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DESIGNING NEARLY ZERO ENERGY BUILDINGS: ENERGY EFFICIENCY AND ON-SITE GENERATION

Rosa Esperanza González Mahecha

Tese de doutorado apresentada ao Programa de Pós-Graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientadores: André Frossard Pereira de Lucena
Alexandre Salem Szklo

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DESENHO DE EDIFICAÇÕES COM CONSUMO DE ENERGIA PRÓXIMO DE ZERO: EFICIÊNCIA ENERGÉTICA E GERAÇÃO IN-SITU

Rosa Esperanza González Mahecha

Abril/2018

Orientadores: André Frossard Pereira de Lucena
Alexandre Salem Szklo

Programa: Planejamento Energético

Esta tese propõe e aplica metodologias para avaliar o potencial técnico e econômico de edificações com consumo de energia próximo de zero. Para isso, quatro estudos são apresentados. O primeiro artigo, chamado “Sistemas construtivos para a implementação de moradias sociais em países em desenvolvimento: uma análise usando avaliação de ciclo de vida do carbono no Brasil” avalia o uso de energia e as emissões de gases de efeito estufa em moradias sociais no Brasil. O segundo artigo, chamado “Potencial de mitigação de gases de efeito estufa e custos de abatimento no setor residencial brasileiro”, avalia oportunidades de abatimento de CO2 custo-efetivas no setor residencial brasileiro. O terceiro estudo, “Avaliação da implementação restrita de energia solar fotovoltaica distribuída no setor residencial em países em desenvolvimento: uma análise por nível de renda na Colômbia”, propõe uma metodologia para calcular o potencial técnico, econômico e de mercado da energia solar fotovoltaica no setor residencial. O último trabalho apresentado, chamado “Modelo de otimização para avaliar tecnologias renováveis de geração in situ e bateria em edificações com consumo de energia próximo de zero”, desenvolve, testa e aplica um modelo de otimização de mínimo custo para avaliar tecnologias renováveis e bateria em edificações. Os resultados mostram que há potencial para reduzir o consumo de energia no setor de edificações, e, portanto, as emissões de gases de efeito estufa associadas. As principais barreiras para a implementação de edificações com consumo de energia próximo de zero também foram identificadas. Finalmente, políticas energéticas são propostas nas conclusões.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

DESIGNING NEARLY ZERO ENERGY BUILDINGS: ENERGY EFFICIENCY AND ON-SITE GENERATION

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April/2018

Advisors: André Frossard Pereira de Lucena
Alexandre Salem Szklo

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This thesis proposes and applies methodologies for assessing the technical and economic feasibility of nearly Zero Energy Buildings. Four studies were conducted. The first study entitled “Constructive systems for social housing deployment in developing countries: An analysis using life cycle carbon assessment in Brazil” assesses the energy use and GHG emission in social housing in Brazil. “Greenhouse gas mitigation potential and abatement costs in the Brazilian residential sector” is the second study. This work assesses cost-effective abatement opportunities to reduce CO_2 emissions in the Brazilian residential sector. The third study entitled “Assessing the restricted deployment of distributed solar photovoltaics in the household sector in developing countries: An analysis by income level in Colombia” proposes a methodology to project the technical, economic and market potential of solar PV in the residential sector. “Optimization model for evaluating on-site renewable technologies with storage in zero/nearly Zero Energy Buildings” is the last paper presented. This study develops, tests and applies an optimization model to evaluate on-site renewable energy technologies with storage in buildings. General findings show that there is a potential for reducing energy consumption in the buildings sector and, hence, GHG emissions. The main barriers for the deployment of nearly Zero Energy Buildings were also identified. Energy policies to overcome the barriers are proposed in the conclusions.

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LIST OF ACRONYMS

EPE	Empresa de Pesquisa Energética.
GABC	Global Alliance for Buildings and Construction
GHG	Greenhouse Gas
IBGE	Instituto Brasileiro de Geografia e Estatística.
ICLEI	International Council for Local Environmental Initiatives
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change.
LCAA	Life Cycle Carbon Assessment
NDC	Nationally Determined Contributions
nZEB	nearly Zero Energy Buildings
OECD	Organization for Economic Co-operation and Development.
SDGs	Sustainable Development Goals
UNFCCC	United National Framework on Climate Change Convection.
WBCSD	World Business Council for Sustainable Development

1 Introduction

1.1 Building sector overview

In 2010, the building sector approximately accounted for 32% of global final energy consumption: 24% in the residential segment, and around 8% in the commercial segment (LUCON et al., 2014). This consumption represented roughly 19% of the energy-related CO_2 emissions. The consumption escalated from 117 Exajoules (EJ) in 2010 to 125 EJ in 2016 (IEA, 2017b; LUCON et al., 2014; UN ENVIRONMENT, 2017a).

Residential energy consumption has grown by more than 50% between 1990 and 2014, due to the fastest growing emerging economies, such as India and Indonesia, while in Africa it has doubled, even though the average per capita consumption in the African buildings sector is still 25% less than the global average in 2014 (IEA, 2017b).

Moreover, an additional 26 EJ was consumed by the buildings construction sector in 2016, which includes the manufacturing of material for buildings, such as steel and cement, which account for roughly 6% of the global final energy consumption (UN ENVIRONMENT, 2017a).

The buildings sector is more important in terms of final electricity demand, consuming 55% of the total final energy (IEA, 2017b). Altogether, electricity consumption in the buildings sector has grown by a multiple of 4.5 in non-OECD countries between 1990 and 2014, while it remained relatively stable in OECD countries due to energy efficiency improvements (IEA, 2017b).

Figure 1-1 displays the global energy consumption in buildings by fuel type. Electricity, natural gas and biomass are the major fuels consumed in the sector. Electricity is the main fuel consumed in OECD countries (UN ENVIRONMENT, 2017a), while the largest share in the non-OECD comes from traditional biomass[1]. Energy consumption from other renewable sources is still in an early stage[2].

The growth in floor area and energy intensity are also displayed in Figure 1-1. The buildings sector energy intensity (energy use/m^2) increased at an average rate of around 1.5% p.a. since 1990, whereas the global floor area grew at 2.3% p.a. (UN ENVIRONMENT, 2017a).

Consumption by end-use is largely dominated by space and water heating, which represented roughly 65% of final energy consumption in buildings in OECD countries and around 50% in non-OECD countries (IEA, 2017b). It is remarkable that demand for cooling represents the largest growth compared to the other end-uses in non-OECD countries. Its consumption has almost doubled over the last ten years (7% p.a.) (IEA, 2017b).

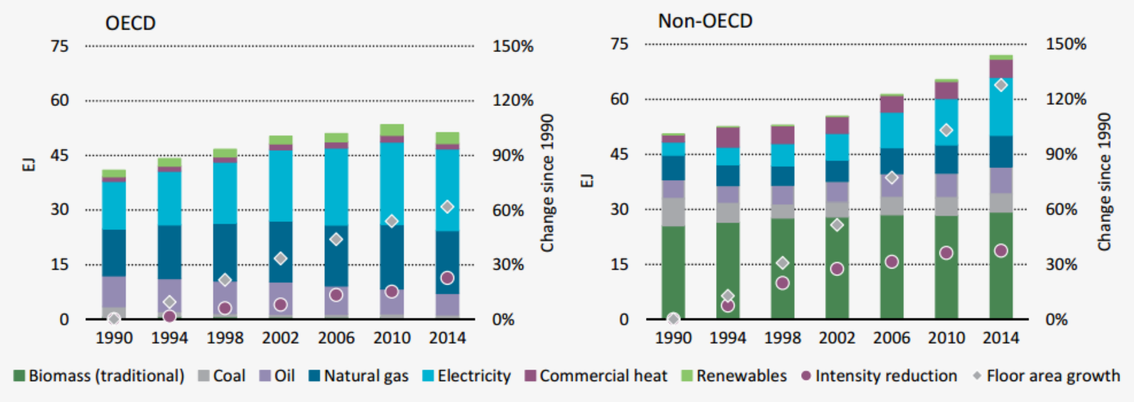

Figure 1-1. Global building sector energy consumption by fuel type (2010-2016)

Source: (IEA, 2017b)

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[1] Correspond to the biomass produced in an unsustainable way, its use is non-commercial. It is usually used in stoves in with very low efficiency in developing countries (GOLDEMBERG; TEIXEIRA COELHO, 2004).

[2] Other renewable energy includes solar thermal energy and biofuels, such as wood pellets (IEA, 2017b).

In 2015, the buildings sector accounted for 28% of the global energy-related CO_2 emissions (See Figure 1-2). Building construction accounted for another 11% of the energy-related CO_2 emissions (UN ENVIRONMENT, 2017a). According to UN Environment (2017a) despite the greater number of countries who have set up policies to improve building energy performance, energy consumption and CO_2 emissions increased, with efficiency improvements offset by population growth, rising per capita floor area and larger demand for energy services.

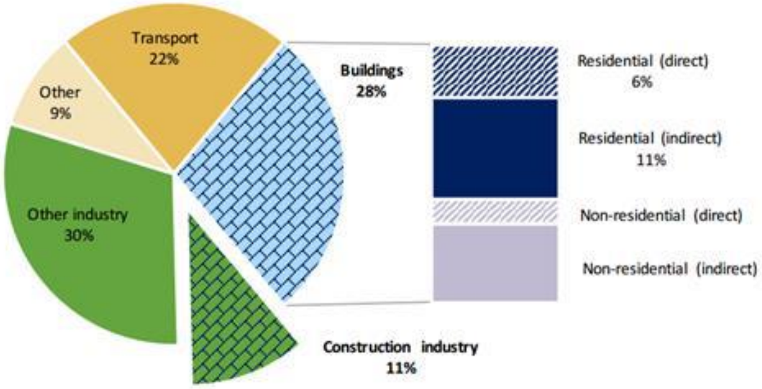

Figure 1-2. Energy-related CO_2 emissions by sector (2015)

Source: (UN ENVIRONMENT, 2017a)

1.2 Key challenges for decarbonizing the building sector: Increasing energy consumption

The global buildings floor area is expected to increase by 230 billion m^2 over the next 40 years (IEA, 2017b) . Demolition rate is less than 1% p.a., then 6.5 billion m^2 in average are projected to be constructed every year in the same period (IEA, 2017b). According to BECQUÉ et al. (2015) an area nearly 60% of the world’s current total building stock will be built or retrofitted in urban areas by 2030, mainly in developing economies like China, India and Indonesia. Then, efforts to reduce energy consumption must focus on both enhancing the energy-efficiency and avoiding a look-in effect[3] which will likely increase efficiency costs over the long-term.

Energy demand depends on many variables, such as climate data, available technology and material, population lifestyle, migration to cities, increasing levels of wealth, change in household size and the age of building and appliances. Final demand tends to increase continuously due to population growth, social development and behavior (HEILIG, 2014; IEA, 2017b). The rapid urbanization and the extension of the built environment represent, at the same time, a major challenge and a major opportunity to configure the forthcoming cities and buildings (BECQUÉ et al., 2015; IRENA, 2016a).

Additionally, it is worth to say the buildings sector also have a challenge regarding the resources shortages and the dependence on the external supply.

To tackle increasing demand, early actions to decarbonize the building and construction sector must be taken, such as on-site renewable technologies dissemination and a deeper energy efficiency retrofitting actions in the current building stock (GBPN, 2015). In developed economies, the challenge is to increase the energy efficiency in the current building stock, while avoiding lock in is imperative in developing economies with rapid urbanization rates (HEILIG, 2014).

1.3 Buildings-related climate commitments

For the first time, the buildings sector took place in the official agenda of the Conferences of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC), in 2015 in Paris, when the Global Alliance for Buildings

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[3] Look-in effect occurs when the investments in durable assets look and hold them into a particular system or technology.

and Construction (GABC) was launched (UN ENVIRONMENT, 2016). The meeting debated how the building and construction sector can contribute to face the climate change considering the most cost-effective measures in the sector (ENKER; MORRISON, 2017; GBPN, 2015).

The GABC arise as an unprecedented coalition oriented to the local, regional and global efforts towards scaling up climate change actions in the sector (GABC, 2018). It focusses on proposing policies for sustainable and energy efficient buildings as well as effective value-chain transformation in the sector to encourage an energy transition. Then, the GABC's target is to support and boost the implementation of the Nationally Determined Contributions[4] (NDCs) by consolidating energy efficiency, increasing the use of renewable energies and reach GHG emission reduction (GABC, 2018).

Thus, the buildings sector has been gaining importance in the global mitigation debate. Implementing early actions in the building sector will lead to short-term and long-term economic, health and environmental benefits (BECQUÉ et al., 2015).

The mandate given to the building and construction sector in COP21 point out key aspects of the sector, such as: a) Need to increase the national ambitions; b) Need to undertake actions before 2020; c) Cities, society and private sector have to be aware they play a key role in the mitigation effort; and, d) 20 nations were part of the Global Alliance initiated at COP21 to move forward and assistance in technology, finance, policy expertise and sustainable buildings knowledge (GBPN, 2015).

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[4] Nationally determined Contributions (NDCs) are voluntary national climate targets to reduce the greenhouse gas emissions signed under the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 2018).

192 NDCs have been submitted to the UNFCCC, with roughly 69% of them explicitly including the buildings sector in their intentions (UN ENVIRONMENT, 2017a). The adoption of energy efficiency measures was contemplated in 101 NDCs, while renewable was considered in 49 NDCs (UN ENVIRONMENT, 2017a). However, specific actions by the buildings sector to achieve the goals have been neglected in nearly one-third of NDCs that mentioned buildings (UN ENVIRONMENT, 2017a). According to UN Environment (2017a), the current commitments only would cover 13% of the total CO_2 emissions in the building sector.

Therefore, a forceful determination is needed to implement the NDCs commitments. In the local sphere, governments have shown their interest in supporting the set of goals by groups as United Cities and Local Governments (UCLG), C40 Cities Climate Leadership Group (C40) and ICLEI (Global Covenant of Mayors for Climate and Energy) (IRENA, 2016a; MCKINSEY, 2017; UN ENVIRONMENT, 2017b; UNFCCC, 2017).

In the private sector, the World Business Council for Sustainable Development (WBCSD) played a key role inviting their members to participate in Energy Efficiency in Buildings (EEB), a project launched in COP22 in Marrakesh. This Council launched a report encouraging all new buildings to operate at net zero carbon after 2030, and the current building stock to operate at net zero carbon by 2050 (WBCSD, 2017).

This report focusses on the following needs: a) Awareness of the benefits of energy efficiency; b) Partnership along the value-chain; c) Suitable model business; and d) Reliable long-term policy (IEA, 2017a).

1.4 Pathways for achieving sustainable buildings

Bearing in mind the global challenges regarding climate change, resources shortages and the dependence of the building sector on the external supply, several studies have been developed for on-site renewable and energy-saving technologies such as: space heating and cooling technologies and lighting (Deng, Wang and Dai, 2014; Kylili e Fokaides, 2015; Mckinsey, 2012; McKinsey, 2017). Besides, building enveloped design, materials and constructions have a large influence on heating and cooling loads. For instance, CO_2 emissions from heating and cooling energy in the building sector represented roughly 3.5 $GtCO_2$ (UN ENVIRONMENT, 2017a).

The integration and interaction between energy-efficiency technologies, improvements in the envelope and on-site renewable energy generation in buildings introduce a concept: Zero Energy Building (ZEB). ZEB is considered as an integrated solution to address problems related to energy saving, energy security (reliability, accessibility and affordability), environmental protection, CO_2 emission reduction and air pollution control in the buildings sector (Deng et al., 2014). However, several concepts have emerged around ZEB terminology, which are briefly explained in the following subsection.

1.5 Zero Energy Buildings

Despite the importance of the concept, a standard definition of the Zero Energy Buildings does not exist yet. The ZEB concept has several definitions around the world (DENG; WANG; DAI, 2014; LAUSTSEN, 2008; MARSZAL, a. J. et al., 2011; MARSZAL, J.; HEISELBERG, 2012; TORCELLINI et al., 2006; WELLS; RISMANCHI; AYE, 2018). According to Hermelink (2014), 71 nZEB (nearly Energy Zero Buildings) definitions were noted from 17 European Union countries and 2 outside countries. Nevertheless, the concept typically is linked to a net balance of energy on-site, or in terms of a net balance of primary energy associated with fuels used in buildings and the electricity exported to the power grid (Marszal et al., 2011).

The literature also lays out a difference between NZEB (Net Zero Energy Builings) and simply ZEB (Zero Energy Buildings). According to Sartori, Napolitano and Voss (2012) the term ZEB refers to a more general approach. ZEB implies an autonomous building, while the term NZEB suggest the building is connected to the energy infrastructure.

To overcome the difficulty of not having a clear definition and international agreements, the Energy Performance of Buildings Directive (EPBD) defined a nearly zero energy building (nZEB) as a:

> *"building that has a very high energy performance. The nearly zero or very low amount of energy required should be to a very significant extent covered by energy from renewable sources, including renewable energy produced on-site or nearby*" (EUROPEAN PARLIAMENT, 2010)

After this definition, the European Commission member-states have been requested to draw up plans for increasing the number of zero energy buildings. According to the paragraph 1 of the Article 9 of the EPBD the national plans shall include application in practice of the definitions, including quantitative indicators (kWh/m^2/year). The European Commission member-states should define nearly energy zero building in the national context. Accordingly, each country can specify the definition, establish intermediate targets, policies and financial or other initiatives that aim for the promotion of nZEB. It means that the European Commission has been encouraging to assist its members to develop policies, financial measures and other instruments for the furtherance of transformation of the existing buildings into nearly ZEB taking into account cost-effective criterion (KYLILI; FOKAIDES, 2015).

Nevertheless, the EPBD definition about nZEB is still controversial in terms of nZEB boundaries and methodologies ((D′AGOSTINO, 2015; HERMELINK, a et al., 2013). Also, there are some issues that must be solved before the implementation of the concept. For instance, the first question is associated with the portfolio of options to reach a nZEB? At this point, it is mandatory to think about energy efficiency and on-site generation technologies. Furthermore, these technologies must be addressed taking into account characteristics such as the climate, roof space, budget and others. The second issue is related to what is considered as nearly zero? There are still other subjects such as what is the acceptable share of renewable and whether nZEB need to be cost-optimal.

A more recently classification reported in (WBCSD, 2017) includes concepts as Energy Positive building (in which the annual energy production is higher than the consumption, so the surplus can be exported to the grid or even to attend to neighbor’s needs), Carbon neutral (net zero carbon emission by balancing the amount of carbon emitted to attend the demand) , Embodied carbon (includes the emission over the lifespan of the building, using an analysis based on a cradle-to-gate[5]).

It can be noted that some initiatives are already in place to promote the development of ZEB. For example, in Europe, the EPBD specifies that in 2020 all new buildings shall be zero energy buildings (EUROPEAN PARLIAMENT, 2012). In the United States, the Building Technological Program point out the strategic goal toward achieving marketable energy zero homes in 2020 and zero commercial energy buildings

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[5] This analysis assesses environmental impacts associated with all the stages of the building´s life from the production stage to the end-of-life stage.

in 2025. Moreover. Likewise, Hong Kong has set a target for carbon reductions by 50%-60% by 2020 compared to a 2005 baseline (FERRARA et al., 2014; SARTORI; NAPOLITANO; VOSS, 2012; SUN; HUANG; HUANG, 2015).

Notwithstanding the several definitions, the main objective of these building is to improve building envelope, foster energy-saving, and on-site renewable technologies and contribute to reducing the energy associated CO_2 emissions. Throughout this work, the term nZEB is treated as equivalent to sustainable building or high-performance building[6].

The following Figure illustrates the main idea behind nZEB in the case of an existing building. For new buildings, a life-cycle assessment should also be considered to assess the environmental impacts associated with all the stage of the building's lifespan. Future building stock also must consider passive strategies such as orientation, geometric and other hybrid solutions to reduce the cooling and heating demand.

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[6] Sustainable building term is more comprehensive due it includes water consumption, occupancy rates and others (SHEALY, 2016), which are out of the scope of this work.

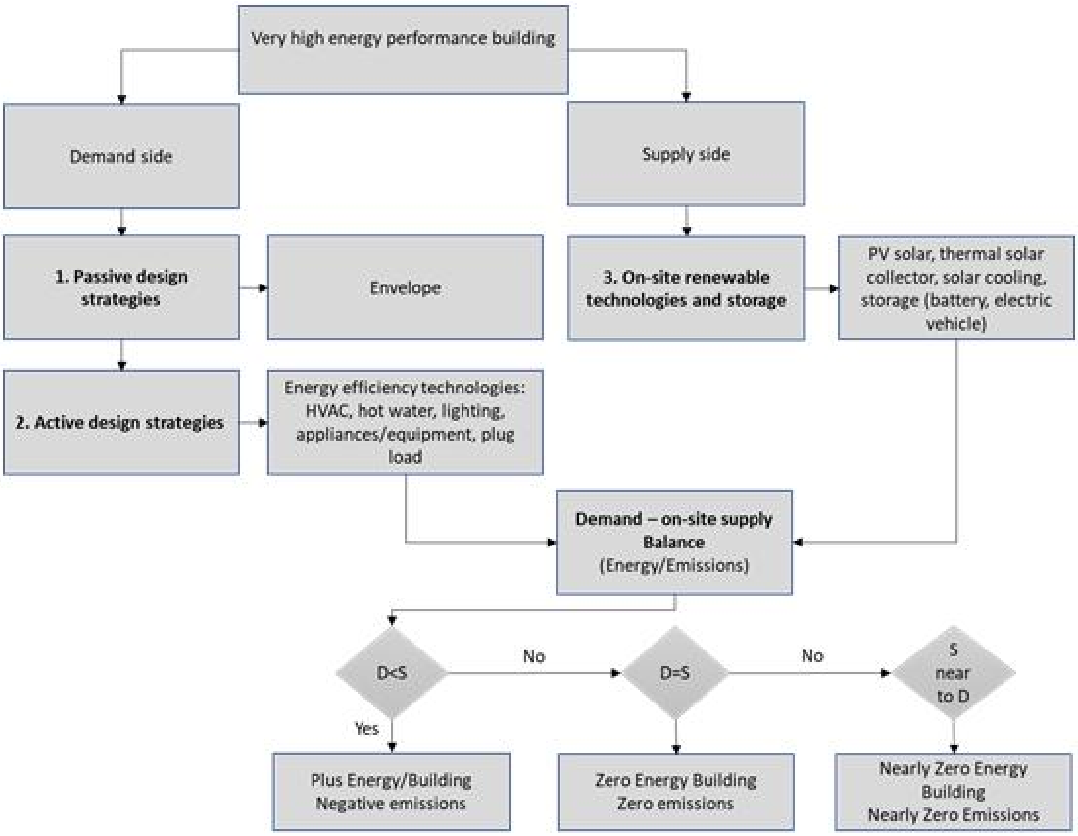

Figure 1-3. Very high energy performance Building

Source: Own elaboration

1.6 nZEB or sustainable buildings beyond their energy consumption and GHG reduction potential

Beyond the contributions in reducing both energy consumption and GHG emissions, the dissemination of nZEB or sustainable buildings can contribute to achieving the Sustainable Development Goals (SDGs). The SDG´s are a set of 17 objectives to end poverty, protect the planet and ensure prosperity for all (UN, 2015). The buildings are key in achieving economic, environmental and health benefits (WBCSD, 2017). Insights about the importance of nZEB and how they contribute to achieving the SDGs are provided in a point-by-point manner below (DOMINIKA CZERWINSKA, 2017):

SDG 3 – Good health and well-being: Diseases caused by poor indoor environmental quality are common in developing countries. The implementation of on-site renewable technologies and energy efficiency measures in buildings, particularly in cities, would improve the health by improvement of air quality.

SDG 7 – Affordable & clean energy: Sustainable energy provides an opportunity to guarantee universal access to modern energy. On-site renewable technologies are technically and economically feasible nowadays. On-site renewable technologies coupled to the building sector are considered clean, since these technologies do not produce emissions.

SDG 8 – Decent work & economic growth: Demand for new buildings should grow to cover the housing deficit and to meet the rising population. As a result, more workforce is necessary to deliver them. Deployment of on-site renewable in the future building sector would contribute to the inclusive employment goal.

SDG 9 – Industry, innovation & infrastructure: Future building stock design should be resilient and adaptable to the global climate change. In developing countries is even more important because these countries are more vulnerable to the effects of the global climate change. In this sense, the deployment of nZEB in the coming building stock would be a driver for industrialization and for innovation to face the global climate change.

SDG 11 – Sustainable cities and communities: Buildings are the heart of the cities. Then, high performance buildings would contribute to ensure a better quality of life for all.

SDG 13 – Climate action: Since building sector is responsible for 32% of the final energy consumption and 19% of the energy-related CO_2 emissions (IEA, 2017b; LUCON et al., 2014; UN ENVIRONMENT, 2017a), CO_2 emissions mitigation in this sector should be considered in climate action.

SDG 17 – Partnerships for the goals: The barriers to a sustainable built environment are not overcame with technical solutions (WBCSD, 2017). Instead of that, the solutions should be related to how effectively the stakeholders collaborate between them, guaranteeing the communal efforts are accurately aligned to achieve much greater impact. In this sense, to strengthening partnership with the institutions involved with the achievement of the rest of the SDG´s is important.

1.7 Research questions and objectives

Buildings sector faces challenges in reducing energy consumption and associated CO_2 emissions. There are multiple actions that can be undertaken in the sector to achieve those goals. The main objectives of this thesis are: a) To propose and discuss methodologies for assessing the technical and economic feasibility of nearly Zero Energy Buildings; b) To apply the methodologies proposed to case studies in the upper-middle income countries, Brazil and Colombia, in the residential sector; and in the high-income country, Portugal, in the public sector; c) To assess the barriers to the implementation of energy efficiency measures and on-site renewable technologies; d) To propose policies to overcome the barriers and boost energy efficiency and on-site renewable technologies in the buildings sector.

The objectives above are addressed in four separate studies that address distinct aspects of nZEB. Those studies are separated papers, however, related between them. Each paper looks for assessing a specific aspect of the nZEB. The studies presented here attempt to cover gaps in the methodological and empirical studies in the literature regarding high-performance buildings in developing countries, mainly, and how they can play a key role in tackling climate change and contributing to achieve the SDGs. Different approaches are presented due the heterogeneity and singularity of the sector. Those approaches might be useful to support policy-makers in understanding and identifying the technical and economic potential for reducing energy consumption and CO_2 emissions in the building sector, as well as the barriers to the diffusion of high-performance buildings in developing economies.

To address these objectives, it is worth answering the research question as follows:

1. Are nearly Zero Energy Buildings technical feasible in developing countries?
2. Are nearly Zero Energy Buildings economic feasible in developing countries?
3. Does income level influence in the economic feasibility of nearly Zero Energy Buildings?
4. What are the barriers for implementing nearly Zero Energy Buildings in developing countries?
5. What are the policies to support the deployment of nearly Zero Energy Buildings in developing countries?

1.8 Thesis outline

This work is divided into 6 chapters. In the second chapter the study “Constructive systems for social housing deployment in developing countries: An analysis using life cycle carbon assessment in Brazil” is presented. This work assesses the energy use and GHG emissions in social housing. Trade-off between quantity and quality in the social housing policy is evaluated by using a Life Cycle Carbon Assessment (LCCA). This paper focus on the first aspect of the nZEB regarding passive designs strategies – envelope (See Figure 1-4).

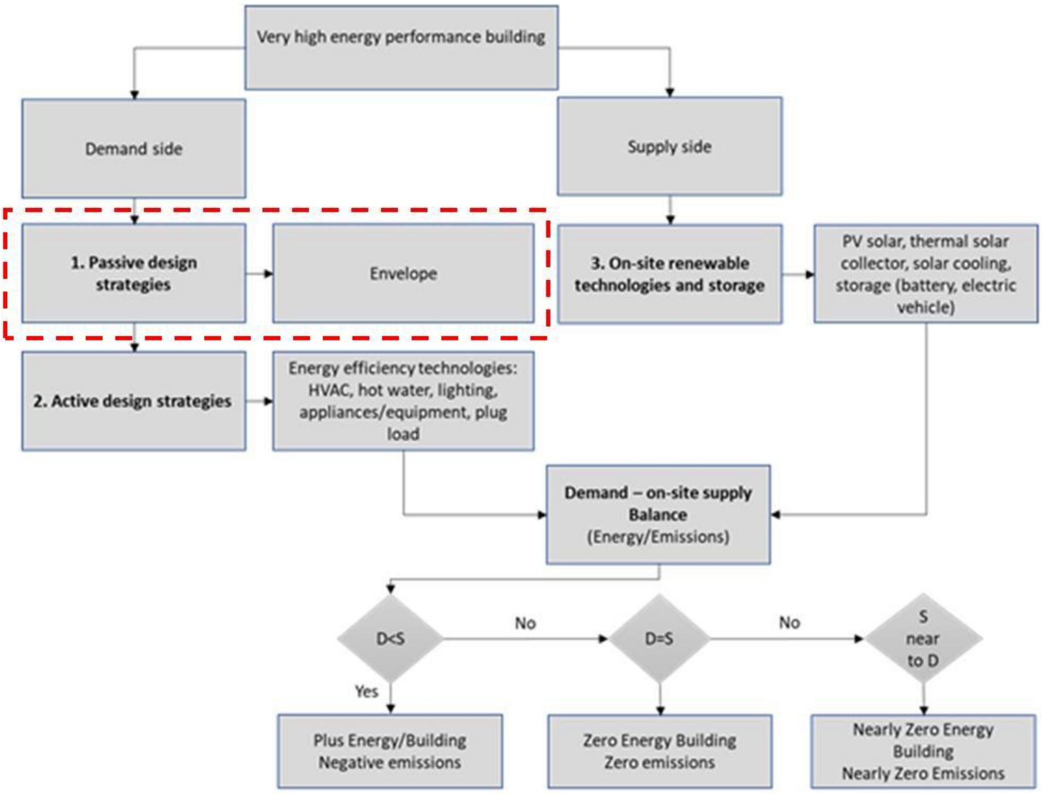

Figure 1-4. Aspect assessed in the second chapter

Source: Own elaboration

The third chapter presents the study entitled “Greenhouse gas mitigation potential and abatement costs in the Brazilian residential sector” This work assesses cost-effective abatement opportunities to reduce CO_2 emissions in the Brazilian residential sector and proposes policies to support their implementation. The abatement opportunities assessed included energy efficiency measure as well as solar PV. This paper focus on the second and third aspects of the nZEB regarding active designs strategies – energy efficiency, and on-site renewable technologies – solar PV (See Figure 1-5).

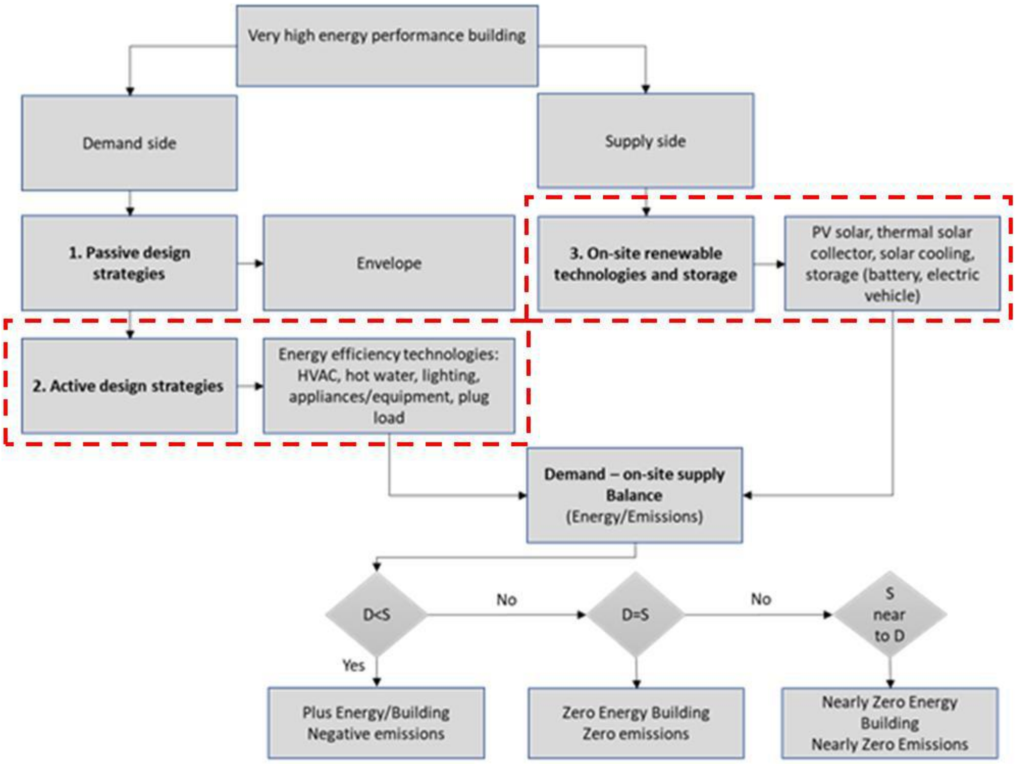

Figure 1-5. Aspect assessed in the third chapter

Source: Own elaboration

The fourth chapter presents the study entitled “Assessing the restricted deployment of distributed solar photovoltaics in the household sector in developing countries: An analysis by income level in Colombia”. This work proposes a methodology to project the technical, economic and market potential of solar PV in the residential sector, disaggregating by urban administrative division and income levels. This paper focus on the third aspect of nZEB about on-site renewable technologies, specifically PV solar for the residential sector (See Figure 1-6).

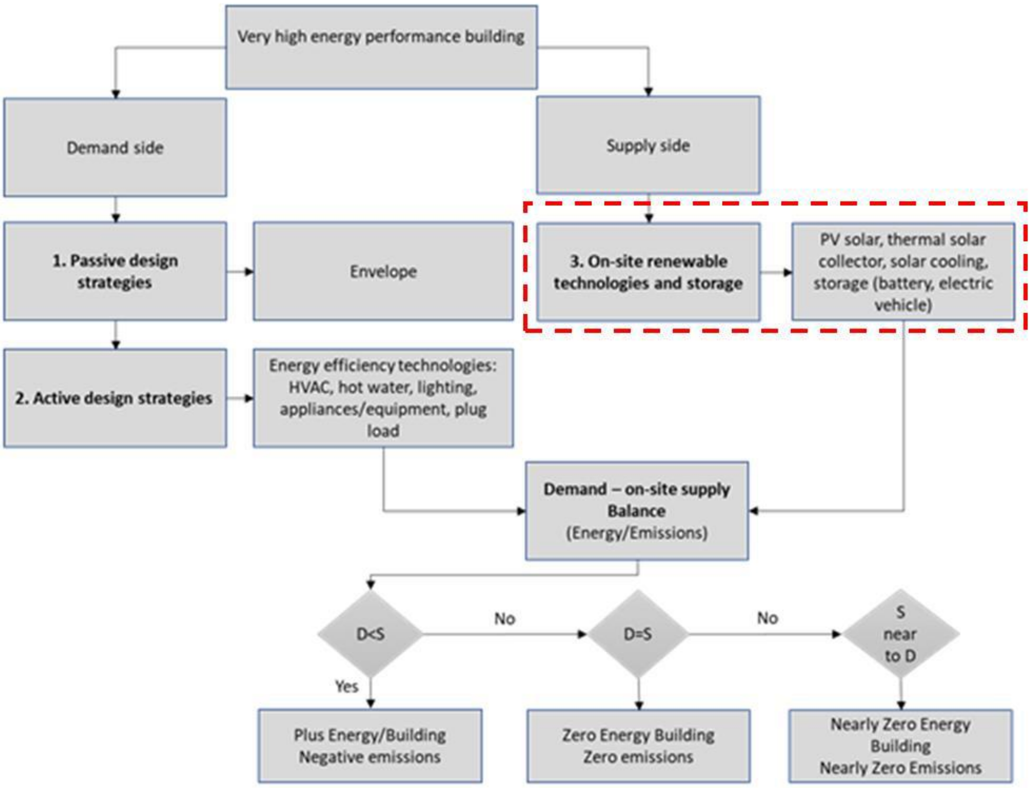

Figure 1-6. Aspect assessed in the fourth chapter

Source: Own elaboration

The study entitled "Optimization model for evaluating on-site renewable technologies with storage in zero/nearly Zero Energy Buildings" is presented in the fifth chapter. This study develops, tests and applies an optimization model to evaluate on-site renewable energy technologies with storage in buildings and assess optimal configurations for zero or nearly zero energy buildings. The proposed model is a single-objective hourly-basis mixed integer linear programing model developed in GAMS and solved by CPLEX. This work on both the first aspect of the nZEB concept and the balance between demand and on-site supply.

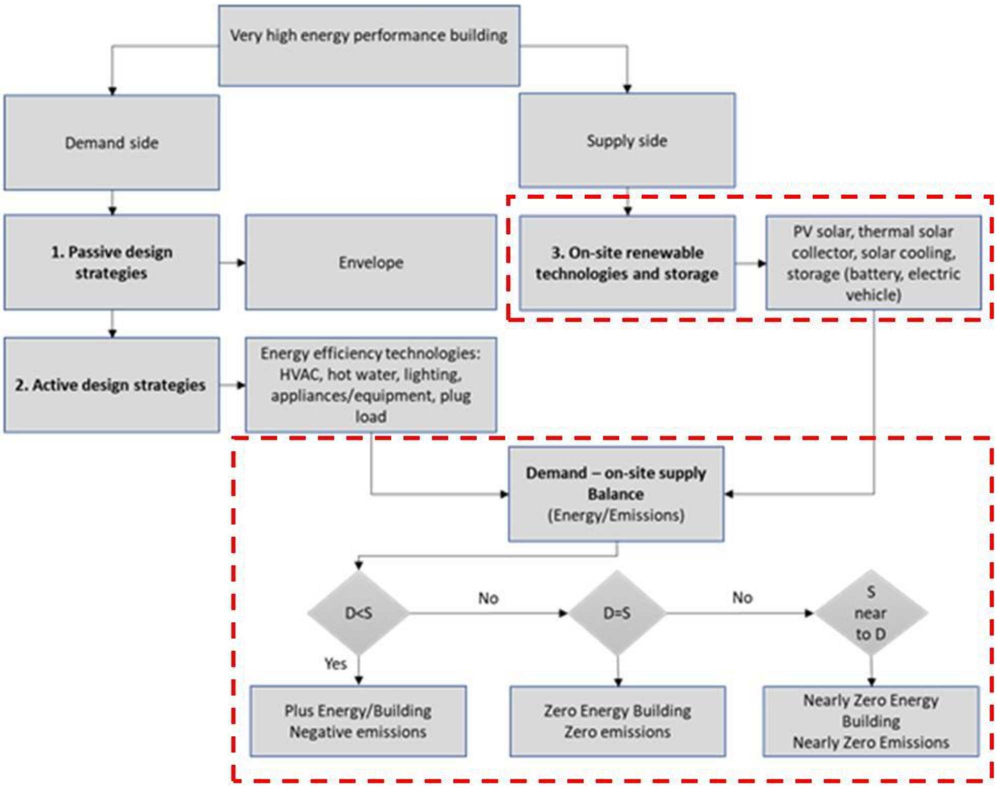

Figure 1-7. Aspect assessed in the fifth chapter

Source: Own elaboration

Each chapter/paper is a self-contained piece of work. Then, they can be read individually with any specific order. It is worth to say I am the lead author of the papers; however, they are not a single-author paper. The papers have been already submitted in scientific journals. The paper in the fifth chapter is an article *in press* in the Energy and Buildings Journal.

