do Rio de Janeiro, 2015), the organic matter represented the 52 % of the domestic urban waste. Therefore, for future calculations, it is assumed an organic fraction equal to 52 %.

3.4 Renewable Energy Resources

Considering the characteristics of the location of Santa Marta, hydro and wind resources were excluded.

3.4.1 Solar Energy

Data Collection

The hourly solar irradiance data for the location of Santa Marta were retrieved from the Photovoltaic Geographical Information System (PVGIS) developed by the European Commission Science Hub (European Commision, 2019). In order to obtain the irradiance values, the PVGIS software requires to insert some inputs data. Firstly, specific geographical coordinates are required; in this case, they were retrieved from (Google Maps, 2019a) choosing a location inside the community of Santa Marta, obtaining the following latitude and longitude: (-22.947, -43.195). No terrain shadows were considered, as the knowledge of the area is not sufficient. Finally, the slope (inclination) and the azimuth (orientation) for the fixed plane irradiance are required: in this case, they were calculated through the software in order to optimize their values, obtaining a slope of 23 °, that is actually equal to the latitude, and an azimuth of -165°. It was then possible to retrieve the hourly values of the following quantities: date and time, global in-plane irradiance (W/m^2) and air temperature (°C). The hourly values were obtained for all the available years in the software whose hourly data were complete (2005, 2006, 2007, 2009, 2010, 2011, 2013, 2015); following, the hourly average values for a year were calculated, which were used for the energy assessment.

Data Analysis

Figure 3.7 illustrates the trends of the global irradiance of a typical day in Santa Marta for each month of the year. It is possible to notice that the month that records the highest irradiance is February, with a peak value of 907 W/m², while the month with the lowest peak value (681 W/m²) is June. As regards the monthly irradiance, the lowest values are recorded in the central months of the year, such as May, June and July, while the highest values are recorded in summer months, such as December, January and February.

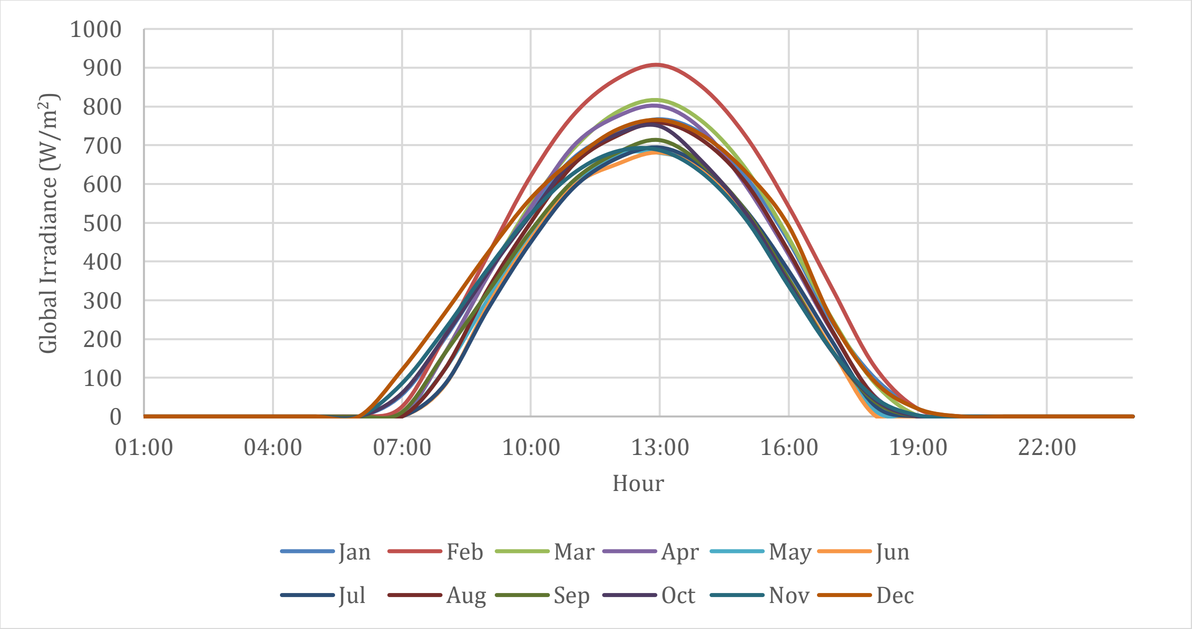

Figure 3.7: Global irradiance in Santa Marta, Rio de Janeiro, for a typical day for each month of the year (2001-17). Source: (European Commision, 2019).

It was calculated that the daily average irradiance corresponds to 4.64 kWh/m², or annually to 1695 kWh/m².

4 Energy Assessment

This chapter is dedicated to the proposal and the energy assessment of the power systems. Only two technologies will be proposed: solar PV and anaerobic digestion system. In fact, it was decided to investigate only renewable-based technologies, and, considering the characteristics of the case study, the two proposed systems were considered the most suitable to be investigated.

4.1 Assumptions

4.1.1 Population projection

When performing an energy-generation analysis over a pre-established period of time, it is necessary to consider the variation that may occur in the size of the population in the case study area. Many different population projection models are described in the literature and they vary according to the city's characteristics. Nevertheless, for the case study of Santa Marta, it was assumed that the population never increases or decreases over the chosen period of time. This choice is due to the fact that, as discussed in Section 3.1, the community is already saturated: the area is in fact sharply delimited by not-movable boundaries and it is already over-crowded.

4.1.2 Initial Electricity Consumption

Considering the arguments presented in Section 3.2.2, it was assumed that the actual electricity demand of the community that needs to be satisfied, is the one reached in 2014 and not the one registered in 2018. In fact, the decrease in the electricity consumption registered over the period 2014-2018 doesn't appear to be related to a reduction of the demand by the users, but it is likely attributable to a reduction of the offer from the utility company and in general from the Brazilian electricity sector over the same period. As regards the number of clients, its value fluctuated over the period 2010-2011. It was assumed a number of clients equal to 1640, which is slightly higher than the average number of clients over the period. Table 4.1 reports the electricity consumption assumed at the beginning of the project.

Table 4.1: Electricity consumption in the first year of the projects. Values per hh and for the whole community.

	Monthly electricity consumption											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
kWh/hh	162	217	193	163	172	138	144	135	131	152	147	157
MWh	269.0	355.9	316.5	267.3	282.2	226.3	236.2	221.4	214.8	249.3	241.1	257.5

4.1.3 Electricity Consumption Growth

In 2014 the average residential consumption in Brazil amounted to 53 kWh/person/month, while in the EU the average amounted to 129 KWh/person/month and in the US to 370 kWh/person/month (Medina et al., 2017). It is expected that, in Brazil, the domestic electricity consumption will increase in the coming years, in order to accommodate the economic growth, the population growth and the improvements related to the human development of Brazilian communities. It was assumed that, for the period of this study, there would not have been a growth in the population; nevertheless, it is likely that the community of Santa Marta will register an economic growth and development in the next coming years, followed by an increment of the energy demand. Long-term electricity demand forecast is a complex practice and several methodologies are described in the literature, however, for the scope of this study, an annual growth of 2.53 % (kWh/household) was assumed, based on the growth recorded between 2010 and 2014 in Brazil (Enerdata, 2016), as shown in Table 4.2.

Table 4.2: Average electricity consumption per electrified household in Brazil 2010-14. Source: (Enerdata, 2016).

Average electricity consumption per electrified household (kWh/hh)						
Year	2010	2011	2012	2013	2014	%/year
Consumption	1860	1868	1918	1990	2056	2,53

4.2 Photovoltaic System Energy Assessment

This section discusses the mathematical model adopted in this study to describe the behaviour of a photovoltaic module, as well as the methodology used to calculate the energy produced from a PV system, based on (Crispim, 2007).

4.2.1 Mathematical Model: The Single Diode Ideal Model

The mathematical model adopted in this study to compute the energy produced by a solar module is the single diode ideal model. The behaviour of a PV module depends both on the temperature and the solar irradiation, and it is this duplicity that makes this mathematical model relatively complex. The single diode model may involve a number of unknown parameters that vary according to the complexity of the configuration. For this study it was assumed that the solar cell behaves ideally, thus involving three unknown parameters. This configuration was adopted for its simplicity in computing the parameters while keeping the error lower when compared with more complex models such as the four parameters and the five parameters.

According to the three parameters model, it is possible to describe an ideal photovoltaic cell with an equivalent circuit composed by a single-diode in parallel with a power source, as shown in Figure 4.1.

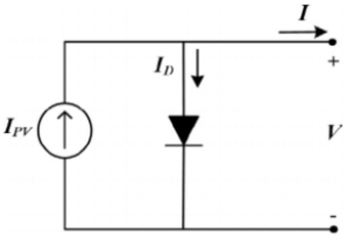

Figure 4.1: Equivalent circuit of the photovoltaic cell. Adapted from: (Villalva et al., 2009).

When the solar light hits the PV cell, a photoelectric current I_{PV} is generated: the value of this current is dependent and proportional to the solar irradiance G (W/m^2). The p-n junction of the cell acts as a diode, with the current I_d flowing through it, which depends on the voltage V at the cell terminals, as described by equation (1).

$$I_d = I_0(e^{\frac{V}{m\,V_T}} - 1) \tag{1}$$

Where V_T is the thermal voltage, described by equation (2).

$$V_T = \frac{K\,T}{q} \tag{2}$$

K is the Boltzmann's constant (K = 1.381 x 10^{-23} J/K), q is the electron charge (q = 1.602 x 10^{-19} C) and T is the cell temperature (K), expressed by equation (3).

$$T = T_{amb} + \frac{(NOCT - 20)G}{800} \tag{3}$$

Where T_{amb} is the ambient temperature (K) and NOCT (Normal Operating Cell Temperature) is the expected cell temperature in a module when ambient is at 20°C, solar irradiance at 800 W/m^2 and wind speed is 1 m/s, and it is given by the manufacturer.

