FEDERAL UNIVERSITY OF PARAIBA
ALTERNATIVE AND RENEWABLE ENERGIES CENTRE
GRADUATION PROGRAM IN RENEWABLE ENERGIES

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FEASIBILITY OF SOLAR PHOTOVOLTAIC AND WIND POWER DISTRIBUTED GENERATION WITH BATTERY ENERGY STORAGE SYSTEMS IN LIGHT OF REGULATORY FRAMEWORK AND ECONOMIC INCENTIVES

JOÃO PESSOA – PB
2021

PPGER – ACADEMIC MASTER N° 78

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Master dissertation presented to the Federal University of Paraíba, as part of the requirements of the Post-Graduate Program in Renewable Energies at the Centre for Alternative and Renewable Energies, concentration area in renewable energies, to obtain the Master Degree.

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JOÃO PESSOA – PB
2021

Catalogação na publicação
Seção de Catalogação e Classificação

D754f Doile, Gabriel Nasser Doyle de.
Feasibility of solar photovoltaic and wind-power distributed generation with battery energy storage systems in light of regulatory framework and economic incentives / Gabriel Nasser Doyle de Doile. - João Pessoa, 2021.
153 f. : il.

Orientação: Paulo Rotella Junior.
Coorientação: Luiz Célio Souza Rocha.
Dissertação (Mestrado) - UFPB/CEAR.

1. Solar photovoltaic and wind-power. 2. Regulatory barrier. 3. Economic viability. 4. Distributed generation. 5. Intermittent energies. I. Rotella Junior, Paulo. II. Rocha, Luiz Célio Souza. III. Título.

UFPB/BC CDU 502.21(043)

Elaborado por WALQUELINE DA SILVA ARAUJO - CRB-15/514

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ACCEPTED on July 27th of 2021.

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ACKNOWLEDGMENTS

I am very thankful to Brazilian citizens for maintain and strengthen the free of charges public University!

I am so grateful to my wife, Isabel T. de Souza P. de Doile, my loyal companion to everything, everywhere, every time!

Thanks to ANEEL Director Board for permit me to work in home-office and make possible my studies!

Thanks so much to my Supervisor PhD Professor Paulo Rotella Júnior for his thoughtful suggestions and guidance throughout my research process, and for challenging me to think deeply about this issue. I am also grateful for the practical inputs and insights of my Second Supervisor, PhD Professor Luiz Célio Souza Rocha.

"*A people that does not invest in science and technology, who does not put money into research, will never be a nation. It will just be a mass of people with no prospects for the future and no prospect to competing in an increasingly competitive world.*"

Lula

ABSTRACT

The worldwide claim for reduced consumption of fossil fuels has highly grown up in recent decades because the burning process of these fuels is one of the greenhouse effects causes. In line with this, the production of electricity from renewable sources has grown exponentially in many countries, including Brazil. Even though the Brazilian electricity matrix is essentially hydraulic, the growth of renewable sources follows the same worldwide pattern. The main difference is that, in Brazil, energy storage is still very incipient, except that one from hydropower reservoirs. Not even the regulation of the electricity sector is prepared to encourage the insertion of new devices for energy storage. This dissertation is organized into chapters that, apart from the first and the last one, gave rise to scientific articles, which analyse and seek to present solutions for specific gaps and incentive ways for the sustainable growth of distributed generation from wind and solar photovoltaic sources, with energy storage. The first chapter presents the general introduction and the main research methods. Whereas the second chapter deals with a systematic literature review, legislation, and regulations applied to the subject. The main finding of this study is that there is very little research on the three themes together and even less on legal and regulatory aspects. Legal and regulatory incentives vary widely among the countries surveyed, but they serve as insight to the Brazilian regulator and legislators. The third chapter deals specifically with the changes in regulation, proposed by ANEEL, and their effects on the already consolidated generation distributed from photovoltaic solar sources. The conclusion points to a significant reduction in these projects' economic viability. In the fourth chapter, energy storage was inserted where, based on the literature review, it was decided to use a battery bank, a more economical alternative for the studied proposal. Although storage brings the economic advantage, as it reduces grid consumption during peak hours when the tariff is more expensive, the business proved to be unfeasible due to the hight batteries' costs. Given the natural complementarity of wind and solar photovoltaic generation, in the fifth chapter, this source was introduced, which is not yet widespread in Brazil for distributed installations. Considering international prices of wind microturbines, without the import tax, these installations proved to be economically viable and may be the alternative that will give economic viability to distributed generation after the end of the cross subsidy proposed by ANEEL, if there are incentives and/or exemptions tax for the purchase and/or import of batteries and wind microturbines. The main conclusion, presented in chapter 6, is that there is still a need for economic and financial incentives for the feasibility of distributed generation from wind and solar photovoltaic sources, with energy storage, in countries with not well-developed distributed energy systems, as Brazil.

Keywords: regulatory barrier, economic viability, intermittent energies, distributed generation, regulation, legislation.

RESUMO

O apelo mundial pela redução no consumo de combustíveis fósseis cresceu muito nas últimas décadas, devido ao processo de queima desses combustíveis ser um dos causadores do efeito estufa. Alinhado a isto, a produção de energia elétrica a partir de fontes renováveis tem crescido de forma exponencial em muitos países, incluindo o Brasil. Em que pese a matriz elétrica brasileira ser essencialmente de fonte hidráulica, o crescimento das fontes renováveis segue o mesmo padrão mundial. A principal diferença é que, no Brasil com exceção dos reservatórios das hidrelétricas, o armazenamento de energia ainda está muito incipiente. Sequer a regulação do setor elétrico está preparada para incentivar a inserção de novos dispositivos para armazenamento de energia. Esta dissertação está organizada em capítulos que, com exceção do primeiro e do último, deram origem a artigos científicos, os quais analisam e buscam apresentar soluções para lacunas específicas e formas de incentivos ao crescimento sustentável da geração distribuída a partir de fontes eólicas e solar fotovoltaica, com armazenamento de energia. No primeiro capítulo são apresentados a introdução geral e os principais métodos usados na pesquisa. Já o segundo capítulo trata de uma revisão sistemática da literatura e da legislação e regulação aplicadas ao tema. O principal achado deste estudo é que há muito pouca pesquisa dos três temas em conjunto e menos ainda endereçada aos aspectos legais e regulatórios. Os incentivos legais e regulatórios variam muito entre os países pesquisados, mas servem de insumos ao regulador e legisladores brasileiros. O terceiro capítulo trata especificamente das mudanças na regulação, propostas pela ANEEL, e seus efeitos na já consolidada geração distribuída a partir de fonte solar fotovoltaica. A conclusão aponta para uma significativa redução na viabilidade econômica desses empreendimentos. No quarto capítulo foi introduzido o armazenamento de energia onde, baseado na revisão da literatura, optou-se pelo uso da banco de baterias, alternativa mais econômica para a proposta estudada. Apesar de o armazenamento trazer vantagem econômica, pois reduz o consumo da rede nos horários de pico quando a tarifa é mais cara, o negócio mostrou-se inviável devido ao alto custo das baterias. Dada a complementariedade natural da geração eólica com a solar fotovoltaica, no quinto capítulo, foi introduzida esta fonte que ainda não está difundida no Brasil para instalações distribuídas. Considerando preços internacionais das microturbinas eólicas, sem o imposto de importação, estas instalações mostraram-se economicamente viáveis e, poderão ser a alternativa que dará viabilidade à geração distribuída após o fim do subsídio cruzado, proposto pela ANEEL, caso haja incentivos e/ou isenções fiscais para compra e/ou importação de baterias e microturbinas eólicas. A conclusão final, apresentada no capítulo 6, é de que ainda há necessidade de incentivos econômico-financeiros para viabilidade da geração distribuída de fontes eólica e solar fotovoltaica, com armazenamento de energia em países onde a geração distribuída ainda não está consolidada, como no Brasil.

Palavras-Chave: barreira regulatória, viabilidade econômica, energias intermitentes, geração distribuída, regulação, legislação.

RESUMEN

El reclamo mundial por la reducción del consumo de combustibles fósiles ha crecido mucho en las últimas décadas porque el proceso de quema de estos combustibles es una de las causas de los efectos de invernadero. En línea con esto, la producción de electricidad a partir de fuentes renovables ha crecido exponencialmente en muchos países, incluido Brasil. Si bien la matriz eléctrica brasileña es esencialmente hidráulica, el crecimiento de las fuentes renovables sigue el mismo patrón mundial. La principal diferencia es que, en Brasil, el almacenamiento de energía es todavía muy incipiente, excepto el de los embalses hidroeléctricos. Ni siquiera la regulación del sector eléctrico está preparada para incentivar la inserción de nuevos dispositivos de almacenamiento de energía. Esta disertación está organizada en capítulos que, además del primero y el último, dieron lugar a artículos científicos, que analizan y buscan presentar soluciones a brechas específicas y vías de incentivo para el crecimiento sostenible de la generación distribuida a partir de fuentes eólicas y solares fotovoltaicas, con almacenamiento de energía. El primer capítulo presenta la introducción general y los principales métodos de investigación. Mientras que el segundo capítulo trata de una revisión sistemática de la literatura, legislación y normativas aplicadas al tema. El principal hallazgo de este estudio es que hay muy poca investigación sobre los tres temas juntos y menos aún sobre los aspectos legales y regulatorios. Los incentivos legales y regulatorios varían ampliamente entre los países investigados, pero sirven como información para el regulador y los legisladores brasileños. El tercer capítulo trata específicamente de los cambios en la regulación, propuestos por ANEEL, y sus efectos sobre la ya consolidada generación distribuida a partir de fuentes solares fotovoltaicas. La conclusión apunta a una reducción significativa de la viabilidad económica de estos proyectos. En el cuarto capítulo se insertó el almacenamiento de energía donde, con base en la revisión de la literatura, se decidió utilizar bancos de baterías, una alternativa más económica para la propuesta estudiada. Aunque el almacenamiento trae la ventaja económica, ya que reduce el consumo de la red durante las horas pico cuando la tarifa es más cara, el negocio demostró ser inviable debido a los altos costos de las baterías. Dada la complementariedad natural de la generación eólica y solar fotovoltaica, en el quinto capítulo se introdujo esta fuente, que aún no está muy desarrollada en Brasil para instalaciones distribuidas. Considerando los precios internacionales de las microturbinas eólicas, sin el impuesto a la importación, estas instalaciones demostraron ser económicamente viables y pueden ser la alternativa que dé viabilidad económica a la generación distribuida luego del final del subsidio cruzado propuesto por ANEEL, si existen incentivos y / o exenciones de impuestos para la compra y / o importación de baterías y microturbinas eólicas. La principal conclusión, presentada en el capítulo 6, es que aún existe la necesidad de incentivos económicos y financieros para la viabilidad de la generación distribuida a partir de fuentes eólicas y solares fotovoltaicas, con almacenamiento de energía, en países con sistemas de energía distribuida no bien desarrollados, como Brasil.

Palabras clave: barrera regulatoria, viabilidad económica, energías intermitentes, generación distribuida, regulación, legislación.

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ACRONYMS AND ABBREVIATIONS

ANEEL	National Electric Energy Agency
ANOVA	Analysis of Variance
ARENA	Australian Renewable Energy Agency
BESS	Battery Energy Storage System
BPR	ANEEL's Reference Price Bank
CA	Cost of Availability
CCST	Earth System Science Centre
CDF	Cumulative Distribution Function
CEP	Clean Energy Package
CER	Clean Energy Regulator
CERC	Central Electricity Regulatory Commission
COE	Cost of Energy
Conama	Brazilian National Environment Council
Cosip	Contribution to the Public Lighting Service
CT	Conventional Tariff
DG	Distributed Generation
DISCO	Distribution Company
DPB	Discounted Payback
EECS	Electric Energy Compensation System
EES	Energy Storage Systems
EPE	Energetic Research Company
EPIA	European Photovoltaic Industry Association
FERC	Federal Energy Regulatory Commission
GCOD	Grid Compensated Own Demand
GIE	Grid Injected Energy
HOMER	Hybrid Optimization of Multiple Energy Resources
IBGE	Brazilian Institute of Geography and Statistics
ICMS	Tax on Circulation of Goods and Services
IEA	International Energy Agency
INPE	National Institute for Space Research

IPCA	Broad Consumer Price Index
IRR	Internal Rate of Return
IWS	ISI Web of Science
LABREN	Modelling and Studies on Renewable Energy Resources Laboratory
LARC	Langley Research Centre
LCCA	Life Cycle Cost Analysis
LCOE	Levelized Cost of Energy
LPSP	Loss of Power Supply Probability
MARR	Minimum Attractiveness Return Rate
MCS	Monte Carlo Simulation
MNRE	Ministry of New and Renewable Energy of India
MOGA	Multiple Objective Genetic Algorithm
MOSaDE	Multiple-Objective Self-Adaptive Differential Evolution
NASA	National Aeronautics and Space Administrations
NPC	Net Present Costs
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
ODM	Own Demand
Ofgem	Office of Gas and Electricity Markets
ORD	Offset Remote Demand
PL	Bill of Law
PROINFA	Incentive Program for Alternative Sources of Electric Energy
PURPA	Public Utility Regulatory Policy Act
PV	Photovoltaic
R3D	Remote Third-Party Demand
REN	Normative Resolution
RES	Renewable Energy Sources
RF	Renewable Factor
RIA	Regulatory Impact Assessment
RQ	Research Question

SC	Scopus database
SCE	Self Consumption Energy
SDG7	The seventh United Nations Sustainable Development Goal
SIGA	ANEEL’s Generation Information System
SLR	Systematic Literature Review
SPD	Surge Protection Device
TPE	Total Produced Energy
TUSD	Usage Tariff of Distribution System
WT	White Tariff

1. CHAPTER 1 – General introduction

Some of biggest global challenges today are climate changes and global warm. As fossil fuels are strongly associated with greenhouse gas emissions, that may contribute to global warm, the promotion of renewable energy, with low carbon dioxide emissions, is a crucial issue (GONZÁLEZ-ÁLVAREZ; MONTAÑÉS; OLMOS, 2020). However, the world energy matrix is dominated by fossil fuels. Fortunately, the share of these fuels has been losing ground to renewable energies in recent decades (GOLDEMBERG, 2020). According to data from the International Energy Agency (EPE, 2019; IEA, 2018), world energy matrix in 2019 was consisted of 81% of fossil fuels, 5% of nuclear and 14% of renewable sources. About 26% of the electricity available was based on renewable sources, with hydroelectric plants accounting for 16.2% of the global matrix. Next comes wind energy with 4.7%, biomass and biofuels with 2.4%, solar photovoltaics (PV) with 2.1% and 0.6% from other renewable sources.

Electricity production from renewable sources has been growing exponentially around the world (IEA, 2021). In Brazil, wind energy grew from 27 MW in 2005 (DE DOILE, 2016) to 18,295 MW in 2021, according to (ANEEL, 2021a). Utility-scale of solar photovoltaic energy began to be implemented in the country a little later, in 2017, but in 2021 it already has 3.295 MW of installed power (ANEEL, 2021a). The distributed generation (DG), most of which is made up of small-scale solar photovoltaic, started in 2012 and reached 5,740 MW in 2021 (ANEEL, 2021b).Wind and solar photovoltaic energy have seasonal and intermittent characteristics, which makes the operation of the electrical system difficult and leads to the need for storage to regulate both the intermittence and the seasonality of generation (PEARRE; SWAN, 2020).

Few countries have the nature privilege as Brazil, which has an extensive river network and adequate relief for the construction of hydroelectric plants. This makes Brazil the largest hydroelectric reservoir in the world, in proportion to demand (ZAMBON; BARROS; YEH, 2019). However, the socio-environmental barriers that have emerged in recent decades make it difficult to build new reservoirs and the trend is that the current reservoirs will run out in the not-so-distant future. The depletion of hydroelectric reservoir capacity will leave the national electrical system without sufficient storage capacity, leading to the investment need in other energy storage technologies. However, there are still no economic-financial incentives or adequate regulation for the insertion of new storage technologies, which adds to some existing technical barriers for the insertion of these enterprises.

This dissertation focuses on distributed generation (DG) from wind and solar photovoltaic sources. Each chapter is based on an excerpt from this theme and seeks to present solutions for specific gaps and forms of incentives for a sustainable growth of renewable energy from these sources. The topic was studied step-by-step: firstly, the DG from solar photovoltaic source; then this source with battery energy storage systems (BESS); and, finally, the three technologies, wind, solar PV, and BESS, together. Each chapter gave rise to scientific articles that are displayed on Appendix 1.1, with their abstracts, co-authors, place of submission, publication and/or presentation.

1.1. General Objective

The research aims to assess the economic feasibility of distributed solar PV and hybrid systems, composed of wind and solar PV, with and without BESS, focused on economic-financial incentives and the Brazilian regulatory framework, to propose insights for technical and economic regulation.

1.2. Specific Objectives

The dissertation is chapter divided, where each one has a particular objective. With each chapter, the study frontier increases, as well as the control variables and the analysis complexity. Results from one previous chapter are frequently used in the follows ones.

1.2.1. Chapter 2

The objective of this chapter is to provide a literature review regarding the economic feasibility of hybrid wind power and solar PV generation with an associated energy storage system (ESS) and its legal and regulatory aspects, in order to understand how researchers are seeing these three technologies working together around the world. For this, the following research questions (RQ) were addressed: (i) what are the main characteristics of the literature regarding the economic analysis of wind-photovoltaic generation with ESS; (ii) what are the observations of the studies and the research frameworks explored (regulatory and economic aspects); (iii) what are the main legal and regulatory aspects for this kind of hybrid generation with ESS; and (iv) how can these regulatory aspects contribute to the recent regulatory discussion in Brazil? Thus, a systematic literature review (SLR) and a legal and regulatory research were performed to answer these RQs.

1.2.2. Chapter 3

The National Electrical Energy Agency (ANEEL) proposed in 2019 that the costs related to the electricity grid should be shared among all consumers. This would do away with cross-subsidies where normal consumers without installed distributed generation (DG) units effectively cover the costs of the grid for consumers with DG's units. The objective here is to compare the economic and financial viability of two scenarios, one before the proposed changes, and the other after the proposed changes, in the five Brazilian geographic regions to understand how this regulation will affect the viability of DG projects in Brazil. This goal was reached through deterministic and stochastic analyses of the economic indicators as net present value (NPV), internal return rate (IRR), and discounted payback (DPB), by varying the initial investment costs, demand, and energy prices for distributed solar PV plants, in addition to a national case also varying the minimum attractiveness rate return (MARR).

1.2.3. Chapter 4

The end of the cross subsidy on tariffs will cause a significant reduction in the economic feasibility of DG. Thus, the insertion of battery banks as ESS could be one of the ways to improve the economic feasibility of DG from solar PV source, by reducing the demand from the grid during peak hours. Although technically sound, the installation of a photovoltaic system with BESS must demonstrate its profitability in the specific context of application, taking into account the regulations in force. The main objective of this chapter is to present an economic viability stochastic analysis, varying seven inputs and analysing the three economic outputs, for distributed solar PV plants in light of the new regulation of the electric energy compensation system (EECS), planned to come into force in 2021, and the hourly tariffs known as white tariff (WT). The classification of distributed power plants is crucial to make them economic feasible or not, by an adequate production for the respective demand. Therefore, the second objective of this chapter is to analyse the current classification and propose a new classification more adequate for residential, commercial, and industrial demands.

1.2.4. Chapter 5

As the economic feasibility of solar PV with BESS has not been attested in most of the analysed scenarios, hybrid power plants using wind power and solar PV together could be the solution. Thus, the aim of this chapter is to assess the economic feasibility of these power plants with BESS, through stochastic analysis varying the initial investment, MARR, energy demand, energy tariff, wind speed, solar radiation, and the installed power of hybrid plants and battery banks. The economic indicators: NPV, IRR, and DPB for three sizes of PV power plant: micro-plant, up to 10 kW; mini plant, from 10 kW up to 1 MW, and small power plant from 1 up to 5 MW installed power, including 5 hours battery bank capacity, was analysed.

1.3. General Theoretical Foundations

The economic-financial theory is the fundamental theory used along chapters of this dissertation. Economic-financial viability analysis is usually conducted to determine if a venture will be viable or not, and thus whether an entrepreneur should invest in the venture or not (ROCHA *et al.*, 2017). Standard financial analysis tools, as NPV, IRR, and DPB, were used. These are essential and most used metrics for analysing the economic viability of energy projects, according to Hawawini and Viallet (2019) and studies conducted by Thevenard and Pelland (2013); Rodrigues, Chen, and Morgado-Dias (2017), Tao and Finenko (2016), and Bendato et al. (2017), that have exemplified these types of analyses. Of all the possible methods for determining the financial viability of a given project, Li, Lu and Wu (2013) state that the NPV method is the best one.

The NPV method is an important financial tool that can be calculated from future cash flows deducting expenses from revenue. In the cash flow, several inputs can be considered, such as initial investments, operation and maintenance costs, facilities life, operating time, electricity tariffs, taxes and, eventually, program credits or state subsidies, among others (ZHOU *et al.*, 2009). Considering all these entries, the cash flow is then discounted by a fixed rate, called MARR in this study.

MARR is the interest rate or discount rate that an investor will be satisfied. According to Vale et al. (2017), this discount rate varies mainly with the business risk, opportunity cost and liquidity. When investors expend an amount of capital, they always expect to obtain returns greater than MARR, on this invested capital, during the lifetime of the project (ZHOU *et al.*, 2009). The NPV formula is shown in Equation 1.1 (LACERDA *et al.*, 2020; SILVA *et al.*, 2021).

$$NPV(r,n) = \sum_{1}^{n} \frac{C_n}{(1-r)^n} - C_0 \tag{1.1}$$

where r is the interest rate, the MARR; n is the project periods, an integer from 1 up to 30 years in this research; and C_0 to C_n are constants that represent the annual cash flows including the initial investment.

An NPV equal to zero suggests that the capital invested will be fully recovered just in the end of analysed period (ARNOLD; YILDIZ, 2015). A negative NPV indicates that the investment is not able to offset opportunity costs, making the project unviable, whereas a positive NPV indicates that the investment is viable with an IRR greater than the MARR (AQUILA *et al.*, 2020).

According to some researchers (RODRIGUES; CHEN; MORGADO-DIAS, 2017), the IRR is found when NPV is null, by Equation 1.2 (FOLES; FIALHO; COLLARES-PEREIRA, 2020), and this rate should be compared to in force interest rates. A high IRR indicates that the investment has a great probability to be lucrative, while an IRR less than the MARR indicates an economically unviable project.

$$r(n) = 1 - \sqrt[n]{\frac{\sum_1^n C_n}{C_0}} \tag{1.2}$$

where $r(n)$ is the *IRR* in the n period.

The payback period is another important metric in investment analysis, according to Tao and Finenko (2016). Payback period is the time it takes to recoup the initial investment or the time that cumulative cash flows become positive. However, it is a criterion considered to be inaccurate and flawed, as it does not consider the time value of money. Thus, a viable alternative used in this research is the DPB, which is determined when the sum of future cash flows brought to date zero is equal to the initial investment, and for this, a discount rate is used. The moment (year plus fraction) corresponding to the last instalment of the cash flow brought to present value to equal the initial investment will be the DPB. This criterion is presented according to relations 1.3 and 1.4.

$$C_0 \leq \sum_1^{n^*} \frac{C_n}{(1-r)^n} \tag{1.3}$$

$$n_F = \frac{C_{n^*+1} - \sum_1^{n^*+1} C_{n^*+1} - C_0}{C_{n^*+1}} \tag{1.4}$$

where n^* is the greater integer n that maintain the inequality true, and n_F is the next period's fraction. Therefore, the DPB will be the sum of n^* plus n_F.

Some tools are needed to calculate economic indicators, such as spreadsheets and numerical simulations. Spreadsheets were used for deterministic calculations, as in (HOLDERMANN; KISSEL; BEIGEL, 2014), (DA SILVA; BRANCO, 2018), and (DEOTTI *et al.*, 2020). Fixed inputs, among them the nominal power, solar radiation, electricity demand, electricity tariffs, and the MARR, are considered in this tool to calculate the outputs NPV, IRR, and DPB.

Numerical simulations are made by varying the chosen inputs to create several stochastic scenarios, normally 10.000 or more, and verify the probability of an output occur. This is the so-called Monte Carlo Simulation (MCS) used by Arnold and Yildiz (2015), who analysed renewable energy sources (RES) projects for energy derived from wood residue, Tudisca et al. (2013), that studied solar energy installations in Sicily factories, and Cucchiella, D'Adamo and Gastaldi (2016), in their analyse of solar energy installation with battery storage units installed at residential buildings in Italy.

A probabilistic model is built to perform an MCS, where parameters can assume a range of possible stochastic values. The parameters will be represented by probability distribution functions based on real parameters. By studying the statistical distribution of past occurrences of a given event, a probability model can be built, the probability distribution function, capable of providing the future value of this same event under the same conditions (HOLLANDS; CRHA, 1987). Arnold and Yildiz (2015) stated in their work that the distribution function determination for model's entries is the main step in the MCS.

Another important theory that helped to delimit this research is the SLR. Unlike traditional systematic reviews, this type of review allows for transparency, replicability, and reduction of authors' bias (TRANFIELD; DENYER; SMART, 2003). According to Kitchenham (2004), the SLR is a tool that identifies, evaluates and allows understanding all articles available for a particular study or research. This study or research is called primary, while the SLR is a secondary study. Morioka, Bolis, and Carvalho (2018) said that the SLR allows us to focus on a global issue or a collection of empirical results in specific research. As a result, one can formulate a general concept, not just a summary.

The SLR must be organized in three stages: (i) planning, (ii) conducting, and (iii) reporting the research, to evaluate and interpret available studies on specific research questions, and finally select the most relevant ones. These three stages are divided into five goals. The planning stage is divided into two objectives: the research question and strings formulation and an exploratory review. The conducting phase is, also, divides in two goals: to find the articles and the selection of interesting ones. The production of a review report is the final stage purpose (KITCHENHAM, 2004).

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2. CHAPTER 2 – Review of literature, legislation, and regulation for hybrid wind and solar photovoltaic generation with energy storage systems

2.1. Abstract

The operation of the electrical system is more difficult due to the intermittent and seasonal characteristics of wind and solar energy. Such operational challenges are minimized by the incorporation of the energy storage system (ESS), which plays an important role in improving the stability and the reliability of the grid. The economic viability of hybrid plants with storage can be improved if the regulation enables the remuneration of the various ancillary services that ESS can provide. Thus, the aim of this study is to provide a literature review regarding economic feasibility of hybrid wind-PV generation with ESS and its legal and regulatory aspects. Observing the world tendency, the new studies should address the techno-economic feasibility of wind power and solar PV in conjunction with, at least, one kind of ESS. Also, it is very important to take in account the regulatory barriers and proposes solutions to remove them. It was observed that although regulatory aspects can influence economic feasibility of hybrid projects, little is discussed about this relationship between the frameworks. The findings presented in this chapter are important not only for Brazil, but also for other countries that do not have regulations in force to support the use of ESS in hybrid systems.

2.2. Introduction

The climate changes are one of the biggest global challenges nowadays. The production of electricity from renewable energy sources (RES), with low CO_2 emissions, become a crucial issue, because the fossil fuels are associated with greenhouse gas emissions (GONZÁLEZ-ÁLVAREZ; MONTAÑÉS; OLMOS, 2020). Gallagher et al. (2019) said that renewable energies are the way to reduce the greenhouse gas emissions and provide the necessary energy matrix changes. Thus, renewable energies, as wind and solar energy, have grown exponentially worldwide.

However, the operation of the electrical system is a challenging due to the intermittent and seasonal characteristics of wind and solar energy (BAKIRTZIS *et al.*, 2018; DAS *et al.*, 2018; MALLAPRAGADA; SEPULVEDA; JENKINS, 2020). These characteristics lead to the need for storage to regulate both intermittency and seasonality in generation (PEARRE; SWAN, 2020).