The final chapter summarizes the main findings of the four studies and provides some conclusions about the main barriers to the deployment of high-performance buildings, mainly, in developing the countries. It also provides some insight about future work.

2 Constructive systems for social housing deployment in developing countries: An analysis using life cycle carbon assessment in Brazil

2.1 Abstract

Developing economies must deal with both housing deficit and improving access to modern energy carriers associated with lower greenhouse gases emissions. Accurate constructive systems can play a core role in attending the thermal comfort and providing least cost solutions. In Brazil, an innovative constructive system – precast reinforced concrete panel (RCP) – has been used to increase the productivity of the building construction stage and to streamline its own production process. We use Life Cycle Carbon Assessment (cradle-to-grave), abatement cost analysis and building thermal-energy simulations to compare the RCP to a conventional constructive system – ceramic block masonry (CBM). The analysis is applied for two Brazilian bioclimatic zones represented by the cities of Brasilia and Rio de Janeiro. Findings show that the RCP displays the worst performance in terms of energy consumption, CO_2e emissions and abatement cost. Thus, policy makers face a trade-off between a higher deployment of social housing and the reduction of GHG emissions.

Keywords: Social housing, Developing countries, Precast concrete, LCCA, Cost, Carbon emissions

2.2 Introduction

Sustainable development goals (SDG) are a set of 17 objectives to end poverty, protect the planet and ensure prosperity for all (UN, 2015). SDG 11 points out the necessity of making cities and human settlements inclusive, safe, resilient and sustainable.

Urban population has grown and changed its allocation pattern substantially over the last decades - 54% of the population now live in urban areas and, by 2050, that will account for 66% of the population worldwide (HEILIG, 2014).

This is even more acute in developing countries, where megacities[7] are concentrated. These cities usually face a mismatch between population and housing supply growth. So far, fragile policies for attending the growing demand have been implemented to tackle the rapid and unplanned housing growth. Low income level populations are especially affected by the lack of consistent policies. Regarding the housing deficit, policy makers face a trade-off between quantity and quality. Lower cost materials are used to attend a higher share of the demand and achieve increasing returns of scale during the construction time. On the other hand, more expensive constructive systems can provide better decent living standards, but will not necessarily meet the housing deficit, due to budget constraints.

Accurate constructive systems are key for thermal comfort requirements, thus affecting energy consumption and greenhouse gases (GHG) emission in the buildings sector. Global warming can lead to an increase in air conditioning use in developing countries (IEA, 2013, 2017b;WAITE et al., 2017). The growth might be driven by middle-income countries, especially in tropical zones, where air conditioning is still poorly disseminated (DAVIS; GERTLER, 2015). For instance, Brazil is an emblematic case. More than 80% of the population lives in urban areas (IBGE, 2016a) and the average number of annual cooling degree days (CDDs)[8] is above 2,000 (DAVIS; GERTLER,

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[7] Megacity is defined as a metropolitan area with more than 10 million people.

[8] A cooling degree day is every degree that the mean temperature is above 65° Fahrenheit during a day.

2015) Therefore, a higher penetration of air conditioning is expected, as income growths and becomes better distributed. The social housing demand is also expected to grow substantially to cover the deficit of 6 million units (FJP, 2016). Demand-side measures are relevant to achieve the Brazilian National Determined Contribution (NDC) for climate mitigation. There is a limited remaining hydroelectric generation potential (EPE, 2015c) and an expectation of higher fossil fuel share in the electricity mix in the coming years (LUCENA et al., 2015; SCHAEFFER et al., 2013).

Furthermore, constructive systems can play a role in both attending the thermal comfort and providing a least cost solution, especially for large scale social housing requirements. For instance, in Brazil the thermal transmittance coefficient (U) for different systems ranges from 2.5 to 3.7 W/m^2K. Innovation is inherent to the civil construction development and innovative materials and systems can increase productivity, reducing construction time and total costs. In Brazil, innovative materials are those that do not have a National technical standard. Hence, they are registered in the National system of technical requirements (SINAT) (MINISTÉRIO DAS CIDADES, 2018) to be verified by laboratories through the DATec certification. The first certified innovative constructive system by SINAT was the precast concrete panels (MINISTÉRIO DAS CIDADES, 2018), a standardized mass construction system.

Life Cycle Assessment (LCA) can be useful to compare and assess the impacts of different constructive systems. Most of the research about LCA and buildings has focused on the energy consumption and CO_2 emissions (CABEZA et al., 2014). The Life Cycle Carbon Assessment (LCCA) considers all the carbon-equivalent emissions (CO_2e) output from a building over different stages of its life cycle (CHAU; LEUNG; NG, 2015). LCCA studies for different countries had focused on residential buildings and some of these studies are based on a cradle-to-gate analysis (BASTOS; BATTERMAN; FREIRE,

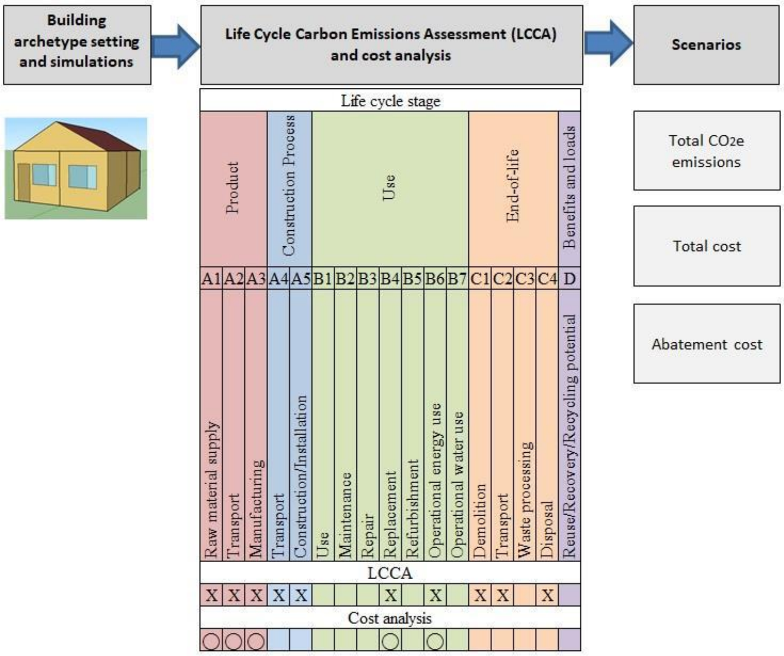
2014; GUSTAVSSON; JOELSSON, 2010; MITHRARATNE; VALE, 2004), including production and use stages. Others rely on a cradle-to-grave analysis, but also including the end-of-life stage (ATMACA; ATMACA, 2015; BLENGINI; CARLO, DI, 2010; PINKY; PALANIAPPAN, 2014). Most of them compared different constructive systems and concluded that the operational (or use) stage is the most impacting in buildings' life cycle (BRÁS; GOMES, 2015; HUBERMAN; PEARLMUTTER, 2008; JIA; CHIN; NOOR, 2015; MASTRUCCI; RAO, 2017; RADHI; SHARPLES, 2013; RAKHSHAN; ALEXANDER; TAJERZADEH, 2013). Usually, the better the thermal performance of the building envelopes are, the lower the total energy consumption and the CO_2e emissions during the building life cycle.

For Brazil, some studies focused on the environmental impacts at the production stage of ceramic and concrete materials and systems (BUENO, C. et al., 2016; CONDEIXA; HADDAD; BOER, 2014; MAIA et al., 2016; DE SOUZA et al., 2015). Other studies (INVIDIATA; GHISI, 2016a; PAULSEN; SPOSTO, 2013) assessed energy consumption through an Life Cycle Energy Assessment (LCEA) including production, use and end-of-life stages. In turn, (CALDAS et al., 2017; TABORIANSKI; PRADO, 2012) evaluated through an LCCA the impacts of the production, use and end-of-life stages on buildings GHG emissions.

The aim of this paper is to assess the energy use and GHG emissions in social housing. We evaluate the trade-off between quantity and quality in the social housing policy through an LCCA and a cost analysis. The impacts of two different constructive systems are assessed: a conventional structural ceramic block masonry house (CBM) and an innovative precast reinforced concrete panel house (RCP). The assessment covers the construction, the use and the end-of-life stages (from cradle-to-grave) of two different Brazilian climate zones (Represented by the cities of Rio de Janeiro and Brasilia). We apply a sensitivity analysis over the grid emission factors and electricity tariffs to quantify the CO_2 emissions and the present cost over the dwelling's lifespan. To our knowledge, this is the first study to consider the impacts of both an innovative constructive system (e.g. RCP) and the Brazilian electricity mix emission factors on the building's life cycle.

2.3 Methodology

The methodological approach is displayed in Figure 2-1. We started by defining and describing the reference and innovative building archetype and its main characteristics. Then, the LCCA stages and the cost analysis are detailed. The LCCA modules (from A1 to D) are presented with the corresponding cradle-to-grave selected options (X marked in Figure 2-1) according to (ABNT, 2013). In turn, the options considered for the cost analysis are marked with O in Figure 2-1. Finally, we present the total CO_2e emissions, the present cost and the abatement cost approaches for each of the scenarios will be define in the case study.



Life cycle stage	Module		LCCA	Cost analysis
Product	A1	Raw material supply	X	○
	A2	Transport	X	○
	A3	Manufacturing	X	○
Construction Process	A4	Transport	X	
	A5	Construction/Installation	X	
Use	B1	Use		
	B2	Maintenance		
	B3	Repair		
	B4	Replacement	X	○
	B5	Refurbishment		
	B6	Operational energy use	X	○
	B7	Operational water use		
End-of-life	C1	Demolition	X	
	C2	Transport	X	
	C3	Waste processing		
	C4	Disposal	X	
Benefits and loads	D	Reuse/Recovery/Recycling potential		

Figure 2-1. Overview methodology

2.3.1 Life Cycle Carbon Emission Assessment (LCCA)

The methodology for LCCA is based on (ES, 2012; RICS, 2017). LCCA accounts for all the CO_2e output over the following stages.

2.3.1.1 Production stage (A1-A3)

In this stage the raw materials supply (A1), their transport (A2) and the manufacturing of each building component (A3) are quantified, including losses.

2.3.1.2 Transport stage (A4)

The distance between the cities of the case study and the materials suppliers are quantified, considering the nearest distances. Transport mode is identified to account for the emissions at this stage.

2.3.1.3 Construction stage (A5)

Energy consumption, including electricity used by the machines and equipment used over the construction process are measured in this stage. Workforce can be accounted if the data is available.

2.3.1.4 Replacement stage (B4)

To calculate the CO2e emissions at this stage, production (A1-A3) and transport (A4) emissions are multiplied by the number of materials replacements, according to their lifespan.

2.3.1.5 Operational energy use stage (B6)

At this stage the energy consumption over the building lifespan is quantified. Energy end-uses include: lighting, appliances, cooking, HVAC, water heating. Dynamic thermal-energy simulation software is commonly used. We have performed the simulation with Open Studio suite 8.5.0 (NREL, 2017) and EnergyPlus 8.8.0 (DOE, 2017).

2.3.1.6 End-of-life stage (C1-C4)

Demolition or deconstruction (C1), waste transport (C2), waste treatment (C3) and final disposal (C4) are quantified at this stage. Benefits regarding the reuse, recovering and recycling of the waste might be included.

2.3.1.7 Life cycle inventory analysis

Good practice recommends adopting regional databases that reflect the local context. However, data for developing countries is limited, albeit the recent advances in data collection. International databases (e.g, Ecoinvent, GaBi) are often adapted to local context. We have used the software SimaPro 8.4.0.0 (SIMAPRO, 2017).

2.3.1.8 Life cycle impact assessment

Life cycle impact assessment (LCIA) methods (CML 2001, TRACI, IMPACT 2002+ etc.) have different categories of environmental impact, such as climate change, global warming potential, acidification, eutrophication and others. For the LCCA only GHG emissions are accounted and the results are expressed in terms of kgCO2e/functional unit. LCIA method IMPACT 2002+, v. 2.14, was chosen in this study, with the endpoint indicator of climate change, following (MAIA et al., 2016).

2.3.2 Cost Analysis

We perform a cost analysis considering the cost of the materials of the constructive systems (reference and innovative) – including waste during construction and replacements over the lifespan (t=50), and the cost of the electricity used for cooling. The ratio between GHG emissions and cost was calculated according to Equation 2-1.

$$\mathrm{NPC}_{\mathrm{i,j,k}} = \frac{\mathrm{GHG}_{k}}{\sum_{t=1}^{50} \frac{INV_{i,j}+O\&M_{i,j}}{(1+r)^{n}}}, \text{ (2-1)}$$

where $\mathrm{GHG}_{\mathrm{k}}$ is the amount of CO_2e emitted during the building archetype lifespan, $\mathrm{NPC}_{\mathrm{i,j}}$is the net present cost in ${}_{2017}$USD for constructive system i and city j; $INV_{i,j}$ is the cost of the materials; $O\&M_{i,j}$ is the operational and maintenance/replacement cost, including the cost of electricity for cooling; k is the case study scenario; r is the real discount rate; and n is the building lifespan.

2.4 Case Study

In this section data inputs are presented according to the methodology. We described an emblematic case of social housing in Brazil for different constructive systems and locations. Furthermore, to handle the uncertainty of the Brazilian grid emission factor, different scenarios have been proposed.

2.4.1 Building features and functional unit

The archetype building – hereafter defined as the functional unit (FU) – assessed represents a one-story single-family interest social house (GIDUR/VT, 2007). The house evaluated coincides to the “My house, my life” program (Programa Minha Casa, Minha

Vida)[9]. We considered a gross floor area (GFA) of 40.32 m2 per dwelling and we assumed a 50-year lifespan[10]. The house has a living room, two bedrooms, a kitchen and one bathroom (see Figure 2-2) The building has three internal doors, two external doors and five windows.

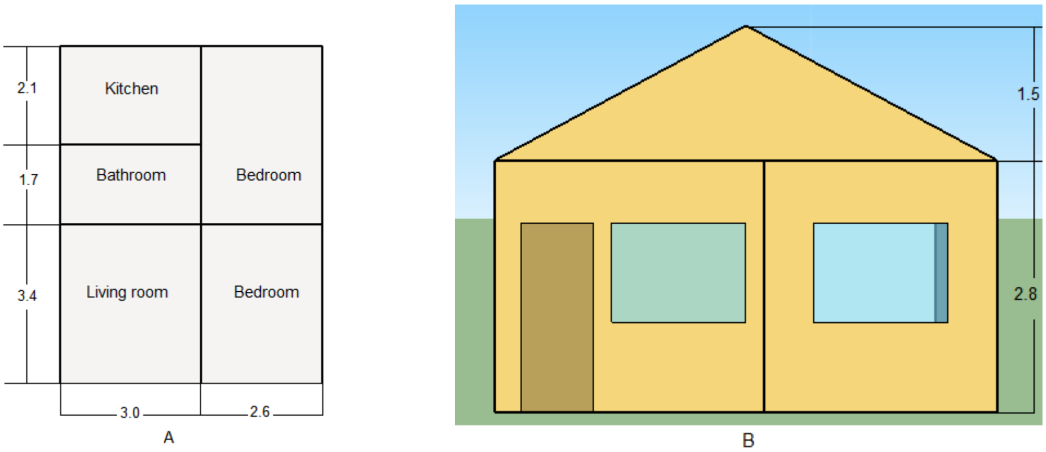


Figure 2-2. Plan (A) and elevation (B) of the building archetype (m)

2.4.1.1 Constructive systems compared

The reference constructive system is denominated ceramic blocks masonry (CBM), with walls made of ceramic blocks (140 x 190 x 390 mm) with plaster coating (width 25 mm). The innovative constructive system is made of precast reinforced concrete panels (RCP), with 100 mm width for external walls and 80 mm for internal walls, steel and mortar joints. The floor, bathroom and kitchen walls are coated by ceramic covering, the external and internal walls are covered with white paint. The roof is structured with wood and covered by ceramic tiles and a PVC ceiling. The scope of LCCA includes the

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[9] The “My house, my life” program provides favorable funding conditions to low income level families for acquisition. Around 2.3 million units were delivered until 2015 (CAIXA, 2016).

[10] According to (ABNT, 2013) the minimum lifespan for residential Brazilian buildings is 50 years.

walls (external and internal) since the other house elements and materials are the same for both constructive systems.

2.4.1.2 Description of the precast reinforced concrete panel system

For the manufacturing of the reinforced precast concrete panels the following stages are required: (1) forms preparation, (2) steel reinforcement introduction in metallic forms; (3) concrete is placed; (4) after 20 hours the panels are desinformed; (5) quality evaluation of the concreted panel; (6) application of adhesive mortar at panels borders to improve the adhesion between the concrete and the grout used between the panels joints; (6) storage and cure of panels with water aspersion with a minimum time of 24 hours; (7) transport and building of panels (they are transported by trucks and hoisted by rolling porch); (8) the plumbing of the panels is guaranteed with the aid of metal supports; (9) welding of connecting frames of adjacent wall panels; (10) Grout injection in the panels joint; (11) in the end, the joints are sealed with the polyurethane resin.

2.4.1.3 Cities compared

According to (ABNT, 2005), Brazil is divided into 8 climate zones, where Z1 is the coldest and Z8 the hottest. We have chosen for this study the cities Rio de Janeiro (RJ) and Brasilia (BSB), which belong to the Z8 and Z4, respectively. Several reasons led us to choose these cities: a) they are barely explored in the literature; b) their housing deficit is significant, around 8.0% for RJ and 13.4% for Brasilia; c) they belong to two different geopolitical regions (Southeast and Mid-west) and to two different climate zones (one with hot summer and the other with dry winter (ALVARES et al., 2013); d) they have different constructive guidelines (ABNT, 2005); and e) the cost of the materials and electricity tariffs are not the same.

2.4.2 Life Cycle Carbon Emission Assessment (LCCA)

2.4.2.1 Production stage (A1-A3)

Wall components have been quantified. We considered the raw materials supply, their transport and the manufacturing of each component. Ceramic blocks, mortar (for joints and coating), grout (with fck 15 MPa) and steel rods for reinforcement were considered for ceramic blocks wall. On the other hand, concrete (with fck of 25 MPa), steel rods (for reinforcement), adhesive mortar, covering mortar, grout, and polyurethane resin (for joints sealing) were considered for precast concrete panels. The forms and braces have not been considered because they are made of metal, which can be reused several times.

2.4.2.2 Transport stage (A4)

In Brazil, most of the construction materials are transported by trucks. Table 2-1 displays the distances between the cities and the manufacturers considered in this study. The web mapping was based on the shortest distance provided by (GOOGLE, 2017). We have assumed a truck's capacity higher than 20t, with a minimum load of 80% and empty return in all cases. Data from Ecoivent v.3.3 (FRISCHKNECHT; REBITZER, 2005) was used.

2.4.2.3 Construction stage (A5)

In this stage, the electricity consumption of machines and equipment used in the construction process was measured. Data were obtained from (CAIXA; IBGE, 2017) and from the manufacturers websites. It is worth to say that the workforce was not assessed. For the CBM the 40-liter mixer was adopted for mortar mix. The average consumption resulted in 0.58 kWh/m2 of GFA. For the RCP construction the following steps were considered: (1) placement of concrete in formworks; (2) transportation and building of panels (they are transported and hoisted by rolling porch); (3) welding of connecting frames of adjacent wall panels; (4) grout mixture (in a 400-liter mixer) and injection in the panels joint. In the end, the electricity consumption was accounted 7.21 kWh/m² of GFA.

Table 2-1. Distances between the city and materials manufacturers [in km]

Material	Brasilia	Rio de Janeiro
Ceramic block	183	124
Mortar covering	127	92
Mortar joint	127	92
Adhesive mortar	127	92
Steel rods	735	248
Concrete	85	66
Polyurethane resin	1,002	678
Grout	85	66

Source: own elaboration based on (GOOGLE, 2017)

2.4.3 Replacement stage (B4)

The replacement of ceramic blocks and the concrete panels was not considered because they are structural elements of the building. They have the same minimum 50-year lifespan of the house (ABNT, 2013). On the other hand, the replacement of other materials was accounted. For CBM one replacement of the mortar coating was considered, while for the RCP one replacement of grout, adhesive mortar and sealant (all of them used in joints) were considered.

2.4.4 Operational energy use stage (B6)

The thermal energy simulation is performed in hourly time-steps using Open Studio suite 8.5.0 (NREL, 2017) and EnergyPlus 8.8.0 (DOE, 2017). Our approach discriminates conditioned zones (bedrooms and living room) and unconditioned zones (bathroom and kitchen). The air conditioner (A/C) operational schedule was set according to (INVIDIATA; GHISI, 2016a,b) and is available during the occupation period to provide cooling and dehumidification. The coefficient of performance (COP) of the A/C equipment was set at 2.8, corresponding to the third best energy efficiency standard11 in Brazil (INMETRO, 2014a). After pre-simulations in Open Studio, the North orientation was chosen because it represents the hottest situation regarding the thermal gains in the house. For the simulation, the set-point was set at 24.9oC (RJ) and 24.3oC (BSB) (PEREIRA; ASSIS, DE, 2010). The properties of the building materials set at Open Studio and are displayed in Table 2-2.

Table 2-2. Properties of the building materials

No	Material	Thickness [m]	Density [kg/m3]	Conductivity [W/m.K]	Specific heat [J/kg.K]
1	Brick hollow	0.1400	0,200	0.70	920.0
2	Clay and ceramic tiles	0.0200	2,000	1.00	800.0
3	Plaster	0.0200	1,800	1.15	1,000
4	Reinforced concrete	0.1200	2,400	1.75	1,000
5	Sand and gravel	0.1500	1,950	1.33	1,950
6	Screed	0.0500	1,800	1.50	1,000
7	Wood structure	0.0200	450.0	0.12	2,300

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[11] Social housing policies are constrained by budget conditions at minimal cost, so they do not acquire the best available technology.

No	Material	Thickness [m]	Density [kg/m3]	Conductivity [W/m.K]	Specific heat [J/kg.K]
8	PVC	0.0008	1,200	0.20	838.0
9	Glass	0.0006	2,500	1.00	840.0
10	Wood door	0.0004	900.0	0.20	1,340
11	Precast RCP exterior	0.1000	2,400	1.75	1,000
12	Precast RCP interior	0.0800	2,400	1.75	1,000

Source: (SARTORI; HESTNES, 2007)

The materials that compose the building elements (walls, roof, floor, etc.) and the U-values are shown in Table 2-3 according to each of the constructive systems. It is worth highlighting that the U-value for RCP is higher than for CBM.

The results obtained from the simulation which are input for the LCCA are displayed in the Appendix (Figure 2-10 and Figure 2-11).

Table 2-3. Building Elements and Components

Building elements	Material composition Layers*	Constructive systems**	U-values [W/m^2K]
Exterior walls	[3, 1, 3]	CBM	2.02
Interior walls	[3, 1, 3]	CBM	2.02
Exterior walls	[11]	RCP	4.40
Interior walls	[12]	RCP	4.90
Roof pitched	[7, 2]	CBM/RCP	1.92
Ceilings (Flat roof]	[8]	CBM/RCP	0.83
Floor	[5, 4, 6, 2]	CBM/RCP	3.93
Windows	[9]	CBM/RCP	5.60
Doors	[10]	CBM/RCP	4.80

* Correspond to the Table 2-2 Source: (ABNT, 2005)

Table 2-4. Electricity consumption for cooling [kWh/year]

City	**Constructive system**	
	CBM	RCP
Brasilia	402.8	713.8
Rio de Janeiro	483.3	808.3

2.4.4.1 End-of-life stage (C1-C4)

The main assumption at this stage is that both constructive systems are demolished at the end of the lifespan. Generate waste from this process is transported to the nearest landfill, within a 50 kilometers distance from the building site (MAIA et al., 2016). Demolition, treatment and collection for final disposal data were gathered from (WERNET et al., 2016). For CBM, it was adopted 0.00601 $kgCO_2e/kg$ and for RCP, 0.00842 $kgCO_2e/kg$, in both cities.

2.4.4.2 Life cycle inventory analysis

In Brazil, building sector life cycle databases are practically non-existent. To overcome this, data coming from (BUENO et al., 2016; WERNET et al., 2016) has been used. Furthermore, we have taken into consideration the real Brazilian energy mix in the software SimaPro 8.4.0.0 (SIMAPRO, 2017). Since operational stage has a huge impact on the energy and carbon life cycle of buildings (CABEZA et al., 2014; CHAU; LEUNG; NG, 2015; SARTORI; HESTNES, 2007) due to the electricity consumption, we have performed a sensitivity analysis with two carbon emissions factors (EF). Emission from electricity production has experienced sharp variations over the last years because the high dependence of hydroelectric generation and its impact in the emission grid factor (Figure 2-12). To manage this uncertainty for the coming years, we pondered two emission factors: (a) minimum emission factor (EF_{min}), representing a large amount of hydroelectric generation (period 2012-2013, for instance); and (b) maximum emission factor (EF_{max}), representing a higher amount of generation coming from fossil fuels (years 2014 and 2015, for instance). Then, the EF_{min} and EF_{max} were set at 0.130 $kgCO_2e/kWh$ and 0.198 $kgCO_2e/kWh$, respectively.

2.4.4.3 Life cycle impact assessment

Results of this study are expressed in terms of $kgCO_2e/m^2$.

Table 2-5. Climate change impact by materials and activities

Materials and activities	**Climate change impact kgCO2e/(unit)**	**Dataset**	**Source**
Ceramic block[2]	0.056/kg	Several[1]	(MAIA et al., 2016)
Mortar covering	0.176/kg	Several[1]	(MAIA et al., 2016)
Mortar joint	0.273/kg	Several[1]	(MAIA et al., 2016)
Adhesive mortar	1.11/kg	Adhesive mortar production (CH)[3]	(WERNET et al., 2016)
Steel rods	3.00/kg	Several[1]	(MAIA et al., 2016)
Concrete	0.163/kg	Several[1]	(MAIA et al., 2016)
Addictive	1.08/kg	Several[1]	(MAIA et al., 2016)
Polyurethane resin	4.22/kg	Polyurethane, flexible foam production (RER)	(WERNET et al., 2016)
Grout[3]	0.11/kg	Cement, unspecified production (CH). Lime, hydrated, loose weight production (CH). Sand gravel and quarry operation (CH).	(WERNET et al., 2016)
Electricity mix - min	0.130/kWh	Electricity, high voltage, production mix[4] (BR)	(WERNET et al., 2016)
Electricity mix - max	0.198/kWh	Electricity, high voltage, production mix[5] (BR)	(WERNET et al., 2016)
Transport	0.098/t.km	Transport, truck > 20t, EURO3, 80% LF, empty return	(WERNET et al., 2016)
Ceramic block waste	0.00601/kg	Waste brick treatment of, collection for final disposal (CH)	(WERNET et al., 2016)
Reinforced concrete waste	0.00842/kg	Waste reinforced concrete treatment of, collection for final disposal (CH)	(WERNET et al., 2016)

[1] (MAIA et al., 2016) used primary data from (ANICER, 2017) and secondary data from (WERNET et al., 2016).
[2] It was used wood residues as fuel for the burning of the ceramic blocks.
[3] It was considered a mix (in volume) of cement:lime:sand:gravel (1:0.04:1.6:1.9), with 20 MPa.
[4] Based on Brazilian electricity matrix of 2012.
[5] Based on Brazilian electricity matrix of 2014.

2.4.5 Cost Analysis

Data for the materials were obtained from SINAPI (CAIXA; IBGE, 2017)the National research of costs of the civil construction. Table 2-6 presents the cost of the materials for RJ and BSB.

Table 2-6. Cost of the materials for RJ and BSB (values in $_{2017}$USD/kg)

Materials	RJ	BSB
Steel rods	0.94	1.16
Adhesive mortar	0.56	0.29
Multipurpose mortar	0.25	0.13
Concrete	0.04	0.04
Grout	0.47	0.45
Polyurethane resin	25.10	24.13
Welded steel screen	1.49	1.31
Ceramic block	0.23	0.07

Source: (INMETRO, 2014b)

Regarding the cost of electricity, tariffs from the local utilities for the base year were considered – USD 99.9/MWh for RJ and USD 100.2/MWh for BSB (ANEEL, 2017). The values in US dollars (USD) were converted by an exchange rate of R$ 3.2/USD, the average for the year 2017 (BACEN, 2017). The tariffs grow based on an inflation rate of 3% p.a. We assumed a nominal discount rate of 8% p.a. to calculate the present value for the scenarios. Over the building lifespan these rates linearly decrease, reaching 1% p.a. and 3.5% p.a., respectively, at the end of the period. We assumed that the Brazilian economic would grow over the next 50 years. In turn, this growth implies a greater capital accumulation leading to a reduction of both interest rates and inflation.

2.4.6 Scenarios

We assessed two constructive systems, reference and innovative (CBM, RCP), in two Brazilian cities (RJ, BSB). To tackle the uncertainty about the Brazilian electricity mix emission factor, we also ponder into the analysis two emission factors (EF_{min}, EF_{max}) The results are presented in the next section as scenarios that are given by combinations between construction systems, cities and emission factor (Figure 2-3).

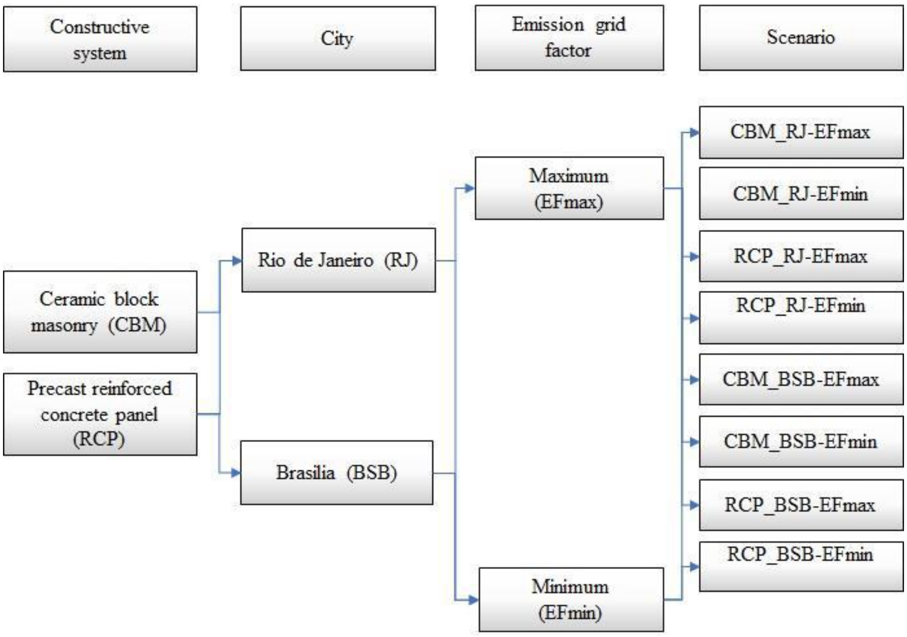

Figure 2-3. Assessed Scenarios

2.5 Results and Discussion

First, the production stage (A1-A3) of the constructive systems were compared in terms of mass, CO2e emissions and costs of each component (See Figure 2-4).

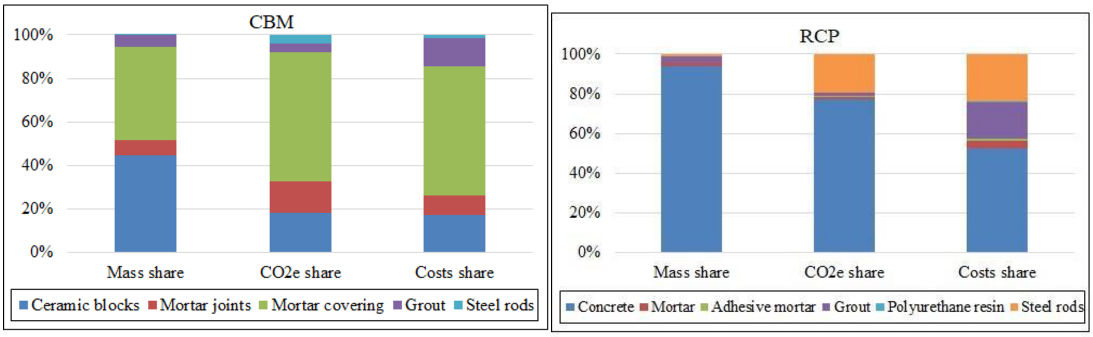

Figure 2-4. Comparison of the production stage between CBM and RCP

For CBM, mortar covering is the main responsible for the mass, CO_2e emissions and costs, followed by ceramic blocks, mortar joints, grout and steel rods. Thus, if we want to minimize the system emissions and costs, we should focus on reducing the mortar consumption. The typical mortar used for covering and joint in Brazil is made of cement, hydraulic lime and sand, with a 2.5 cm thickness (the value adopted in this article). The cement is the material that most contributes in terms of CO_2 emissions and costs because of the calcination process. Moreover, a mortar with less cement content tends to have less impacts. On the other hand, less cement in the mortar composition leads to a decrease in its resistance and durability. Therefore, an optimum mortar mix should be evaluated and used in the ceramic block masonry system.

Another strategy to minimize the impact of mortar is to reduce its thickness, which will lead to less material consumption. However, this alternative will also affect the durability of the system and thermal performance, which may increase the energy consumption in the use stage. In Brazil, the minimum thickness allowed (according to standards) is 2 cm for internal walls and 2.5 for external walls. The ceramic blocks presented high mass share but low CO2e emissions. This result has a strong a correlation with the use of wood chips as fuel on blocks fabrication, as shown in (MAIA et al., 2016). In Brazil, the use of wood chips (or other biomass sources) for ceramic blocks and bricks firing stage (at factory) is a common practice[12], in which the quality and the origin of the biomass might influence the CO_2 emitted.

For RCP, the concrete was the material that most contributes to mass, CO_2e emissions and costs, followed by steel rods, grout, adhesive mortars and polyurethane resin. The cement used in concrete is also responsible for the higher CO_2e emissions and costs. A strategy to decrease the impacts on GHG emissions of this constructive system is to use alternative materials, such as supplementary cementitious materials (SCM) in the concrete mix design. The wall thickness is already at the minimum value (10 cm), therefore the solution goes through replacing the cement for other less carbon footprint materials, without compromising the minimum 25 MPa compression strength of the concrete.

The CO_2e emissions of the buildings life cycle are presented in Figure 2-5. The RCP presented higher total CO_2e emissions of all scenarios. Values range from 242.99 $kgCO_2e/m^2$ ($\text{RCP BSB} - \text{EF}_{min}$) to 355.59 $kgCO_2e/m^2$ ($\text{RCP\_RJ} - \text{EF}_{max}$). For the CBM, values range from 207.84 $kgCO_2e/m^2$ ($\text{CBM\_BSB} - \text{EF}_{min}$) to 315.19 $kgCO_2e/m^2$ ($\text{CBM\_RJ} - \text{EF}_{max}$).

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[12] For instance, if it was considered natural gas (or any other fossil fuel), the impact on GHG emissions of the ceramic block would probably be greater.

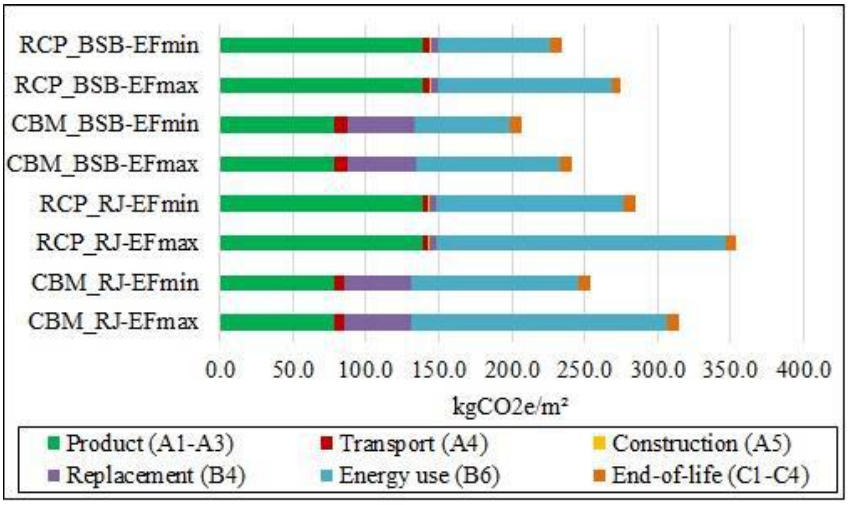

Figure 2-5. Total CO_2e emissions of the building life cycle by stage

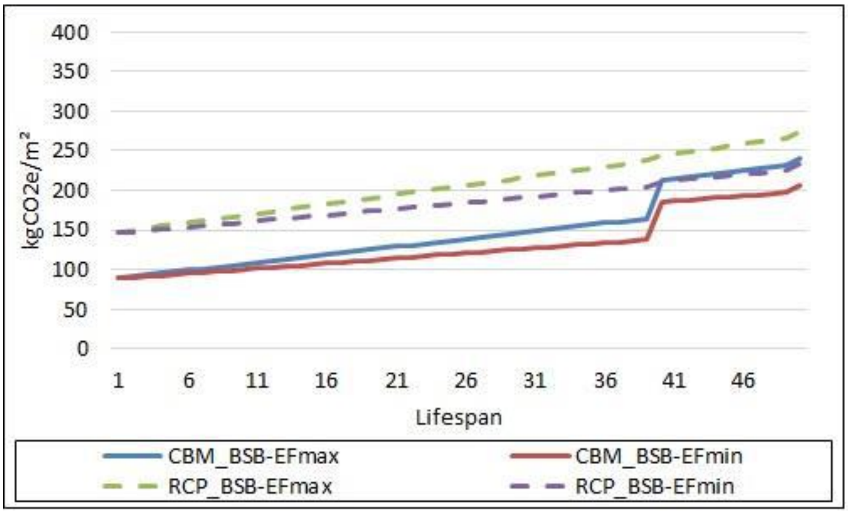

Figure 2-6. Accumulated emissions over the lifespan of the building (Brasilia)

With regard to the constructive system, the highest difference within scenarios is 17.2% ($\text{RCP\_BSB} - \text{EF}_{max}$ vs $\text{CBM\_BSB} - \text{EF}_{max}$), while the minimum is 12.5% ($\text{RCP\_RJ} - \text{EF}_{min}$ vs $\text{CBM\_RJ} - \text{EF}_{min}$). In relation to changes in the emission factor, the highest difference occurred between ($\text{RCP\_RJ} - \text{EF}_{max}$ and $\text{RCP\_RJ} - \text{EF}_{min}$) (24.4%) and the lowest between ($\text{CBM\_BSB} - \text{EF}_{max}$ and $\text{CBM\_BSB} - \text{EF}_{min}$) (16.7%). Finally, when comparing the two cities, the highest difference was observed between ($\text{CBM\_RJ} - \text{EF}_{max}$ and $\text{CBM\_BSB} - \text{EF}_{min}$) (30.1%), while the lowest difference was observed between ($\text{RCP\_RJ} - \text{EF}_{min}$ and $\text{RCP\_BSB} - \text{EF}_{min}$) (21.7%). In this sense, the results show that the Brazilian bioclimatic zones and the grid emission factor are critical for LCCA studies in the Brazilian context. They strongly influence the final LCCA results and cause more impacts than the constructive systems, when just façades are evaluated. The CO_2e emissions of the production stage (A1-A3) and the energy use (B6) stage accounted for the highest share of the total buildings carbon life cycle.