By analyzing the circuit (Figure 4.1) and applying the Kirchoff law, it is possible to deduce the following equation (4), which represents the governing equation for the single diode ideal model.

$$I = I_{pv} - I_d = I_{pv} - I_0(e^{\frac{V}{m\,V_T}} - 1) \tag{4}$$

In order to determine the three parameters of the model, it is necessary to consider the following equations (5)-(6)-(7), derived from equation (4) respectively when the cell operates at the open circuit (oc) point, at the short circuit (sc) point, and at the maximum (max) power point.

$$0 = I_{pv}^r - I_0^r \left(e^{\frac{V_{oc}^r}{mV_T^r}} - 1 \right) \tag{5}$$

$$I_{pv}^r = I_{sc}^r \tag{6}$$

$$I_{max}^r = I_{pv}^r - I_0^r \left(e^{\frac{V_{max}^r}{m\,V_T^r}} - 1 \right) \tag{7}$$

The apex *r* refers to values that are measured under reference conditions, also called standard test conditions: they are the industry standard for the conditions under which a solar module is tested. Standard test conditions imply a temperature of the solar cell of 25°C, a solar irradiance of 1000 W/m^2 and an air mass of 1.5. Considering (5) and (6) it is possible to write:

$$I_0^r = \frac{I_{sc}^r}{e^{\frac{V_{oc}^r}{m\,V_T^r}} - 1} \tag{8}$$

Applying equation (8) in (7) it is possible to deduce:

$$m = \frac{(V_{max}^r - V_{oc}^r)}{V_T^r\; ln\left(1 - \frac{I_{max}^r}{I_{sc}^r}\right)} \tag{9}$$

Thus, the three parameters are identified with I_{pv}, I_0 and m and the model can be solved using the equations (6), (8) and (9). The ideality factor m is a constant parameter of the solar module and it can be computed through the data given by the panels' manufacturer.

4.2.2 Yearly Energy Production

When calculating the energy generated from a solar module, it is necessary to consider how the temperature and the irradiance influence the maximum power production. It is possible to find that the short circuit current is linearly dependent on the irradiance, as described by equation (10). On the other hand, the diode saturation current depends on the temperature, according to (11), and also the energy gap factor depends on the temperature, according to (12).

$$I_{sc} = I_{sc}^r \frac{G}{G^r} \tag{10}$$

$$I_0 = I_0^r \left(\frac{T}{T^r}\right)^3 exp\left(\frac{qN_s}{m}\left(\frac{E_g^r}{K\,T^r} - \frac{E_g}{K\,T}\right)\right) \tag{11}$$

$$\frac{E_g}{E_g^r} = 1 - C(T - T^r) \tag{12}$$

Where $E_g^r = 1.121\;eV$ and $C = 0.0002677$.

The power output of a solar module is given by equation (13). Applying equation (4) and (6) in (13), deriving (13) and imposing it equal to zero it is possible to characterize the maximum power point operation according to (14). Equation (14) is a non-linear equation and requires an iterative method to be solved and to find the value of maximum power voltage; for this study, it was solved through the Goal Seek function in the Excel software. Once the maximum power voltage is found, it is possible to compute the maximum power current through equation (7) and finally the maximum power output through equation (13).

$$P = V_{max} \cdot I_{max} \tag{13}$$

$$\frac{dP}{dV} = 0 \Leftrightarrow e^{\frac{V_{max}}{m\,V_T^r}} = \frac{\left(\frac{I_{sc}}{I_0^r} + 1\right)}{\left(1 + \frac{V_{max}}{m\,V_T^r}\right)} \tag{14}$$

PV modules generate DC power (equation (13)) and in order to supply it to the grid or to the final users, it is necessary to convert it in AC power. The power is degraded due to many factors, such as the site characteristics, the system design and the quality of the components; these factors are known as *derate factors*. Equation (15) describes the energy produced by PV panels based system over a certain period, considering the overall derating of the system.

$$E_i = \sum_{j=1}^{ni} P_{j,i}^{max} \cdot \Delta t \cdot Derate \tag{15}$$

In this study hourly intervals *j* were considered through all the year, as described in section 3.4.1., and the energy output was calculated for each month *i* of the year. The calculation was carried for 25 years, based on the PV module assumed useful life. Equation (15) involves the maximum power due to the fact that PV based systems are provided with a component whose aim is to make the system always operating at the maximum power point, called Maximum Power Point Tracker (MPPT). The overall derate factor, excluding the temperature effects which are considered as in (12) and (13), involves the following derate factors (Enphase Energy, 2014):

- PV module nameplate DC rating.
- Inverter and transformer: it accounts for the efficiencies of the inverter and the transformer in operating the conversion from DC to AC power.
- Module mismatch: it accounts for the mismatch that occurs when more modules are connected together electrically, as they do not operate at their maximum peak efficiency.

- DC and AC wiring derate.
- Soiling: this derate factor takes into account dirt, snow or other matter on the surface of the PV panel that induces a reduction in the amount of solar irradiation reaching the solar cell of the module.
- System availability: this parameter considers the times when the PV system is off because of maintenance or utility and inverter outages.
- Shading: the shading derate factor is associated with the moments when the PV modules are shaded by surrounding objects, like nearby buildings, trees, or other PV modules.
- Sun tracking.
- Age.

4.2.3 Characterization of the System's Components

The PV module adopted to carry on the power calculation is the Canadian Solar CS6U-330 P, whose main characteristics, used in this study, are reported in Table 4.3. This module was adopted due to the fact that the Canadian Solar corporation is a PV project developer and a solar panels manufacturer that is largely recognized worldwide; in particular, it is the leading company in the Brazilian solar photovoltaic distributed generation market, representing the first chosen brand by local companies and users in respect to solar modules (Greener, 2018). Moreover, the Canadian Solar modules represent the main choice for Insolar, which operates in Santa Marta. The useful life of the PV modules, as well as the PV project lifetime, is assumed to be 25 years.

Table 4.3: Data for the Canadian Solar CS6U-330 P solar module. Source: (Canadian Solar, 2016).

ELECTRICAL DATA STC		
Nominal Max. Power	P_{max}	330 W
Opt. Operating Voltage	V_{max}	37.2 V
Opt. Operating Current	I_{max}	8.88 A
Open Circuit Voltage	V_{oc}	45.6 V
Short Circuit Current	I_{sc}	9.45 A
Module efficiency	-	16.97%
MECHANICAL DATA		

Cell type	-	Poly-crystalline
Cell Arrangement	N_s	72
Dimensions	-	196x99.2x4 cm
Guaranteed Lifetime	-	25 years
TEMPERATURE CHARACTERISTICS		
Temperature Coefficient (I_{sc})	α	0.053 %/°C
Temperature Coefficient (P_{max})	-	-0.41 %/°C
Nominal Operating Cell Temperature	NOCT	45 °C

In order to carry on the computation for this study, it was necessary to characterize the inverter's efficiency and lifetime. Table 4.4 reports the inverter's characteristics: the efficiency is adopted based on the values characterizing the monophasic inverters manufactured by Fronius (Fronius, 2015), which is the leading company as regards inverters in the Brazilian distributed generation market (Greener, 2018). The lifetime of the inverter was assumed to be equal to 12.5 years, based on (Vilaça Gomes, 2018).

Table 4.4: Inverter characteristics.

Inverter Efficiency	η_{inv}	97.1 %
Inverter Lifetime	-	12.5

As regards the derate factors, Table 4.5 shows the typical reference ranges for these parameters adopted from (Marion et al., 2005) as well as the values assumed to conduct this study.

Table 4.5: Derate factors for the PV system.

Item	**Assumed Derating**	**Range**
Nameplate DC rating	0.95	0.8 – 1.05
Inverter and transformer	0.971	0.88 – 0.98
Module mismatch	0.98	0.97 – 0.995
Diodes and Connection	1.00	0.99 – 0.997

DC wiring	0.98	0.97 – 0.99
AC wiring	0.99	0.98 – 0.993
Soiling	0.95	0.3 – 0.995
System Availability	0.98	0 – 0.995
Shading	1.00	0 – 0.995
Sun tracking	1.00	0.95 – 1.00
Age	1.00	0.7 – 1.00
Overall Derate Factor	0.8165	

Finally, it was assumed that the power produced by the PV modules declines annually at a rate of 0.5 %, as the maximum annual power decline is stated to be 0.7% based on (Canadian Solar, 2018).

4.3 Anaerobic Digestion System Energy Assessment

The methodology used to calculate the electric energy produced by the anaerobic digestion system is based on a study conducted for a Brazilian municipality by (R. E. dos Santos, 2019). The lifetime of the project is assumed to be 16 years, starting from 2020. As adopted in the aforementioned study, the annual growth for the produced waste is assumed at 1%. In 2012, Comlurb declared that Santa Marta produced every day 8 tons of waste (V. Santos, 2012); therefore, it was calculated that the total waste collected in the year 2020 would amount to 8.66 tons/day.

The energy produced was calculated on a yearly basis, following equations (16)-(21).

$$W_i = W_{i-1} \cdot (1 + \lambda) \tag{16}$$

$$W_{o,i} = W_i \cdot F_o \tag{17}$$

$$Q_{BG,i} = W_{o,i} \cdot I_{BG} \tag{18}$$

$$Q_{col,i} = Q_{BG,i} \cdot \eta_{col,i} \tag{19}$$

$$P_i = Q_{col,i} \cdot \eta_{conv} \cdot LCV_{BG} \tag{20}$$

$$E_i = P_i \cdot F_C \cdot 8760 \tag{21}$$

The yearly amount of total waste collected was computed through equation (16). The available organic waste W_o (t/y) was calculated according to equation (17), where the organic fraction was assumed to be 52% (see Section 3.3.1). The total amount of biogas produced from the anaerobic digester was estimated following equation (18). The average amount of biogas I_{BG} produced by the digester was adopted from the literature (Henríquez, 2016) as 119 m^3/t, based on worldwide installed digesters working at a temperature of approximately 35 °C. The quantity of biogas collected was calculated through equation (19), assuming a collection efficiency of 90%, based on (C. R. Faulhaber et al., 2012). Lastly, the yearly available power and energy which can be produced from the biogas were computed according to equations (20) and (21). The energy conversion efficiency was assumed at 33%, considering an internal combustion motor, based on (Ferreira et al., 2014). The lower calorific value of the produced biogas was assumed to be 22 MJ/m^3, based on (Guerini Filho et al., 2018). Finally, the capacity factor was hypothesized to be equal to 80% (R. E. dos Santos, 2019). The self-consumption of the anaerobic digestion plant was not considered in this study.