Energy storage technologies can be applied at electric power systems to perform functions such as: operational support of the grid, load shifting, peak shaving, stabilization of the grid by frequency and voltage control, reliability and, in general, issues related to power quality improvement (EVANS; STREZOV; EVANS, 2012; YEKINI SUBERU; WAZIR MUSTAFA; BASHIR, 2014). In this way, ESS can play an important role in the reliability and stability of the grid (DIVYA; ØSTERGAARD, 2009; YEKINI SUBERU; WAZIR MUSTAFA; BASHIR, 2014). ESS can generate revenue by providing ancillary services, in addition to contributing to a greater insertion of RES in the energy matrix. On a smaller scale, like distributed generation (DG), ESS can be used to add flexibility to operational strategies and achieve the objectives set on the demand side management. In both situations, one of the critical aspects is the investment cost in ESS (ROTELLA JUNIOR *et al.*, 2021). Due to the complexity of these systems, technical and economic feasibility studies are essential.

The Brazilian production of electricity from wind reach 18,295 MW in 2021, while from solar PV achieve 9,035 MW, including utility-scale and DG power plants (ANEEL, 2021a, 2021b). As in the rest of the world, this intermittent RES insertion in the energy matrix requires greater energy storage capacity. However, the lack of adequate incentives and regulations for inserting energy storage technologies are added to the technical barriers and are configured as an impediment to this market.

In some countries that have more advanced markets, discussions on legal and regulatory framework have developed to allow the economic viability of energy storage technologies. In this sense, knowing the legislation of other countries and what has been presented in the literature is important for countries that do not have a proper regulation yet, such as Brazil. Based in other experiences they can develop their own legislation, facilitating the insertion of ESS in hybrid systems.

The economic viability of hybrid plants with storage can be improved if technical regulation allows the insertion of ESS to increase the power plants assured energy by smoothing the natural intermittence, as well as if the economic regulation enables the remuneration of the various ancillary services that storage systems can provide.

Thus, the aim of this chapter is to provide a literature review regarding economic feasibility of hybrid wind-PV generation with ESS and its legal and regulatory aspects. It addresses the following research questions (RQ):

RQ1: What are the main characteristics of the literature regarding economic analysis of wind-PV generation with ESS?

RQ2: What are the studies remarks and the research frameworks explored on regulatory and economic aspects?

RQ3: What are the main legal and regulatory aspects worldwide for hybrid wind-PV generation with ESS and how they can contribute to the recent regulatory discussion in Brazil?

For that, a systematic literature review (SLR) was carried out to identify, evaluate, and understand all available papers that may answer the RQs (KITCHENHAM *et al.*, 2009). Morioka et al. (MORIOKA; BOLIS; CARVALHO, 2018) said the SLR allow us to focus a global question or an empirical finding collection on a specific research. Its result is the formulation of a general concept, not only a summary.

In the next section is presented the methodology used in this study, along with the presentation of descriptors. Then, the results are shown with their discussion. Finally, the conclusions are summarized in the last section.

2.3. Methodology

The systematic literature review was the methodology chosen in this chapter. Unlike traditional systematic reviews, this type of review allows for transparency, replicability and reduction of authors' bias (TRANFIELD; DENYER; SMART, 2003). To answer the research questions, this methodology was developed in three main stages: (i) definition of the sample, (ii) descriptive and network analysis and (iii) content analysis.

2.3.1. Definition of the sample

The search for publications was developed in ISI Web of Science (IWS) and Scopus (SC) databases, the most important bibliographic data sources for physical sciences, as concluded by Visser, VanEck and Waltman (2019). The purpose was to study the technologies of wind, solar PV and energy storage, together in hybrid systems, related to the knowledge fields of technical and economic viability and regulatory aspects. We assume that, if the project is economically viable, it is also technically feasible. The bibliographic search in the databases was developed in April 2021, including the following descriptors:

1) (wind AND (solar OR photovoltaic) AND storage) AND (economic* OR financial*) AND (feasibility OR feasible OR viability OR viable);

2) (wind AND (solar OR photovoltaic) AND storage) AND (law* OR legal OR legislation* OR rule* OR regulation*)

The descriptors should be present in the title, abstract or keywords. Only publications with the following characteristics were included: (i) type of document: “articles” or “review”; (ii) language: English; (iii) publication year: no time frame restriction. Only publications with the availability of full text in English was considered.

The studies were screened using elimination criteria by reading the title and abstracts of the selected articles. Papers were excluded if the technology (wind, solar PV or energy storage) was not the central subject of the study and/or if there are not addressed economic or regulatory aspects.

The flowchart of the sample definition process was included in the results section.

2.3.2. *Descriptive and network analysis*

The sample was initially analysed descriptively using MS Excel®. The world map of publications quartiles was constructed using the open software Geographic Information System QGIS® 3.16.1 Hannover version. The quartile distribution was calculated by the following Equation 2.1.

$$Q_k \leq \frac{k \sum p}{4} \tag{2.1}$$

where Q_k is the k quartile; k is the quartile order from 1 up to 4 and Σp is the publications sum of the country with greatest number of articles.

The sample metadata was analysed to identify the most frequent journals and the articles most cited in the sample. Then, the VOSviewer® software (VAN ECK; WALTMAN, 2010) was used to provide co-citation of the journal and keyword network.

Each type of information was analysed in detail, to provide an initial overview of the article's sample. In particular, the keyword network was relevant to identify thematic groups, favouring the follow-up of the research phase related to the categorization and qualitative analysis of the papers.

2.3.3. *Content analysis*

The follow information was used to compile the articles: authors, title, publication periodic, year of publication, country of main author, number of citations, and abstract. According to White and Marsh (2006), the content analysis is flexible and can be used as a systematic approach to assess generated data on the research in qualitative and quantitative way.

This stage is dedicated to scientific findings interpretation. It is the research main step, as the results will be the core of the primary study. Here, we had obtained an articles overview, based on quantitative and qualitative analyses, observing the studies carried out focused in the three technologies working in hybrid systems, as well the worldwide regulatory frameworks.

To complete the legal and regulatory research, with the help of CEDOC/ANEEL (the ANEEL documentation centre), we found all legislation and regulation for renewable energies of five regions or countries to compare with the Brazilian legal framework. The regions or countries chosen are the USA, the UK, Spain to represent the EU, India, and Australia. These regions or countries were chosen due to geographic or/and electrical system similarity with Brazil. Russia and China are also very similar with Brazil, but unfortunately, the full legislation translated was not find, what is understood as a limitation of the research.

2.4. Results and Discussion

A systematic review of the literature was developed based on the presented analyses, integrating the economic and regulatory studies related to the three technologies, wind, solar photovoltaic and energy storage. The flowchart of the sample definition is shown on Figure 2.1. In the identification stage, publications were identified using the WoS and SC databases, for each descriptor. Duplicate articles were eliminated before the screening phase. According to the information in the methodology section, the papers were screened using some elimination criteria. At the end, the final sample of each descriptor was assembled. An article was deleted because it was duplicated. The final sample was composed by 95 articles (for more information, see Appendix 2.1), and after reading these studies in full it is possible to state that 77 connected to economics feasibility, 13 connected to regulatory aspects and 5 connected to both aspects. The words rule and regulation have multiple meanings, as technical rules and frequency or voltage regulation. That is the reason that few documents match regulatory aspects filters.

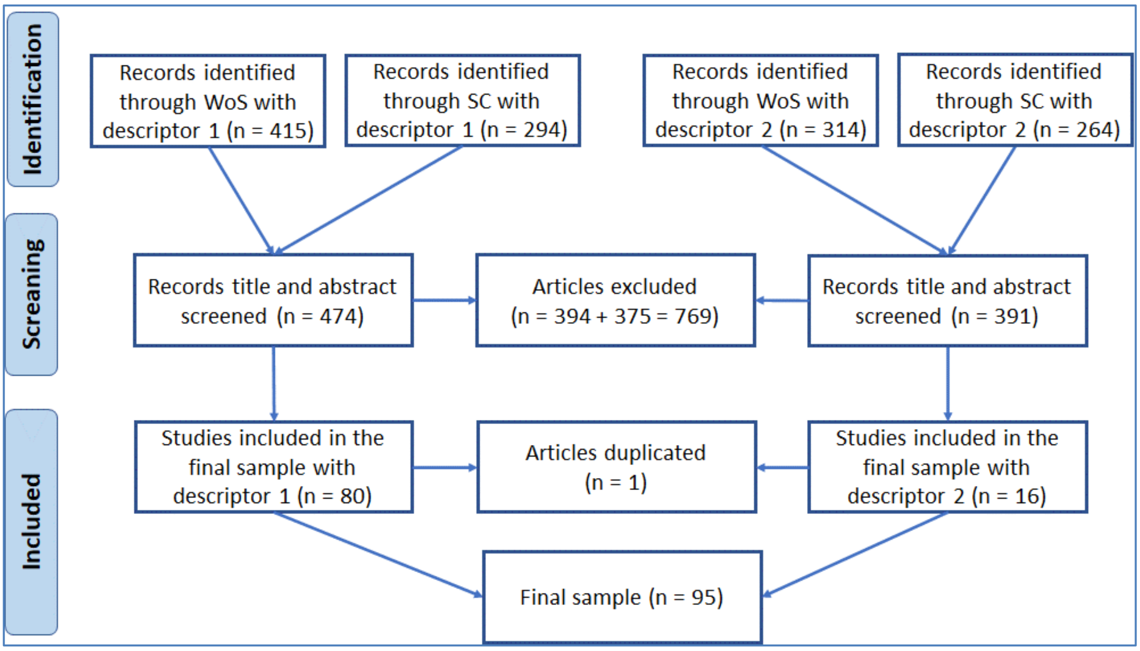

Figure 2.1 - Flowchart of the sample definition
Source: the author, 2021

Data analysis begins by responding to RQ1 (*what are the main characteristics of the literature regarding economic analysis of wind-PV generation with ESS?*) to provide an initial and general understanding of this literature. Thus, the scientific studies, about the economic and regulation aspects, related to the three technologies together was found in 29 distinct countries, as shown on Figure 2.2. China is the main researcher in this scientific field, followed by India, Iran, and Spain. 42% of the studies are from these four countries. The next 9 countries with three or more publication sum 35% of the sample and, the others 16 countries with publications, in conjunction, have less than 25% of the total. The three papers in this sample produced in Brazil have addressed their research to other countries, Chile, Iran, and Nicaragua, respectively. So, the scientific gap is still present in Brazil.

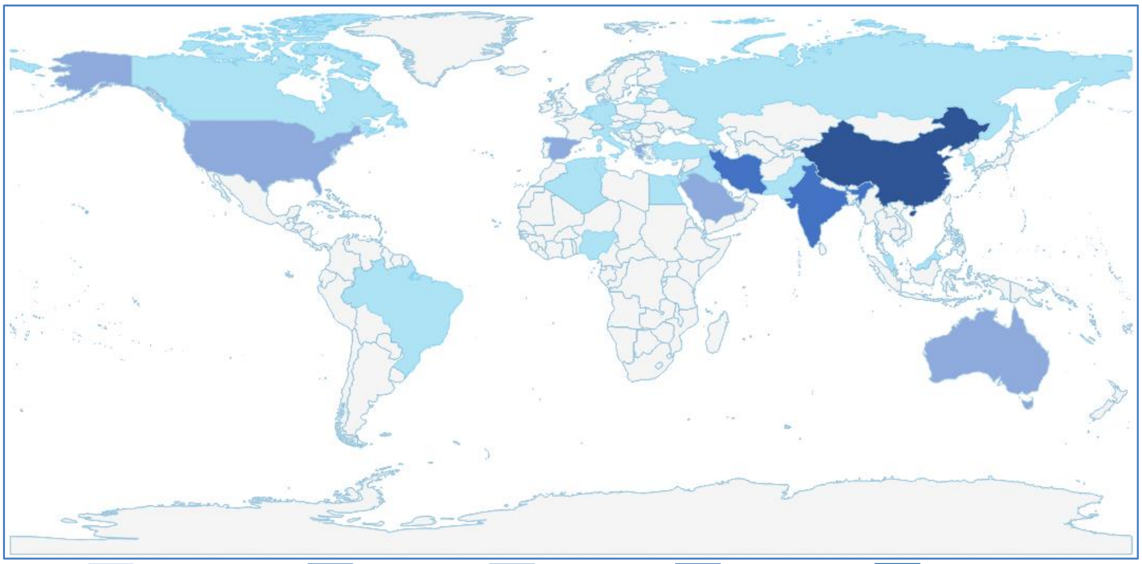

Figure 2.2 – Spatial distribution of publications by quartiles among countries.
Source: the author, 2021

Years of evolution publications related to wind, solar PV, and ESS in economic and regulatory studies of final sample are shown on Figure 2.3. The oldest article in the sample was published in 1994. The second oldest paper was published 11 years later. After this publication, another decade passed with a little number of publications. An enhancing number of publications start from 2016, indicating a growing interest in hybrid wind-PV generation with ESS.

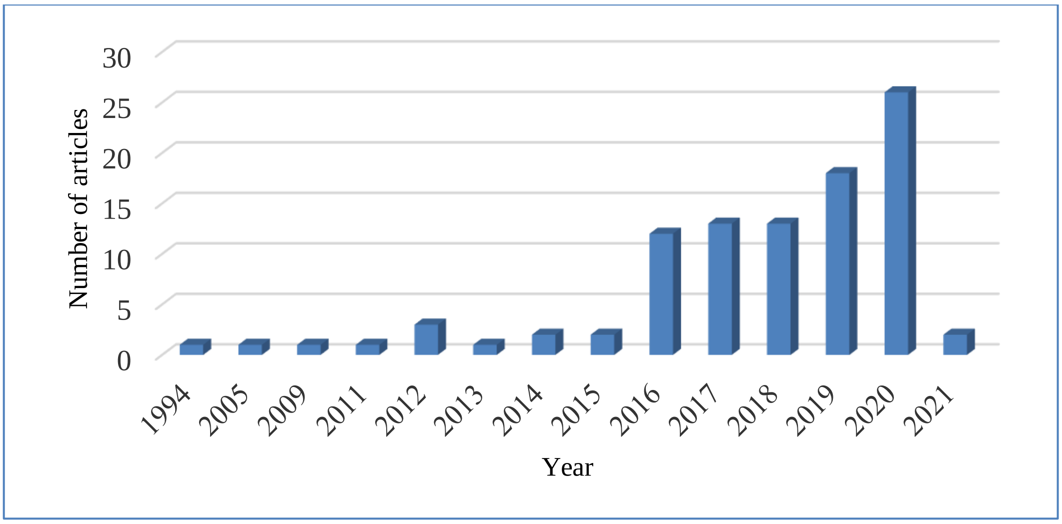

Figure 2.3 – Annual publication evolution
Source: the author, 2021

The main journals present in the final sample, that have at least three articles in the sample are listed in Table 2.1.

Table 2.1 – Main journals of the sample

Journal	Number of articles
Renewable & Sustainable Energy Reviews	11
Renewable Energy	7
Applied Energy	5
Energy Conversion and Management	5
Energy	4
International Journal of Hydrogen Energy	4
International Journal of Energy Research	3
International Journal of Renewable Energy Research	3
Sustainable Energy Technologies and Assessments	3

This analysis allows to affirm the predominance of publications in journals focused directly on the energy area. The most significant journal in the sample was Renewable & Sustainable Energy Reviews, with 11 articles; followed by Renewable Energy, with 7 publications; and Applied Energy and Energy Conversion and Management, with 5 issues each. The 9 journals of Table 1 represent around 48% of the papers in the sample. The remaining 52% of articles is divided among 40 journals. This subject is of widespread interest among many journals in the energy field, but also in other related fields of knowledge.

The analysis of co-occurrence of author keywords used at least by 3 documents in the sample is presented on Figure 2.4. The keywords colours indicate the average year of publications that used a specific keyword. The keywords in dark blue are associated with the beginning of their use in older studies and the yellow ones to newer articles. At the same time, the size of each node represents the number of times that each term was used as a keyword in the articles. The importance of terms such as "renewable energy", "optimization", "homer software" and "cost of energy" are revealed on that figure, considering that such terms were not used as search strings, as were used, for example, " wind" and "photovoltaic". It is worth mentioning terms that have been used more recently, such as "optimal sizing" and "loss of power supply probability". The recent use of the search string "energy storage system" stands out. And, finally, considering that this chapter is dedicated to studies that deal with economic and financial aspects, there is a lower occurrence than expected for the term "techno-economic analysis", or terms such as "net present cost".

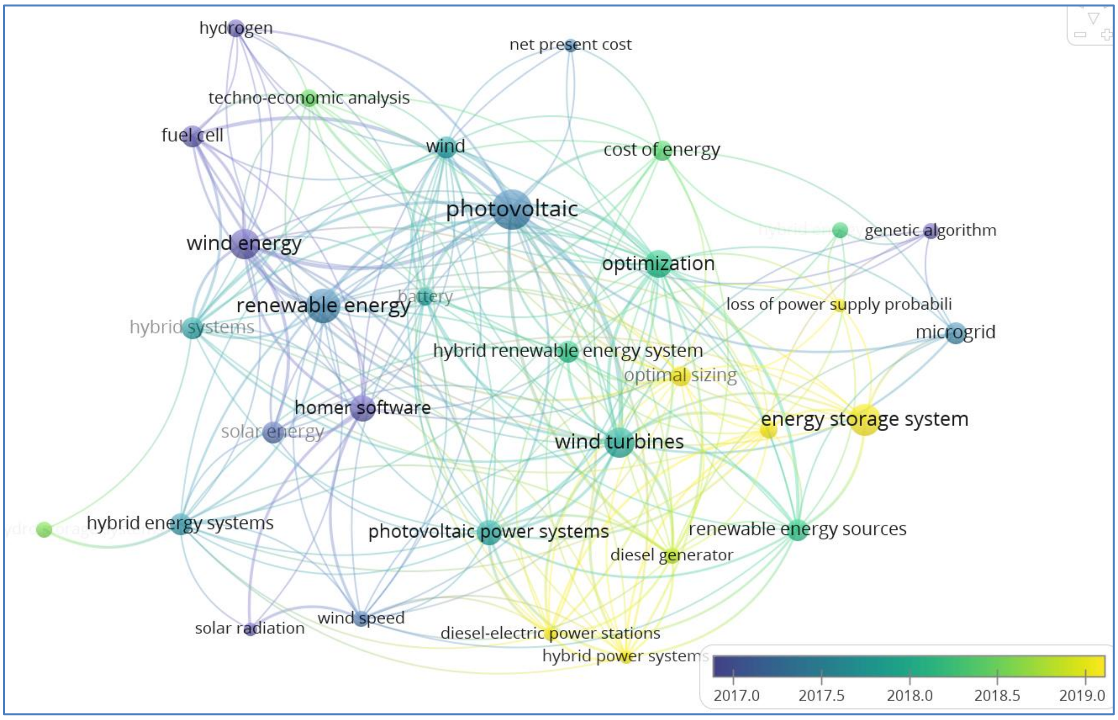

Figure 2.4 – Keyword’s co-occurrence map.
Source: the author, 2021

To complement information about the sample, shows the distribution of the most cited articles over time is displayed on Figure 2.5. For its elaboration, the 15 most cited papers in the sample were selected (more information will be presented in Table 2.2 below).

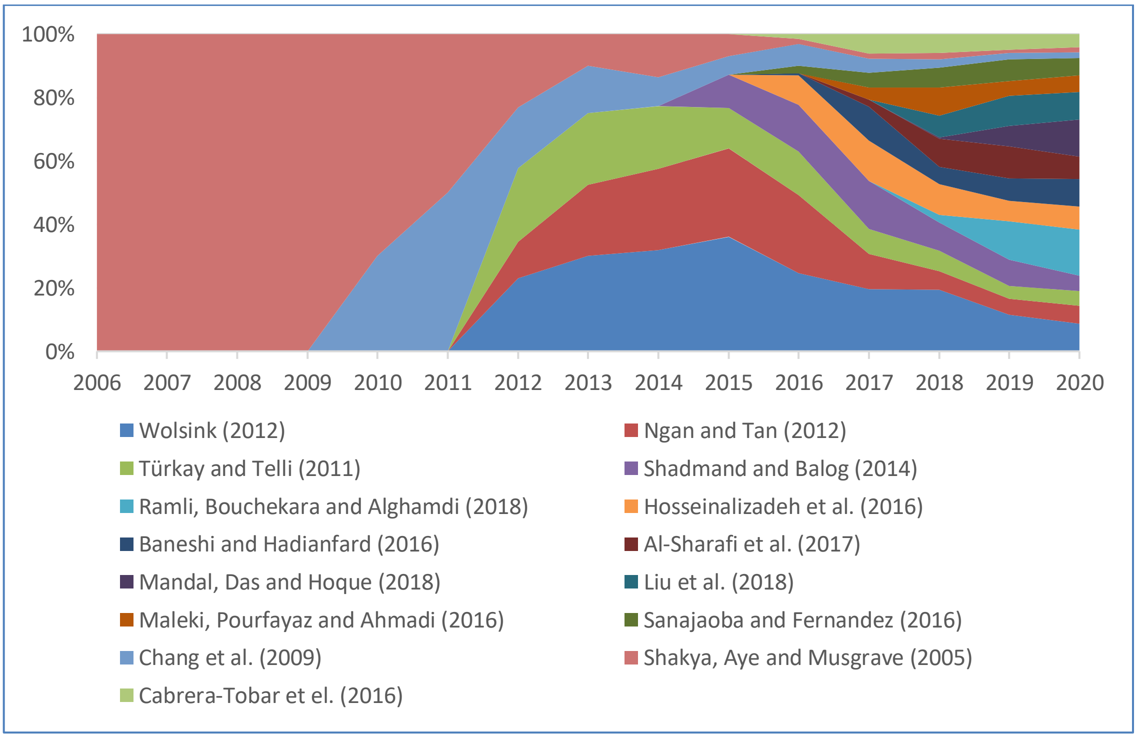

Figure 2.5 - Evolution of article citations over the years.
Source: the author, 2021

Despite these 15 publications exerting influence on the literature, some trends should be highlighted. Shakya, Aye and Musgrave (2005) and Chang et al. (2009) had the domain over the number of citations until 2011. However, the authors suffered a reduction in their influence on current publications, considering the percentage drop of citations received over time. Wolsink (2012) is the author with the highest absolute number of citations and since 2011 still has great influence in recent publications, followed by Ngan and Tan (NGAN; TAN, 2012) and Türkay and Telli (2011). Finally, it should be noted the recent emergence of references that received a large number of citations in the years 2019 and 2020, standing out even among the others, as is the case of Ramli, Bouchekara and Alghamdi (2018) and Mandal, Das and Hoque (2018).

To answer RQ2 (*what are the studies remarks and the research frameworks explored on regulatory and economic aspects?*), on Table 2.2 are listed the most cited articles in the sample with at least 15 citations. This table was built from a reading of the papers, which were reclassified in relation to the search field. It was noted that some studies, although not having terms related to both economic and regulatory aspects in their title, abstract and keywords, could discuss both aspects in the body of the text.

Table 2.2 – Most cited articles, with more than 15 citations

Reference	Field	Remarks	Citations
(WOLSINK, 2012)	Regulatory	A review about the gap for social participation in RES implementation. A worldwide view study.	277
(NGAN; TAN, 2012)	Economic	Feasibility of Wind, PV, Diesel, and Storage using HOMER to calculate NPC and LCOE. Malaysia.	168
(TÜRKAY; TELLI, 2011)	Economic	A stand-alone pilot project for hybrid Wind, PV plus hydrogen as ESS is analysed at HOMER software, in Istanbul, Turkey.	128
(SHADMAND; BALOG, 2014)	Economic	Feasibility of Wind, PV plus batteries using MOGA to calculate COE and availability, in Texas, USA.	127
(RAMLI; BOUCHEKARA; ALGHAMDI, 2018)	Economic	Wind, PV, Diesel, batteries using LPSP, COE and RF by MOSaDE to evaluate, in Saudi Arabia.	123
(HOSSEINALIZADEH *et al.*, 2016)	Economic	Feasibility of Wind, PV plus batteries or fuel cell in Iran. Cost analyses.	118
(BANESHI; HADIANFARD, 2016)	Regulatory and Economic	It uses HOMER to analyse the feasibility of three technologies together in Iran facing government incentives.	100
(AL-SHARAFI *et al.*, 2017)	Economic	Hydrogen production in Saudi Arabia by hybrid wind, PV, Storage. COE analyses.	98
(MANDAL; DAS; HOQUE, 2018)	Economic	It uses HOMER to calculate NPC and COE to 3 technologies in Bangladesh.	95
(LIU *et al.*, 2018)	Regulatory and Economic	LCOE is calculated, for a typical case in Hong Kong, to analyse the feasibility of three technologies together, considering cost and regulatory incentives.	88

(MALEKI; POURFAYAZ; AHMADI, 2016)	Economic	Assessment for a hybrid PV, Wind, hydrogen storage system to produce fresh water in Iran.	81
(SANAJAOBA; FERNANDEZ, 2016)	Economic	Explore the new software Cuckoo Search to optimise Wind, PV plus Storage in India.	78
(CHANG *et al.*, 2009)	Regulatory	Evaluate the policies and laws encouraging renewable energy systems in China.	76
(SHAKYA; AYE; MUSGRAVE, 2005)	Economic	Australian study for three technologies by LCOE and cashflow.	74
(CABRERA-TOBAR *et al.*, 2016)	Regulatory	A comparison among grid codes from Germany, USA, Puerto Rico, Romania, China and South Africa.	68
(FAZELPOUR; SOLTANI; ROSEN, 2016)	Economic	HOMER is used to assesses a hybrid system in Iran.	66
(LIAN *et al.*, 2019)	Economic	Review study of optimization techniques for various hybrid energy systems worldwide.	66
(NADJEMI *et al.*, 2017)	Economic	A literature review in optimization techniques for techno-economic analyses of hybrid Wind, PV plus Storage system in Algeria.	62
(DUMAN; GÜLER, 2018)	Economic	They use HOMER to calculate COE for a hybrid Wind, PV battery or hydrogen storage in Turkey.	60
(KHAN; PAL; SAEED, 2018)	Economic	A review on feasibility of hybrid Wind, PV and Storage system.	59
(KHOSRAVI *et al.*, 2018)	Economic	An energetic analysis was done to a hybrid Wind, PV hydrogen storage system in Iran.	54
(ZHOU *et al.*, 2018)	Economic	It purposes a regulation system for typical energy communities with RES production in California, USA.	50
(ELKADEEM *et al.*, 2019)	Economic	Feasibility of a hybrid Wind, PV, Diesel plus Storage in isolated systems in Sudan.	47
(OLATOMIWA; MEKHILEF; OHUNAKIN, 2016)	Economic	Also use HOMER to economic assessment of a hybrid Wind, PV, Diesel + Storage in Nigeria.	44
(MAATALLAH; GHODHBANE; BEN NASRALLAH, 2016)	Economic	A Tunisian study using HOMER to calculate NPV and LCOE of a hybrid Wind, PV, Diesel plus batteries.	44
(EYPASCH *et al.*, 2017)	Economic	Feasibility of a hybrid Wind, PV and hydrogen storage in Germany.	43
(KRISHAN; SUHAG, 2019)	Economic	It uses HOMER and MATLAB to calculate NPC and COE for a hybrid Wind, PV, battery system in India.	39
(ASKARI; AMERI, 2012)	Economic	Feasibility of hybrid Wind, PV batteries in Iran, using HOMER to calculate NPC.	39
(ALI; SHAHNIA, 2017)	Economic	In Australia, feasibility is studied by HOMER to calculate NPC plus COE of a hybrid Wind, PV, battery.	33
(KAZEM *et al.*, 2017)	Economic	Using HOMER to analyse a hybrid Wind, PV, Diesel + batteries in Masirah Island, Oma.	30
(ABDIN; MÉRIDA, 2019)	Economic	Five locations in USA, Canada and Australia are studied by HOMER to calculate COE for a hybrid Wind, PV, battery, or hydrogen storage system.	27
(RAD *et al.*, 2020)	Economic	Techno-economic feasibility for hybrid wind, PV and ESS in a rural area of Iran	26
(KATSAPRAKAKIS; CHRISTAKIS, 2016)	Regulatory	A proposal for a better regulation of licensing, dimensioning and land occupation by RES in Greek islands.	24
(TELARETTI; DUSONCHET, 2017)	Regulatory	Review of states' storage regulation in the USA.	23

(AL-SHETWI; SUJOD, 2018)	Regulatory	A review of global grid codes focused on PV connections.	22
(NYECHE; DIEMUODEKE, 2020)	Economic	Feasibility of a hybrid Wind, PV, pumped storage in Nigeria. HOMER, MATLAB and Excel to calculate LCOE.	21
(LACKO *et al.*, 2014)	Economic	Feasibility of hybrid Wind, PV, hydrogen storage by NPC in Slovenia.	18
(FATHIMA; PALANISAMY, 2015)	Economic	Feasibility of hybrid Wind, PV, focused on battery storage investments in India.	17
(NGUYEN *et al.*, 2020)	Economic	An optimization study for hybrid wind, PV, hydrogen, and batteries for industrial purposes in Vietnam.	16
(COMBE *et al.*, 2019)	Economic	An economic analysis for replacement of diesel generation by RES with ESS in South Australia.	16
(AL-GHUSSAIN *et al.*, 2020)	Economic	General study of techno-economic feasibility of Wind, PV, and Storage.	15
(KATSAPRAKAKIS, 2016)	Regulatory	Feasibility of hybrid Wind, PV plus battery or hydrogen or pumped storage systems in Greek islands.	15
(KIWAN; AL-GHARIBEH, 2020)	Economic	A techno-economic study to supply all Jordan load from Wind, PV plus Storage.	15

Notes: UAE – The United Arab Emirates; Wind – Wind power electric generation; PV – Solar photovoltaic electric generation; Storage – It refers to any kind of energy storage.