The energy use stage ranged from 31% $\text{CBM\_BSB} - \text{EF}_{min}$ to 56% $\text{CBM\_RJ} - \text{EF}_{max}$. In the production stage, values ranged from 25% ($\text{CBM\_RJ} - \text{EF}_{max}$) to 57% ($\text{RCP\_BSB} - \text{EF}_{min}$). In the replacement stage (B4), from 1% ($\text{RCP\_RJ} - \text{EF}_{max}$) to 22% ($\text{CBM\_BSB} - \text{EF}_{min}$. In the transport (A4) and end-of-life (C1-C4) stages, values were lower than 5%. The construction stage (A5) presented negligible share on the total share on the total CO_2 emissions (lower than 0.5%), because most of the construction process is handmade and due to the low emission factor of the Brazilian electricity mix.

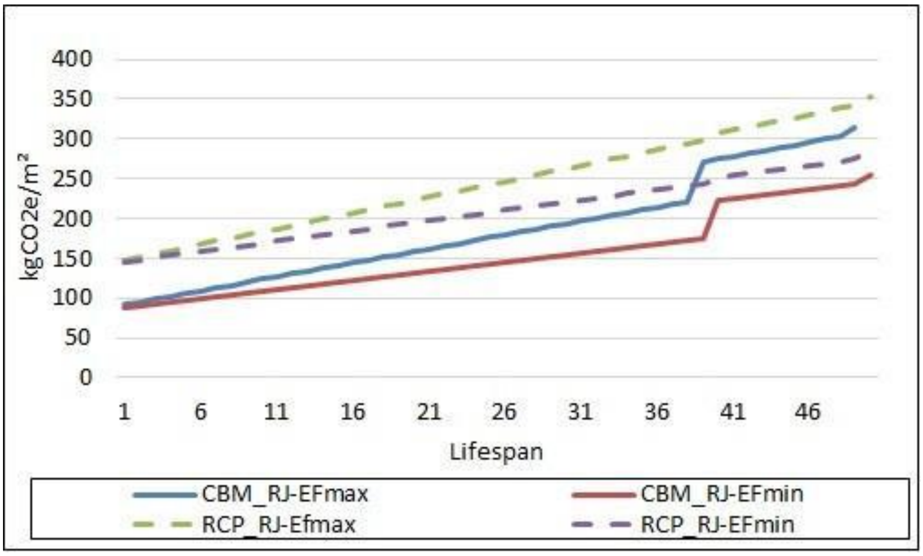

Figure 2-7. Accumulated emissions over the lifespan of the building (Rio de Janeiro)

Figure 2-6 and Figure 2-7 display the emissions over the lifespan of the houses. In the case of CBM, the accumulated emissions reveal a disruption in the year 40 due the replacement of mortar covering, while this trend is not verified for the RCP since the materials adhesive mortar and grout- used in the panel joints were considered.

These results are in line with the literature (see (PAULSEN; SPOSTO, 2014) and (CALDAS et al., 2017)). Although those studies have different scopes and assumptions, they have showed that the operational and production are the most impacting stages on the carbon life cycle of houses. These stages must deserve a special attention of building designers.

Figure 2-7 presents the present value of costs for RJ and BSB according to the building archetype - CBM or RCP. The share of materials in the total costs is higher in all cases because only the electricity used for cooling is considered. Naturally, if the costs for all energy end-uses were computed, the cost of materials would represent a lower share in the total costs.

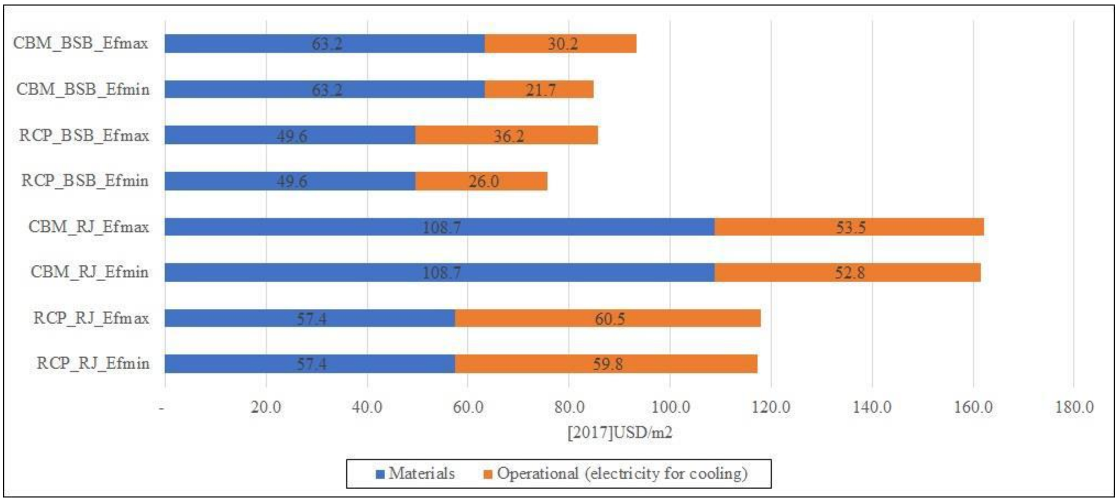

Figure 2-8. Present costs for RJ and BSB according to the building archetype - CBM or RCP (in 2017USD and %)

The results also show that RJ is a more expensive city than BSB, regarding both the cost of materials and the electricity. The differences reach 2017USD/m^2 per GFA in the CBM scenario, mostly because of the price gap of the mortar (covering and joint) between the cities, according to [47] data. The difference in the total cost between the

RCP and CBM scenarios in BSB is around 92,017 USD/m2 per GFA, but in RJ the differences in the total cost are around five times higher (45$_{2017}$ USD/m2) per GFA.

The results in Figure 2-8 show CO_2e emissions per $_{2017}$USD invested in materials and operational stage. This ratio for RCP varies from 2.8 $kgCO_2e/_{2017}USD$ in the $RJ-EF_{min}$ to 3.2 $kgCO_2e/_{2017}USD$ in $BSB-EF_{max}$. For CBM, the range is 1.7 $kgCO_2e/_{2017}USD$ in the $RJ-EF_{min}$ to 2.6 $kgCO_2e/_{2017}USD$ in $BSB-EF_{max}$. RCP is less efficient than CBM because for each USD invested in the RCP, the emissions are higher than CBM. We also observed that for Brasilia city (red columns), the ratio $kgCO_2e/_{2017}USD$ is higher than Rio de Janeiro (blue columns). This reveals that in Brasilia is more difficult to achieve a cost efficient CO_2e emissions reduction.

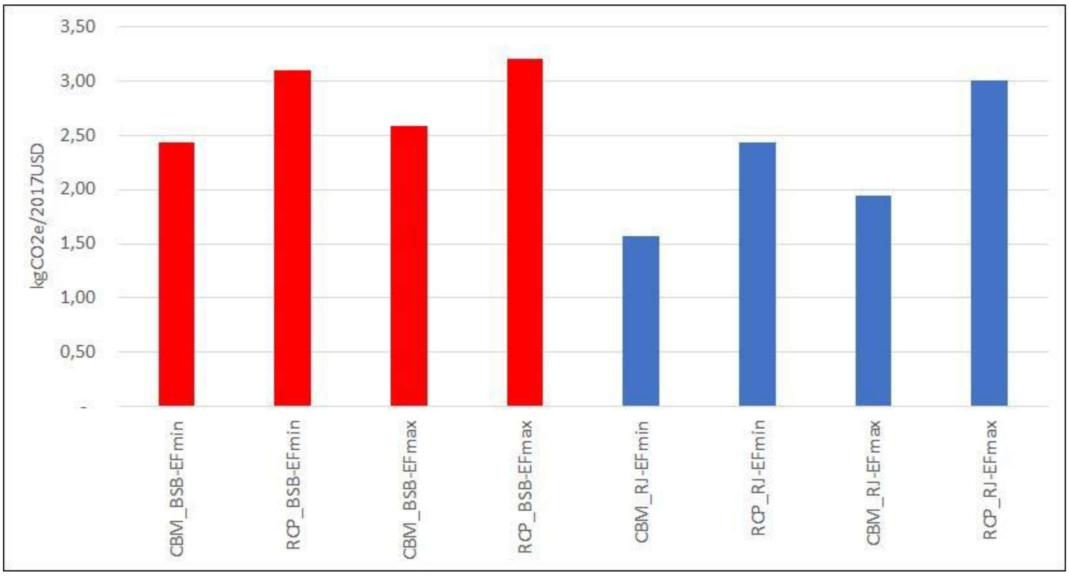

Figure 2-9. CO_2e emissions per 2017USD invested ratio

When taking into account only CO_2e emissions, the RCP performs worse than the CBM for all scenarios (see Figure 2-5) However, regarding the total costs, the RCP is cheaper than the CBM in all scenarios. The abatement cost analysis provides a broader view on the results. For instance, the results for RCP reveal that this constructive system is a non-effective cost measure in both cities. Perhaps, for other Brazilian bioclimatic zones the RCP could result in cost-effective measures.

2.6 Final remarks

This study assessed whether the solution for attending the growing demand for housing in developing countries could create a conflict under a GHG global mitigation context if the constructive systems are not properly chosen. On the one hand, the replacement of the typical constructive system could deteriorate the thermal conditions in social housing, leading to a higher electricity demand to meet the cooling end-use and, hence, to higher GHG emissions. Short term objectives of reaching a higher deployment of social houses could conflict with the global objective of reducing the GHG emissions in the long-term. On the other hand, choosing constructive systems that can provide better living standards over the long term may face barriers related to the short-term budget constraints.

To test this issue, this study applied LCCA and a costs analysis to investigate the CO_2e emissions and abatement costs, respectively, during the life cycle of two constructive systems. A case study for social houses in Brazil for two different cities (Brasilia and Rio de Janeiro) was considered. The variables of the study were the buildings' external and internal wall systems. A ceramic block masonry (CBM) system that is conventionally used in Brazil was compared to a precast reinforced concrete panel (RCP) – an industrialized innovative system with growing trends in Brazilian social house construction. Thermal performance, electricity use, CO_2e emissions and costs in the operational stage for both houses and cities were evaluated, using computational simulation. The worst thermal performance of RCP resulted in more electricity consumption for air conditioning at the operational stage. The climate zones of the cities evaluated, and the emission factors of the Brazilian electric mix have greater effects on the final results of the different constructive systems. Therefore, in the Brazilian context (with 8 bioclimatic zones) these issues must be integrated into LCCA along with cost analysis and evaluated on ongoing research.

The RCP displayed higher total CO_2e emissions and abatement costs when compared to the CBM, for all scenarios. To our knowledge, this is the first study to consider the impacts of both an innovative constructive system (RCP) and the emission factors on the building's life cycle, in the case of Brazil. It provides insights to create a national map to support climate change policies and help building designers to guide low carbon pathways for social housing in Brazil.

The study does not consider the returns of scale of the RCP innovative constructive system. In this case, the differences between the workforce required to build the RCP and the CBM systems could be accounted, since the construction time could vary. This limitation does not invalidate our results but could be explored in further studies, especially in a life cycle social analysis framework.

It is also important to mention that just the walls (external and internal) and the energy required for air conditioning were considered in our scenarios. For further research, the authors intend to evaluate other cities and another innovative constructive system, such as concrete panels produced with bio-based materials that are still being developed in our laboratories.

2.7 Appendix

Figure 2-10. Demand base and alternative case Brasilia

Figure 2-11. Demand base and alternative case Rio de Janeiro

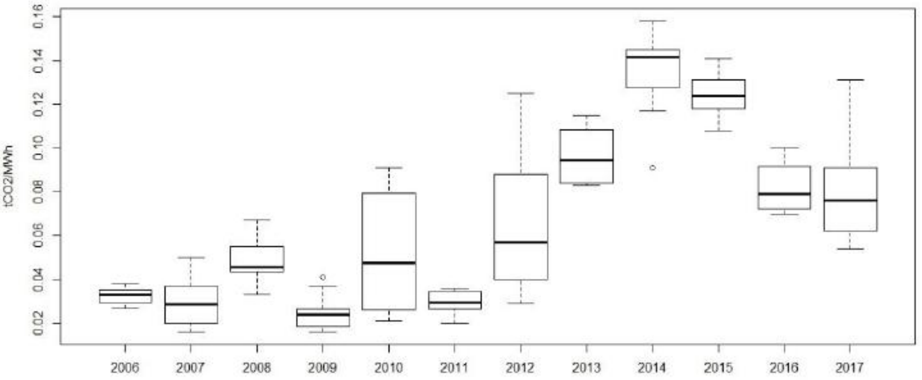

Figure 2-12. Boxplot for the Brazilian grid emission factors from 2006 to 2017

3 Greenhouse gas mitigation potential and abatement cost in the Brazilian residential sector

3.1 Abstract

For the first time, in Paris 2015, the building sector took place in the official agenda of the Conferences of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC). The Global Alliance for Buildings and Construction (GABC) was launched to support and boost the implementation of the Nationally Determined Contributions (NDCs) by consolidating energy efficiency, increased use of renewable energies to reduce GHG emissions. Energy efficiency can be seen as a “resource in abundance”, characterized by the fastest and least-cost mode to reduce energy consumption and achieving energy security. This paper assesses cost-effective abatement opportunities to reduce CO_2 emissions in the Brazilian residential sector and proposes policies to support their implementation. Findings show that, if implemented, the energy efficiency measures in the cooking end-use and photovoltaic (PV) solar panels would represent together more than 70% of the abatement potential. Assuming the implementation of all measures, the energy consumption in 2050 would increase only 18% in relation to the base-year. The total cumulative avoided emissions until 2050 would be 642 $MtCO_2$ in Brazil over 2010-2050.

Keywords:

Energy efficiency, Residential sector, Marginal abatement curve cost, Brazil

3.2 Introduction

Energy use has been largely responsible for progresses in welfare and quality of life over the XX and XXI centuries. Energy use in the buildings sector provides services such as thermal comfort, hygiene, food preparation and preservation, entertainment and communication (GEA, 2012). For the first time, the buildings sector took place into the official agenda of the Conferences of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC), in 2015 in Paris, when the Global Alliance for Buildings and Construction (GABC) was launched (UN ENVIRONMENT, 2016). Its target is to support and boost the implementation of the Nationally Determined Contributions (NDCs) by consolidating energy efficiency, increasing the use of renewable energies to reach GHG emission reduction. Thus, the buildings sector has been gaining importance in the global mitigation debate.

The buildings sector is responsible for 32% of the final energy consumption worldwide (117 EJ) and 19% of the global GHG emissions in 2010 (9.2 $GtCO_2$) (LUCON et al., 2014). The sector become even more important in terms of final electricity demand consuming 55% of the total (IEA, 2017b). Altogether, electricity consumption in the buildings sector has grown by multiple of 4.5 in non-OECD between 1990 and 2014, while in OECD countries has continue quite unalterable because the energy efficiency improvements (IEA, 2017b).

In Brazil, final energy consumption in the buildings sector has been increasing at 1.60% p.a. between 2000 and 2016 (EPE, 2016a). The buildings sector accounted for 16% of the Brazilian final energy consumption (24,851 ktoe) and more than half of the electricity consumption in 2016 (11,426 ktoe) (EPE, 2016a).

In the coming years, the energy consumption from this sector is expected to continue increasing because of population growth, changes in the consumption patterns and migration to cities (HEILIG, 2014; IEA, 2017b).

Several studies have addressed the strategies to reduce the sector's dependence on external energy supply – e.g., electricity from the grid – and the GHG emissions associated with its consumption (ASCIONE, 2017; D'AGOSTINO; PARKER, 2018; DENG; WANG; DAI, 2014; KYLILI; FOKAIDES, 2015; WELLS; RISMANCHI; AYE, 2018). Energy efficiency measures, improvements in buildings' envelope and the deployment of the on-site renewable technologies have been identified as the three main strategies for the reduction of the energy consumption and GHG emissions (RODRIGUEZ-UBINAS et al., 2014). Suffice to say that more efficient appliances have reached commercial stage in the last years and on-site renewables, such as solar thermal collectors and photovoltaic (PV) solar, contribute to reduce housing the dependence on external energy supply. Improved building envelopes are also key for reducing the lighting, space-cooling and space-heating demands. Therefore, these strategies can play a crucial role regarding climate change mitigation and resources depletion. Moreover, energy efficiency can be seen as a "resource in abundance" characterized by the fastest and least-cost mode for achieving energy security, reducing energy consumption and avoiding environmental impacts (IEA, 2017a).

Despite the importance of the sector, few studies assess mitigation options for the building sector in Brazil. Schaeffer et al. (SCHAEFFER et al., 2009) conducted a study for calculating the technical, economic and market potential for electricity conservation in the Brazilian household sector. The results were translated into carbon dioxide emission reductions. In turn, De Mello et al. (MELO, DE; JANNUZZI; FERREIRA

TRIPODI, 2013) evaluated public policies to encourage the deployment of energy efficiency and on-site renewable technologies in the Brazilian residential sector by using a multi-criteria analysis and marginal abatement cost analysis (MELO, DE; JANNUZZI; FERREIRA TRIPODI, 2013). The modelling complexity due to its heterogeneity (residential, commercial and public segments have their own characteristics), the diversity of its energy end-uses and the limited availability of public data contribute for this gap in the literature.

The main objective of this paper is to assess mitigation measures in the Brazilian residential sector. To our knowledge this study is the first to present a detailed methodology for assessing the cost-effectives of opportunities to reduce CO_2 emissions in Brazil´s residential sector and to propose policies to support their implementation. The study focused on energy efficiency measures and solar PV. Other on-site renewable technologies and improvements in the buildings envelope were not considered. The policies are discussed in the light of the marginal abatement cost (MACC) [13] for the Brazilian residential sector up to 2050.

Because of the limited availability of public data on the commercial, services and public sectors, this study retains its focus only on the residential segment. Future research is required to investigate the other two.

This paper is organized in five sections. Section 3.3 presents the methodology used to calculate the GHG emissions and abatement costs of the reference (Ref_S) and low-carbon (LoC_S) scenarios. Section **Erro! Fonte de referência não encontrada.**

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[13] It is an economic concept that measures the cost of reducing one more unit of emission.

outlines a set of energy efficiency measures considered in the LoC_S scenario. Section 3.4 summarizes the results of implementing the energy efficiency measures proposed and discusses the marginal abatement results. Section 5 brings final remarks and policy implications, focusing on the barriers found for implementing the LoC_S scenario.

3.3 Methodology

Figure 3-1 presents the methodological approach. The reference (Ref_S) and low-carbon (LoC_S) scenarios are defined by identifying low-carbon measures in a bottom-up model (BU). The Ref_S scenario follows a business-as-usual case in which currently used technologies are adopted and limited gains in energy efficiency are assumed. This definition is useful because it allows to measure the GHG mitigation potential of low-carbon technologies in relation to the case where no measures are applied. The main residential energy end-uses assessed in both scenarios were: lighting, air conditioning, cooling, cooking and water heating.

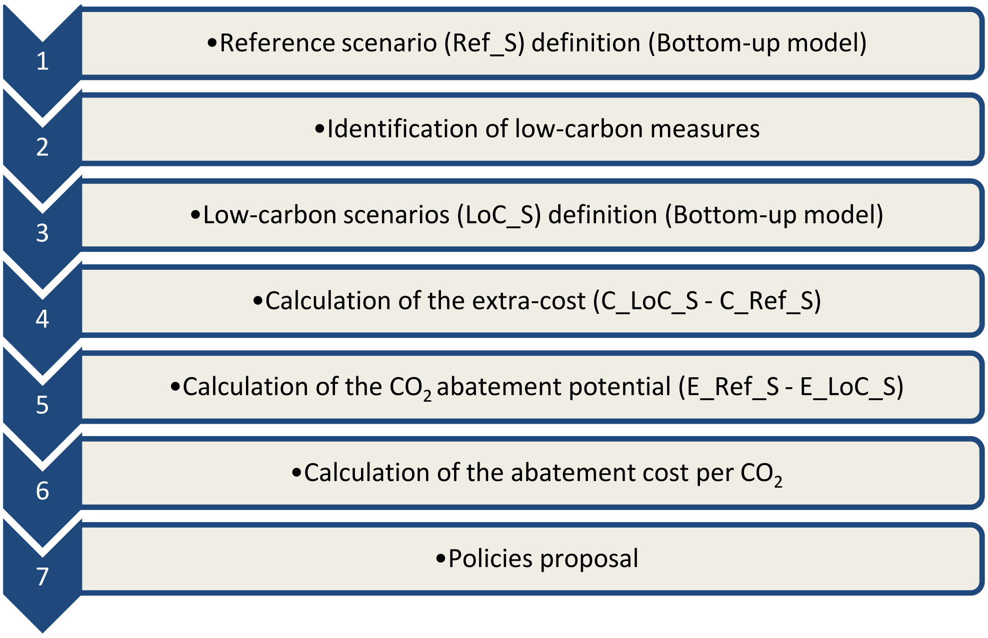

Figure 3-1. Methodological approach

Based on the scenarios defined, the additional cost of mitigation measures of the low-carbon scenario is calculated. Next, the CO_2 abatement potential of the low-carbon scenario is calculated. The abatement cost per tCO_2 is then calculated, providing results for building a MACC.

Scenarios are projected from the base year of 2010 up to 2050. The BU representation of energy demand in base year 2010 is calibrated with aggregate data reported by the National Energy Balance (2010) (EPE, 2010, 2014c;PROCEL/ELETROBRAS, 2007a) and information on total energy consumption by end-uses (EPE, 2014b). This aggregate information allowed to calibrate the BU equations presented in the next section for the parameter with the highest uncertainty or whenever data was not available.

The energy efficiency measures assessed by end-use in LoC_*S* scenario are summarized in the Table 3-1 as follows:

Table 3-1. Energy efficiency measures in the LoC_*S* scenario

Energy-end use	Measure description
Lighting	Higher penetration of LED technology, replacing both fluorescent compact and florescent tub lamps from 2015 on.
Air conditioning	Penetration of more efficient technologies based on the high-efficiency equipment of the Energy Star program (ENERGY STAR, 2014).
Cooling	It was assumed a two-phase measure: 1) Transition between 2015 and 2020, when standard refrigerators are replaced by efficient technologies, and, 2) From 2021 onwards, high-efficiency refrigerators penetrate in households with an income higher than 10 times the minimum wage[14].

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[14] We adopted this assumption based on that high-volume efficient-technology as the US standard will continued be purchased by high-income families

Energy-end use	Measure description
Cooking	Improved oven for both LPG and natural gas stoves (minimum) efficiency standards based on (INSTITUTO NACIONAL DE METROLOGIA QUALIDADE E TECNOLOGIA, 2016).
Water heating	There mitigation options were considered: a) More efficient natural gas heaters, b) More efficient electrical showers and c) Replacement of electrical showers for a higher penetration of SWHS, assuming the projections of (EPE, 2014a).
Distributed generation	Solar panel would be installed following economic feasibility. PV feasibility occurs from the moment in which grid parity is achieved.

3.3.1 Bottom-up (BU) approach

The bottom-up (BU) approach considers three variables, namely: ownership, use patterns and equipment/appliances efficiency. Equation (3-1) represents the general BU representation of energy consumption for each end-use:

$$EC_{end-use} = \sum_{i,j} Households_{ij} * AOHA_{ij} * PA_j * UP_{ij} \,, \qquad (3\text{-}1)$$

where $EC_{end-use}$ is the energy consumption for each end-use (in kWh), $AOHA$ is the average appliance ownership per household (Appliance/Household), PA is the appliance power (kW), UP is the use pattern (h), i is the region, j is the appliance type or the energy source.

Equation 3-1 decomposes energy consumption in the activity, the structure and the intensity effects. The activity effect is determined by the number of households, the structure effect is defined by the average appliance ownership, and the intensity effect is determined by the appliance’s efficiency and its use pattern.

To calibrate the scenarios in the base-year, we have estimated the parameters for Equation 3-1 using the best available information (described individually below, for each end-use). The parameter with the highest uncertainty was calibrated to meet the total energy consumption, under the assumption that the values should be in line with those found in the literature. The scenarios were projected according to the changes of the activity, structure and intensity effects based on the general premises presented in 3.3.3. The results of the following uses: lighting, air conditioning[15], cooling (refrigeration), cooking, water heating and other appliances are then aggregated for energy consumption and CO_2 emissions in each scenario.

To calculate the investment required for the abatement measures (in the LoC_S), a hypothetical sales curve, considering the lifespan and the cost of each technology, was estimated from 2010 to 2050. The BU equation for each end-use and the main assumptions considered are described in the following subsections.

3.3.1.1 Lighting

The lighting end-use consumption is calculated based on Equation 2-2:

$$EC_{lighting_t} = \sum_{i,j,t} Household_{i,j,t} * AOHA_{i,j,t} * PA_{i,j,t} * UP_{i,j,t}, \qquad (3\text{-}2)$$

where $EC_{lighting}$ represents the energy consumption for lighting end-use (in kWh), $AOHA$ is the lamp average ownership per household, PA is the lamp power (in kW), UP is the use pattern (in hours), i is the region and j is the appliance type (incandescent lamp, fluorescent tub lamp, fluorescent compact lamp and LED), for the full time horizon (t = 2010, …,2050).

For fluorescent tub and compact lamps, we have considered a lifespan of 6 and 4 years, respectively. For incandescent light bulb, a one year lifespan was considered, and

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[15] It is important to note that space heating is not a relevant end-use in Brazil, given the tropical climate prevalence.

for the LED lamps, a 20-year nameplate lifespan (MCTIC, 2017a). Regarding the cost of the technology, we have assumed US$41.5/bulb for the most efficient technology (LED), US$4.6/bulb for the florescent tub lamps, US$3.7/bulb for fluorescent compact lamps and US$0.92/bulb for incandescent lamps in the base-year. We have estimated that the cost of the LED technology would decrease to US$4.06/bulb by 2050. Since the other type of lamps are in a mature stage, we have estimated that their cost would decrease between 5% to 10% up to 2050. The Ref_S scenario includes the ban of the incandescent technology from 2016 onwards according to (MME, MCTI, 2010).

3.3.1.2 Space cooling

The energy demand for air-conditioning end-use is projected as follows (Equation 3-3):

$$EC_{air\ conditioning_t} = \sum_{i,j,t} Household_{i,j,t} * AOHA_{i,j,t} * COP_j * CT_i, \qquad (3\text{-}3)$$

where $EC_{air\ conditioning}$ represents the energy consumption for air conditioning, $AOHA$ is the air-conditioner equipment average ownership by household, COP is the coefficient of performance and CT is the thermal load.

The air conditioning ownership was estimated based on information of (IBGE, 2000) and (ABRAVA, 2014).. , according to Equation 3-4:

$$AHOA_{i,j,t} = \frac{\sum_{t-n}^{t} s_{i,j,t}}{Household_{i,j,t}}, \qquad (3\text{-}4)$$

where “S” is the number of units sold per year and “*n*” is the lifespan of the air conditioning units. A lifespan of 10 years was adopted for this study (NAHB, 2007). For estimating CT, we have adopted the methodology used by (CARDOSO et al., 2012). It considers the difference between the external temperature and a standard comfort temperature (26.7°C) (CARDOSO et al., 2012). The data for the external temperatures were gathered on an hourly basis for a standard day per month (24x12) from (EMBRAPA, 2018). Capacity was set in 9,000 BTUs for the standard air-conditioner unit. The standard technologies were defined based on (INMETRO, 2014a). The parameters for air-conditioning technologies are shown in Table 3-2.

Table 3-2. Parameters for air conditioning technologies

Type	**Capacity (thermal kw)**	**COP**	**Capacity (kW electric)**	**Price (US$ 2010)**
Split standard	2.6	3.05	0.86	1361
Split efficient*	2.6	16.1	0.86	3111
Window standard	2.6	3.02	0.86	527
Windows efficient*	2.6	9.8	0.86	1022

Source: (INMETRO, 2014a), (ENERGY STAR, 2014)

3.3.1.3 Refrigeration and freezer

The methodology to estimate the cooling service requirements in households comprises the use of refrigerators and freezers as follows in Equation 3-5:

$$EC_{cooling_t} = EC_{refrigerators_t} + EC_{freezers_t} = \sum_{i,j,t} Household_{i,j,t} * AOHA_{refrigeratorsi,j,t} * v_{refrigerators} * ec_{refrigerators,i} + \sum_{i,j,t} Household_{i,j,t} * AOHA_{frezzers,i,j,t} * v_{freezers} * ec_{freezers,i}, \qquad (3\text{-}5)$$

where $EC_{refrigerators}$ and $EC_{freezers}$ represents the energy consumption for refrigerators and freezers, respectively. $AOHA$ is the refrigerators/frezzers average household ownership, v is the standard volume of the refrigerator/freezer and ec represents the specific energy consumption of one refrigerator/freezer. IBGE (IBGE, 2012) provides *AOHA* for refrigerators and freezers per household. The sales of refrigerators and freezers were estimated as follows (Equation 3-6):

$$Sells_{i,j,t} = AOHA_{\,i,j,t} * Household_{i,j,t} - \sum_{t=to-n,j,i}^{to-1} sells_{i,j,t}, \tag{3-6}$$

where n is the lifespan of the equipment and t_o represents the base year. For freezers/refrigerators, a 12-year lifespan was assumed, based on (ELETROBRÁS-PROCEL, 2007). Table 3-3 shows the technologies considered for the projections and their costs. For both standard refrigerators and freezer parameters, data from the PROCEL program was used (INMETRO, 2014a). The efficient refrigerator and freezers parameters were based on the Energy Star program (ENERGY STAR, 2014). For the high-efficiency refrigerators, we took the frontrunners of the European Union as reference (TOPTEN.EU, 2014).

Table 3-3. Parameters and costs used for cooling technologies

Technology	**Volume (L)**	**Energy Consumption (kWh/year)**	**Average Power (kW.year)**	**Specific Energy Consumption (kWh.year/L)**	**Cost (US$ 2010)**
Standard Refrigerator	282.3	367	0.042	1.3	570
Efficient Refrigerator	282.3	211	0.024	0.75	1,006
High-efficiency Refrigerator	282.3	135	0.015	0.48	1,526
Standard Freezer	200	374	0.04	1.87	449
Efficient Freezer	200	111	0.01	0.56	982

Source: (INMETRO, 2014a), (ENERGY STAR, 2014), (TOPTEN.EU, 2014)

For the Ref_S projection, the (estimated) sales of the standard refrigerator/freezer were used as the least cost and least efficiency technology. In 2050, the efficiency of the standard refrigerator/freezers reaches the best-performance technology found in 2010 in the Brazilian market, corresponding to 1,08 kWh/L-year and 1,64 kWh/L-year for refrigerators and freezers, respectively (INMETRO, 2014a).

3.3.1.4 Cooking

The energy consumption for cooking was estimated based on Equation 3-7:

$$EC_{cooking_{i,t}} = \sum_i \%\, source_{i,t} \cdot \frac{population_t}{buildings_t} \cdot \frac{tep_{i,t}}{population_t} \cdot buildings_t\ , \tag{3-7}$$

where $EC_{cooking_{i,t}}$ represents the energy consumption for cooking, *i* represents the energy source used for cooking (natural gas and LPG); *% source$_i$* represents the household share of the source *i*; (*tep$_i$ / population*) is the *per capita* specific consumption coefficient (for each energy source *i*); and *t* is the time horizon ($t = 2010, \ldots, 2050$).

The share of each source (*% source$_i$*) used for cooking was obtained on (EPE, 2016b) and, when necessary, adjusted based on data from (SINDICATO NACIONAL DAS EMPRESAS DISTRIBUIDORAS DE GÁS LIQÜEFEITO DE PETRÓLEO – SINDIGÁS, 2015) and (ASSOCIAÇÃO BRASILEIRA DAS EMPRESAS DISTRIBUIDORAS DE GÁS CANALIZADO, 2015). Based on (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2014), it was assumed that all Brazilian households would own at least one stove by 2050. The specific energy consumption per capita (*tep$_i$ / population*) was assumed constant throughout the period of analysis, since it historically does not show large variations (SCHAEFFER et al., 2003)[16]. Table 3-4 shows the specific consumption per capita, per energy source.

Table 3-4. Specific consumption per capita for cooking by source

Source	tep/habitant.year	MJ/habitant.day
Natural Gas	0,026	3,0
Biomass	0,722	82,8
LPG	0,035	4,0
Charcoal	0,246	28,2

Source: Own elaboration based on (EPE, 2011, 2014c, 2015b)

In addition, the share of LPG on household cooking was assumed to decrease linearly from 92.92% (in 2010) to 66.70% (in 2050), being replaced by the natural gas that would reach a 27.30% share by 2050. Finally, by 2050, biomass and charcoal would

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[16] The authors show that, historically, the specific energy consumption per capita does not variate significantly in Brazil.

reach a 6.00% share, respectively, and electricity would not play a significant role on cooking, especially because of the increased natural gas expansion.

It was adopted a 15-year average lifespan for both LPG and natural gas ovens, based on market research data (INSTITUTO BRASILEIRO DE DEFESA DO CONSUMIDOR, 2013). The overnight capital cost of the most efficient technologies – i.e., those that replace the old ones at the end of their lifespan – was assumed to be US$ 40/kW, for both LPG and natural gas stoves, while a US$ 20/kW overnight capital cost was assumed for the standard technologies.

3.3.1.5 Water Heating

The energy consumption for water heating was estimated based on Equation 3-8:

$$EC_{water\ heating_{i,t}} = \sum_i \%\ source_{i,t} \cdot \frac{population_t}{buildings_t} \cdot \frac{tep_{i,t}}{population_t} \cdot buildings_t, \tag{3-8}$$

where $EC_{water\ heating_{i,t}}$ represents the energy consumption for water heating, i represents the energy source used for water heating (electricity, solar energy, natural gas and LPG); $\%\ source_i$ represents the household share of the source i; ($tep_i/population$) is the *per capita* specific consumption coefficient (for each energy source i); and t is the time horizon ($t = 2010, \ldots, 2050$).

We have considered the forecast pointed in (EPE, 2014a) regarding the water heating use, which indicates that the penetration of the solar energy through Solar Water Heating System (SWHS) would reach 20.20% of residences up to 2050. However, this perspective predicts both the expansion of current SWHS promotion as the expansion of the natural gas distribution grid.

Table 3-5. Energy source share in water heating in the Brazilian residential sector - LoC_*S* scenario (%)

Source	2010	2020	2030	2040	2050
No heating	20.0	19.8	18.7	17.5	16.4
Solar	2.7	5.0	5.0	5.0	5.0
Natural Gas	3.5	5.0	8.0	11.0	15.0
GLP	2.2	2.0	2.4	2.9	3.8
Electricity	71.6	68.2	65.9	63.6	59.8

Source: Own elaboration, based on (EPE, 2014a)

Regarding the per capita specific energy consumption ($tep_i/population$), (SCHAEFFER et al., 2003) presents that it historically does not show large variations. Therefore, we have kept it constant throughout the period of analysis. Table 3-6 shows the *per capita* specific consumption, per energy source for water heating.

Table 3-6. Specific consumption per capita in water heating by source

Source	tep/habitant.year	MWh/habitant.year
Solar	0.003	0.038
Natural Gas	0.022	0.256
GLP	0.023	0.267
Electricity	0.012	0.141

Source: Own elaboration based on (EPE, 2011, 2014c, 2015b)

We have considered the electric shower as an auxiliary system for the SWHS, when the low solar fractions[17] take place over rainy seasons, low solar radiation periods and/or occasional high consumption rates. An average annual solar fraction of 73% was considered (CRUZ, 2016), which is in line with the literature review (ABRAVA, 2008; KULB, 2013; RODRIGUES, 2010). Table 3-7 presents the share of each energy source in water heating for Ref_*S* and LoC_*S* scenarios.

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[17] The solar fraction is defined as the amount of energy demanded for water heating that is supplied by thermal solar energy.

Table 3-7. Share of energy source in water heating in the Brazilian residential sector by 2050 for each scenario (%)

Source	Ref_S	LoC_S	
		NG heaters more efficient	**Replacement of electrical shower for SWHS**
Does not heat	16.4	16.4	16.4
Solar	5.0	5.0	20.2
Natural Gas	15.0	15.0	15.0
GLP	3.8	3.8	3.8
Electricity	59.8	59.8	44.6

Source: Own elaboration (MCTIC, 2017b)

The lifespan, the efficiency and equipment/technology costs used in water heating were based on manufacturers' information and on (INMETRO, 2014a), and the SWHS average cost was taken from (CRUZ, 2016), as presented in Table 3-8.

Table 3-8. Technical-economic data of the Technologies used for water heating

Technology	**Lifespan (year)**	**Efficiency**	**Cost (US$)**
Electric shower	8	0.95	20
Natural gas heater (E)	15	0.76	200
Natural gas heater (A)	15	0.90	400
SAS	20	-	1,410.32

Source: Self elaboration based on (INMETRO, 2014a), (CRUZ, 2016) and manufacturers

We have assumed that the natural gas heater efficiency varies from 76% in 2010 (INMETRO label E) to 90% in 2050 (INMETRO label A) (INMETRO, 2014a).