5 Economic Assessment

5.1 Methodology for the Profitability Evaluation

With the aim of assessing the profitability of the realization of both the projects, the Cash Flow (CF), the Net Present Value (NPV), the Internal Rate of Return (IRR), the payback time (PB), and the Levelized Cost of Electricity (LCOE) were evaluated.

$$CF_{i(t)} = R_{i(t)} - C_{i(t)} \tag{22}$$

$$NPV = \sum_{i=0}^{N} \frac{CF_i}{(1+r)^i} \tag{23}$$

$$0 = \sum_{i=0}^{N} \frac{CF_i}{(1+IRR)^i} \tag{24}$$

$$LCOE = \frac{\sum_{i=0}^{N} \frac{C_i}{(1+r)^i}}{\sum_{i=0}^{N} \frac{E_{gen,i}}{(1+r)^i}} \tag{25}$$

The Cash Flows, calculated through equation (22), express the difference between the revenues (cash inflow) and the expenditures (cash outflow) over the same time period (Lester, 2017). The Net Present Value was computed through equation (23). The NPV provides a strong decision criterion for investment: it calculates the amount of money that investment exceeds or fails to meet. When the NPV is positive, the rate of return of the investment is higher than the opportunity cost of capital, and therefore, generally, the project should be accepted (McAllister, 2013). The Internal Rate of Return, computed through equation (24), expresses the discount rate when the NPV of the project is exactly equal to zero. Also, the IRR represents a valid decision metric of the profitability of a project: the higher the IRR, the more economic potential has a project, and it must be higher than the cost of the capital to create value for the investor (Belyadi et al., 2017). As regards the Payback Time, it is defined as the minimum time taken by the project to recover the total investment costs (Gude, 2018), and, since the annual revenues are not constants, it was computed by analyzing the cumulative cash flows. Finally, the Levelized Cost of Electricity was calculated through equation (25), based on (R. E. dos Santos, 2019; Vilaça Gomes, 2018). If the value of the LCOE is lower than the local energy market prices, or at least close to it, it means that the renewable technology is economically competitive.

The cost of opportunity (annual discount rate) was assumed at 6%, based on (Pinto, 2016; Vilaça Gomes, 2018), thus obtaining an equivalent monthly rate of 0.487%. This annual rate almost corresponds to the average return of savings in Brazil, which was highly stable over the last years.

5.2 PV System Economic Assessment

The cost analysis of the PV system was conducted assuming three different financing modes; for all the three modes, the analysis was performed on a monthly basis, therefore the subscripts i are to referred to monthly values. The project lifetime is assumed to be 25 years, with no residual value of the components, starting from year 2020.

5.2.1 Business Model Proposal

Considering the site characteristics, the Community-Shared Model and Solar Cooperative model seemed to be the most promising one; therefore, the proposal is to implement the PV project through the creation of multiple solar cooperatives inside the community of Santa Marta. This business model for solar distributed generation would bring several advantages when compared to single-household installation: it ensures to reach the cost efficiency, thanks to the larger scale of the project, and it allows to overcome site issue. In fact, it is likely that many of the households in Santa Marta cannot install a PV system on the rooftop, due to shadowing, orientation, and inadequacy of the roof structure. With the cooperative model, the most adequate dwellings would be chosen according to the site characteristics to receive the PV technologies, and at the same time, other households with no site potentiality would be given the possibility to participate and benefit from the project.

The capacity to be installed for a single solar cooperative should take into account different factors, such as the number of participants and the roof area and structure of the dwelling designated to receive the system. Also, it is necessary to consider that the lowest possible investment cost per Watt is obtained with the highest possible installed capacity, for a maximum of 1 GW installed, which is the upper limit for the distributed generation system.

Moreover, similar to Insolar business model, it is supposed that there would be one entity that is in charge of collaborating with the community and that would take care of: (1) the engineering of the project; (2) the mediation with financial and governmental institutions to eventually offer credits and grants to the customers; (3) the training of part of the locals to allow them to take care of the installation and the O&M of the technology; (4) sensitizing the locals on different topics related to the project and involving them through courses, classes, workshops.

It is supposed that the tool to support all of these goals would be the collaboration with multiple variegated partners, such as NGOs, privates, solar technicians, business entities, and so on, in order to create a bridge between the community and entrepreneurial and job opportunities, with the aim of maximizing the social value and empowering the community.

For future calculation, it was assumed that all the households in the community would participate in the project.

5.2.2 Financing Mode 1: Self Financing

In Financing Mode 1, it is assumed that the residents would finance themselves the totality of the investment costs, following the methodology described in Section 2.3.1.1. In this case, the total monthly costs were calculated through equation (26), which was adapted from (Vilaça Gomes, 2018), summing the contributions of the investment costs, the operation and maintenance costs and the monthly electricity bill.

$$C_i = I_i + O\&M_i + B_i \tag{26}$$

5.2.2.1 Investment and O&M costs

Since different scenarios will be investigated for the PV solar system, a fixed investment price per Watt installed was used. Firstly, the total investment cost of the PV based power system was calculated by summing up the cost of each component, mainly based on an economic viability study for PV systems in Brazil conducted in 2018 (Dantas, 2018). The hypothesis assumed to calculate the investment unit price are the following:

- All the 1640 households participate in the project;
- Six solar modules per household are installed (around six modules would cover the energy demand requested at half of the lifetime of the project, considering the equivalent demand of electricity availability);

- The households are organized in cooperatives of five units each thus obtaining a total of 328 cooperatives, for a total of 30 solar modules (equivalent to 9.9 kW) per cooperative and one inverter unit of 8.2 kW.

It is remarkable to mention that these assumptions were made with the only purpose of assessing the investment price, and, bearing in mind the aim of this study, configurations and arrays will not be further investigated. Table 5.1 reports the prices for the equipment, the quantities, and the sources as well. All the listed costs are reported in USD: for the conversion rate, it was assumed that 1 USD is equal to 3.9002 BRL, based on the average conversion rate registered in the period March-August 2019 (Exchange Rates, 2019).

Table 5.1: Investment cost (USD) for the PV System.

Component	Price	Unit	Quantity	Investment	Source
PV Module	174.1	USD/module	9840	1,713,081	(Minha Casa Solar, 2019b)
Inverter	3630	USD/unit	328	1,190,747	(Minha Casa Solar, 2019a)
Safety Box	450.5	USD/unit	328	147,761	(Dantas, 2018)
Instalment	64.10	USD/module	9840	630,737	(Dantas and Pompermayer, 2018)
Electrical Wiring	305.4	USD/house	1640	500,805	(Pinto, 2016)
Total	-	USD	-	4,183,131	-
Total	-	USD/W	-	1.288	-

Following this methodology, the total upfront cost resulted to be 4,183,131 USD for 3247.2 kW of installed power, thus obtaining 1.288 USD/W, which will be the value assumed for this study. The inverters' investment represents the 28.5% of the initial cost; this value is consistent with the shares calculated by (Lacchini et al., 2015) and (Dantas, 2018) who report respectively 30% and 29%. The inverter lifetime was assumed to be 12.5 years, therefore it is supposed that the inverters are replaced at half of the project lifetime.

The annual O&M cost is set at 1% of the total investment, based on different solar projects (EPE, 2012; Miranda et al., 2015; Moon, 2018). Generally, a photovoltaic system requires very little maintenance over its useful lifetime; maintenance operations mainly involve periodical cleanings, which are necessary, and replacement of the inverters or other components.

Comparison of the investment cost with values from other sources

The investment cost obtained with the methodology presented in this section was compared with the different sources available in the literature. In general, the result was found to be quite lower than most of the other values reported in the literature of the past recent years. According to the International Renewable Energy Agency (IRENA, 2018), the average total installed cost for solar PV residential systems in Brazil decreased by 26% between 2007 and 2017, reaching a value of 2,5 USD/W in 2017. According to a study conducted in Brazil in 2015 based on direct consultation with official suppliers established in the country, a complete installed PV distributed system in Brazil cost from 8 BRL/W to 10 BRL/W, equivalent to 2.4 USD/W and to 3.0 USD/W with the conversion rate of 2015 (Miranda, 2015; OECD, 2018). A more recent source reported that in the southern region of Rio Grande do Sul, the initial cost of a median residential PV system with a nominal power of 3.84 kW was equal to 1.96 USD/W (Pillot, 2018). This value is still relatively high when compared with the result obtained in this study. However, it was found that, in recent years, the cost of photovoltaic based technologies is rapidly decreasing with time in Brazil, and these systems will significantly increase their competitiveness in the near future (Garlet, 2019).

The Brazilian Research and Consulting company Greener, publishes regular reports on the Brazilian market of distributed solar generation. (Greener, 2019) reported the average national prices for final users (in BRL/W), updated to December 2018, as in Table 5.2. For the currency conversion, it was assumed that 1 USD was equal to 3.8813 BRL in December 2018.

Table 5.2: Prices of solar distributed generation for final clients, updated to December 2018. Source: (Greener, 2019).

Power	**2 kW**	**4 kW**	**8 kW**	**12 kW**	**30 kW**
Maximum Price (USD/W)	2.00	1.59	1.42	1.37	1.23
Average Price (USD/W)	1.67	1.35	1.22	1.17	1.04
Minimum Price (USD/W)	1.34	1.10	1.02	0.97	0.84

It is possible to see that the prices in Table 5.2 are significantly lower if compared with the values found for the last recent years. Also, according to (Greener, 2019), the final prices reduced on average by 7.5% between June 2018 and January 2019. The obtained value of 1.288 USD/W, assuming an 8.2 kW inverter and 9.9 kW installed, is consistent with the average price reported by (Greener, 2019) for the 8 kW system. Therefore, the calculated value will be kept for conducting the economic assessment.

5.2.2.2 Electricity Bill & Revenues

The electric energy bill calculation was mainly based on (Vilaça Gomes, 2018) and it was performed for all the 300 months of the lifetime of the project. The sets of equations (27)-(36) were used to carry on the computation. The energy bill was computed for one client and then multiplied by the number of households in the community, given that if it had been computed for the whole community from the beginning, the taxes applicable to the energy balance would have been considerably higher.

$$E_{PV,i,t} = E_{PV,i,t=1} \cdot (1-\delta)^{t-1} \qquad \forall\, t > 1 \tag{27}$$

$$E_{req,i,t} = E_{req,i,t=1} \cdot (1+\gamma)^{t-1} \qquad \forall\, t > 1 \tag{28}$$

$$EB_i = E_{PV,i} - E_{req,i} \tag{29}$$

$$CR_i = \begin{cases} EB_i & if\ EB_i > 0 \\ 0 & otherwise \end{cases} \tag{30}$$

$$EB_{neg,i} = \begin{cases} EB_i & if\ EB_i < 0 \\ 0 & otherwise \end{cases} \tag{31}$$

$$X_i = \begin{cases} 0 & if\ i < 61 \\ CR_{i-60} + \sum_{i=1}^{60} EB_{neg,i} & if\ i = 61 \\ CR_{i-60} + EB_{neg,i-1} + X_{i-1} & if\ i > 61\ and\ X_{i-1} < 0 \\ CR_{i-60} + EB_{neg,i-1} & if\ i > 61\ and\ X_{i-1} > 0 \end{cases} \tag{32}$$

$$CR_i' = \begin{cases} CR_i & if\ X_i \leq 0 \\ CR_i - X_i & otherwise \end{cases} \tag{33}$$

$$EB'_i = \begin{cases} CR'_i + EB_{neg,i} + EB'_{i-1} & if\ EB'_{i-1} > 0 \\ CR'_i + EB_{neg,i} & otherwise \end{cases} \tag{34}$$

$$T = \begin{cases} 0.162163 & if\ EB'_i \geq -50\ (\text{or } \mathrm{EB'_i} \geq -\mathrm{d_{cea}}) \\ 0.199985 & if -300 \leq EB'_i < -50 \\ 0.240493 & if -450 \leq EB'_i < -300 \\ 0.236802 & otherwise \end{cases} \tag{35}$$

$$B_i = \begin{cases} |EB'_i| \cdot (1+\beta)^i \cdot T & if\ EB'_i \leq -d_{cea} \\ d_{cea} \cdot (1+\beta)^i \cdot T & otherwise \end{cases} \tag{36}$$