The most cited study (277 citations) is a Dutch review study published in 2012 addressed to social and regulatory question faced by renewable energies, smart grids, and energy storage (WOLSINK, 2012). The most cited article in the economic feasible field (168 citations) is a Malaysian paper, also, published in 2012 (NGAN; TAN, 2012). Such paper analysed the implementation potential of a hybrid system composed by photovoltaic panels, wind turbine, and diesel machines. This list of the most cited articles is composed of eight papers related to regulatory or legal field, 33 in economic feasibility, and two addressed to both aspects.

There are six reviews and 37 articles among the most cited in the sample. Six of them are global studies. The others 37 studies are focused on a specific region or country. The most studied country is Iran, possessor of seven papers, followed by the USA and Australia, with four articles. Three documents are addressed to India. Greece, Saudi Arabia, and Nigeria had two papers each, and more 14 countries with one study each are in the sample. The regulatory studies varying from global purposes to local regulatory assessment and reviews of regulatory frameworks.

The most used tool to techno-economic analyses in the sample was the Hybrid Optimization of Multiple Energy Resources (HOMER), a software produced by the USA National Renewable Energy Laboratory (NREL) to optimize hybrid energy systems. HOMER was 12 times used while Multiple Objective Genetic Algorithm (MOGA), Multiple-Objective Self-Adaptive Differential Evolution (MOSaDE) algorithm, and

Cuckoo Search algorithm was used only once each. The other articles do not identify the used software for economic analyses.

The preferred economics tools were cost of energy (COE) and net present value (NPV), but the authors, also, used levelized cost of energy (LCOE), net present costs (NPC), loss of power supply probability (LPSP), life cycle cost analysis (LCCA), and renewable factor (RF), among others did not cited. It is worth mentioning that, normally in the research presented in the previous table, the COE refers to the costs related to generation, investments, operation and maintenance (O&M), battery charging or other cost variables, while the LCOE is a ratio between these costs and energy generated. Finally, NPC and LCCA are seen as equivalent in the literature (ROTELLA JUNIOR *et al.*, 2021).

As articles published in 2019 and 2020 had not enough time to be well cited but can be already relevant in this field of study, the most cited papers of the sample published in 2019 and 2020 with 10 to 15 citations are shown on Table 2.3.

Table 2.3 – Most cited papers of the sample published in 2019 and 2020 with 10 to 15 citations.

Reference	Field	Remarks	Citations
(GONZALEZ-GARRIDO *et al.*, 2019)	Regulatory and Economic	An economic study for an optimal strategy to face the market rules in Iberian market (Portugal and Spain).	14
(AYODELE *et al.*, 2019)	Economic	Feasibility of small, islanded hybrid Wind, PV, batteries systems in Nigeria.	13
(MEZA *et al.*, 2019)	Economic	Tecno-economic analyses for hybrid wind, PV plus ESS in Ometep Island, Nicaragua.	13
(HEMEIDA *et al.*, 2020)	Economic	An analysis for hybrid Wind, PV plus batteries storage in Egypt	13
(PALIWAL; SINGH; SINGH, 2019)	Regulatory and Economic	Feasibility of a hybrid system in India facing the SDG7, issued by United Nations.	11
(MAZZEO *et al.*, 2020)	Regulatory and Economic	A worldwide assessment of Wind PV systems considering techno-economic feasibility, feed in tariffs, and subsidies.	11
(KATSAPRAKAKIS *et al.*, 2019)	Economic	Analyses of a hybrid Wind, PV and pumped hydro storage system in the Faroe Islands, Denmark.	10

Note: SDG7 – The seventh United Nations Sustainable Development Goal

These papers reveal the tendency of academic sector to study hybrid systems composed by wind power, solar PV and energy storage, especially battery banks. This selection present more worldwide studies in recent years. The most used techno-economic tool still being the HOMER software, but some articles had explored other economic tools.

The most recent studies (among them, those shown in Table 2.3) seem to be dedicated to the development of techno-economic analyses, supporting the sizing of hybrid power systems (optimal sizing), words that stand out in Figure 2.4 as being more recently used in the literature. At the same time, the most frequent use of BESS stands out, and some studies are still dedicated to issues like power quality and reliability.

On Table 2.3 are, also, demonstrated that studies with economic and regulatory aspects together are growing up. This is one of the main finding of this literature review: only in the last years regulatory and economic aspects were discussed together. To analyse the connection between economic and regulatory aspects, Figures 2.6 and 2.7 were constructed. Using the VOSviewer® software, a map was created to reveal the citation connections among documents in the final sample.

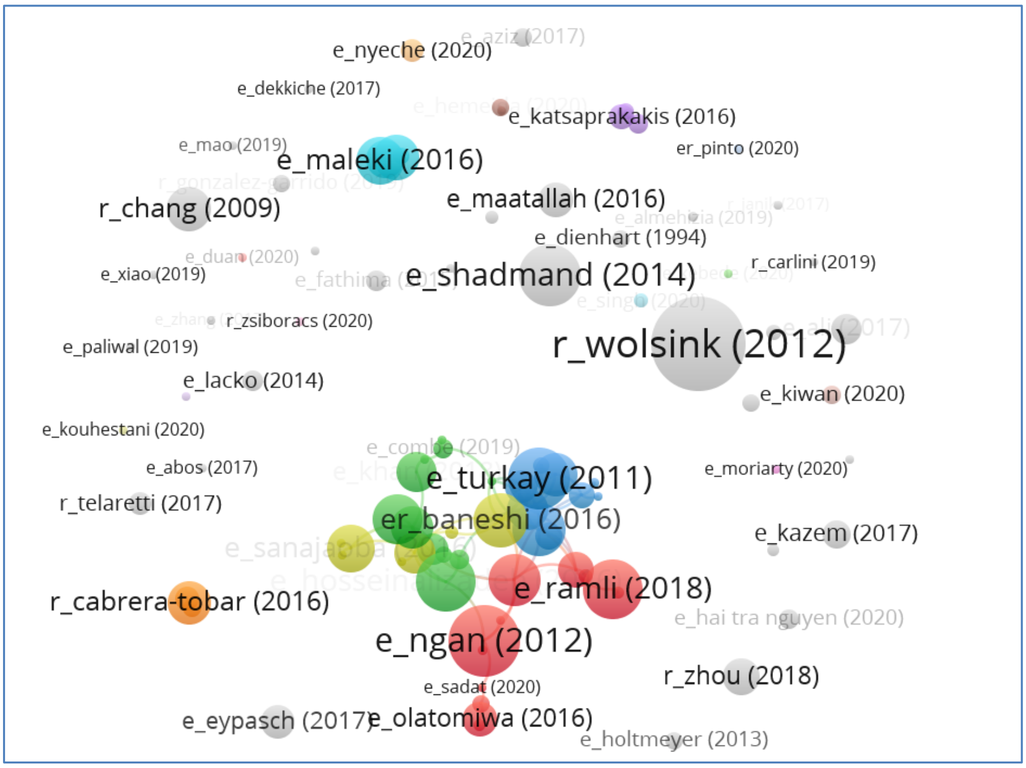

Figure 2.6 – Citation map with all publications in the final sample.
Source: the author, 2021

All articles in the sample are displayed on Figure 2.6. It is worth remembering that the letter that precedes the authors' names refer to the search field (e – economic, r – regulatory, and er – both fields). In this map, 40 papers are connected to each other (at the bottom and central part of the figure) and 55 articles remain isolated from each other. Studies related exclusively to regulatory aspects remain almost entirely among non-connected articles, as one can see in this first figure.

In Figure 2.7, the connected articles are all related to economic viability, with only two incorporating both aspects (BANESHI; HADIANFARD, 2016; LIU *et al.*, 2018). Based on this, it is possible to affirm that although regulatory aspects influence and may allow a greater economic viability of hybrid projects, little is yet discussed about this relationship. The fact of not having enough academic publications, that can help to direct public policies to encourage the development of more sustainable energy generation and storage systems, is a problem that consists in a gap to new studies.

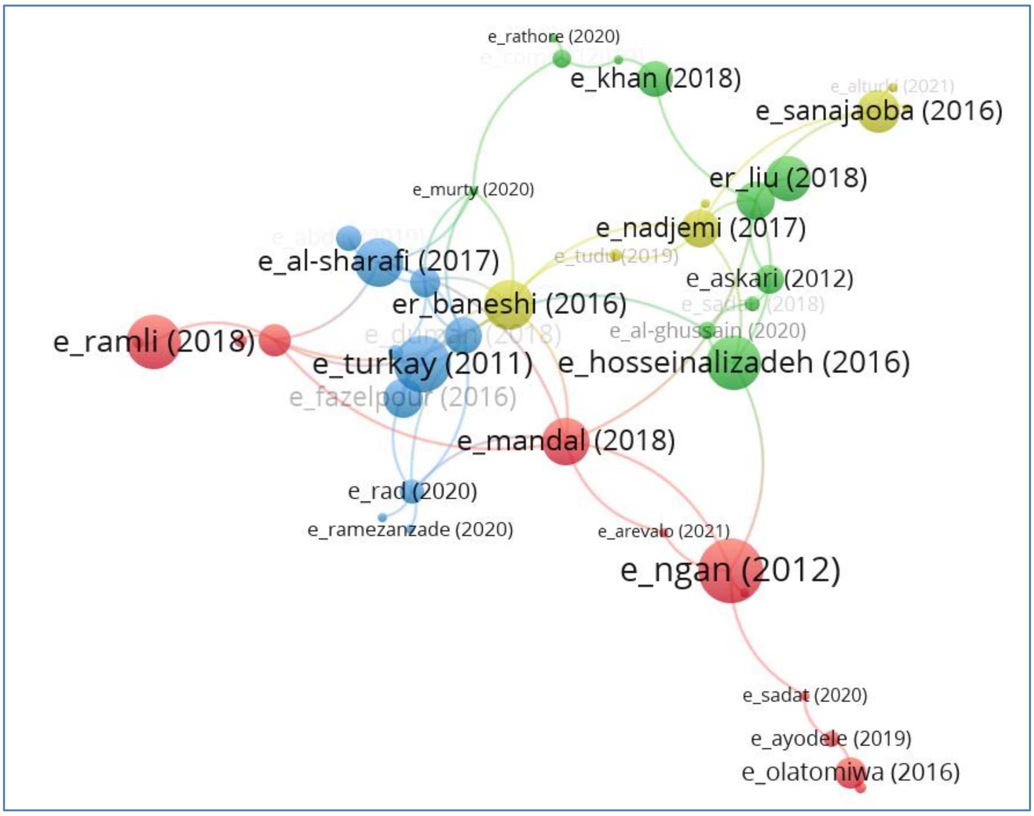

Figure 2.7 – Citation map with connected publications in figure 2.6.
Source: the author, 2021

As can be seen in the literature, there are few articles dedicated to feasibility studies involving regulatory aspects in electricity generation by hybrid wind-PV systems with ESS. Thus, to answer RQ3 (*what are the main legal and regulatory aspects worldwide for hybrid wind-PV generation with ESS and how they can contribute to the recent regulatory discussion in Brazil?*), it was decided to seek the main legal and regulatory aspects in force in similar regions or countries worldwide, compare them to the Brazilian legal framework and provide a brief discussion of how these can contribute to the recent discussion in Brazil or in other countries that do not yet have regulations for hybrid wind-PV systems with ESS.

The results of legislation search for six chosen regions (Europe Union (EU) and 4 other countries, besides Brazil) demonstrate there are many differences in the legislation ways around the world, as shown on Table 2.4 (for more information, see Appendix 2.2). In general, electricity sectors worldwide are divided into four segments: generation, transmission, distribution, and electricity trade. Generation and trade are competitive markets and almost deregulated, while transmission and distribution are natural monopolies strongly regulated. These segments were defined, in Brazil, by Decree nº 41,019 (BRAZIL, 1957) in the year 1957, meanwhile the real separation was observed after the unbundling in late 90's. Brazil and USA have more rules than other countries, but it does not mean the others are less regulated. In the EU, for example, all regulation for renewable energies is compilated in a single document.

Table 2.4 – Legislation for renewable energies

Country	Low	Decree	Rule	Other	Total
USA	4	0	13	0	17
UK	3	0	10	0	13
Spain/EU	1	5	5 (1)	4	15 (11)
India	2	0	3	0	5
Australia	5	0	1	0	6
Brazil	3	5	7	2	18

Source: Research on government websites, 2021.

As the USA is a federated nation many of their regulation are states issued. The federal regulation is addressed to interconnection policies (CHERNYAKHOVSKIY *et al.*, 2016), including all interstate and wholesale electricity trade. States have intrastate interconnections jurisdiction, but they have no authority over facilities that provide services across state borders or participate in the interstate electricity markets. The transmission or distribution utilities, where the generator proposes to connect, determines the final rules and technical specifications for the interconnection and use of the distribution or transmission grid. Generators under 20 MW installed power usually are classified as DG connected to distribution grid.

The Public Utility Regulatory Policy Act (PURPA) (USA, 1978), published in 1978, is the first and foundational policy that paved the way for small non-utility generators to enter the market, including renewable energy as wind and solar PV. In 1990 US Congress issued the Energy Policy Act of 20 Solar, Wind, Waste, and Geothermal Power Production Incentives (USA, 1990), whose objective was to encourage the production of electricity from solar PV, wind, waste and geothermal sources. There are two more US Acts that make some changes in these two first laws (USA, 1992, 2005).

US federal regulation regarding renewable energies is composed by 13 FERC orders. Among them, the FERC Order 2006 (FERC, 2005) established a fast-track process and reduced the timeframe and cost of interconnection for small renewable energy generators. Several states used the FERC Order 2006 as a model for their own regulation for connecting small distributed generation plants, since federal regulation does not affect small local connections. Some states, such as California, Hawaii, and New Jersey, have not imposed a size limit for DG (FINK; PORTER; ROGERS, 2010). Energy storage devices was included in the Small Generator Interconnection Procedure and Small Generator Interconnection Agreement by FERC Order 792 (FERC, 2013). There are many regional, state, or municipal regulation for small producers connected to the distribution grid, in the USA.

In the EU, according to Nouicer et al. (2020), the Clean Energy for all Europeans Package, also referred to as the Clean Energy Package (CEP) (EU, 2020) is a compilation of eight legislative acts related to renewable energies. The European Commission published the final text in the Official Journal of the European Union in June 2019, after an agreement among the European Commission, Council and Parliament. The CEP consists in 4 Directives and 4 Regulations.

The EU directives must be regulated by state members, while the regulations are directly applicable in all EU members (MARTÍN-SONSECA, 2020). Therefore, among the 5 regulations of Spain found in this study, 4 are to regulate the EU directives. Thus, the legislation of Spain/EU for renewable energies consists in 11 documents. All legislation of Spain for electric energy, including renewable energies, is compiled in a unique document called Código de la Energía Eléctrica (MARTÍN-SONSECA, 2020).

The main UK electricity law is the Electricity Act, promulgated in 1989 (UK, 1989), with general rules for the sector. The first law related to RES is the Sustainable Energy Act 2003 (UK, 2003), where provisions about the development and promotion of a sustainable energy policy were made. Sustainability and RES are better regulated in the Energy Act 2004 Part 2 (UK, 2004). Microgeneration and DG are defined in this law.

There are, also, 10 national rules related to renewable energies and DG. Ofgem is the Office of Gas and Electricity Markets, a non-ministerial government department and an independent national regulatory authority responsible for regulation of gas and electricity markets in the UK.

Regarding India, through the Electricity Act 2003 (INDIA, 2003) the Indian Parliament have consolidated all previous legislation regarding to generation, transmission, distribution, trading and use of electricity and constituted the regulatory authority named Central Electricity Regulatory Commission (CERC). The main authority for renewable energies is the Ministry of New and Renewable Energy (MNRE).

By Electricity Rules 2020 (INDIA, 2020), published by Central Indian Government in December of 2020, the figure of prosumer and its rights and duties was regulated. Prosumers are allowed to install their own renewable energy plants by themselves or through a service provider. Each state regulatory body specifies limits for this kind of DG. The CERC has issued three regulatory acts for technical, economic and tariffs regulations of renewable energy systems.

In Australia, the production of electricity from renewable sources has been regulated since 2000, by the Renewable Energy (Electricity) Act (AUS, 2000a). The Law was well defined in the Statutory Rule 2 in 2001 (AUS, 2001). Still in the year 2000, due to intermittence and seasonality of renewable sources, a new Act was promulgated to regulate the large-scale generation shortfall charge (AUS, 2000b). Only in 2010 the same regulation was issued for small-scale generation from renewable sources (AUS, 2010).

Regulatory bodies were created in 2011. The Australian Renewable Energy Agency (ARENA), created by Act 151 (AUS, 2011a) is a funding agency responsible for improving the competitiveness of renewable energy technologies and increase the supply of renewable energy in Australia. Meanwhile, by Act 163 (AUS, 2011b), the Clean Energy Regulator (CER) was stablished as a national regulatory body for renewable energies.

Finally, in the Brazilian scenario, the first law related to renewable energy was Law nº 10,438 (BRAZIL, 2002), promulgated in 2002, where was created the Incentive Program for Alternative Sources of Electric Energy (PROINFA). Such Program aimed to incentive the installation at least of 3,000 GW from wind and biomass sources. Currently in 2021, there are two bills pending in the Brazilian National Congress. Bill of Law (PL) 5,829/2019 (BRAZIL, 2019) creates a subsidy by reducing the tariff for the use of transmission and distribution systems for DG. PL 616/2020 (BRAZIL, 2020), on the other hand, deals with the prosumer regulatory framework, creates the figures of the supplier of last resort and of the retail trader, releases the sale of energy by prosumers and revokes the electric energy compensation system (EECS).

Brazilian regulation for renewable energy is addressed to formal documentation, techno-economic aspects, and economic subsidies. Five decrees and seven regulatory norms discipline renewable energy in Brazil. They consider generation sources separated and there was no regulation for energy storage systems in force in 2021. The Normative Resolution (REN) 482/2012 (ANEEL, 2012), amended by REN 687/2015 (ANEEL, 2015), is the main norm for DG up to 5 MW of installed capacity. It lays down general conditions for accessing to distribution systems and created the EECS. REN 538/2013 (ANEEL, 2013) establishes the procedures and conditions for obtaining and maintaining the operational situation and defining the installed and net power for all electricity generation enterprises, including installations of DG. REN 876/2020 (ANEEL, 2020) defines generating plants with reduced installed capacity, up to 5 MW of installed power, and the way for bureaucratic procedures with ANEEL.

The Brazilian National Environment Council (Conama) is a governmental advisory body for environmental questions. Conama Resolution 259/2001 (CONAMA, 2001) establishes procedures for simplified environmental licensing of electrical projects with small potential for environmental impact. On the Conama Resolution 462/2014 (CONAMA, 2014), the council have dispensed the environmental licence for micro centrals up to 100 kW installed power.

As happened in the US and Europe, the electricity produced from new renewables sources is undergoing a rapidly grow in Brazil, despite the little economic incentive and investment in research and development. The budget to research and development (R&D) for all Brazilian electric sector is around 100 million dollars per year, based on last 10 years data (ANEEL, 2021c). This is very different when compared to other nations. For instance, in the end of 2000's the US have approved the Smart Grid Demonstration Program, that allowed an investment of 1.5 billion dollars in R&D only for smart grid and energy storage projects (TELARETTI; DUSONCHET, 2017).

The correct payment for ancillary services is an important issue that still not well addressed in the Brazilian regulatory framework. Meanwhile in the US, the FERC Orders 755 and 890 allows installations like energy storage systems to be paid for provided ancillary services (FERC, 2007, 2011). Many US states, such California, Hawaii, New Jersey, New York and Texas, have also offered economic incentives for energy storage systems as financial support and/or feed-in-tariff (TELARETTI; DUSONCHET, 2017). Utilities and RES generators are obligated to install ESS to provide services as stability, reliability, frequency control, among others.

In the EU, as predicted on the CEP (EU, 2020), the member states have created incentive mechanisms to RES and ESS, such as subsidized financing, feed-in-tariffs and tax exemptions. India and Australia consider clean energy production to be so important that they have created specific government bodies for this area: the Indian MNRE and the two Australian regulatory agencies, ARENA and CERC. Both countries have economic and financial incentives for RES and ESS.

Therefore, Brazilian legislators and regulators should follow the international example and create more kind of incentives for hybrid wind power plus solar PV generation and ESS. Mixed auctions for wind and solar PV energy must be allowed and economic incentives offered for ESS to be installed together with these installations. Resources for subsidies must come from the national treasury to not affect tariffs, as it happens with cross subsidies.

2.5. Conclusions

This literature review allowed to analyse the main elements of the research carried out on economic feasibility and regulatory aspects of hybrid wind power and solar PV generation with energy storage systems. Among the different results, this analysis identified the limitation in the connections of studies discussing economic feasibility and regulatory aspects in these enterprises. In the context of Brazil this is a major bottleneck. The lack of specific regulation on these hybrid systems creates uncertainties and little economic convenience for entrepreneurs. For this reason, the article explored how legislation in different countries around the world was organized to point out examples to be followed in countries with no adequate regulation yet.

The research also allows to identify that around the world most scientific studies focus mainly on only one of renewable energy technologies. There are only few studies focused on the wind power, solar PV and ESS technologies working together, and even less that also addressed to regulatory or legal aspects. In fact, studies involving regulatory or legal aspects are rare, as these two themes are dynamic and have regional content. A few studies comparing regulatory framework, especially grid codes, were found. It was not found any scientific study addressed to these three technologies working together in Brazil. As academic interest in these subjects is growing rapidly up in other countries, there is an important gap to be fulfilled here in Brazil.

The study identified that recent themes of academic studies stand out, such as optimal sizing and loss of power supply probability. The problem of optimizing sizing is more related to techno-economic and financial feasibility studies, while studies on loss of power supply probability are related to issues involving grid quality and reliability, and therefore more related to energy storage systems.

Observing the world tendency, the new studies should address the techno-economic feasibility of wind power and solar PV in conjunction with, at least, one kind of ESS. Also, it is very important to take in account the regulatory barriers and proposes solutions to remove them. It was observed that although regulatory aspects can influence economic feasibility of hybrid projects, little is discussed about this relationship between these frameworks.

The Brazilian electric matrix is essentially from hydraulic source. However, the growth of renewable sources follows the same worldwide pattern. The main difference is that, in Brazil, energy storage is done by storing water in the hydropower reservoirs. The other types of energy storage are still very incipient, but the capacity of hydraulic reservoirs tends to run out in a few years, which will lead to the need for other forms of energy storage. Even the regulation of the electric sector is not prepared to encourage the insertion of devices for energy storage. It is important to emphasize that the findings presented in this chapter are important not only for Brazil, but also for other countries that do not have current regulations that support the use of ESS in hybrid systems.

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3. CHAPTER 3 – Impact of proposed regulatory changes on the economic feasibility of distributed solar photovoltaic generation

3.1. Abstract

The current distributed generation technologies are evolving towards the progressive integration of micro-power plants in the electrical distribution grid. The main challenge is to make these micro-power plants economically feasible and, if possible, profitable for the users or for suitably formed energy communities. Micro-photovoltaic power plants are seen as the solution that can be installed more easily, especially because of high modularity and adaptability to different installation in buildings or in the terrain. The assessment of the economic feasibility of micro-photovoltaic power plants is particularly effective when it is conducted at the nation-wide level, particularly for a big country. For this purpose, after recalling the situation in countries that have already adopted specific policies for promoting micro-power solutions, Brazil is considered as an effective test case for analysing how to promote viable solutions starting from a relatively low initial diffusion of micro-photovoltaic plants. In fact, Brazil is undergoing important changes in its distributed generation regulations, including the production of electric energy from micro-photovoltaic power plants. The proposed amendment by ANEEL (the national regulatory body for electricity) provides economic compensation only for the cost of energy, whereas the costs of services and charges included in the tariff should be prorated, according to the consumption of all consumers connected to the grid. Consumers with already installed plants and their representative entities contest this proposal in a way that became known as "sun fees" through many public interventions from those entities, but we have not found scientific work to corroborate these claims. Indeed, the new regulation proposes the end of cross-subsidy, in which consumers without distributed generation pay for tariffs and charges of transmission and distribution systems used, also, by the consumers with distributed generation installed. In this paper, a comparison of the economic and financial viability of residential photovoltaic micro-generation before and after the new standard proposed by the Brazilian regulatory agency is carried out. Data as, averages of the solar radiation, tariffs and demands, in the five geographic Brazilian regions are used for comparisons. Stochastic analyses varying the initial investment, demand and energy tariff are carried out. Finally, a stochastic analysis of the Brazilian context is performed, varying the minimum attractiveness rate. Despite the high probability of viability in both scenarios, reductions in the average NPV are

clearly identified after the proposed change. The study concludes that there is a statistically significant reduction in the economic viability of distributed photovoltaic generation in all Brazilian regions.

3.2. Introduction

Renewable energy sources (RES) has been the focus of governments worldwide, in an effort to expand its share in electricity production (ESEN; INALLI; ESEN, 2006). Governments worldwide have been pushing legislation to ease integration of solar power into the energy markets (DUMAN; GÜLER, 2020), however recent policy proposals of National Electric Energy Agency (ANEEL) are running against the global trend of supporting the solar power (TIMILSINA; KURDGELASHVILI, 2017).

According to the European Photovoltaic Industry Association (EPIA, 2016), the photovoltaic solar energy generation technology has the potential to become the largest renewable energy source in the world, due to the great and continuous growth in the use of this energy source. Solar energy stands out as one of the most promising alternatives to increase the use of renewable sources, and governments work on mechanisms, regulations, and policies to encourage the promotion of investment in solar energy (DUMAN; GÜLER, 2020).

Up until the late 2000s in Brazil, when the first grid connected pilot projects went into operation (ANEEL, 2021a), solar power units were comprised of small installations in islanded areas that did not have access to the distribution grid, as it was not economically viable to expand the coverage to these areas. This was somehow changed by the two most important solar distributed generation Brazilian policies, 2012 and 2015 regulations REN nº 482 (ANEEL, 2012) and REN nº 687 (ANEEL, 2015).

The National Electric Energy Agency (ANEEL) which is responsible for drafting and passing legislation on electrical energy in Brazil passed a resolution nº 482 in July 2012 that set out the guidelines for micro generation and mini generation in Brazil. Micro generation was defined as up to 75 kW installed power, while mini generation, in turn, was defined from 75 kW up to 1 MW installed power, both when connected to the distribution grid. The resolution also established the conditions for compensation, the so-called Electric Energy Compensation System (EECS).

In November 2015 ANEEL published another regulation, REN nº 687, outlining benefits to micro and mini generators, and defining included joint and remote distributed generation systems, stating that generated energy can be shared among several consumer units, as long as they fall within the same concession area. Furthermore, energy credits were adjusted and the validity period was increased from 36 to 60 months (DRANKA; FERREIRA, 2018). Also, maximum generation power per unit increased from 1 MW to 5 MW and the process of connecting the distributed generation (DG) unit to the distribution grid was simplified (ANEEL, 2015).

Public Hearings were also held to help ANEEL improve existing regulation. Two examples of these were Public Hearing nº 001/2019 and Public Hearing nº 025/2019 (ANEEL, 2019a), which conducted regulatory impact assessment (RIA) and allowed the public to suggest changes to a resolution that would be published in 2021.

