FEDERAL UNIVERSITY OF RIO DE JANEIRO

GRADUATE SCHOOL OF BUSINESS

Marina de Gusmão Bastos

Economic feasibility study of a wind power plant in Rio de Janeiro using an alternative metric to the Cost Benefit Index

Rio de Janeiro

2019

Marina de Gusmão Bastos

Economic feasibility study of a wind power plant in Rio de Janeiro using an alternative metric to the Cost Benefit Index

Master and MBA dissertation presented to the Full-Time MBA of COPPEAD Business School – Universidade Federal do Rio de Janeiro

Supervisor: Professor Otavio Figueiredo

Rio de Janeiro

CIP - Catalogação na Publicação

dB327e

de Gusmão Bastos, Marina
Economic feasibility study of a wind power plant in Rio de Janeiro using an alternative metric to the Cost Benefit Index / Marina de Gusmão Bastos. - Rio de Janeiro, 2019.
68 f.

Orientador: Otavio Figueiredo.
Dissertação (mestrado) - Universidade Federal do Rio de Janeiro, Instituto COPPEAD de Administração, Programa de Pós-Graduação em Administração, 2019.

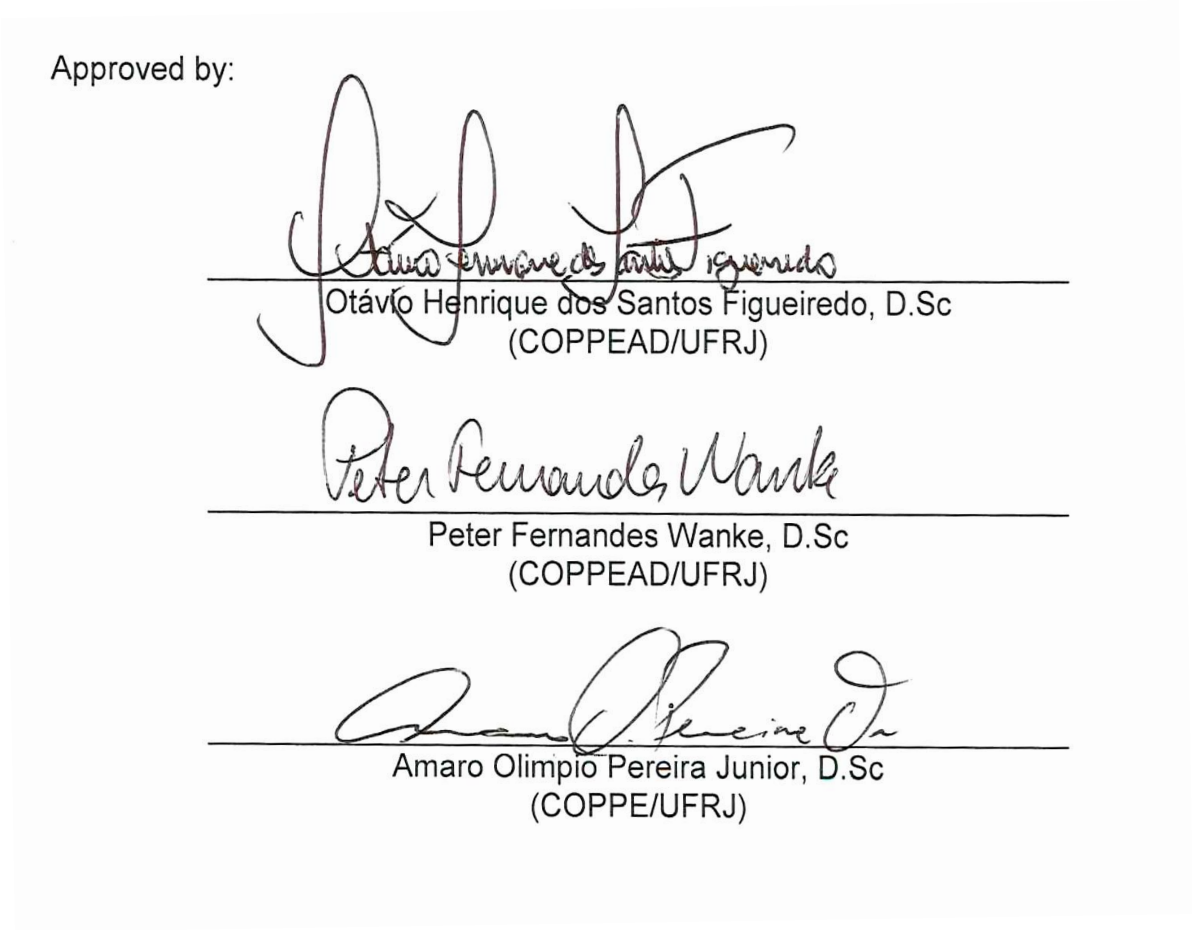
1. Levelized cost of electricity. 2. Levelized avoided cost of electricity. 3. Wind power generation. 4. Renewable energy auctions. I. Figueiredo, Otavio, orient. II. Título.

Elaborado pelo Sistema de Geração Automática da UFRJ com os dados fornecidos pelo(a) autor(a), sob a responsabilidade de Miguel Romeu Amorim Neto - CRB-7/6283.

Marina de Gusmão Bastos

Economic feasibility study of a wind power plant in Rio de Janeiro using an alternative metric to the Cost Benefit Index.

Master and MBA dissertation presented to the Full-Time MBA of COPPEAD Business School – Universidade Federal do Rio de Janeiro



Approved by:

Otávio Henrique dos Santos Figueiredo, D.Sc
(COPPEAD/UFRJ)

Peter Fernandes Wanke

Peter Fernandes Wanke, D.Sc
(COPPEAD/UFRJ)

Amaro Olimpio Pereira Junior, D.Sc
(COPPE/UFRJ)

ACKNOWLEDGEMENT

Gostaria de agradecer primeiramente ao professor Amaro Pereira Jr. Muito obrigada pelo suporte, paciência e conhecimento compartilhado ao longo de todo o percurso. Sem você esse trabalho não seria possível.

Ao professor Otavio Figueiredo, muito obrigada pela flexibilidade e por ter aceitado ser meu orientador.

Quero agradecer também ao meu amado marido por ser meu porto seguro e por trazer maturidade, equilíbrio e amor à minha vida.

Agradeço também à minha avó, mãe e irmão por estarem sempre ao meu lado me amando incondicionalmente.

Quero agradecer também às minhas queridas amigas Joanna e Clarice por serem meu colo e me fazerem sorrir sempre que estamos juntas ou até mesmo quando estamos distantes.

Por fim gostaria de agradecer ao Instituto COPPEAD e a todos os funcionários. Termino o mestrado com a consciência de que evolui imensamente na minha vida acadêmica e profissional.

ABSTRACT

Historically, the selection of electricity generation technologies to expand the capacity of an electric system has been based on comparisons between their costs. Brazil follows this worldwide traditional model using the Cost-Benefit Index in the energy auctions. However, this method disregards the location of the plants, for example if they are close to important load centers, and the temporal variability of the energy productions, in other words if it happens during a peak in demand or in a period of drought. These aspects are very important to the economic feasibility of intermittent sources like wind. In addition, the transmission cost between the main producing region and the most important load center is neglected. In case these aspects are considered in the Brazilian energy auctions, the wind plants located in the Southeast region may gain substantial competitiveness. In order to evaluate that, the net economic value, a metric developed by EIA/DOE (2013), will be used to compare the economic attractiveness of wind plants located in the Northeast (the greatest wind energy producer region) and Rio de Janeiro (located in the main load center). The Port of Açu was the location chosen to house a hypothetical wind plant in Rio de Janeiro. The study found that the Port of Açu's net value including the avoided transmission cost is significantly higher than the Northeast's. Additionally, the minimum net value for a 90% confidence interval ($P_{5\%}$), even when the avoided transmission cost is neglected, is still higher for the Port of Açu than for the plants analyzed in Northeast. These results indicate that a wind energy project in Port of Açu may face lower economic risks if the avoided cost criteria are used in the Brazilian energy auctions and that a wind plant projected to attend the demand in Rio de Janeiro should be built in this same region. This methodology is relevant and can be applicable to other large interconnected systems like China, Europe and Argentina.

Keywords: Levelized cost of electricity; Levelized avoided cost of electricity; ICB; Wind power generation; Renewable energy auctions; Expansion of power generation

TABLE OF CONTENTS

1. INTRODUCTION 11
2. THE BRAZILIAN ELECTRICAL SYSTEM 16
  2.1. OVERVIEW 16
  2.2. THE DILEMMA OF THE ELECTRICAL SYSTEM OPERATION 17
  2.3. THE ENERGY AUCTIONS IN BRAZIL IN 2018 18
  2.4. WIND POTENTIAL IN BRAZIL 21
3. THE PORT OF AÇU 23
4. LITERATURE REVIEW 25
  4.1. LEVELIZED COST OF ELECTRICITY (LCOE) 25
  4.2. OTHER CRITERIA FOR ENERGY INVESTMENT SELECTION 26
  4.3 THE CHOICE FOR OPTIMAL PORTFOLIOS 29
5. METHODOLOGY 31
  5.1. THE CHOSEN WIND PLANTS IN NORTHEAST SUBSYSTEM 32
  5.2 LCOE 33
  5.3 LACE 35
    5.3.1 Average marginal general price 36
    5.3.2 Average Expected Generation Hours 37
    5.3.3 Capacity Payment 37
    5.3.4 Capacity Credit 37
  5.4. TRANSMISSION COSTS 38
6. RESULTS 39
  6.1 VALIDATION 40
    6.1.1 Northeast data validation 40
    6.1.2 Port of Açu data validation 41
  6.2 LCOE 42
    6.2.1 LCOE for the Northeast 42
    6.2.2 LCOE for the Port of Açu 44
  6.3 CAPACITY CREDIT 45
    6.3.1 Wind capacity credit for the Northeast 45
    6.3.2 Wind capacity credit for the Port of Açu wind plant 47
  6.4 LACE 47
    6.4.1 LACE results for the Northeast 47
    6.4.2 LACE results for the Port of Açu 52
  6.5 NET VALUE 54
    6.5.1 Net Value for the Northeast 54
    6.5.2 Net Value for the Port of Açu 56

7. DISCUSSION AND METHODOLOGY LIMITATIONS 58
8. CONCLUSIONS 62
9. BIBLIOGRAPHIC REFERENCES 64

LIST OF FIGURES

Figure 1: Graph of Wind Power Generation (GWh) in Brazil from 2007 to 2017 12
Figure 2: Graph of the monthly wind power generation (MWmed) in 2017 by subsystem 12
Figure 3: Graph of the monthly solar power generation (MWmed) in 2017 by subsystem 13
Figure 4: Consequences of operational decisions for the Brazilian electrical system 17
Figure 5: Matrix Selected by ICB: Contracted Energy (MWmed) 20
Figure 6: Wind Energy Potential in Brazil..... 21
Figure 7: Port of Açu aerial picture 24
Figure 8: Areas with the greatest wind potential in the State of Rio de Janeiro 24
Figure 9: Location of the chosen wind farms in Northeast subsystem 33
Figure 10: Schematic representation of the methodology to calculate the LCOE 35
Figure 11: Schematic representation of the methodology to calculate the LACE 36
Figure 12: Validation results for the Northeast's capacity factor 41
Figure 13: Validation results for the Gargaú's wind plant capacity factor 42
Figure 14: LCOE probabilistic distribution for a plant generating the average of the stochastic generation of the four selected plants in Northeast 43
Figure 15: LCOE probabilistic distribution for each of the four selected plants in Northeast 43
Figure 16: LCOE probabilistic distribution for the Port of Açu 45
Figure 17: Yearly capacity credit from 2016 to 2026 for the four selected plants in Northeast 46
Figure 18: Yearly capacity credit from 2016 to 2026 for the Port of Açu 47
Figure 19: CMO regression in terms of the weekly simulated generation of the four plants in Northeast 48
Figure 20: CMO regression in terms of the weekly simulated generation disregarding Areia Branca wind farm 48
Figure 21: LACE probabilistic distribution considering the average capacity credit of the four plants and the CMO as a function of the three wind plants generation 49
Figure 22: CMO regression in terms of the weekly simulated generation of São Clemente wind plant 50
Figure 23: LACE probabilistic distribution considering the average capacity credit and the CMO as a function of the São Clemente wind plant generation 50
Figure 24: CMO regression in terms of the weekly simulated generation of Icaraí wind plant 51
Figure 25: LACE probabilistic distribution considering the average capacity credit and the CMO as a function of Icaraí wind plant generation 52
Figure 26: CMO regression in terms of the weekly simulated generation of Port of Açu wind plant.. 53
Figure 27: LACE probabilistic distribution for the Port of Açu including the avoided transmission costs 53
Figure 28: LACE probabilistic distribution for the Port of Açu NOT including the avoided transmission costs 54
Figure 29: Net value probabilistic distribution considering the average generation of the four plants in Northeast 55
Figure 30: Net value probabilistic distribution for the São Clemente wind plant..... 55
Figure 31: Net value probabilistic distribution for the Icaraí wind plant..... 56
Figure 32: Net value probabilistic distribution for the Port of Açu wind plant including the avoided transmission costs in the LACE component 57
Figure 33: Net value probabilistic distribution for the Port of Açu wind plant NOT including the avoided transmission costs in the LACE component..... 58
Figure 34: Regional weighted average LCOE and ranges of onshore wind in 2010 and 2016 59

LIST OF TABLES

Table 1: Number of Wind and solar plants winners of Brazilian energy auctions with supply start date after 2018 13
Table 2: Energy installed capacity in Brazil in December 2018 17
Table 3: Average capacity credit for the period from 2006 to 2016 for the four selected plants in Northeast 46
Table 4: Summary of LCOE results 58
Table 5: Summary of LACE and Net Value results 60
Table 6: Levelized Avoided Costs range for different energy sources technologies in 2015 61

LIST OF EQUATIONS

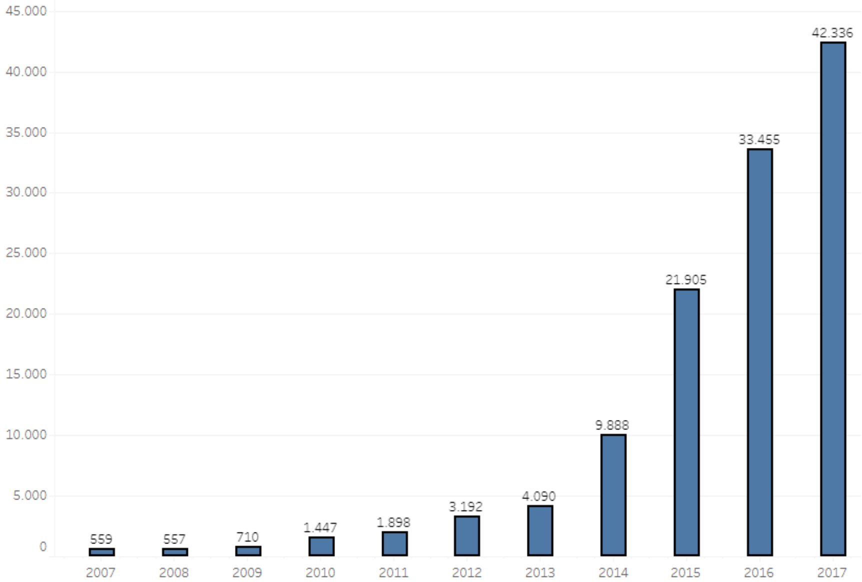
Equation 1: ICB Equation 18
Equation 2: LCOE Equation 19
Equation 3: LACE Equation 26
Equation 4: Equivalence between the Net Present Value of the Total Revenue (NPVTR) and the Net Present Value of the Total Cost (NPVTC) 33
Equation 5: Total revenue and total costs are detailed 34
Equation 6: P_{MW} is considered constant and is isolated outside the sum 34

1. INTRODUCTION

Brazil's total energy load is expected to increase approximately 40% from 2016 to 2026 according to studies from the Brazililian Energy Research Office (EPE in its Portuguese acronym). In order to meet this growing demand, Brazil needs to plan the capacity expansion of its electric system. The Brazilian hydroelectric potential is estimated at 172 GW, of which more than 60% is already being used. Approximately 70% of the remaining available hydroelectric potential is located in the Amazon and Tocantins - Araguaia basins (EPE, 2018). The issue of meeting future demand through hydroelectric plants in the Amazon is the potential risk of causing environmental and social negative impacts. Cunha and Ferreira (2012) showed that the completion of the Belo Monte reservoir will result in habitat reductions and will consequently reduce the richness and diversity of pioneer formations. For Latrubesse *et al.* (2017), the accumulated negative environmental effects of existing dams and proposed dams, if constructed, will trigger massive hydrophysical and biotic disturbances that will affect the Amazon basin’s floodplains, estuary and sediment plume. In addition to environmental issues, exploration of the hydroelectric potential in the Amazon basin finds constraints due to the notorious difficulties to build new hydroelectric power plants and, in particular, large reservoirs. Thus, most projects do not contain new reservoirs, but are operated as run-of-the-river power plants.

Due to limitations in hydroelectric expansion capacity, other sources of energy are being considered. The great potential of the country to generate wind and solar energy as well as the complementarity between these sources and hydroelectric production allow wind and solar generation to be increasingly present in the Brazilian electricity matrix. According to numbers from the Brazilian National Operator of the Electric System’s (ONS) website, wind power generation in Brazil increased from 559 GWh in 2007 to 42.336 GWh in 2017 (Figure 1), an average growth of 67% in the last three years. Solar power is expected to add approximately 1 GW in the Brazilian power system by the end of 2018, doubling the capacity at 2017 (Portal Solar, 2018).