Equation (27) was used to calculate the monthly energy generated by the PV system after the first year, as it was assumed that the power degrades every year. Equation (28) expresses the amount of electricity requested by the users, which was assumed to increase every year. A first monthly energy balance was calculated through equation (29) in order that its value is negative when the energy generated by the distributed PV system is not enough to satisfy the demand. A more accurate balance needs to consider that, when a monthly energy balance is positive, it is added to the next monthly balance, as it represents the surplus value injected into the grid which can be used in the form of credits in the next 60 months, according to the RN482. Monthly credits are calculated through equation (30). while formula (31) accounts for the negative balances, that represent the energy required from the grid. Equation (32) allows checking whether a monthly credit has (partly) expired after 60 months or not. From the 61st month, formula (32) evaluates if the credits obtained 60 months before were used to cover the energy required from the users or not; if not, the equation returns a positive value that corresponds to the amount of monthly expired credits, which are subtracted from the current monthly credits as described by equation (33). It may happen that equation (33) returns a negative value of credits; it is important to bear in mind that this value represents a monthly balance, and actually, credits will never be negative considering the cumulative balance, as for equation (34). This last equation allows calculating the actual energy balance considering cumulative credits, their lifetime and the energy required from the grid.

Equation (36) was used to compute the monthly electricity bill, taxes included; the formulation was done considering the Agreement ICMS 16 and the Normative Resolution 414. When the monthly energy balance is lower than or equal to the negative value of the equivalent demand of the cost of electricity availability, then the base to calculate the bill is the monthly energy balance itself, otherwise, the base is the cost of the electricity availability. It was assumed that the grid connections in Santa Marta are monophasic, and therefore the cost of electricity availability is equivalent to the consumption of 30 kWh.

The electricity tariff varies according to equation (35); it was assumed that tariffs in the first month of the project are equal to the ones described in Table 3.1, and they increase each month at a rate of 0.20%, based on (Lacchini, 2015).

Lastly, the revenues, used in equation (22), consist of the avoided cost due to the PV system installation, namely the avoided electricity bills. The revenues, or the avoided electricity bills, were calculated considering that the procedure described before applies also for the calculation of the bill without distributed generation, just assuming that $E_{PV,i} = 0$ for every month.

It is worth mentioning that, for the calculation of the electricity bill, cooperative configurations were not taken into account, mainly because the electricity consumption was assumed constant for each member of the community and because the cooperative configuration (installed capacity, members) was not characterized. However, based on (ANEEL, 2016a), the amount to be billed for each member of the cooperative is the difference between the energy consumed and the credits allocated to the member that month, considering also eventual credits of past months; if the difference is less than the equivalent cost of electricity availability, this cost will be charged to the single user.

5.2.3 Financing Mode 2: Debt financing

Grants and financial incentives play a crucial role in distributed renewable energy projects, especially if the target users are low-income families. Likely, most of the families in the community cannot afford to pay the whole investment cost of the PV residential system, or they might be reluctant in investing such an amount in a project whose economic benefits are visible in the long-term period. The introduction of a consistent loan could make the upfront expenses affordable for all the families who cannot bear them.

In Brazil, different funds exist for the distributed solar generation; interests and conditions may vary a lot whether the borrower is a business identity or a private customer, being more favorable in the first case. Interest rates for private individuals are relatively high in the country: hereafter different finding sources for financing solar projects for privates are briefly presented. Santander Bank offers, under specific requirements, loans at monthly interest rates that vary between 0.99% and 1.08% (12.55% and 13.76% annually equivalent). The financing institution BV gives loan with an interest rate that starts from 1.48% per month (19.28% annually equivalent) (BlueSol, 2019). The "Fundo Clima" program launched by the National Bank for Economic and Social Development (BNDES) in 2009 and extended to private customers in 2018, has the final aim of supporting projects related to the reduction of greenhouse gases and the adaptation to climate change and its effect. The banks who participate in the program, offer loans at a very convenient rate: 4.03% or 4.55% per year, according to the private's income. The maximum amortization period is 144 months and it is possible to borrow an amount up to 80% of the initial investment (BNDES, 2019). The Northeast Bank announced in 2016 the creation of a credit line for mini and micro distributed generation addressed to businesses and other organizations, which later, in 2018, was extended also to private customers. The program provides for loans with a paying period up to 144 months and interest rates that vary between 6.5% and 11% per year, according to the client's characteristics (Kenning, 2016).

In this study, it is assumed that a third party, which can be identified as a business corporation, would mediate to obtain the loan for the local inhabitants, thus probably having the advantage of accessing to more competitive debt's terms, when compared to the loan's characteristics offered to private customers. However, from the point of view of the investor, this project might result as risky because the final user is a low-income community characterized by economic instability; therefore, there could be the possibility that the interest rate proposed by the financing entity will fall into the range of the highest values.

In the Financing Mode 2, the total monthly cost has to take into account of the installment that the residents have to pay back to the financing entity, according to equation (37).

$$C_i = I_i + O\&M_i + B_i + L_i \tag{37}$$

The monthly installments were calculated through equation (38), adapted from (Pillot, 2018), where the borrowed amount, the interest rate and the amortization period are defined by the loan's term.

$$L_i = A\frac{r_l\,(1+r_l)^{N_l}}{(1+r_l)-1} \tag{38}$$

In this case, the equity initial investment is defined by equation (39).

$$I_0' = I_0 - A \tag{39}$$

As regards the total investment and the O&M costs, the same methodology described in Section 5.2.2.1 was applied.

5.2.4 Financing Mode 3: Debt & Grant Financing

In Financing Mode 3, it is assumed that a grant is received from a funder to cover part of the investment cost of the project. In the financing mode 2, the upfront cost is supposed to be more bearable by the residents thanks to the access to credits; however, still the project might not be attractive for the locals, who might be seeking for more immediate benefits and cost savings. Therefore, it is here assumed that, besides offering a credit to the residents, the entity taking care of the project would also cooperate with a third party to obtain a grant for financing part of the upfront costs.

In this case, the equity initial investment is defined by (40).

$$I_0'' = I_0 - A - G \tag{40}$$

Also, in this case the total investment and the O&M costs were calculated as described in Section 5.2.2.1.

5.3 Anaerobic Digestion System Economic Assessment

In the case of the anaerobic digester project, the costs were calculated on an annual basis, therefore the subscripts *i* are to refer to annual values. The total annual costs were calculated using equation (41). The project lifetime is assumed to be 16 years based on (Ivan Felipe Silva dos Santos et al., 2016), with no residual value of the components, starting from year 2020.

$$C_i = I_i + O\&M_i \tag{41}$$

5.3.1 Investment and O&M Cost

For the calculation of the investment cost, the prices of each component were summed up based on the study conducted by (R. E. dos Santos, 2019). Table 5.3 reports the cost of the equipment; the quantity for the compressor, the gasometer, the generator, the drain, and the separation is to be referred to the values at year 16 of the project. Referring to the pipeline, a maximum length of 500 m was assumed (Ivan Felipe Silva dos Santos, 2016); referring to the drain, one drain was adopted every 20 kW (I.F.S. Santos et al., 2018), while, as regards the generator, it was assumed that its useful life is 8 years (Ivan Felipe Silva dos Santos, 2016). In this case, differently from the PV project, the investment cost is calculated by summing up the actual components' prices and not assuming a price per Watt installed.

Table 5.3: Cost of the components for an anaerobic digester based power plant, adapted from (R. E. dos Santos, 2019).

Component	Cost	Unit	Source
Pipeline	215	USD/m	(Ivan Felipe Silva dos Santos, 2016)
Compressor	565	USD/(m^3/h)	(Ivan Felipe Silva dos Santos, 2016)
Flare	100	USD/unit	(Ivan Felipe Silva dos Santos, 2016)
Gasometer	60	USD/m^3	(Ivan Felipe Silva dos Santos, 2016)
Generator	510	USD/kW	(Ivan Felipe Silva dos Santos, 2016)
Drain	508	USD/(20 kW)	(I.F.S. Santos, 2018)
Separation	67,103	USD/t/h	(Luz et al., 2015)
Crusher	146,090	USD/unit	(Alibaba Group, 2019)
Bio-digester	20% of initial investment	USD/unit	(Ivan Felipe Silva dos Santos, 2016)

With respect to the O&M costs, they were assumed to be 7% of the initial investment, based on (FEAM, 2012).

5.3.2 Revenues

The revenues generated by the system consist of the sale of the produced electricity. This choice was adopted because the anaerobic digestion plant does not have the potential to satisfy the whole demand of the community. Annual revenues were calculated through equation (42).

$$R_i = E_{gen,i} \cdot S \tag{42}$$

The energy sale rate is set to be 92.30 USD/MWh, based on the upper limit value set at the first public auction for thermal gas power plants (ANEEL, 2016b).

6 Results and Discussion

6.1 PV Project Results

The main assumptions used for all the Scenarios of the PV project are summarized in Table 6.1.

Table 6.1: Assumptions used for the PV project.

	Symbol	**Value**	**Unit**
Project Lifetime	N	25	years
Population Growth	-	0	% per year
Electricity Consumption Growth	γ	2.53	% per year
Electricity Prices Growth	β	0.20	% per month
PV Module Power Degradation	δ	0.5	% per year
Overall Derate Factor	-	81.65	%
Inverter Useful Life	-	12.5	years

6.1.1 Energy Yield and Installed Capacity

The yearly energy yield collected by the solar system in the first year resulted to be 1195 kWh/kW. The subsequent sizing of the PV system needs to take into account the following statements:

- At the end of the first year of the project, the yearly production of the solar module amounts to 1195 kWh/kW, while the yearly electricity demand is 1913 kWh/hh, thus meaning that one household requires 1.6 kW to satisfy its annual consumption.
- At year 25 of the project, due to the PV power degradation and the electricity consumption growth, 3.39 kW are required to satisfy the consumption.
- Costs and revenues of the solar project are linked to the monthly energy yield by complex relationships, which need to take into account local policies, as described in section "Electricity Bill & Revenues".