The price of electricity is influenced by many factors, including transmission costs, and charges for electrical losses etc. These costs are fixed costs and are divided among all consumers. However, many consumers that have installed DG systems were not paying these costs, per the regulations set out in REN nº 482. This cost was therefore effectively paid for by other non-DG consumers (ANEEL, 2019a).

For DG users, ANEEL therefore proposed that only energy costs should be compensated for. All ventures that have already been installed, or that have completed their installation requests up until the publication date of the new standard, will be allowed a transition period, and will continue with the subsidy under the standard until 2030. New entries will be subject to the new rule.

A natural policy question is to ask how much the proposed removal of a subsidy will affect the financial viability of solar DG, in light of natural, economic, and regional specific conditions. We answered this question by using a before and after financial analysis. We took data on demand, energy prices, and solar incidence from five regions in Brazil: the northeaster, the southeaster, the central western, the north and the south Brazilian regions. These five regions cover the whole area of Brazil. We varied demand, installed capacity, energy prices, and initial investments using stochastic analysis via Monte Carlo Simulations (MCS). Lastly, we conducted stochastic analysis on a national scale by changing the minimum acceptable rate of return (MARR).

The existing literature shows that microgeneration technologies have been more widely adopted because they save energy and are cheaper (ROCHA *et al.*, 2018). Users end up reducing their electricity costs and have positive returns on their investment, according to Walters and Walsh (2011). Furthermore, micro generation units help to prevent transmission blockages, replace capital intensive infrastructure or postpone investment on it, and reduce transmission losses (BAYOD-RÚJULA, 2009).

In our analysis we use standard financial analysis tools of net present value (NPV), the discounted payback time (DPB), and the internal rate of return (IRR), complemented wit MCS. These are all essential metrics for analysing the economic viability of energy projects, as explained on section 1.3. General Theoretical Foundations.

3.3. Methodology

Initially, an exploratory research was carried out, through a literature review and consultation of normative resolutions, in addition to documents made available by ANEEL in consultations and public hearings on the topic. Thus, more information could be obtained, such as: cost determination; identify demands, prices and quantities of solar panels, frequency inverters and other items necessary for the process of installing a photovoltaic micro-plant to generate distributed electricity.

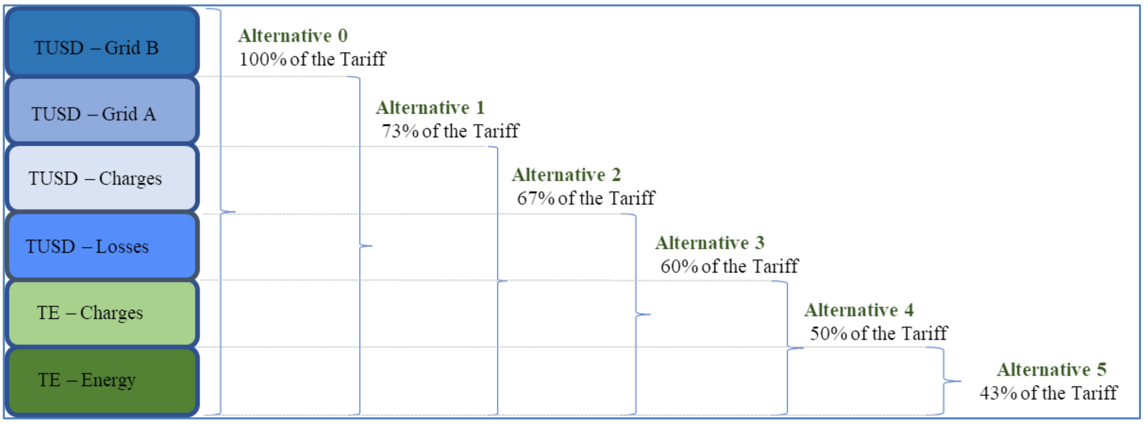
3.3.1. Proposed changes to regulation

In 2012, Resolution nº 482 was issued, creating the electric energy compensation system (EECS), a ruling that allowed surplus energy generated by DG consumer units to be injected back into the distributor grid. Future consumption could be discounted from this surplus supply.

The valid model in 2019 of this mechanism, which was maintained in its original form after the revision of REN nº 482/2012 by REN nº 687/2015, stated that the injected energy is used to fully reduce the consumed energy, considering all tariffs, so that the energy injected into the grid by the DG ends up being valued by the full electricity price established for all consumers.

The main solar distributed generation policy discussion in Brazil is on how to value the surplus energy injected into the electrical grid. On the one hand, distributors and some consumers claim that the current electricity compensation system does not provide adequate remuneration for the use of the distribution grid, transferring costs to other users who have not chosen to install their own power generation. On the other hand, installers and consumers interested in self-generation emphasize the benefits of generation distributed to society and consider that the current model must remain, to allow the consolidation of the market. This discussion is within the scope of Public Hearing nº 025/2019.

The REN nº 482 aims to reduce barriers to the connection of generation plants powered by small renewable sources. In addition to adapting the connection rules to the size of these users, the standard sought to make them economically viable. This was done, mainly, to reap the benefits that this source provides to the electricity sector and to society in general. However recently ANEEL made a proposal, which can be seen in Alternative 5 from Figure 3.1, where in only 43% of surplus energy injected into the national grid will be offset for.



Legend:
TUSD – Grid A: distribution system usage tariff, unmanaged by the distribution company.
TUSD – Grid B: distribution system usage tariff, directly managed by the distribution company.
TUSD – Charges: it refers to distribution sector charges, not including fees and taxes.
TUSD – Losses: it refers to electric and not-electric losses.
TE – Charges: it refers to generation sector charges, not including fees and taxes.
TE – Energy: Electric energy tariff.

Figure 3.1 – Alternatives for tariffs proposed by ANEEL.
Source: Adapted from CP 025/2019 (ANEEL, 2019a)

3.3.2. Main input variables

For this work, five inputs are necessaries: three of them vary by the analysed region (solar radiation, demand, and tariffs), so they will be considered as input factors. The MARR will be fixed, except for the stochastic analyse for the national case. Further, in a stochastic analysis, three of these variables will be treated as stochastic: investment, energy tariff and demand. The nominal power of the power-plant will vary according to demand and will be calculated for each simulation.

3.3.2.1. Solar radiation

According to Brazilian Institute of Geography and Statistics (IBGE), the Brazil's national territory is 8,510,345,538 km^2 which makes it the fifth largest country in the world after Russia, Canada, USA and China (IBGE, 2021a). With such vast land reserves with a high incidence of sun and winds, the National Laboratory for Renewable Energy

(NREL, 2021) has projected that RES will be highly expanded in Brazil into both wind and solar energy. Pereira et al. (2017), in their Brazilian Solar Energy Atlas, have shown that daily total annual average solar radiation in Brazil makes it an excellent country for solar installations, Figure 3.2.

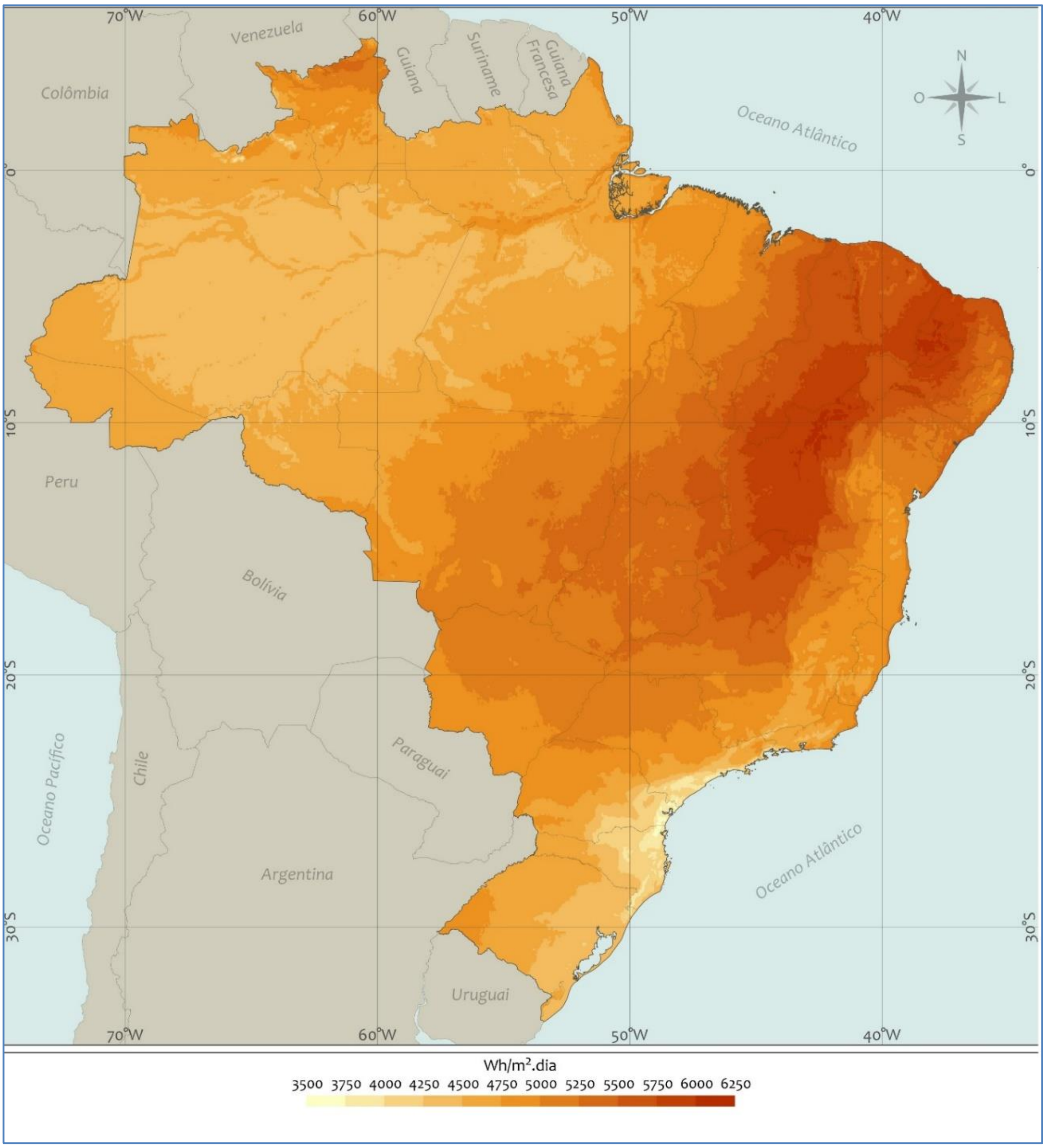


Figure 3.2. Annual average of daily total of global solar radiation.
Source: (PEREIRA *et al.*, 2017).

Even though the strongly variation of Brazilian climatic conditions through the territory, solar radiation is nonetheless quite uniform. Maximum Brazilian solar radiation is 6,5 kWh/m² per day. This occurs in the northern part of Bahia state, close to the border with the Piauí state. This area has a semi-arid climate with low rainfall throughout the year (approximately 300 mm/year), and the lowest annual average cloud cover. This area belongs to North-Eastern region, according to division used in the analytical part of this study. The lowest global solar radiation is 4,25 kWh/m² per day and, occurs on the north shore of Santa Catarina state in the south of Brazil where precipitation is well distributed all year long. This area belongs to Southern region, in the terminology of this chapter. The annual mean of daily horizontal global solar radiation in any region of the Brazil (1500-2500 kWh/m^2) is greater than the most European countries, like Germany (900-1250 kWh/m^2), France (900-1650 kWh/m^2), and Spain (1200-1850 kWh/m^2) where projects to harness solar resources are already widely implemented, with many government incentives (PEREIRA *et al.*, 2017). In this study, the average radiation for each analysed region was used, as shown in follows tables 3.1 and 3.3.

3.3.2.2. Residential demand

The electric power market is key to the growth and development of any economy. An accurate identification of the demand function parameters for residential energy consumption is relevant for the provision of estimates of future demand (UHR; CHAGAS; UHR, 2017). The demand to be adopted should considers the monthly consumption of middle-income family homes, but it can be extended to small business or small industrial applications. For the deterministic scenarios, the values adopted in this study are shown in tables 3.1 and 3.3 on next section, which were obtained according to the average residential demand in Brazilian regions published by ANEEL (ANEEL, 2021d). The Energetic Research Company (EPE), a Brazilian state company for energy studies, presented in the Technical Report 01/2020 (EPE; ONS; CCEE, 2020) the growth in electricity demand for the next years. Residential demand will grow up 3,9%, where 2,5% corresponds to new consumers and 1,4%, to the growth in consumption of each residential unit. This second number, 1,4%, was adopted linearly for all studied scenarios.

3.3.2.3. Installed power capacity

Dias et al. (2017) stated that panels that provide the best performance are those of mono and polycrystalline silicon. In this chapter was adopted a typical polycrystalline silicon panel with 250 W nominal power, 15.85% efficiency and 1.6 m² usable area. A useful life of 30 years was adopted with an annual loss of efficiency of 0.7%, predicted by some manufacturers.

The local average solar radiation, and average consumer demand, in addition to the characteristics of the panels to be used, must be known to accurately determine the power levels of a DG solar power-plant. The nominal power must be such that the set of solar panels produces an average annual energy equal to the average consumer demand. As the panels have discrete sizes, the most suitable or efficient power (optimal power) for a power-plant unit is calculated in a way that meets all the demand with the minimum residue. First the minimum required area must be determined, as shown in Equation 3.1.

$$A_T = \frac{D_m}{R_m * \varepsilon} \quad (3.1)$$

where: A_T is the total area of the solar panels' array in m²; D_m is the average annual demand in kWh; R_m is the average annual radiation in kWh/m² and ε is the efficiency of solar panels.

The number of solar panels will be found by the next integer of quotient between A_T and 1.6 (the panel's area adopted). Therefore, the nominal power (Pn) of the power-plant, in kilowatts, was calculated in this work for each simulation by (3.2).

$$P_n = nextInt(\frac{A_T}{1.6}) * 0.25 \quad (3.2)$$

3.3.2.4. Electricity consumption tariff

The ANEEL is the government agency responsible for the calculation and approval of electricity tariffs in Brazil. To calculate those tariffs, some costs are considered, such as: the price of energy; the cost of distribution and transmission grids; taxes and sector charges. Again, for the deterministic scenarios, the values adopted in this study are shown in tables 3.1 and 3.3 on next section, which were obtained according to the history determined by (ANEEL, 2021e).

It is important to explain that final consumers have no choice about the energy source in Brazil. Small consumers are all captive consumers and are into the so-called regulated market. In this market, the distributors purchase energy, from various sources located throughout the country, in public auctions. Next, based on the average price of energy purchased by each distributor, among other costs, ANEEL calculates the tariff for each one distributor companies.

3.3.2.5. Minimum attractiveness return rate

MARR is the discount rate or interest rate with which an investor will be satisfied. This discount rate varies primarily with the business risk, opportunity cost, and liquidity (VALE *et al.*, 2017). The intention of any investment is to obtain maximum benefits. Therefore, each company usually has its own economic parameter to analyse the project. There are usually many choices for an investment. When investors invest a sum of capital, they always expect to obtain a benefit for the capital greater than the MARR, in the project life period (ZHOU *et al.*, 2009). In this work, it was considered an investment being made by an individual; in this case, the same value adopted by (EPE, 2020), of 8% per year, was used. For the whole Brazil case, a stochastic analysis was carried out, using the MCS in the Crystal Ball® tool, varying the MARR from 0.5% per month, considering the worst scenario of saving accounts in Brazil, which results in a rate of 6.5% per year, up to an amount of 20% per year, which is a scenario in which consumers prefer to invest their capital in a high-risk investment.

3.3.3. Initial investment and costs

To determine the initial investment, a price survey was carried out at five regional retailers, covering 51 types and sizes of mini photovoltaic power plants from different manufacturers. For the deterministic scenarios, the value calculated for the photovoltaic panels was US$ 1,221.10 per kilowatt installed. The frequency inverters reach US$ 654.38 per kilowatt, which represents approximately 50% of the photovoltaic plant costs.

In addition to the initial investment, the installation of a micro-power plant requires costs, which include all the expenses necessary for the installation of the main equipment and accessories, defined in the Reference Price Bank for Transmission (BPR) (ANEEL, 2019b). As it is a micro power plant, several of the costs considered by ANEEL can be neglected or reduced. In this work, only the cost of technical labour to install the equipment was adopted, which corresponds to about 25% of the initial investment.

Equipment maintenance consists of cleaning the solar panels, the frequency of which depends on the location of the installation; in the replacement of the surge protection device (SPD) each 5 years in average and in the change of the inverters every 15 years. Bringing these amounts to present value and distributing them homogeneously over the 30 years of the project's useful life, a maintenance cost of approximately 1% of the initial investment per year was found, which was adopted in this study.

3.3.4. Output economic variables

Many economic parameters are usually used in a deterministic manner to estimate the economic viability of a system. In the first stage of this study fixed input parameters was used, as: solar radiation, residential demand, electricity tariffs, MARR and nominal power of the plant in a deterministic manner to estimate the outputs NPV, IRR and the DPB. After the firsts results, a stochastic analyse was carried out varying the nominal power, demand, energy tariff and investment. Finally, a stochastic analysis was performed, varying the MARR. In all scenarios the output economic variables NPV, IRR and DPB was observed.

3.4. Results and Discussion

Cash flows are determined by many factors, including investment, operation and maintenance cost, life span, payback period, inflation rate, minimum attractive rate of return, non-returnable subsidy rate, interest rate of loans, sale price of electricity, income tax rate and whether additional revenue generated by carbon credits is included or not (ZHOU *et al.*, 2009).

In this study, five base cases were used in a deterministic cash flow analysis, one for each political region of the country, considering the regulations in force in 2019. That regulation provided that the energy produced and injected into the grid was 100% offset by the consumed energy, that is: one injected kWh is equal to one later consumed kWh. The results for the base cases are shown in Table 3.1.

Table 3.1 – Results before proposed changes

Political region	Inputs			Outputs		
	ET (US$)	AD (kWh)	AR (kWh/m²)	NPV (US$)	IRR	DPB (years)
North-Eastern (NE)	0.18	112.69	5.9	2,189.27	18.03%	9.88
South-Eastern (SE)	0.18	175.35	5.6	3,728.38	18.33%	8.83
Central-Western (CW)	0.18	171.36	5.7	4,125.97	23.00%	6.72
Northern (N)	0.21	167.15	5.5	4,745.83	25.75%	5.59
Southern (S)	0.17	176.93	5.2	3,271.79	16.92%	9.87
Brazil (BR)	0.18	158.61	5.58	3,598.21	20.78%	7.79

Inputs: Electricity Tariff (ET); Average Demand (AD) and Average Solar Radiation (AR).

Considering approved the ANEEL's proposal, only the cost of energy, equivalent to 43% of the tariff, will be compensated. In this case, the calculation becomes more complex, as it is necessary to consider the amount of energy that the DG owner generates and consumes, without injecting it into the distribution grid. The reduction in compensation to 43% will be only about the amount of energy injected into the grid and then offset by the consumer, that is: only for the effective use of the distribution grid.

In this case, based on the information available at (ANEEL, 2019a), an annual average of energy produced and consumed by consumers (area A on Figure 3.3) was calculated. The average annual demand was used because the active consumer, the one who is able to adjust their own demand according to tariffs and production schedules, the so-called prosumer, was not technically possible in the entire Brazilian electricity sector in 2019. The economic feasibility calculations were made considering the reduction to 43% only on the amount injected into the grid (B on Figure 3.3) and, later, offset. The sum of the two C areas in the Figure 3.3 represents consumption from the grid which, according to REN nº 482, can be offset by the energy injected into the grid. From this C area the cost of availability (CA) must be subtracted. The CA is the minimum regulatory charge amount, modality take-or-pay, which is equivalent to the consumption of 30 kWh per month for single-phase grid connection (ANEEL, 2010).

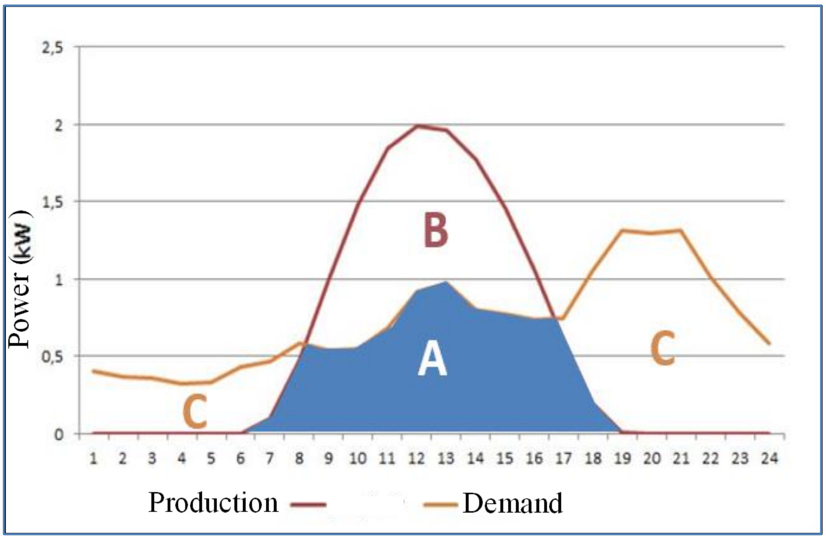


Figure 3.3 – Brazilian daily average of residential consumption and distributed solar PV generation. Source: (ANEEL, 2019a).

There are three situations in the case discussed above, which will have different treatments with and without the reduction to 43%, Table 3.2.

Table 3.2 - Hypotheses with and without reduction

Hypotheses	With no reduction	With reduction to 43%
B=C–CA	Consumer pays only the CA tariff.	Consumer pays 0.57(C–CA)+CA
B>C–CA	Consumer pays only the CA and get credits of difference B–(C–CA) of 1 kWh for each kWh consumed in the future.	Consumer pays 0.57(C–CA)+CA and gets 43% credits of difference B–(C–CA) to each kWh in the future.
B<C–CA	Consumer pays CA+(C–CA–B–Credits).	Consumer pays CA+(C–CA–0.43B–0.43Credits).

Note: B and C are areas on the Figure 3.2. CA is the Cost of Availability. Credits are the energy credits from the previous periods, whose was gotten in the center line hypothesis

The integral of A area on Figure 3.3 corresponds to 42.86% of electricity consumption and 54.33% of generation. The C area corresponds to 57.14% of consumption, while B area corresponds to 45.67% of the total of electric energy generated from photovoltaic power plant. In this case, which represents a national average of demand and production, 36.03% of consumption is compensated by surplus generation and only 21.11% is consumed from the grid. With these data and considering the proposed of ANEEL to reduce subsidies (reduction to 43%), the base cases are in the third hypothesis of Table 3.2 and they present the deterministic results in Table 3.3.

Table 3.3 - Results after proposed changes

Political region	Inputs			Outputs		
	ET (US$)	AD (kWh)	AR (kWh/m²)	NPV (US$)	IRR	DPB (years)
North-Eastern (NE)	0.18	112.69	5.9	1,184.27	12,97%	16,95
South-Eastern (SE)	0.18	175.35	5.6	2,136.23	13,49%	13,94
Central-Western (CW)	0.18	171.36	5.7	2,558.97	16,67%	10,90
Northern (N)	0.21	167.15	5.5	3,020.19	18,45%	8,83
Southern (S)	0.17	176.93	5.2	1,796.78	12,48%	17,96
Brazil (BR)	0.18	158.61	5.58	2,168.31	15,20%	11,91

While the comparisons of before and after policy change situation shown in tables 3.1 and 3.3 provides already a first indication of the effects of ANEEL's proposal, it was provided additional insights through following stochastic analysis. The MCS was performed using the Crystal Ball® tool, considering the parameters shown in Table 3.4. These parameters will have their own probability distribution function.

Table 3.4 – Input variables and their distribution functions

Input parameter	Distribution	Region	Minimum	More Probable	Maximum
Investment (US$)	Triangular	All	707.72	1,221.65	2,416.65
Energy Tariff (US$/kWh)	Triangular	NE	0.185	0.185	0.253
		SE	0.173	0.196	0.221
		CW	0.167	0.185	0.202
		N	0.152	0.192	0.307
		S	0.113	0.173	0.221
		BR	0.113	0.186	0.307
Electrical Demand (kWh)	Triangular	NE	73.13	106.75	132.81
		SE	103.75	163.68	215.06
		CW	120.73	168.66	213.54
		N	119.04	194.01	298.15
		S	118.59	173.24	282.62
		BR	73.13	163.85	298.15

The results for this first stochastic analysis are shown in the Table 3.5. In this table are presented the results of probability of viability for each of the five regions under analysis: North-Eastern (NE), South-Eastern (SE), Central-Western (CW), Northern (N), Southern (S) and Brazilian case (BR), for the scenario before and after the proposed change. In summary, the probability values of obtaining an NPV greater than 0, in which it is possible to verify scenarios of high probability of economic feasibility, are shown in that table.

Table 3.5 – Probability of viability by region before and after the changing proposed

P (NPV) > 0	NE	SE	CW	N	S	BR
Before	99.94%	100%	100%	100%	99.80%	99.88%
After	95.48%	99.66%	99.80%	99.90%	93.20%	97.12%

To better understanding the results for each region, figures 3.4 to 3.9 are presented. In these, for each proposed scenario under analysis (before and after the changing) and based on the simulations, the histogram and cumulative distribution function (CDF) are presented. In these figures, the scenario before is shown in blue, and the scenario after the changing proposed is presented in red colour. For example, in the case of the NE region (Figure 3.4), for the scenario before, the cumulative probability for NPV less than 0 is 0.06%; then, the probability of NPV greater than 0 is equal to 99.94%. However, for the scenario after the proposed change, the cumulative probability for NPV less than 0 is 4.52%; then, the probability of NPV greater than 0 is equal to 95.48%.

In the two y axis are shown the frequency and cumulative probability, respectively, whereas in the x axis is shown the NPV value. The same interpretation of results can be performed for the SE (Figure 3.5), CW (Figure 3.6), N (Figure 3.7), S (Figure 3.8) regions and the Brazilian case (Figure 3.9).

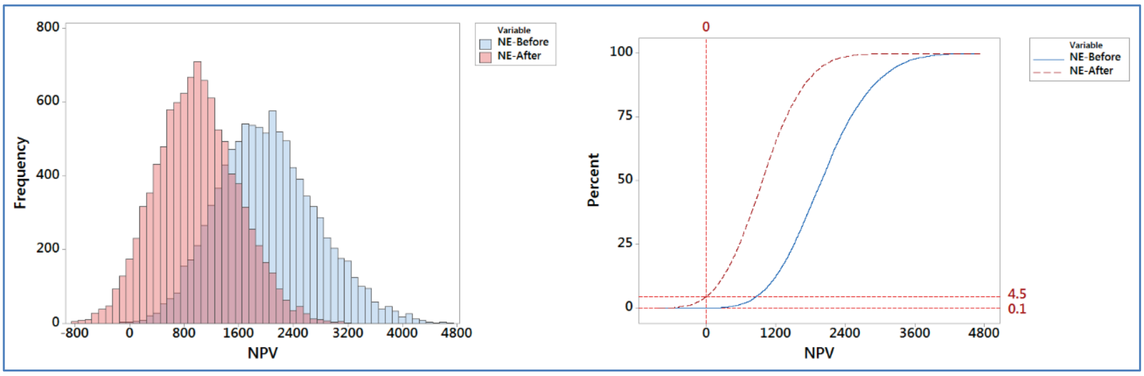


Figure 3.4. Probabilities of economic feasibility for the NE region.