3.3.1.6 Other uses

The consumption in other end-uses is calculated based on Equation 3-9:

$$CE_{other-uses_t} = CE_{main\ appliances_t} + CE_{other\ appliances_t}, \qquad (3\text{-}9)$$

$$CE_{main\ appliances_t} = \sum_{i,j,t} Household_{i,j,t} * AOHA_{i,j,t} * PA_{i,j,t} * UP_{i,j,t},$$

where $CE_{other-uses}$ represents the energy consumption for other uses (in kWh), $CE_{main\ appliances_t}$ is the energy consumption required for the main appliances,

$CE_{other\ appliances_t}$ is the energy required for the rest of the appliances, $AOHA$ is the appliance average ownership per household, PA is the appliance power (in kW), UP is the use pattern (in hours), i is the region and j is the appliance type (television, washing machine, computer and iron have been considered as the main appliances), for the full time horizon (t = 2010,…,2050).

Regarding the $CE_{other\ appliances_t}$ calculation, we have adopted an income-elasticity approach. Table 3-9 displays the average parameters considered in the base-year for the main appliances.

Table 3-9. Technical-economic data of the Technologies used for appliances

Appliance	Power (W)	Ownership (Unit)	Use pattern year (Hours)
Television	90	1.41	1800
Washing machine	500	0.63	144
Computer	100	0.60	1080
Iron	1221	0.93	144

Source: Own elaboration based on (PROCEL/ELETROBRAS, 2007b)

3.3.1.7 On-site generation

On-site generation was also assessed as a potential mitigation alternative. In this case, however, the methodology follows a different methodological approach, based on (MIRANDA, R. F. C.; SZKLO; SCHAEFFER, 2015). Only PV solar technology has been analyzed, as it is the major on-site electricity generation option in the residential segment.

The five Brazilian regions (North – N; Northeast – NE; Mid-West– CO; Southeast – SE; South – S) were divided into sub-groups based on the solar resource applied (MIRANDA, R. F. C.; SZKLO; SCHAEFFER, 2015). In the residential sector, all Brazilian households were separated into four sub-groups based on monthly income.

Other socioeconomics aspects, such as household energy consumption, rooftop availability, load curve and capital cost were inputted in order to quantify the total residential sector potential, as described in (MIRANDA, R. F. C.; SZKLO; SCHAEFFER, 2015). The PV potential was defined based on the sector electricity demand forecast up to 2050 (EPE, 2014c), from which 0.7% would be served by PV energy up to 2030 and 1% by 2050.

The solar resource quality was assessed based on 20 local spots for the entire country. Thus, in cities where solar data were not available, the closest resource available was used[18]. Current PV costs were assessed through suppliers established in the Brazilian market. Costs forecast were estimated by setting technology learning rates at 18% up to 2020 and 16% up to 2050 - the historical rates were around 20% on average (IPCC, 2012; IRENA, 2012; RUBIN et al., 2015) - and also considering an installed capacity outlook worldwide (MIRANDA, R. F. C., 2013). By this, we assume that future prices should follow the global trend, regardless of a possible strengthening of the photovoltaic Brazilian industry (Table 3-10).

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[18] For more info regarding PV capacity factors, please access (MIRANDA, R. F. C.; SZKLO; SCHAEFFER, 2015)

Table 3-10. PV price forecast

	2015	2020	2025	2030	2035	2040	2045	2050
(R$/Wp)	9,0	7,35	6,84	6,44	6,07	5,82	5,67	5,54
(US$)	4,15	3,39	3,15	2,97	2,80	2,68	2,61	2,55

Source: (MIRANDA, R. F. C.; SZKLO; SCHAEFFER, 2015)
Note: *Includes installation costs

Since it is not reasonable to consider that all the residential building rooftops could be shortly covered by solar panels due to limited human and material resources – even if there is willingness to pay for it –, a maximum penetration curve has been defined. It indicates the time in which a given additional potential is available for mitigation purposes (Figure 3-2).

From an end-consumer perspective[20], PV economic feasibility occurs from the moment in which grid parity is achieved, that is, the point where the cost of the energy generated from PV systems is equal or smaller to the value paid to the local utility.

We defined the low-carbon capacity as the Brazilian economic potential minus the baseline projections (Figure 3-2).

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[19] 2010 Exchange rate: US$1,00 = R$ 2,17

[20] Feasibility from an end-consumer perspective might not be valid considering the whole energy system and/or economic agents, once PV integrations incurs in additional costs not included in its own levelized cost.

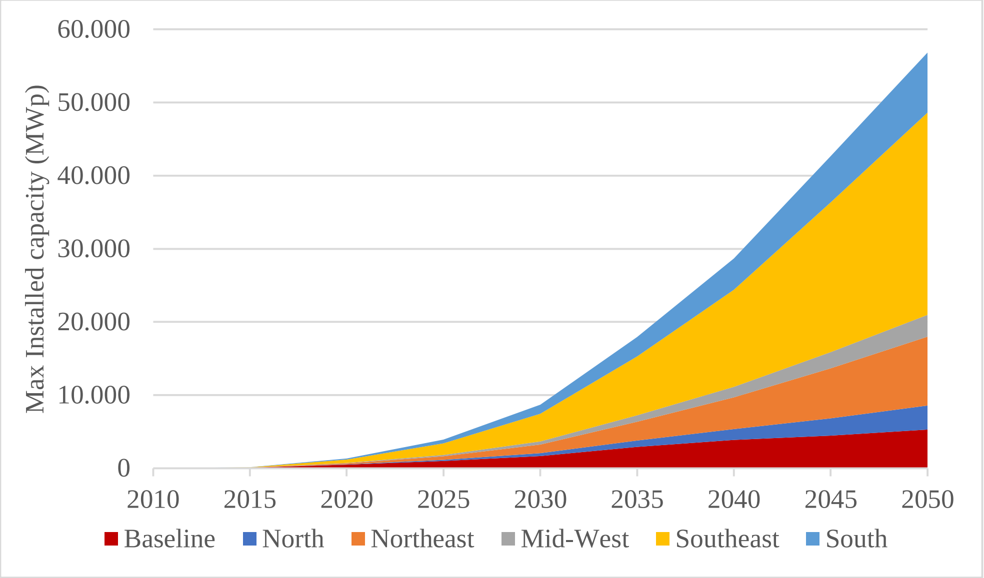

Figure 3-2. Max PV Penetration (2015-2050)

Additional costs from distributed PV generation in residential sector were quantified for all Brazilian regions, based on the system's Levelized Cost of Electricity (LCOE) minus the energy prices from the local utility (Figure 3-3). One should bear in mind that these relative high costs are due to higher discount rates considered for the sector and as the result of lower economics of scale in small systems.

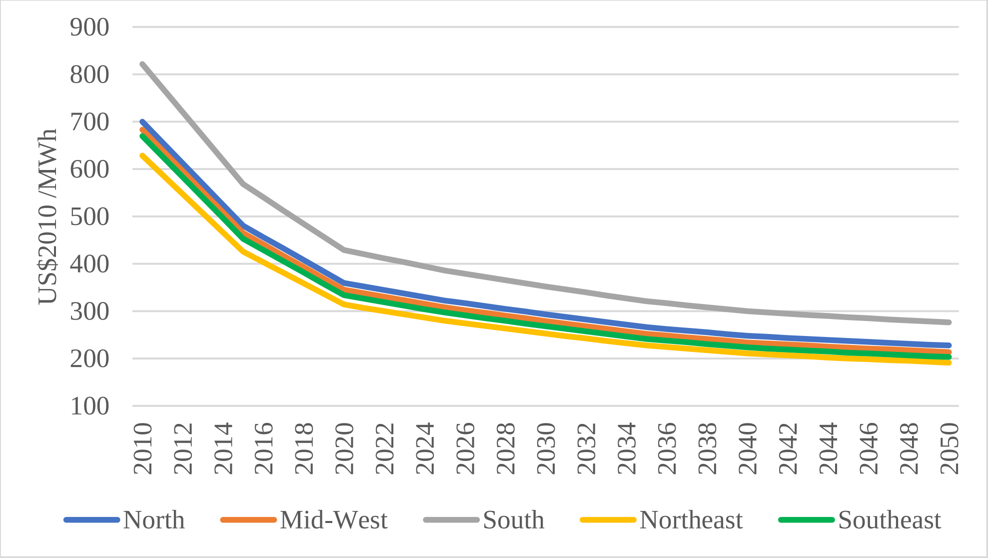

Figure 3-3. Yearly PV Additional (US$ 2010/MWh) related to local energy prices (Average per region)

Source: Own development

The marginal abatement cost, displayed in Equation 3-10, is then assessed based on the grid emission factor projection up to 2050. These costs depend on the installation year (since PV system cost vary throughout the period), as well as the grid emission factor. The lower the grid emission factor (tCO_2 / MWh) is, the higher will be the mitigation costs (US$ /tCO_2).

$$Abatement\ costs\ \left(\frac{US\$}{tCO_2}\right) = PV\ additional\ costs\ \left(\frac{US\$}{MWh}\right)\ x\ Grid\ emission\ factor^{-1}\left(\frac{MWh}{tCO_2}\right) \quad (3\text{-}10)$$

3.3.2 Abatement cost

The previous methodological steps provide inputs for calculating the abatement cost per tCO_2 (US$/$tCO_{2e}$). These results provide relevant information for proposing policies measures. The Equation 3-11 expresses the abatement cost (AC_i):

$$AC_i = \frac{C\_LoC\_S - C\_Ref\_S}{E\_Ref\_S - E\_LoC\_S}, \quad (3\text{-}11)$$

where:

AC_i : Abatement cost of low-carbon option *i* (US$/k CO_2e)

C_LoC_S: Net present value of all costs related to the low-carbon alternative k (US$)

C_Ref_S: Net present value of all costs from the baseline option (US$)

E_Ref_S: Amount of CO_2e emitted assuming the baseline technology throughout its lifetime

E_LoC_S: Amount of CO_2e emitted assuming the low-carbon alternative throughout its lifetime

Low-carbon options and their potential are then classified according to the lowest cost to build a marginal abatement cost curve (MACC)[21] for the Brazilian residential sector. This tool has been widely used over the last 20 years and it has been progressively used in climate change mitigation analysis (TIMILSINA et al., 2017). Even though the criticism of the methodology regarding absence of transparency, poor treatment of uncertainty, intertemporal issues and interaction between sectors (KESICKI; EKINS, 2012; LEVIHN, 2016; WARD, 2014), the methodology has an advantage regarding the low budget for conducting the research, and the results are easily interpreted by policymakers and investors. Then, in developing countries (TIMILSINA et al., 2017) the tool is often used.

3.3.3 Additional data and general assumptions for the Ref_*S* and LoC_*S* scenarios

Demographic variables are crucial for residential sector scenario building. Table 3-11 shows the projections for number of households[22] by region, while Table 3-12 displays the Brazilian population for the base year and projected years. Data for the base year was extracted from (IBGE, 2016b), while the information for the years 2020, 2030, 2040 and 2050 were taken from (EPE, 2014a).

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[21] Marginal cost is an economic concept that measures the cost of an additional unit.

[22] Number of permanent private households. Defined as the domicile that was built in order to serve exclusively for housing and, on the reference date, had the purpose of serving one or more people (IBGE, 2010).

Table 3-11. Brazilian households' projections by region (in thousands)

Region	2010	2020	2030	2040	2050
North	3,975	4,934	5,700	6,357	6,828
Northeast	14,922	18,524	21,398	23,863	25,633
Southeast	25,199	31,281	36,135	40,297	43,285
South	8,891	11,036	12,749	14,218	15,272
Center-West	4,334	5,380	6,215	6,931	7,445
Brazil	**57,324**	**71,158**	**82,201**	**91,669**	**98,466**

Source: Own elaboration, based on (IBGE, 2016b) (EPE, 2014a)

Table 3-12. Brazilian population projection by region (in thousands)

Region	2010	2020	2030	2040	2050
North	15,775	18,087	19,168	19,450	18,824
Northeast	52,888	60,641	64,263	65,209	63,110
Southeast	79,922	91,637	97,110	98,540	95,369
South	27,241	31,234	33,099	33,587	32,506
Center-West	13,962	16,009	16,965	17,215	16,661
Brazil	**189,790**	**217,609**	**230,607**	**234,003**	**226,471**

Source: Own elaboration, based on (IBGE, 2016b) (EPE, 2014a)

Table 3-13 displays the residential energy prices in 2010 US dollars. The prices were kept constant during the whole period of analysis. We assumed that, in the integrated modeling framework of MSB-8000, the cost of electricity generation, although oscillating over time, shows few variations, on average. As for the costs of fossil fuels, they do not vary throughout the period of analysis due to conservative assumptions about oil and natural gas prices.

Table 3-13. Regional energy price per source (in 2010 US$/MWh)

Region	Electricity	Natural Gas	LPG
Southeast	197,0	183,8	103,3
South	191,7	137,9	106,3
Midwest	188,9	128,7	117,4
North	177,8	128,7	106,5
Northeast	182,8	128,7	100,0

Source: (ANEEL - AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2015), (SINDICATO NACIONAL DAS EMPRESAS DISTRIBUIDORAS DE GÁS LIQÜEFEITO DE PETRÓLEO – SINDIGÁS, 2015), (ASSOCIAÇÃO BRASILEIRA DAS EMPRESAS DISTRIBUIDORAS DE GÁS CANALIZADO, 2015) and (EPE - MINISTÉRIO DE MINAS E ENERGIA, 2015)

Note: All prices include taxes

Given several limitations[23], the residential sector's discount rate for investments in energy efficiency was estimated based on the historical series of medium/long-term financial investments, short-term loans (overdraft) and construction loan rates, according to the data in Table 3-14. Initially, a representative borrower’s portfolio was estimated based on the households’ marginal propensity to consume (MgPC) (LEITE, 2015). Secondly, the weighted average of the portfolios for indices was calculated resulting in a 65.4% p.a. market potential discount rate, as shown in Table 3-14. Such a high value for the discount rate seeks to simulate real world decision by the Brazilian residential sector. It should be noted that an economic potential from a social perspective would imply in

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[23] For calculating the abatement cost per CO2 (US$/t$CO_2$) a discount rate is necessary. This parameter reflects the agent’s time preference. Nonetheless, estimating a single discount rate for all Brazilian households is a difficult task, due to the sector’s heterogeneity. Usually, higher income classes can access better investment options and it is reasonable to consider that lower income classes have a stronger preference for the present, due to greater budget constraints and risk aversion.

the assumption of a much lower social discount rate, which would, in turn, favor the adoption of capital intensive mitigation alternatives.

Table 3-14. Representative borrower's portfolio discount rate

Loan/Investment	**Index (% p.a.)**	**MgPC**	**Discount rate (% p.a.)**
Short-term loan	114.7	0.5	57.4
Construction sector loan	37.3	0.1	3.7
Mid-term investment	11.1	0.2	2.2
Long-term investment	10.7	0.2	2.1
Total		100	65.4

Source: based on (BANCO CENTRAL DO BRASIL, 2014, 2018;BANCO DO BRASIL, [s.d.]; VALOR, 2015)

In the next step, we assumed that the economic potential represents 45% of the market potential (MCTIC, 2017b). Finally, considering an inflation rate of 4.5% p.a. (BANCO CENTRAL DO BRASIL, 2008), the real discount rate for the residential sector was estimated in 23.8%[24] p.a.

The grid emission factor is also required for calculating the abatement cost per unit of CO_2e. In the last 10 years, electricity represented around 40% of the final household energy consumption in Brazil (EPE, 2014a; SZKLO et al., 2017). In this regard, most of the GHG in this sector are indirect emissions because they are originated in electricity generation. Thus, it is necessary to consider the grid emission factor, which displays the amount of CO_{2e} equivalent per unit of electricity consumed in households. Brazil is a hydropower-based country, so this factor is dynamic according to the hydrologic conditions which increases or reduces the amount of fossil fuel generation

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[24] It was calculated according to the Fisher equation $(1 + \mathrm{r}) = {(1+i)}/{(1+\pi)}$, where r denotes the real interest rate, i is the nominal interest rate and π denotes the inflation rate.

required for meeting demand. Figure 3-4 displays the grid emission factors used in this study.

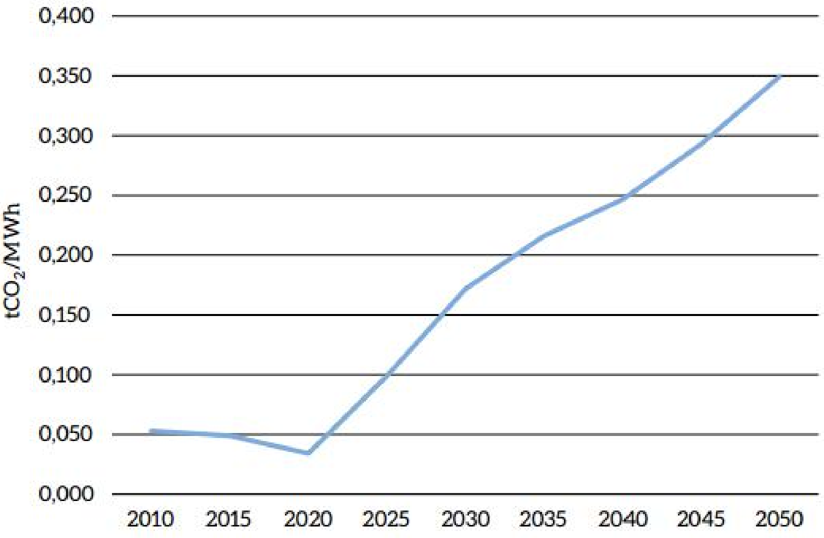


Figure 3-4. Electricity generation emission factor

Source: (MCTIC, 2017b; SZKLO et al., 2017)

3.4 Results

The results of the abatement measures proposed in the previous section are displayed in the Figure 3-5. The capital cost (CAPEX) and the operational cost (OPEX) for each energy end-use were estimated based on the technology cost, the hypothetical sales curve and the appliance/equipment stock throughout their lifespan. The avoided cost of energy results from the penetration of more efficient technologies, which lead to energy savings. The total abatement cost was calculated by the difference between the total cost (CAPEX + OPEX) and the avoid cost of the energy, considering the grid emission factor and the discount rate[4].

Regarding the replacement of inefficient lightbulbs (Figure 3-5.a), results shows that the ban of incandescent lamps (MME, MCTI, 2010) lead to a decrease in the energy consumption of 744 ktoe (9 TWh). With the implementation of the abatement measures

(LoC_*S*), the electricity consumption and the emissions reduction would achieve, respectively, 430 ktoe (5 TWh) and 1.6 MtCO2e by 2050. That would require an investment of 28,995 million U.S. dollars up to 2050. However, this measure would save 6,965 ktoe and 15 $MtCO_2$ in the same period.

As shown in this Figure 3-5.b), air-conditioners are the appliance with the highest potential to increase electricity consumption in households (threefold in less than four decades). Beyond the demographic expansion, the increased penetration of this equipment in households is the main reason for increasing energy demand. This trend is confirmed by the ramp-up of sales of air-conditioning in the last years (ABRAVA, 2014). For implementing the LoC_*S*, it is necessary an extra cost of US$ 236,732 million compared with the Ref_*S* and saves 22,528 ktoe and 38 $MtCO_2$ up to 2050.

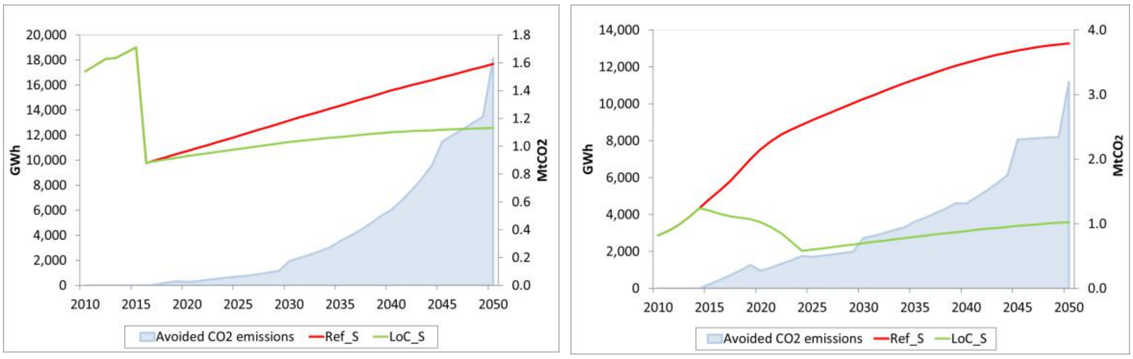
Figure 3-5.c) and Figure 3-5.d) show the results for the refrigeration end-use (refrigerator and freezer, respectively). The Ref_*S* scenario projects the possibility of almost doubling the energy consumption by refrigeration technologies. This is not explained by a higher penetration of refrigeration devices in Brazilian households, but mainly by the demographic expansion.

It is worth to highlight that with the penetration of efficient technologies proposed in the LoC_*S* scenario, the energy consumption to meet the demand for this end-use in 2050 would be lower than today. The LoC_*S* scenario projected additional refrigeration costs of US$ 4,457 million and US$ 543 million for refrigerator and freezer, respectively. The measures for refrigerators would save 608 TWh and avoid 96 $MtCO_2$, while saving 106 TWh and avoiding 15 $MtCO_2$ for freezers.

As for cooking, the energy consumption in both abatement scenarios (improved LPG and natural gas stoves) and the avoided CO_2 emissions are shown in Figure 3-5.e) and Figure 3-5.f). Interestingly, the implementation of the LoC_*S* scenario for both measures is cheaper than the Ref_*S* scenario. By installing improved LPG and natural gas stoves the cost of the energy saved would be US$ 4,841.6 million. Efficient LPG stoves would save 735 TWh and avoid 200,79 $MtCO_2$, while improved natural gas stoves would save 139 TWh and avoid 44,05 $MtCO_2$.

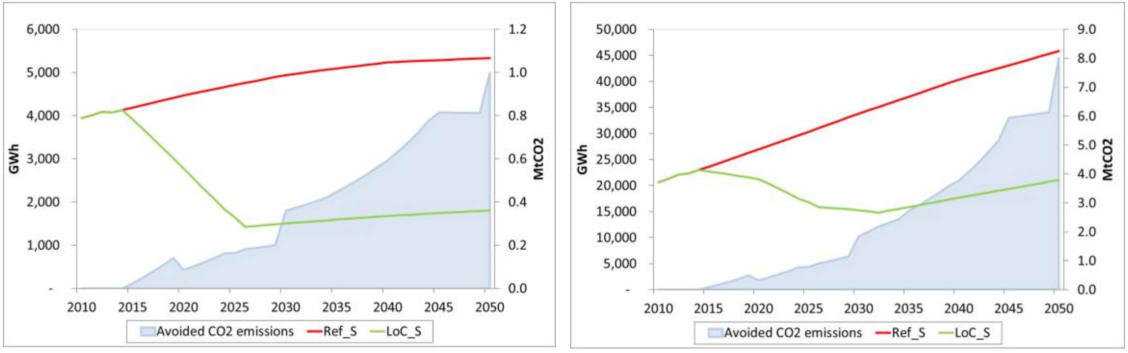
Figure 3-5.g) and Figure 3-5.h) display the results for the water heating end-use, including the replacement of electrical showers by SWHS, the deployment of efficient natural gas heaters and the dissemination of more efficient electrical showers. By implementing these three measures, the reduction of CO_2 emissions would be 14 $MtCO_2$. The cost of the energy saved would be US$ 269 million.

Findings in the solar PV shows that the potential in the residential sector is 51.5 GW, 27 GW of which are in the Brazilian Southeast. The total distributed potential in Brazil is around 56 GW. Aggregately, PV solar deployment has the largest abatement potential, reducing 219 $MtCO_2$, most of which in the SE region (145 $MtCO_2$). The implementation of the measure would cost US$ 562,560 million.



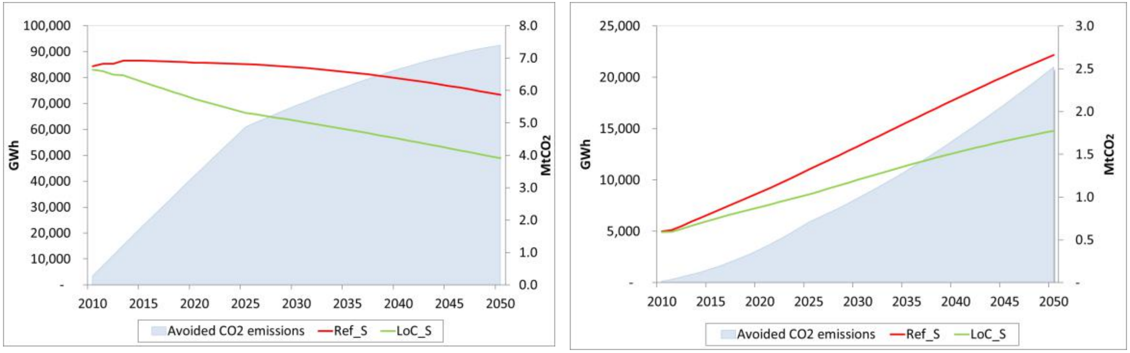
a) Lighting

b) Space cooling



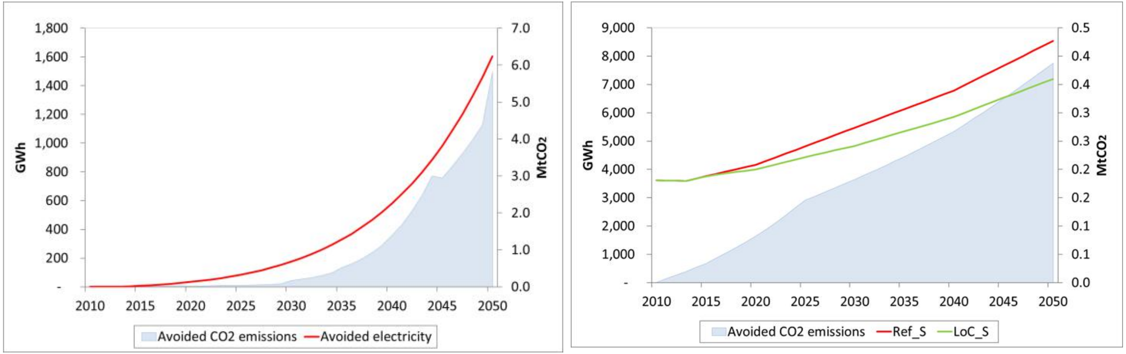
c) Refrigeration (Freezer)

d) Refrigeration (Refrigerator)



e) Cooking (GLP)

f) Cooking (NG)



g) Water heating (SWHS)

h) Water heating (NG heater)

Figure 3-5. Energy consumption in the Ref_S and LoC_S scenarios and avoided CO2 emissions for each energy end-use

Mitigation potential by distributed PV systems depend on the moment in which the technology would be installed. For a given installed capacity, abatement potential is decreasing for PV adoption from 2025 onwards, since only the energy generation within the period assessed — up to 2050 — is considered, even if the system is still able to produce after this cycle[25]. This is a caveat from the chosen approach, in which only the energy/mitigation potential within the period assessed is considered. By the same reason the GHG mitigation is more expensive, as the system produces energy only during a small period for the same system-full-upfront cost. Figure 3-6 shows the avoided GHG emission per unit of PV installed capacity, according to the installation year.

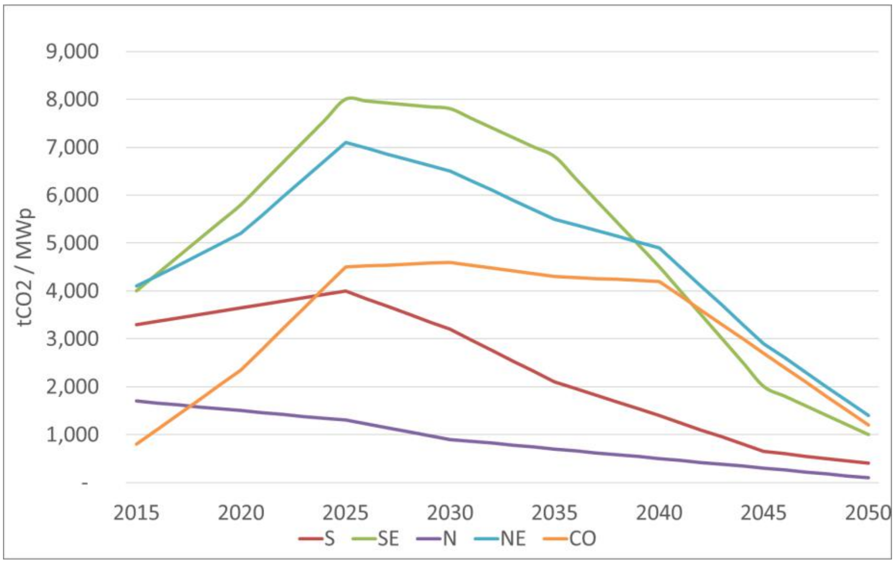


Figure 3-6. Mitigation potential per installed capacity

The costs of PV also depend on the grid emission factors of the projected year in each region. Investment costs decrease throughout the period due to technology learning. As a result, abatement costs vary inversely with the grid emission factor, added by a variability trend associated with the technological learning factor (MCTIC, 2017b).

Costs also depend on yearly grid emission factors of Brazilian regions. Costs also decrease throughout the period due to technology learning rates, but to a lesser extent.

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[25] For instance, a PV system adopted in 2045, considering a system lifetime of 25 years.

Therefore, abatement costs present an inverse variation to the grid emission factor, added by a variability trend associated to the technological learning factor (MCTIC, 2017b).

3.4.1 Analysis of abatement costs and potentials

Figure 3-7 summarizes the aggregated results for all the energy efficiency measures. Assuming the implementation of all measures, the energy consumption in 2050 would increase only 8% in relation to the base-year. Aggregately, energy efficiency measures in the residential sector are estimated to reduce 641 MtCO2 in Brazil over 2010-2050.

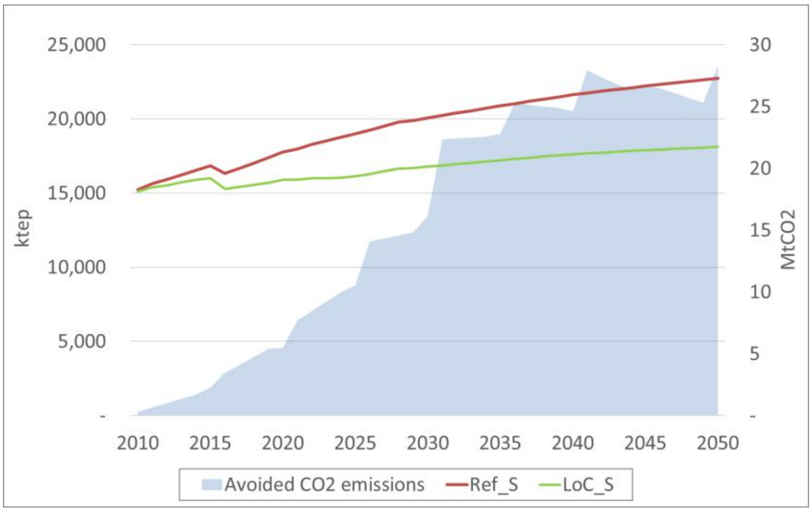

Figure 3-7. Energy consumption (Ref_S and LoC_s) and avoided CO_2 emissions

Table 3-15 presents the total cost of the abatement measures, the emission potential reduction and the abatement cost of each mitigation measure. Findings show that 40% of the potential has negative abatement cost. Despite of that, there are several measures with extremely high abatement cost (above 1500 USD/tCO_2).

The measures with the highest potential are those that directly replace fossil fuels (Natural gas and GLP). LPG efficient stoves measure has the highest potential because its emission factor is higher than the natural gas. Additionally, the GLP is the fuel more often used for cooking in the residential sector.

The first three measures listed in the Table 3-15. show negative marginal abatement costs (NG efficient stoves, NG efficient water heating and LPG efficient stoves). The most relevant measure in terms of emissions reduction potential is the penetration of more efficient LPG stoves. This measure accounts for 31% of the emissions potential reduction in the residential sector and its abatement cost is negative (-10 USD/tCO_2).

Table 3-15. Emission potential reduction and marginal cost of the mitigation measures in the Brazilian residential sector

No.	**Measure**	**Emissions potential reduction (MtCO2)**	**Marginal abatement cost (USD/tCO2)**
1	NG efficient stoves	44	-488
2	NG efficient heater (water)	7	-36
3	LPG efficient stoves	201	-10
4	Electric shower	2.93	218
5	Solar PV (NE region)	44	1,633
6	SWHS	4	1,933
7	Solar PV (SE region)	145	2,092
8	Efficient lighting	15	2,655
9	Solar PV (S region)	15	2,908
10	Efficient freezer	15	2,974
11	Efficient refrigerator	96	5,668
12	Efficient air conditioner	38	6,200
13	Solar PV (N region)	3	7,120
14	Solar PV (CO region)	12	10,199
	Total	**641.93**	

Source: Own elaboration

Considering the total PV capacity potential estimated in Brazilian rooftops during the studied period, there is a total mitigation potential of about 218 million tons of CO_2 at a cost of US $ $_{2010}$ 379.60 / tCO_2 up to US $ 33,400 / tCO_2. One should bear in mind that these costs are not at present value but are valid at the time of the availability of a given PV potential. The abatement curve for all the considered years is presented in

Figure 3-8 and Figure 3-9. Eight distinct marginal abatement curves were made to present the abatement potential for every 5 years in the period 2015-2050 (Figure 3-8 and Figure 3-9).

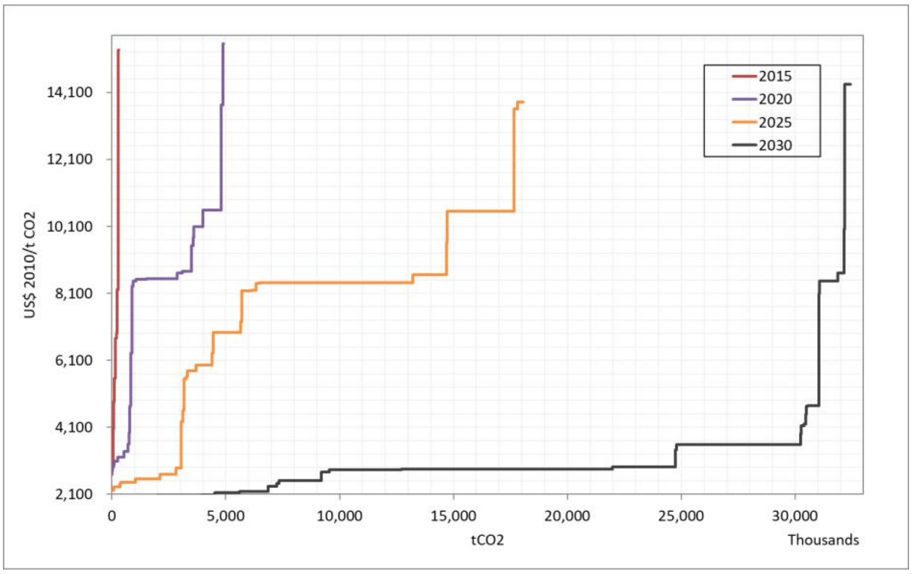

Figure 3-8. Marginal abatement cost for PV available capacity in period 2015-2030 – Yearly line values are not cumulative

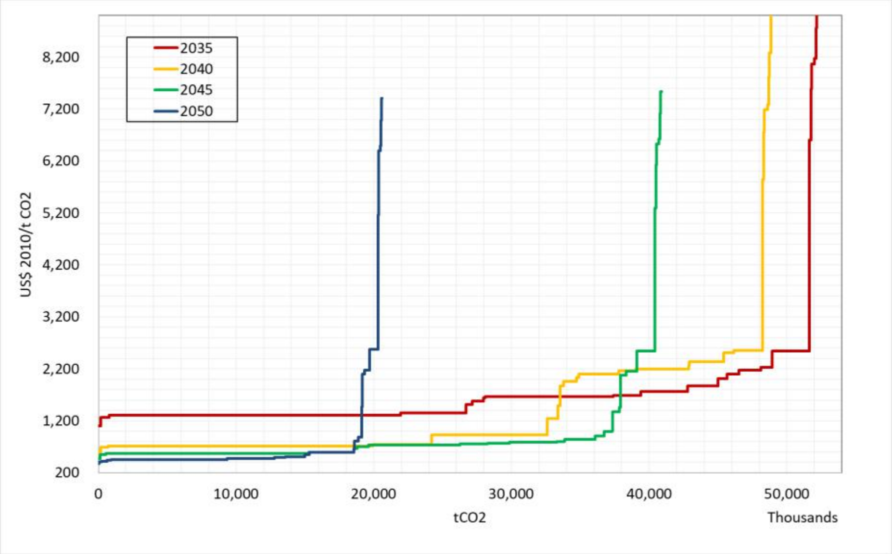

Figure 3-9. Marginal abatement cost for PV available capacity in period 2035-2050 – Yearly line values are not cumulative

Figure 3-10 displays the marginal abatement cost curve, built from the various CO2 mitigation options presented in Table 3-15 . Figure 3-10 illustrates the abatement measures, ordering them from the cheapest to the most expensive one. The curve shows the importance in terms of amount of CO_2 and their cost associated per united abated - US$/$tCO_2$.

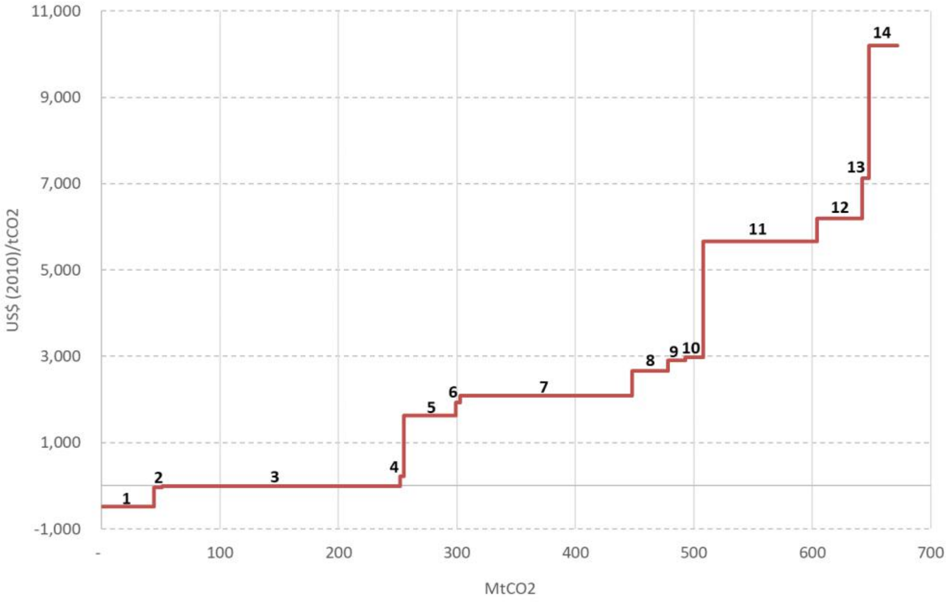

Figure 3-10. Marginal abatement cost curve

Note: The numbers correspond to the measures listed in the Table 14

Finally, the low grid emission factor is one of the main reasons for the wide range of the abatement costs. A small amount of CO_2 is abated per one each MWh avoided. It is worth to highlight that the abatement cost relies on the discount rate. The discount rate in the residential sector is usually high as showed in the section 3.3.3. reducing the attractiveness of the abatement measures.