It was therefore decided to design the solar system with the aim of maximizing the Net Present Value of the project. The result was achieved by creating different scenarios for the power installed in the software Excel, starting with the value of 1.98 kW/hh (equivalent to 6 PV modules), which corresponds approximately to the average value of power to be installed between year 1 and year 25 in order to satisfy the electricity quantity corresponding to the difference between the actual demand and the equivalent demand associated to the cost of electricity availability (30 kWh/hh per month).

It was found that the maximum value of NPV is obtained with the installation of the integer number of modules equal to 9720 for the whole community, corresponding to 3207.6 kW, which are equivalent to 5.9 panels per household, a result that is relatively close to the assumed value. The final optimal number of panels have to be chosen according to the type of system configuration designed. For example, if the same configuration hypothesized for the calculation of the investment cost is assumed, then the optimal number of modules would be 29.6, namely 30, per consortium and 9840 for the whole community. However, bearing in mind the aim of this study, configurations and arrays will not be further investigated, and results for the whole community will be presented.

Comparison of the energy yield with other sources

The yearly energy yield calculated in this study (1195 kWh/kW) was compared with values reported from other sources; in particular, according to the Global Solar Atlas by the World Bank Group, the power output per kW installed in Rio de Janeiro with a panel tilted of 23° amounts to 1355 kWh/year (The World Bank Group, 2016); the percentage difference with the results obtained with the ideal model corresponds to 13.4%, that is quite significant. However, the overall derate factor assumed by the World Bank Group is 88.83%, while the one assumed for this study was 81.65%. By using the first derate factor with the methodology implemented in this study, it was calculated a yearly energy production of 1300 kWh/kW, which differs only by 4.2% from the referenced value. Therefore, the relatively high difference (13.4%) can be mainly accounted for the assumed derate factors; other parameters that might influence the result are the error in the model implemented in this study, the particular characteristics of the PV module and the solar irradiance values used for the calculation.

6.1.2 Financing Mode 1 Results

The input parameter characterizing the system are summarized in Table 6.2. The total investment cost is more than 4 million dollars, corresponding to 2,520 USD per household.

Table 6.2: Input parameters for Financing Mode 1.

Input Parameter	Value per community	Value per household

Installed Power	3207.6 kW	1.96 kW
Solar Modules	9720	5.93
Investment Cost	4,132,117 USD	2,520 USD
Investment Cost	1.288 USD/W	1.288 USD/W
Production (1st y)	1195 kWh/kW	1195 kWh/kW

Table 6.3 reports the economic results. The obtained NPV is strongly positive, exceeding 3 million dollars and corresponding to 1,913 USD per household. The IRR is more than twice the cost of capital. The LCOE is 0.1680 USD/kWh, which is 8.9% higher than the current tariff without taxes, while it's closer to the current tariff with PIS/COFINS taxes (3.6% higher) and it is even lower than the current tariffs that include the ICMS tax (16%-30% lower). Overall, the LCOE registered a relatively good result. As regards the PB period, it amounts to 8 years and 8 months, which is less than half of the project lifetime.

Table 6.3: Economic results for Financing mode 1.

Parameter	**Value**	**Unit**
NPV	3,137,621	USD
IRR	12.38	%
PB	8 y 8 m	years
LCOE	0.1680	USD/kWh

This project, generally speaking, represents a good investment, due to the NPV, the IRR and the LCOE obtained; nevertheless, one may argue that, due to the socio-economic background of the community, the PB period is too high and the locals might not be interested in investing in a project whose economic benefits are not immediately visible, but long-term; moreover, it is likely that most of the families doesn't have the required budget to participate in this project.

6.1.3 Financing Mode 2 Results

The base-case characteristics assumed for the financial credits are summarized in Table 6.4. They were assumed considering the existing funds in Brazil (see "Financing Mode 2: Debt financing") and consulting the study by (Mehmedova, 2016).

Table 6.4: Loan's term for Financing Mode 2.

Characteristics of the Loan	
Borrowed Amount	80%
Interest Rate	9.5%
Amortization period	96 months

Table 6.5: Debt-associated costs and economic results for the Financing Mode 2.

Parameter	Value per community	Value per household
Equity Investment	826,423 USD	504 USD
Monthly Installment	48,617.66 USD	29.64 USD
NPV	2,721,867 USD	1,660 USD
IRR	13.87%	13.87%
PB	10y 9m	10y 9m
LCOE	0.1767 USD/kWh	0.1767 USD/kWh

The results are shown in Table 6.5. Compared to the results of the self-financed project, the NPV is still positive, even if smaller, the IRR is higher, but the payback time increased by almost 2 years, reaching 10 years and 9 months. Moreover, for the entire duration of the loan, the cash flows are mostly negative, with the exception of a few months per year. This means that, during this period, the project-related costs incurred by the inhabitants exceed the cost of the electricity bills (without DG generation) that the residents would pay over the same span, making the investment less attractive.

6.1.4 Financing Mode 3 Results

For the Financing mode 3, the credit's characteristics are the same described in Table 6.4; moreover, a grant equal to 20% of the total investment cost in year 0 is introduced.

Table 6.6: Grant, debt-associated costs and economic results for the Financing Mode 3.

Parameter	Value per community	Value per household
Equity Investment	0 USD	0 USD
Grant	826,423 USD	504 USD
Monthly Installment	48,617.66 USD	29.64 USD
NPV	USD3,548,290	2,164 USD
IRR	22.64%	22.64%
PB	9y 6m	9y 6m
LCOE	0.1595 USD/kWh	0.1595 USD/kWh

Table 6.6 reports the results for the Financing Mode 3. The NPV of the project is higher than the values obtained with the previous financing modes, and also the IRR is particularly high. The PB period, that in this case was calculated as the amount of time necessary to make the cumulative cash flow positive, amounts to 9 years and 6 months. The LCOE, that was calculated excluding the grant, is 0.1595 USD/kWh, which is a value extremely competitive with the current tariffs.

For all these reasons, this project can be defined as convenient. Nevertheless, due to the loan's term, the PB period, which in this case was calculated as the minimum period to make the accumulated cash flow positive, is still quite high, meaning that the local resident would start to see the benefits of installing the solar system only after years.

6.2 Anaerobic Digestion Project Results

6.2.1 Energy and Economic Results

The main assumptions used to assess the anaerobic digestion based system are summarized in Table 6.7, while results are summarized in Table 6.8.

Table 6.7: Assumptions for the anaerobic digester based system.

Parameter	Symbol	Value	Unit
Project Lifetime	N	16	years
Population Growth	-	0	%/year
Waste Growth	λ	1	%/year
Waste (year 1)	W	3162	t/year
Organic Fraction	F_0	52	%
Electricity Sale rate	S	92.3	USD/MWh
Engine Useful Life	-	8	years

Table 6.8: Parameters and results for the anaerobic digestion based technology.

Parameter	Value	Unit
Investment	388,066	USD
Power	40.54-47.54	kW
Unit Cost	8.24	USD/W
Energy	284-333	MWh/year
Energy	0.17	MWh/ton
Energy covered	9.1-6.7	%/year
NPV	-395,276	USD
IRR	-22.1	%
PB	>16	years
LCOE	0.2215	USD/kWh

The investment cost, which was calculated so to accommodate the potential of the system in the last year of the project, amounts to 388,066 USD, corresponding to 8.24 USD/W, which is definitely higher in comparison with the unit cost of the solar system. The energy generated per ton of organic waste amounts to 0.17 MWh, a result that is consistent with the values proposed by (FEAM, 2012; R. E. dos Santos, 2019). Taking into account the annual growth of electricity demand and the annual growth of production of waste, and not considering the plant self-consumption, the energy produced by the technology cover between the 9.1% and the 6.7% of the whole demand of the community, thus being not sufficient alone to satisfy this need.

The economic parameters of this project are strongly negative. The NPV is negative: the generated revenues barely cover the O&M costs. The IRR is negative, and the PB period is not achieved within the lifetime of the project. The LCOE amounts to 0.2215 USD/kW, a value that is not competitive with the actual tariff. It can be concluded that, with the current case study characteristics, the project is not economically viable.

One may argue that, the revenues of the project were calculated based on the electricity sell and not as the avoided cost related to the electricity bill; however, as the energy results showed, the amount of the community energy need coverable by the biogas plant is such a small percentage that the economic feasibility would have not been reached in any case.

6.2.2 Economic Viability

The economic viability of the anaerobic digestion technology is strongly dependent on the amount of input waste that the system receives. Therefore, the minimum amount of waste necessary to make the project economically feasible was investigated. Keeping fixed the remaining assumptions (Table 6.7), the value of the input waste was varied in order to obtain a NPV equal to 0; the result was obtained by implementing the Goal Seek Excel function.

The minimum amount of waste required in year 1 resulted to be 35.99 tons/day, which is almost four times the actual input value (8.66 t/day). If the project's aim is to create value for the investors and provide a competitive form of electricity, the input amount of waste should be considerably larger than 35.99 tons/day. Such an amount could be reached by collaborating with more communities located nearby Santa Marta. However, there are other "external" factors that might influence the viability of anaerobic digestion systems, such as adequate policies and subsidies.

6.3 Project Results and other cases

The PV project results demonstrated that solar PV could be a solution to provide cheaper electricity to the low-income community. In fact, for each of the financing modes, the NPV and the IRR are strongly positive, while the LCOE is generally lower than the current electricity prices and the PB period is always lower than half of the project lifetime. For each of the financing modes, it was calculated that the optimum installed power corresponds to 1.96 kW for a total investment of 2,520 USD per household.

The comparison of the results with the values obtained for the Brazilian study cases of Jardim Nosso and the Social Housing Program analysed in section 2.1.1, shows that the economic results are definitely more favourable, especially if compared with Jardim Nosso community case. In fact, the assumed investment price is notably different (4.585 vs 1.288 USD/W). This difference is likely attributable to the high reduction that occurred in the costs of PV technologies in Brazil in the last recent years, as discussed in section 5.2.2.1. As regards the installed capacity per household the result is quite similar to the ones obtained for the two cases of the literature review. In fact, so to maximise the NPV, it was calculated that 1.96 kW should be installed per house, while 2.1 kW were assumed by (Vale, 2017) and between 0.85 and 1.52 kW, according to the location, were assumed by (Pinto, 2016).

Differently from (Walton, 2014), solar thermal systems were not investigated. In fact, the objective of this thesis focused on finding a competitive way of providing electricity. Also, differently from (Babatunde, 2019), the use of fossil fuel based generators were not assessed, even though they could provide a cheap form of electricity during extreme events, such as blackouts. In fact, in this thesis, it was decided to investigate only renewable systems.