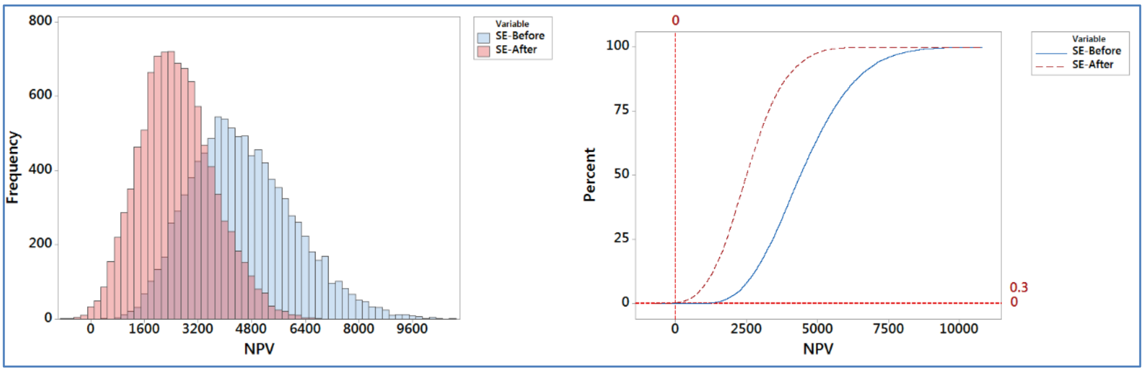


Figure 3.5. Probabilities of economic feasibility for the SE region.

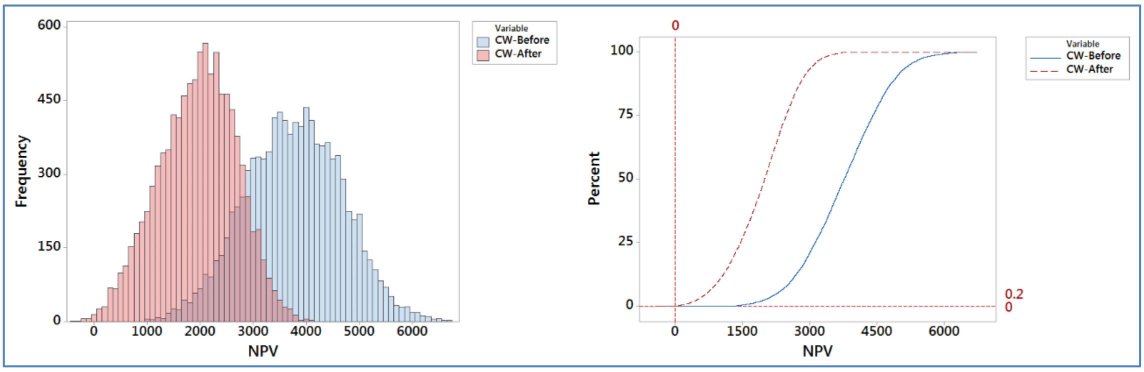


Figure 3.6. Probabilities of economic feasibility for the CW region.

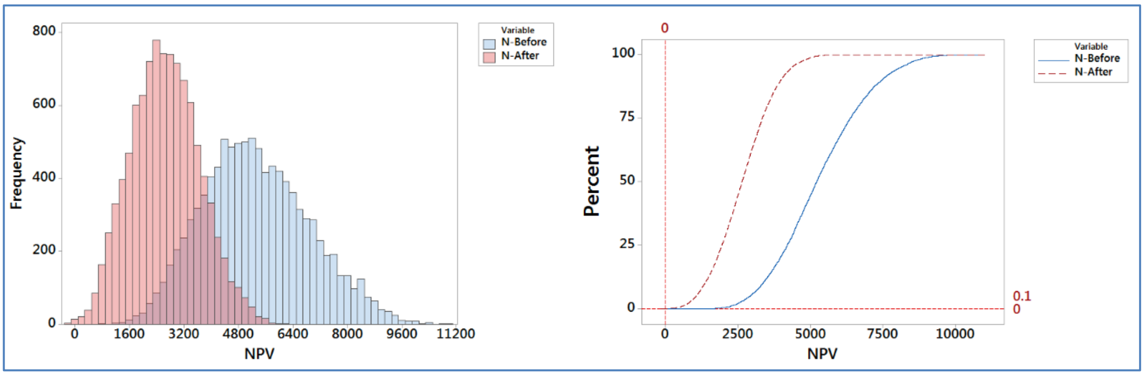


Figure 3.7. Probabilities of economic feasibility for the N region.

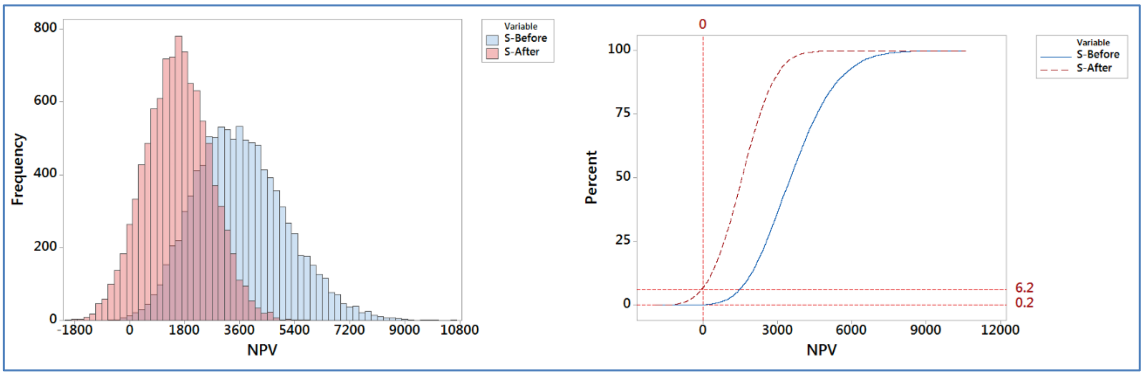


Figure 3.8. Probabilities of economic feasibility for the S region.

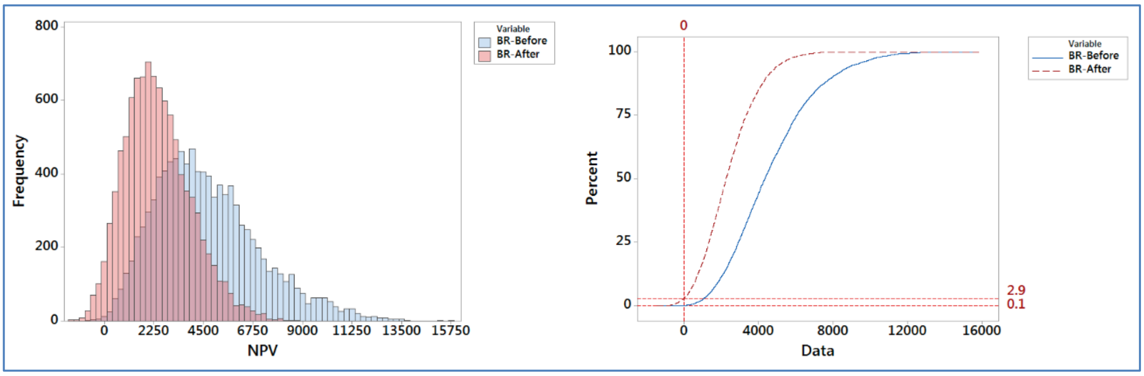


Figure 3.9. Probabilities of economic feasibility for the BR scenario.

Furthermore, the series of NPV results were collected from each scenario for each region and the analysis of variance (ANOVA) test was carried out, aiming at understanding whether there is a statistically significant difference for the average NPVs between the scenarios before and after the changing proposed. The results are shown in Table 3.6 and the values obtained in these analyses for the statistical tests are p-value of 0.000. These results confirm the existence of statistically significant differences between the analysed means of the NPV for each scenario. In Table 3.6 are also presented the number of simulations, the NPV averages before and after, and the p-values for each region.

Table 3.6 - Results of the ANOVA test by regions and between scenarios

Region	Simulations	Mean (Before)	Mean (After)	P-value
NE	10,000	2,030.80	990.30	**0.000**
SE	10,000	4,537.15	2,573.63	**0.000**
CW	10,000	3,764.43	1,951.78	**0.000**
N	10,000	5,320.95	2,660.23	**0.000**
S	10,000	3,633.10	1,581.18	**0.000**
BR	10,000	4,685.18	2,429.68	**0.000**

Note: Values in bold represent statistical significance.

The NPV distributions that were generated are graphically represented in Figure 3.10, using boxplots. It is clear that the returns in the scenarios before the proposed regulatory changes are higher in average and variance. Additionally, one can see that there is a difference in the NPV average values for each region.

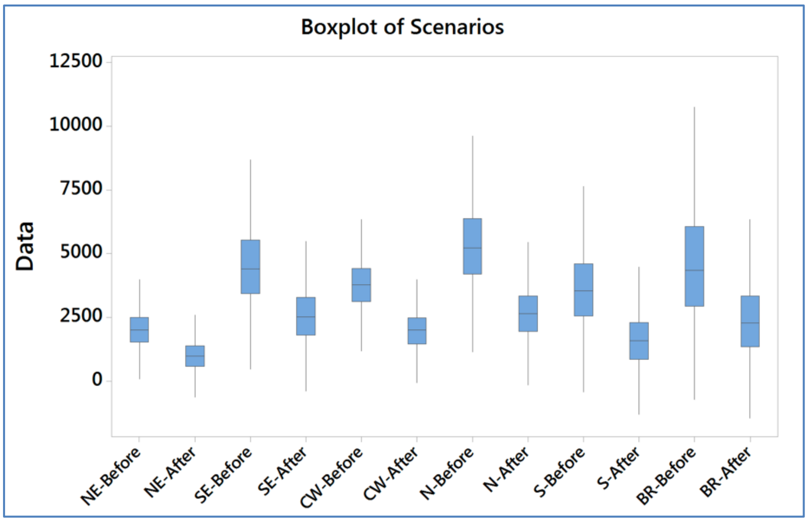


Figure 3.10 – Boxplots for NPV returns for each scenario

Using these same simulation results for the NPV, it was possible to apply the Test of Levene, which analyses whether there is a statistically significant difference between the variances in each scenario after the changing proposed. The comparison of variations allows the analysis of the dispersion of returns for electricity consumers who invest in photovoltaic microgeneration in different regions. The results, which are listed in Table

3.7, reveal that between regions, the variance of returns have statistically significant differences. Also, in Table 3.7 the standard deviation values for each of the compared regions are demonstrated.

Table 3.7 – Levene's Test results comparing the variance between regions after the changing proposed.

Regions	St dev 1st region	St dev 2nd region	P-value
NE x SE	601.68	1,108.86	**0.000**
NE x CW	601.68	725.70	**0.000**
NE x N	601.68	1,006.06	**0.000**
NE x S	601.68	1,062.21	**0.000**
SE x CW	1,108.86	725.70	**0.000**
SE x N	1,108.86	1,006.06	**0.000**
SE x S	1,108.86	1,062.21	**0.000**
CW x N	725.70	1,006.06	**0.000**
CW x S	725.70	1,062.21	**0.000**
N x S	1,006.06	1,062.21	**0.000**

As the first results show the feasibility for micro-plants after the proposed change in the entire country, a stochastic analysis was carried out varying the MARR, for the whole Brazil case (BR). This case represents the average of solar radiation, electricity tariffs, and demand in the entire country. Thus, in this case, in addition to the stochastic variables presented in Table 3.4, a variation of 6.5 up to 20% in the MARR was considered. For this end, a triangular distribution was used, in which the minimum, more probable and maximum values are 6.5%, 8% and 20%, respectively.

The NPV in this analysis behaved as in the Figure 3.11, in which the histogram and CDF are presented. The results have shown a 78.60% probability of being positive, which demonstrates a good economic feasibility for these projects.

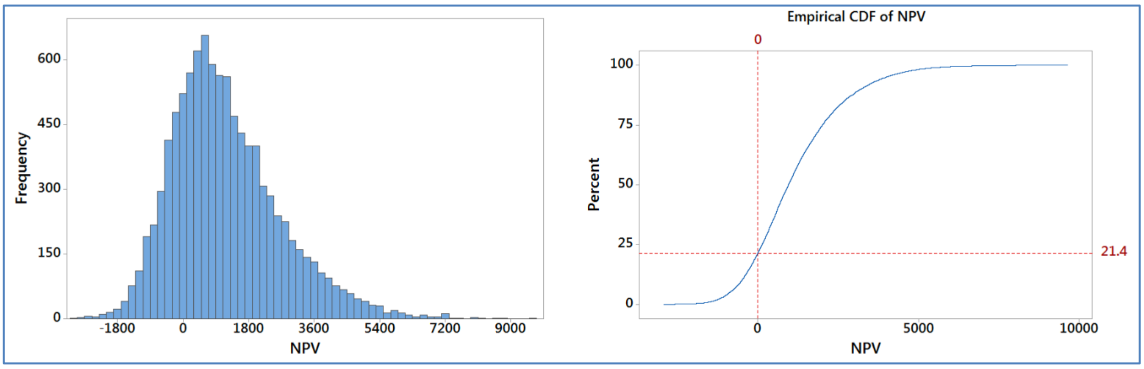


Figure 3.11 –Probability of economic feasibility varying the MARR for the Brazilian case (BR).

Holdermann, Kissel and Beigel (2014) examined the economic viability of small-scale, grid-connected photovoltaics in the Brazilian residential and commercial sectors. Rocha et al. (2017), in their study, analysed the impact of tax exemption on the circulation of goods and services, and the returns and risks of the photovoltaic microgeneration project in different regions of Brazil.

In both studies, the viability probability of investments in photovoltaic microgeneration was lower. The explanation for this difference stems from the fact that the equipment is more efficient, more durable and at a lower investment cost, showing the evolution of technology in recent years. In addition, from 2014 to the present, there has been an increase in the energy tariff in Brazil, making the technology more and more viable. Despite these positive points, the Brazilian photovoltaic industry has not progressed adequately and is still dependent on equipment imports, which exposes investors to exchange rate-related risk. According to de Souza and Cavalcante (2016), Brazil does not have significant internal production of photovoltaic technology, although it has large silicon reserves.

3.5. Conclusions

In deterministic analysis, when analysing the NPV and IRR, it is clear that residential micro-plants are viable throughout the country. However, it is necessary to consider other indicators, such as the discounted payback, that can discourage investors who are in a hurry to receive financial returns. Before the reduction to 43%, the DPB was around 8 years and, after the reduction, it grew to 12 years. This DPB time is very close to the moment when the operation and maintenance requires a great investment in the inverters exchange.

In the stochastic feasibility analysis, once again, a highly probability of viability was found, both in the scenario before and after the proposed change. In addition, two statistical tests were carried out to prove that there are statistically significant differences for the results of NPV. First, in the ANOVA test, it was evident that there is a significant difference between the means of NPV results on both scenarios (before and after) in each region. With the Levene's test, only the scenarios after the proposed change were analysed, in which it was found that there are significant differences among regions.

It should be noted that, when ANEEL proposal is in-force, there will be a significant reduction in the attractiveness of the photovoltaic micro-generation business for residential purposes. The results show that the business will still be viable, with an investment return in the long term, which discourage investors that are looking for economic results in the short term.

ANEEL proposal promotes tariff justice by making those who use the power grid pay the corresponding value to their own usage amount. However, based on the experience of other countries that have adopted subsidies for renewable energy sources, the national government and regional governments should consider other ways to subsidize this energy source that is so necessary to Brazilian sustainable development.

Despite having one of the lowest solar radiation averages, the Northern region, against the common sense, presents itself as the best region for investments in residential micro-plants. This is due to the high demand and the high electricity price paid by Brazilian northerner people. These variables are not stable in the long-term, as they depend on the behaviour of consumers and government policies. The opposite occurs in the North-eastern region, where, due to low demand and prices in the national average, presents less attractive economic indicators for investments in residential photovoltaic micro-plants, even with a high solar radiation incidence. Still, the Northeast region presented the smallest standard deviation of the NPV. This means that the financial results for this region revealed the least oscillation and, therefore, the lowest risk for investors in photovoltaic microgeneration.

The stochastic analyse for the national case varying the MARR shows that more than 79.60% of the cases results in a positive NPV. It means only investors who demand high IRR, around 20% a year or higher, will be out of Brazilian photovoltaic micro-generation market.

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4. CHAPTER 4 – Photovoltaic distributed generation and battery energy storage systems under technical-economic regulations

4.1. Abstract

Photovoltaic systems are largely involved in the process of decarbonization of the electricity production. Among the solutions of interest for deploying higher amounts of photovoltaic (PV) energy generation for reducing the electricity taken from the grid, the inclusion of local battery energy storage systems has been considered. Battery energy storage (BES) provides an energy buffer useful to better manage the fluctuations of PV energy production, or to serve the demand when PV generation is absent or insufficient and the price of the electricity taken from the grid is high. Even though technically sound, the installation of a PV system with battery energy storage has to demonstrate its profitability in the specific context of application, also depending on the regulation in place in the relevant jurisdiction. This chapter presents the stochastic economic feasibility analysis for the installation of distributed PV power plants facing the new regulation of electric energy compensation system, planned to be in force in Brazil since the second half of 2021, with the hourly tariff, known as white tariff (WT). Three classifications of distributed power plants are proposed, and the related models introduce battery banks to regulate the peak demand when tariffs are more expensive. Stochastic analysis varying the initial investment, minimum attractiveness return rate, energy demand, energy tariff, solar radiation and the installed power of the plants and battery banks are carried out. The results show that, in the absence of economic incentive policies to support this kind of renewable energy generation associated with battery energy storage systems (BESS), there is a small probability of economic viability, especially for micro-plants up to 10 kW of installed power. Thus, energy storage systems must still be economically incentivized to be installed in conjunction with distributed generation.

4.2. Introduction

The main component of the world energy matrix still being non-renewable sources (TESTA *et al.*, 2016). Thus, the environmental impacts caused by burning fossil fuels are still growing worldwide (WESSEH; LIN, 2016) and the scientific community is researching sustainable and energy efficient solutions. Also, an attention to this topic is increasing among worldwide policy makers (MEYAR-NAIMI; VAEZ-ZADEH, 2012). Data on world electricity production point out that renewable energies were the second largest contributor to global electricity production at the end of 2018 (IEA, 2018).

According to the Generation Information System of ANEEL (SIGA) (ANEEL, 2021a) the Brazilian electric matrix is predominantly hydroelectric with 52%, followed by thermoelectric, 26%, wind, 14%, and solar photovoltaic, 9%. Brazilian solar photovoltaic production essentially started when the Normative Resolution (REN) nº 482 482, the norm for distributed energy generation was issued in 2012 (ANEEL, 2012). However, the exponential grow is observed only from 2018 with the first utility-scale solar power plant auctioned by ANEEL in commercial operation.

The REN nº 482 establishes grid access conditions for micro and mini generators, as well as the electric energy compensation system (EECS). In 2019 ANEEL propose the end of cross-subsidy reducing the profits from injected energy to the distribution grid and late offset. This end of the cross-subsidy causes a significant reduction in the economic feasibility of distributed photovoltaic micro-plants (DE DOILE *et al.*, 2020). In this perspective, energy storage systems (ESS) applied to distributed generation can become attractive, as energy would no longer be injected into the grid and would be available for later consumption, without the discount proposed in the new normative (BOICEA, 2014).

The increasing use of intermittent renewable energy sources (RES), both for utility-scale electricity generation and for DG, substantially alters grid operations (DAS *et al.*, 2018; MALLAPRAGADA; SEPULVEDA; JENKINS, 2020). These operational challenges can be minimized by the incorporation of ESS, which play a prominent role in increasing the reliability and stability of the grid (YEKINI SUBERU; WAZIR MUSTAFA; BASHIR, 2014), and performing functions of operational support, load displacement, and power quality (WASIAK; PAWELEK; MIENSKI, 2014).

Energy storage systems are categorized as: mechanical, electrical, thermal, thermochemical, chemical, and electrochemical (DECAROLIS, 2019). For electrical energy applications, mechanical, electrochemical, and electrical types are generally used (MA; YANG; LU, 2014), whereas thermal energy storage may be of interest for specific solutions (ENESCU *et al.*, 2020). Currently, electrochemical systems, among which batteries stand out, have shown greater relevance due to their versatility (DECAROLIS, 2019).

Battery energy storage systems (BESS) have been used more frequently in the provision of various services to the grid, at different voltage levels (ROTELA JUNIOR *et al.*, 2019). In DG applications, BESS are used to add flexibility to operational strategies, and allow the monitoring of objectives for the demand side management. In all situations, one aspect considered critical is the cost of the batteries (LI; LU; WU, 2013).

The integration of distributed power plants with battery banks or other EES is a solution for the seasonality and better reliability of these generation systems (AL-GHUSSAIN *et al.*, 2020). Other authors consider at least three solar photovoltaic (PV) generation problems that can be solved by an appropriate ESS: (i) the dependence on the weather, (ii) the generation only during daytime, and (iii) the strong fluctuation of the generation (HEMEIDA *et al.*, 2020; HOPPMANN *et al.*, 2014). Battery banks are considered a more adequate ESS for small power plants due to its modularity and easy installations. However, even with battery prices decreasing in the last years (LIU *et al.*, 2020), the battery bank cost is still an economic barrier.

There was no regulation for ESS in Brazil in-force until 2021. Moreover, there are few studies related to this topic in Brazil. A study for a northern Brazilian city of Belem concluded for unfeasibility of small PV power plant with battery banks as ESS (DA SILVA; BRANCO, 2018). In a more recent study the authors, also, concluded for economic unfeasibility of hybrid solar PV plus lithium-ion battery banks (DEOTTI *et al.*, 2020). On the other hand, Cucchiella, D'Adamo and Gastaldi (2016) conducted an analysis for photovoltaic energy systems with battery storage for residential areas, without subsidies, in Italy. They conclude that residential PV plants with battery banks are profitable business in a fully developed electricity market, like in Italy. However, they recommend economic incentives at least in the beginning of market development for countries with electricity trade system not mature yet.

The present study aims to assess the economic feasibility of distributed solar photovoltaic power-plants with battery banks as ESS. The main barriers for ESS in Brazil are the lack of techno-economic regulation and economic incentives, as feed-in-tariffs or economic subsidies. Stochastic analyses are carried out by varying seven of the main variables in three sizes of PV power plant: micro-plant, up to 10 kW; mini plant, from 10 kW up to 1 MW, and small power plant from 1 up to 5 MW installed power. In all of them, battery banks supply capacity for five hours, one day, or four days were considered.

4.3. Methodology

The exploratory research, carried out previously, was deepened, as well as new documents made available by the Regulatory Agency (ANEEL, 2019a). The costs were obtained through market research and other necessary data, such as demand, tariffs, etc., from ANEEL's databases (ANEEL, 2021e, 2021d). Finally, several economic simulations using the Monte Carlo Simulation technique (MCS) were carried out.

4.3.1. Regulation in force in 2021

The regulation changes proposed by ANEEL were planned to be finished in 2020, but their application was postponed to 2022 due to the necessary changes in regulation priorities, caused by Covid-19 pandemic. This study considers the new regulation in-force and its effects on distributed generation. The main standards for DG still contained in REN nº 482, with subsequent amendments. The last change is related to the EECS, where only 43% of the energy injected into the grid will be compensated. This amount corresponds to the electric energy cost only.

In this chapter the following regulatory concepts are considered:

(i) Electricity compensation system, a system in which the energy injected into the network is provided, free of charge to distribution company (DISCO), and subsequently compensated by using energy from the distribution grid.

(ii) Multiple units' enterprise, characterized by a group of users sharing the same private electric grid, as condominiums or similar.

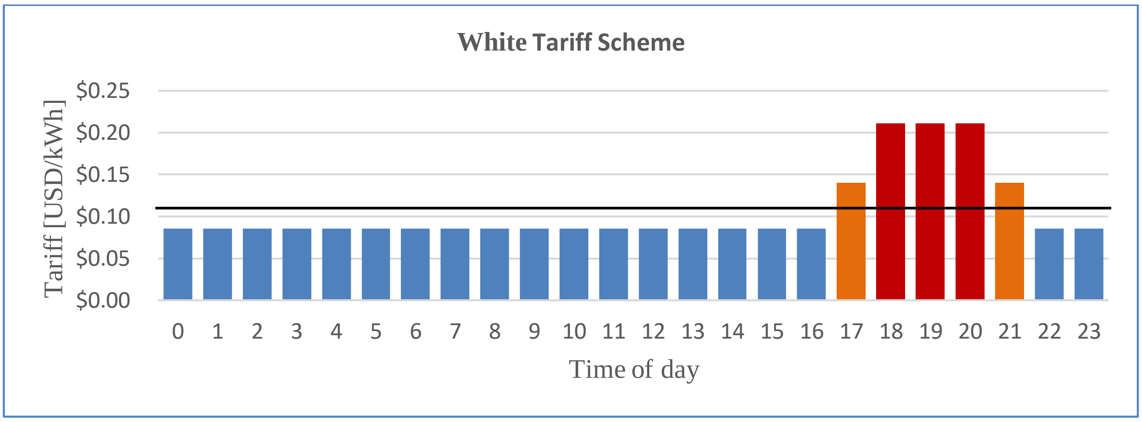
(iii) Remote consumption: when the generating units are far from the units where the surplus injected into the grid is compensated.

(iv) Shared generation: the union of electric energy producers through a consortium or cooperative with or without remote consumption.

(v) Energy credits: an amount of 43% of injected energy into the grid and not offset in the current tariff month, valid for 60 months; and,

(vi) Cost of availability (CA): a minimum fee that will be charged even if the consumer has excess of energy credits. The amount to be paid as CA is equivalent to a consumption of 30 kWh for single-phase installations, 50 kWh for double-phase users and, 100 kWh for three-phase grid connections.

Tariff billing is regulated by the REN nº 733, issued on September 6th, 2016 (ANEEL, 2016). This normative regulates the white tariff (WT), which consists of hourly billing, with three tariff points, peak, intermediate and off-peak, Figure 4.1. Consumers with DG who choose the WT will have their credits compensated primarily in the period in which they were generated (peak, intermediate or off-peak), observing the respective tariff values. The CA will be charged by conventional tariff.



Notes: peak tariff in red, intermediate tariff in yellow, and off-peak tariff in blue. Black line set the conventional tariff.

Figure 4.1 – White tariffs average graphic.
Source: Adapted from REN 414 (ANEEL, 2010)

The WT was set in art. 56-A of REN nº 414. The peak period, of three consecutive hours, is defined by each DISCO, according to the consumption profile of their consumer markets. On average, this period is between 6 and 9 PM. The intermediate tariff is applied one hour before and one hour after the peak period. The other hours, from Monday to Friday, are considered off-peak periods, as well as weekends and national holidays. There are eleven national holidays, two of them always during the non-weekend days. The probability of one of the other holidays falling during the non-weekend period is 71.4%. That is, in each year there will be, on average, six holidays during the week, added to the two that are always during the week. Thus, there are 52 weekends, plus eight holidays, totalling 112 days with off-peak tariffs for 24 hours. Therefore, there are 253 days with peak-tariff in-force (365 - 112), totalling 759 peak hours per year, that means 8.67% of the year. The intermediate period corresponds to 506 hours, meaning 5.78% of the year. The rest, 7,495 hours, corresponding to 85.55% of the year, are charged by off-peak tariff.

4.3.1.1. Electrical energy compensation system

As explained in the previous chapter, the REN nº 482 created the EECS, where the original issue predicts each kWh injected into the grid should be compensated in equal amount, is changing by ANEEL's proposals to only 43% (DE DOILE *et al.*, 2021).

The electricity tariff has several components before fees and taxes. The TUSD – Grid A, is all grid costs not managed by DISCO, as transmission tariff and grid ampliations and reinforcements. This part corresponds to 27% of electricity tariff. Others 6% are related to TUSD – Grid B. This is the cost of operation and maintenance (O&M), under DISCO management. Moreover, 14% of the tariff are sector charges used to maintain some governmental programs and subsidies and 10% correspond to electrical and non-electrical losses. The non-electrical losses are basically stolen electricity. Then, only 43% of the electricity tariff, corresponding to electric energy costs, was considered in this study.

4.3.1.2. Tax incentives

In Brazil there are three administrative divisions: National, the so-called Union, state and municipal. Each one has their own tax system, as follow: (i) National: Social Integration Program (PIS) and Contribution for Social Security Financing (Cofins). Together, they are 9% in average, varying according to companies' profits. (ii) State: Tax on Circulation of Goods and Services (ICMS). It varies among states from 15% up to 25% of the net electricity tariff. (iii) Municipal: Contribution to the Public Lighting Service (Cosip). It corresponds to 3% of the net electricity tariff in average, varying among municipalities.

The Union contributions were waived, under Art. 8 of Law nº. 13,169, of October 6th, 2015 (BRAZIL, 2015), for the amount of energy injected into the electrical grid and subsequently offset, under the terms of REN nº 482. Likewise, the ICMS was dismissed after the accession of all states to the ICMS Agreement 16/15 (CONFAZ, 2015). No information was found on Cosip exemptions in any municipality through the country. As the tax exemption is only for the injected energy, which is later used, when consumers use energy from the grid without energy credits to be compensated, such energy will be charged with taxes.