Aggregating the results by energy end-use (Figure 3-11), findings show that energy efficiency measures implemented in cooking and solar PV panels would represent together more than 70% of the potential reduction of CO_2 emissions. This result reveals an interesting insight about where the actions should focus on.

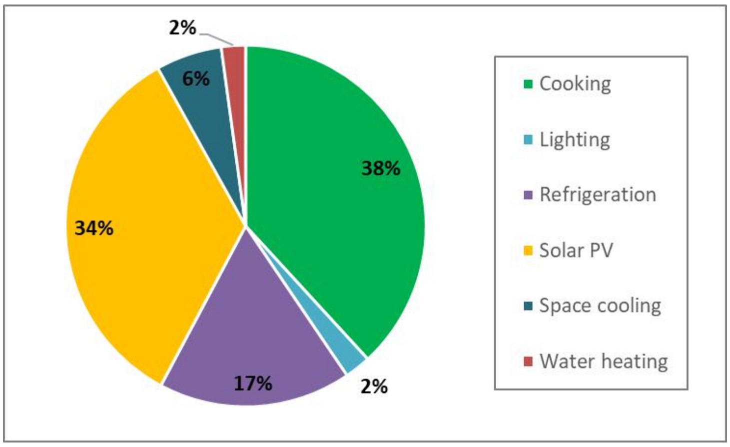

Figure 3-11. Share emission reduction potential by energy end-use

3.5 Conclusion and policy implications

Energy efficiency in the residential sector is a key measure to reduce the CO_2 emissions. There is a wide range of technological options that can save energy and, hence, mitigate GHG emissions in Brazil. However, the implementation of such measures in the residential sector faces barriers that must be addressed to achieve this potential.

These barriers can be related to market, financial, energy costs, technological, and cultural or informational issues. The design of appropriate policies, programs and instruments can remove the barriers that prevail in the sector (ÜRGE-VORSATZ, 2012). In this study, the mitigation policies were categorized in two types: energy efficiency in appliances and distributed generation.

The main Brazilian energy efficiency policy for the residential sector is the Brazilian Labeling Program (PBE)[26]. The program focusses on residential appliances, but other equipment as motors, PV system and SWHS are also labelled. Although it has achieved satisfactory results in saving electricity through the PROCEL and CONPET

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[26] The PBE is part of the National Program of Electrical Energy Conservation (PROCEL)[26] established in 1985.

labels (CONPET, 2017), more aggressive standards are required. The most efficient categories in the Brazilian labeling programs show lower efficiencies when compared to international standards. Therefore, a detailed evaluation of the PBE allows us to conclude that most of the “A” label appliances cannot be considered as top-runners anymore. Also, the gap between the labeling ranges is minimal – i.e., most of the appliances assessed were in the highest categories. At the same time, few appliances fall in the lower efficiency categories – for instance, there are no boilers with D or E labels – leaving little room for the consumer to compare appliances. Thus, we conclude that the program is currently not setting the best standards and a dynamic update of the labels could reset the efficiency standards according to the latest developments in energy efficiency in appliances.

Therefore, the improvement of the existing labeling programs, with more rigorous values and international benchmarking should be adopted. Also, the creation of subcategories should be considered, as in the “Energy Star Most Efficient” program in the United States, to identify the best energy consuming performance with A+ or A++ label. Finally, the CONPET label could be used as the best performance index, reflecting the real top-runners of each category and avoiding labeling redundancy[27].

The labeling policy focus mainly on removing informational barriers, but there are other hurdles that must be overcome to influence the decision making by the residential consumer. For instance, financial barriers, especially for budget constrained residential, upfront costs and high interest rates. These aspects influence the consumer’s

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[27] In 2016, 70.4%, from 552 tested, of the cooking equipment that were labeled in PBE were also CONPET labeled. Regarding gas boilers to heat water, this was about 94.3% [28].

choice, favoring a decision for the cheapest equipment available, and not necessarily the most efficient. Special financial instruments might be considered for reducing the cost of the most efficient equipment available.

Although the mitigation potential of solar PV presented in this study is significant, the costs of an installed PV system are still high. Thus, the deployment is limited since only a few households have the investment capacity for installing PV systems. The situation is highlighted by the analysis by income level groups.

In 2012, the National Regulatory Agency of Electricity (ANEEL) introduced the net metering mechanism to stimulate the distributed generation segment, focusing on low and medium voltage distribution networks. The aim of the net metering is to remove some barriers related to the distributed generation, and it is expected that this regulatory measure will decrease in the installation and connection costs for decentralized generation. The aforementioned policy was updated in March 2016 and is expected to deepen the entry of solar PV in the residential market (ANEEL, 2016).

The limitations of the study are regarding the MACC methodology itself and the assumptions adopted such as the discount rate and the grid emission factor. The first limitation consists in the sectoral analysis done since the abatement potentials are not considered additives. Thus, the abatement potential may not represent the net potential reduction emission of the sector. This is just the total potential reduction per each measure applied in relation with the baseline scenario. Then, the results can be product of a double accounting of the emissions due to the reduction in the energy consumption of two measures is not necessarily equal to the sum of their individual contributions. This feature of the conventional marginal abatement analysis shows the need of the integrated modelling.

The discount rate is key for the abatement measures analysis; however, its estimation is difficult, mainly for the investments in energy efficiency due to their heterogeneity. On the other hand, the grid emission factor depends on the evolution of the future electricity demand, which cause circularity in the results. This problem can be overcome with an integrated modelling, that it is not used in this sectoral study.

Further studies should extend the analysis to other segments belong the buildings sector. Because of the limited availability of public data on the commercial, services and public sectors, this study retains its focus only on the residential segment. Future research is required to investigate the other two.

4 Assessing the restricted deployment of distributed solar photovoltaics in the household sector in developing countries: An analysis by income level in Colombia

4.1 Abstract

Despite the cost of the solar photovoltaics technology having decreased sharply over the last few years and the suitable climate conditions in most developing countries, the deployment of the technology in the residential sector is still in its infancy. This study provides a methodology to estimate the technical, economic and market potentials of solar photovoltaic systems in the residential sector, disaggregating the analysis by urban administrative divisions and income levels. The methodology considers the rooftop area and electricity needs, financial aspects and conditions for financing the acquisition of the PV equipment. We have applied the methodology to Colombia. Findings indicate that the current technical potential in the residential sector is 9.1 GWp (13.10 TWh/year). In 2030, the economic potential will reach 3.2 GWp. However, the market potential is significantly smaller, reaching in the best-case scenario 1 GWp by 2030. In light of the results, this paper discusses and proposes a set of energy policies and provides insights on solar PV deployment in the residential sector in developing countries.

Keywords: Photovoltaic solar energy, Deployment, Developing Countries, Market potential, Household, Socio-economic stratum, Colombia

4.2 Introduction

Solar Photovoltaic (PV) has become a promising source of electricity generation recently. Worldwide, PV installed capacity has grown from 2.6 GW in 2004 to 303 GW in 2016 (REN21, 2017). The deployment of PV solar has been fast, with 77% of the current installed capacity added over the last five years (REN21, 2017). In 2016, for the second consecutive year, China has installed the highest PV solar capacity (34 GW), becoming, by far, the world leader. In 2016, distributed solar PV annual capacity additions decreased slightly by 3%, to 21.9 GW, accounting for 29% of the total global PV installed capacity (75 GW) (NAVIGANT RESEARCH, 2017).

Despite the growing installed capacity and the substantial fall in cost of the technology over the last few years, its diffusion is still limited in the buildings sector. Regardless of the quality of the solar resource in several developing countries, the adoption of this technology still faces barriers in its deployment (IRENA, 2016b). Nieuwenhout et al. (2001) stress the issue by asserting that, even in countries where subsidies and loans have been implemented, growth is still restricted. Several studies indicate that the high upfront cost is a barrier to the dissemination of renewable energy technologies on a building-scale in developing countries (GOEL, 2016; IEA, 2014; LAY; ONDRACZEK; STOEVER, 2013; NIEUWENHOUT et al., 2001; PODE, 2013; TSE; OLUWATOLA, 2015) . The lack of flexible means of payment is deterring penetration into larger markets of lower-income groups and rural populations as well (PODE, 2013).

Heiskanen and Matschoss (2017) notice that even in the high-income economies the deployment of renewable technologies on a building-scale faces difficulties due to the diversity of home owners and their investment perspectives, the influence from their neighbor´s behavior, exchange of experiences and the lack of qualified installers. Karakaya and Sriwannawit (2015) review the barriers that hinder the PV deployment in low-income and high-income economies. They classified barriers into four groups, namely: sociotechnical, management, economic and policy.

Although these studies offer an overview of the issue, the willingness-to-pay by income-level groups is not addressed. Moreover, a quantitative approach for assessing the gap between the technical potential and market potential is not conducted extensively in the literature, especially for developing countries. Recently Ramírez-Sagner et al. (2017) addressed the economic feasibility of residential and commercial PV technology in Chile. However, they did not encompass the market potential and the difficulties inherent to the deployment of the technology in the residential sector by income level.

Bearing in mind these issues, this study offers a methodology to estimate the technical, economic and market potentials for solar PV in the residential sector. Technical potential only assumes the availability of the rooftop area and electricity needs and evaluating the possibility of using solar resource for fulfilling household requirements. Economic potential adds financial aspects to evaluate the share of the technical potential that reaches a positive net present value (NPV), for a given discount rate. As for the market potential, current mechanisms and conditions for financing the acquisition of the PV equipment are considered. Therefore, the market potential evaluates the share of the economic potential that is feasible when real market conditions are accounted for. For the results regarding the market potential, this paper sets six scenarios assuming different lending interest rates. The proposed approach distinguishes households according to different characteristics, such as socio-economic stratum, household electricity consumption, tariffs charged by local utilities and capital cost of the required PV system. Even though the proposed methodology might be applied in high-income economies, this paper aims to provide insights on developing countries by accounting for the technical, economic and market potential of PV solar in the residential sector considering income levels.

This paper also aims to contribute with propositions for policy-makers, emphasizing that, while each country has its own institutional, legal, socio-economic and cultural conditions, developing countries tackle similar problems in the majority of the cases.

South America is an emblematic region because of the favorable solar irradiation; however, the deployment of the solar market is still at an early stage. Natural conditions represent a significant opportunity to develop solar PV and reach high growth rates in the long-term. Furthermore, in the case of equatorial countries, having low variation on seasonal patterns throughout the year is an advantage. Chile accounts for the highest installed capacity reaching about 493 MWp (GTM RESEARCH, 2016), followed by Brazil with 50 MWp (EPE, 2015a), both in 2015. Installed capacity in Colombia in 2015 was 11.5 MWp (UPME, 2014, 2015a). The highest irradiance in South America is reported in Chile, with a maximum of 2,800 kWh/m2 per year (SOLARGIS, 2013c), followed by Bolivia with 2,700 kWh/m2 per year (SOLARGIS, 2013a) and Brazil with 2,300 kWh/m2 per year (BUENO, E. et al., 2006; SOLARGIS, 2013b).

We have chosen Colombia as a representative country case. The Colombian region with the highest irradiance is Guajira, with 2,190 kWh/m2 per year (SOLARGIS, 2013b). The lowest irradiance noticed is on The Pacific Coast with 1,277 kWh/m2 per year (UPME, 2015b). 85% of the Colombian territory has a solar irradiation rank between 4.5 – 5.0 kWh/m2, showing 8,055 km2 are in the areas with the highest solar irradiation (Figure 4-1).

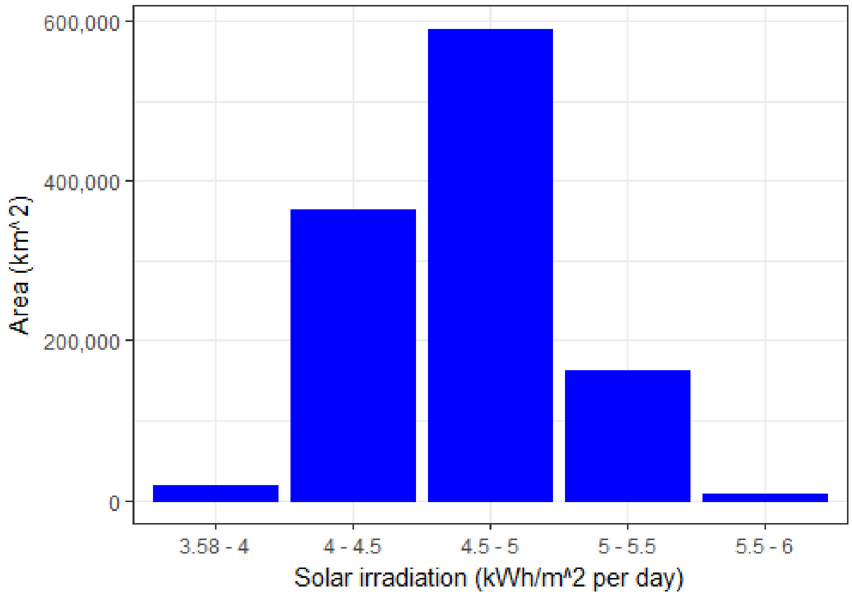

Figure 4-1. Solar potential area in Colombia.

Source: Own elaboration, based on (CORPOEMA, 2010)

Few studies have addressed the renewable energy systems in Colombia (GAONA; TRUJILLO; GUACANEME, 2015; GONZALEZ-SALAZAR et al., 2014; HAGHIGHAT MAMAGHANI et al., 2016; RADOMES; ARANGO, 2015). With the enactment of Law 1,715 of 2014, the Colombian government established the legal framework and instruments for the promotion of non-conventional energy sources. However, the energy exchange mechanism between the generating unit and the grid has not yet been clearly defined[28].

This paper is organized into 4 more sections. Next section presents the methodology used to calculate the technical, economic and market potentials. Section 4.4

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[28] Law 1715 does not specify the meaning of energy credit. However, it gives the possibility of distributed generators selling the energy produced by them. The CREG has the function of establishing the compensation mechanism.

presents additional input data for the case study. Section 4.5 describes the results for the potentials, including a spatial analysis. Conclusions are drawn in the last section, where barriers for the dissemination of solar PV in the residential sector are briefly outlined and a set of policies and incentives to achieve a larger market potential are proposed.

4.3 Methodology

4.3.1 Methodological Procedure

In this study, three main tools have been used. The first one is the RETScreen energy model, developed and maintained by the Government of Canada (GOVERMENT OF CANADA, 2016). The software was applied to quantify system energy production (kWh) from climate and system configuration data. Excel was the second tool, used for the computation of the Levelized Cost of Energy (LCOE) and the estimation of the penetration of the technology over time in each municipality. The last one was a geographical information system (GIS) to present the results under a spatial analysis. The analysis has been split into 1,120 Colombian municipalities obtained from (DANE, 2016; SUI, 2016).

This study proposes different assumptions to estimate three potentials as follows:

Technical Potential – corresponds to the sum of the photovoltaic potential of all households within a specific municipality, based on their monthly electricity consumption. A specific household is assumed to install a given amount of photovoltaic capacity that equals its own electricity consumption; if not, this consumer would never recover all the energy sent to the grid based on the *net metering* compensation system. For the sake of simplicity, it is assumed that apartment buildings only harness 20% of the potential based on their energy consumption, due to rooftop constraints (MIRANDA, Raul F.C.; SZKLO; SCHAEFFER, 2015).

Economic Potential – corresponds to the yearly household potential that has reached grid parity defined as when the LCOE becomes equal or lower than the price of purchasing energy from the grid in that specific year. The economic potential that is supposed to grow over time, due to both the increasing number of households reaching grid parity every year and the growth in the number of households themselves[29].

Market Potential – ideally, this potential should be based on the economic potential assumptions but now including aspects such as labor availability, consumers' knowledge of the solar technology, financial opportunities in an environment with multiple options and market barriers among other aspects. However, given the difficulty to measure all these factors, in this study the market potential relies only on the assessment of financing conditions according to the consumer stratum and length of the debt, to analyze the role of the high upfront cost on the deployment of the technology.

The key factors for the model implementation are solar radiation data, number of households, residential power tariffs, electricity consumption and energy system costs. All this data is available by municipality and socio-economic strata in Colombia.

Levelized cost of energy (LCOE)

The levelized cost of energy is calculated from the initial investment capital, discount rate as well as operation and maintenance costs and loan installments, as follows.

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[29] The household rates growth are calculated according with the forecasting done by (DANE, 2016).

$$LCOE_t = \frac{[DP + O\&M\ PValue + FIN] \Big/ \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]}{\sum_{t=1}^{T=25} E_{t-1}(1-x) \Big/ t} \text{ , (4-1)}$$

where:

$LCOE_t$: Levelized cost of energy in the year t

DP : (Down Payment, which is the upfront Fraction of Capex) = Capex . a

O&M : PValue (Annual Opex Sum Present Value) $= \text{Annual Opex} . \frac{\left[\frac{((1+\mathrm{i})^{\mathrm{n}} - 1)}{\mathrm{r}}\right]}{(1+\mathrm{i})^{\mathrm{n}}}$

FIN : PValue (Loan Installment Sum Present Value) $= \text{Installment} . \frac{\left[\frac{((1+\mathrm{i})^{\mathrm{t}} - 1)}{\mathrm{r}}\right]}{(1+\mathrm{i})^{\mathrm{t}}}$

$CAPEX_t$: Investment expenditures in the year t

$OPEX_t$: Operation and maintenance expenditure in the year t

E_t : Electricity generation in the year t,

Financed Amount = Capex.b,

a : Down Payment factor

b : Loan factor

a + b = 1

x : Deterioration of the module

i : Discount % rate

n : Economic lifetime of the photovoltaic system.

t : Loan Term

The fixed cost of photovoltaic plants is not expected to remain constant over time due to a learning effect. It might decrease annually by a learning rate (LR) of 0.18 until 2020 and a LR of 0.16 from 2020 to 2030 (YADAV; CHANDEL, 2013). Operation and maintenance expenditures are assumed to be 1% of the initial investment (MIRANDA, Raul F.C.; SZKLO; SCHAEFFER, 2015). PV system has a very low maintenance cost over its lifetime, a large share of which is due to the need of replacing the inverter (MIRANDA, Raul F.C.; SZKLO; SCHAEFFER, 2015). To include the photovoltaic module deterioration, an annual reduction factor of 0.5% on generation output has been applied (LIMMANEE; UDOMDACHANUT; SONGTRAI, 2016) over an economic lifetime of 25 years (LAU et al., 2010; MIRANDA, Raul F.C.; SZKLO; SCHAEFFER, 2015; PENG; LU, 2013). The costs are annualized by the Equivalent Annual Annuity (EAA) method (DAYANANDA et al., 2002), which allows distributing these costs uniformly for each year (Equation 3-1). A discount rate of 7.9% p.a. has been taken into account which guarantees a minimum desirable return (UPME, 2015a).

4.3.2 Typical PV Module Size and System Configuration

The installed capacity potential for each household has been built under the logic of the net metering mechanism. The monthly household average electricity consumption was specified for each of the six strata groups considered within each municipality. Hence, a household consumer would adopt a PV capacity that generates its own electricity consumption on a yearly basis. Otherwise, some energy credits may never be recovered.

The PV system energy output has been calculated using the RETscreen energy model (Table 4-1). After the first year of generation, an annual reduction factor has been applied due to module degradation. Aiming the maximization of the energy output, the usual rule of thumb indicates that the tilt of the system array should be equal to the local latitude or quite close to this value (GOPINATHAN, 1991; GUNERHAN; HEPBASLI, 2007), although other studies come up with some variation for this (YADAV; CHANDEL, 2013). The optimal azimuth is oriented to the north for sites located in the southern hemisphere, and orientation to the south for sites located in the northern hemisphere (MEHLERI et al., 2010; YANG; LU, 2005). Thus, all Colombian systems have been oriented to the south, except the ones in the Leticia municipality.

This study used the polycrystalline silicon technology, as this is the most used worldwide. The module brand chosen is also commonly used in different countries and may be easily applied in Colombia. Each system energy yield (Table 4-2), has been defined based on the system configuration (Table 4-1).

Table 4-1. Photovoltaic System Configuration

System	
Solar Tracking	Fixed
Slope	Local latitude
Azimuth	South oriented*
PV Module	
Technology	Polycrystalline
Efficiency	14.1 %
Plate Capacity	240 Wp
Area	1.7 m^2
PV System	
N° Modules	**5**
Total Capacity	1.2 kWp
Inverter Capacity	1.0 kW
Inverter	96%

*Except Leticia solar site

4.4 Case Study

This section presents the main input data for Colombia used to develop the case study, namely: solar data, house and apartment share, household socioeconomic stratum and electric power consumption, tariffs by utility, evolution of prices for Distributed PV Systems and lending interest rate.

4.4.1 Solar Data

Solar resource database (global horizontal irradiance) was taken from (NASA, 2016). This study randomly selected 16 solar data sites in order to cover the whole country (yellow circles in Figure 4-2) after which each municipality has been related to the closest solar site by a geo-processing tool. All solar sites are located in the northern hemisphere, except for Leticia (negative latitude). The higher solar incidence occurs in the north of the country. According to (MIRANDA, Raul F.C.; SZKLO; SCHAEFFER, 2015), in the cities close to the Amazon forestry the solar irradiation is usually affected by cloudy days, predominantly in the summer.

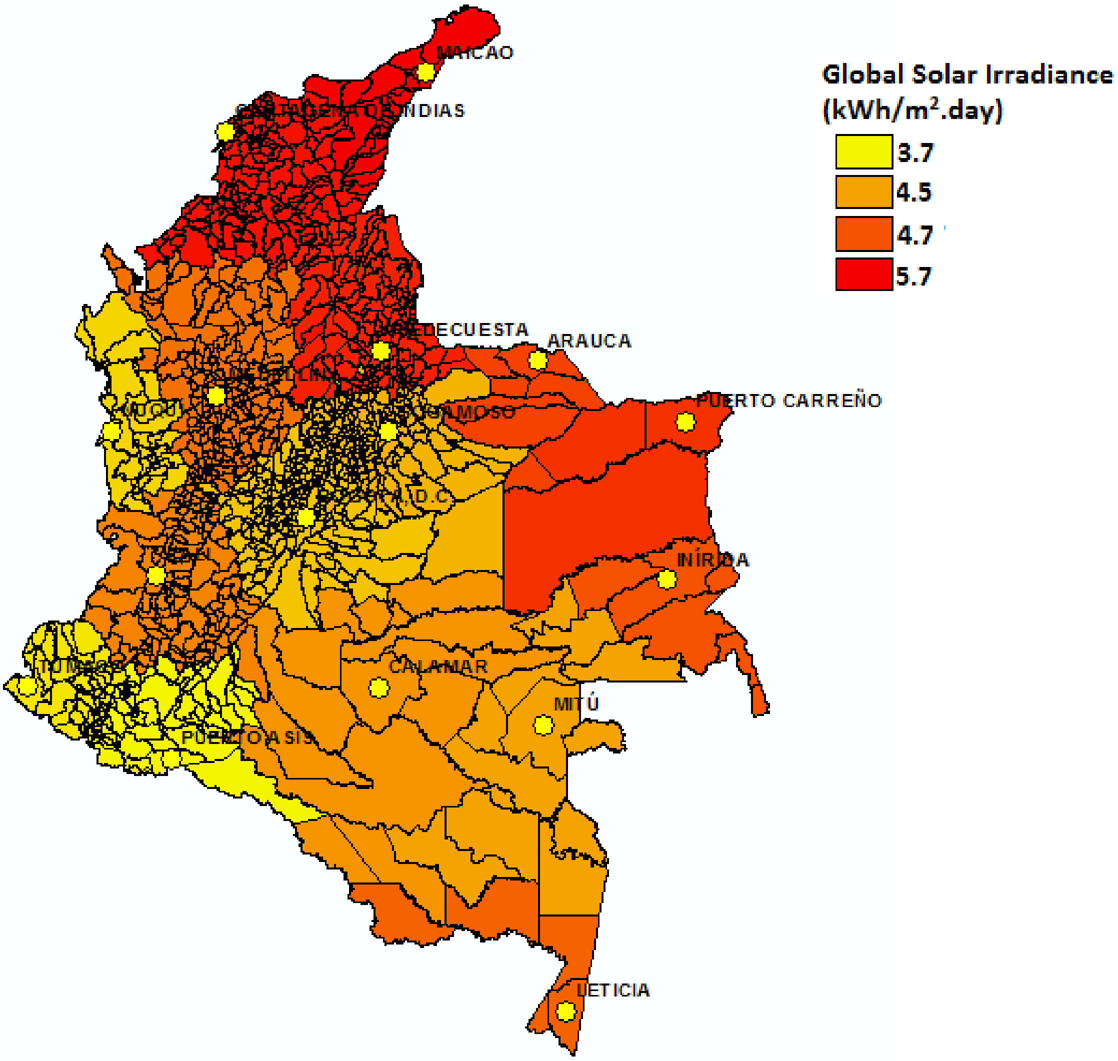

Figure 4-2. Solar horizontal irradiance by municipality in Colombia

Table 4-2 shows the number of municipalities allocated under a specific solar site. For instance, for twenty-four municipalities, data from the city of Maicao, which has the highest solar radiation in Colombia, was used. Sites with the lowest solar radiation are located along the Pacific Coast. Although Nuqui, Puerto Asis and Tumaco have the lowest solar radiation, these values are higher than the most impressive solar radiation figures in Germany, where it is reported 3.8 kWh/m^2 per day or 1,200 kWh/m^2 per year (SOLARGIS, 2016).

Table 4-2. Solar radiation horizontal data and PV system performance

Cities	Latitude (degree)	GSI ($kWh/m^2.day$)	Capacity Factor (%)	Yield (kWh/kW	Municipalities
Arauca	7.1	4.83	16.06	1406.66	7
Bogotá D.C.	4.7	4.26	15.15	1326.88	179
Calamar	2.0	4.59	15.45	1353.47	14
Cali	3.6	4.66	15.87	1390.15	122
Cartagena	1.3	5.73	18.22	1596.48	140
Inírida	3.9	4.75	16.01	1402.07	6
Leticia	- 4.2	4.72	15.99	1401.16	5
Maicao	11.4	5.86	18.74	1641.41	24
Medellín	4.2	4.68	15.93	1395.65	179
Mitú	1.2	4.56	15.39	1347.97	13
Nuquí	5.7	3.95	13.42	1175.58	25
Piedecuesta	7.0	5.34	18.02	1578.14	139
Puerto Asís	0.5	3.76	13.01	1139.81	60
Puerto	6.2	5.21	17.22	1508.44	3
Sogamoso	5.7	4.48	15.37	1346.14	161
Tumaco	1.8	3.84	13.06	1144.40	43

4.4.2 House and apartment share

The share of houses and apartments within the household sector for the entire country were estimated based on the values reported by (DANE, 2015a). For municipalities with 25,000 households or less, this study considered a 100% house share. For the ones beyond this level, the distribution between individual houses and apartments is shown in Figure 4-3 in line with what is reported in (DANE, 2015a). When no information was available for a specific municipality, this study adopted the share reported for Popayán, which is the municipality with the lower population taken into account in the survey.

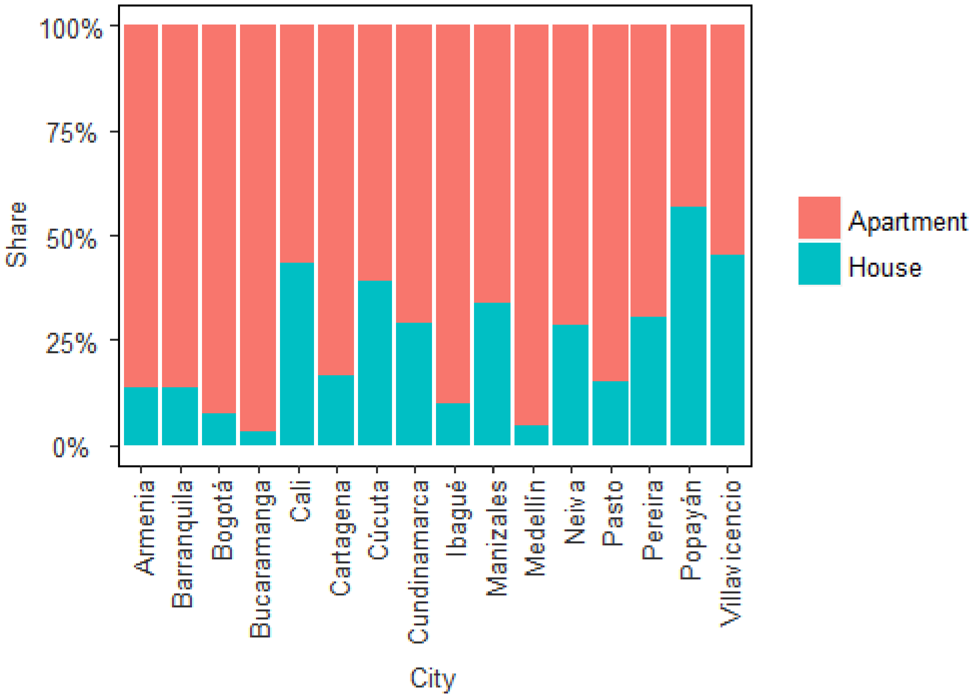

Figure 4-3. Percentage of individual house and apartments in Colombian municipalities.

Source: Own elaboration, based on Ref. (DANE, 2015a)

4.4.3 Household socioeconomic stratum and electric power consumption

Socioeconomic classification in Colombia is formed by the National Administrative Department of Statistics (DANE). Energy prices are determined for each specific socioeconomic stratum[30], providing subsidies to lower income groups and levy contributions to the higher ones. Classification allows identifying geographical locations

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[30] There are six socioeconomic strata in Colombia: 1 (Low-Low), 2 (Low), 3 (Medium-Low), 4 (Medium), 5(Medium-high), 6 (High). This classification considers both cadastral homogenous zones and physical characteristics of each residential building. For instance, land use, utilities in the zone, roads, topography, land value, materials of bathroom and kitchen are taking into account in the classification. The income of the population is not considering in this classification due to can be change in the short-term. It supposes both zones and characteristics of the building are a proxy of the income. In this sense, strata 1,2 e 3 correspond to the poorer people a strata 5 and 6 correspond to the richest people (DANE, 2015b).

with different socioeconomic characteristics to guide the planning of public investment, to carry out social programs such as expansion and improvement of public services infrastructure and roads, health and sanitation, educational service and guidelines on the planning of land use. Thus, those classified in strata 5 or 6 must pay a higher price for public services, contributing to the lower prices paid by the low income social classes (strata 1, 2 and 3). Municipality and social strata data have been taken from (SUI, 2016). Energy consumption and household energy prices were collated with the same disaggregation level as presented in Table 4-3.

Table 4-3. Number of consumers by socio-economic stratum in Colombia

Stratum	Consumers	Socio-economic classification
Stratum 1	3,173,466	Low-Low
Stratum 2	4,542,507	Low
Stratum 3	2,654,935	Medium-Low
Stratum 4	862,837	Medium
Stratum 5	343,953	Medium-high
Stratum 6	204,375	High
Total	**11,782,073**	

Source: Own elaboration, based on Ref. (DANE, 2015b; SUI, 2016)

4.4.4 Utility Tariffs

Utility tariffs are used to calculate the PV economic potential, in which grid-parity is considered. Some assumptions were made to associate each social stratum to a specific energy price. Electricity unit costs are composed by the sum of the remunerations in the entire energy supply chain. There are thirty-two commercialization utilities in Colombia, but only 17 represent 96% of the market share, which are considered in the analysis. Table 4-4 shows the unit cost (CU – Costo Unitario) or tariff breakdown in the electricity value chain for the seventeen utilities for stratum 4[31] in December 2015[32].

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[31] Reference tariff, it does not have either subsidy or contribution.

[32] In order to express the tariff in USD, we applied the mean exchange rate for years 2014 and 2015, as follows US$1=COP$2,200 COP (BANREP, 2016).

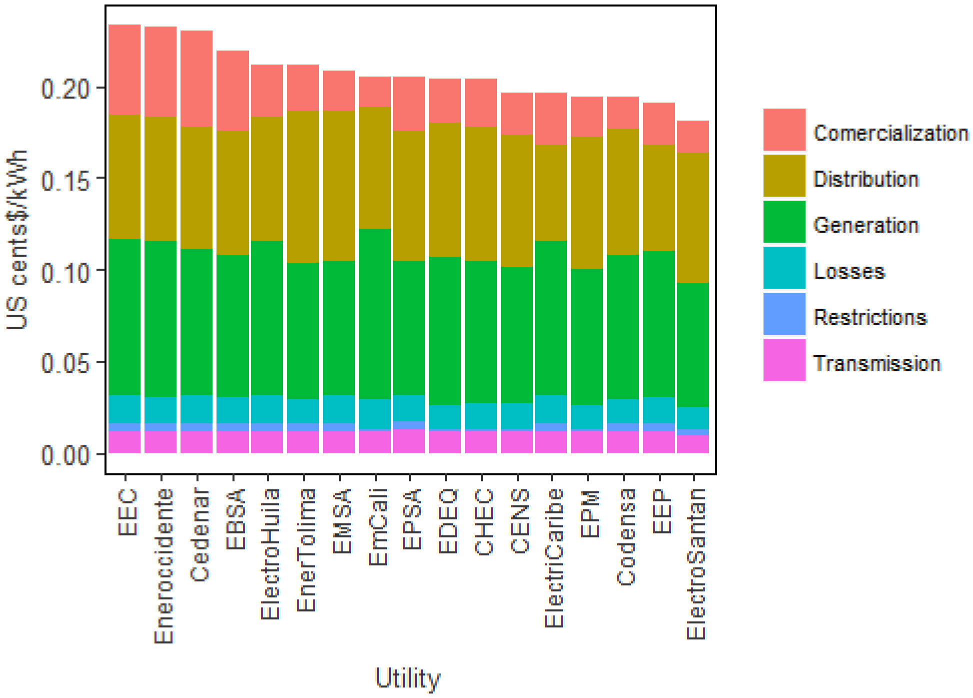

Figure 4-4. Breakdown of tariffs by utility, stratum 4 in Colombia (December 2015).

Source: Own elaboration, based on (CENTRAL HIDROELÉCTRICA DE CALDAS S.A. E.S.P., 2015; CENTRALES ELÉCTRICAS DE NARIÑO S.A. E.S.P., 2015; CODENSA S.A. E.S.P., 2015; COMPAÑÍA ENERGÉTICA DE OCCIDENTE S.A.S. E.S.P., 2015; COMPAÑÍA ENERGÉTICA DEL TOLIMA S.A E.S.P, 2015; ELECTRIFICADORA DEL CARIBE S.A. E.S.P., 2015; ELECTRIFICADORA DEL HUILA S.A. E.S.P., 2015; ELECTRIFICADORA DEL META S.A. E.S.P., 2015; EMPRESA DE ENERGÍA DE BOYACÁ S.A. E.S.P., 2015; EMPRESA DE ENERGÍA DE CUNDINAMARCA S.A. ESP, 2015; EMPRESA DE ENERGÍA DE PEREIRA S.A. E.S.P., 2015; EMPRESA DE ENERGÍA DEL PACÍFICO S.A. E.S.P., 2015; EMPRESA MUNICIPALES DE CALI E.I.C.E E.S.P, 2015; EMPRESAS PÚBLICAS DE MEDELLÍN E.S.P., 2015)

The contribution for both strata 5 and 6 is 20% over the reference tariff. The tariff for strata 1, 2 and 3 perceive a subsidy of 60%, 50% and 15%, respectively. These assumptions are in line with the Law 142/1994. Subsidy is only applied to household consumption less than 173kWh; otherwise, these strata must pay the full reference tariff[33]. This study computes the mean consumption of each stratum within the municipality and allocated the tariff accordingly. Several utilities may supply electricity in the same

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[33] The contributions and subsidies are according with the Law 142/1994 sets. The law aforementioned considers as a subsistence consumption 173 kWh/month as well. It means, consumers from the strata 1, 2 and 3 consumers have right to receive a subsidy if their consumption is less than this value.

municipality, however, for the sake of simplicity, the utility with the largest number of consumers within a municipality was used as a reference. To be conservative, increases in energy prices up to 2030 were not considered, since the higher the energy prices the greater the PV economic potential.

4.4.5 Evolution of Prices for Distributed PV Systems

So far, Colombia does not have a photovoltaic manufacturing industry. However, photovoltaic panels, inverters and battery suppliers are available, most of them made in China and India (BRP, 2015) . In the short and medium term, there are no clear incentives or plans to consolidate a national photovoltaic industry. We consider an average PV investment cost of 4.8 USD/Wp (UPME, 2015a), which is in line with the international market. In South America both Brazil and Chile have lower costs than Colombia. For instance, in the Chilean market the cost is 2.98 USD/ Wp. (BID, 2015; MIRANDA, Raul F.C.; SZKLO; SCHAEFFER, 2015; NRDC, 2012; REN21, 2015; UPME, 2015a). In the United States the cost is between 3.50 USD/ Wp and 5.25 USD/ Wp. Germany and China reported the lowest capital cost: 2.20 USD/Wp and 2.15 USD/Wp, respectively. These costs correspond to a peak capacity between 3-5 kW that can be considered small-scale projects. This study also considered a learning rate approach, based on previous studies (BREYER; GERLACH, 2013; IIASA, 2000; NEMET, 2006; RIGTER; VIDICAN, 2010; SARK et al., 2013).

4.4.6 Lending interest rate

Many banks in Colombia lend money under different conditions. To calculate the market potential, this study considered the interest rate of seven local banks, in which lending conditions are different according to the household stratum. For instance, the higher stratum can obtain a better interest rate given the terms of the loan. Thus, it is assumed that the strata 1 and 2 have up to 96 months to pay the loan, the strata 3 and 4 have up to 60 and 24 months to pay the loan, respectively. Strata 5 and 6 would not need a loan to buy a solar PV but the simulations will consider their opportunity cost.

Table 4-4. Lending interest rate in Colombia (%)

	Banco Davivienda	**Banco de Bogotá**	**Banco Popular**	**Bancolombia**	**Banco de Occidente**	**Banco Falabella**	**Average**
Until 12 months	17.60	28.90	31.90	31.99	31.99	31.99	29.06
Until 24 months	17.60	28.90	31.90	31.99	31.99	31.99	29.06
Until 36 months	19.70	28.90	31.90	31.99	31.99	31.99	29.41
Until 48 months	19.70	28.90	31.90	31.99	31.99	31.99	29.41
Until 60 months	19.70	28.90	31.90	31.99	31.99	31.99	29.41
Until 72 months	21.56	28.90	31.90	31.99	31.99	31.99	29.72
Until 84 months	23.14	28.90	31.90	31.99	31.99	31.99	29.99
Until 96 months	24.31	28.90	31.90	31.99	31.99	31.99	30.18

Source: Own elaboration, based on Ref.