As regards the anaerobic digestion plant, results showed that the project is not economically viable considering the assumed amount of organic waste produced in the community. The NPV and the IRR are negative, the payback period is not reached within the project lifetime and the LCOE is higher than the electricity from the grid. Also, the producible energy would satisfy only a small part of the community demand. One may argue that, the project would have shown more economical potential if the revenues were associated to the avoided cost rather than the electricity sell; however, the produced energy is such a small amount when compared to the community's demand that economic parameters would not have been affected as much.

After analysing different case studies, reported in section 2.1.1, these negative results could be expected. (Junior, 2011) in fact, reported that anaerobic digestion system for a low-income community in Brazil is very expensive. Also, it was found that many anaerobic digestion projects implemented in low-income communities were completely or mainly financed by grants from the government or from other development organizations (Mangoyana, 2011; Vögeli, 2014).

For the aforementioned reasons, the anaerobic digestion system was not considered a solution to the problem presented in this thesis, and its possible location was not thorough analysed. However, since Santa Marta is an urban over-crowded area, in case of implementation of the project thanks to the collaboration with other communities, it is likely that the plant should be installed outside the boundaries of Santa Marta, in the territory of another community or an area provided by the municipality.

Following, the possible location of the PV system is analysed.

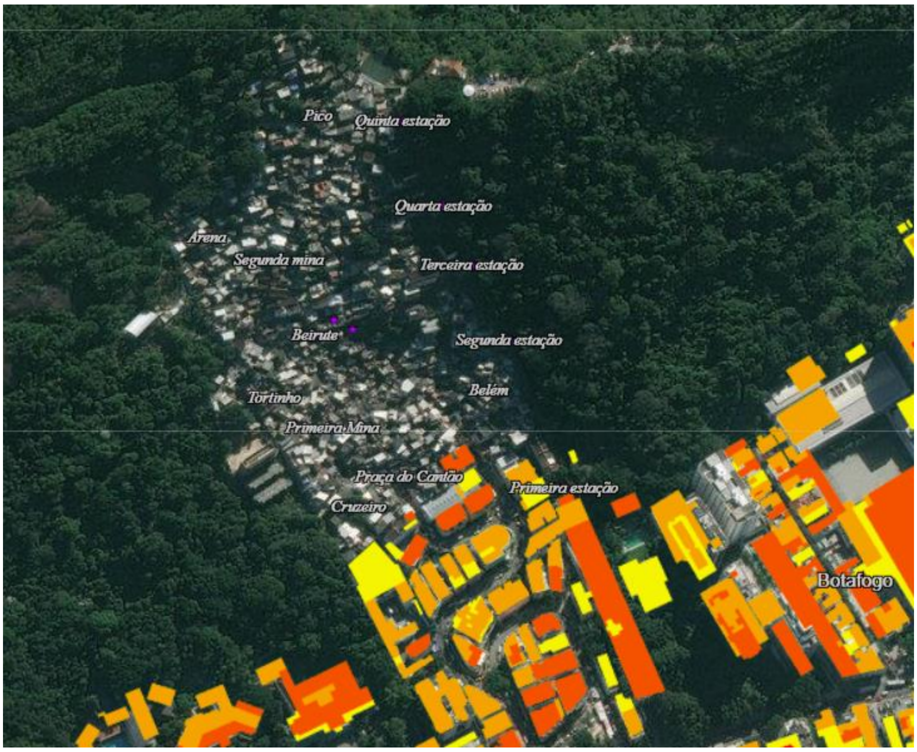

Figure 6.1: Solar map of the city of Rio de Janeiro, no available data for Santa Marta. Scale: 1 : 5,000. Source: (ArcGis, 2019).

Through the Software ArcGis, which is available online (ArcGis, 2019), it is possible to access to the solar map of Rio de Janeiro, where the solar potential of each rooftop, during the winter season, is estimated. However, no data are available for the community of Santa Marta, as it is possible to see in Figure 6.1. To serve 1640 households, 9720 solar modules need to be installed, which would occupy a total area of 18,861 m^2. Considering that the whole area of the community is 53,706 m^2, the PV modules would occupy 35% of the area. The technology should be located on rooftops since no other common areas in the community are available and free. Figure 6.2 shows some of the PV solar installations completed by Insolar in Santa Marta community and nearby. Similarly, the proposal involves the exploitation of rooftops.

However, without conducting a field trip in the location, it is hardly possible to design the optimal location in the community, especially it is difficult to assess the solidity of the structure of the rooftop. The dimension of each cooperative, which was standardized for this study, would have to consider the actual space available for the potential solar production. If the whole community electricity demand needs to be satisfied, when a rooftop is considered adequate as a site location for the PV system it should be exploited at its maximum potential, by occupying the maximum possible area.

In details, as regards the orientation and the inclination of the solar modules, as a rule of thumb, the slope of fixed solar modules should be equal to the latitude of the site location, while as regards the orientation (azimuth), the panels should face the true North, as Rio de Janeiro is located in the Southern Hemisphere (Hafez et al., 2017). The optimum coordinates that were calculated through the software PVGIS (see "Solar Energy") confirmed the rule, as the slope corresponds to a value of 23 °, which is actually equal to the latitude, and the azimuth to a value -165°, which is slightly North-East.

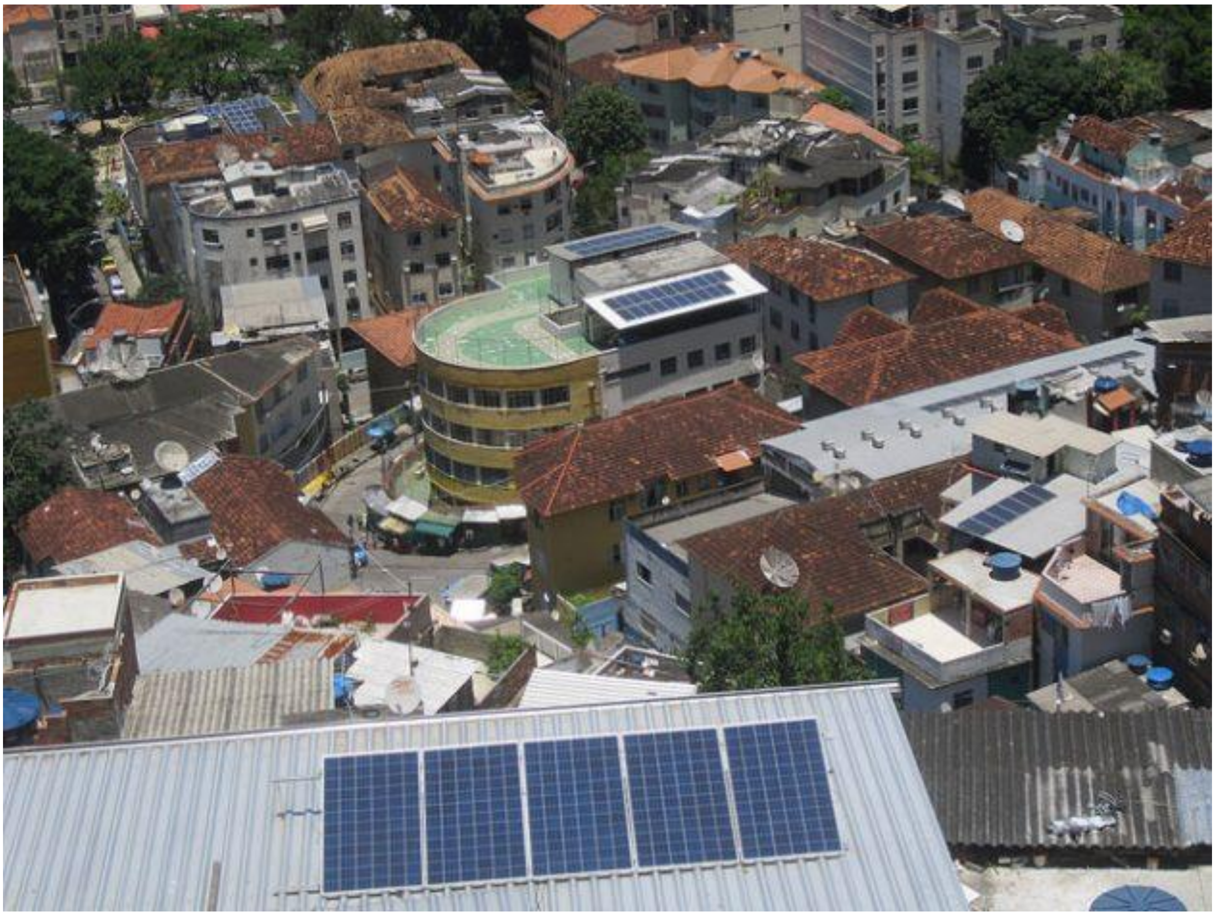

Figure 6.2: PV installations implemented by Insolar in Santa Marta community and nearby. Source: (IPS, 2018).

7 Sensitivity Analysis

Sensitivity analysis is a relevant tool for the evaluation of issues related to errors and uncertainties in the structure of the implemented model, or in parameter or input values. Sensitivity analysis has multiple objectives: to evaluate the uncertainty in the model's predictions due by uncertainty in the inputs values; to analyse the consequences of varying the model's structure on its predictive capacity; to determine the magnitude of errors in prediction caused by inaccuracies in assumed values (Landsberg et al., 2011).

For this study, the sensitivity analysis was conducted considering only the PV project; this decision was taken as a consequence of the economic unavailability of the anaerobic digestion system. The main objective of the analysis is to determine how the economic results (NPV, IRR, PB time, LCOE) change by varying some input parameters, which were defined for each financing mode.

7.1 Financing Mode 1

For the self-financing mode, the key inputs of the sensitivity analysis are:

- Investment unit price (USD/W) of the PV system.
- The system's energy yield (kWh).
- The electricity tariff prices (USD/kWh).

7.1.1 Investment Unit Price

An investment unit price of 1.288 USD/W was assumed for the base-case study. However, this value differs a lot when compared with references of the past recent years, and it might vary substantially according to the size of the installed system (see "Comparison of the investment cost with values from other sources"). For this reason, a variation of the investment unit price between -10% and +30% was considered. As the initial cost of the system is a variable that is known before the implementation of the project, the optimum number of solar modules - namely the value that maximizes the NPV - and consequently the economical parameters, were found for each price's variation.

Table 7.1 reports the results obtained for the whole community, while Table 7.2 reports the values per household (only the installed power, the number of panels and the NPV vary). Figure 7.1 illustrates the variation of the results of the sensitivity analysis, compared with the base-case.

Table 7.1: Sensitivity analysis results for the whole community by varying the investment unitary cost.