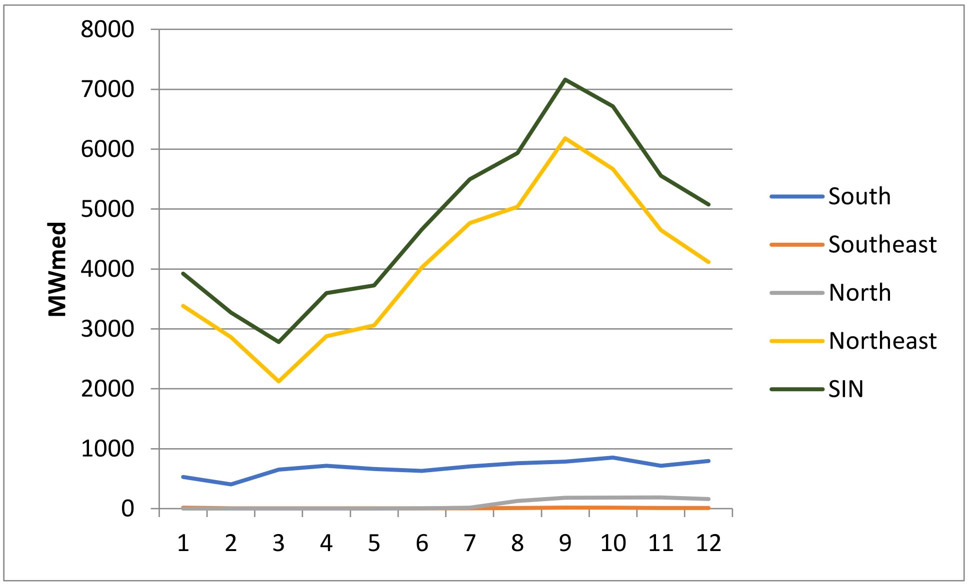
Figure 1: Graph of Wind Power Generation (GWh) in Brazil from 2007 to 2017



Source: ONS's website (2018)

Despite the strong progress in the insertion of renewable generation in the Brazilian Interconnected System (SIN), only one subsystem, the Northeast, receives almost all of the investments. Wind generation in 2017 was largely produced by the Northeast, with a small contribution from the South region (Figure 2).

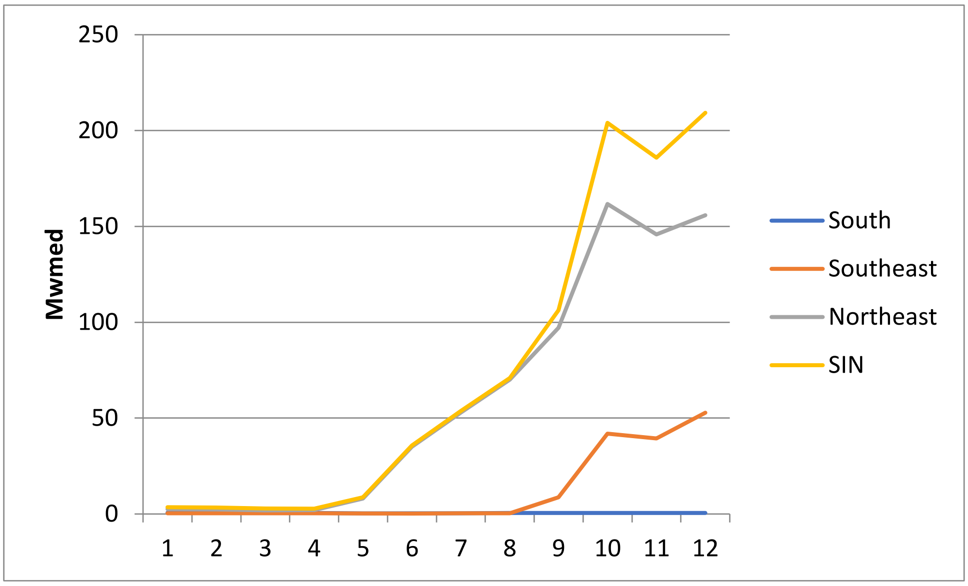
Figure 2: Graph of the monthly wind power generation (MWmed) in 2017 by subsystem



Created by the author. Source: ONS's website (2018)

The Northeast predominance is also verified in the solar generation in 2017 (Figure 3).

Figure 3: Graph of the monthly solar power generation (MWmed) in 2017 by subsystem



Created by the author. Source: ONS's website (2018)

Most future generation of wind and solar energy will also come from the Northeast according to energy auctions conducted until July 2018 by the Brazilian Chamber of Electric Energy Commercialization (CCEE, 2018). 95% of wind farms and 80% of solar projects expected to start after the beginning of 2018 (Table 1) are located in the Northeast.

Table 1: Number of Wind and solar plants winners of Brazilian energy auctions with supply start date after 2018

State	Future Wind Plants	Future Solar Plants
RN	1456	4
BA	2127	34
MA	297	0
PB	339	1
PE	215	90
PI	1236	158
CE	462	242
MG	0	111
SP	0	22
RS	350	0
TO	0	3
Total	6482	665
Total NE	6132	529
% NE	95%	80%

Created by the author. Source: CCEE, 2018

The hegemony of the Northeast region in the production of wind and solar energy is due to the method of investments prioritization used in energy auctions in Brazil, called Cost Benefit Index (Índice Custo-Benefício in Portuguese, or ICB). The ICB privileges the Northeast since this is the region with the greatest wind and solar potential. However, the ICB has drawbacks. It does not differentiate the moment of the day in which the generation of energy takes place, whether it is during a peak in demand or in a period of drought, for example. Therefore, the energy generated at any time of the day is valued in the same way (Castro, 2015). Additionally, the ICB does not consider the benefit to the system as a whole since it analyzes the new energy projects individually.

The southeast region is the largest load center in Brazil. Therefore, a wind plant in the southeast region could be potentially more beneficial to the country than a wind plant located in the northeast during a peak load moment in the southeast. The wind plant in the southeast would avoid operating expensive thermal plants in addition to savings in transmission in case an energy exchange is needed.

Other criteria for the comparison and selection of energy investments have already been proposed. The Energy Information Administration (EIA) of the US Department of Energy (DOE) has developed an alternative method called LACE (Levelized Avoided Cost of Eletricity). This method accounts for all costs avoided throughout the project lifecycle. By generating power with the new installed capacity, the system stops activating other plants which have a higher marginal cost of operation. The formula proposed by the EIA/DOE does not disregard the levelized cost of energy (LCOE), the most traditional criteria to select energy investments, but rather it intends to compare the levelized costs with the avoided costs when implementing new projects. The net value, the difference between LACE and LCOE, can be thought of as the potential profit (or loss) per unit of energy production for the plant (EIA/DOE, 2013).

There is a tradeoff that potentially affects large interconnected systems like Brazil, China, Europe and Argentina. Due to their size, huge transmission costs are often an issue. At the same time, the government aims to bring incentives to the regions that face economic problems, developing their energy potentialities. In order to find an equilibrium among transmissions costs and life time project costs, the net value metric shall be used to evaluate renewable energy projects in different regions of the interconnected electric system.

The objective of this study is to evaluate the economic feasibility of wind projects in Rio de Janeiro using the net value criteria, the difference between LACE and LCOE. This will be done by means of a case study of a hypothetical wind power plant located in the Port of Açu in Rio de Janeiro. The net value of the wind power plant in Port of Açu will be compared to the ones found in four different states in Northeast.

2. THE BRAZILIAN ELECTRICAL SYSTEM

The Brazilian electrical system, as expected for a large country, is a complex system. To understand it better, an overview of the system will be carried out. Then the problem of reservoir management will be discussed as the generation of renewable energy helps offset variations in hydro electricity supply. An explanation of the current auction system will be followed in order to show that, although renewable energy has a fundamental role in the system, the current criterion for selecting investments does not adequately capture its benefits for the system as a whole. Finally, a brief discussion will be made on the wind potential in the Northeast and Rio de Janeiro.

2.1. OVERVIEW

The energy system in Brazil as it is in 2018 is a result of a restructuring process that took place during the years 2003 and 2004 after an increase of wholesale electricity prices by more than 100%. The reform had the goal of establishing a regulated and efficient structure for energy generation, transmission and distribution.

The National Interconnected System (SIN), or “Sistema Interligado Nacional” in Portuguese, is the name of the interlinked power grid that serves all Brazilian states and encompasses over 98% of all the energy produced in the country, being one of the largest interconnected systems in the world (ROMEIRO; ALMEIDA; LOSEKANN, 2015). The National Interconnected System consists of four subsystems: South (S), Southeast / Center-West (SE/CO), Northeast (NE) and most part of the North (N).

The institution responsible of coordinating the SIN plant operation is the National Operator of the Electric System (ONS). According to their Monthly Schedule of Operation (“Programa Mensal de Operação” in Portuguese) from January 2019, Brazil has almost 162 GW of installed capacity (Table 2). Hydro, thermal (gas, diesel and biomass fuels) and wind power plants respectively generate 67.5%, 21% and 9% of the total amount. The other 2.8% comes from nuclear, photovoltaic and other generation sources.

Table 2: Energy installed capacity in Brazil in December 2018

Type	Installed Capacity (MW)	%
HYDRO	109,058	67.50
THERMAL GAS + LNG	12,821	7.9
THERMAL OIL + DIESEL	4,614	2.9
THERMAL BIOMASS	13,696	8.5
WIND	14,142	8.8
NUCLEAR	1,990	1.2
PHOTOVOLTAIC	1,780	1.1
OTHERS	0.779	0.5
Total	**161,552**	**100**

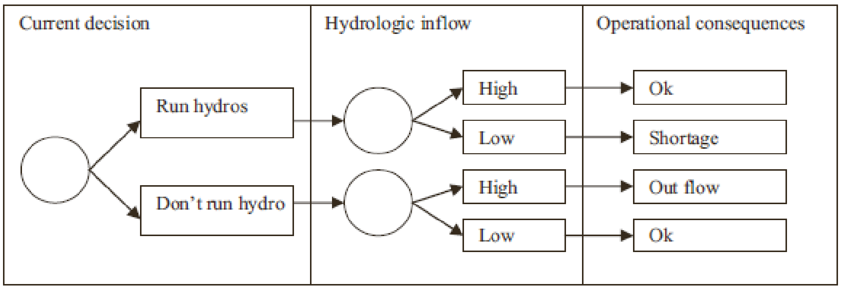
Created by the author. Source: (ONS,2019)

2.2. THE DILEMMA OF THE ELECTRICAL SYSTEM OPERATION

The operation of the Brazilian electricity sector is a large scale optimization problem. The sector needs to optimize the water stored in the reservoirs as well as minimize the operational costs and risk of power failure. According to expected future inflows, the operator dispatches the thermoelectric plants using the merit order, meaning that the plants with lower unit variable cost (CVU) are dispatched first. The CVU of the last dispatched plant in a given period is configured as the marginal operating cost of the system (CMO) for that period.

The Brazilian electrical system is basically hydro-thermal, the ONS must therefore find an operational trade-off between using water contained in its reservoirs for immediate needs or keeping water stored for future needs, thus triggering thermoelectric plants that have a higher operating cost than hydroelectric plants. If there is a period of drought after the ONS has decided to use water from the reservoirs, more thermal energy will have to be produced to meet the demand. Figure 4 illustrates this dilemma.

Figure 4: Consequences of operational decisions for the Brazilian electrical system



Source: Carpio and Pereira Jr. (2006)

Wind and solar energy play a key role in compensating variations in hydro electricity supply. As such, thermoelectric plants activation can be avoided and expensive operating expenses saved. However, the current auction system does not fully capture those potential savings since the current criteria for investment looks only at the cost of individual competitors, rather than the whole picture.

2.3. THE ENERGY AUCTIONS IN BRAZIL IN 2018

The last reform of the electric sector in 2004 established two contracting environments: regulated and free. In the regulated contracting environment (ACR), distributors form a buyer pool and firm long-term contracts to cope with the expansion of their markets. In the free environment, free consumers have contractual freedom (price and term) to sign contracts directly with generators. (ROMEIRO, ALMEIDA AND LOSEKANN, 2015).

In the regulated contracting environment (ACR), the energy auctions in Brazil use the Cost Benefit Index (ICB) as a criterion for selecting investments. The ICB is defined as the ratio between the total cost (from the energy buyers' perspective) and the energy benefit of the investment. The energy benefit is represented by the physical guarantee (EPE, 2018). The ICB formula (Equation 1) is found below.

Equation 1: ICB Equation

$$ICB = \frac{Fixed\ Revenue}{Bid} + \frac{E(Operational\ Costs) + E\ (Short\ term\ economic\ cost)}{Physical\ guarantee} \qquad (1)$$

Fixed Revenue represent the revenue required by the investor in order to cover the total cost of implementing the project, including socio-environmental costs, interest during construction, investment compensation and all fixed costs related to the operation and maintenance of the plant.

The expected value of the *Operational Costs* represents the operating cost for the generation that exceeds the operational inflexibility.

The expected value of the *Short-term economic costs* results from the monthly differences between the actual dispatch of the plant and its physical guarantee, valued according to the settlement price for the differences (in Portuguese, Preço de Liquidação das Diferenças), the PLD. This portion corresponds to the accumulated value of short-term market settlements, based on the CMO. The CMO is limited to the minimum and maximum PLD, according to current values established by the National Electric Energy Agency (ANEEL).

The *Physical Guarantee* corresponds to the maximum electrical energy and power capacity which an energy plant can commercialize.

The ICB is calculated by the Energy Research Office (EPE in its Portuguese acronym) through a mathematical model that is not openly available to the public. However, the ICB has strong similarities with the LCOE (Levelized Cost of Eletricity), an internationally recognized method for comparing different technological alternatives in which the selection of projects for generation expansion is guided by the lowest technological cost. Likewise the ICB, the LCOE comprises the ratio between all project costs and its benefits. Therefore, due to the inaccessibility of the ICB model, it will not be calculated in this study and the LCOE will work as the current used criteria for comparison purposes.

The LCOE formula is found below in Equation 2.

Equation 2: LCOE Equation

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^n}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^n}} \qquad (2)$$

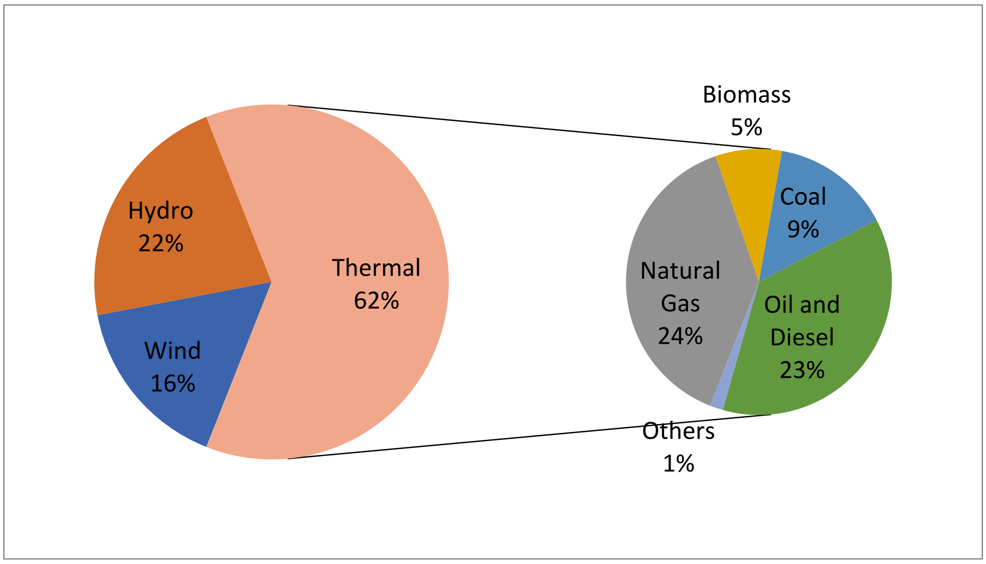
I_t, M_t and F_t represent respectively, the cost of investment, operation and fuel. E_t corresponds to the energy generated by the plant. Finally, r and n are respectively the discount rate and the duration of the project expressed in years.

Despite being a traditional criterion, LCOE does not take into account important aspects of the current energy market, such as the insertion of intermittent renewable sources. These sources have higher value for the system when they produce energy at a time of high demand or, as in the case of Brazil, at a time of drought and limited hydroelectric generation. However, the LCOE does not distinguish renewable supply availability variation throughout the day, month or even year.

With the exception of fixed costs, the other components of the ICB (operational costs, short-term economic costs and the physical guarantee) formula are calculated based on a sample of CMO values disclosed by EPE. As the CMO increases with water shortages in times of drought, intermittent renewable plants will on that occasion be more attractive. However, this benefit to renewable intermittent plants occurs only indirectly and does not capture the differences in load between the subsystems, the complementarity of the sources between subsystems and the overall system cost minimization.

Romeiro, Almeida and Losekann (2015) pointed out another problem in the use of ICB. In the history of the auctions, the ICB privileged flexible thermal plants, mainly driven by oil and diesel, as illustrated by Figure 5, by oversizing the physical guarantee attributed to these plants.