4.5 Results

4.5.1 Technical Potential

The current PV distributed installed capacity in Colombia is 11.5 MWp. Technical potential directly depends on the number of households and the share of houses and apartments. The technical potential was estimated under a net metering logic. The Colombian technical potential reached 9.1 GWp or 13.10 TWh/year (Figure 4-5 - Figure 4-6)[34]. The highest potential occurs in Bogotá with 840 MWp, followed by Cali, Cartagena and Medellin with 430 MWp, 332 MWp and 272 MWp, respectively. The technical potential is concentrated in the most populated municipalities. The household

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[34] Blank municipalities in the figures are those for which there are no data about consumers, consumption and tariffs in (SUI, 2016).

type (house or apartment) is another weighing factor. When separated by stratum, results show that 88% of the technical potential occurs in strata 1, 2 and 3. For instance, in Bogotá and Cali findings indicate that the highest potential is in stratum 3. In Cartagena the highest technical potential is found for strata 1 and 2, which may never be explored, since these households have low average income. These findings indicate that there is still a huge potential to develop but supporting energy policies are required for the effective boosting of the sector, mainly for strata 1, 2 and 3.

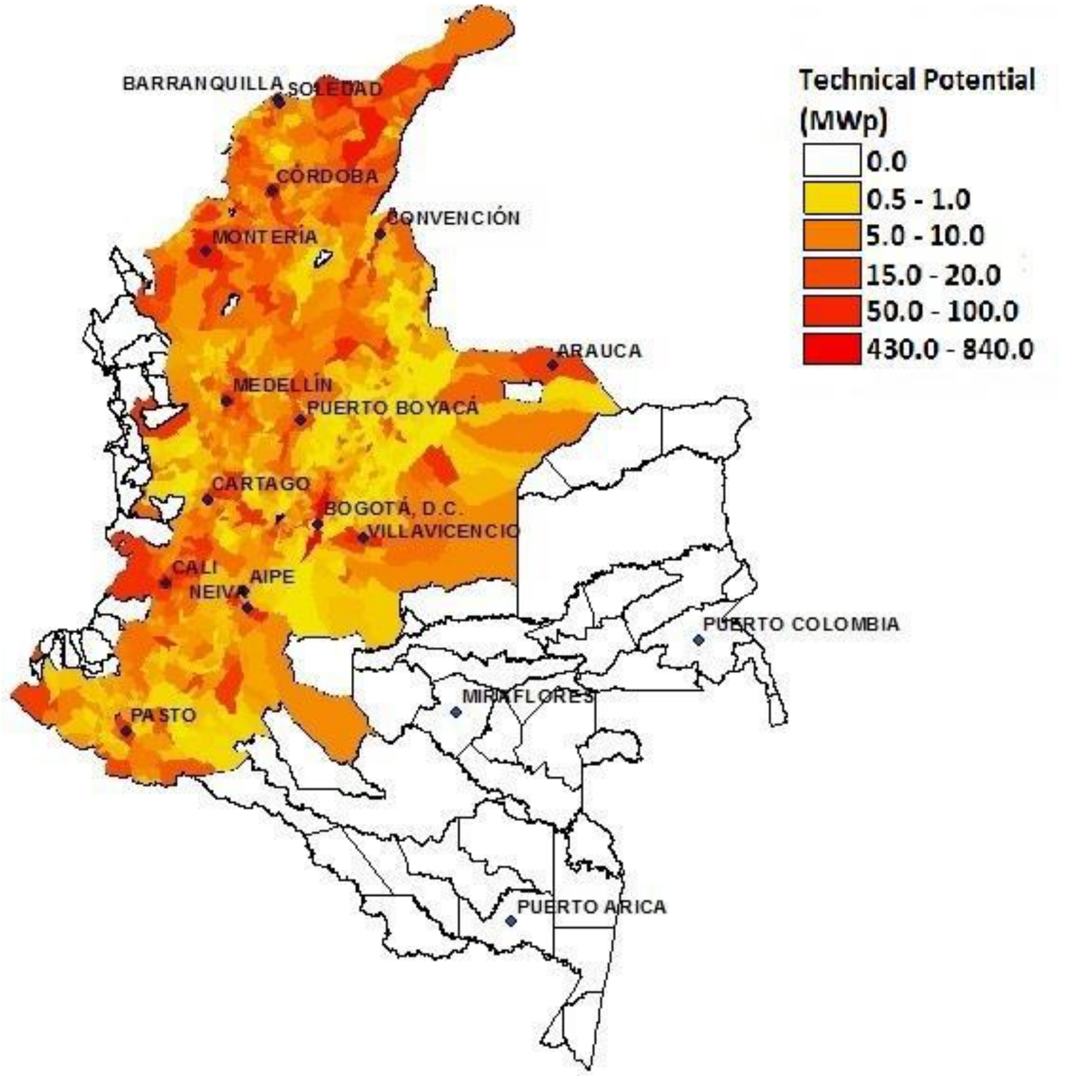

Figure 4-5. Technical potential for distributed PV generation in the residential sector in Colombia (MWp) – year 2015

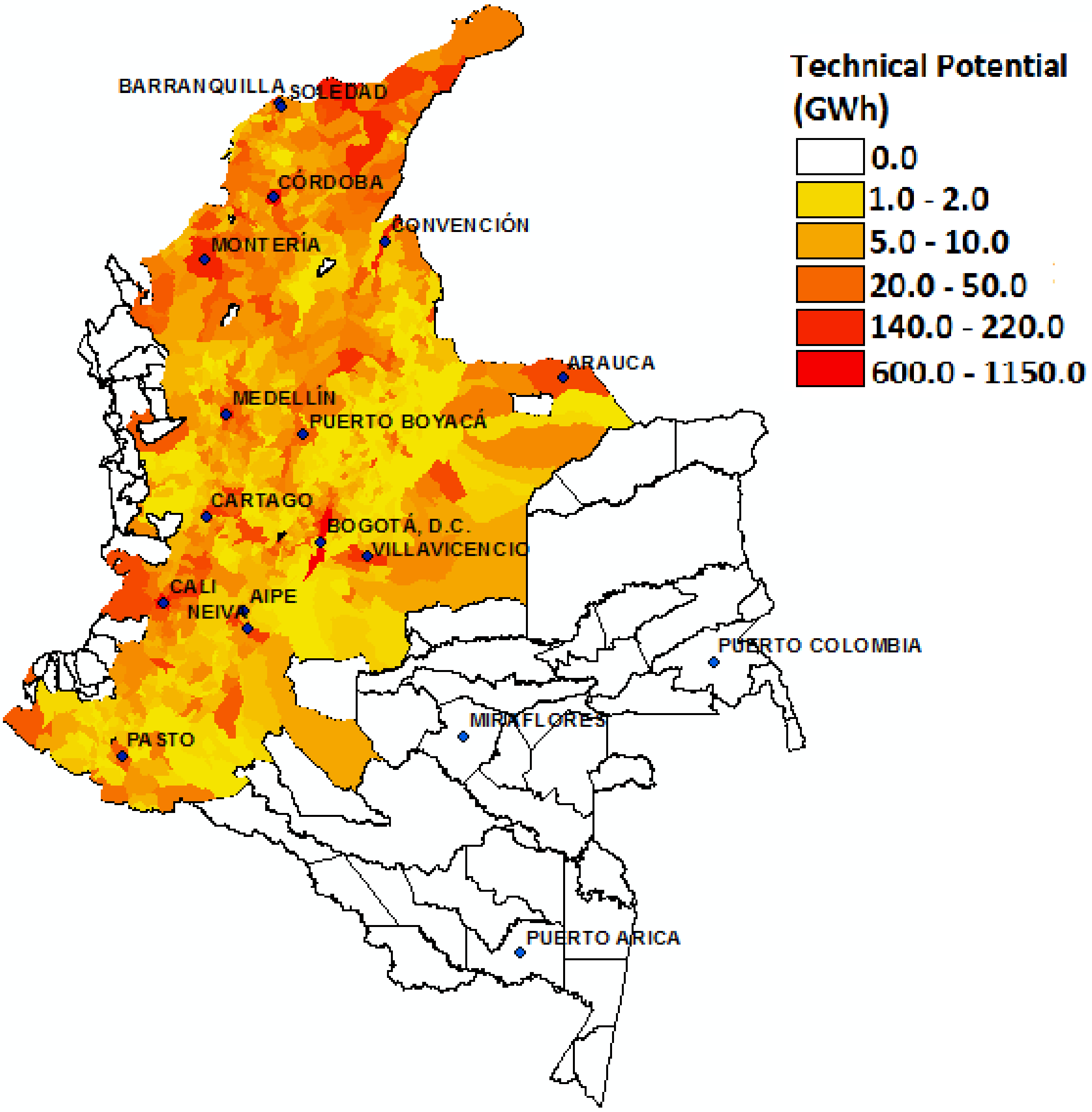

Figure 4-6. Technical potential for distributed PV generation in the residential sector in Colombia (GWh) – year 2015

4.5.2 Economic Potential

4.5.2.1 Levelized Cost (LCOE) and grid parity

The economic potential is calculated by comparing LCOE to local electricity tariffs. The cost of the energy annually delivered by the PV system is given by the LCOE, as showed in Figure 4-7. Because of the assumed learning rate, the system LCOE is expected to decrease along the period. For instance, PV energy would cost 296.24

USD$/MWh for a system under the Bogota solar data in 2020, but the same energy is expected to be delivered at 225.14 USD$/MWh in 2030.

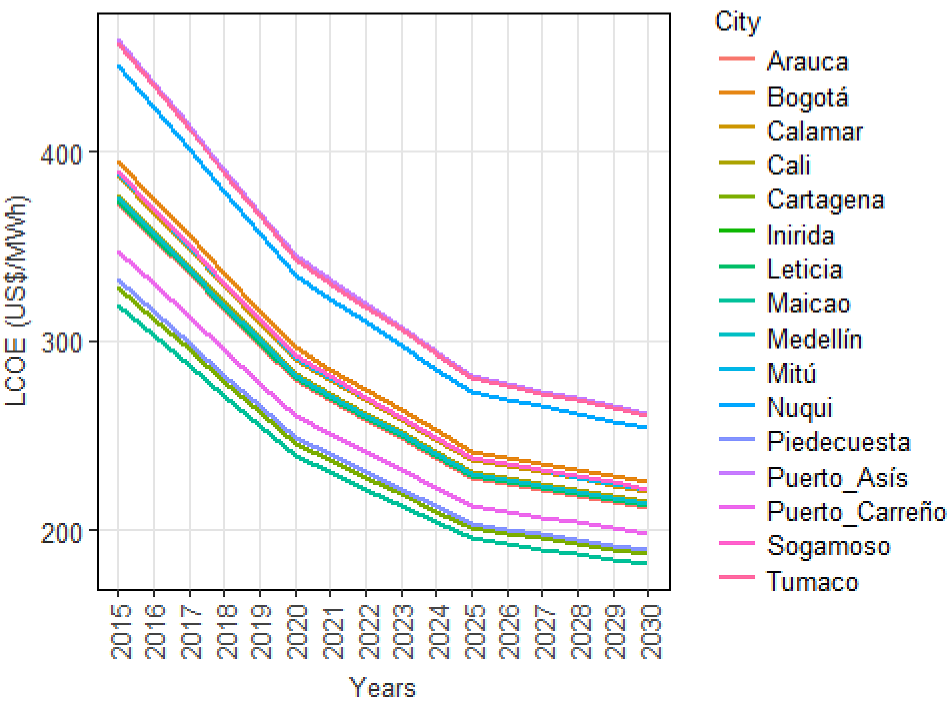

Figure 4-7. LCOE for the 16 solar sites in Colombia

Grid parity is achieved when LCOE reaches a value equal to the price of purchasing energy from the grid in a specific year. PV feasibility is found firstly in the municipalities with both the best solar resource quality and higher power tariffs. Figure 4-8 and Figure 4-9 display in a histogram the difference between LCOE and energy tariff for stratum 1 (left graph) and stratum 6 (right graph) in 2015 and 2030, respectively. This difference is represented by the bins in the horizontal axis, while the frequency is represented in the vertical axis. Grid parity is reached in the negative values, meaning that solar energy is cheaper than the energy purchased from the grid.

For year 2015 no municipality reached grid parity (Figure 4-8). This fact can be easily notice by looking at the vertical red dotted line, which represents the grid parity. In stratum 1, Riohacha has the lowest difference between LCOE and the tariff (123 USD$/MWh) and Tumaco displays one of the highest value. Several reasons explain this result, namely: a) average radiation is better in the north of the country than in the Pacific Coast, so LCOE is lower for Riohacha as the municipality is in the north, and, b) the household average consumption in Riohacha is 291kWh/month, while in Tumaco it is 90 kWh/month. Riohacha's household tariffs are generally higher, since the average local consumption is greater than the maximum liable for receiving subsidy as stated by the law. According to these average consumptions in stratum 1, the average tariff practiced in Riohacha is USD$200/MWh (Electrificadora del Caribe S.A. E.S.P. utility) and in Tumaco is USD$90/MWh (Centrales Eléctricas de Nariño utility). For stratum 6, Santa Marta, supplied by Electrificadora del Caribe S.A. E.S.P, has the lowest value and thus it is the municipality closest to parity. The difference between LCOE and tariff in the national capital Bogotá, fell from 317$USD/MWh to 162$USD/MWh when comparing stratum 1 to 6.

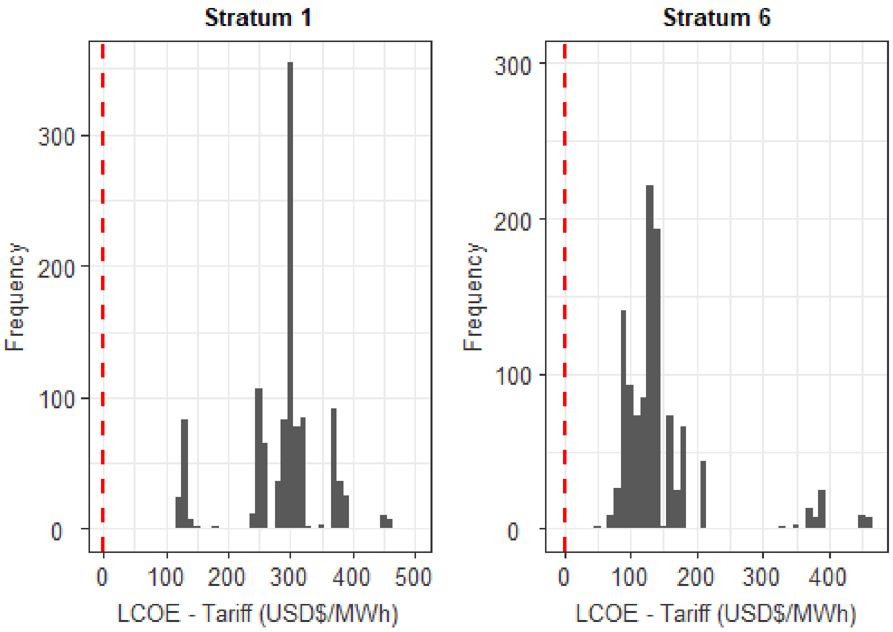

Figure 4-8. Levelized cost of energy and residential sector bill relationship for i) stratum 1 and ii) stratum 6 – Year 2015

Results for 2030 show several municipalities achieving grid parity for both strata 1 and 6, 116 and 984 municipalities, respectively (Figure 4-9). For instance, in stratum 1, Cartagena and Barranquilla do not achieve grid parity in 2015 but do in 2030. It is interesting to note that stratum 1 in Bogotá will not achieve the grid parity in 2030, whilst, in stratum 6, 984 municipalities will achieve grid parity. Some of them can even achieve this economic viability in 2021, such as Valledupar, Riohacha and Santa Marta, while, Barranquilla and Cartagena can reach it in 2022. The main municipalities that will achieve it later on are Cali (2024), Medellín (2025), Pasto (2027) and Bogotá (2028). Once again, the vertical dotted red line is useful to notice the grid parity.

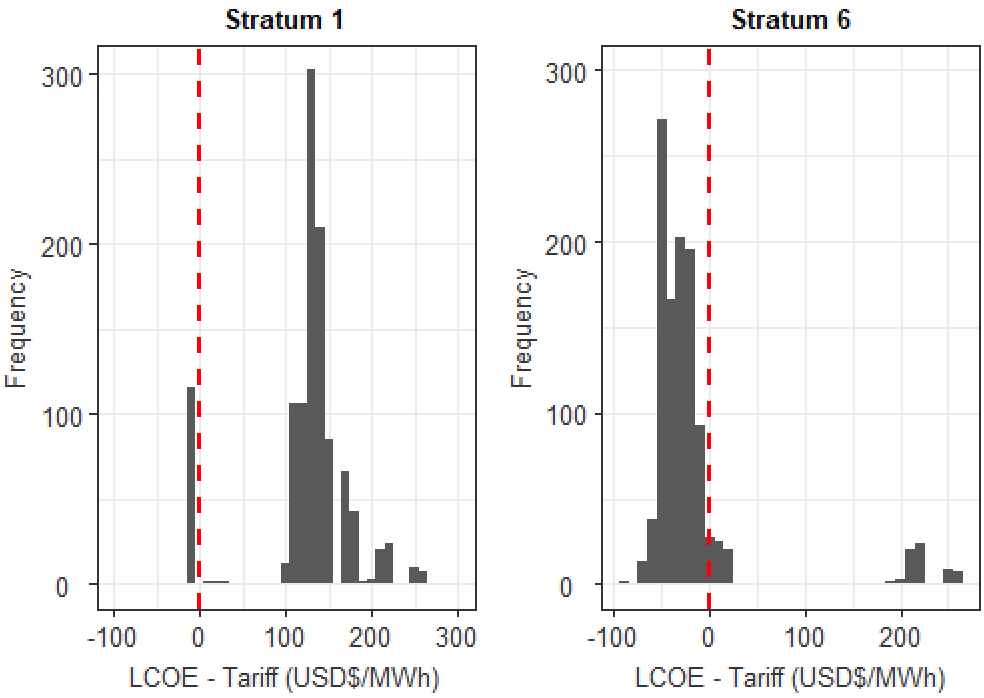

Figure 4-9. Levelized cost of energy and residential sector bill relationship for i) stratum 1 and ii) stratum 6 – Year 2030

Once a specific municipality stratum achieves grid parity, its technical potential turns into economic potential, based on the methodology described. The economic potential is supposed to grow over time, since more households reaches grid parity for each new year and also by the growth of the number of households themselves.

4.5.2.2 Spatial Analysis

The geographical distribution of the economic potential is shown in Figure 4-10 and Figure 4-11, aiming at showing how this potential grows in the assessed period. The economic potential of the country is 3.2 GWp by 2030. Distinctively from the technical potential, the uppermost economic potential by 2030 is in Cartagena, Barranquilla, Santa Marta, Montería y Valledupar with 449.1 MWp, 264.2 MWp, 186.5 MWp, 156.0 MWp and 155.5 MWp, respectively, which achieve grid parity by 2022. The first strata to achieve economic feasibility are strata 5 and 6. For instance, in Cartagena 22.4 MWp in stratum 5 and 40.2 MWp in stratum 6 become economically feasible by 2022. Regarding stratum 1, Santa Marta and Valledupar 54.5 MWp and 46.9 MWp, respectively, achieve economic feasibility by 2025. In Bogotá, 43.8 MWp and 65.4 MWp achieve economic feasibility in 2028 for strata 5 e 6, respectively. The total economic potential in Bogotá is 111.4 MWp by 2030. This is the municipality with the sixth highest economic potential in the country at the end of the period. The analysis was done for the whole of Colombia, detailed by stratum and within each municipality.

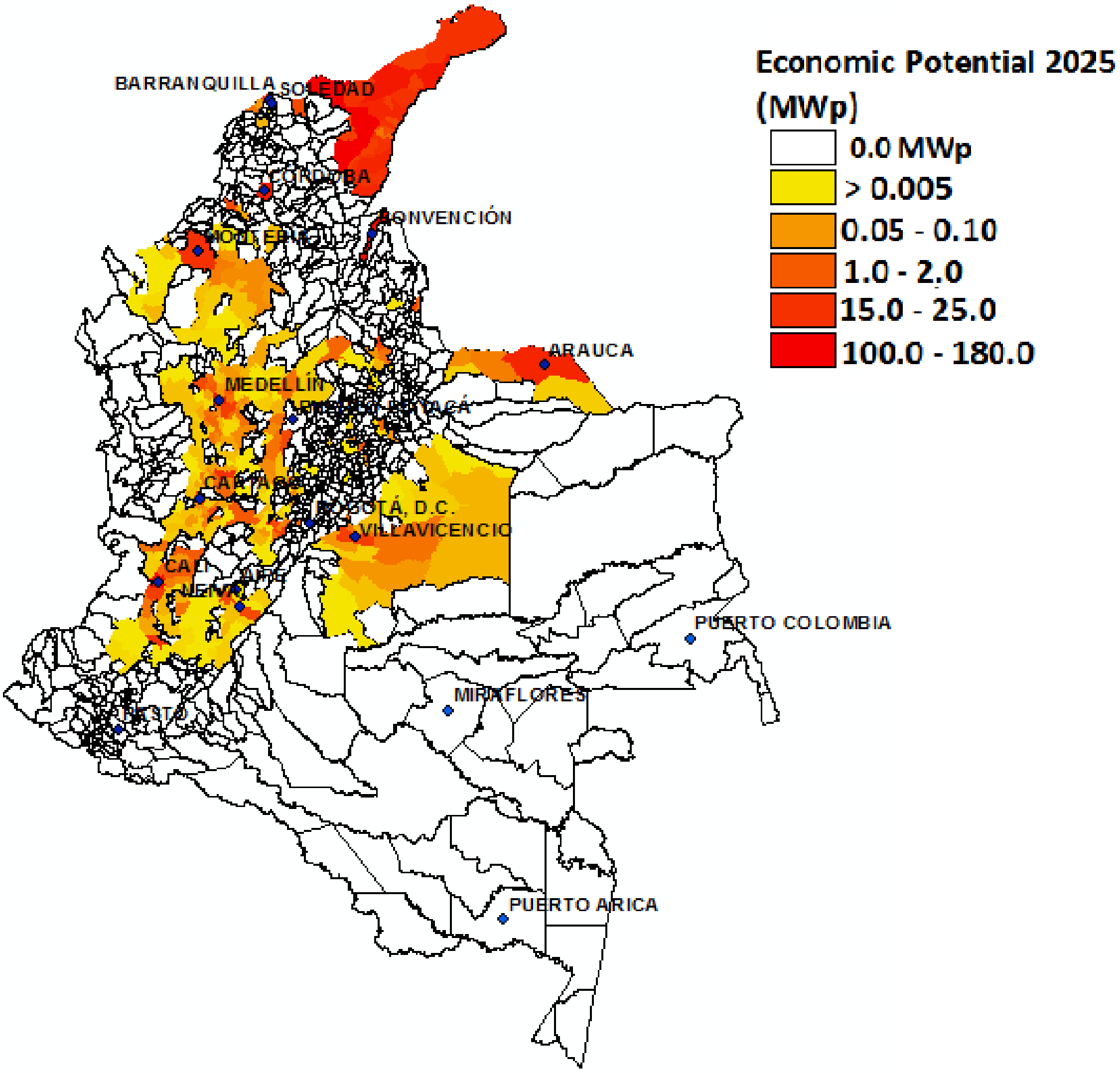

Figure 4-10. PV installed capacity in municipalities that reached grid parity (Year 2025)

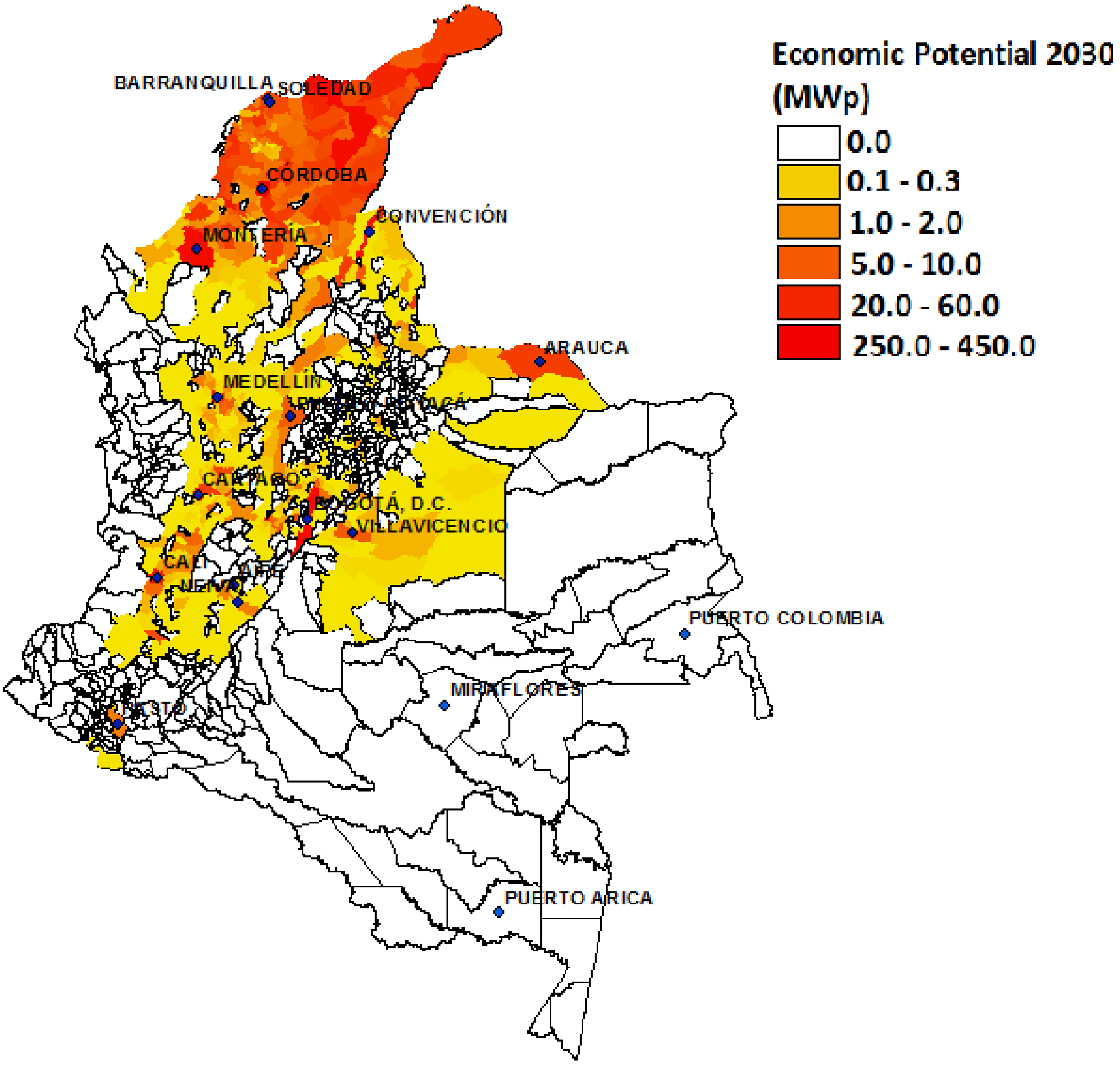

Figure 4-11. PV Installed capacity in states that reached grid parity – (Year 2030)

4.5.3 Market Potential

The market potential is calculated from the relationship between LCOE and local tariffs but taking into account real market lending conditions and their impact on the LCOE computation. The other assumptions about investment expenditures and learning rate remain unchanged comparatively to the economic potential. The market potential approach considers six scenarios, which depend on both the funding percentage and the lending interest rate used to calculate the LCOE. The market potential was assessed according to different equity ratios to install the solar PV system. Thereby, this study considers three funding fractions levels, namely: 50%, 80% and 100%. Lending interest rates reflect the fact that the households must leverage when there is no cash available to invest in the solar PV system.

For strata 1, 2, 3 and 4, this study examines the lending interest rate conditions displayed in Section 3.5 to calculate the LCOE. For a particular scenario in calculating the LCOE for strata 1 and 2, the results using a social interest[35] rate were also analyzed. By computing the LCOE using this special rate, it is assumed that the poorest people have the possibility of financing the solar PV equipment with a lower interest rate. This study assumes that no funding is required for both strata 5 and 6, so the LCOE will be equal to the one obtained under the economic potential assumptions.

Figure 4-12 lists the scenarios for computing the different financing conditions used to calculate the PV system LCOE in six market potential scenarios.

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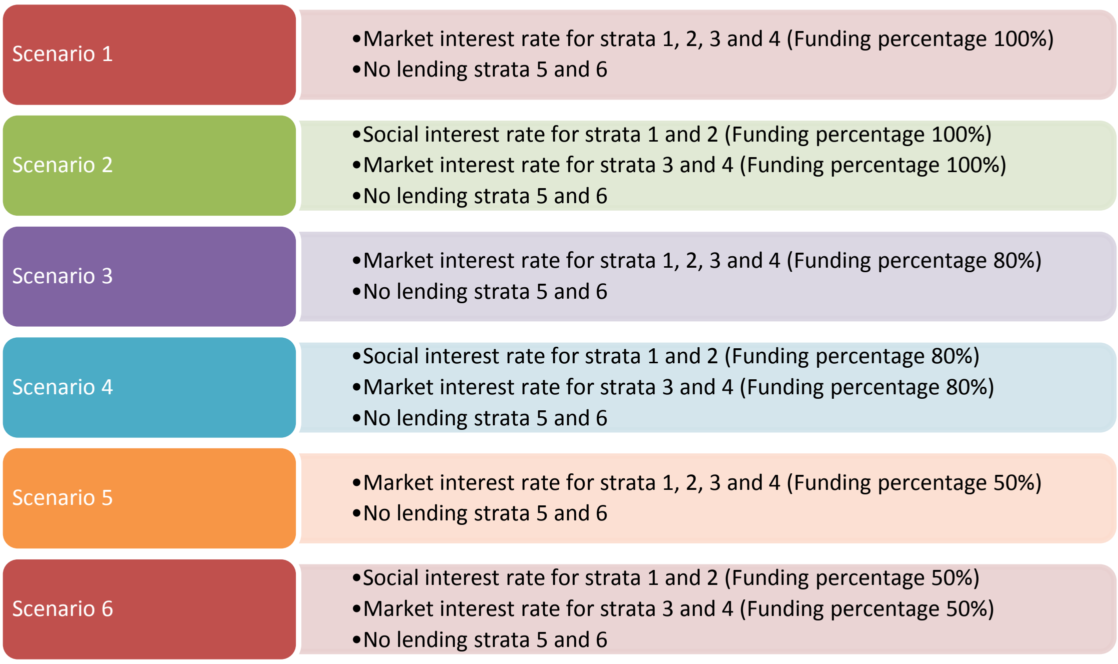
[35] A rate equal to the mortgage interest rate to buy a house under the Colombian social projects framework was used in this case (11.12% p.y.)



Scenario 1
- Market interest rate for strata 1, 2, 3 and 4 (Funding percentage 100%)
- No lending strata 5 and 6

Scenario 2
- Social interest rate for strata 1 and 2 (Funding percentage 100%)
- Market interest rate for strata 3 and 4 (Funding percentage 100%)
- No lending strata 5 and 6

Scenario 3
- Market interest rate for strata 1, 2, 3 and 4 (Funding percentage 80%)
- No lending strata 5 and 6

Scenario 4
- Social interest rate for strata 1 and 2 (Funding percentage 80%)
- Market interest rate for strata 3 and 4 (Funding percentage 80%)
- No lending strata 5 and 6

Scenario 5
- Market interest rate for strata 1, 2, 3 and 4 (Funding percentage 50%)
- No lending strata 5 and 6

Scenario 6
- Social interest rate for strata 1 and 2 (Funding percentage 50%)
- Market interest rate for strata 3 and 4 (Funding percentage 50%)
- No lending strata 5 and 6

Figure 4-12. Scenarios to calculated the LCOE for market potential computation

Table 4-5 shows the LCOE for each of the 16 solar sites for the year 2015. The colors (from green to red) indicate the conditions that yield the lowest (dark green) and the highest (dark red) LCOE. For instance, considering a market interest rate and 100% of funding, the LCOE is 744.19 USD$/MWh for strata 1 and 2 in Bogotá. On the other hand, if the funding falls down to 80% or 50%, the LCOE drop to 674.87 USD$/MWh and 569.91 USD$/MWh, respectively.

Table 4-5. LCOE for the 16 solar sites in Colombia for computing market potential- Year 2015

Funding percentage	**Solar sites**	**Market interest rate**			**Social interest rate**
		Stratum 4	**Stratum 3**	**Stratum 1 and 2**	**Stratum 1 and 2 (Social)**
100%	MAICAO	405.35	499.51	602.12	362.43
	CARTAGENA DE INDIAS	416.76	513.57	619.06	372.63
	PIEDECUESTA	421.60	519.53	626.26	376.96
	PUERTO CARREÑO	441.08	543.54	655.19	394.38
	ARAUCA	473.00	582.87	702.60	422.91
	INIRIDA	474.55	584.77	704.90	424.30
	LETICIA	474.86	585.16	705.36	424.58
	MEDELLÍN	476.73	587.46	708.14	426.25
	CALI	478.61	589.79	710.94	427.94
	CALAMAR	491.58	605.77	730.21	439.53
	MITÚ	493.59	608.24	733.19	441.33
	SOGAMOSO	494.26	609.07	734.19	441.93
	BOGOTÁ, D.C.	501.44	617.91	744.84	448.34
	NUQUÍ	565.97	697.44	840.71	506.05
	TUMACO	581.39	716.44	863.61	519.83
	PUERTO ASÍS	583.73	719.32	867.09	521.92
80%	MAICAO	388.14	463.47	545.55	353.80
	CARTAGENA DE INDIAS	399.06	476.51	560.91	363.76
	PIEDECUESTA	403.70	482.05	567.42	367.99
	PUERTO CARREÑO	422.35	504.32	593.64	384.99
	ARAUCA	452.91	540.81	636.60	412.85
	INIRIDA	454.40	542.58	638.68	414.20
	LETICIA	454.69	542.93	639.10	414.47
	MEDELLÍN	456.49	545.07	641.62	416.10
	CALI	458.29	547.23	644.15	417.75
	CALAMAR	470.71	562.06	661.61	429.07
	MITÚ	472.63	564.36	664.31	430.82
	SOGAMOSO	473.28	565.12	665.22	431.41
	BOGOTÁ, D.C.	480.15	573.33	674.87	437.67
	NUQUÍ	541.94	647.12	761.73	494.00
	TUMACO	556.71	664.75	782.48	507.46
	PUERTO ASÍS	558.95	667.42	785.63	509.50
50%	MAICAO	362.32	409.40	460.71	340.86
	CARTAGENA DE INDIAS	372.52	420.92	473.67	350.46
	PIEDECUESTA	376.85	425.82	479.18	354.53
	PUERTO CARREÑO	394.26	445.49	501.32	370.91
	ARAUCA	422.79	477.72	537.59	397.75
	INIRIDA	424.17	479.29	539.35	399.05
	LETICIA	424.45	479.60	539.70	399.31
	MEDELLÍN	426.12	481.49	541.83	400.88
	CALI	427.81	483.40	543.97	402.47
	CALAMAR	439.40	496.50	558.72	413.38
	MITÚ	441.20	498.52	561.00	415.06
	SOGAMOSO	441.80	499.20	561.76	415.63
	BOGOTÁ, D.C.	448.21	506.45	569.91	421.66
	NUQUÍ	505.90	571.63	643.26	475.93
	TUMACO	519.68	587.20	660.79	488.90
	PUERTO ASÍS	521.77	589.56	663.45	490.86

Figure 4-13 shows the expansion of the market potential by 2030, including the six scenarios computed according to the LCOE calculated, assuming the conditions presented in Figure 4-12. As such, for each calculated LCOE, a corresponding market potential scenario is estimated.

Scenarios 1 and 2 reach the same results, only strata 5 and 6 achieve the market potential of 570 MWp by 2030. For the other strata, the tariff is always lower than the LCOE, even in the last few years of the period of analysis. In fact, the market potential added by strata 5 and 6 is 570 MWp by 2030 in all the scenarios. Scenario 3 points out that stratum 4 can achieve market feasibility by 2030 with a small penetration of 0.12 MWp. Scenario 4 shows that market feasibility is achieved by 2030 for strata 2 and 4 with 2.84 MWp and 0.12 MWp, respectively. The maximum market potential is achieved in Scenario 6. The market feasibility in stratum 2 is achieved by 2027, while stratum 1 and 4 only achieve market feasibility by 2030. The market potential by 2030 is 1,080 MWp split as follows: Stratum 1 (248.6 MWp), Stratum 2 (260.6 MWp), Stratum 4 (0,12 MWp), Stratum 5 (281,1), Stratum 6 (289,8). For Stratum 3, even under scenario 6 market feasibility is not reached.

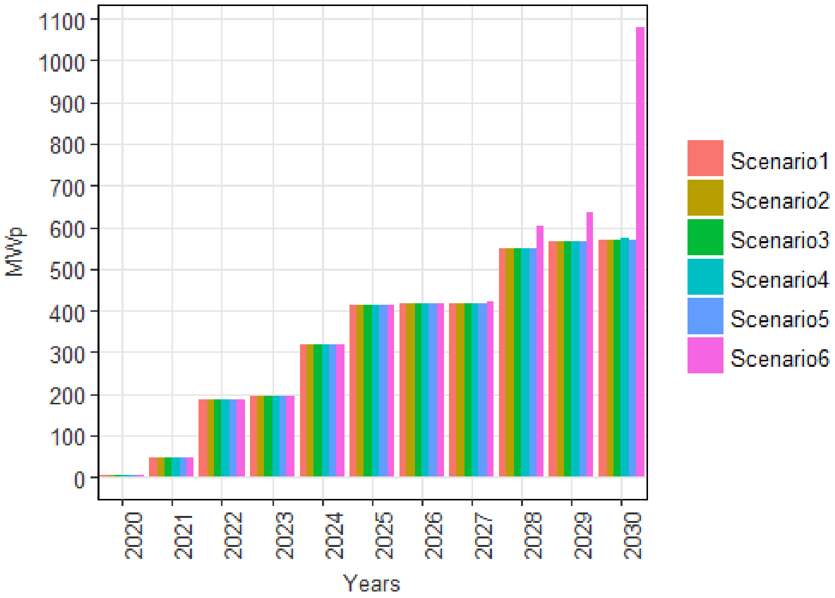


Figure 4-13. Market potential scenarios

Therefore, results indicate that there is still a huge gap between technical, economic and market potentials (See Figure 4-14). This gap is particularly evident for strata 1 and 2, which include the poorest people in Colombia.