Parameter	Unit	Value	Value	Value	Value
Price Variation	%	-10	+10	+20	+30
Investment Unitary Cost	USD/W	1.16	1.42	1.55	1.67
Opt. Installed Power	kW	3,339.60	3,111.90	3,047.55	3,024.78
Opt. Number of Panels		10,120	9,430	9,235	9,166
NPV	USD	3,672,484	2,617,922	2,117,158	1,620,390
IRR	%	13.63	11.18	10.05	8.95
PB		8y 2m	9y 2m	9y 8m	10y 4m
LCOE	USD/kWh	0.1507	0.1843	0.1992	0.2116

Table 7.2: Sensitivity analysis results per household by varying the investment unitary cost.

Parameter	Unit	Value	Value	Value	Value
Price Variation	%	-10	+10	+20	+30
Investment Unitary Cost	USD/W	1.16	1.42	1.55	1.67
Opt. Installed Power	kW	2.04	1.90	1.86	1.84
Opt. Number of Panels		6.17	5.75	5.63	5.59
NPV	USD	2,239	1,596	1,291	988
IRR	%	13.63	11.18	10.05	8.95
PB	y & m	8y 2m	9y 2m	9y 8m	10y 4m
LCOE	USD/kWh	0.1507	0.1843	0.1992	0.2116

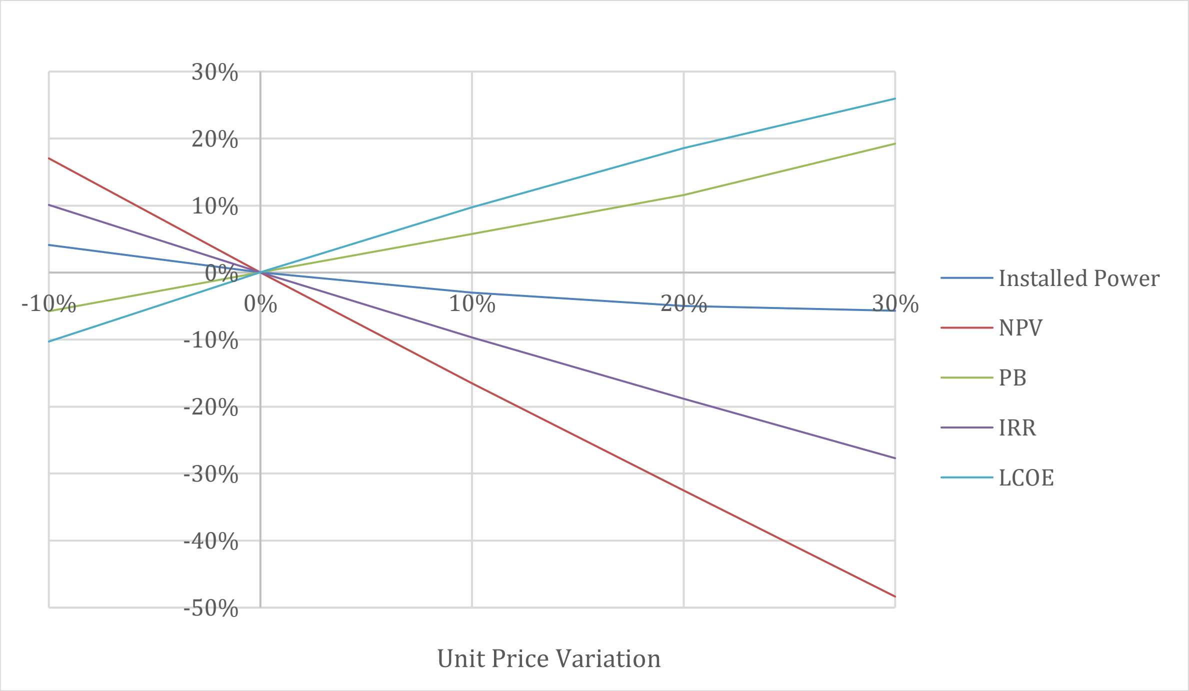

Figure 7.1: Percentage variation of the power installed, the NPV the PB, the IRR, and the LCOE compared with the base case, by varying the investment unit price.

It was found that the optimum value of installed power slightly decreases with the increase of the investment unit price: the optimum value decreases by less than 5% for each increment of 10% of the price. Generally speaking, as expected, the lower the investment price, the higher the performance of the economic profitability parameters. The NPV is the parameter that registered the highest variation: its value approximately decreases by 18% for each price variation. However, even considering an increment of 30% of the price, the PV project would still be economically viable, with a positive NPV and a IRR higher than the cost of capital; the PB time would increase of about 2 years, compared to the base case and the LCOE would amount to 0.2116 USD/kWh, which would not actually make the technology very competitive with the grid.

7.1.2 Energy Production

It was decided to conduct a sensitivity analysis by varying the energy yield for mainly two reasons: first, the model adopted for the energy calculation might over or underestimate the energy yield, due to imprecisions. Second, the calculation was based on average values of irradiance and not on the actual values, which are not precisely predictable. For these reasons, a production's fluctuation between -10% and 10% was assumed.

Table 7.3: Sensitivity analysis results by varying the energy yield.

Parameter	**Unit**	**Value**	**Value**
Production Variation	%	-10	+10
Production (1st y)	kWh/W	1075.64	1314.67
NPV	USD	2,483,980	3,588,462
IRR	%	11.44	12.87
PB	y & m	8y 9m	8y 8m
LCOE	USD/kWh	0.2018	0.1442

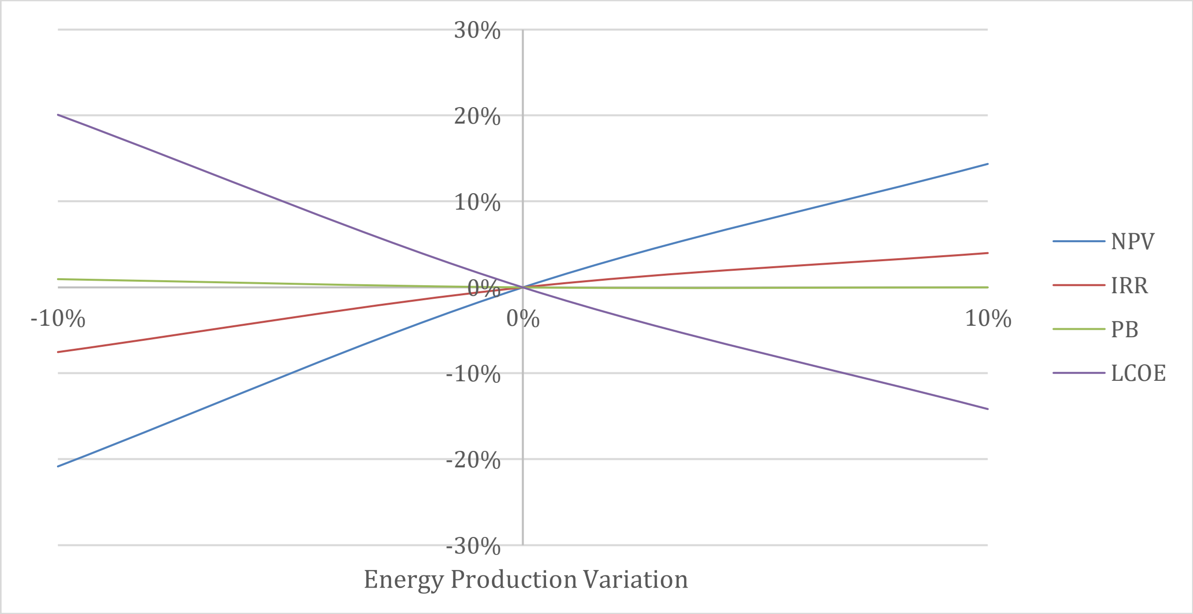

Figure 7.2: Percentage variation of the economic results by varying the energy yield.

Table 7.3 reports the results of the sensitivity analysis of the energy yield, while Figure 7.2 illustrates the percentage variation of the economic parameters, compared with the base-case. In the worst-case scenario (-10% of the energy production), the PV project would be still economically viable, whit a NPV (1,515 USD/hh) lower by the 20%, a still positive IRR, and a PB period that almost didn't change; the LCOE would amount to 0.2018 USD/kWh, which makes it less competitive with the actual tariff. On the other hand, if the energy yield would increase by 10%, which is more likely to happen due to the solar production trends in Rio de Janeiro (see "Comparison of the energy yield with other sources"), the NPV

(2,188 USD/hh) would register an increment of the 15%, the IRR would be strongly positive and the LCOE would amount to 0.1442 USD/kWh, which would make it extremely competitive with the actual tariffs, since it is even lower than the actual tariff excluding taxes.

7.1.3 Electricity Prices

For the base-case, social-tariff prices and influence of the tariff flags were not considered. Moreover, electricity tariffs generally depend on many factors that were neglected. For all the aforementioned reasons, a tariff's fluctuation between -10% and 10% was assumed, keeping constant the price growth rate.

Table 7.4: Sensitivity analysis results by varying the electricity prices.

Parameter	**Unit**	**Value**	**Value**
Tariffs Variation	%	-10	+10
NPV	USD	2,299,818	3,975,425
IRR	%	10.80	13.89
PB	y & m	9y 5m	8 y 0m
LCOE	USD/kWh	0.1621	0.1739

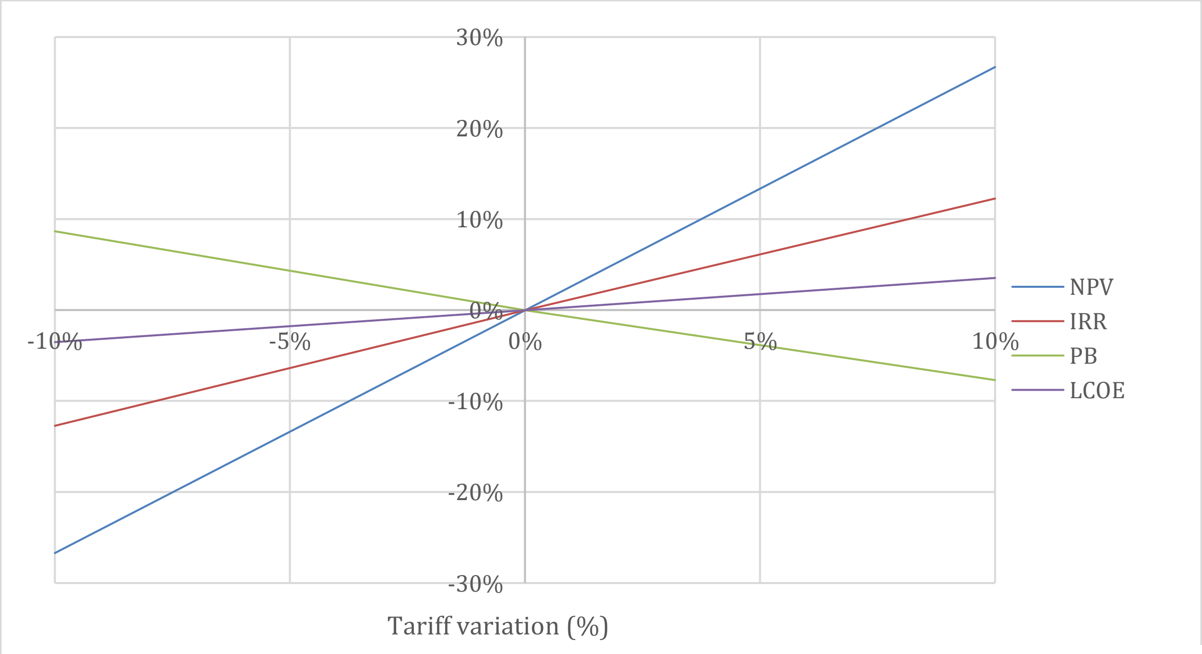

Figure 7.3: Percentage variation of the economic parameters by varying the electricity prices.