4.3.2. Input variables

For this study seven inputs are necessary:

(i) the nominal power (Pn), also called installed capacity, in kW;
(ii) solar radiation, in kWh/m² per day;
(iii) consumer demand, in kWh per month;
(iv) electricity tariff, in USD/kWh;
(v) initial investment of PV panels array, in USD/kW;
(vi) initial investment of battery bank, in USD/kWh; and,
(vii) the Minimum Attractiveness Return Rate (MARR), in percent.

4.3.2.1. Classification of the power plants

The current regulation divides into two bands, microgeneration up to 75 kW and mini generation from 75 kW to 5 MW. However, based on the grants in-force until July 2020, installations classified as microgeneration have Pn of 1.16 kW in average. Those classified as mini generation have an average Pn of 1.5 MW. Of the 3,751 installations classified as micro-plant, only 24 of them, or 0.65%, have a Pn greater than 10 kW. Among the mini-plants, 61% have Pn less than 1 MW (ANEEL, 2021a).

There are only three DG classifications in the USA: Residential, from 3 to 10 kW of installed power; Commercial, from 10 kW to 2 MW and Utility-scale above 2 MW (FU; FELDMAN; MARGOLIS, 2018). In the UK, as regulated by OFGEM (2010), to be eligible for feed-in tariff scheme, installations must follow these four classifications: less than 4 kW; from 4 up to 10 kW; from 10 up to 50 kW, and from 50 kW up to 5 MW. In Ireland, also there are three DG classifications, and the maximum installed power is only 50 kW (CRU, 2020). In Italy, the nominal power classes for DG are from 1 to 3 kW; over 3 kW up to 20 kW; over 20 kW up to 200 kW; over 200 kW up to 1 MW; over 1 MW up to 5 MW, and over 5 MW (AGRILLO; SURACE; LIBERATORE, 2020).

Three ranges of installed nominal power Pn are proposed in this study, as follows:

a) Micro-plant, with Pn up to 10 kW. Predominant in residential installations on the roofs or walls, where micro frequency inverters inside the house are used.

b) Mini plant, with Pn greater than 10 kW up to 1 MW. Adequate for commercial installations or even small industries. These power-plants can use microinverters or centralized frequency inverters, according to their size.

c) Small power plant, Pn greater than 1 MW up to 5 MW. These are facilities whose main objective, in general, is to share energy with remote consumers. For economy of scale reasons, they will use centralized frequency inverters and connection to the three-phase electrical grid.

4.3.2.2. Initial investment and costs

Firstly, the power plant and battery bank adequate sizes have to be determined. For this purpose, the demand is used as a main input factor, together with the solar radiation and standard panel data. The standard panel data, defined by De Doile et al. (2021) are 0.25 kW of nominal power, 1.6 m² of useful area, and 19% of efficiency. As demand and solar radiation are stochastic input variables, the panel and battery bank layout sizes will be calculated in each MCS iteration. Pn in kilowatts is calculated by the following Equation (4.1).

$$P_{\mathrm{n}} = 0.156 \times \frac{D_{\mathrm{m}}}{R_{\mathrm{m}} \times \varepsilon} \quad (4.1)$$

where 0.156 is the nominal power of a standard panel in kW/m² (0.25 kW/1.6 m²); D_m is the average demand in kWh; R_m is the average solar radiation in kWh/m², both in the same time dimension, and ε is the dimensionless standard panel efficiency. In this study 30-year useful life project and 0.7% annual efficiency loss of the PV panels are considered (AZEVÊDO *et al.*, 2021). The inverters useful life is 15 years, and the lead-acid batteries must be substituted each five years of lifetime.

The three battery bank sizes will be determined by the total energy consumption in five hours peak demand, the total energy consumption in a day, and the total energy consumption in four days. In the first case the battery bank must be able to supply the demand during the peak hours to avoid the higher tariffs. In the other cases, the battery bank is called to supply the demand in case of lack of production or energy outage in a period from one up to four days. According to Glaize and Genies (2012), battery nominal capacities are shown in manufactures catalogues and on battery specification plate as Cn. This n means the number of hours the battery capacity should be used. For example, a battery specified by 100 Ah C10, must therefore provide a current of 10 A over a period of ten hours (100 Ah/10 h). Considering a 12 V nominal voltage, it means 120 Wh for 10 hours or 1.2 kWh of energy supplied. Battery bank nominal power for five hours, one day, and four-day supply in kilowatts will be calculated by Equations 4.2 to 4.4, respectively.

$$B_{P5} = \frac{D_{pk}}{5} \tag{4.2}$$

$$B_{P1d} = \frac{D_{pk}}{5} + \frac{D_{19h}}{19} \tag{4.3}$$

$$B_{P4d} = \frac{D_{pk}}{5} + \frac{D_{19h}}{19} + \frac{D_{72h}}{72} \tag{4.4}$$

where, B_{P5}, B_{P1d}, and B_{P4d} are battery bank nominal power in kW, by respective supply time capacity; D_{pk} is the total demand in five hours daily peak in kWh, D_{19h} is the daily off-peak demand, and D_{72h} is the three days ahead demand, both in kWh.

The optimum four-hour capacity battery bank size for solar power plants is around 60% of Pn, according to a study conducted at National Laboratory for Renewable Energy (NREL) (FU; REMO; MARGOLIS, 2018). Khatib and Muhsen (2020) have dimensioned a battery bank 1.4 times the installed power for an autonomy of two days. Jing et al. (2019) have used in a rural area in Malaysia 1.6 times for 15 hours battery bank autonomy, whereas Kebede et al. (2020) in Ethiopia found an optimum value of 77% of Pn, for a 10-hours battery storage system. Dimensioning a battery bank is not an easy task. However, in a stochastic study the bank size can change as desired, considering the range used in previous studies. In this study, battery banks vary from 40% up to 100% for five hours autonomy; from 60% up to two times the installed power for one day autonomy; and from one up to three times Pn for four-days autonomy. The maximum battery discharge of 80% was considered, as predicted by Glaize and Genies (2012).

Battery modelling is crucial in a hybrid power system study due to the lifetime uncertainty since the cost of battery banks is a significant investment parcel (BINDNER *et al.*, 2005). Typically, the battery life cycle is measured by the loss of its energy supply capacity compared to its initial capacity. Less than 80% capacity is considered a dead battery. On the other hand, in recent studies five-year lifetime lead-acid batteries are considered (KHATIB; MUHSEN, 2020; LIU *et al.*, 2020; SHADMAND; BALOG, 2014). Therefore, a five-year lifetime with 4% efficiency loss per year for lead-acid batteries was considered in this study.

As for PV panels and inverters, a survey was done here to determine the battery banks average price and the density function shape to be used in stochastic simulations. Lithium-ion battery prices have been found to be 30 times higher than lead-acid battery prices, in average on Brazilian retail market. In Thailand Anuphappharadorn et al. (2014) found lithium-ion battery prices five times higher than lead-acid battery prices in 2014, while a German study in Tanzania found three times in 2018 (PAUL AYENG'O *et al.*, 2018). In a more recent study, the difference dropped to 1.7 times in Malaysia (JING *et al.*, 2019). Even though the lifetime of the lithium-ion battery is twice the lifetime of the lead-acid battery (HEMEIDA *et al.*, 2020; WOLSINK, 2012), the Net Present Values (NPV) of initial investments plus reinvestments is still less for lead-acid batteries in Brazil. To have the same NPV, considering only the investments, lithium-ion battery price must be around 1.5 times the lead-acid price, depending on the desired MARR. An 80% reinvestment in battery banks was considered each five years for lead-acid batteries, and each ten years for lithium-ion batteries. Further studies for off-grid applications indicate a trend towards higher convenience of solutions with lithium-ion batteries with respect to lead-acid batteries, also because of longer lifetime and faster charging capabilities (KESHAN; THORNBURG; USTUN, 2016). This trend could become more evident if the price of the lithium-ion batteries will decrease more than the price of the lead-acid batteries. In any case, there is still no general evidence about which technology is more convenient, and case-dependent detailed studies are needed to draw conclusions. On a wide range of applications, each technology could find specific margins of convenience.

In this work, the battery bank cost is a stochastic input. Thus, the possibility that some investors found best prices in the international markets was considered. Moreover, 25% initial investment as installation cost and 1% a year as operation and maintenance cost are used (DE DOILE *et al.*, 2020, 2021). No specific container for micro-plants, 50% of mini plants installed on containers and 100% of small power plants installed on containers are also considered.

Battery bank size will be chosen by consumer profile. It is expected that all consumers will store enough energy to avoid grid consumption on the peak time, where tariffs are high. However, as the energy surplus injected on the grid is only 43% offset and grid consumption is tax charged when the consumers do not have energy credits, some of them will chose to store energy for a time greater than the peak time. Based on Brazilian electricity outages history (ONS, 2021), let us suppose 20% will be extremely conservative and choose four-days storage systems, 50% choose one-day storage systems capacity, and 30% choose five-hour storage systems. It is not a simple choice, because there is a risk to waste money if the weather long term prediction is not confirmed. More sunny days represent more energy produced, less grid consumption needed, and more money saved by energy stored.

4.3.2.3. Solar radiation

Brazil has an excellent annual average of daily total of global solar irradiation, as shown by Pereira et al. (2017) in their atlas. That atlas is based on several studies make by Brazilian universities coordinated by the Modelling and Studies on Renewable Energy Resources Laboratory (LABREN), in Earth System Science Centre (CCST) of the National Institute for Space Research (INPE), a governmental body to make spatial phenom research.

Also, The Power Project, managed by Langley Research Centre (LARC) of the National Aeronautics and Space Administrations was an important data source for this study (NASA, 2021). Combining these two data sources, the density function shape used in this study varies from 2.4 up to 7 kWh/m^2 per day, following a beta-shaped distribution curve, as shown in Table 4.1.

4.3.2.4. Other inputs

This study considers the electricity demand and electricity tariffs from databases provide by Regulatory Agency (ANEEL, 2021e, 2021d). According to Energetic Research Company (EPE, 2020), in the last five years, residential demand grew by an average of 2.21% per year, commercial demand 0.36% per year and industrial demand decreased by 0.24% per year. These percentiles are adopted in this work, except for industrial demand, which remained constant. The tariffs real growth adopted here, beyond the inflation measured by IPCA, an official Brazilian indicator, was 0.63% based on historical data (IBGE, 2021b). Such historical data allowed to define the data range and its form of distribution, presented in Table 4.1. A normal distribution with 0.5% standard deviation for a central point of 8% as MARR was used in this research, Table 4.1.

4.3.3. Electricity production schemes and tariff application

The electricity production and consumption schemes are displayed on Figure 4.2. In some scenarios, production is not sufficient to meet the demand at one or more tariff points. In these cases, a demand from the grid, not compensated demand (NCD), in addition to DG production, total produced energy (TPE), is necessary to supply all consumption, total energy consumption (TEC), columns (i) and (ii) on the figure. In the column (iii) is shown the consumption division between own demand (ODM) and remote third-part demand (R3D), where the sum must be equal to TEC. For better economic comparison, it is considered that all the surplus energy, grid injected energy (GIE) is used for own consumption, grid compensated own demand (GCOD) plus the remote consumption of third parties, offset remote demand (ORD), columns (iv) and (v). Any excess of consumption by third parties is considered in the NCD. As the NCD is equal for consumer with DG and others without DG, such part was not considered in the economic comparisons. The own demand (ODM) will be supplied by three sources: by the Self Consumption Energy (SCE), that energy produced and used at the same place with no distribution grid usage; by the (GCOD), where the distribution grid is used to consume part of (GIE); and by the NCD, when SCE plus GCOD are not sufficient to supply the ODM.

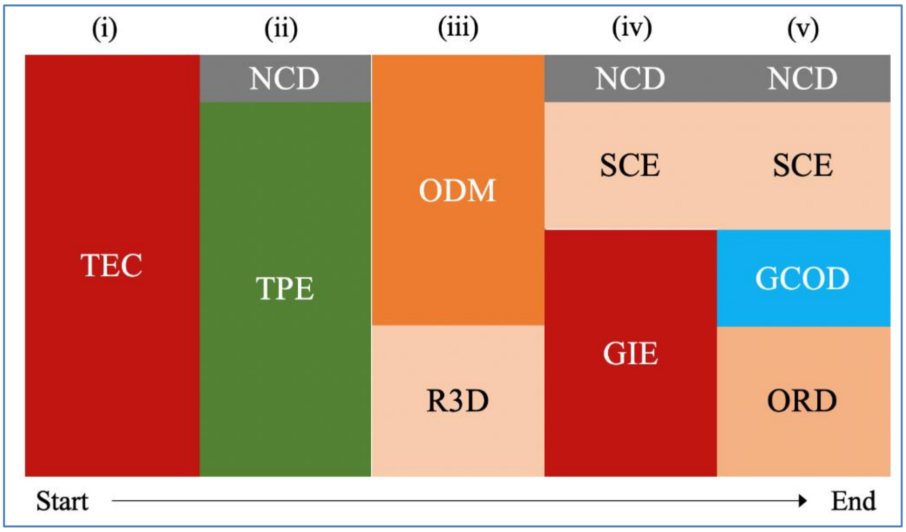


Figure 4.2 – Electricity production and consumption scheme.
Source: Produced by this dissertation author

Comparisons are shown among consumers without DG and consumers with DG installed, Figure 4.3. As the NCE is charged by taxed tariff in both cases, this consumption was not considered for comparison. Consumers without DG have electricity bill composed of TEC minus NCE to consider the same amount of consumption in both sides of the balance scale. This electricity bill is charged by white tariff (WT) plus taxes. TEC includes the cost of availability (CA). Consumers with DG installed have more complex electricity bills. They need to pay the CA, charged by conventional tariff (CT) with no taxes, plus the GCOD, 53% charged by WT with no taxes. SCE is not charged. Remote consumers also pay the CA plus the offset remote demand (ORD), 53% charged by WT without taxes.

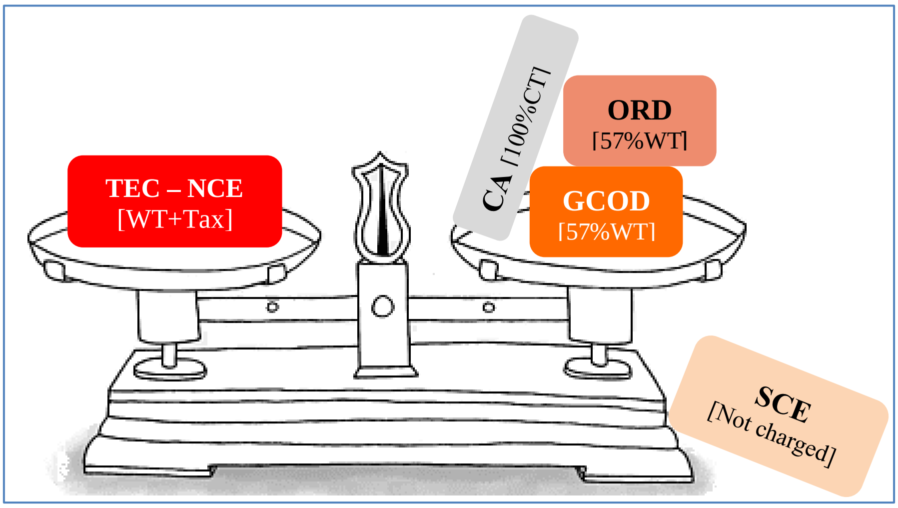


Figure 4.3 – Balance between consumers with and without DG.
Source: Adapted by this dissertation author

4.3.4. Outputs

As explained in previous chapters, the main tools to assess the economic viability are the net present value (NPV), the internal rate return (IRR), and the discounted payback (DPB). The NPV helps an investor to decide the optimal timing for new project, especially in case of new technologies (FARZIN; HUISMAN; KORT, 1998). In the study presented in this chapter, stochastic analysis varying seven inputs, solar PV plant and BESS investments and sizes, electricity demand and tariffs, solar radiation, and return rate, was carried out through Monte Carlo Simulations (MCS). Finaly, the outputs observed was NPV, IRR and DPB.

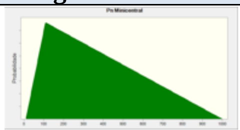
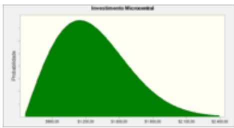
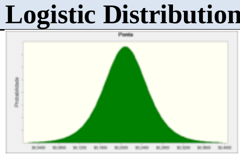
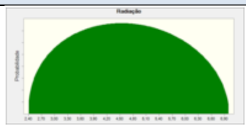
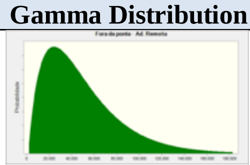
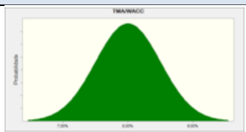
4.3.5. Parameters setting for simulation

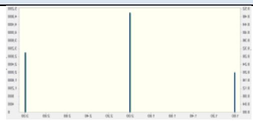
In this study, three base cases were used: (i) micro-plant, from 0.5 to 10 kW of nominal power; (ii) mini plant from 10 kW to 1 MW, and (iii) small plant from 1 to

5 MW. The maximum limit for DG in Brazil is 5 MW. Firstly, a deterministic analysis using the input parameters average was carried out to validate the simulation datasheet.

To perform the stochastic analyses, the MCS does simulations 10.000 times for each scenario, varying parameters as shown in Table 4.1. In this case, a probabilistic model is built, where parameters can assume a range of possible stochastic values. The parameters will be represented by probability distribution functions based on real parameters as explained on section 4.3.2.

Table 4.1 – Input parameters distribution and limits

Parameter	**[2] Distributions** **Triangular Distribution**	**Power-plant size**	**Minimum**	**[1] More Probable**	**Maximum**
Nominal Power [kW]	 Figure 4.4	Micro	0.5	1.45	10
		Mini	10	109	1,000
		Small	1,000	1,400	5,000
	Weibull Distribution		**Local**	**Scale**	**Form**
Power plant Investment [USD/kW]	 Figure 4.5	Micro	650	700	2
		Mini	500	550	2
		Small	500	550	2
			Local	**Scale**	**Form**
Battery bank Investment [USD/kW]		Micro	268	130	2
		Mini	275	140	2
		Small	290	145	2
	Logistic Distribution			**Average**	**Scale**
Energy Tariff [US$/kWh]	 Figure 4.6	Peak tariff		0.2078	0.0272
		Intermediate		0.1374	0.0166
		Out of peak		0.0849	0.0073
		Conventional		0.1075	0.0095
	Beta Distribution		**Minimum**	**Beta parameter**	**Maximum**
Solar radiation [kWh/m^2]	 Figure 4.7	All cases	2.40	1.51	7.00
	Gamma Distribution		**Local**	**Scale**	**Form**
Electrical Demand [kWh]	 Figure 4.8	Micro	92	250	1,9
		Mini	1,840	25,000	1,9
		Small	184,000	100,000	1,9
	Normal Distribution		**Average**	**Standard deviation**	
MARR [%]	 Figure 4.9	All cases	8%	0.5%	

	Discrete Distribution		5 hours	1 day	4 days
Battery bank size [kWh]	 Figure 4.10	All cases	30%	50%	20%

Notes: [1] Average power calculated from ANEEL data (ANEEL, 2021a).
[2] Figures 4.4 to 4.10 – Graphical representations of probability distributions.

The nominal power follows a triangular distribution between classification limits power of the plant. The most probable nominal power, presented in Figure 4.11, was calculated by the average of ANEEL data (ANEEL, 2021a) for micro and small plants and approximated to mini-plant, a new classification proposed in this study. Weibull distribution was the best approach for investment variation. This curve shape is one where the scale means the main value more present in the sample. Small values follow a fast-decreasing curve and high values, a smooth decreasing curve. Energy tariffs follow a logistic curve that is like a normal curve but decreasing more quickly. Solar radiation data are represented with a Beta distribution (able to represent non-zero values only in the specified range from the sunrise to the sunset), while electricity demand is represented by a Gamma distribution. Then, the MARR follows a normal curve with 8% average and 0.5% standard deviation. Battery size is a discrete function based on consumer behaviour.

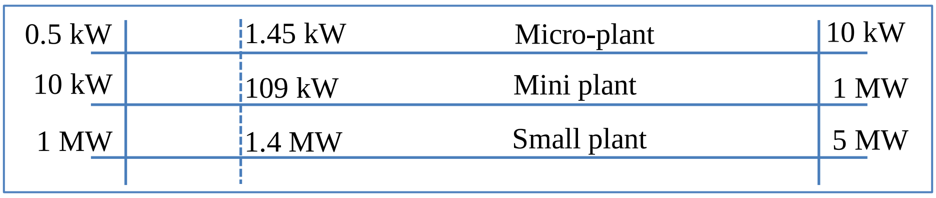


Figure 4.11 – Nominal power limits for each plant classification.
Source: The author based on ANEEL data (ANEEL, 2021a)

As concluded in chapter 3, if ANEEL proposal were approved, a significant reduction in the economic feasibility would occur for PV micro-plants (DE DOILE *et al.*, 2021). Here, in this work, the rule changes are considered to be approved and in force. The WT was, also, considered. Thus, based on ANEEL data (ANEEL, 2021a), annual average of generation and demand are shown in Table 4.2.

Table 4.2 – Electrical production and demand by tariffs points

Tariff point	PV production	Demand		
		Residential	Commercial	Industrial
Off-peak	97.96%	65.35%	67.70%	92.54%
Intermediate	1.70%	11.47%	12.85%	5.74%
Peak	0.34%	23.18%	19.45%	1.72%

To set up a practically significant approach, it is considered a mix among residential, commercial, and industrial demands for each classification of plant, as presented in Table 4.3. Micro-plants are predominately to supply residences but also small commerce. Mini plants are more adequate for commercial buildings and small plants for medium size industries.

Table 4.3 – Demand mix among power-plant classification

Classification	Demand		
	Residential	Commercial	Industrial
Micro-plant	90%	10%	0%
Mini plant	10%	50%	40%
Small plant	0%	40%	60%

4.4. Results and Discussion

The performance of three DG unit sizes including remote consumption and white tariff (WT) was compared. In the first simulations, whose result is shown in Table 4.4, the probability values of obtaining a positive NPV, an IRR equal or greater than 12% and, a DPB of five years or more, without energy storage system (ESS), was analysed. By first results, economic indicators are better to conventional tariff (CT) than to WT, for mini and small plants. However, the opposite happens for microgeneration plants. It happens due to the out-off peak PV production in conjunction of the rule, where energy surplus is preferentially offset at the same tariff point that was produced. The industrial demand at peak period is very small when compared to the demand at out-off peak. This fact, coupled with the CT that is higher than WT in the off-peak period leads to a better economic performance of these projects, even against the common sense.

Table 4.4 –Economic indicators by power plant classification using CT and WT without battery banks

Power-plant classification	White Tariff			Conventional Tariff			Difference WT-CT		
	NPV	IRR	DPB	NPV	IRR	DPB	NPV	IRR	DPB
Micro-plant	81.49	53.89	8.11	79.26	51.81	7.91	2.23	2.08	0.20
Mini plant	94.42	80.21	20.13	94.08	81.39	24.28	0.34	-1.18	-4.15
Small plant	95.32	81.23	18.78	96.82	86.52	26.51	-1.50	-5.29	-7.73

Note: all results are in percent [%]

The stochastic results varying all inputs, as explained in section 4.3.5, with the addition of battery banks and after 10,000 interactions by MCS, are shown in Table 4.5. Once again, the probability of economic viability for the three power-plant classifications proposed in this work was presented using the WT scheme. The results demonstrate economic unfeasibility for most scenarios with battery banks, even for battery banks with only five hours capacity. The NPV for most five-hour battery bank scenarios shows profitable projects. However, the IRR reveals low probabilities of results greater than 12% per year and, in very few scenarios the entrepreneur will have return in periods up to five years.

Table 4.5 – Probability of economic viability by power plant classification with ESS and WT

Power-plant classification	5 hours battery bank			1-day battery bank			4-days battery bank		
	NPV	IRR	DPB	NPV	IRR	DPB	NPV	IRR	DPB
Micro-plant	63.68	36.02	1.32	53.14	27.01	0.74	33.09	12.48	0.11
Mini plant	75.70	50.67	3.69	63.55	38.55	1.79	39.17	16.42	0.18
Small plant	80.55	55.76	4.21	69.08	41.17	1.59	42.24	17.67	0.20

Note: all results are in percent [%]

If there were economic viability for battery banks, all consumers would desire at least five hours battery bank capacity, to avoid grid consumption during the peak point, where tariffs are highest. Considering the probable consumer behaviour presented in section 4.3.2.2, other analyses was performed, and the results presented in Table 4.6 Projects still being economically unfeasible in almost all scenarios. In addition, the results for the same scenarios using CT are shown. The worst result is for micro-plant that one predominantly for residential users. Also, NPV reveals that projects can be economically feasible in some five-hours and one-day battery bank capacity scenarios, however, the vast majority with long-term investment return. Micro-plants with five-hours and one-day battery bank capacity can be economically viable, in few scenarios. The same happens with mini and small plants in other battery bank capacity scenarios. Other simulations must be carried out if the investor accepts a return rate less than 12% annually and a financial return within more than five years.

Table 4.6 – Results by power plant classification 30% 5h, 50% one day and, 20% four days storage

Power-plant classification	Using WT			Using CT			Difference WT-CT		
	NPV	IRR	DPB	NPV	IRR	DPB	NPV	IRR	DPB
Micro-plant	52.17	26.08	0.67	47.97	23.62	0.87	4.20	2.46	-0.20
Mini plant	62.99	37.50	2.00	67.01	42.35	4.08	-4.02	-4.85	-2.08
Small plant	66.96	40.51	2.26	75.22	51.66	5.06	-8.26	-11.15	-2.80

Note: all results are in percent [%]

When comparing WT with CT, it is evident that WT is better for micro-plants, as well as it is worst for mini and small plants. It has to be emphasized that this phenomenon happens due to tariff prices, consumers behaviour, and the compensation scheme (EECS), where the injected energy must be compensated as a priority at the same tariff point in which it was generated. The most generated energy by solar PV is in the out-off peak tariff point.

There are some similar economic feasibility studies for distributed photovoltaic generation with and without energy storage systems in Brazil since the beginning of the 2010s. A comparison between the previous studies and the present study are presented in Table 4.7. The studies were carried out in different years, therefore different prices and tariffs were considered. As it can be seen, panels price dropped while tariffs grown. It, by itself, is enough to make distributed generation from PV economic feasible. However, when added battery banks as storage systems, the set had a low probability of economic feasibility.

Table 4.7 – Comparison among previous studies

Reference and year	Scenario	Analysis	Investment	Tariffs	Results
(HOLDERMANN; KISSEL; BEIGEL, 2014)	PV as DG	Deterministic	2,508 €/kW	0.11 up to 0.22 €/kWh	Unfeasible
(ROCHA *et al.*, 2017)	PV as DG	Stochastic	5,827 up to 6,427 $/kW	0.07 up to 0.15 $/kWh	Most unfeasible
(DA SILVA; BRANCO, 2018)	PV + BESS	Deterministic	3,539 $/kW	0.19 $/kWh	Unfeasible
(DA SILVA; BRANCO, 2018)	PV + BESS	Deterministic	4,410 R$/kW	0.53 up to 1.24 R$/kWh	Unfeasible
(DE DOILE *et al.*, 2021)	PV as DG	Stochastic and Deterministic	1,630 $/kW	0.22 up to 0.28 $/kWh	Feasible
Present study 2021	PV + BESS	Stochastic	777 up to 2,966 $/kW	0.06 up to 0.42 $/kWh	Most unfeasible

As the PV business was beginning in Brazil, Holdermann et al. (2014) used UK prices to calculate investments. In that time electricity tariffs were slightly subsidized by reduction in energy prices, contributing for business unfeasibility. Rocha et al. (2017) studied the effects of tax exemption. With no tax, the PV enterprise started becoming feasible from that time. Da Silva and Branco (2018) have considered battery storage system combined with solar PV distributed generation for the first time. The battery prices turned the projects unfeasible in that time. Two years after Deotti et al. (2020) repeated the study with currented data and have had the same conclusion of unviability. More recently, de Doile et al. (2021) in a study derived from chapter 3, with no energy storage systems, using the current lower prices and high tariffs, the PV business feasibility was attested. It was found good results for NPV and IRR for micro and mini photovoltaic plants with no remote consumption. The DPB was not that good, with investment return in a long term. Unfortunately, battery prices still making PV projects combined with battery banks unviable, as demonstrated in this chapter.