Figure 5: Matrix Selected by ICB: Contracted Energy (MWmed)



Source: Romeiro, Almeida and Losekann (2015)

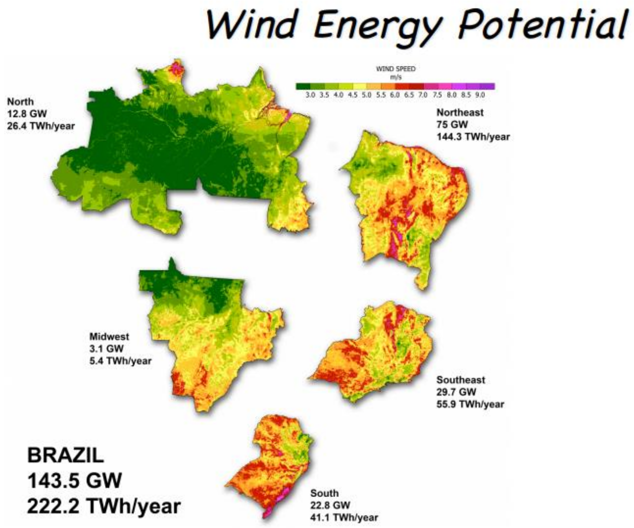
These plants have low fixed costs, but result in high variable operating costs when operating. Privileging flexible thermal plants was in line with the operational logic of the past, when reservoirs of hydroelectric plants were significant enough to meet demand and thermal dispatches were sporadic. However, the demand for energy grows significantly and reservoir expansion is limited.

Therefore, new criteria for the selection of energy investments should be analyzed in order to make the energy matrix more adequate to the current reality of the market, considering the renewable supply availability variation throughout the day and the reduction of the overall cost of the electric system. The present study intends to evaluate an alternative metric of investment selection by comparing the economic attractiveness of wind farms in the Northeast of Brazil and in Port of Açu in Rio de Janeiro.

2.4. WIND POTENTIAL IN BRAZIL

According to Brazilian Electrical Energy Research Center (CEPEL in its Portuguese acronym) winds are characterized as twice the world average and with a velocity oscillation of around 5%, which is considered an optimum potential, since the velocity indicates good predictability of winds (CEPEL, 2001). Furthermore, as previously discussed, there is a hydric-wind complementarity that can be exploited at times of reservoir drought. The largest wind potential in Brazil is concentrated in the Northeast and Southeast regions of the country as illustrated by Figure 6 (AMARANTE et al., 2001).

Figure 6: Wind Energy Potential in Brazil



Source: Amarante et al. (2001).

Of all the auctions already carried out in Brazil, 82% supply the Northeast submarket. For Cabral (2015), the fact that most of the Brazilian wind potential is concentrated in the Northeast region may be an element to combat regional inequalities. This is because the implementation of wind farms in the Northeast is accompanied by the generation of direct and indirect jobs, the need for training of skilled labor, the installation of the supply chain of wind energy, etc.

However, the state of Rio de Janeiro has been suffering a serious economic period due to the crisis in the Brazilian oil sector, a decrease in ICMS tax collection and expenses with the organization of the Olympic Games and the World Cup (DW, 2018).

Rio de Janeiro has a satisfactory wind potential for energy use, according to the Rio de Janeiro’s wind atlas (AMARANTE et al., 2004), and yet it has never been the winner of any wind farm auction. Moreover, the wind generated in the Northeast and South coasts are relatively distant from the main generation centers (AMARANTE et al., 2001), which gives Rio de Janeiro a competitive advantage since it is located in the main load center, the Southeast region. The use of its wind potential could bring new investments to the city and contribute to its economic recovery.

3. THE PORT OF AÇU

Since the aim of this study is to compare the economic attractiveness of a wind plant in Northeast and in the Southeast regions using a different criterium from the current one used to select wind energy ventures in Brazilian energy auctions, the exact location of these plants must be designated. Since the Northeast region houses most of the country's wind farms, some wind plants that are currently in operation were chosen to represent the Northeast region. The methodology used to choose those plants will be further discussed. Since there is no wind plant in the Southeast region linked to the ONS, it was not possible to choose a wind plant in this region using the same criteria. The Southeast region has only one operational wind plant that is not linked to the ONS, the Gargaú wind park, located in the São Francisco de Itabapoana County, in the north region of Rio de Janeiro state. In order to be able to use the wind energy production from this plant in this study's calculation, it was found useful to choose a place to represent the Southeast region that was close to the Gargaú wind plant and this place was the Port of Açu. The Port of Açu is located 30 km away from the Gargaú wind plant which was considered a good proximity.

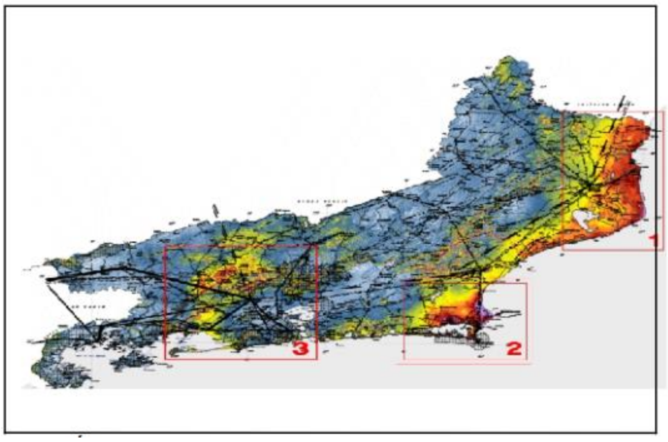
The Port of Açu is located in São João da Barra County in the State of Rio de Janeiro. It has a total area of 130 km^2 and nine terminals, divided into offshore and onshore areas (PORT OF AÇU, 2018). Figure 7 shows an illustration of the current area occupied by the Port of Açu. According to the project's entrepreneurs, the largest thermoelectric park in Latin America will be developed on-site. In the first phase of the project two plants will be built, one is currently under construction, and in the second phase, up to three new plants are planned. Due to Decree No. 41,318, which imposes investments in clean energy and energy efficiency for all natural gas, fuel oil and coal generation projects in Rio de Janeiro, the project must invest in renewable energy to ensure its licensing.

Figure 7: Port of Açu aerial picture

Source: Porto do Açu Website (2018)

In addition to the need to invest in renewable energy and the fact that Port of Açu has a large area available for wind generation, the venture is located in a region with great wind potential. According to the map of Figure 8, the Port of Açu is located in region 1. For all these reasons, the chosen location to represent the Southeast region in the present study is the Port of Açu.

Figure 8: Areas with the greatest wind potential in the State of Rio de Janeiro



Source: Rio de Janeiro State Wind Atlas (AMARANTE et al., 2004)

4. LITERATURE REVIEW

This study's literature review will firstly address the most classical criteria used to economically evaluate energy projects, the LCOE. Then, other criteria that try to overcome the LCOE's pitfalls, such as the disregard of the location of the plants and the temporal variability of the energy productions, will be discussed. In this subsection, criteria such as the LACE and the value factor were considered. Lastly, an alternative approach to choose energy investments in order to expand the generation capacity will be presented, the choice for optimal portfolios.

4.1. LEVELIZED COST OF ELECTRICITY (LCOE)

The Levelized cost of electricity (LCOE) is the economic modelling that is widely used by many decisions makers to compare generation sources that have different useful lives, fuel costs, and use profiles. However, LCOE is not a useful tool to compare the cost of different generation options, unless the options being compared have substantially similar operational profiles and system value (NAMOVICZ, 2013). The use of LCOE is flawed because it treats all kWh supplied as a homogeneous product with a single price. Specifically, traditional levelized cost comparisons fail to take account of the fact that the value of electricity supplied is time and location specific (PARIENTE-DAVID, 2016).

There is a vast literature that quantifies different factors in the full cost of electricity that is not considered in a typical LCOE calculation. However, these studies typically focus on quantifying the costs of one factor (local air pollution or greenhouse gases), on environmental externalities or on integration costs of renewables. Other studies either look at an individual source or compare a renewable source to conventional (fossil fuel) generation sources (BENES AND AUSGUSTIN, 2016).

In Brazil, few studies specifically examine the LCOE for grid connected renewable technologies (DE JONG, KIPERSTOK AND TORRES, 2015). Silva, de Oliveira and Severino (2010) made a comparative study between the technologies and potential configurations meeting the needs of isolated communities in the Amazon. Cardemil and Colle (2010) examined the economic viability of concentrated solar thermal power system in Brazil. De Jong, Kiperstok and Torres (2015) estimated the costs of environmental and social externalities for case study plants and adjusted their initial LCOE results accordingly. They also assessed the costs and energy losses of extended transmission line systems in dams located in remote areas such as the Amazon. This study found that, if all environmental externalities and transmission system costs are taken into consideration, the wind farm case studies become more competitive than Belo Monte and have the lowest LCOE among all the case studies analyzed.

To alleviate LCOE´s comparative challenges, alternate metrics to LCOE have been proposed but none has been widely adopted (BENES AND AUSGUSTIN, 2016).

4.2. OTHER CRITERIA FOR ENERGY INVESTMENT SELECTION

EIA (2013) has developed a metric to provide a more useful tool for comparative analysis, the levelized avoided cost of energy (LACE). The insertion of a new plant in the energy matrix implies a change in the order of future dispatches. When generating power with the new installed capacity to supply the load, at least in the first moment, the system stops to use some other source that has a greater marginal cost of operation. Thus, the avoided cost is a measure of what it would cost the system to meet the load if it could not count on the contribution of the energy produced by the evaluated project (ROMEIRO, ALMEIDA AND LOSEKANN, 2015). The LACE formula is found below in Equation 3.

Equation 3: LACE Equation

$$\text{LACE} = \sum_{t=1}^{Y} \frac{(\text{marginal generation price}_t \times \text{dispatched hours}_t) + (\text{cap payment}_t \times \text{cap credit}_t)}{\text{annual expected generation hours}} \quad (3)$$

- t is the time period and Y is the number of time periods in the year.
- Marginal generation price is the cost of serving load to meet the demand in the specified time period. This price is typically determined by the variable cost (fuel cost plus variable O&M) of the most expensive generating unit that needs to be dispatched to meet energy demand.
- Dispatched hours is the estimated number of hours in the time period the unit is dispatched.
- Capacity payment is the value to the system of meeting the reliability reserve margin. It is determined as the payment that would be required to incentivize the last unit of capacity needed to satisfy a regional reliability reserve requirement.
- Capacity credit is the ability of the unit to provide system reliability reserves. For dispatchable units, the entire nameplate capacity is allowed to participate in the reliability capacity market (capacity credit of 1 or 100%). For intermittent renewables, the capacity credit is derated as a function of the availability of the

resource during peak load periods and the estimated probability of correlated resource-derived outages within a given region. For example, the capacity credit is the probability that if the wind is not blowing in on part of the region, it is or isn’t blowing in a different part of the region.

- Annual expected generation hours are the number of hours in a year that the plant is assumed to operate;

The estimated cost avoided with the introduction of the new plant, calculated by EIA/DOE, covers two dimensions. The first refers to the energy generated by the plant during the life cycle of the project. When used, the plant avoids the operation of more expensive plants. Thus, its contribution can be estimated by the expected amount of energy produced by the plant multiplied not by its variable operating cost, but by the marginal operating cost of the system. This calculation is close to an opportunity cost analysis (ROMEIRO, ALMEIDA AND LOSEKANN, 2015).

The other dimension refers to the contribution to the guarantee of supply. By having the new plant, the installed capacity of the generating plant rises, increasing the safety margin of the system. If it did not have the dispatch of the plant under study, the system would have to increase the installed overcapacity required to safely meet the peak load (ROMEIRO, ALMEIDA AND LOSEKANN, 2015).

Comparison of LCOE to LACE for any given technology provides a quick, intuitive indicator of economic attractiveness. According to EIA/DOE (2013), the net value is simply the difference between the LACE and the LCOE, and can be thought of as the potential profit (or loss) per unit of energy production for the plant.

Many studies used LACE to economically compare different technologies. Brown et *al*. (2016) estimated the economic potential of several renewable resources available for electricity generation in the United States. Beiter et *al*. (2017) assessed site-specific variation of levelized cost of energy (LCOE) and levelized avoided cost of energy (LACE) to understand the economic potential of fixed-bottom and floating offshore wind technologies in major U.S. coastal areas. Mulongo and Kholopane (2018) used both LCOE and LACE tools to compare the economic viability of conventional (coal, gas, nuclear) and renewable technologies (biomass, geothermal, hydroelectric, wind offshore, wind onshore, solar photovoltaic and concentrated solar power) in South Africa. Milbrandt, Heimiller and Schwabe (2018) estimated renewable energy development on tribal lands in U.S. by comparing the estimated cost of renewable energy to the reported LACE prices in the regional electricity markets.

In Brazil some studies using LACE were found. Castro (2015) calculated the two LACE portions, one corresponding to the energy value and the other to the capacity value for the comparison of different configurations of Concentrated Solar Power (CSP). Leal, Rego and Ribeiro (2017) made an economic comparison between different thermoelectric technologies in Brazil such as natural gas, coal, biomass, and fuel oil. They calculated a modified levelized cost of electricity (MLCOE) and the LACE for these technologies. The major modifications in the traditional LCOE methodology were the introduction of the cost of leakage in the natural gas production chain, the transmission costs, and the fuel prices analysis for the different technologies involved.

Another way to compare projects incorporating the location of the plants and the temporal variability of the productions generated by the sources in the analysis is using the value factor. Hirth (2013) defines value as the market value of new renewable sources, that is, the revenue that generators can obtain in the market, without considering income from subsidies. Morais (2015) calculated the wind and solar value factors of several locations in Brazil and concluded that the location where the plant is installed affects its value.

Several authors proposed alternative metrics that considers aspects that LCOE ignores. Ueckerdt et *al*. (2013) proposed the System LCOE that allows the economic comparison of generating technologies and deriving optimal quantities in particular for VRE (variable renewable sources). System LCOE is defined as the sum of the marginal integration costs and the marginal generation costs of VRE. Rabiti et *al*. (2015) introduced the effective cost of energy (ECE), as opposed to the standard levelized cost of electricity (LCOE), as an economic metric for integrated energy system evaluations. The proposed ECE is computed as the LCOE, but the capacity factor is replaced by the effective usage of each plant as a function of energy demand. Reichelstein and Sahoo (2015) demonstrated that for intermittent renewable power sources a traditional life-cycle cost calculation should be appended by a correction factor which they called the Co-Variation coefficient. This coefficient is responsible to capture any synergies, or complementarities, between the time-varying patterns of electricity generation and pricing. Heuberger et *al*. (2017) formalized a new concept for power generation and storage technology valuation which explicitly accounts for system conditions, integration challenges, and the level of technology penetration. Bruck, Sandborn and Goudarzi (2018) developed a new cost model to evaluate the LCOE from a wind power source under a PPA contract.

From all the proposed metrics in the literature to economically evaluate energy ventures, this study chose to use the net economic value, the difference between the LCOE and the LACE, as the alternative method for comparing wind projects in the southeast and northeast of Brazil. It stems from the fact that the LACE criteria has been addressed in a larger number of studies than other proposed metrics.

4.3 THE CHOICE FOR OPTIMAL PORTFOLIOS

There is a complex and intricate relationship between prices, renewable costs and conventional plant profitability. A high level of renewable capacity tends to depress wholesale electricity prices. This implies lower revenues for conventional plants, which tend to be decommissioned. This in turn reduces power system reliability and flexibility, which decreases the ability of the power system to integrate a high level of renewables. This vicious circle needs to be broken to find an economic equilibrium that optimizes the renewable contribution. A holistic approach is needed to power system analysis and planning (PARIENTE-DAVID, 2016).

Many authors believe that the metric needed is an approach that determines the optimal mix of plants to meet electricity demand. This line of research argues that the generation capacity should not be expanded by choosing alternative technologies, but rather by choosing alternative portfolios (ROMEIRO, ALMEIDA AND LOSEKANN, 2015).

The concept of portfolio optimization "is widely used in a number of problems and industries as a way to simultaneously deal with expected returns/costs/impacts and their risks" (ODEH, R.P.; WATTS, D.; FLORES, Y., 2018). Portfolio optimization exploits the idea of diversification in which the performance of the entire set of investments is more important than the performance of the individual investments. Markowitz's research argues that the diversification is measured by the correlation matrix. This correlation, in an energy context, is related to the complementarity between renewable energy and conventional energy or alternatively, by combining different renewable energies technologies for a carbon-free environment (ODEH, R.P.; WATTS, D.; FLORES, Y., 2018).

Several studies have investigated the use of wind power as an alternative to hydro power due to the strong complementarity between hydro and wind resources (AMARANTE ET AL, 2011;

SCHMIDT ET AL, 2014). A strong seasonal complementarity can be observed between North-Eastern wind and hydropower inflows in the South-East, North- East, and North (Schmidt et al, 2014). There is also complementarity between wind and the water regime of São Francisco river which is the most important resource of electricity in the Northeast region of Brazil. Dutra and Szklo (2008) showed that the largest wind speeds occur in northeast exactly when the flow of water of São Francisco River is at a low level.

The complementarity between the winds in Northeast and Southeast subsystem is also important. As the great majority of the installed wind capacity is located in the Northeast, the Brazilian electrical system becomes very dependent on a favorable wind regime in this region. The location diversification of the wind power plants in Brazil may contribute to reduce this risk.

The portfolio approach in the electric sector seeks to introduce established concepts of finance in the selection of investments in new generation plants, incorporating ideas of return, risk and efficient frontier. Several studies attest that adding renewable energy (RE) to a conventional fossil portfolio generates diversity-related benefits (ODEH, R.P; WATTS, D.; FLORES, Y.,2018; BHATTACHARYA, A., KOJIMA, S., 2012; DELARUE, E. ET AL, 2011). According to Neto, D.P. et al (2017), the complementarity between wind and solar sources helps to reduce the economic risk in Brazil. Studies done in the US also corroborate this idea. Jenkin, T. et al (2017) attest that solar and wind generation significantly reduce the exposure of electricity costs to natural gas price uncertainty in fossil-based generation portfolios on a multi-year to multi-decade time horizon in the U.S region considered.