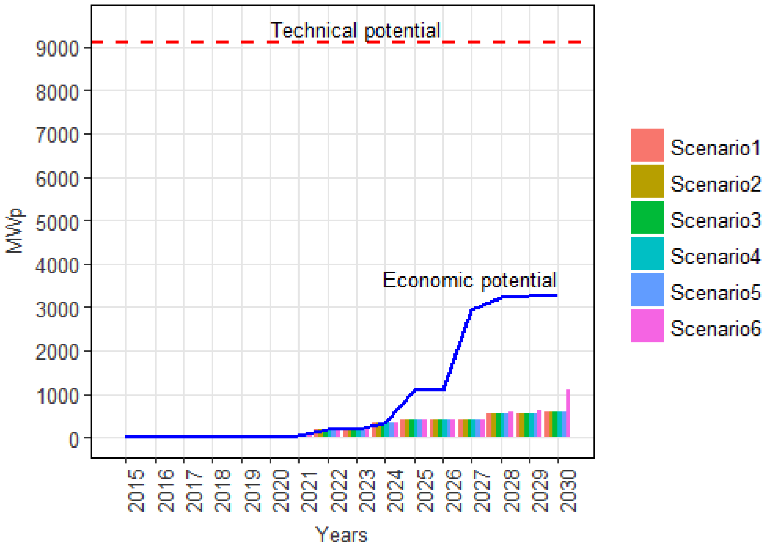


Figure 4-14. Technical, economic and market potential comparisons (6 scenarios)

These findings, along with the still incipient regulation in Colombia for small scale renewable power projects, shows the importance of designing policies that can effectively encourage PV solar panels. This regulation and specific incentive schemes should have a high impact on the adoption of the technology overcoming financial barriers to investment and recognizing the huge social and economic diversity of the residential sector.

4.5.4 Conclusion and policy implications

This study developed and applied a methodology to estimate the technical, economic and market potentials for solar PV in the residential sector, considering inherent features of the sector and detailing the spatial and income distribution. This methodology can be replicated in any other country, but it is most suitable for those with higher income inequalities (usually, developing countries). By considering market conditions, it also can help policy-makers formulating policies to incentivize the deployment of PV systems especially in low income households.

For the case study of Colombia, findings indicate that the technical potential is allocated in the most populated municipalities (9.1 GWp or 13.10 TWh/year). The highest technical potential is in Bogotá (840 MWp), followed by Cali, Cartagena and Medellin (430 MWp, 332 MWp and 272 MWp, respectively). Meanwhile, economic potential shows that PV economic feasibility happens in municipalities with both the best solar resource quality and the highest tariffs. Several municipalities can achieve the grid parity from both strata 1 and 6 in 2030. In particular, for stratum 1, Cartagena and Barranquilla municipalities did not achieve grid parity in 2015 but are expected to achieve it in 2030. On the other hand, stratum 1 in Bogotá never achieves the grid parity.

The most uncertain estimation refers to the market potential, which includes different levels of funding fraction (debt-equity ratio) and market lending interest rates for the acquisition of PV systems. Firstly, the real market conditions were tested, indicating that market feasibility is reached only for strata 5 and 6. In this case, market feasibility is achieved in 2020, and reaches only 6.27% of the technical potential. As the highest technical potential was found in strata 1 and 2, this study also performed a sensitivity analysis to evaluate the possibility of these strata having access to better financial conditions. Nevertheless, the results show that even under these conditions, solar PV feasibility would remain low until 2027. The market potential for the country could represent, in the best case scenario, 11.86% of the technical potential by 2030. The uppermost market potential by 2030 would be in Santa Marta, Valledupar, Maicao and Riohacha with 114 MWp, 111 MWp, 57 MWp, and 31 MWp, respectively.

Barriers to the PV solar dissemination are related to the high upfront cost of PV technology, lack of financing mechanisms and lack of awareness and capacity building. Innovative business model and financing mechanisms should be considered by the policy-makers. Moreover, the policy-oriented to the solar PV dissemination in the residential sector in developing countries should consider the inclusion of poor people either as consumers or producers. This policy can be based on the following mechanisms:

a. *Feed in tariffs*. This incentive strategy provides long time price stability to self-producers creating additional interest to investors. Nevertheless, this strategy requires an in-depth study to define the values assigned for the *feed in tariffs*. When the income level groups analysis come into the discussion, the high upfront cost plays a key role because the poorest people are not available to install the technology. Nevertheless, they would have to pay for the scheme as well. The consumer pays for this scheme because all the suppliers, regardless of whether they have a license to produce, must cover the cost of the scheme. Consequently, the overcharge is passed onto the consumers, even the poorest income level citizen, if it is not well-designed.

b. To tackle the upfront cost issue, innovative model businesses might be considered. For instance, mechanisms such as leasing, public private partnership approach (PPA) and crowdfunding might be explored for the policy-makers in developing countries.

c. Setting-up an effective communication process directed towards different consumers' strata is a fundamental aspect to be considered, providing relevant information to the consumer and resulting in a better understanding of the technology, its importance for the country and the gains to the investors. Raising awareness of the population towards renewables and PV solar, in particular, is an essential factor to ensure the success of a massive program.

d. Besides the aforementioned suggestions, mainly focused on the demand-side, additional incentives should be directed towards the technology suppliers. A quality certified PV solar equipment scheme could be considered as a way of providing confidence to the investors and rewarding high quality local producers/suppliers of the equipment.

e. The implementation of training programs for local technicians should not be overlooked. Setting up technical institutes for vocational courses in the direction of educating PV solar designers, workers and engineers must be considered in order to improve work efficiency and boost the local and national economy.

f. Development of downstream energy policies are necessary. Policy focus on tax incentives for industry should be considered in order to promote domestic participation and “local content” development of the equipment sector, with important economic revenues.

4.6 Appendix

Appendix 1. Top 20 municipalities with the highest technical potential by strata in the residential sector in Colombia (MWp)

	Municipality	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5	Strata 6	Total
1	Bogotá	35.36	179.40	445.34	84.85	38.30	57.13	840.37
2	Cali	57.11	86.49	120.56	62.38	56.20	48.10	430.84
3	Cartagena	108.29	86.72	59.71	23.81	19.32	34.65	332.49
4	Medellín	21.20	69.70	89.07	42.57	28.23	22.01	272.77
5	Barranquilla	81.24	31.66	42.78	28.46	14.29	20.13	218.57
6	Santa Marta	52.12	29.40	47.43	19.95	7.46	18.49	174.84
7	Montería	68.20	31.07	16.84	10.74	4.55	4.60	136.00
8	Valledupar	41.84	42.62	28.22	9.33	6.95	2.57	131.53
9	Cúcuta	26.87	51.04	26.32	18.22	4.97	0.60	128.01
10	Cartago	6.76	19.19	64.21	7.43	3.08	0.13	100.79
11	Palmira	4.17	57.52	19.62	8.22	1.28	0.00	90.81
12	Villavicencio	18.76	23.82	33.98	7.57	3.62	1.48	89.22
13	Barrancabermeja	25.56	27.28	16.43	11.56	1.03	-	81.86
14	Sincelejo	28.83	20.55	10.20	4.85	0.81	1.74	66.98
15	Neiva	13.59	35.46	8.78	6.34	2.18	0.19	66.54
16	Soacha	13.08	25.98	24.73	0.00	-	-	63.79
17	Maicao	28.45	26.50	7.00	0.00	-	-	61.95
18	Pereira	7.40	16.54	10.97	11.46	6.59	7.84	60.79
19	Itagüí	3.61	23.66	30.53	2.87	0.00	-	60.68
20	Soledad	30.08	25.68	2.22	0.01	0.00	-	57.98
21	1100 municipalities	2,057.15	2,362.59	885.86	215.46	73.56	51.42	5,646.05
	Total	**2,729.65**	**3,272.84**	**1,990.81**	**576.07**	**272.42**	**271.08**	**9,112.87**

Appendix 2. Top 20 municipalities with the highest economic potential by strata 2025 in the residential sector in Colombia (MWp)

	Municipality	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5	Strata 6	Total
1	Santa Marta	54.51	30.74	49.60	20.86	7.80	19.33	182.84
2	Valledupar	46.95	47.82	31.67	10.47	7.79	2.88	147.58
3	Cúcuta	-	51.82	26.73	18.50	5.04	0.61	102.70
4	Cali	-	-	-	-	42.75	36.59	79.34
5	Cartagena	-	-	-	-	23.76	42.62	66.38
6	Maicao	29.19	27.19	7.19	0.00	-	-	63.57
7	Medellín	-	-	-	-	31.02	24.17	55.19
8	Riohacha	18.74	14.37	6.50	0.66	0.25	-	40.52
9	Barranquilla	-	-	-	-	16.28	22.93	39.21
10	La Jagua de Ibirico	16.76	7.00	0.02	-	-	-	23.78
11	Arauca	-	13.14	4.24	1.27	-	-	18.65
12	San Juan del César	8.25	7.55	1.59	0.09	-	-	17.48
13	Agustín Codazzi	10.65	4.58	0.87	-	-	0.00	16.11
14	Fonseca	8.99	4.29	2.58	-	-	-	15.85
15	Uribia	6.70	5.04	0.06	-	-	-	11.80
16	Barrancas	5.90	3.47	1.26	-	-	-	10.63
17	Montería	-	-	-	-	5.01	5.06	10.06
18	Villanueva	3.42	4.89	0.85	-	-	-	9.16
19	Becerril	5.43	3.36	0.00	-	-	-	8.80
20	Dibulla	3.18	5.39	0.01	-	-	-	8.58
21	1100 municipalities	24.28	24.52	3.41	5.70	77.99	41.99	177.90
	Total	**242.95**	**255.18**	**136.56**	**57.56**	**217.68**	**196.18**	**1,106.11**

Appendix 3. Top 20 municipalities with the highest economic potential by strata 2030 in the residential sector in Colombia (MWp)

	Municipality	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5	Strata 6	Total
1	Cartagena	146.28	117.13	80.65	32.16	26.10	46.81	449.12
2	Barranquilla	98.21	38.27	51.72	34.40	17.28	24.34	264.21
3	Santa Marta	55.60	31.36	50.59	21.28	7.95	19.72	186.51
4	Montería	78.26	35.66	19.32	12.32	5.22	5.28	156.07
5	Valledupar	49.49	50.41	33.38	11.04	8.22	3.04	155.58
6	Bogotá	-	-	-	-	44.71	66.70	111.41
7	Cúcuta	-	52.18	26.91	18.63	5.08	0.61	103.41
8	Soledad	44.02	37.59	3.25	0.01	0.00	-	84.87
9	Cartago	-	-	69.69	8.06	3.34	0.15	81.23
10	Sincelejo	30.45	21.70	10.77	5.12	0.86	1.84	70.73
11	Cali	-	-	-	-	37.81	32.36	70.17
12	Maicao	29.53	27.50	7.27	0.00	-	-	64.30
13	Medellín	-	-	-	-	32.43	25.28	57.71
14	Girardot	-	15.85	14.40	11.95	1.11	3.60	46.91
15	Puerto Colombia	6.59	8.48	9.53	10.26	0.81	5.45	41.11
16	Malambo	27.25	10.82	0.80	0.01	-	-	38.88
17	Riohacha	17.85	13.68	6.19	0.63	0.23	-	38.58
18	Ciénaga	18.28	12.49	5.51	-	-	-	36.28
19	Lorica	24.07	7.41	1.07	0.01	-	-	32.56
20	Turbaco	6.87	17.37	2.41	3.12	-	-	29.76
21	1100 municipalities	528.69	373.30	89.92	35.71	89.98	54.66	1,172.26
	Total	**1,161.44**	**871.20**	**483.38**	**204.69**	**281.13**	**289.82**	**3,291.66**

Appendix 4. Market potential 2030 in the residential sector in Colombia (MWp)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
2015	-	-	-	-	-	-
2016	-	-	-	-	-	-
2017	-	-	-	-	-	-
2018	-	-	-	-	-	-
2019	-	-	-	-	-	-
2020	5.61	5.61	5.61	5.61	5.61	5.61
2021	45.91	45.91	45.91	45.91	45.91	45.91
2022	185.36	185.36	185.36	185.36	185.36	185.36
2023	192.93	192.93	192.93	192.93	192.93	192.93
2024	317.84	317.84	317.84	317.84	317.84	317.84
2025	413.86	413.86	413.86	413.86	413.86	413.86
2026	414.88	414.88	414.88	414.88	414.88	414.88
2027	418.34	418.34	418.34	418.34	418.34	421.17
2028	547.26	547.26	547.26	547.26	547.26	602.14
2029	564.48	564.48	564.48	564.48	564.48	633.93
2030	570.95	570.95	571.07	573.92	571.07	1,080.38

5 Optimization model for evaluating on-site renewable technologies with storage in zero/nearly Zero Energy Buildings

5.1 Abstract

This study develops, tests and applies an optimization model to evaluate on-site renewable energy technologies with storage in buildings and assess optimal configurations for zero or nearly zero energy buildings. The proposed model is a single-objective hourly-basis mixed integer linear programing model developed in GAMS and solved by CPLEX. The model considers the rooftop availability for installing solar PV and mini wind turbines and the available volume constraint for installing battery. It was tested for different assumptions of electricity prices in a virtual case. Then, a case study for a real building in Portugal was performed, according to scenarios taking into account the current grid-electricity tariffs. Feed-in tariffs in different schemes were also analyzed, as well as the cost evolution of the technologies and the implementation of a bi-hourly tariff. Findings show that the developed model is suitable to evaluate options to implement zero or near zero energy buildings (nZEB), based on renewable technologies. However, for nZEB become competitive, some conditions should be met, especially in terms of the price differentials between the tariffs to purchase electricity from the grid and sell it back.

Keywords: Mixed-integer linear model, On-site generation technologies, Battery, Nearly Zero Energy Buildings (nZEB)

5.2 Introduction

The building sector accounts for an important amount of final energy use worldwide: 117 EJ. It represents about 32% of the final energy consumption (24% for residential and 8% for commercial), and 19% of the energy-derived CO_2 emissions in 2010 (LUCON et al., 2014). Between 1970 and 2010, the greenhouse gas (GHG) emissions associated with energy use in buildings have more than doubled. In the 1970s the total GHG emissions (indirect and direct[36]) were 3.8 $GtCO_2$, 2.5 $GtCO_2$ of which came from direct emissions. In 1990, total emissions were 6.3 $GtCO_2$, while in 2010 this value reached 9.2 $GtCO_2$, 3.2 $GtCO_2$ of which were direct emissions (LUCON et al., 2014).

One of the challenges for a sustainable building sector is reducing the CO_2 emissions (HAN; KIM, 2017). The use of renewable energy is an efficient solution for environmental pollution prevention and sustainable energy development (AHADI; KANG; LEE, 2016). The building sector can play a significant role in using more sustainable natural resources and in increasing its energy conversion efficiency (LUCON et al., 2014). Indeed, the EPBD (Energy Performance Building Directive – 2002/91/CE) established, for the first time in Europe, guidelines for improving energy performance in the sector. The Directive 2010/31/EU updated the aforementioned law defining in Article 9 the concept of nearly Zero Energy Building (nZEB) as a "Building that has a very high energy performance. The nearly zero or very low amount of energy required should be to a very significant extent covered by energy from renewable sources, including renewable

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[36] Direct emissions refer to the emissions that take place at the point where they are discharged. This point in the energy chain can be corresponds to either a sector, or technology or activity. On the other hand, indirect emissions correspond to emissions accounted at the end-use sector, which take place in their upstream production (B. METZ, O.R. DAVIDSON, P.R. BOSCH, R. DAVE, 2007).

energy produced on-site or nearby". It also established that all new buildings shall be nZEB by 2020. In the UK, the policy target "zero carbon homes" point out the new homes have to be zero carbon by 2016. Likewise, Hong Kong has set a target for carbon emission reductions in buildings by 50%-60% by 2020 when compared to 2005 (FERRARA et al., 2014; SARTORI; NAPOLITANO; VOSS, 2012; SUN; HUANG; HUANG, 2015).

Several studies have focused on on-site generation and energy-saving technologies in buildings (DENG; WANG; DAI, 2014; KYLILI; FOKAIDES, 2015), aiming to reduce the dependence of the building sector on the external energy supply and recognizing the importance of the global challenges related to climate change and resources shortages. These options are seen as an integrated solution to address targets related to fuel saving, energy security (reliability, accessibility and affordability) and environmental protection (mainly CO_2 emission and air pollution) in the buildings sector (DENG; WANG; DAI, 2014). As pointed out by (GONZÁLEZ et al., 2015) the renewable on-site generation technologies will play an import role in the coming years towards to the energy transition.

To accomplish nZEB standards a significant effort to implement renewable energy technologies is required. Several renewable and non-renewable technologies can supply energy to buildings (OGUNJUYIGBE; AYODELE; AKINOLA, 2016). However, wind and PV systems can become the most common choice given their availability in almost every region of the World. Furthermore, these technologies involve zero greenhouse gas emissions and fossil fuel consumption (AHADI; KANG; LEE, 2016). Extra advantages of these technologies are the simplicity of their design and the low maintenance requirements (AHADI; KANG; LEE, 2016; BIANCHI et al., 2014). There are, however, challenges regarding the intermittency and unpredictability of these renewable resources (OGUNJUYIGBE; AYODELE; AKINOLA, 2016). The output from these technologies does not necessarily meet the load demand. Hence, on stand-alone solar PV and wind systems, energy storage is desirable to ensure a continuous power flow to attend the demand and minimize the interaction with the grid when possible (BIANCHI et al., 2014). The battery also allows for a stable and constant output by stabilizing the solar PV systems and compensating sudden drops in output due to solar radiation changes, for example. Energy storage has several advantages, namely: providing time fluctuating energy demand, enhancing system reliability, dealing with peak energy demand, seasonal variations in renewable sources and smooth load oscillations (AHADI; KANG; LEE, 2016; BERRADA; LOUDIYI, 2016). In the case of a self-sufficient building, the implementation of a battery is compulsory to act as a back-up for the system.

This study aims to contribute to the analysis of nZEB options, costs and technical challenges by developing an optimization model to evaluate the least-cost combination of solar PV, mini wind turbine and battery. This work provides a tool to assess energy policies, such as bi-hourly tariffs, feed-in tariffs schemes and buy down cost of technologies, for instance. This study also tests and applies the model to a case study of a building in Portugal. The optimization model runs an algorithm available with GAMS to obtain the optimal installed capacity of solar PV, mini wind turbine and battery and their operation on an hourly-basis, given restrictions associated with the capacity, conversion efficiency and available space and volume to install the on-site generation systems. Space and volume constraints have been marginally approached in the literature; however, they are important to consider since in a commercial building, for instance, the space for installing the technologies competes with the core-business of the building. The results from GAMS are summarized by an interface between GAMS and R package gdxxrw. Graphical outputs are also developed under the R software.

This paper is organized into 5 sections, in addition to this introduction. Next section reviews briefly the literature on optimization models for buildings. Then, Section 5.4 thoroughly presents the model. In Section 5.5, the case study is characterized, scenarios are projected, and their results are displayed. Finally, the main conclusions regarding the methodology proposed and the further improvements are presented as final remarks in section 5.6.

5.3 Literature review

Several techniques and different objective functions have been used in energy systems studies, such as: minimize the total cost of the system, minimize the cost of the operation of the system and minimize local or global atmospheric emissions. The techniques include genetic algorithm, mixed integer linear and non-linear programming, probabilistic approaches, iterative techniques, as well as stochastic mixed integer programming models (EVINS, 2013; LU; WANG; SHAN, 2015; MACHAIRAS; TSANGRASSOULIS; AXARLI, 2014). Several studies were made on simulation and optimization of on-site generation technologies in buildings. Some of them focused only on the electricity demand, while more comprehensive ones also included thermal energy demand. For the simulation-based optimization in the buildings sector, EnergyPlus, TRNSYS and DOE-2 models have been used in 82% of the studies (NGUYEN; REITER; RIGO, 2014). Nonetheless, these models did not focus on the optimization of on-site generation systems, but applied accounting and simulation tools to selected case studies (STADLER et al., 2014).

Lu et. al (2015) conducted a research on the recent studies concerning design optimization of nearly/net Zero Energy Buildings (nZEB). Findings showed that the

HOMER[37] tool is one of the most used models. However, Milan and Milan et. al (MILAN, 2014; MILAN; BOJESEN; NIELSEN, 2012) indicated that there is no available tool to obtain the optimal configuration of the on-site renewable supply in Zero Energy Buildings focusing on a single-family dwelling unit.

Some studies focus on isolated/off-grid communities/buildings and others consider the possibility of interaction with the grid (AHADI; KANG; LEE, 2016; MALHEIRO et al., 2015; OGUNJUYIGBE; AYODELE; AKINOLA, 2016). Moreover, some studies have one single-objective function (usually minimizing costs), while others, applied multi-objective functions.

For example, Ahadi et al (AHADI; KANG; LEE, 2016) developed a model to find the least-cost combination of PV/wind system and battery to reduce the dependence on diesel generators at an isolated community. Bianchi et al. and Ascione et. al (ASCIONE et al., 2016; BIANCHI et al., 2014) aimed to optimize the design of the mix of on-site renewable energy technologies in a residential building to attend the end-use demands by utilizing EnergyPlus and MATLAB. Stadler et. al (STADLER et al., 2014) developed mixed integer-linear models to evaluate retrofits in buildings.

The present work contributes to the existing literature by developing an open source optimization model which can be easily adapted to different case studies. Also, this model includes the space and the volume availability as constraints to install on-site generation and storage options in buildings. Also, a major contribution of this work is to encompass a more comprehensive modelling for battery, which builds on the analysis of (MALHEIRO et al., 2015).

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[37] HOMER (Hybrid Optimization Model for Electric Renewable) is a model for microgrid optimization focusing on optimal power system that meet the demand.

5.4 Methodology

This study tests and applies an integer linear model developed in GAMS, which runs with the solver CPLEX. In fact, other optimization solver for mixed-integer could be used for our numerical results, but benchmarking optimization solvers is out of this paper scope. The assessed on-site technologies are solar PV systems, mini-wind turbines and batteries. The model is applied to obtain the optimal capacities (size) and operation of the renewable on-site technologies aforementioned. The optimization is performed by considering the cost minimization subject to technology and physical constraints. The model runs on an hourly basis for an entire representative year.

5.4.1 Objective function

The objective function considers the total economic cost, including the capital expenditures of the on-site renewable technologies and the tariff for purchasing and selling energy back to the grid. The objective function (OF) is defined as follows:

$$OF = capPV * ccPV * CRF_{PV} + capW * ccW * CRF_{W} + ccB * capB * CRF_{B} - \sum_{h} fit_{tariff_h} * (ePV\_S_{h}e + eW\_S_{h}) + \sum_{h} e_{tariff_h} * eGRID_{h} \text{ , (5-1)}$$

where $CRF_i = \frac{\mathrm{j}*(1+\mathrm{j})^{\mathrm{ni}}}{(1+\mathrm{j})^{\mathrm{ni}}-1}$ is the capital recovery factor by technology, i represent each technology considered in the model, j is the discount rate (% p.a.), ni is the technology lifetime (months), $capPV$ is the required capacity of the PV module (kW), $capW$ is the required capacity of the mini wind turbine (kW) and $capB$ is the required capacity of the battery storage (kWh), $ccPV$ is the capital cost of the PV module (USD/kW), ccW is the capital cost of the mini wind turbine module (USD/kW), ccB is the capital cost of the battery storage (USD/kW), e_{tariff_h} is the tariff charged by the utility for electricity from the grid (USD/kWh), fit_{tariff_h} is the feed-in tariff (USD/kWh), ePV_S_h is the electricity surplus from the PV (kWh) and eW_S_h is the electricity surplus from the mini wind turbine. $capPV$, $capW$ and $capB$ correspond to the decision variables of the minimization problem.

The optimal sizing of solar PV, mini wind turbine and battery is obtained through minimizing the total system cost. Particularly, the main objective of the optimum design is to find out the amount of mini wind turbines, the square meters of solar PV and the battery capacity that minimize the annual cost taking into consideration operational restrictions, as well as rooftop availability and volume restrictions.

5.4.2 Technological modelling

5.4.2.1 PV system modelling

The capacity of the PV module, $capPV,$ is proportional to the installed area. In order to calculate the capacity of the PV module, the standard conditions are assumed, as shown in (AHADI; KANG; LEE, 2016; MILAN; BOJESEN; NIELSEN, 2012; OGUNJUYIGBE; AYODELE; AKINOLA, 2016):

$$capPV = aPV * \eta^{PV} * 1kW/m^2, \quad (5\text{-}2)$$

where aPV is the required area of PV array, η^{PV} is the PV array nominal efficiency and $1kW/m^2$ represents the standard irradiation condition. Moreover, the following constraint must to be satisfied:

$$\mathrm{aPV} \leq A^{roof}, \qquad (5\text{-}3)$$

where A^{roof} denotes the available facing roof space for installing solar PV. Weather conditions should be considered to account for the electricity supplied e_h^{PV} (output) by the PV module, so it is necessary to include the hourly global solar irradiance (G_h):

$$e_h^{PV} = aPV * \eta^{PV} * G_h \quad (5\text{-}4)$$

5.4.2.2 Micro wind turbine modelling

The capacity of the mini wind turbines $capW$ depends on the number of turbines installed and its rated power P_r. There is a constraint regarding space, which means the number of turbines installed $,nT,$ depends on the total linear meters available, aT, to install the base of the turbines (Equation 4-6). This study assumed that the base of the turbine is the same to the rated diameter, D, of the turbine (m). Thus, to quantify the number of mini wind turbines that can be installed in the rooftop, the denominator of the equation (4-7) assumed that the space between each mini wind turbine should equal half of the diameter of these turbines.

$$capW = nT * P_r \quad (5\text{-}5)$$

$$nT \leq \frac{aT}{1.5D} \quad (5\text{-}6)$$

$$aS = \frac{\pi * D^2}{4}, \quad (5\text{-}7)$$

where aS is the swept area for the mini wind turbine (m^2).

Power output and wind velocity relationship is formalized by Equation 5-8. How well a wind turbine performs is function of the wind speed. Cut-in (V_{ci}) speed and cut-off (V_{co}) speed are determined by the manufacturer to protect the turbine from damage. Cut-in speed is the point at which the turbine starts generating electricity. Cut-off speed denotes the speed up to which the turbine can work. Then, the output of the turbine (P_h^W) is represented as follows:

$$P_{m,h}^W = \left\{ \begin{array}{cc} 0, & V_h \leq V_{ci} \\ Prm * \frac{V_h - V_{ci}}{V_R - V_{ci}}, & V_{ci} < V_h \leq V_R \\ Prm, & V_R < V_h \leq V_{co} \\ 0, & V_h > V_{co} \end{array} \right\}, (5\text{-}8)$$

where Prm is the rated power of mini wind turbine per swept area (kW/m^2), V_R is the rated speed of mini wind turbine and V_h is the wind speed in the area studied. The total output of all mini wind turbines depends on the number of turbines installed (nT) and their efficiency[38] (η^w):

$$e_h^W = P_h^W * aS * \eta^w * nT \quad (5\text{-}9)$$

5.4.2.3 Battery for storage

The mode considers a set of batteries acting as a single battery (ASHOURI et al., 2013; MALHEIRO et al., 2015). However, some additional constraints are proposed to guarantee that: a) the energy flow is greater than zero when the binary variables that register the battery energy flow are equal to 1; b) the battery does not act as a generator and, c) the battery satisfies the available volume restriction.

The efficiency of charging and discharging modes, η_{BC} and η_{BD} (%), as well as the power equipment efficiency, η_{AD} and η_{AD} (%), in AC-DC and DC-AC conversions

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[38] Strictly speaking, the efficiency of the wind turbines varies with the tip-speed ratio. However, this study did consider this relationship, for the sake of simplicity.

are taken into account in the model. The battery state of charge (BL_h) is calculated as follows[39]:

$$BL_h = BL_{h-1} + eB\_in_h * (\eta_{BC} * \eta_{AD}) - \frac{eB\_out_h}{\eta_{BD} * \eta_{DA}}, \quad \text{(5-10)}$$

where eB_in_h is the power flow into the battery (kWh) and eB_out_h is the power flow out the battery. For each time period (h), the model keeps a minimum energy level of charge in the batteries, represented as SOC_{min} (%). The model must satisfy the following constraints regarding to the battery state of charge:

$$BL_h \geq SOC_{min} * capB \quad \text{(5-11)}$$

$$BL_h \leq capB \quad \text{(5-12)}$$

$$BL_{h=1} = capB \quad \text{(5-13)}$$

$$BL_{h=8720} = capB \quad \text{(5-14)}$$

The set of constraints that follows represent the maximum charge/discharge amount into the battery and the battery energy flow, F_{max} is the maximum charge/discharge rate (%) and κ_h and φ_h are binary variables that register the battery energy flow. κ_h register the charging battery mode on when it takes the value of 1 and φ_h register the discharging battery mode on when it takes the value of 1.

$$eB\_in_h * (\eta_{BC} * \eta_{AD}) + \frac{eB\_out_h}{\eta_{BD} * \eta_{DA}} \leq F_{max} * capB * \Delta h \quad \text{(5-15)}$$

$$eB\_in_h \leq capB * \kappa_h \quad \text{(5-16)}$$

$$eB\_out_h \leq capB * \varphi_h \quad \text{(5-17)}$$

$$\kappa_h + \varphi_h \leq 1 \quad \text{(5-18)}$$

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[39] The battery state of charge is affect by the self-discharge rate, but this was not considered by this study.

Equations 5-19 to 5-22 are necessary to guarantee the energy flow into the battery when the binary variables κ_h and φ_h are 1.

$$eB\_in_h - Mbig * \kappa_h \leq 0 \qquad \textit{(5-19)}$$

$$eB\_in_h + Mbig * (1 - \kappa_h) \geq \varepsilon \qquad \textit{(5-20)}$$

$$eB\_out_h - Mbig * \varphi_h \leq 0 \qquad \textit{(5-21)}$$

$$eB\_out_h + Mbig * (1 - \varphi_h) \geq \varepsilon, \quad \textit{(5-22)}$$

where ε represents the minimum amount of energy flowing into the battery when the binary variables take the value 1. Following the logic of space restriction, for installing the battery, is considered the volume availability for install the battery also. Equation 4-23 displays the volume of the battery installed, which is constrained by the volume availability represented in the Equation 5-24.

$$DB = capB * vbc \ \textit{(5-23)}$$

$$DB \leq TDAB, \quad \textit{(5-24)}$$

where vbc is the volume per kWh of the battery (m^3/kWh), DB is the volume of the battery installed and $TDAB$ (m^3) is the total volume available for installing the battery.

5.4.3 Balancing energy consumption

The energy balance is a demand constraint to the optimization problem given by the following equation:

$$e_h^{demand} + eB\_in_h = ePV\_edemand_h + eW\_edemand_h + eB\_out_h + eGRID_h, \textit{(5-25)}$$

where e_h^{demand} is the electricity consumption rate of building (kWh), $ePV\_edemand_h$ and $eW\_edemand_h$ correspond to the energy produced by PV systems and mini wind turbines to attend the demand (electricity final demand and electricity for charging the battery), respectively. $eGRID_h$ corresponds to the electricity purchased from the grid. The energy surplus from on-site renewable technologies is evaluated under a similar balance as follows:

$$ePV_h = ePV\_edemand_h + ePV\_S_h \quad (5\text{-}26)$$

$$eW_h = eW\_edemand_h + eW\_S_h, \ (5\text{-}27)$$

where ePV_S_h and eW_S_h represent the surplus generation from solar PV and mini-wind, respectively, which can be exported to the grid.

5.5 Case Study: Lisbon Municipality building

The case study to demonstrate the operation of the proposed algorithm is the Lisbon Municipality (CML) building (Figure 5-1), which holds an energy performance certificate40 B-. The building area is 23,941 m2. It is composed by six blocks. The block A has eleven floors, the block B, C and D have ten floors each. Block E has fifteen floors and block F has five floors. There are four floors of underground parking.

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[40] There is a performance certificate applied to buildings in Portugal. The certificate is sorted from A^+ to F, where, A^+ represents the highest efficiency, while F represents the lowest efficiency of the building. The classification is calculated by comparing the building performance in the current conditions with the building performance compulsory for the buildings (Case reference). The building of the CML obtained a performance certificate B^-, which means its efficiency is 85% compared with the case reference.

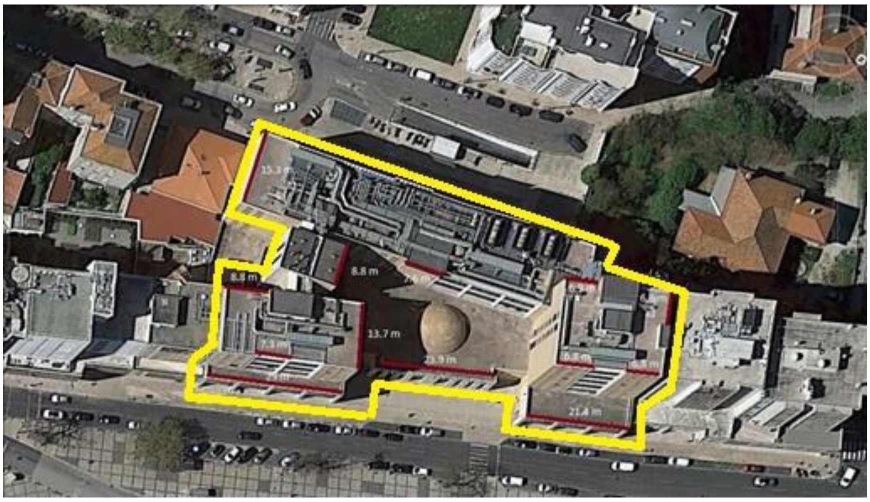

Figure 5-1. Lisbon Municipality (CML)

5.5.1 Characterization of CML building

5.5.1.1 Electric power consumption

CML provided us the instantaneous power measured every fifteen minutes to this study. This data was adjusted to an hourly basis (Figure 5-2) database. To calculate the energy consumption by hour, the area under the 15 minutes curve was calculated. This area can be readily determined as the area of the triangle plus the area of a square. Then, the energy demand for quarter of an hour is calculated as follows:

$$e_t^{demand} = min[P_t, P_{t-1}] * 0.25 + \left\{\frac{max[P_t, P_{t-1}] - min[P_t, P_{t-1}]}{2}\right\} * 0.25, \quad (5\text{-}28)$$

where P_t is instantaneous power in the quarter t, e_t^{demand} is the demand for each quarter of an hour. Demand considered correspond to the block A, B, C, E and elevator (Figure 5-2). Total annual demand is 1.16 GWh.

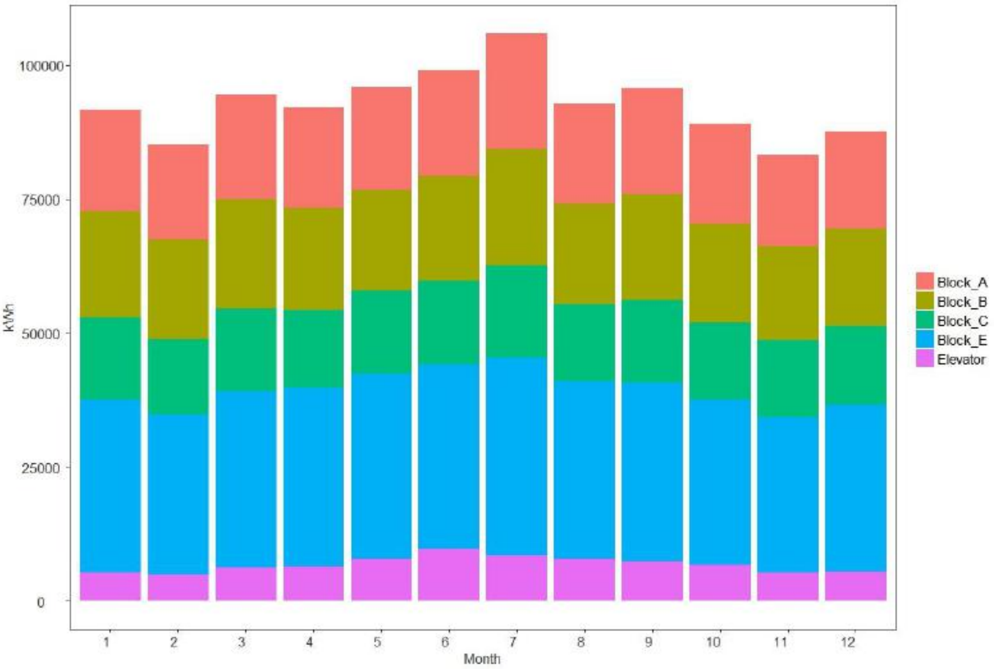

Figure 5-2. Electric power consumption by block

5.5.1.2 Economic parameters

Utility tariffs and feed-in tariffs are used to calculate the cost of buying electricity from the grid and to sell it back, in the case of a surplus. The utility tariff was set as 141.30 USD/MWh[41], which corresponds to the average tariff in 2015 for the band – ID[42], including non-recoverable taxes and levies (DIREÇÃO GERAL DE ENERGIA E GEOLOGIA, 2016). For the existing installations the feed-in tariff was set at 394.05

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[41] In 2015, US$1.00=1.11€.

[42] Band ID includes buildings with annual electricity consumption hovering between 2,000 and 20,000 MWh.

USD/MWh which corresponded to PV microgeneration[43] in Portugal (INOVAÇÃO, 2007). However, this feed-in tariff and overall support schemes for microgeneration changed after Decree-law 153/2014 which entered into force in January 2015 and established the legal regime for the production of electricity for self-consumption. For these self-consumption units, only the surplus can be sold to the grid and the tariff is determined according to the average tariffs of the Iberian electricity market which can easily lead to values lower than 59 USD/MWh.

The discount rate used was 4.8% p.y., according to the Loan for investment in renewable energy of Montepio -TAEG (Crédito Energias Renováveis de Montepio). This bank finances the acquisition and installation of renewable energies equipment (MONTEPIO, 2017). The capital cost of the technologies and their lifespans are presented in Table 5-1.