4.5. Conclusions

The most recent literature reveals that, when studied distributed PV system without battery banks the viability was attested. It is clear that for micro-plant with distributed generation, that one predominantly residential, the option for white tariff is better than for conventional tariffs scheme. It happens due to high consumption at peak time. As the industrial demand is less at peak time, white tariff scheme is not ideal for this kind of enterprise. Another kind of economic incentives, beside white tariffs, should be created for them.

When added battery banks as energy storage systems, the projects presented low probability of economic feasibility. A few cases with five-hours battery bank capacity show themselves economically viable. The main problem, undoubtedly, are the battery prices. Even, considering many scenarios with imported batteries at lower price, the projects still having a low probability of viability. The battery storage systems introduction into the Brazilian electrical grid must be economically subsidised.

The last results considering the three battery bank sizes show a low probability of viability. Therefore, nobody will have economic reason to choose large battery banks. There is a double interest to reduce peak demand. On one side the government wants to reduce the dispatch of expensive power plants. On other hand, consumers would like to reduce electricity bill by consuming they own produced energy during the peak time, when tariffs are high. For this reason, small battery banks for residential PV plants should be economically incentivised to reduce the undesirable peak demand.

All studied scenarios have considered the tax exemption in-force in 2021. Because of this, tax exemption may incentivize distributed photovoltaic plants, however, it is not enough to economically encourage the inclusion of energy storage systems.

As the white tariffs scheme combined with energy compensation system sound as a problem for economic viability of distributed PV power plants, because the electricity production is in the out-off peak period, the insertion of another electricity source is suggested for future studies. This additional source must be able to produce electricity at night and during the peak time.

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5. CHAPTER 5 – Hybrid wind and photovoltaic distributed generation and battery energy storage systems under technical-economic regulation

5.1. Abstract

Many countries have considered the possibility of hybrid generation from renewable energy sources, aiming at benefits for the electrical system. The increasing use of intermittent sources, as solar and wind, substantially alters grid operations. These operational challenges can be minimized by the incorporation of energy storage systems, which play a prominent role in increasing the reliability and stability of the grid. Thus, this study aims to assess the economic feasibility of distributed hybrid power-plants with battery energy storage system. Stochastic analyses are carried out by varying nine of the main variables in three sizes of hybrid power-plants: micro-plant, up to 10 kW; mini plant, from 10 kW up to 1 MW, and small power-plant from 1 up to 5 MW installed power. Battery banks with supply capacity for five hours were considered in all studied scenarios. All scenarios for distributed hybrid wind plus PV system with battery banks presented a high probability of viability. However, widespread use of batteries only will be encouraged by drop of their cost or some subsidy for new energy storage systems. The combined use of wind and solar photovoltaic sources have partially solved the problem related to white tariffs scheme in conjunction with electric energy compensation system, aggregating energy production at night and in the peak demand period.

5.2. Introduction

In recent years, the world has witnessed an energy transition process, which can be defined as a change from energy matrices based on fossil fuels to energy from renewable energy sources (RES) (IRENA, 2018). In this context, wind and solar photovoltaic (PV) generation technologies have been of fundamental importance. Thanks to the evolution of these technologies, the generation cost for these sources has fallen considerably in recent years, making them more competitive (REDISKE *et al.*, 2019).

Furthermore, many countries have considered the possibility of hybrid generation from solar PV and wind sources, aiming at benefits for the electrical system, among which, the following stand out: (i) the fact that these sources have complementary behaviour, since solar PV generation occurs during the day, and wind generation is usually more intense at night; and (ii) achieve economies of scale, which may allow investors to reduce their average cost (AQUILA *et al.*, 2018).

The energy transition is also causing changes in the electricity markets, and systems are being shifted from centralized to decentralized systems with the existence of thousands of small generators. Therefore, electricity generation is changing from a highly predictable scenario to one where intermittency and unpredictability predominate (BLAZQUEZ; FUENTES; MANZANO, 2020).

The same benefits of battery energy storage systems (BESS) to solar PV power-plants, as the increasing of reliability and stability, as well as the supply of ancillary services, explained on previous chapter, can be reach on a hybrid wind plus solar plant. With the emergence of the prosumers (active consumers who can produce and store energy as well as consume it), energy storage can become an additional part of the electricity market value chain. Thus, new business models should focus efforts on figuring out how to monetize the services provided by energy storage systems (ESS), which would cause a revolution in the sector, now focused on commodities, to business models focused on services. (BLAZQUEZ; FUENTES; MANZANO, 2020).

According to Blazquez, Fuentes, and Manzano (2020), the energy transition is driven more by policies than by technological evolution. In this context, it was only after the publication of REN nº 482 (ANEEL, 2012), that the production of PV solar energy gained momentum. Although the distributed generation (DG) is essentially from solar PV source, the norm predictions can be used for any other energy source and was considered in this study for hybrid wind and solar PV sources.

In this chapter it is aimed to assess the economic feasibility of DG from hybrid wind plus solar PV power-plants with 5 hours capacity battery banks as ESS. Stochastic analyses are carried out by varying nine of the main input parameters in three proposed power-plant sizes.

5.3. Methodology

The legislation on the matter, specially that material available at ANEEL website (ANEEL, 2019a), was revised once again, as well as the academic production related to the theme that was exploratorily researched. The initial investments related to wind turbines, solar PV systems, and battery banks was obtained by a price research at retail market. Monte Carlo Simulation (MCS) scheme was used to perform stochastic analyses on many scenarios, to obtain the expected results.

5.3.1. Current rules on the topic

As in the previous chapters, the ANEEL proposal to change the DG rules, specially the electric energy compensation system (EECS) providing 57% discount on offset energy, related to grid costs and sector charges (ANEEL, 2019a), was considered in this study, as well as the rest of in-force normative. The white tariff (WT) provided three tariff points, as presented in Table 5.1. The WT tariff is less expensive than conventional tariff (CT) during the off-peak time, whereas on peak and intermediate hours it is higher. The energy credits must be offset at the same tariff point where they were generated.

Table 5.1 – Electricity tariffs schemes

Tariff scheme	**Tariff price in USD**			
	Peak-time	Intermediate	Off-peak time	Cost of availability
White tariff (WT)	$ 0.21	$ 0.14	$ 0.09	$ 0.11
Conventional (CT)	$ 0.11	$ 0.11	$ 0.11	$ 0.11

Notes: peak-time from 6 to 9 PM, intermediate 1 h before and after peak-time, and off-peak the rest of the day, holydays and weekends.
Source: Adapted from REN nº 414 (ANEEL, 2010) in conjunction with (ANEEL, 2021e).

5.3.1.1. Tax exemptions

In this chapter was also considered the tax exemptions for National: Social Integration Program (PIS) and the Contribution for Social Security Financing (Cofins), pursuant to art. 8 of Law nº 13,169 (BRAZIL, 2015), and for Tax on Circulation of Goods and Services (ICMS), based on ICMS Agreement nº 16 (CONFAZ, 2015).

5.3.2. Input parameters

Nine inputs parameters were considered in this study: (i) the power plant capacity or nominal power (Pn), in kilowatts; (ii) the average of local solar radiation, in kWh/m² per day; (iii) the daily average of wind speed, in meters per second; (iv) the electricity demand, in kWh per month; (v) tariffs of electric energy, in USD/kWh; (vi) solar PV power plant installation costs, in USD/kW; (vii) wind power plant installation costs, in USD/kW; (viii) battery banks investments, in USD/kWh; and, (ix) the Minimum Attractiveness Return Rate (MARR), in percent.

5.3.2.1. Power-plant dimensions

The same proposed power-plant dimensioning, in previous chapter, is considered in this study: (i) micro-plants with Pn from 500 W up to 10 kW, (ii) mini plant with Pn greater than 10 kW up to 1 MW, and (iii) small plants with Pn greater than 1 MW up to 5 MW.

5.3.2.2. Investments in the year zero

The first data needed are the number of wind turbines, solar panels, and batteries suitable for the plants to be studied. The amount of wind turbines and solar panels is calculated from the nominal power of the plant, which is a stochastic input data. The each one of the energy sources percentage, wind and solar PV, is the second input for these calculations. Inverters are calculated by the total installed power, as they will be used for both energy sources. In this chapter, the useful life considered was 30 years with a photovoltaic panels' loss of efficiency of 0.7% per year (FU; FELDMAN; MARGOLIS, 2018). The useful life of inverters considered was 15 years, and five years for lead-acid batteries (LIU et al., 2020). Investment ranges are presented in Table 5.2 on next sub-section 5.3.5.

5.3.2.3. Wind speed

The correct wind speed forecasting is crucial to well design a wind farm (DEMOLLI *et al.*, 2019). Thus, based on Brazilian Wind Potential Atlas (AMARANTE *et al.*, 2001)(DUTRA *et al.*, 2017), only the eastern regions of Brazil, composed by northeast, southeast, and southern geographic regions, where wind speed average is greater than the minimum required to wind turbine operation, were considered in this study (VITA *et al.*, 2021)(IE EUROPE, 2011). The Brazilian wind speed annual average are shown in Figure 5.1. As we can see by the large dark green area in the map, northern and western regions present low wind speed average, not suitable for wind power generation.

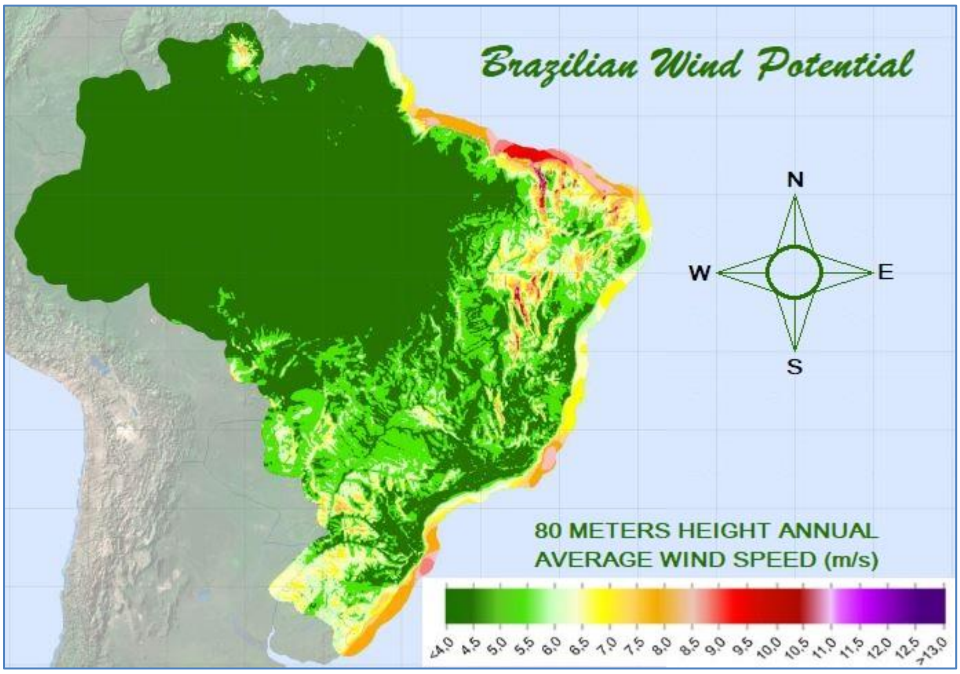


Figure 5.1 – Wind speed average.
Source: Adapted from Brazilian Wind Potential Atlas (DUTRA et al., 2017).

Wind speed average is not constant and, there is a literature consensus that its variation follows a Weibull curve (AMARANTE *et al.*, 2001). Based on statistical data Weibull curve presents the best adherence to the most varied cases of wind regimes, and it is given by Equation 5.1.

$$w(v) = \frac{k}{C}\left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^{k}} \tag{5.1}$$

where, *v* is the wind speed in m/s; *k* is the dimensionless shape factor; *C* is the scale factor in m/s.

When *k* is equal to 1 the Weibull curve become a negative exponential dependent only on wind speed. Greater constancy of winds with fewer extreme speeds are represented by higher values of *k*. *C* is calculated by a Gamma function dependent on wind speed average and on *k* factor. *C* is approximately 11% greater than the average wind speed for Brazilian data (AMARANTE *et al.*, 2001). In this study *k* = 2.7 and *C* = 7.8 m/s, based on New Brazilian Wind Potential Atlas' data (DUTRA *et al.*, 2017), was used to determine the wind speed.

5.3.2.4. Additional inputs

Data from Brazilian Atlas of Solar Energy (PEREIRA *et al.*, 2017), as explained on previous chapters, was also used for this study. Additionally, data from ANEEL databases, such as: white tariff, conventional tariff, and residential, commercial, and industrial demands (ANEEL, 2021e)(ANEEL, 2021d), are considered, as well as the MARR from EPE studies (EPE, 2020). All input parameters are presents in Table 5.2 on sub-section 5.3.5.

5.3.3. Generation and demand balance

To explain the balance between the distributed energy generated and the demand, it is necessary to start from the demand, assuming that the total demand (TD) is the sum of the own demand (OD) plus the third parties demand (TP). TD can be supplied 100% by the total generated energy (GE) or, in many scenarios, by GE plus one part from the grid (FG). It was assumed, in this study, that there will be no excess of GE, as there will always be available TP to consume it.

Part of GE will be consumed on site, the so-called self-consumption (SC). If there is a surplus, it will be injected into the grid (GI). GI will be consumed in part by OD and in part by TP, where applicable. Thus, the OD will be provided by the SC plus a part of the GI that will be compensated through the network (GC) and, eventually, a consumed part of the network without credits to offset (FG). If there is still a surplus of GI, it will be consumed by a third party from the grid (TC). Therefore, the balance can be represented by following equations set, (5.2) to (5.5), where on the left side are consumptions and on the right side are generation and/or energy supply sources.

$$\mathrm{TD} = GE + FG \tag{5.2}$$

$$\mathrm{OD} + \mathrm{TP} = GE + FG \tag{5.3}$$

$$\mathrm{OD} + \mathrm{TP} = SC + GI + FG \tag{5.4}$$

$$\mathrm{OD} + \mathrm{TP} = SC + GC + TC + FG \tag{5.5}$$

TP and FG may be equal to zero in some scenarios. It was compared hypothetical consumers with equal demand, with DG and with no DG, Figure 5.2. The cases with no DG will be charged by 100% of taxed tariffs. In cases with DG, the SC will not be charged, GC and TC will be charged by 57% of tariffs without tax and FG should be charged by full tariffs with tax. Cost of availability (CA) is charged by taxed conventional tariff in both cases, if applicable. As FG happens on both cases, it will not be considered for economic comparisons.

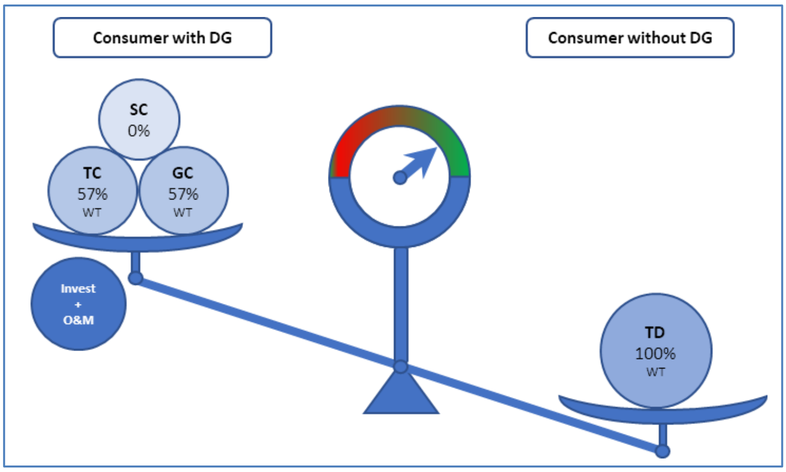


Figure 5.2 – Balance between consumers with and without DG.

When considering only the tariff, the consumer with DG obviously pays less than the consumer without DG, except when both consume less than the equivalent of the CA, in which case both will pay the same amount. However, the portion related to the investments necessary for DG installation, as well as the O&M expenses, the dark blue circle in Figure 5.2, must be added on the weighing dish. Thus, the DG project will only be feasible when inequality (5.6) is true during the project lifetime. If the metered demand is less than the equivalent demand for the CA, the DG will always be economically unfeasible.

$$0.57(TC + GC) + Inv_{DG} + O\&M < TD \quad (5.6)$$

where, the first term corresponds to reduced tariffs exempt of tax paid by the consumer with DG; Inv_{DG} is the investment to install the DG; and *TD* is the taxed full tariff paid by consumers without DG.

5.3.4. Criteria decision

The same criteria presented along this dissertation are, also, used in this last research. The purpose of the net present value (NPV) is to calculate the present value of a project future cash flows (ZORE *et al.*, 2018), discounted by a desirable discount rate, the minimum attractiveness return rate (MARR) in this case. Whereas another alternatives beyond NPV can help to better economic decision (FALCONETT; NAGASAKA, 2010), the internal return rate (IRR) and the discounted payback (DPB) were used in this work.

5.3.5. Simulation inputs setup

The present study was based on the power-plant sizes as defined in sub-section 5.3.2. For the stochastic analysis, 10,000 simulations for each scenario were performed by MCS, using the parameters and their distribution functions shown in Table 5.2.

Table 5.2 – input parameters and distribution functions

Input	**Distribution**	**Plant size**	**Minimum**	**Most Probable**	**Maximum**
Power-plant capacity [kW]	Triangular Distribution	Micro	0.5	1.45	10
		Mini	10	109	1,000
		Small	1,000	1,400	5,000
			Local	**Scale**	**Form**
Investments on Solar PV plant [USD/kW]	Weibull Distribution	Micro	650	700	2
		Mini	500	550	2
		Small	500	550	2
Investments on Wind-power plant [USD/kW]		Micro	133	400	2
		Mini	640	600	2
		Small	1,150	750	2
Investments on Battery Banks [USD/kW]		Micro	268	130	2
		Mini	275	140	2
		Small	290	145	2
				Average	**Scale**
Tariffs of electricity [US$/kWh]	Logistic Distribution	Peak tariff		0.2078	0.0272
		Intermediate		0.1374	0.0166
		Out of peak		0.0849	0.0073
		Conventional		0.1075	0.0095

			Local	Scale	Form
Wind speed [m/s]	Weibull Distribution	All cases	2	7.8	2.7
			Minimum	**Beta parameter**	**Maximum**
Solar radiation [kWh/m^2]	Beta distribution	All cases	2.40	1.51	7.00
			Local	**Scale**	**Form**
Electricity demands [kWh]	Gamma distribution	Micro	92	250	1,9
		Mini	1,840	25,000	1,9
		Small	184,000	100,000	1,9
			Average	**Standard deviation**	
MARR [%]	Normal distribution	All cases	8%	0.5%	

The power plant capacity is limited to the extremes of the respective classification and follows a triangular distribution. The most probable power capacity is given by the average of ANEEL data for micro and small plants and approximated for a new classification proposed in this study, the mini plant. Investments are well represented by a Weibull distribution. The scale, on the Weibull curve, represents the predominant value in the sample. Values smaller than the scale decay rapidly while high values fall slowly. Energy tariffs adapt to a normal curve with accelerated decay, also represented by a logistic curve. As discussed in several literatures, wind speed follows a Weibull curve, in our case, shaped based on Brazilian data (DUTRA *et al.*, 2017). As solar radiation is present from sunrise up to sunset, the best curve to represent it is a beta distribution able to represent non-zero values only in this specific range. Finally, the demand is represented by a Gamma distribution and the MARR following a normal curve.

Considering the proposed changes by ANEEL in-force and the effects of white tariff (WT), its necessary the use of correct amount of generation and demand in each tariff post as displayed in Table 5.3.

Table 5.3 – percentual of annual electrical production and demand by tariffs posts

Tariff point	Wind-power production	Solar PV production	Demands		
			Residential	Commercial	Industrial
Off-peak	84.59%	99.50%	65.35%	67.70%	92.54%
Intermediate	6.06%	0.49%	11.47%	12.85%	5.74%
Peak	9.34%	0.02%	23.18%	19.45%	1.72%

Source: Based on ANEEL (ANEEL, 2021a).

The most important for economic evaluation is the daily complementary production between wind and solar PV as shown on Figure 5.3. Whereas solar PV is exclusively produced during daytime, the wind power production is almost flat during the 24 hours of the day.

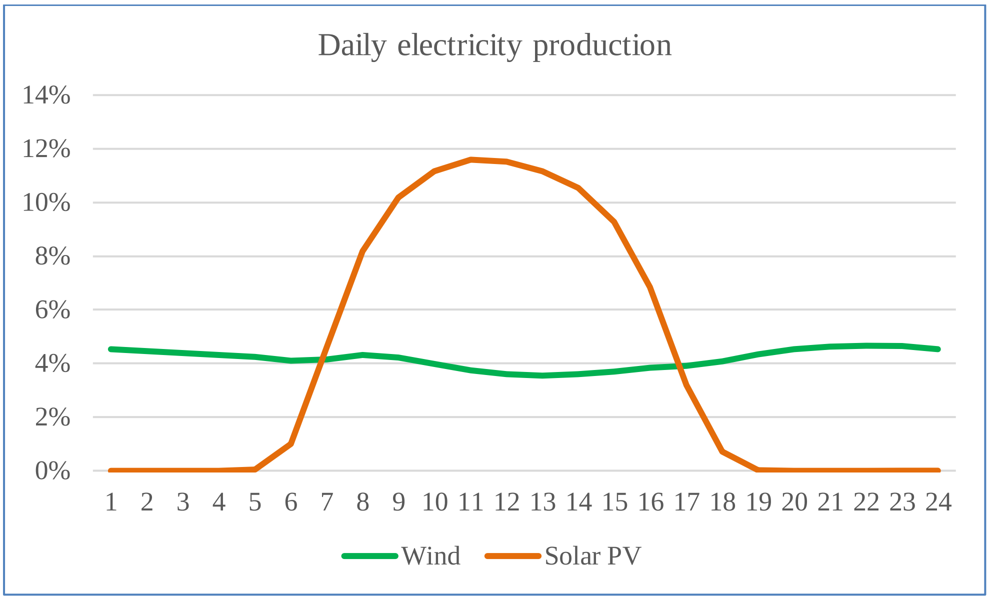


Figure 5.3 – Wind and solar PV daily production.
Source: Based on ANEEL (ANEEL, 2021a).

As in previous chapter, a percentage of each of the residential, commercial, and industrial demands in each of the proposed plant sizes was also considered, Table 5.4. The micro-plants were considered exclusively residential, the small plants dedicated to remote consumption, in addition to commercial and medium-sized industries. Mini plants are in the middle of classification and can be used for both applications considered here.

Table 5.4 – Demand percentiles among power-plant sizes

Classification	Demand		
	Residential	**Commercial**	**Industrial**
Micro-plant	90%	10%	0%
Mini plant	10%	50%	40%
Small plant	0%	40%	60%

5.4. Results and Discussion

Two parcels are needed to calculate the total produced energy. The first one is related to wind power generation and calculated by the product of nominal power times turbine yield in a desired time, Equation 5.7.

$$E_w = P_{nw}\eta_w t \quad (5.7)$$

If the nominal power (P_{nw}) is in kW and the time (t) in hour, the wind power produced energy (E_w,) will be in kWh. The turbine yield (η_w) based on manufacturers catalogues (IE EUROPE, 2011), is given by Figure 5.4. For the manufacturers researched, the best operational region is between wind speed of 12 and 20 m/s (red ellipse in the figure), that do not happen with high frequency in Brazil.

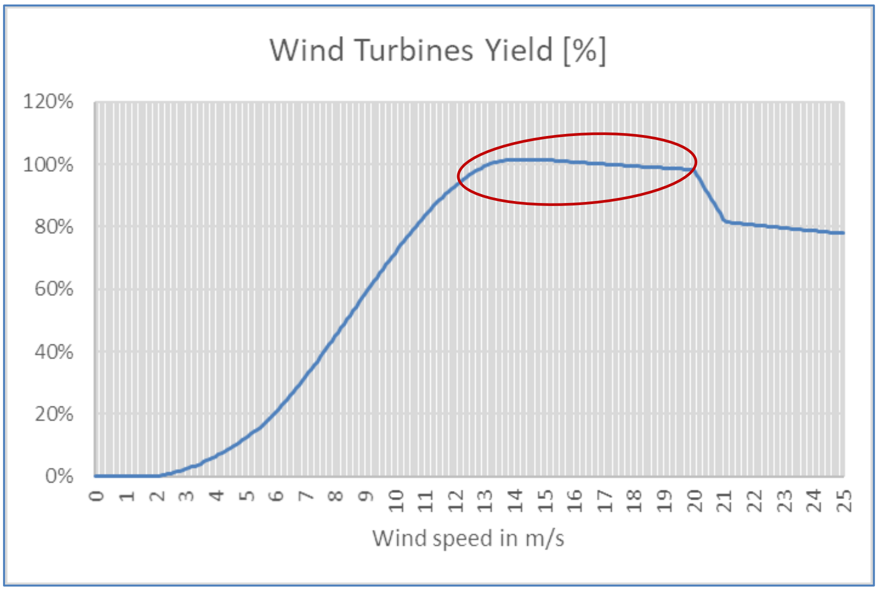


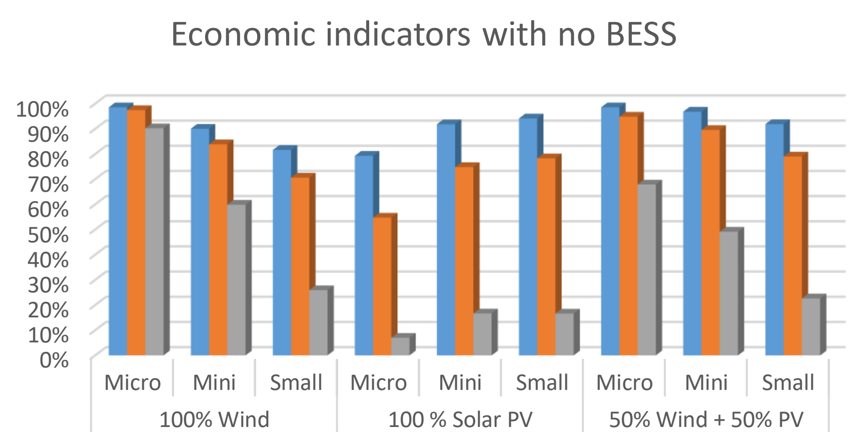
Figure 5.4 – Wind turbine yield.
Surce: Catalogue of European Urban Wind Turbine Manufacturers (IE EUROPE, 2011).

On the other hand, the solar PV produced energy, E_{PV} in kWh, is calculated by (5.8):

$$E_{PV} = P_{nPV}\left(\frac{A_p}{P_p}\right)R_m\eta_{PV}t \tag{5.8}$$

where, P_{nPV}, is the PV plant nominal power in kW; A_p and P_p are respectively the area in m^2 and nominal power in kW of a typical solar PV panel as defined in chapter 3 (DE DOILE *et al.*, 2021). The parcel $P_{nPV}(Ap/Pp)$ represents the total area of the photovoltaic solar panels array in m^2; R_m is the daily average soral radiation in kWh/m^2; η_{PV} is the dimensionless PV panel yield; and t is the time in days.