The optimal mix between energy sources can be formulated with other objectives than minimizing financial risk. Iqbal, M. et al. (2014) in a review study identified the following goals in the literature: maximization of revenue, minimization of emission, maximization of reliability, maximization of production, minimization of operating cost, minimization of investment cost, minimization of fuel cost, maximization of life span and minimization of waste material.

For Costa, O.L.V. et al. (2017) one of the major challenges for policy makers and investors is to create an electricity mix in which energy security, affordable costs and environmental concerns are balanced. The issue is that there is not a general solution that simultaneously optimizes all purposes since they are usually conflicting. To overcome this situation multi-objective optimization techniques are sorely useful. In this kind of analysis it is possible to select one of the objective functions to be optimized considering the other objectives as constraints (LUZ, T.; MOURA, P.; DE ALMEIDA, A., 2018). For example, the objective function can be the minimization of the total expansion cost but the model is restricted to a determined amount of CO_2 emission.

The optimum portfolio as an approach to select energy investments makes more sense when a different mix of energy sources is considered in the analysis. Since the objective of this work is to evaluate the economic viability of a wind power project in the state of Rio de Janeiro and to compare its economic potential with the ones found in the Northeast region, only one type of technology, the wind turbines, will be evaluated. Therefore, the net economic value will be the solely metric used to assess the regional variability of the economic potential. A study with this objective was never carried out in Brazil.

5. METHODOLOGY

In this section the steps needed to reach the economic net value for the selected plants in the Northeast and for the Port of Açu are explained. First, the reasoning for the selection of the four plants in Northeast is presented. Then, the LCOE and LACE calculation are depicted. The terms presented in the LACE formula are detailed in further subsections. Lastly, the avoided transmission cost was discussed.

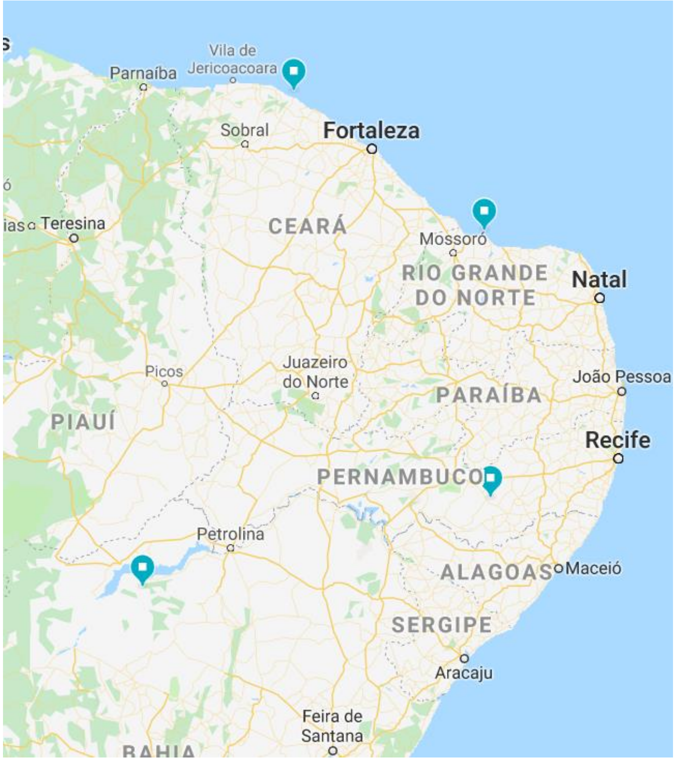
5.1. THE CHOSEN WIND PLANTS IN NORTHEAST SUBSYSTEM

The Northeast energy production and wind capacity factor were represented by four wind plants. The criteria below were used to select these wind farms.

- The wind power plants should be properly scattered in the Northeast region in order to capture different wind flows.
- Two plants should be located in the coast and the other two inland.
- The plants should be located in the states with the highest installed wind capacity in Northeast subsystem.
- The plants should be in operation before the beginning of 2016 since this is the last year available in the simulator dataset for the calculation of wind speeds and wind energy production.

Therefore, the following plants were chosen: Icarai (CE), Areia Branca (RN), São Clemente (PE) and Pedra Branca (BA). The spatial distribution of these plants is shown in the Figure 9 below.

Figure 9: Location of the chosen wind farms in Northeast subsystem



Source: Elaborated by the author

5.2 LCOE

In this study, the costs to produce electricity from different wind farms located in Rio de Janeiro and the Northeast are compared using the Levelized Cost of Electricity (LCOE) calculation following the methodology of the Nuclear Energy Agency (NEA), the International Energy Agency (IEA), and the OECD. It is based on the equivalence between the Net Present Value of the Total Revenue (NPVTR), and the Net Present Value of the Total Cost (NPVTC), both at the assumed discount rate (i), as shown in Equation 4:

Equation 4: Equivalence between the Net Present Value of the Total Revenue (NPVTR) and the Net Present Value of the Total Cost (NPVTC)

$$\sum_{t=1}^{n} \frac{TR_t}{(1+i)^t} = \sum_{t=1}^{n} \frac{TC_t}{(1+i)^t} \qquad (4)$$

Assuming the premise of a market with fixed price (ACR), the total electricity revenue is composed of Q_{MW} which is the amount of electricity generated in MWh in the year t and which is sold at a stable and constant price P_{MW} throughout the lifetime of the power plant.

The most relevant costs that constitute the inputs of the wind power plants are the cost of investment (Cinv_t) and the cost of operations and maintenance (Cop_t) as shown in Equation 5.

Equation 5: Total revenue and total costs are detailed

$$\sum_{t=1}^{n} \frac{Q_{MW} * P_{MW}}{(1+i)^t} = \sum_{t=1}^{n} \frac{\mathrm{Cinv}_t + \mathrm{Cop}_t}{(1+i)^t} \qquad (5)$$

Since the equation term P_{MW} is a constant, it can be isolated outside of the sum, this way, rearranging the terms we reach Equation 6:

Equation 6: P_{MW} is considered constant and is isolated outside the sum

$$LCOE = P_{MW} = \frac{\sum_{t=1}^{n} (\mathrm{Cinv}_t + \mathrm{Cop}_t) * (1+i)^{-t}}{\sum_{t=1}^{n} Q_{MW} * (1+i)^{-t}} \qquad (6)$$

Due to the hegemony of the Northeast in wind generation, the supply chain of towers, blades and other large components can be considered more developed in the Northeast than in Rio de Janeiro. However, Rio de Janeiro has a more efficient transportation network. Thus, the cost of investment and operation were considered the same for wind farms in Rio de Janeiro and Northeast region.

The average power capacity of wind plants winners of the last energy auctions (27º New Energy Auction, 3º Renewable Source Auction and 8º Reserve Energy Auction) was calculated (CCEE, 2018). The result achieved was 28MW. The average cost of investments with capacity around 28MW was R$ 128,038,571. Therefore, the investment cost considered was R$ 128 million. The lead construction time is assumed to be one year (NEA, IEA, 2010).

According to NEA/IEA (2010), the operation and maintenance cost ($/MWh) can be approximated to 1% of the investment cost per year. This value is considered constant throughout the whole project. The assumed life time of the technology was 25 years (NEA, IEA, 2015). The average supply time contracted at the last auction was 20 years; however, it is considered that the plant will continue to operate in similar conditions until the end of its useful life.

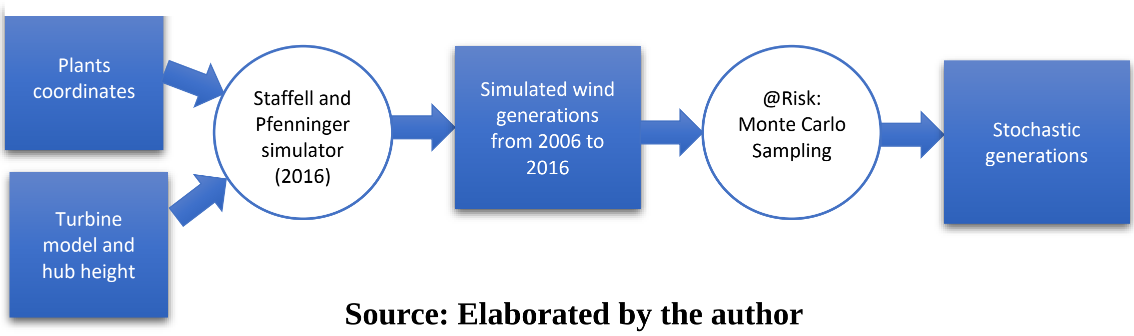
The WACC (Weighted Average Cost of Capital) used in the financial statement of a wind energy generating company in 2017 was 8.68% in real terms for energy trading contracts.

Therefore, the discount rate considered in this study will be 8.68% (OMEGA GERAÇÃO S.A, 2017).

The amount of electricity generated is the only variable that can vary in the LCOE calculation depending on the location of the plant. Using wind plants coordinates as inputs, hourly wind speeds can be obtained through the simulator developed by Staffell and Pfenninger (2016). It uses NASA MERRA-2 global reanalysis models. According to the turbine model and hub height, the capacity factor and the hourly production are simulated. The model of the turbine chosen for the simulation was the Enercon E-82 of 2 MW (ENERCON, 2010) and the height of the tower was 80m.

This study simulated hourly energy generation from 2006 to 2016 for all the four plants in Northeast as well as for a hypothetical plant located in Port of Açu. The latest dataset available is for the year 2016. Since eolic energy generation has a stochastic characteristic, the amount of electricity generated in LCOE formula follows a stochastic behavior. The Figure 10 shows a schematic representation of the methodology to calculate the LCOE.

Figure 10: Schematic representation of the methodology to calculate the LCOE



Source: Elaborated by the author

The validation of the results was done comparing simulated capacity factors using real turbine heights and models with registered capacity factors.

The LCOE was simulated considering the eolic generation uncertainty due to meteorological conditions. The output of this simulation is, therefore, a probability distribution using Monte Carlo sampling.

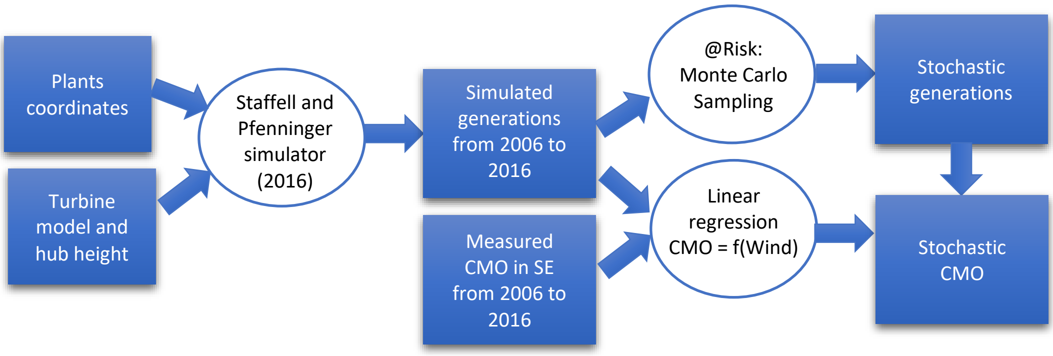
5.3 LACE

LACE can be derived by estimating the cost of displaced energy and displaced capacity. These two cost components are reflected in the formula below. Marginal generation price and capacity are presented in "levelized" terms (average costs per MWh of generation). The Equation 3 was used to estimate LACE.

$$\text{LACE} = \sum_{t=1}^{Y} \frac{(\text{marginal generation price}_t \times \text{dispatched hours}_t) + (\text{cap payment}_t \times \text{cap credit}_t)}{\text{annual expected generation hours}}$$

All terms in the formula will be further discussed in the next topics. The methodology used to calculate the LACE is illustrated in the Figure 11.

Figure 11: Schematic representation of the methodology to calculate the LACE



Source: Elaborated by the author

5.3.1 Average marginal general price

The marginal generation price is the cost of serving load to meet the demand in a specified time period, which can be determined by the variable cost of the most expensive generating unit that is needed to be dispatched to meet energy demand (EIA 2013). In Brazil, this variable corresponds to the marginal operating cost (Custo Marginal de Operação, or CMO in Portuguese). ONS provides weekly CMOs for each subsystem (ONS, 2018). There is a CMO for each load level (light, medium and heavy) depending on the time and day of the week. However, there is no significant change in CMOs for different load levels and, therefore, the average CMO was considered in this study.

The CMO is limited to the minimum and maximum PLD. From January 2020, the PLD is expected to be calculated on an hourly basis. From April 2018 until the effective implementation, the CCEE (Electric Energy Trading Chamber) will provide preliminary hourly prices. These prices are called "Preço horário sombra" in Portuguese or "Shadow" hourly price in English. The main objective is to anticipate the possible impacts of the adoption of the hourly price (CCEE, 2018).

Hourly time resolution makes the analysis more reliable since it takes into account the existing variation in short intervals of time. However, the present study could not use the “Shadow” hourly price provided by CCEE because there wasn’t sufficient data to the time of the analysis.

The CMO depends among other factors on the availability of energy resources such as water reservoirs level, wind speed and solar irradiance. Therefore, the CMO follows a stochastical process. This study will relate the CMO with the wind energy generation through a regression in which the CMO is the dependent variable. Thus, the CMO will incorporate the stochasticity present in the wind energy generation. The CMO from Northeast will depend on the wind energy generated in the four selected wind farms and the CMO from Southeast will be a function of the wind energy generated in the Port of Açu.

5.3.2 Average Expected Generation Hours

Like the amount of energy generation present in LCOE formula, the average expected generation hours was calculated stochastically. Hourly energy generations were simulated from 2006 to 2016 and used to calculate a weekly (same time frame as the CMO) capacity factor. The capacity factor leads to the average expected generation hours when it is multiplied by the total weekly hours (168h). The inherent uncertainty of eolic generation will be accounted in the LACE output since it will be shown as a probability distribution.

5.3.3 Capacity Payment

The second LACE component comprises a capacity payment and a technology-specific capacity credit. The product of these two components approximates the capacity value of a generation project (EIA/DOE, 2013). The capacity payment captures the value a generation project can offer to the system in meeting reliability reserve margin, and can be determined by estimating the payment necessary to “incentivize the last unit of capacity needed to satisfy a regional reliability reserve requirement” (EIA/DOE, 2013).

The capacity payment used in this study is US$60,000/MW/year, the one used by EIA/DOE (2013) as the cost of a new combustion turbine to meet reliability requirements. Using an exchange rate of R$4 to USD 1, the capacity payment is R$240,000/MW/year.

5.3.4 Capacity Credit

The capacity credit captures “the ability of a unit to provide system reliability reserves” (EIA 2013, p. 3) and depends upon the dispatchability of a generation project. A number of different methods have been used to calculate the capacity value of renewable and conventional generators (SÖDER, L.; AMELIN, M. (2008); PUDARUTH, G.R.; LI, F. (2008); MILLIGAN, M.; PORTER, K. (2008)). These methods differ in terms of computational time, complexity, and data requirements.

This study uses the highest-load hours approximation method to find the average capacity credit of the four wind plants in Northeast of Brazil as well as the capacity credit for a hypothetical wind plant in Port of Açu. This approach uses the average capacity factor of the plant during the highest-load hours as an approximation for the capacity credit. The number of hours considered in the analysis is important since the capacity credit can be highly sensitive to this parameter. Milligan and Parsons (1999) studied the capacity credit of wind and their result show that the top 10% load hours give an approximation that is closest to the effective load carrying capability (ELCC) method, one of the most robust and widely accepted techniques for estimating capacity credit.

Firstly, hourly load data from the last 10 years were extracted from ONS's website, then, the 10% highest load hours in each year were selected and the simulated wind generation in this highest load hours were computed for the four wind plants in Northeast as well as for the hypothetical wind plant in Port of Açu. Lastly, the capacity factor was calculated considering the nominal capacity of the plants (28MW) and they were used as a proxy for the capacity credit in LACE calculation.

5.4. TRANSMISSION COSTS

The transmission cost was included for a scenario in which energy exchange is necessary to satisfy the demand in the southeast, the region with the greatest demand in the country. A wind plant located in Rio de Janeiro is closer to the highest load centers, thus most of the transmission cost would be avoided. Therefore, the avoided transmission cost is included in the LACE calculation for the plant located in Port of Açu.

In order to capture the inherent uncertainty of the avoidable transmission cost, this study considered it as a uniform distribution with a minimum of USD300/KW/year and a maximum of US$1500/KW/year. Pereira Jr et al (2012) used a transmission cost of US$1500/KW/year in their study. The aim was to have a conservative value and, therefore, avoid an overestimation of the LACE result which would favor the plant located in Port of Açu.

6. RESULTS

The study compared the economic attractiveness of wind plants located in the Northeast and in the Port of Açu in Rio de Janeiro. The criteria used for the comparison is the net economic value, which is determined by subtracting the value of avoided electricity consumed from the grid (LACE) from the assumed capital cost of the system (LCOE). In case the value of LACE-LCOE is positive, the project is assumed to have economic attractiveness. Before showing the results for the net value, the current section will show partial results that were necessary steps to calculate the final net value.

Firstly, the simulator is validated by comparing its results with actual data. After the validation, the LCOE component is found. The following step is the calculation of the wind capacity credit, which is present in the LACE formula. Next, the LACE results are presented and finally, the net value is showed. The results for all these steps are showed for the plants in Northeast and for the hypothetical plant at Port of Açu.

The results for the LCOE, LACE and Net value components will appear as a probabilistic distribution in order to incorporate the stochastically nature of wind generation.

6.1 VALIDATION

The wind generation data used in this study are from the simulator developed by Staffell and Pfenninger (2016). It uses NASA MERRA-2 global reanalysis models. Since this data was not measured, it needs validation. The validation was done comparing the modeled capacity factor with the measured capacity factors provided by ONS.