Table 7.4 reports the results of the sensitivity analysis of the electricity prices, while Figure 7.3 illustrates the percentage variation of the economic results, compared to the base-case. It is possible to notice that the prices strongly influence the values of NPV. The higher the tariff, the more convenient it is to install the PV system, even though the LCOE increases due to the higher cost of the electricity availability that needs to be paid to the utility in any case. However, the economic feasibility is reached even if the prices are 10% lower than the actual ones.

7.2 Financing Mode 2

For the debt-financing mode, the key inputs of the sensitivity analysis are the values characterizing the loans, namely the borrowed amount, the interest rate and the amortization period. It was assumed that the three input parameters vary at the same time, and for this reason, two different scenarios were created, an optimistic one and a pessimistic one. The loan's terms for Scenario 1 and Scenario 2 are visible in Table 7.5, while Table 7.6 reports the results for both the Scenarios.

Table 7.5: Loan's terms for Scenario 1 and 2.

Characteristics of the Loan		
	Scenario 1	Scenario 2
Borrowed Amount	100%	60%
Interest Rate	4.03%	13.5%
Amortization period	144 months	60 months

Table 7.6: Scenario 1 and 2 Results.

Parameter	**Unit**	**Value**	**Value**
		Scenario 1	Scenario 2
Installment	USD	-36,093	-56,069
NPV	USD	3,539,807	2,705,557
IRR	%	51.85	12.16
PB	y & m	4y 11m	10y 1m

LCOE	USD/kWh	0.1597	0.1770

Compared to the base case loan terms (Table 6.5), the Scenario 1 is significantly more profitable: the NPV amounts to more than 3.5 million dollars (2,158 USD/hh), the monthly installment is equal to 36,093 USD (22.0 USD/hh), the IRR is significantly high and the payback period decreased to 4 years and 11 months. As regards the Scenario 2, no consistent variations are registered compared to the base case of the financing mode 2. The NPV is slightly minor, equal to 2,705,557 dollars (1650 USD/hh), the monthly installment amounts to 56,069 USD (34.2 USD/hh), and the payback period is even lower. It can be added that, due to the shorter amortization period, the Cash Flows of Scenario 2 are more negative during the first years, if compared with the base case and especially with the Scenario 1, meaning that there are no savings for the locals during this first period.

7.3 Financing Mode 3

For the Financing Mode 3, the key inputs of the sensitivity analysis are the values characterizing the loans and the grant, namely the borrowed amount, the grant amount, the interest rate and the amortization period. It was assumed that the four input parameters vary at the same time, and for this reason, two different scenarios were investigated.

The characteristics of Scenario 3 and Scenario 4 are visible in Table 7.7. Table 7.8 reports the results for both the Scenarios.

Table 7.7: Scenario 3 and Scenario 4.

Characteristics of the Financing Mode		
	Scenario 3	**Scenario 4**
Equity's Investment	0%	30%
Grant	15%	10%
Borrowed Amount	85%	60%
Interest Rate	4.03%	13.5%
Amortization period	144 months	60 months

Table 7.8: Results for Scenario 3 and 4.

Parameter	**Unit**	**Value**	**Value**
		Scenario 3	**Scenario 4**
Instalment	USD	30,679	56,069
NPV	USD	4,099,296	3,118,769
IRR	%	-	13.93
PB	y & m	0 m	9y 4 m
LCOE	USD/kWh	0.1481	0.1684

Scenario 3 resulted to be the most performing scenario registering the highest NPV value, which amounts to more than 4 million dollars (2,500 USD/hh). The monthly installment would amount to 18.71 USD/hh, meaning that there would be cost-savings for the locals from the immediate, since the annual cash flows would be positive from the first year. The LCOE, which was obtained not considering the grant, would amount to 0.1481 USD/kWh, and it would be extremely competitive.

Scenario 4 still registered positive results, having a NPV (corresponding to 1,902 USD/hh) very close to the original result for the Financing Mode 1, and a high IRR. However, the PB period would still be quite elevated, making this investment less attractive.

8 Conclusion

8.1 Conclusions

Electric energy represents a basic service whose access should be affordable also by low-income communities. The potential use of local renewable resources, and in particular of solar energy, as appointed by (Babatunde, 2019; Pinto, 2016), could represent an economically and environmentally viable solution to improve and reduce the cost of the electricity service for the urban community of Santa Marta, in Rio de Janeiro, Brazil.

In particular, due to their potential, solar photovoltaic and anaerobic digestion systems were investigated with the scope of individuating a renewable affordable solution, which is competitive with the electricity supplied by the grid, for the case study of Santa Marta. The attention focused also on the possible business models and financing modes to be implemented for PV distributed projects.

Results showed that the electricity obtainable by treating the organic waste produced in the community through an anaerobic digestion plant (284-333 MWh/year) would not be enough to cover the demand of electricity required by the locals. Moreover, the economic profitability parameters resulted to be extremely negative: the NPV and the IRR are negative, the PB period is not obtained within the project lifetime and the LCOE result is not competitive with the current electricity prices. It was estimated that, in order to reach the economic viability of the project, so to obtain a positive NPV, the minimum input amount of waste in the first year of the project would be 36 tons/day, which is actually almost four times the collected amount assumed for the community. The anaerobic digestion project didn't show the potentiality to offer a competitive solution for the low-income community, and therefore it was not further investigated.

As regards the solar project, results showed that PV systems can represent a competitive solution for low-income communities through the implementation of adequate business models and credits lines. It was assessed that the optimum installed capacity so to satisfy the demand and at the same time maximise the NPV of the project corresponds to 1.96 kW per household, for an investment of 2,520 USD. Three different scenarios for the financing method were created: (1) a self-financing mode, where the users pay 100% of the investment cost; (2) a debt-financing mode, where the users are offered credits to cover part of the upfront costs; (3) a debt and grant financing mode, where the locals, besides the credit, are offered a grant by a donor entity.

In particular, results showed that the project would be economically feasible in any of the three financing scenarios hypothesized; however, not in any case, the project might be considered as convenient by the locals. With the self-financing mode, the NPV amounts to 1,913 USD per household, the IRR corresponds to 12.38 %, and the LCOE is 0.1680 USD/kWh, a value that is competitive with the current electricity tariffs. However, the total investment cost is 2,520 USD per household and the PB period amounts to 8 years and 8 months. It is likely that considering the socio-economic characteristics of the community, most of the families could not bear the total upfront costs, and, even if they could, they might be reluctant in investing in a project whose economic benefits are visible in the long-term. By introducing a credit, which was characterized with a borrowed amount equal to 80% of the total investment, a 9.5% annual interest rate and an amortization period of 8 years, it is more likely that the customer could bear the upfront cost, which would amount to 504 USD per household, but the PB period would be even higher, amounting to 10 years and 9 months. Assuming the same loan's characteristics and introducing a grant equal to the 20% of the initial cost, the project resulted to be highly profitable, with a NPV of 2,164 USD and an IRR of 22.64%; but still, the PB period would be relatively high, amounting to 9 years and 6 months.

Through a sensitivity analysis, different scenarios for each of the financing methods were investigated. It resulted that, even in the worst cases, considering a reduction in the electricity production, or; a decrease of the electricity prices, or; an increment of the investment cost of the system, or; an increment of the loan's interest rate, the project would still be economically viable. The scenario that gave the best results was obtained by assuming a grant equal to the 15% percent of the total investment, a borrowed amount covering the remaining 85%, a very competitive annual interest rate, equal to 4.03%, and an amortization period of 12 years. In this case, the NPV amounts to 2,500 USD per household and the LCOE to 0.1481 USD/kWh. Moreover, only with this scenario, the monthly revenues overcome the monthly costs related to the project starting from the first month, meaning that there would be cost-savings for the locals from the immediate. However, very positive results were obtained also excluding the grant and assuming 100% of the borrowed amount, obtaining a NPV of 2,158 USD per household, an IRR of 52%, a LCOE equal to 0.1597, and a payback period of 4 years and 11 months. These results proved the feasibility of the project even without resorting to external grants if credits are offered with low interest rates for a relatively long period.

Finally, the PV project would not only bring economic benefits to the community but with an adequate business plan, it would also maximize the social impact. First of all, the creation of multiple solar cooperatives inside the community would allow households that don't have the site possibility of receiving the PV technology to still benefit from the system, giving the project the potential to impact the whole community. Moreover, the project could be managed by an entity that would operate in collaboration with the community so to maximize the social impact. In fact, the positive example of Insolar suggests that a collaborative approach allows maximizing the creation of opportunities for the empowerment of the community itself.

8.2 Future Work

The research presented in this Thesis presents some limitations and can be further extended in future work.

Due to the impossibility of conducting a field trip in the location, the whole analysis was conducted based on data collected through various sources.

- The PV energy assessment was based on the community average electricity consumption; in future work, the real demand and the actual number of households existing in the community need to be assessed.
- It was assumed that multiple solar cooperatives would be implemented in the area and the whole community would participate in the project. However, it is possible that not all the members would like to join; research and surveys on this topic should be carried in the community. Also, an investigation should be carried in order to establish how many dwellings in the community have the site potentiality to receive the PV System.
- The terms of the loan were assumed consulting the existing credit lines in Brazil. Different credits possibilities should be further investigated.

Finally, solar thermal systems were excluded from the assessment, since the aim of this study was to explore the use of renewable systems to provide electricity. However, further analysis can be conducted on this topic, assessing how much electric water heaters influence on the electricity consumption of the members of the community, and how much would be possible to save by installing solar thermal panels.

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