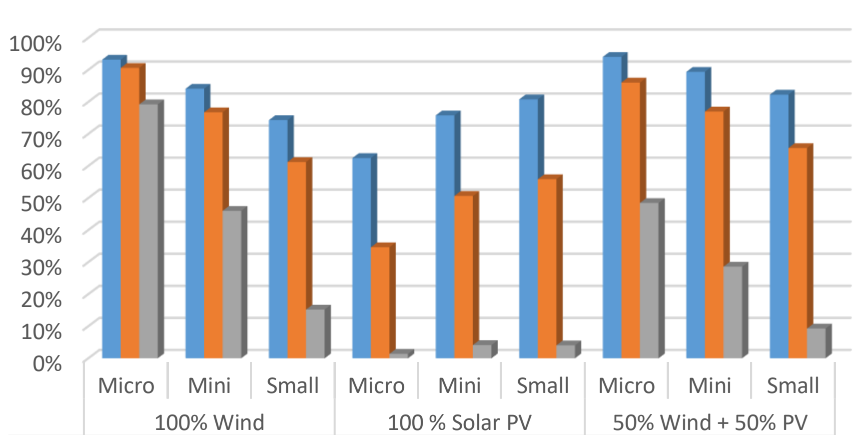
The performance of three DG unit sizes, micro, mini, and small plants, including remote consumption and white tariff (WT) scheme is compared. In the first stochastic simulations using MCS method, whose result is shown in Figure 5.5, the probability values of obtaining an NPV $\geq$ 0, an IRR $\geq$ 12% and, a DPB of 5 years or more, without battery energy storage system (BESS), was analysed. By the first results, the economic indicators show to us that the mix between wind and solar PV is better than the use of a single source. Results also reveal, in case of single source use, that micro-plants present best economic feasibility using wind power, in opposition of small plants that present best economic performance with solar PV. These results happen due to the consume profiles, where residential demand, predominantly from micro-plants, is high in peak time, and industrial consume is higher during daytime.



	Micro (100% Wind)	Mini (100% Wind)	Small (100% Wind)	Micro (100 % Solar PV)	Mini (100 % Solar PV)	Small (100 % Solar PV)	Micro (50% Wind + 50% PV)	Mini (50% Wind + 50% PV)	Small (50% Wind + 50% PV)
NPV	99%	90%	82%	79%	92%	94%	99%	97%	92%
IRR	97%	84%	71%	55%	75%	78%	95%	90%	79%
DPB	90%	60%	26%	7%	17%	17%	68%	49%	23%

Figure 5.5 – Results with no BESS.

The stochastic results varying all inputs, as explained in sub-section 5.3.5, with the addition of the 5 hours capacity battery banks and after 10,000 MCS, are shown in the following figures. In Figure 5.6 we can see the results for the same configuration used before, 100% of each source and a fifty-fifty case. As concluded in the chapter 4, the 100% solar PV case is unfeasible in almost all scenarios. However, the fifty-fifty case reveals once again that the mix between solar PV and wind power is economically better in many scenarios, evidencing the necessity to find the best proportion wind/PV. Micro-plant still being economically better when using wind power, if considered only single sources.



	Micro (100% Wind)	Mini (100% Wind)	Small (100% Wind)	Micro (100 % Solar PV)	Mini (100 % Solar PV)	Small (100 % Solar PV)	Micro (50% Wind + 50% PV)	Mini (50% Wind + 50% PV)	Small (50% Wind + 50% PV)
NPV	93%	84%	74%	62%	76%	81%	94%	89%	82%
IRR	91%	77%	61%	35%	51%	56%	86%	77%	66%
DPB	79%	46%	15%	1%	4%	4%	48%	29%	9%

Figure 5.6 – Results of economic indicators with 5 hours capacity BESS.

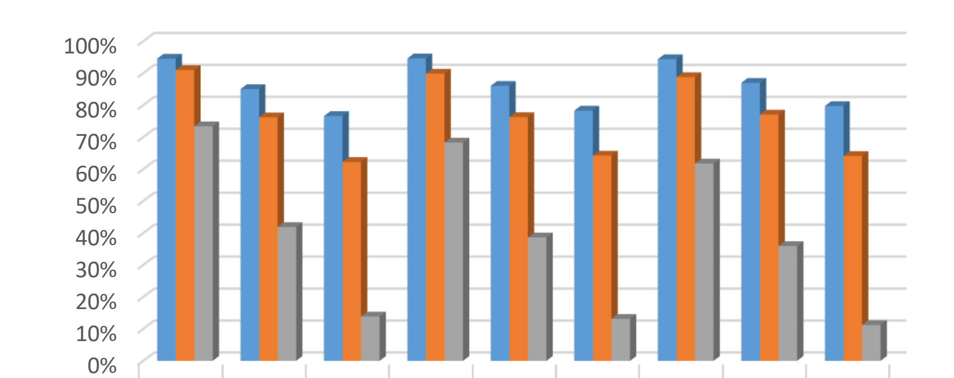
To determine the best proportion between wind power and solar PV, a sensitiveness simulation was done varying the proportion from 100% wind power up to 100% PV. The 10,000 results obtained by the MCS were sorted and the 1000 results with the best economic indicators were verified. In these best results, the predominant wind power and PV proportion was observed, as presented in Table 5.5. As expected, for each plant size and each economic indicator a different proportion was found.

The best proportion in general average is around 73% wind power and 27% solar PV. Micro-plants perform better with a higher proportion of wind farms, while small plants perform better with a lower proportion of wind farms. There are two explanations for why larger plants have better economic performance with a lower proportion of wind turbines. The first one is due to the electricity offset system (EECS) that benefits the production of energy during the day, when solar PV produces more. And, the second, is due to the cost per kW of wind turbines. For DG, the cost of small wind turbines is much less than the cost of large wind turbines. Therefore, the bigger the hybrid wind/solar PV plant is, the lower will be the percentage of wind energy.

Table 5.5 – Best proportion of wind power in a hybrid wind/PV power plant

	NPV	IRR	DPB	Average
Micro	76%	85%	85%	82%
Mini	71%	73%	72%	72%
Small	72%	60%	61%	64%
Average	73.00%	72.67%	72.67%	72.78%

The results for three different proportions, including the best one 73% wind and 27% PV, are shown in Figure 5.7. The results confirm what was predicted by previous results in Table 5.5. Micro-plants have satisfactory economic performance in all scenarios. However, scenarios with a higher proportion of wind energy present better results. Small power plants, where industrial consumption and the usage of large wind generators are predominant, demonstrate slightly better results for smaller proportions of wind power, around 65%. However, the payback period tends to get longer the smaller the wind power proportion is. A similar behaviour to this latter happens with mini plants. To obtain an optimum result, it is necessary to know the better data of the power plant installation site. Some small areas in the country have excellent solar radiation coincidentally with high wind speeds.



	82% Wind + 18% PV			73% Wind + 27% PV			64% Wind + 36% PV		
	Micro	Mini	Small	Micro	Mini	Small	Micro	Mini	Small
NPV	95%	85%	77%	95%	86%	78%	94%	87%	80%
IRR	91%	76%	62%	90%	76%	64%	89%	77%	64%
DPB	73%	42%	14%	68%	39%	13%	62%	36%	11%

Figure 5.7 – Results of economic indicators for best proportions Wind/Solar PV.

It was not found any economic feasibility study for hybrid wind plus solar PV power plants in Brazil as distributed generation (DG). However, there are a few studies for distributed solar PV and wind generation individually, with and without BESS. The studies were carried out in different years, therefore different prices and tariffs were considered. From the first deterministic study (HOLDERMANN; KISSEL; BEIGEL, 2014) that attested unfeasibility for solar PV as DG in Brazil, solar panel prices dropped from around 3.000 USD/kW to 1.000 USD/kW nowadays. As the PV business was beginning in Brazil, the authors used UK prices to calculate investments. In that time electricity tariffs were slightly subsidized by reduction in energy prices, contributing for business unfeasibility.

Rocha et al. (2017) concluded for majority unfeasibility of PV as DG in a stochastic study concluded in 2017. In this work the effects of tax exemption were considered. Without taxes, some cases of PV as DG projects began to become economically viable from that time onwards. The first economic feasibility study for solar PV with BESS was concluded in 2018 and attested the unfeasibility of analysed projects (DA SILVA; BRANCO, 2018), especially due to the high prices of battery banks. Deotti et al. (2020) in a similar study in 2020 had the same results and conclusions, as not viable projects. Both were deterministic studies considering high price PV panels and battery banks.

Solar panels price dropped in the last decade while electricity tariffs grown up. De Doile et al. (2021), in a deterministic and stochastic study derived from this dissertation chapter 3, attested for the first time the economic viability of solar PV as DG in Brazil.

On the other hand, DG studies from wind sources (LACERDA *et al.*, 2020;

ROCHA *et al.*, 2018; ROTELA JUNIOR *et al.*, 2019), without the use of BESS, were found to have a low probability of economic viability, and these were developed in Brazil between the years 2018 to 2020. Studies related to wind power DG with BESS were not found for the Brazilian scenario.

5.5. Conclusions

As conclude in the previous chapter, the literature reveals an economic feasibility for solar photovoltaic plants with no energy storage systems, whereas for the wind source, a low probability of viability was found. The drop of solar panels price and the rise in tariffs, by themselves, are enough to make distributed generation from solar photovoltaic source economically viable. However, when battery banks as energy storage was added, the set presents a low probability of economic viability.

In this work, the introduction of wind power together solar photovoltaic made the distributed generation with 5 hours capacity battery banks economic viable in almost all studied scenarios. The investment return period for small plants, greater than 1 MW installed power, still being in a long term.

All scenarios for a distributed hybrid wind plus solar photovoltaic system with battery banks demonstrated a high probability of feasibility. These systems, including energy storage, may have benefited from new energy offsetting regulation, which increased the cost of the grid for prosumers.

Finally, the addition of wind power to solar photovoltaic have partially solved the problem related to white tariffs scheme combined with the electric energy compensation system, aggregating energy production at night ant in the peak demand period. However, the widespread use of battery energy storage systems only will be encouraged by drop of batteries cost or some subsidy for energy storage systems.

One must remember that wind speed in Northern and Western Brazilian regions is not suitable for wind-power generation. Therefore, other energy sources must be studied in conjunction with solar photovoltaic energy in these regions.

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1. CHAPTER 6 – Final considerations

This dissertation is arranged in 6 chapters, 4 of which, dedicated to the presentation of researches carried out during the course. The first chapter is dedicated to a general introduction, where the main aspects of renewable energies (RES) theme in the world and in Brazil are presented, finishing with the distributed generation (DG) specific theme. The general objective and the specific objectives of each of the following chapters are presented, in addition to the general theoretical foundations used throughout the dissertation.

Firstly, in chapter 2, a systematic literature review (SLR) and legislation and regulations on the subject is presented, looking for gaps to be studied in the main research. In addition to the traditional SLR, it was decided to include a review of the laws and regulations of some countries, as technical and economic standards strongly affect the main objective of the work, which is the DG from renewable sources economic analyses. The main findings are: (i) there is little research into wind, solar PV and energy storage systems (ESS) in conjunction. The few articles found were produced recently, demonstrating a tendency to study these three technologies, which are complementary, together. (ii) there are limitations for reviewing legislation and regulations due to these documents being available in the respective languages, without translation into English, and being very volatile, i.e., laws and regulations normally change frequently. However, it can be seen that, in the 5 countries researched, there are incentives for the inclusion of new DG technologies and ESS.

Chapter 3 is dedicated to effects analyses of regulatory changes in progress in Brazil, on the, already established, DG from solar photovoltaic (PV) sources. Such effects were analysed in the 5 geopolitical regions of the country, and it was concluded that the proposed changes, in particular the end of the cross-subsidy supported by the tariff of consumers without DG, will cause a significant reduction in the economic viability of these projects.

Whereas, new regulatory changes, such as remote consumption and the white tariff, with differentiated values for peak-demand, intermediate and off-peak, were added in chapter 4, as well as the addition of battery banks as ESS. A new power-plant classification in three bands of installed power is proposed in this chapter. Contrary to expectations, there was no improvement in the economic viability of the DG from solar

PV source with battery energy storage system (BESS). Even having used all the legal and regulatory incentives in-force, these systems proved to be economically unfeasible in most of the studied scenarios. It was clear the need to add another source of generation and/or new forms of subsidies, especially for BESS.

In Brazil, wind microturbines have not yet spread and are not found in the local market, leading to the need to import this equipment. Even so, in chapter 5, wind generation was included in the economic feasibility analyses. Retail prices in the international market were considered without the import tax, which can reach 80% if there is no law that exempts it. The results demonstrated that this arrangement with wind-power plus solar PV and BESS is viable in most cases, depending on the percentage of each source. This percentage varies between 60 and 85% of wind farms and should be studied for each specific case, taking into account, mainly, the exact location of the project.

The main contributions of this study are aimed at decision makers, policy makers and regulators. There is a need for economic and financial incentives for the entry of wind microturbines into distributed generation, as well as for new storage technologies. The cross-subsidy must be maintained for micro power plants up to 10 kW of nominal power, at least for residential consumers. Additional studies to this one is needed for inclusion of utility-scale power plants and ESS in the economic analyses, as well as other energy sources should be studied in conjunction of solar PV in regions where the wind speed is not suitable for electrical generation. Technical studies should be carried out to determine the extent to which energy storage in the reservoirs of hydroelectric power-plants will be sufficient for integration of new renewable energy from intermittent sources.

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APPENDIX 1.1 – List of produced articles based on this research

Based on chapter 2	
Title	Hybrid wind-photovoltaic generation with energy storage systems: a systematic literature review and contributions to techno-economic regulation
Authors	DE DOILE, Gabriel Nasser Doyle [1] ROTELLA JUNIOR, Paulo [2] ROCHA, Luiz Célio Souza [3] BOLIS, Ivan [4] AQUILA, Giancarlo [5] COELHO JUNIOR, Luiz Moreira [6]
August/2021 Under Review	Journal of Energy Storage, July 2021
Abstract	The operation of the electrical system is more difficult due to the intermittent and seasonal characteristics of wind and solar energy. Such operational challenges are minimized by the incorporation of the energy storage system (ESS), which plays an important role in improving the stability and the reliability of the grid. The economic viability of hybrid plants with storage can be improved if the regulation enables the remuneration of the various ancillary services that ESS can provide. Thus, the aim of this study is to provide a literature review regarding economic feasibility of hybrid wind-PV generation with ESS and its legal and regulatory aspects. Observing the world tendency, the new studies should address the techno-economic feasibility of wind power and solar PV in conjunction with, at least, one kind of ESS. Also, it is very important to take in account the regulatory barriers and proposes solutions to remove them. It was observed that although regulatory aspects can influence economic feasibility of hybrid projects, little is discussed about this relationship between the frameworks. The findings presented in this article are important not only for Brazil, but also for other countries that do not have regulations in force to support the use of ESS in hybrid systems.
Based on chapter 3	
Title	Viabilidade econômica de microcentrais fotovoltaicas conectadas a rede brasileira frente à “taxação do sol”
Authors	DE DOILE, Gabriel Nasser Doyle [1] DE ARAÚJO, Dalila Medeiros [1] CARNEIRO, Priscila França Gonzaga [1] GONÇALVES, Kalliny dos Santos [1]
Presented in November/2020	I CERES 2020 – Congresso Nacional de Energias Renováveis, Exergia e Sustentabilidade; novembro de 2020, Natal, Brasil. https://sigeventos.ufrn.br/evento/CERES2020
Abstract (paper in Portuguese)	Distributed generation technologies are growing rapidly up and lead to the progressive integration of electrical micro-plants in the distribution network. The main current challenge is to make these micro-plants economically viable and profitable for entrepreneurs and users of the national electricity system. Photovoltaic micro-plants are seen as a solution, as they can be easily installed, mainly due to the high modularity and adaptability to different forms of installation in buildings or terrain. Currently, Brazil is undergoing important changes in its distributed generation regulations, including the production of electricity from photovoltaic micro-plants. These are amendments proposed by the National Electric Energy Agency, the Brazilian electricity sector regulator, which provide, in particular, that only the portion of the tariff corresponding to the cost of energy is compensated and the costs of services and charges included in the tariff are prorated, proportionally to the demand used from the network, among all users. Consumers already installed and their representative entities contested this proposal by the regulatory agency, in a way that became known as “sun taxation” through the numerous public interventions of these entities. In fact, the new regulation proposes the end of the cross subsidy, in which consumers with distributed generation stop paying for charges and transmission and distribution services related to compensated energy. These costs are then apportioned among the other consumers who do not have distributed generation

	systems installed. In this study, was carried out a comparison of the economic and financial viability of residential photovoltaic micro-plants before and after the new standard proposed by the Brazilian regulatory agency. Average demand, energy tariff and solar radiation from the five political-geographic regions of Brazil were used, in addition to the national average in the comparisons. Stochastic analyses were also carried out, varying the installed power of the micro-plants and a sensitivity varying the minimum attractiveness rate for the national case.
Title	Economic feasibility of photovoltaic micro-plants connected to the Brazilian distribution grid facing the regulation changes proposed
Authors	DE DOILE, Gabriel Nasser Doyle [1] ROTELLA JUNIOR, Paulo [2] CARNEIRO, Priscila França Gonzaga [1] PERUCHI, Rogério Santana [2]
Presented and Published in September/2020	2020 55th International Universities Power Engineering Conference (UPEC), Turin, Italy, 2020, pp. 1-6, DOI: 10.1109/UPEC49904.2020.9209842 https://ieeexplore.ieee.org/abstract/document/9209842
Abstract	Brazil may undergo changes in its distributed generation regulations, including the production of electricity from small solar power plants. The proposed amendment by Regulatory Agency provides for only the cost of energy should be compensated. The costs of services and charges included in tariff should be prorated among all consumers. Consumers already installed and their representative entities contest this proposal in a way that became knew as "sun fees", but there is no scientific work to corroborate these claims. Indeed, the new regulation proposes the end of cross-subsidy, in which consumers without distributed generation pay for charges, transmission and distribution systems used, also, by the consumers who has installed distributed generation. In this paper, a comparison of the economic viability of microgeneration before and after the new standard proposed is carried out. The averages of the electrical demand, energy price and solar radiation in the five geographic Brazilian regions ware used in comparisons. The national averages were also used in the comparisons in addition to stochastic analyses varying the installed power of the micro-plants and the minimum attractiveness rate. The study concludes that there will be no significant changes in the economic feasibility of photovoltaic micro-centrals, but the payback will be extended.
Title	Economic feasibility of photovoltaic micro-installations connected to the Brazilian distribution grid in light of proposed changes to regulations
Authors	DE DOILE, Gabriel Nasser Doyle [1] ROTELLA JUNIOR, Paulo [2] CARNEIRO, Priscila França Gonzaga [1] PERUCHI, Rogério Santana [2] ROCHA, Luiz Célio Souza [3] JANDA, Karel [7] AQUILA, Giancarlo [5]
Published in March/2021	Energies 2021, 14, 1529. https://doi.org/10.3390/en14061529
Abstract	Brazil is currently undergoing changes to regulations on distributed generation (DG), specifically for solar energy micro-generation. The changes proposed by the Brazilian Regulatory Agency suggest that only the cost of energy be compensated to investors. The service costs and other charges related to energy tariffs must be divided among consumers. Investors with existing installations and class entities have contested these proposals, calling them “sun-fees”. To date, no scientific papers have been published discussing these changes. The new regulations propose an end to cross subsidies, where all consumers (even those who do not have DG) pay for the transmission and distribution systems. This study compares the economic feasibility of micro-generation before and after implementing the new standards proposed by the regulatory agency. We used data on average electrical energy demand, energy

	price, and solar radiation in different regions. The national averages were used as a base comparison with other scenarios. The results show that projects are viable for all analysed scenarios, however, after implementing the proposed changes, the discounted payback time is extended. This, however, does not make projects unfeasible.
Title	Impact of regulatory changes on economic feasibility of distributed generation solar units in Brazil
Authors	DE DOILE, Gabriel Nasser Doyle [1] ROTELLA JUNIOR, Paulo [2] ROCHA, Luiz Célio Souza [3] CARNEIRO, Priscila França Gonzaga [1] PERUCHI, Rogério Santana [2] JANDA, Karel [7] AQUILA, Giancarlo [5]
August/2021 Under Review	Sustainable Energy Technologies and Assessments, June 2021.
Abstract	The Brazilian regulatory agency on National Electrical Energy (ANEEL) proposed in 2019 that the costs for accessing the electricity grid should be shared among all consumers. This would do away with cross-subsidies where normal consumers without installed solar distributed generation (DG) units effectively cover the costs of access to the grid for consumers with DG units. We compared the economic and financial viability of two scenarios, one before the proposed changes, and the other after the proposed changes, to understand how this legislature will affect the viability of DG projects in Brazil. We did this by studying all 5 regions covering the whole Brazilian area by analysing data on average solar radiation, demand, and energy prices. We conducted stochastic analysis by varying the initial investment costs, demand, and energy prices, for DG solar plants. Lastly, we conducted stochastic analysis for the whole of Brazil by varying the Minimum Acceptable Rate of Return (MARR). We confirmed that there is a statically significant reduction in economic viability for DG solar units in Brazil for all regions if the proposed legislation were to be enacted, while the payback period and other financial indicators for DG solar units differ across regions. We also confirmed that solar radiation is not the decisive factor in determination of economic viability of DG solar production.
Based on chapter 4	
Title	Stochastic economic feasibility analysis of photovoltaic distributed generation and battery energy storage systems under the Brazilian economic regulation
Authors	DE DOILE, Gabriel Nasser Doyle [1] ROTELLA JUNIOR, Paulo [2] ROCHA, Luiz Célio Souza [3] JANDA, Karel [7] PERUCHI, Rogério Santana [2] CHICCO, Gianfranco [8]
August/2021 Under Review	Renewable Energy, May 2021
Abstract	Photovoltaic systems are largely involved in the process of decarbonization of the electricity production. Among the solutions of interest for deploying higher amounts of photovoltaic (PV) energy generation for reducing the electricity taken from the grid, the inclusion of local battery energy storage systems has been considered. Battery energy storage provides an energy buffer useful to better manage the fluctuations of PV energy production, or to serve the demand when the PV generation is absent or insufficient and the price of the electricity taken from the grid is high. While technically sound, the installation of a PV system with battery energy storage must demonstrate its profitability in the specific context of application, also depending on the regulation in place in the relevant jurisdiction. This paper presents the stochastic economic feasibility analysis for the installation of distributed PV power plants facing the new regulation of electric energy compensation system, planned to be in force in Brazil since the second half of 2021, with the hourly tariff known as White Tariff. Three classifications of distributed power plants are proposed,

	and the related models introduce battery banks to regulate the peak demand when tariffs are more expensive. Stochastic analysis varying the initial investment, minimum attractiveness return rate, energy demand, energy tariff, solar radiation and the installed power of the plants and battery banks are carried out. The results show that, in the absence of economic incentive policies to support this kind of renewable energy generation associated with battery energy storage systems, there is a small probability of economic viability, especially for micro-plants up to 10 kW of installed power. Thus, energy storage systems must still be incentivized to be installed in conjunction with distributed generation.
Based on chapters 3 and 4	
Title	Propostas para redução dos impactos da "taxação do sol" na geração distribuída no Brasil
Authors	DE DOILE, Gabriel Nasser Doyle [1] ROTELLA JUNIOR, Paulo [2] ROCHA, Luiz Célio Souza [3]
August/2021 Approved	XII Congresso Brasileiro de Regulação, ABAR – Associação Brasileira de Agências de Regulação, novembro de 2021, Foz do Iguaçu.
Abstract (paper in Portuguese)	As tecnologias de geração distribuída (GD) têm evoluído rapidamente e, levam à uma progressiva integração de microcentrais elétricas na rede de distribuição. Para além das questões técnicas e operacionais, o principal desafio vigente é tornar essas micro usinas economicamente viáveis e lucrativas para os empreendedores e, com preços da energia acessíveis para os usuários do sistema elétrico nacional. As microcentrais fotovoltaicas associadas a bancos de baterias são vistas como uma solução prática, pois podem ser facilmente instaladas, principalmente pela elevada modularidade e adaptabilidade às diferentes formas de instalação em edifícios ou terrenos. O armazenamento de energia, entre outras vantagens, tem se mostrado uma importante alternativa para redução do pico da demanda e da sazonalidade das fontes alternativas de energia, como eólica e solar fotovoltaica. Atualmente, o Brasil está passando por mudanças importantes em seus regulamentos de geração distribuída, impactando sobretudo a produção de energia elétrica a partir de micro usinas fotovoltaicas. Trata-se de alterações da regulamentação propostas pela Agência Nacional de Energia Elétrica (ANEEL). A principal alteração proposta é no Sistema de Compensação de Energia Elétrica (SCEE), que atualmente prevê a compensação de um kWh para cada kWh de energia injetada na rede. A ANEEL quer que apenas a parcela da tarifa correspondente ao custo da energia seja compensada. Os custos dos serviços e encargos que integram a tarifa devem ser custeados da mesma forma por todos os usuários da rede, independente se eles têm ou não GD instalada. Os consumidores já instalados e suas entidades representativas contestaram esta proposta da Agência Reguladora, no que ficou conhecido como "Taxação do Sol" através das inúmeras intervenções públicas dessas entidades. Porém, não se trata da criação de nenhum novo imposto ou taxa. De fato, o novo regulamento propõe o fim do subsídio cruzado, no qual os consumidores que possuem GD deixam de pagar pelos encargos e serviços de transmissão e distribuição referentes à energia compensada. Estes custos são, então, rateados entre os demais consumidores que não possuem sistemas de GD instalados. Neste estudo realizou-se uma comparação da viabilidade econômico-financeira de microcentrais fotovoltaicas residenciais antes e depois da nova norma proposta pela Agência Reguladora brasileira. Foram utilizadas as médias de demanda, tarifa da energia e radiação solar das cinco regiões político-geográficas do Brasil, além da média nacional nas comparações. Foram feitas, também, análises estocásticas variando a potência instalada das microcentrais e uma sensibilidade variando a taxa mínima de atratividade para o caso nacional. O principal resultado mostra que grande parte das microcentrais solar fotovoltaicas tornar-se-ão inviáveis sob a ótica econômico-financeira, com retorno financeiro apenas no longo prazo. De posse desses resultados foi feita uma análise da proposta da ANEEL. Foram avaliados os documentos disponibilizados nas consultas e audiência públicas do processo de alteração da Resolução Normativa nº 482/2012. A proposta de alteração está focada no SCEE e não avaliou alterações no tamanho (potência instalada) nem na classificação das centrais de geração distribuída. Adicionalmente, a ANEEL deixa de avaliar a inserção de sistemas de armazenamento associado às centrais de geração

	distribuída, o que em tese pode contribuir para viabilidade econômica dessas instalações. Além de verificar a predominância no Brasil de micro centrais com potência instalada inferior a 10 kW, neste estudo fez-se uma comparação com as classificações de centrais de geração distribuída nos Estados Unidos, no Reino Unido e na Irlanda. Conclui-se que a alternativa da ANEEL pode ser melhorada com a inclusão de novos níveis de classificação, além dos existentes. Notadamente, microcentrais de até 10 kW instalados; minicentrais de 10 kW a 1 MW e pequenas centrais de 1 a 5 MW de potência instalada. Um tratamento diferenciado do SCEE para cada uma dessas classificações é proposto, bem como a inclusão de incentivos para instalação de sistemas de armazenamento de energia associados às centrais de GD. Como as microcentrais (com potência instalada inferior a 10 kW) contribuem com um percentual muito pequeno no total da geração instalada no País, propõe-se que o subsídio cruzado seja mantido, pois do contrário essas instalações serão inviabilizadas do ponto de vista econômico-financeiro. Para as demais, propõe-se alternativas que minimizam o impacto da ausência do subsídio cruzado, em especial para aquelas que optarem pela instalação de armazenamento associado às centrais de geração.
Based on chapter 5	
Title	Feasibility of hybrid wind and photovoltaic distributed generation and battery energy storage systems under techno-economic regulation
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August/2021 Under review	Energy – June 2021
Abstract	Many countries have considered the possibility of hybrid generation from renewable energy sources (RES), aiming at benefits for the electrical system. The increasing use of intermittent sources, as solar and wind, substantially alters grid operations. These operational challenges can be minimized by the incorporation of energy storage systems (ESS), which play a prominent role in increasing the reliability and stability of the grid. Thus, this study aims to assess the economic feasibility of distributed hybrid power-plants with battery energy storage system (BESS). Stochastic analyses are carried out by varying nine of the main variables in three sizes of PV hybrid power-plants: micro-plant, up to 10 kW; mini-plant, from 10 kW up to 1 MW, and small powerplant from 1 up to 5 MW installed power. In all of them, we have considered battery banks with supply capacity for five hours. All scenarios for distributed hybrid wind-PV system with BESS presented a high probability of viability. However, widespread use of BESS only will be encouraged by drop of batteries cost or some subsidy for ESS. The combined use of these RES have partially solved the problem related to white tariffs scheme combined with electric energy compensation system, aggregating energy production in the peak demand period.

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APPENDIX 2.1 – Sample of articles found by SLR

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