6.1.1 Northeast data validation

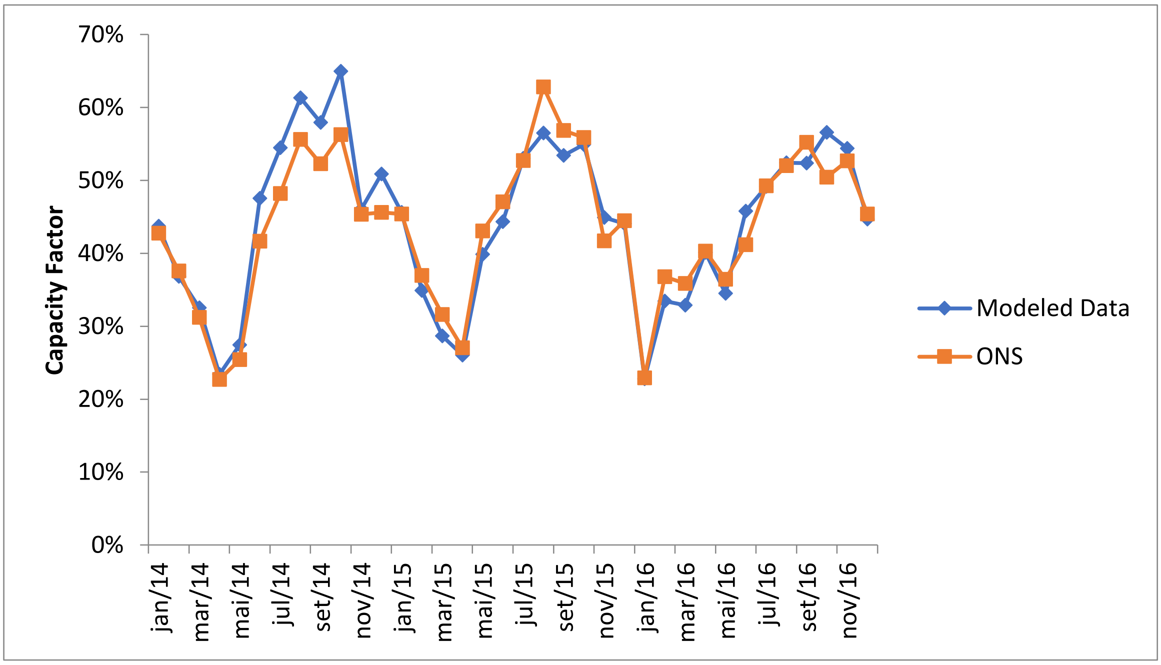
The last year available in the simulator is 2016. This study considers the last three years as the most significant in terms of wind generation in the northeast of Brazil. Therefore, monthly capacity factors from 2014 to 2016 were used for the validation, totalizing 36 observations. The measured capacity factors were found in the monthly journal of wind generation (or in Portuguese “Boletim Mensal de Geração Eólica”) available in ONS’s website.

Four wind plants were selected to represent the wind generation in the Northeast subsystem: Icarai (CE), Areia Branca (RN), São Clemente (PE) and Pedra Branca (BA). During the whole year of 2014, only Rio Grande do Norte (RN), Bahia (BA) and Ceará (CE) states produced wind energy, therefore, the modeled monthly capacity factors in this year were the average between the capacity factors of the Icarai (CE), Areia Branca (RN) and Pedra Branca (BA) wind plants. Those values were compared to the average of monthly capacity factor for the states of Bahia, Ceará and Rio Grande do Norte provided by ONS. From February 2015 the state of Pernambuco started its wind generation and, therefore, from that date the São Clemente wind plant was also included in the calculation.

In order to simulate the wind generation and capacity factors from the four selected plants, their real turbine model and turbine heights were inputted in the simulator.

Figure 12 shows the modeled (from the simulator) and measured (from ONS) monthly capacity factors. The simulator in average overestimates the capacity factor by 0.79%. The R2 for the regression between the two variables is 0.9 which indicates a high correlation and a satisfactory result for the validation.

Figure 12: Validation results for the Northeast's capacity factor



Source: Elaborated by the author

Piauí was the only state in Northeast region not included in this study since its wind generation became significant in 2016. Therefore, due to the low number of observations required to have reliable results this state was not considered.

6.1.2 Port of Açu data validation

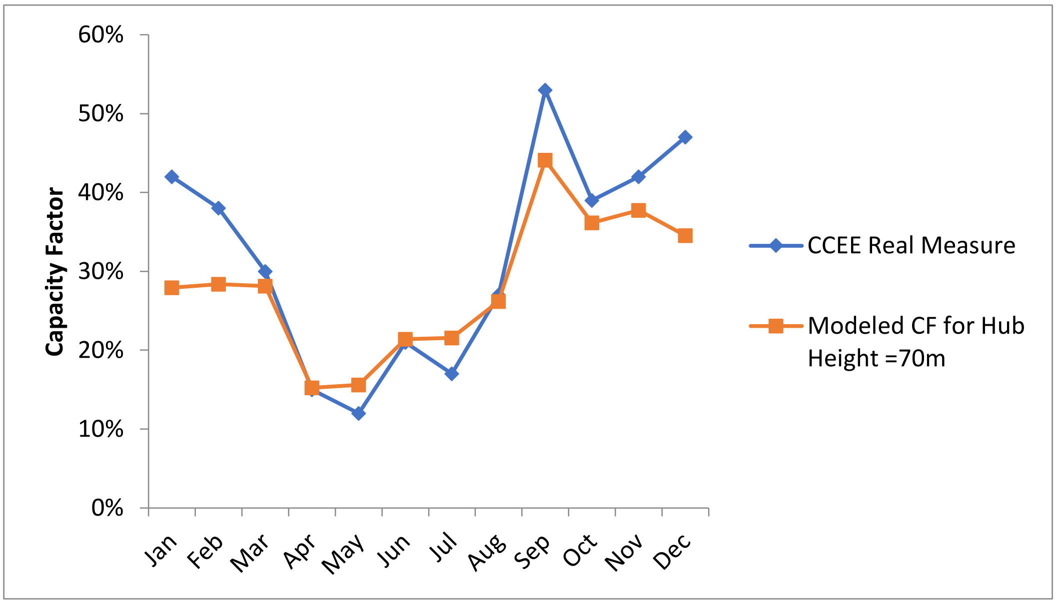
Gargaú is the only wind farm in Rio de Janeiro state. It is located in São Francisco do Itabapoana, 30 km from Port of Açu. Thanks to the proximity to Port of Açu, Gargaú wind farm was used to validate the modeled data from the simulator. Monthly capacity factors from 2014 (totalizing 12 observations) is public available in the Wind farm journal (or in Portuguese

"Boletim das Usinas Eólicas") provided by CCEE (CCEE, 2014). Capacity factors from other years were not found for the Gargaú wind plant.

The hub height of Gargaú wind turbines was not known. According to Vestas, Gargaú's turbine manufacturer, it can vary from 60m to 80m. The height selected to the validation was 70m since most of the wind farms that use the same turbine model in Brazil have this same hub height.

Figure 13 below shows the measured and simulated monthly capacity factors for the year 2014. A regression with the two variables shows an 86% fit, which indicates a high correlation. In average, the simulated capacity factors underestimate the real values by 5.75%. The validation was considered satisfactory although January, February and December values show higher deviation.

Figure 13: Validation results for the Gargaú's wind plant capacity factor



Source: Elaborated by the author

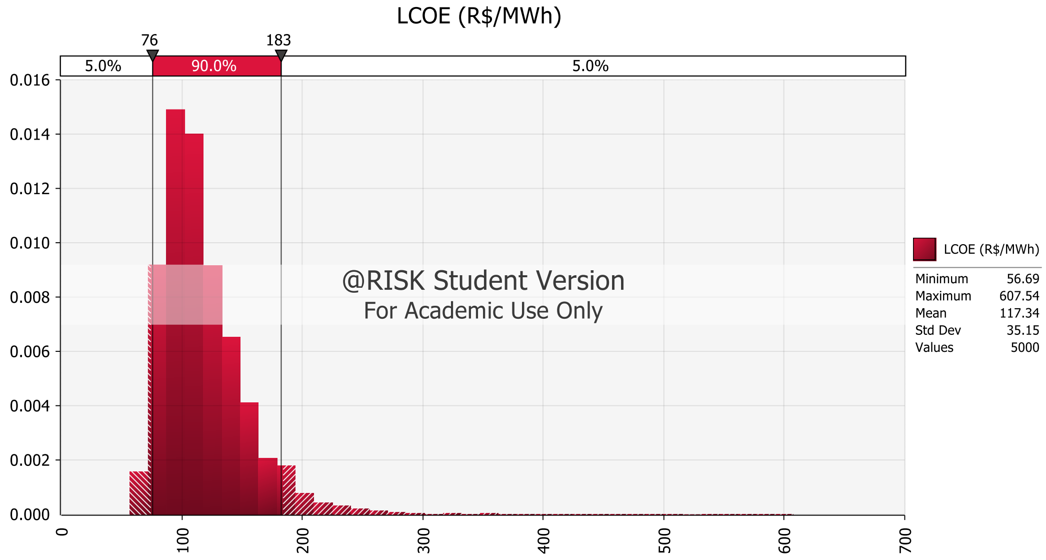
6.2 LCOE

The levelized cost of energy (LCOE) will be shown as a probabilistic distribution for the wind farms in Northeast as well as for the hypothetical wind plant located in the Port of Açu.

6.2.1 LCOE for the Northeast

From the simulated weekly generations from 2006 to 2016, stochastic monthly energy generations were originated and used to calculate the LCOE. The LCOE probabilistic distribution considering the average energy generation of the four selected plants is found in the Figure 14 below. The mean value is R$117/MWh. The minimum and maximum values for a 90% confidence interval are R$76/MWh and R$183/MWh.

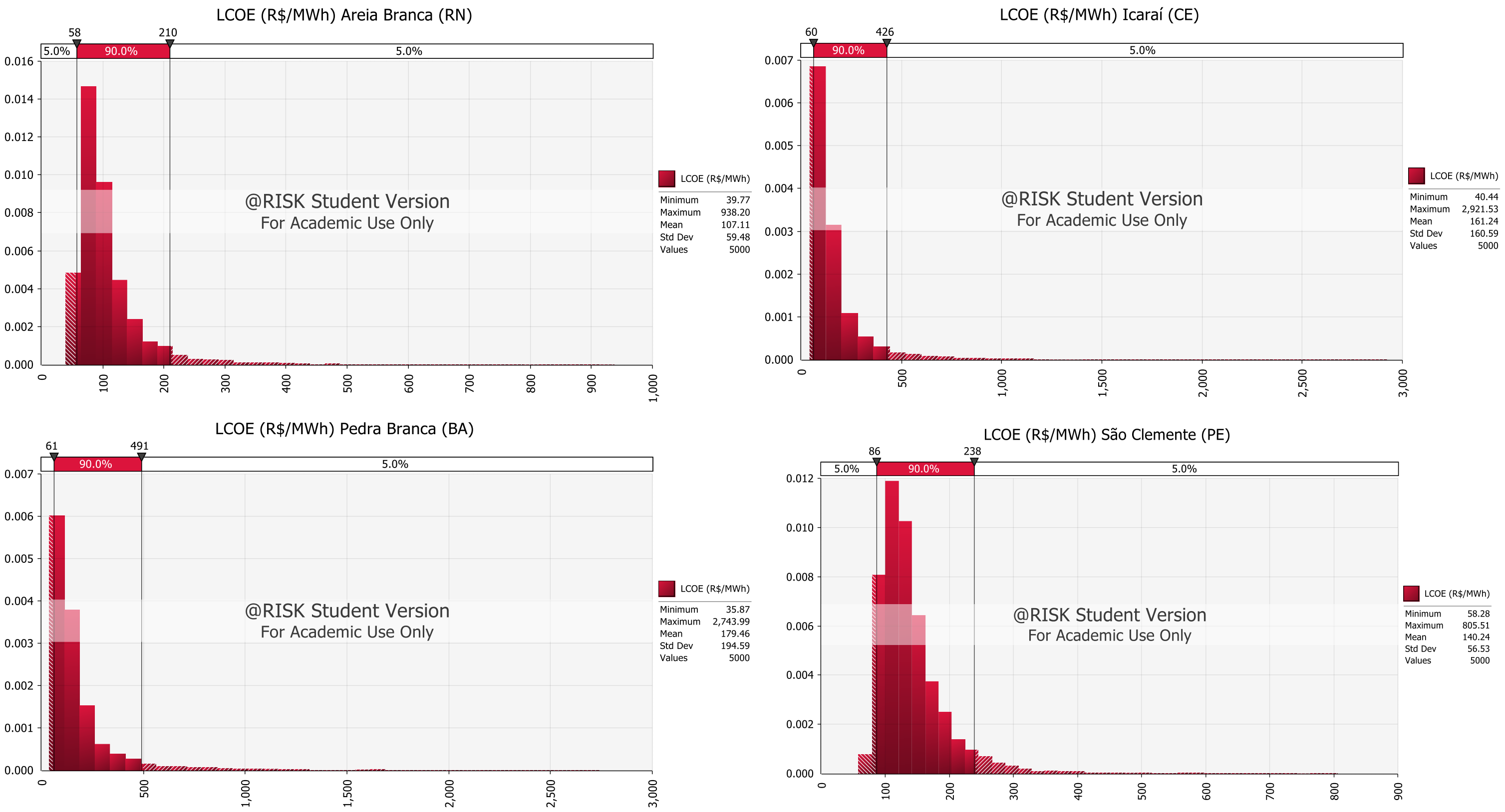
Figure 14: LCOE probabilistic distribution for a plant generating the average of the stochastic generation of the four selected plants in Northeast



Source: Elaborated by the author

The LCOE probabilistic distribution considering the stochastic weekly energy generation for each of the four selected wind plants in Northeast is found in the Figure 15 below. The Pedra Branca wind farm in Bahia has the highest mean and the Areia Branca wind farm located in Rio Grande do Norte has the lowest.

Figure 15: LCOE probabilistic distribution for each of the four selected plants in Northeast

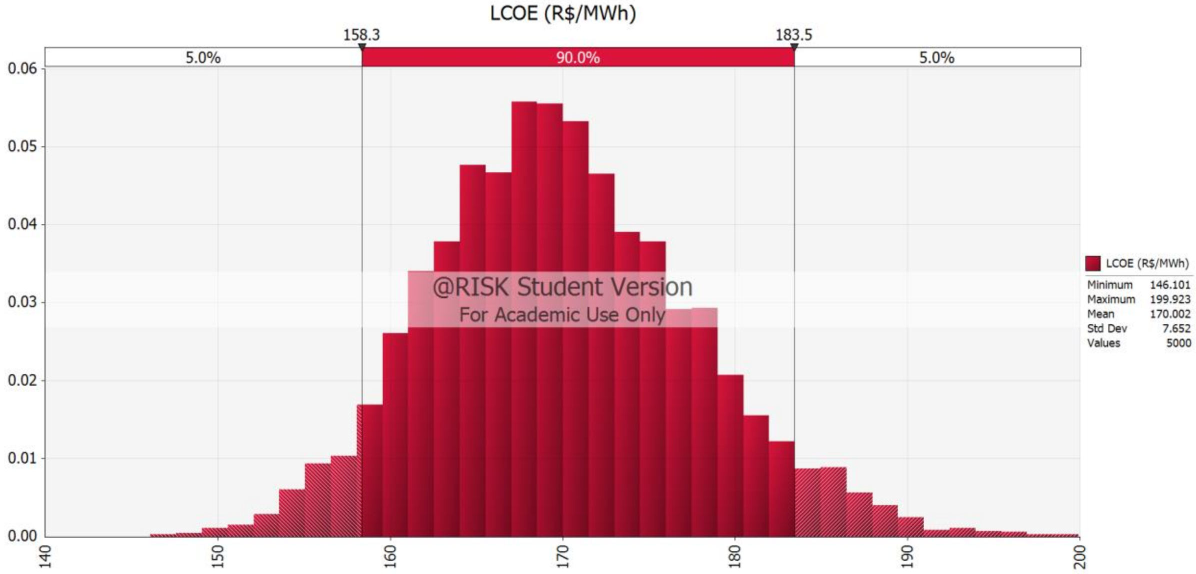


Source: Elaborated by the author

6.2.2 LCOE for the Port of Açu

From the simulated monthly generations from 2006 to 2016, stochastic weekly energy generations were originated and used to calculate the LCOE. The LCOE probabilistic distribution considering the stochastic electricity production in the Port of Açu is found in the graph below. The mean value is R$ 170/MWh. The minimum and maximum values for a 90% confidence interval are R$158/MWh and R$183/MWh.

Figure 16: LCOE probabilistic distribution for the Port of Açu



Source: Elaborated by the author

6.3 CAPACITY CREDIT

In order to calculate the levelized avoided cost of energy (LACE), the capacity credit for the wind generation must be found. The 10% highest load hours for each year from 2006 to 2016 were extracted from the hourly load curve provided by ONS (ONS, 2018). The capacity factor of the four selected wind plants in Northeast and for a hypothetical wind plant in Port of Açu were computed during these load hours. According to Milligan and Parsons (1999), the average of these values can be an approximation for the wind capacity credit. The results for the Northeast and for the Port of Açu are detailed in the subtopics below.

6.3.1 Wind capacity credit for the Northeast

The Northeast wind capacity credit was calculated considering Southeast’s hourly load curve since the objective is to assess how the wind plants in Northeast may contribute to meet the energy demand in the southeast, the region with the highest energy demand in the country.