Table 5-1. Initial capital cost and life-time of the technologies

Technology	Lifespan (years)	CAPEX
Solar PV	25	3,210 USD/kW
Mini-wind turbine	15	1,600 USD/kW
Battery storage	10	500 USD/kWh

5.5.1.3 Climate Data

Solar resource (global horizontal irradiance) and wind speed were taken from the database provided by Energy Plus (ENERGYPLUS, 2017). Weather data are arranged by the regional and meteorological organization according to (ENERGYPLUS, 2017). In the

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[43] The regulation has recently changed, according to Decree-Law 153/2014, which establishes that the output refers the self-consumption and only the surplus power can be sold to the grid at a tariff defined each month. This feed-in tariff was valid for systems with installed capacity between 5 kW and 150 kW.

case of Portugal the data was provided to Energy Plus database by the INETI[44] (INETI, 2005) . We consider the data correspond to Lisbon {N 38° 43'} {W 9° 8'} {GMT +0.0 Hours}, elevation 71 m above sea level, Standard Pressure at Elevation -- 100475Pa.

Figure 5-3 displays the average hourly global horizontal irradiation by month for Lisbon, Portugal. The peak solar irradiation is over the summer (June, July and August). The highest solar horizontal global irradiation was reported on July between 11:00 to 12:00 m (870 Wh/m^2).

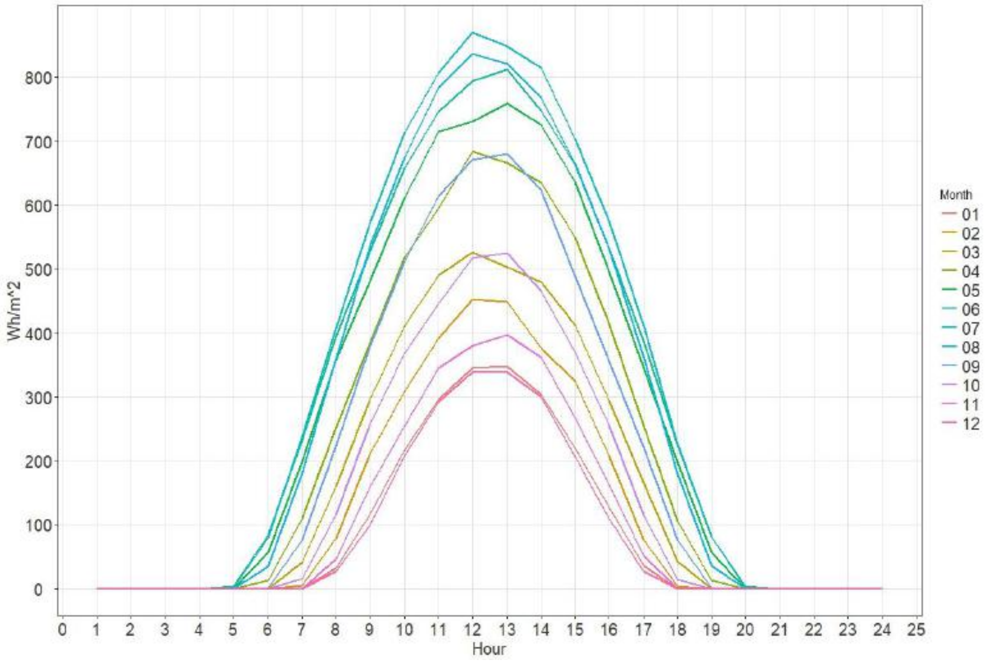

Figure 5-3. Average hourly global irradiation

Source: Own elaboration based on (ENERGYPLUS, 2017)

Wind speed is displayed in Figure 5-4. The higher wind speeds on average are also reported over the summer. However, the highest observation was 11.4m/s on November 19 at 3:00 p.m.

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[44] Currently, INETI is in extinction. Its functions has been taken by Laboratório Nacional de Energia e Geologia (LNEG).

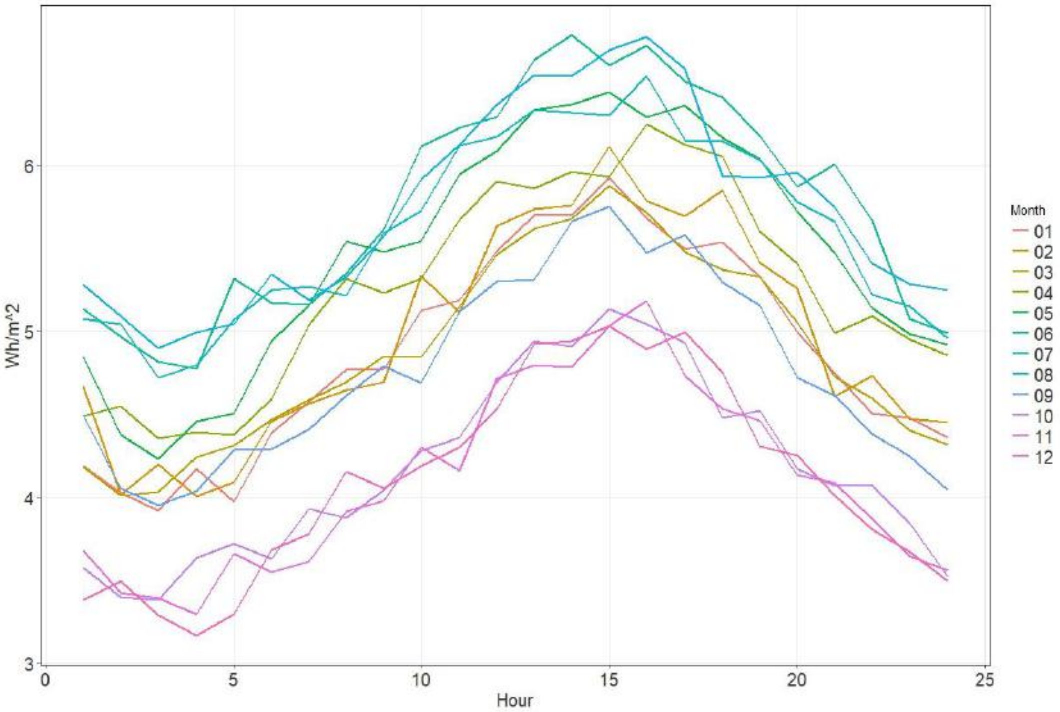

Figure 5-4. Average hourly wind speed

Source: Own elaboration based on (WUNDERGROUND, 2017)

5.5.2 Technical parameters of the assessed on-site technologies

For obtaining the optimal-configuration of the proposed on-site renewable technologies, the basic parameters, including energy efficiencies, available roof space for solar PV and mini wind turbine, available volume of battery and some characteristics inherent for each technology need to be defined the Table 5-2.

Table 5-2. Basic technological parameters

Solar PV	
Efficiency	12%
Available roof space (m^2)	1350
Mini-wind turbine	
Model number	Angel-300
Turbine efficiency	50%
Rated power (W)	300
Rotor diameter (m)	1.44
Rated Voltage (V)	12/24
Cut-in speed of mini wind turbine (m/s)	2
Rated wind speed (m/s)	9
Cut-out speed of mini wind turbine (m/s)	35
Available linear meters to installing mini wind turbine	163
Battery storage	
Maximum charge or discharge rate	10%
Minimum state of the battery	10%
Efficiency out of the battery	100%
Efficiency flow into the battery	80%
Power equipment efficiency AD-DC	93.40%
Power equipment efficiency DC-AC	93.40%
Battery density (m3/kWh)	0.0099
Available density for installing battery (m^3)	2992

Source: (AHADI; KANG; LEE, 2016; EC, 2011; MALHEIRO et al., 2015; VIVA POWER ENERGY CONSULTING, 2016)

To establish the space constraints of the optimization problem, the available roof space was taken directly from an interview with CML and the available linear meters to install mini wind turbines were estimated considering the rooftop edges available (see red lines in Figure 5-1). The available volume for installing battery was estimated according to the already existing available space in the warehouse of CML (873 m^2) (VIVA POWER ENERGY CONSULTING, 2016) times the minimum ceiling height established by (EC, 2011). The battery density was calculated following the specifications of the Tesla battery model (L x W x D: 44" x 29" x 5.5"(1150mm x 755mm x 155mm) and the usable capacity (13.5 kWh).

5.5.3 Simulated scenarios

We propose six scenarios to evaluate the policy options to transform CML into a nZEB. These scenarios are defined according to parameters such as grid tariffs, feed-in tariffs and cost of the technologies:

- Scenario 1: This is the base scenario. It looks for the optimal configuration with the current cost of the technologies and tariff for purchasing electricity from the grid. Feed-in tariff in force is also considered. This scenario corresponds to the current real conditions in Lisbon.
- Scenario 2: In this scenario the optimization considers the feed-in tariff established before the Decree-Law 153/2014. The costs of the technologies were kept unaltered.
- Scenario 3 and 4: These scenarios set up a sensitivity analysis of the cost of the technologies in light of market expectations associated with technological learning rates. We assume the cost of the technologies would decrease 50% and 75%, respectively. The tariffs considered in the scenario 1 are kept unchanged.
- Scenario 5 and 6: These scenarios assesses a bi-hourly tariff policy for purchasing electricity from the grid. Out of peak and peak periods are considered. The first regime is set between 6 pm to 7 am, and the second in the remaining hours. The tariffs in peak periods are two times higher the tariffs of out of peak periods, following the bi-hourly composition in the residential sector. The costs of the technologies follow the assumptions described for the scenarios 3 and 4. Feed-in tariff in force is also considered.

Table 5-3. Parameters considered in the scenarios run

CAPEX Technologies	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Solar PV	USD/kW	3210	3210	1650	963	1650	963
Mini-wind turbine	USD/kW	7700	7700	3850	2310	3850	2310

Battery	USD/kWh	500	500	250	150	250	150
Tariff for purchasing electricity	USD/kWh	0.1413	0.1413	0.1413	0.1413	8 am – 5 pm: 0.2826 6 pm – 7 am: 0.1413	8 am – 5 pm: 0.2826 6 pm – 7 am: 0.1413
Feed-in tariff	USD/kWh	0.059	0.3940	0.059	0.059	0.059	0.059

5.5.4 Model implementation and results

The mixed integer problem (MIP) was solved by using the CPLEX solver for the GAMS software platform. The numerical results were obtained in a Microsoft Windows operating system using 3.6GHz Intel Core i7-4790 with 16 GB of RAM memory. The model was run in hourly-basis for an entire year. We have used the software R in order to read the result from the GAMS output file gdx. Graphical outputs have been created by using the same tool.

Table 5-4 displays the optimal configuration for meeting the demand defined in the section 5.5.1.1 for the six scenarios tested in this study. Figure 5-5 to Figure 5-9 display the operation of the technologies. Operation of the battery is also presented when the result considers it into the optimal configuration.

Table 5-4. Summarized annual results

			Scenarios					
		Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Installed Capacities	PV	kW	0	270	270	270	270	270
	Wind	kW	0	15	0	15	15	15
	Battery	kWh	0	0	0	0	0	808
Electricity production/imported/exported and battery energy flow	ePV	kWh	0	445,034	445,034	445,034	445,034	445,034
	eW	kWh	0	32,127	0	32,127	32,127	32,127
	eB_out	kWh	0	0	0	0	0	203,670
	eB_in	kWh	0	0	0	0	0	291,809
	eGRID	kWh	1,135,865	1,135,865	765,206	737,498	737,498	763,083
	ePV_edemand	kWh	0	0	370,659	369,244	369,244	429,651
	eW_edemand	kWh	0	0	0	29,122	29,122	31,269
	ePV_S	kWh		445,033	74,374	75,789	75,789	15,383
	eW_S	kWh	0	3227	0	3,004	3,0	857
Cost (Annuity)		USD	160,497	160,497	43,741	134,714	120,933	198,716

For the sake of simplicity, we have plotted 182 hours, which correspond to an entire week. We have arbitrarily chosen to plot the period between the hour 48 to 216 to represent weekday and weekend. Moreover, results are available for the entire year.

The optimization performed for the scenario 1 shows that under the current tariffs for purchasing electricity from the grid and the feed-in tariffs in force, the minimum cost to meet the demand is achieved by purchasing all the electricity from the grid. Results do not include any on-site renewable technology or storage. The total cost of this scenario is 160,497 USD, which correspond to the amount paid for 1.13 GWh from the grid.

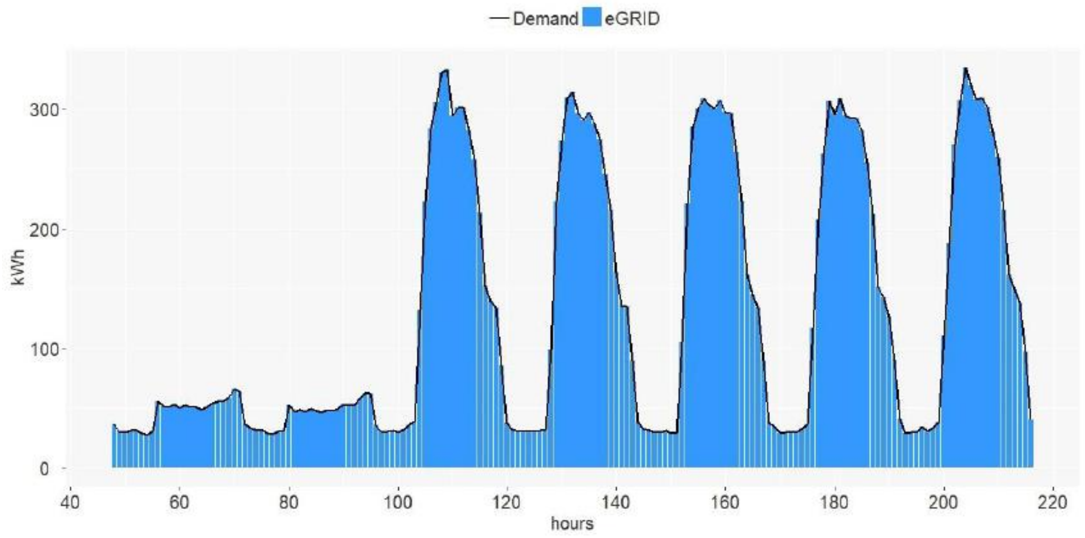

Figure 5-5. Operation over 1 week – Scenario 1 and 2

The second scenario is a hypothetical scenario that considered the feed-in tariff adopted before the Decree-Law 153/2014. With the implementation of this new legal framework the tariffs decreased by 72%. The results indicate that if the analysis was done under the past conditions, the optimal solution would be to install all the potential of PV solar and mini wind turbines in order to export the energy produced on-site to the grid, and the demand would be met by purchasing electricity from the grid. The total cost of this scenario is 42,060 USD, cost which corresponds to 26% of the cost obtained for scenario 1. These results corroborate the issues raised by the Decree-Law 153/2014, which argued that new conditions should be defined to promote self-consumption.

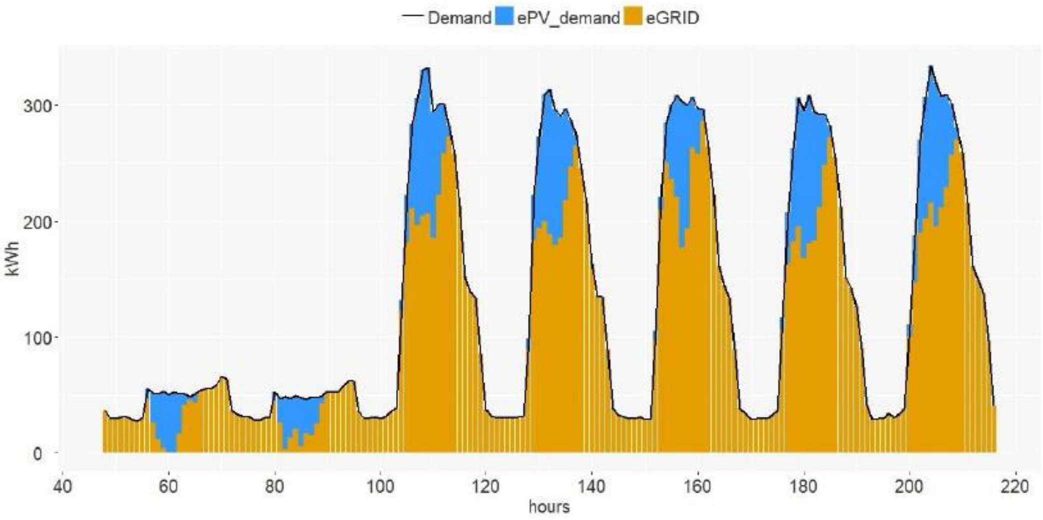

Figure 5-6. Operation over 1 week – Scenario 3

Scenario 3 considers the cost of the technologies decreasing 50% comparing to the base scenario. The cost for providing electricity would be 134,714 USD yearly. Solar PV would be part of the optimal configuration. Total output from solar PV would be 445 MWh. The demand is met 33% by the solar PV and 67% by the grid (Figure 5-6). In Scenario 4, we consider an even sharper fall in the cost of the technologies. Mini wind turbines play a role under this scenario. The optimal configuration cost decrease 11% comparatively with Scenario 3. Electricity demand is met by the grid, solar PV and mini wind turbines in 64.93%, 32.51% and 2.56% respectively (Figure 5-7). The optimal solution also considers selling electricity to the grid, in both cases.

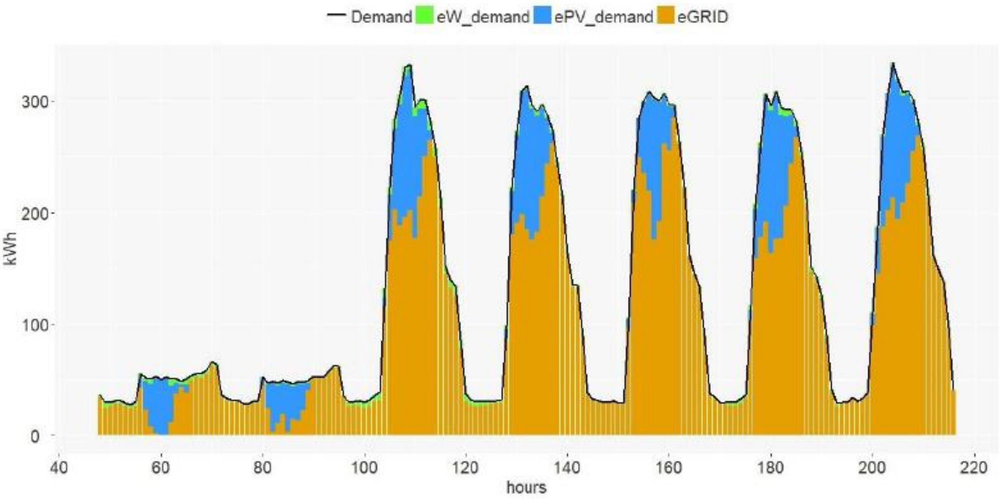

Figure 5-7. Operation over 1 week – Scenario 4

Scenario 5 and Scenario 6 aim to assess a bi-hourly tariff policy, following the residential sector scheme and taking into account the cost of the technologies proposed in Scenarios 3 and 4, respectively. The feed-in tariff in force is also considered. The cost in Scenario 5 for providing electricity would be 198,716 USD yearly, which represents an over cost of 40% when compared to the Scenario 4. This happens due to the higher tariff over the peak hours. Furthermore, the technological configuration is identical to the one found in Scenario 4. In Scenario 6, the battery plays a role. Figure 5-8 and Figure 5-9 outline the results of this scenario. The annual cost of the optimal arrangement reached USD 178,627 USD. This cost is even higher than those of Scenarios 3 and 4, due to the higher tariffs over the peak hours. Figure 5-9 displays the operation of the battery and its state of the charge. Given the possibility of charging the battery with energy from the grid (Equation 4-25), the results show that it would be better charging the battery from the grid during the out of peak hours, when the tariff is cheaper, in order to meet the demand with the energy stored over the peak hours. Results in Scenario 6 show that only under stress conditions, both sharper fall in the cost of the technologies and bi-hourly tariff, the battery would play a role in the optimal technological configuration.

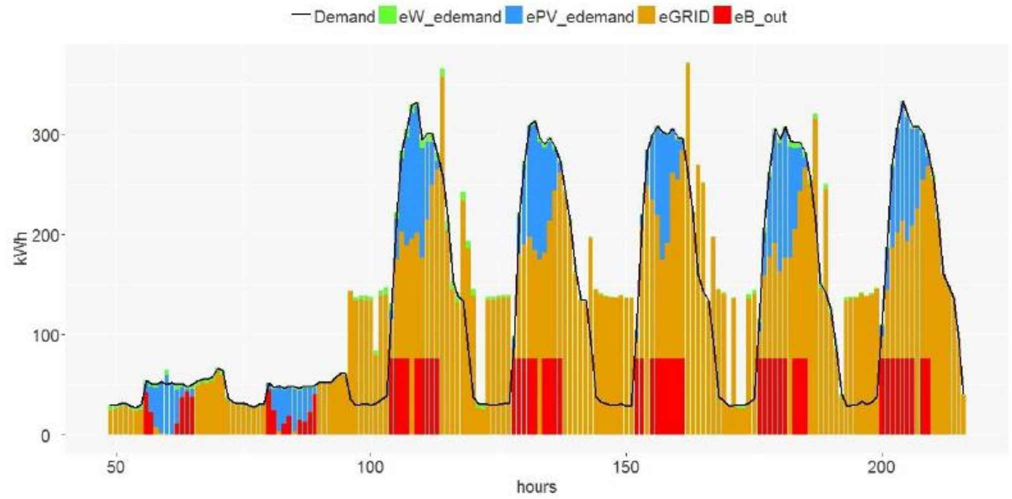

Figure 5-8. Operation over 1 week – Scenario 6

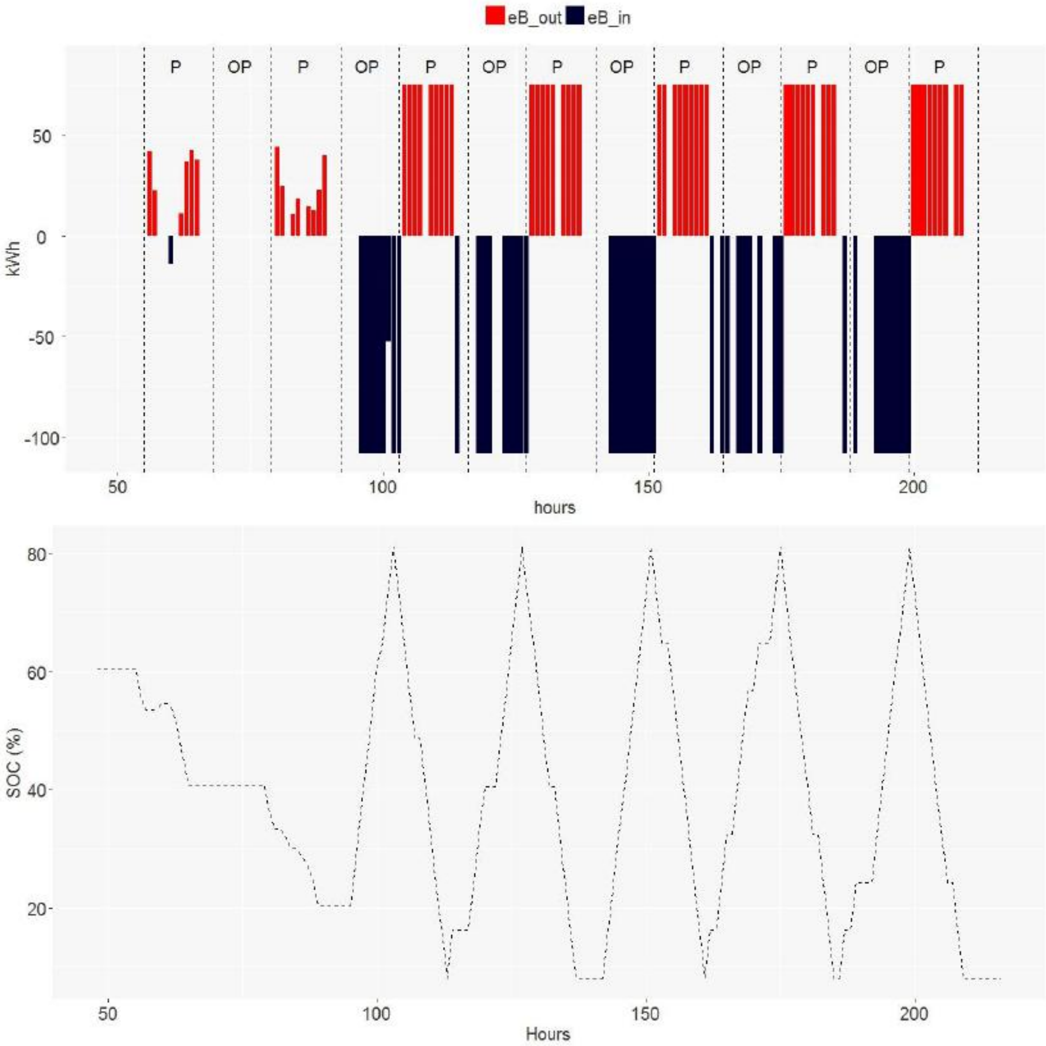

Figure 5-9. Battery operation and state of charge of the battery (SOC) over 1 week – Scenario 6

*** In the battery operation figure is added P (Peak hours) and OP (Out of peak hours)*

In the light of the scenarios run, incentive policies to nZEB should focus on feed-in tariffs, PV, wind and battery price reductions (fiscal incentives, local content, capacity building) and low grid tariff.

5.6 Final Remarks

This study developed, tested and applied an open source methodological procedure using a linear modelling formulation for optimizing the expansion and operation of a system composed by solar PV, mini-wind turbines and battery in buildings. Interactions with the grid were also considered in the model. The algorithm was based on a single-objective function to minimize the annual cost of the system, given technical, economical and physical (space/density) constrains. The results show that the proposed model, responded very well for different tests in the parameters.

The model was then applied for the case of a real building (Lisbon Municipality). Findings show that the developed model is suitable to evaluate options to implement zero or near zero energy buildings (nZEB), based on renewable technologies. However, for nZEB become competitive, especial conditions should be met, especially in terms of the price differentials between the tariffs to purchase electricity from the grid and sell it back to the grid. Worldwide experience has shown the feed in tariffs mechanism provides long time price stability to self-producers and it also create an interest to the investors. However, a study must be done to assign the right feed in tariff specially when the residential sector is considered given the income level distribution. High upfront cost could hinder the deployment of the technology. To tackle this issue, innovative model businesses might be considered into the equation. For example, leasing, public private partnership approach (PPA) and crowdfunding can be explored by the policy-makers.

For the case of Lisbon Municipality, the base case scenario indicates that under the cost minimization approach there is no on-site electricity production and the building demand is met by the grid. Moreover, the price differential between the tariffs to purchase electricity from the grid and sell it back to the grid was explored given the trend to reduce the financial incentives for microgeneration, as highlighted in Decree-Law 153/2014 for Portugal, and the emerging of new business models based on self-consumption. Then, the results show the model are suitable to test feed-in tariffs policy, shocks in technologies cost and bi-hourly tariffs for buying electricity from the grid.

Finally, further studies could improve the developed model to introduce new options of on-site renewable technologies under the nZEB framework. Particularly, thermal energy storage (including ice banks) and cooling and heat generation could be added to the model. In this case, the objective would become to meet the useful energy (cooling, heat, lightening and driving demands) with on-site technologies for electricity and heat generation, and thermal and electricity storage.

5.7 Appendix: Model validation and verification

Whatever the solution technique being used, it is worth testing if the model provides a good representation of different conditions. Naturally, what is a suitable model is subjective, as the model always simplifies reality. However, some tests could be made to assess if the developed model can properly answer the problem for which it was developed.

Therefore, before presenting the case study, some tests are proposed and applied to see if the model representing a virtual building responds suitably to changes in the utility company tariff, feed-in tariff and market prices of the considered on-site technologies. It is worth to highlight the data used for the following tests are solely illustrative of possible conditions – i.e., they are used to test extreme values to validate the expected model response under stressed conditions. The tests and their results are summarized in Table 5-5.

Table 5-5. Model tests virtual data

Sensitivity test	**Result**	**Test data**
*Utility company tariffs (UT) *Feed-in tariff (FIT) *Market price of the technologies (MP)	The cost-optimal configuration does not consider any on-site generation technology. The demand is attended with energy from the grid.	UT = 0.087 USD/MWh FIT = 0.379 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (5 USD/kWh)
*Higher utility tariffs (UT) *Feed-in tariff (FIT) *Market price of the technologies (MP)	The cost-optimal configuration installs PV, mini-wind turbine and battery. The demand is attended by production from on-site renewable technologies. The surplus is for charging the battery or exported to the grid.	UT = 1 USD/MWh FIT = 0.379 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (5 USD/kWh)
*Very higher utility tariffs (UT) *Feed-in tariff (FIT) *Market price of the technologies (MP)	The cost-optimal configuration installs PV, mini-wind turbine and battery. The demand is attended by production from on-site renewable technologies. The surplus is for charging the battery. There is not any surplus to selling to the grid.	UT = 100 USD/MWh FIT = 0.379 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (5 USD/kWh)
*Utility company tariffs (UT) *Feed-in tariff higher than utility tariffs *Market price of the technologies (MP)	The cost-optimal configuration installs PV and mini-wind turbine. The energy surplus is exported to the grid.	UT = 0.087 USD/MWh FIT = 100 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (5 USD/kWh)
*Higher utility company tariffs during the peak of the demand (UT) *Feed-in tariff (FIT) *Market price of the technologies (MP)	The cost-optimal configuration installs PV, mini-wind turbine and battery. The demand is attended with the energy from the battery during the higher tariffs and the production is exported. During the off-peak period, the production is exported and the demand is attended by the grid.	UT = 100 USD/MWh during the peak demand, for the other hours it was considered 0. FIT = 0.379 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (5 USD/kWh)

Sensitivity test	Result	Test data
*Higher utility company tariffs during the peak of the demand (UT) *Feed-in tariff (FIT) *Market price of the technologies PV and mini wind turbine. Battery with a less capital expenditure (MP)	The cost-optimal configuration installs PV, mini-wind turbine and battery. The demand is attended by the energy from the battery during the higher tariffs and the production is exported. During the off-peak period, the production is exported and the grid attends the demand and charge the battery.	UT = 100 USD/MWh during the peak demand, for the other hours it was considered 0. FIT = 0.379 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (0 USD/kWh)
*Higher utility company tariffs during the peak of the demand (UT) *Feed-in tariff (FIT) *Market price of the technologies PV and mini wind turbine. Battery with a less capital expenditure.	The cost-optimal configuration does not install PV and mini-wind turbine. Demand is attended by the battery during the peak and with the grid during the off-peak.	UT = 100 USD/MWh during the peak demand. 0.087 USD/MWh during the off-peak. FIT = 0 USD/MWh MP = Solar PV (3.2 USD/kW), Mini-wind turbine (1.6 USD/kW), Battery (0 USD/kWh)

The results of the tests followed the expected pattern and demonstrated that the model was able to respond to the proposed shocks. As the objective function of the problem involves the minimization of the total cost for energy consumption, the result of the tests displays the best technology configuration given the relative prices between the on-site generation technologies and the grid. For some tests, there is no appropriate level of installed on-site capacity, as supplying entirely the demand with the grid can be more cost effective.

6 CONCLUSIONS

The potential for reducing final energy consumption and CO_2 emissions in the buildings sector was widely discussed over the 2015 United Nations Climate Change Conference, COP21, hold in Paris. This international climate negotiation was a framework for the buildings sector.

The buildings sector is characterized by its heterogeneity. For this reason, this Thesis proposed diverse methodologies for assessing the potential of nearly Zero Energy Buildings (nZEB). The methodologies include simulation and optimization methods, which have been applied to case studies in middle-upper income countries, such as Brazil and Colombia, in the residential sector; and in high-income country, Portugal, in a public building.

The four essays presented in this thesis have carefully investigated the key aspects regarding how the building sector might support actions to tackle the climate change through the implementation of energy-efficiency measures and boosting the on-site renewable technologies coupled into a building. The essays proposed methodologies for assessing the technical and economic feasibility of nearly Zero Energy Buildings, sustainable buildings or high-performance buildings to contribute to reducing energy consumption and its associated CO_2 emissions. Emblematic case studies in developing countries were addressed. Findings provide useful insights regarding the poor deployment of these buildings in developing economies, mainly, and allow to propose policies for encouraging the construction of these buildings.

In the first paper, a Life Cycle Carbon Emission Assessment and cost analysis was made to compare two constructive systems used in Brazil used in social housing in Brazil. Findings show that the short and long-term goals might be conflicting. The higher deployment of social houses could conflict with the reduction of GHG emissions when the constructive system is not properly chosen. This line of research provides suitable insights to designers to create a comprehensive roadmap for social housing in developing countries.

In the second essay, findings show that there is a potential for reducing energy consumption and CO_2 emissions by implementing energy efficiency measures as well as disseminating solar PV in Brazil. Around 40% of the energy efficiency measures display negative marginal abatement costs, meaning that the low carbon option is cheaper than the reference or business-as-usual option. The remaining 60% of the potential is attributed to measures whose cost are extremely high. The measures with the highest potential are those that directly replace fossil fuels (e.g. natural gas and GLP). Despite the potential, barriers to the low carbon scenario have been identified in the Brazilian residential sector.

The third essay assesed the potential for solar PV generation in the Colombian residential sector. By splitting the assessment into urban administrative and income levels, findings reveal that there is a large technical and economic potential for solar PV generation in the Colombian residential sector. Despite the large potential, the deployment of this technology is still very limited due barriers identified.

Solar PV potential was assessed in the second and third essays. The case studies conducted were Brazil and Colombia. These countries are middle-upper income countries; however, the poor deployment of solar PV in the residential sector is consequence of the high upfront cost and high discount rate, mainly in the low-income groups of the population. In the residential sector investments must compete with living expenses, for instance.

In the fourth essay, an optimization model for minimizing the total economic cost of on-site renewable technologies such as solar PV, mini wind turbines and battery is proposed. The interaction with the grid is also measured. Results show that under certain conditions the optimal configuration would include these technologies.

The above-mentioned three essays display consonant results by approaching the issue using three different methodologies, which include simulation and optimization methods. There are several barriers to the deployment of energy efficiency measures and on-site renewable technologies in the building sector, which must be overcome.

The barriers acknowledged along these essays are: a) high upfront cost; b) high discount rate in the residential segment; c) lack of financing mechanism; d) lack of awareness; e) cultural and informational issues; and, e) capacity building. These barriers reduce the attractiveness of the abatement measures, even when the abatement cost is negative as observed in the second essay.

It is worth to say the discount rate considered along the essays are divergent for any study case because depends on the country and the sector which would undertake the investment. For instance, in the first and second papers was considered Brazil However, in the paper where two constructive systems are compared, the discount rate is lower (8%) than in the paper where energy-efficiency measures are assessed (23.8%). The reason of that is the investment in the first case, in spite is for social housing, would be by the government. In the second case, the families would make the investment. For the budget constrain, they would likely have to go to the financial system. In the Colombian study case, the discount rate corresponds to the reported by the government for such investments. In the fifth paper, Portugal is the case study. In this work, the discount rate adopted is 4.8%. The reasons are mainly two: discount rate is less in high-income country compared with middle-income countries and the public sector would make the investment for Lisbon Municipality case study.

To surpass the barriers some common strategies have been identified, including an innovative business model and financial mechanism. The strategies gain relevance when the analysis includes the income distribution.

A policy based on the following strategies could be implemented in developing countries:

- Feed-in tariffs for the deployment of on-site renewable technologies: This scheme provides long-term stability to self-producers by creating a fixed remuneration over a period. Nevertheless, an in-depth study is required to define the value attributed to the *feed-in tariff* since all the users must pay for the scheme. Therefore, low-income level groups are can be overcharged if the scheme is not well designed.
- Innovative business model: To tackle the high upfront cost, mechanisms such as leasing, public private partnership approach (PPA) and crowdfunding might be explored by policy-makers in developing countries. Recently, disruptive technologies, as blockchain, it is worth being explored. This technology assists in the energy trade between prosumers[45] in a peer-to-peer network, reducing transaction costs (GROSJEAN, 2018; IRENA, 2017; KESHAV, 2018; MIT, 2017).
- Informational strategy: An effective communication process is required to make the consumers aware of the gains from energy efficiency and on-site renewable technologies. When a labeling policy is already in place, it must be

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[45] A prosumer is both a power consumer and a producer.

updated to make sure the efficiency categories gradually respond to better energy efficiency patterns.

- Training programs: On-site renewable technologies dissemination entails highly qualified technicians to install and to strengthen post-purchase relationship.
- Tax incentives: This policy would encourage the industrial domestic participation and “local content” in the manufacturing of more efficient appliances and equipment. This policy should be carefully analyzed since the advantages would be largely for the industry. The initial impact in the buildings sector could get the technology more expensive.

These fourth essays approach some issues regarding the building sector. The essays intend to contribute both methodologically and with the case studies to the whole understanding of the building sector and the potential impact in tackling the climate change through the energy consumption reduction. In this sense, energy efficiency measures, suitable construction systems, on-site renewable and storage technologies that would contribute to face the growing energy demand from the buildings sector have been identified.

Nevertheless, many issues are still unresolved due the peculiarities of the sector. Hence, the methodologies proposed, and the findings reported introduce interesting and new research lines, which can be explored in futures studies, for example:

1) Since most of the devices used in the buildings sector work in idle power mode, the analysis of energy-efficiency measures could consider measures such as unplug appliances due the stand by losses and energy-efficiency improvements in those devices.

2) The optimization model proposed in the fifth chapter was tested in a public building; however, it can be applied to the residential sector as well. Several studies can be derived, for instance: a) Understanding the role of technologies in reducing and controlling the peak electricity demand in the building sector; b) The impact of energy policies as bi-hourly tariffs, feed-in tariffs and different discount rates (region, income level) could be assessed; c) Analyzing the role of on-site renewable technologies in reducing grid consumption and GHG emissions, considering the reduction of the investment cost over the time.
3) The optimization model presented could be improved by including new options of on-site renewable technologies and thermal energy storage such as: solar cooling, solar thermal collector, geothermal heating and cooling, ice bank and others.
4) The optimization model could be more comprehensive including as decision variables the energy efficiency measures and the improvements in the envelope to calculate the most cost-effective option.
5) Comparative studies between the residential and commercial segments could be conducted by using the methodologies proposed in this thesis.
6) The feasibility of on-site renewable technologies depends on the relation between the levelized cost of the energy and the tariffs. High tariffs would make these technologies feasible. However, the rising on-site generation would lead to a fall in the demand from the grid. Then, the tariffs could fall also – because of a fall in the generation component of the tariff –, which would make these technologies less attractive. Thus, this paradox should be deeply studied.
7) The LCCA methodology could be useful to conduct a cradle-to-grave analysis of the on-site renewable technologies considered in the buildings sector.
8) To explore linkages between NDCs commitments, SDGs and the building sector.

9) The most recently line of research has included the buildings in a more comprehensive analysis coined as Climate Change and Cities, which might also be explored in future studies.

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