The average capacity credit for the four plants was 39.54% over the 2006 to 2016 period. Table 3 shows the average capacity credit for each one of the four plants. The Areia Branca wind farm in Rio Grande do Norte state has the highest average capacity credit (47.52%) while the Pedra Branca wind farm in Bahia state has the lowest (31.11%).

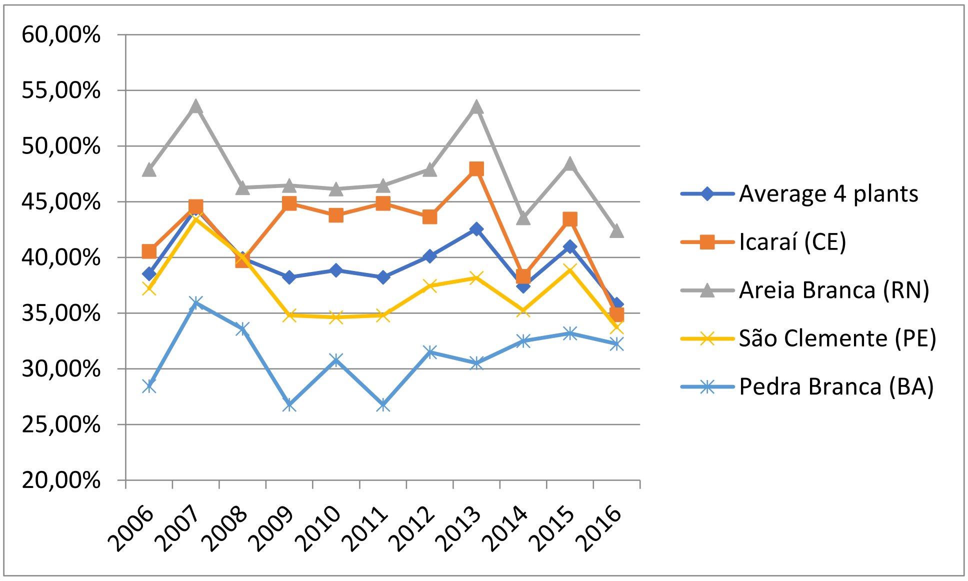
Table 3: Average capacity credit for the period from 2006 to 2016 for the four selected plants in Northeast

Wind Plant	Average Capacity Credit 2006-2016
Areia Branca (RN)	47.52%
Icaraí (CE)	42.41%
São Clemente (PE)	37.12%
Pedra Branca (BA)	31.11%
Average 4 plants	39.54%

Source: Elaborated by the author

Figure 17 shows that Areia Branca (RN) and Icaraí (CE) capacity credits are consistently above the average over the specified time period while São Clemente (PE) and Pedra Branca (BA) wind farms are below it.

Figure 17: Yearly capacity credit from 2016 to 2026 for the four selected plants in Northeast



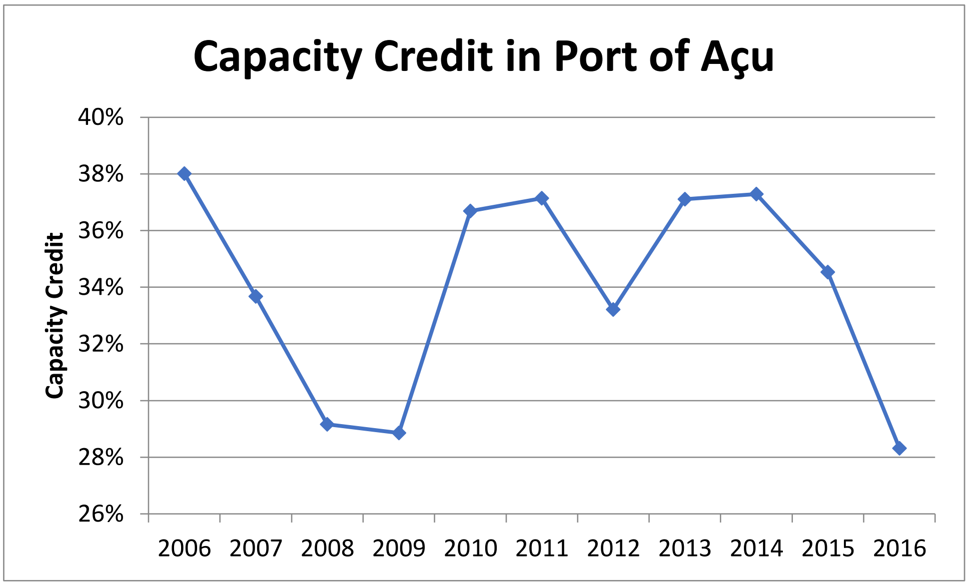
Source: Elaborated by the author

Since the capacity credit is associate to the availability of the resource during peak load periods, this result indicates that Areia Branca and Icaraí wind farms strongly contribute to the system reliability reserves.

6.3.2 Wind capacity credit for the Port of Açu wind plant

The wind capacity credit in the Port of Açu also considered the hourly load curve in the Southeast subsystem. The yearly average capacity credit is 34%, which will be the value used in the LACE formula. Figure 18 shows the wind capacity credit in the Port of Açu from 2006 to 2016. The minimum and maximum values are 28.32% and 38.01%, respectively.

Figure 18: Yearly capacity credit from 2016 to 2026 for the Port of Açu



Source: Elaborated by the author

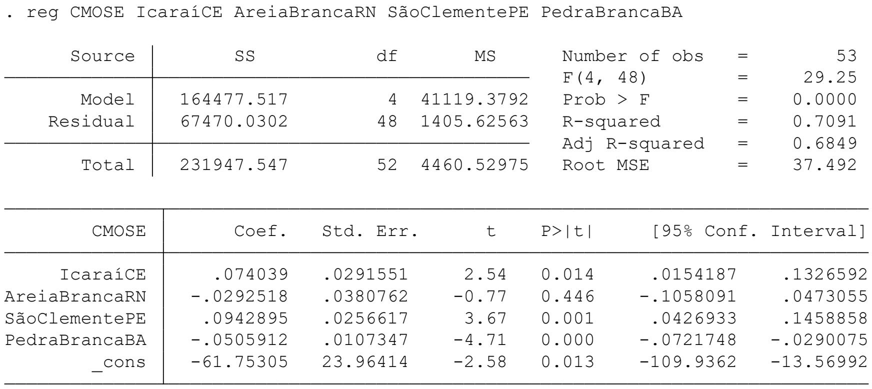
6.4 LACE

The Marginal Operating Cost (CMO) is present in the LACE formula (formula 3) as the average marginal generation price. In order to incorporate a stochastic behavior, the CMO will be a function of the wind energy generated in the designated wind plants. By taking weather data from global reanalysis models and satellite observations, weekly wind energy generation were simulated for the year 2016. From the simulated data, stochastic weekly generations were produced and then used to find the LACE value. The LACE results will be shown first to the Northeast and then to the Port of Açu.

6.4.1 LACE results for the Northeast

Since the LACE aims to evaluate the contribution that the wind plants can provide to reduce the system economic cost, it makes sense to use the CMO from Southeast in its formula as this subsystem has the highest demand and, therefore, the highest thermal cost. The weekly wind energy generation simulated for the four operating wind plants are used to create a regression in which the real (measured) CMO in Southeast for the year 2016 is the dependent variable. The total number observations are 53 and the resulting regression is found below (Figure 19).

Figure 19: CMO regression in terms of the weekly simulated generation of the four plants in Northeast

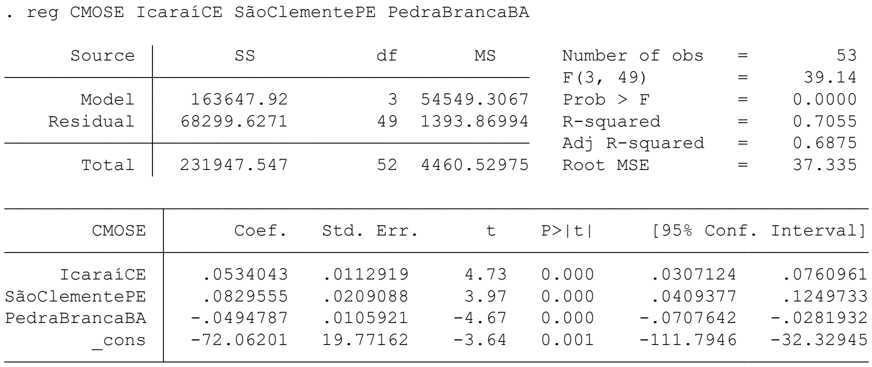


```
. reg CMOSE IcaraíCE AreiaBrancaRN SãoClementePE PedraBrancaBA

      Source |       SS           df       MS      Number of obs   =        53
-------------+----------------------------------   F(4, 48)        =     29.25
       Model |  164477.517         4  41119.3792   Prob > F        =    0.0000
    Residual |  67470.0302        48  1405.62563   R-squared       =    0.7091
-------------+----------------------------------   Adj R-squared   =    0.6849
       Total |  231947.547        52  4460.52975   Root MSE        =    37.492

------------------------------------------------------------------------------
       CMOSE |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
   IcaraíCE |    .074039   .0291551     2.54   0.014     .0154187    .1326592
AreiaBrancaRN |  -.0292518   .0380762    -0.77   0.446    -.1058091    .0473055
SãoClementePE |   .0942895   .0256617     3.67   0.001     .0426933    .1458858
PedraBrancaBA |  -.0505912   .0107347    -4.71   0.000    -.0721748   -.0290075
       _cons |  -61.75305   23.96414    -2.58   0.013    -109.9362   -13.56992
------------------------------------------------------------------------------
```

Source: Elaborated by the author. The generations are in MWh and the CMO is in R$/MWh. The adjusted R^2 shows a 68% fit.

Areia Branca wind farm located in Rio Grande do Norte is not significant to explain the Northeast CMO if we consider a 95% confidence interval, therefore, a new regression was made without it. The Figure 20 shows the result for this regression.

Figure 20: CMO regression in terms of the weekly simulated generation disregarding Areia Branca wind farm



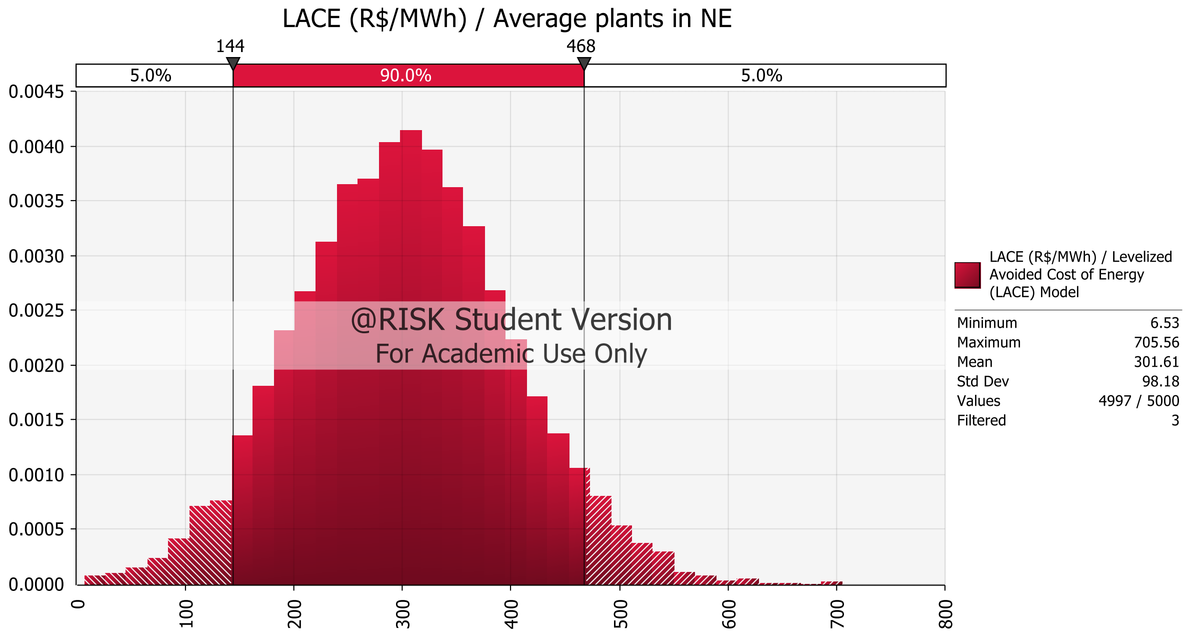
```
. reg CMOSE IcaraíCE SãoClementePE PedraBrancaBA

      Source |       SS           df       MS      Number of obs   =        53
-------------+----------------------------------   F(3, 49)        =     39.14
       Model |   163647.92         3  54549.3067   Prob > F        =    0.0000
    Residual |  68299.6271        49  1393.86994   R-squared       =    0.7055
-------------+----------------------------------   Adj R-squared   =    0.6875
       Total |  231947.547        52  4460.52975   Root MSE        =    37.335

------------------------------------------------------------------------------
       CMOSE |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
   IcaraíCE |   .0534043   .0112919     4.73   0.000     .0307124    .0760961
SãoClementePE |   .0829555   .0209088     3.97   0.000     .0409377    .1249733
PedraBrancaBA |  -.0494787   .0105921    -4.67   0.000    -.0707642   -.0281932
       _cons |  -72.06201   19.77162    -3.64   0.001    -111.7946   -32.32945
------------------------------------------------------------------------------
```

Source: Elaborated by the author. The generations are in MWh and the CMO is in R$/MWh. The adjusted R^2 shows a 69% fit.

Icaraí and São Clemente wind farms have positive coefficients whereas Pedra Branca wind farm has a negative one which indicates that the first two can positively contribute to the system when the prices are high.

After finding the regression, stochastic weekly generations were produced and the correspondent CMO and capacity factor were computed to integrate the LACE equation. The LACE value considering the average capacity credit of the four plants and the CMO as a function of the three wind plants generation is found in the Figure 21. The mean is R$302/MWh and the minimum and maximum values for a 90% confidence interval are R$144/MWh and R$468/MWh respectively.

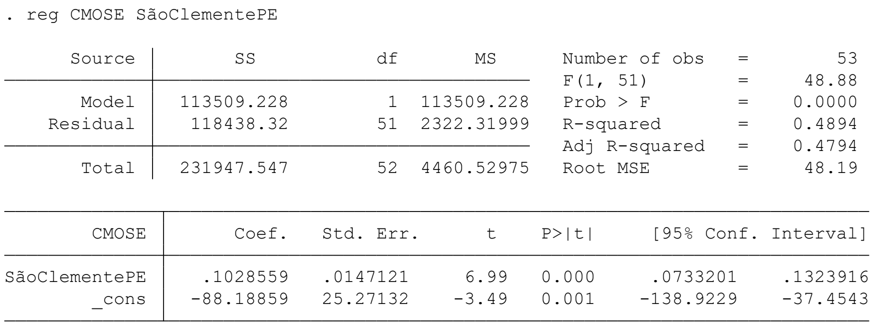
Figure 21: LACE probabilistic distribution considering the average capacity credit of the four plants and the CMO as a function of the three wind plants generation



Source: Elaborated by the author.

The same procedure was repeated but now only for the São Clemente wind farm. First, the CMO regression was found taking as the independent variable only the weekly simulated energy generation from the São Clemente wind plant. It is shown in the Figure 22.

Figure 22: CMO regression in terms of the weekly simulated generation of São Clemente wind plant

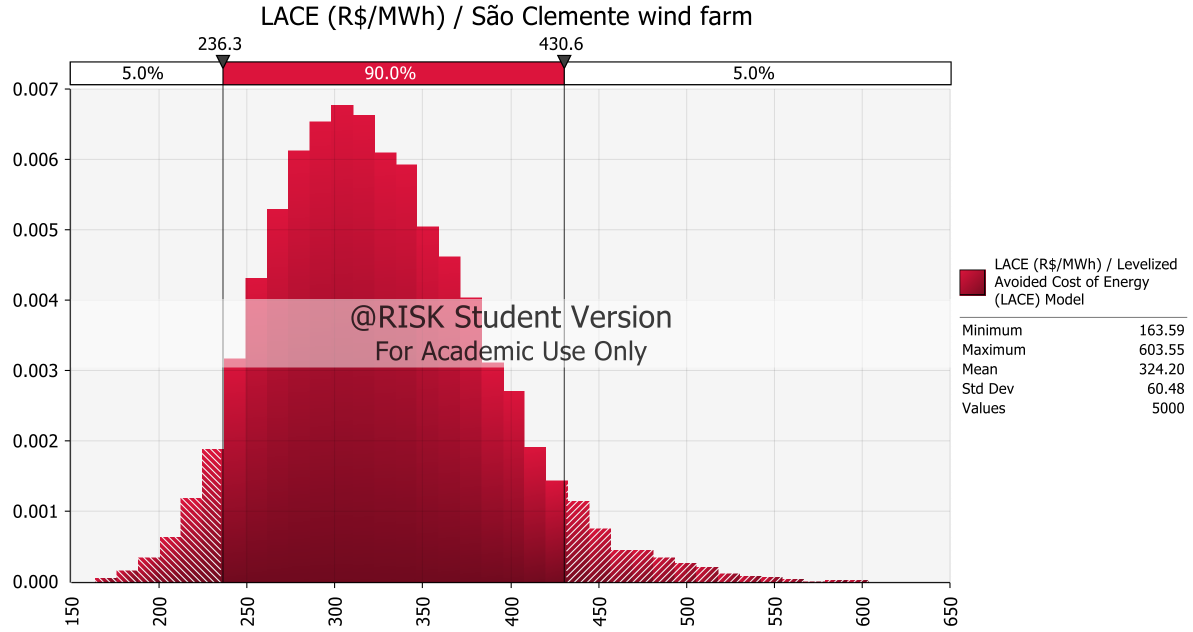


```
. reg CMOSE SãoClementePE

      Source |       SS           df       MS      Number of obs   =        53
-------------+----------------------------------   F(1, 51)        =     48.88
       Model |  113509.228         1  113509.228   Prob > F        =    0.0000
    Residual |   118438.32        51  2322.31999   R-squared       =    0.4894
-------------+----------------------------------   Adj R-squared   =    0.4794
       Total |  231947.547        52  4460.52975   Root MSE        =     48.19

------------------------------------------------------------------------------
       CMOSE |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
SãoClementePE |   .1028559   .0147121     6.99   0.000     .0733201    .1323916
       _cons |  -88.18859   25.27132    -3.49   0.001    -138.9229   -37.4543
------------------------------------------------------------------------------
```

Source: Elaborated by the author. The generations are in MWh and the CMO is in R$/MWh. The adjusted R² shows a 48% fit.

The LACE probabilistic distribution taking the CMO as a function of the São Clemente wind generation and using the capacity credit (37.12%) and wind generations relative to the São Clemente wind farm is shown in the Figure 23. The mean is R$324/MWh and the minimum and maximum values for a 90% confidence interval are R$236/MWh and R$431/MWh respectively.

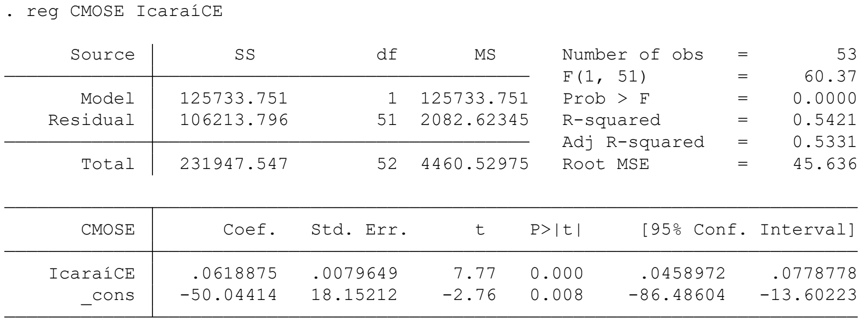
Figure 23: LACE probabilistic distribution considering the average capacity credit and the CMO as a function of the São Clemente wind plant generation



Source: Elaborated by the author.

The individual LACE value for the Icaraí wind farm in Ceará was also calculated. Firstly, the regression was done in order to estimate the CMO. The resulting regression is found in Figure 24.

Figure 24: CMO regression in terms of the weekly simulated generation of Icaraí wind plant

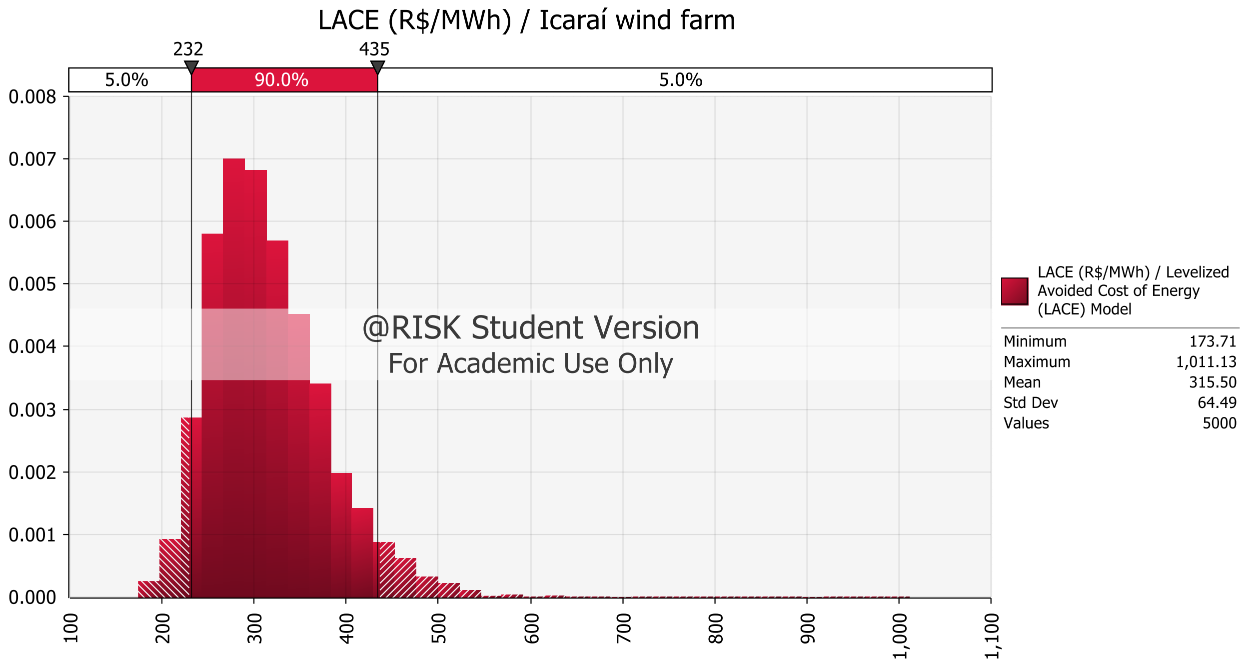


```
. reg CMOSE IcaraíCE

      Source |       SS           df       MS      Number of obs   =        53
-------------+----------------------------------   F(1, 51)        =     60.37
       Model |  125733.751         1  125733.751   Prob > F        =    0.0000
    Residual |  106213.796        51  2082.62345   R-squared       =    0.5421
-------------+----------------------------------   Adj R-squared   =    0.5331
       Total |  231947.547        52  4460.52975   Root MSE        =    45.636

------------------------------------------------------------------------------
       CMOSE |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    IcaraíCE |   .0618875   .0079649     7.77   0.000     .0458972    .0778778
       _cons |  -50.04414   18.15212    -2.76   0.008    -86.48604   -13.60223
------------------------------------------------------------------------------
```

Source: Elaborated by the author. The generations are in MWh and the CMO is in R$/MWh. The adjusted R^2 shows a 53% fit.

The LACE probabilistic distribution for the Icaraí wind farm, using the correspondent capacity credit (42.41%) and stochastic generations for this plant is found in the Figure 25. The mean is R$315/MWh and the minimum and maximum values for a 90% confidence interval are R$232/MWh and R$435/MWh respectively.

Figure 25: LACE probabilistic distribution considering the average capacity credit and the CMO as a function of Icaraí wind plant generation



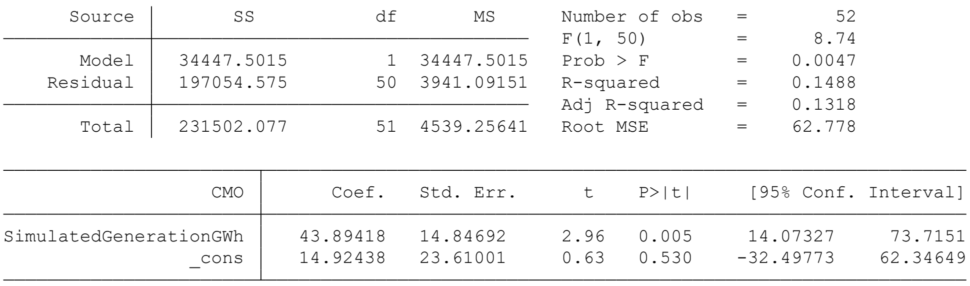
Source: Elaborated by the author

The individual LACE distribution was not done for the Pedra Branca and Areia Branca wind farms since they were not significant to explain the CMO alone. Their p-values were higher than 0.05 or the R^2 was too low.

6.4.2 LACE results for the Port of Açu

Similarly to the LACE calculated for the Northeast, simulated weekly generation and the measured CMO in the Southeast for the year 2016 were used to generate a regression. The resulting regression is shown in the Figure 26.

Figure 26: CMO regression in terms of the weekly simulated generation of Port of Açu wind plant

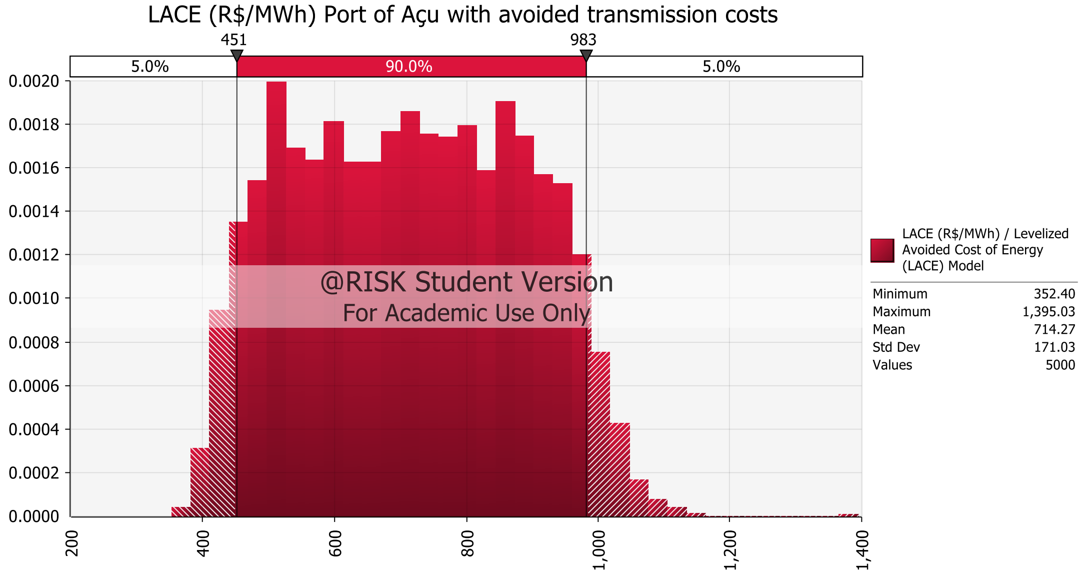


```
      Source |       SS           df       MS      Number of obs   =        52
-------------+----------------------------------   F(1, 50)        =      8.74
       Model |  34447.5015         1  34447.5015   Prob > F        =    0.0047
    Residual |  197054.575        50  3941.09151   R-squared       =    0.1488
-------------+----------------------------------   Adj R-squared   =    0.1318
       Total |  231502.077        51  4539.25641   Root MSE        =    62.778

------------------------------------------------------------------------------
         CMO |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
SimulatedGenerationGWh |   43.89418   14.84692     2.96   0.005     14.07327     73.7151
       _cons |   14.92438   23.61001     0.63   0.530    -32.49773    62.34649
------------------------------------------------------------------------------
```

Source: Elaborated by the author. **The generations are in MWh and the CMO is in R$/MWh. The adjusted R^2 shows a 13% fit.**

After finding the regression, stochastic weekly generations were produced and the correspondents CMO were calculated. The LACE calculation for the Port of Açu considers the avoided cost of transmission which, in order to incorporate an uncertainty, was considered as a uniform distribution with a minimum of US$300/KW and a maximum of US$1500/KW. Finally, the LACE value was found using the capacity credit calculated for the Port of Açu (34%). The LACE probabilistic distribution is found in the Figure 27.

Figure 27: LACE probabilistic distribution for the Port of Açu including the avoided transmission costs

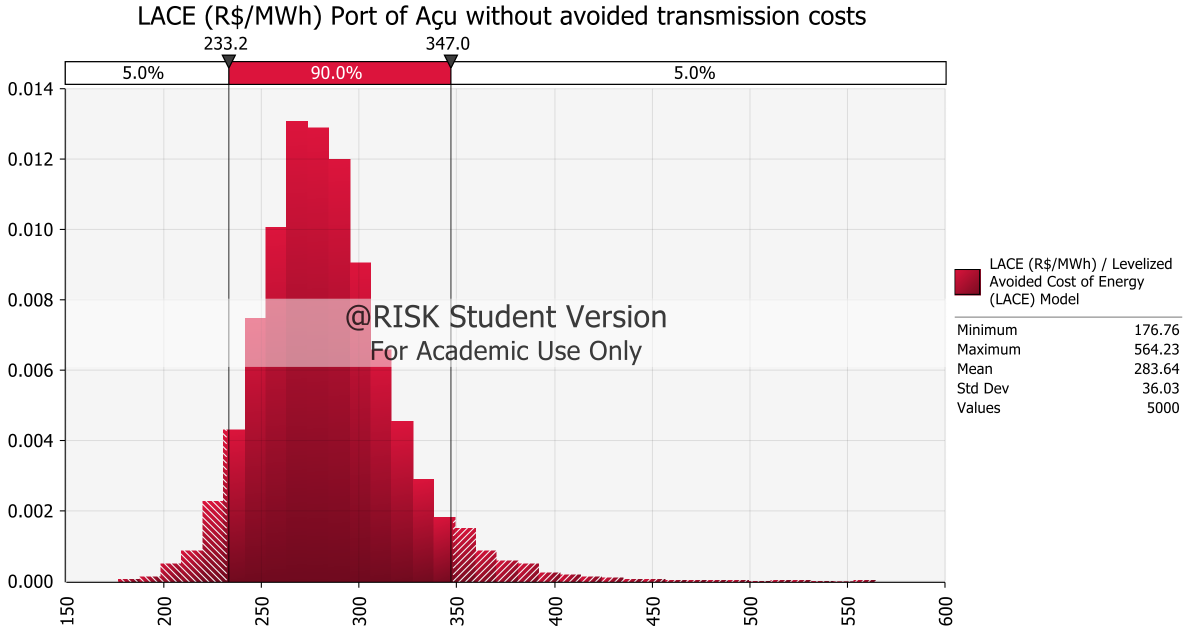


Source: Elaborated by the author

The mean is R$714/MWh and the minimum and maximum values for a 90% confidence interval are R$451/MWh and R$983/MWh respectively.

In case the avoided cost of transmission is not included, the LACE probabilistic distribution has a different result as shown in Figure 28. The mean is R$284/MWh and the minimum and maximum values for a 90% confidence interval are R$233/MWh and R$347/MWh respectively.

Figure 28: LACE probabilistic distribution for the Port of Açu NOT including the avoided transmission costs



Source: Elaborated by the author

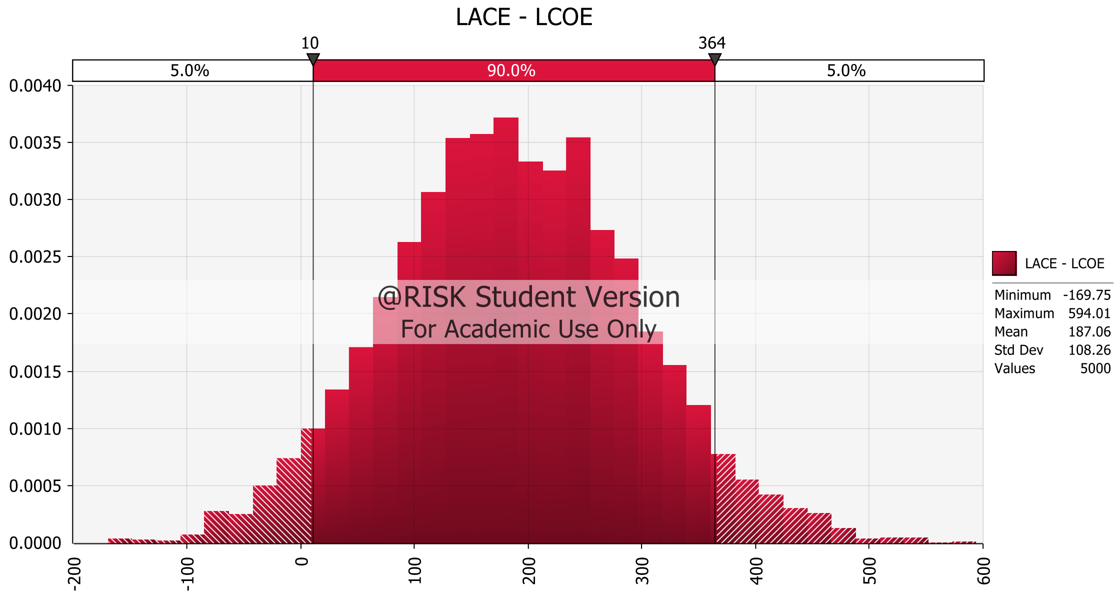
6.5 NET VALUE

The net value of a project to the grid is the difference between the LACE and LCOE. The net economic value provides a comparison of competitiveness amongst the wind plants located in the Northeast and Port of Açu. The results will be shown as a probabilistic distribution.

6.5.1 Net Value for the Northeast

The net value considering the average generation of the four selected plants in Northeast is shown in the Figure 29. The mean is R$187/MWh and the minimum and maximum values for a 90% confidence interval are R$10/MWh and R$364/MWh respectively.

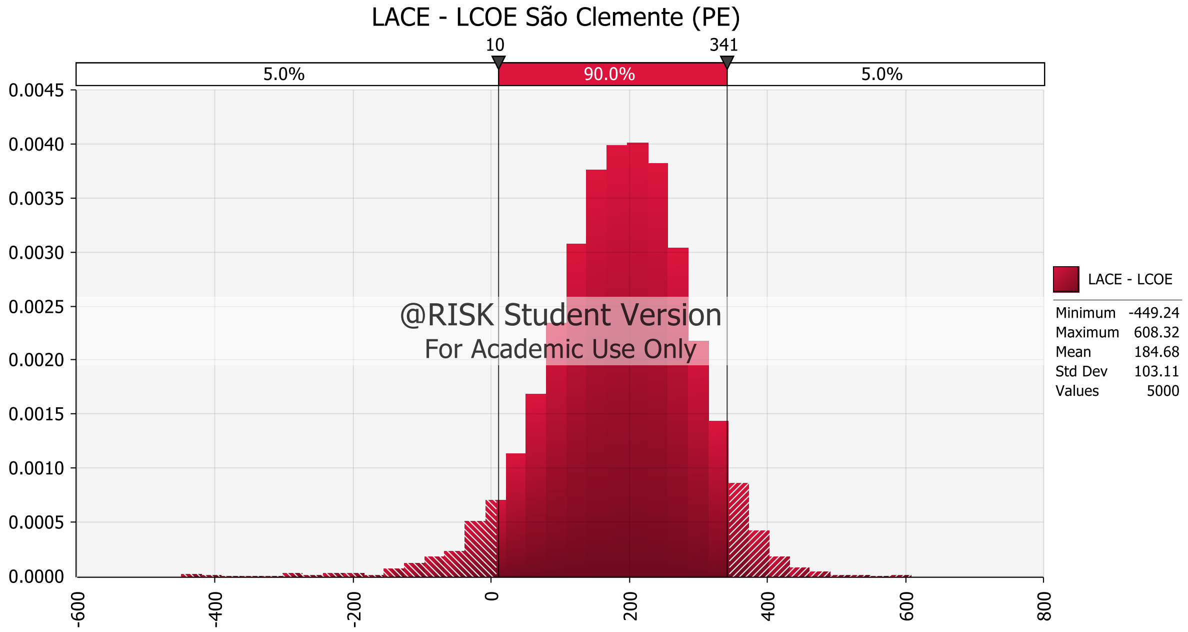
Figure 29: Net value probabilistic distribution considering the average generation of the four plants in Northeast



Source: Elaborated by the author

The net economic value for the São Clemente wind plant alone was also calculated and is shown in the Figure 30. The mean is R$185/MWh and the minimum and maximum values for a 90% confidence interval are R$10/MWh and R$341/MWh respectively.

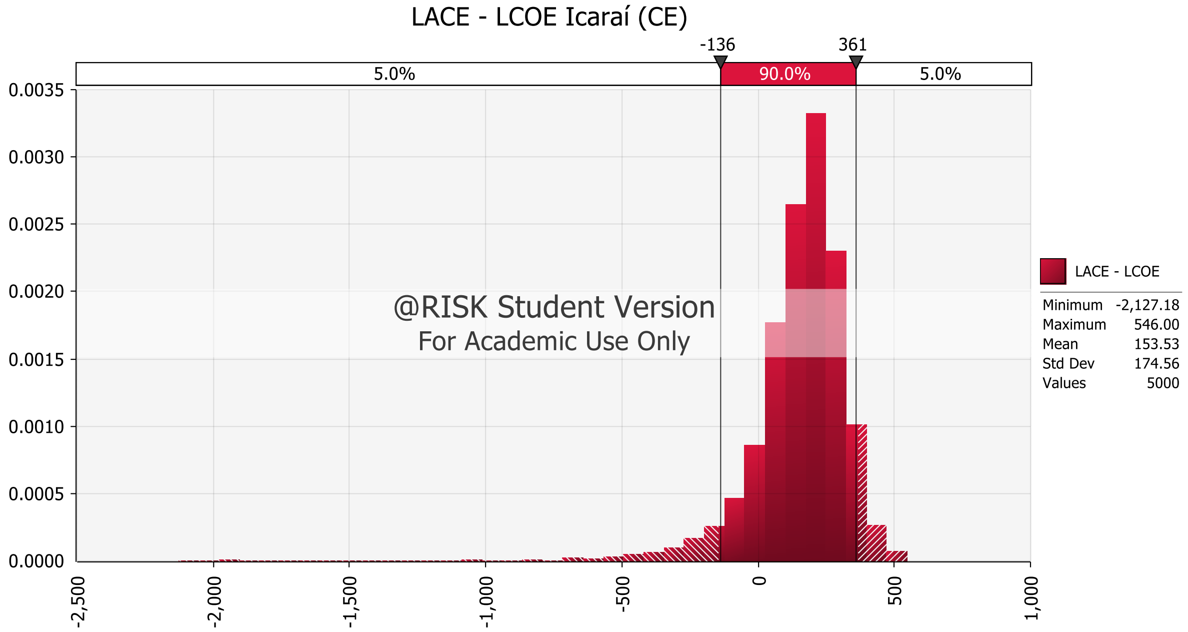
Figure 30: Net value probabilistic distribution for the São Clemente wind plant



Source: Elaborated by the author

The net economic value for the Icaraí wind plant was also calculated and is found in the Figure 31. The mean is R$153/MWh and the minimum and maximum values for a 90% confidence interval are R$-136/MWh and R$361/MWh respectively.

Figure 31: Net value probabilistic distribution for the Icaraí wind plant

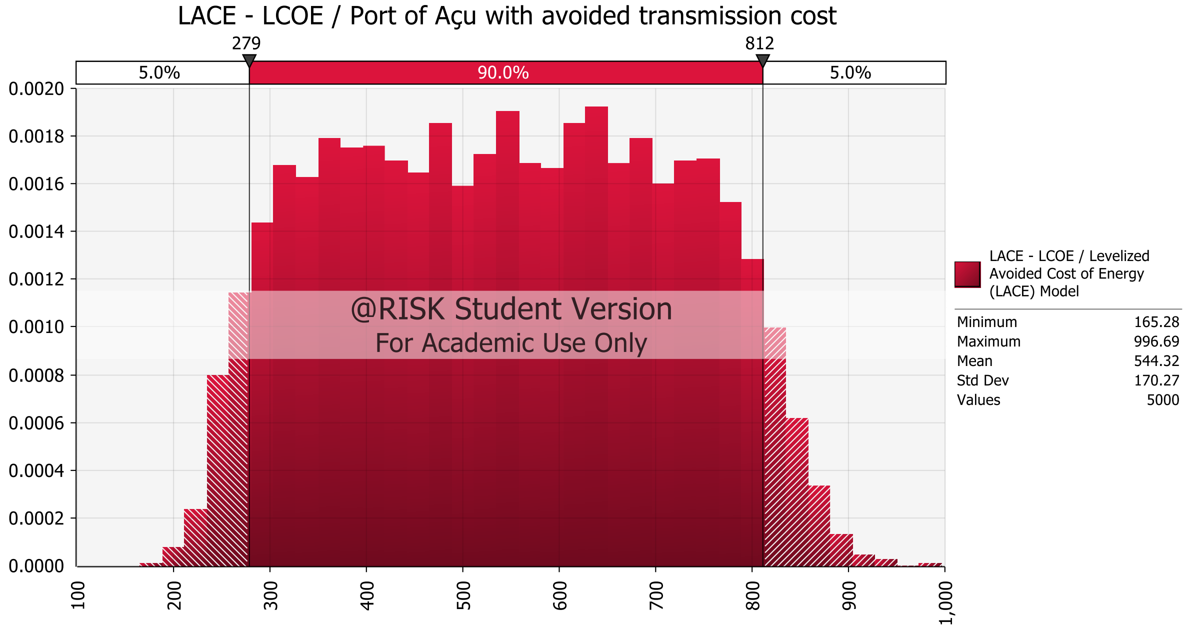


Source: Elaborated by the author

6.5.2 Net Value for the Port of Açu

The net value for a hypothetical wind plant located in Port of Açu including the avoided transmission cost is shown in the Figure 32. The mean is R$544/MWh and the minimum and maximum values for a 90% confidence interval are R$279/MWh and R$812/MWh respectively.

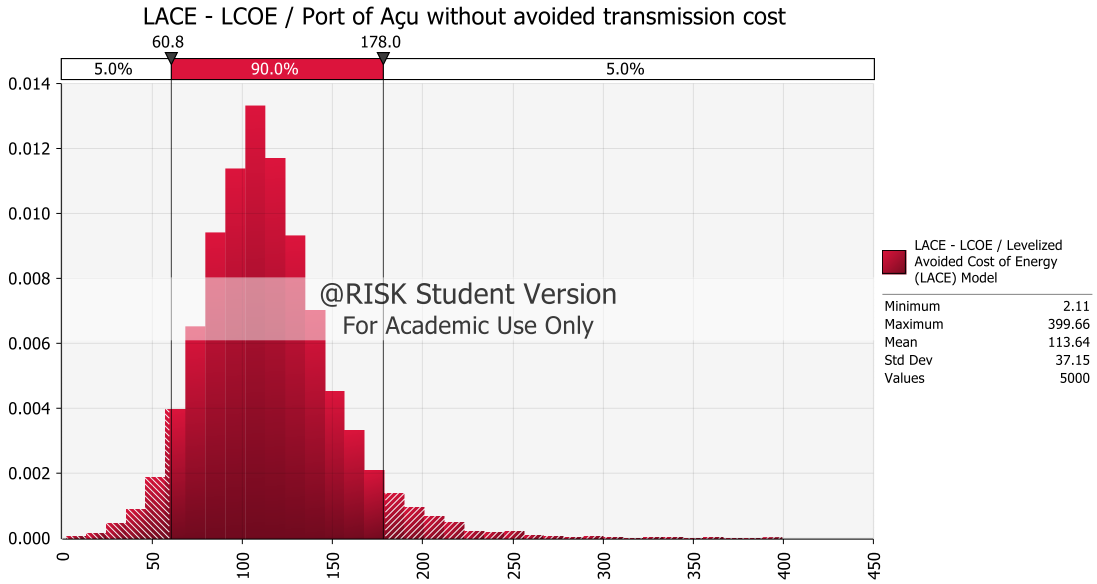
Figure 32: Net value probabilistic distribution for the Port of Açu wind plant including the avoided transmission costs in the LACE component



Source: Elaborated by the author

In case the avoided cost of transmission is not included in the calculation, the net economic value probabilistic distribution is shown in the Figure 33. The mean is R$114/MWh and the minimum and maximum values for a 90% confidence interval are R$61/MWh and R$178/MWh respectively.

Figure 33: Net value probabilistic distribution for the Port of Açu wind plant NOT including the avoided transmission costs in the LACE component



Source: Elaborated by the author

7. DISCUSSION AND METHODOLOGY LIMITATIONS

A summary of LCOE results is found in Table 4 below.

Table 4: Summary of LCOE results

Wind Plant	Mean (R$/MWh)	$P_{5\%}$ (R$/MWh)	$P_{95\%}$ (R$/MWh)
Average 4 plants	117	76	183
Areia Branca (RN)	107	58	210
Icaraí (CE)	161	60	426
Pedra Branca (BA)	179	61	491
São Clemente (PE)	140	86	238
Port of Açu	170	158	183

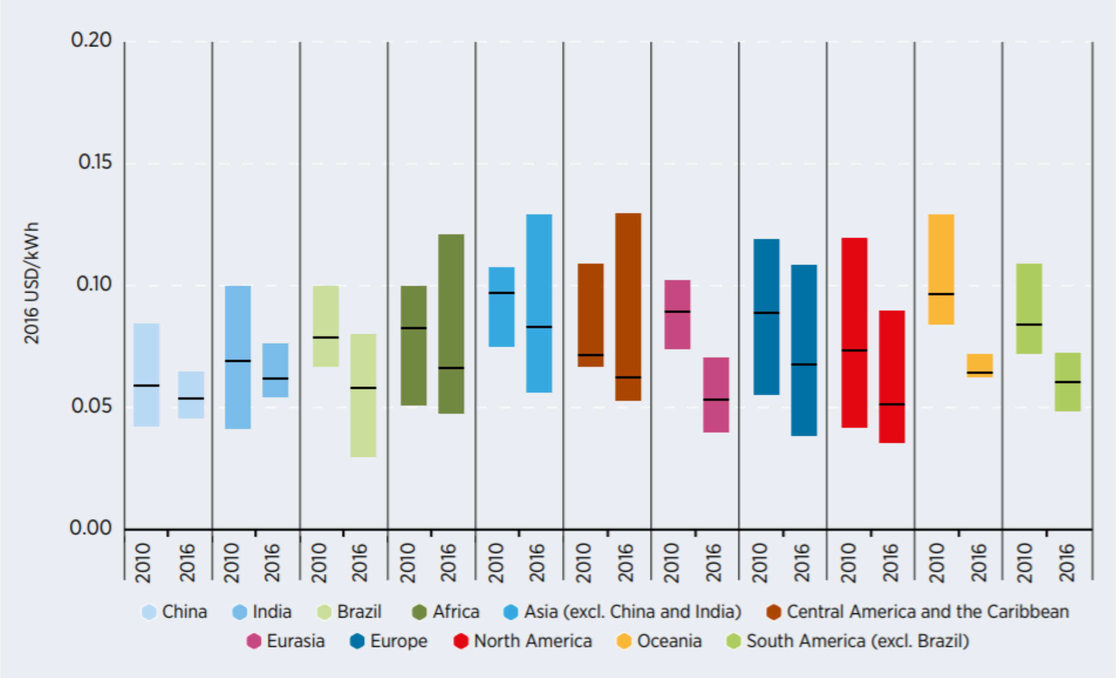
Source: Elaborated by the author

The results show that Port of Açu has a high mean; it is not only higher than Pedra Branca wind plant. It also has the highest minimum value for a 90% confidence interval ($P_{5\%}$). This result confirms that a wind plant in this location is not as competitive as the projects located in Northeast if this traditional criterion to choose energy investments is used.

Among the four wind plants analyzed in the Northeast, Areia Branca has the lowest mean, minimum ($P_{5\%}$) and maximum ($P_{95\%}$) values for a 90% confidence interval. These results indicate that Areia Branca wind farm located in Rio Grande do Norte is the most competitive wind farm among the ones analyzed in this study what may justify the fact that this state was the first to develop the wind energy production in Brazil.

These values are consistent with the ones found by IRENA (IRENA, 2018). According to their report called “Renewable Power Generation Costs in 2017”, the LCOE in Brazil is slightly higher than US$ 0.05/kWh, as illustrated in the Figure 34. This study found that the average LCOE for the four plants in Northeast is US$0.03/kWh (or R$117/MWh) and for the Port of Açu is USD 0.052/kWh (or R$170/MWh), which are fairly close.

Figure 34: Regional weighted average LCOE and ranges of onshore wind in 2010 and 2016



Source: Renewable Power Generation Costs Report (IRENA, 2018)

The Table 5 below summarizes the LACE and net value results.

Table 5: Summary of LACE and Net Value results

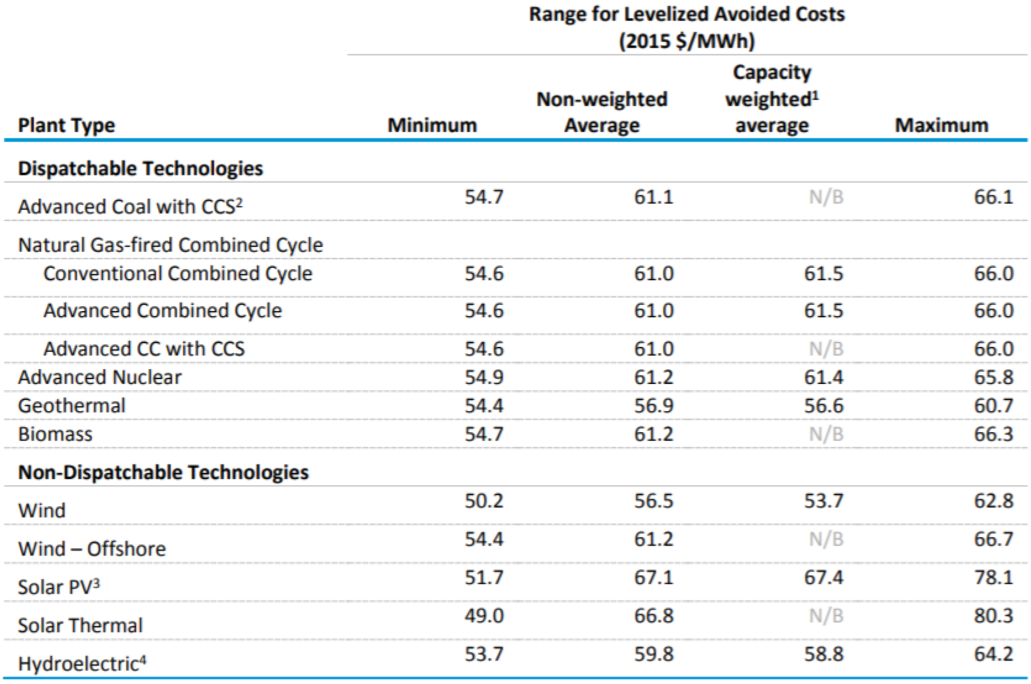
Wind Plant	LACE (R$/MWh)			Net Value (R$/MWh)		
	Mean	$P_{5\%}$ (R$/MWh)	$P_{95\%}$ (R$/MWh)	Mean	$P_{5\%}$ (R$/MWh)	$P_{95\%}$ (R$/MWh)
Average of 4 plants in NE	302	144	468	187	10	364
São Clemente (PE)	324	236	430	185	10	341
Icaraí (CE)	315	232	435	154	-136	361
Port of Açu with avoided transmission costs	714	451	983	544	279	812
Port of Açu w/o avoided transmission costs	284	233	347	114	61	178

Source: Elaborated by the author

The table shows that the Port of Açu net value including the avoided transmission cost is significantly higher than the ones found in Northeast. However, when the avoided transmission cost is neglected, the net value falls sharply, nevertheless, its minimum value for a 90% confidence interval (R$61/MWh) is still higher than the ones found in Northeast which may indicate that a wind energy project in Port of Açu faces lower economical risks.

The Levelized Avoided Costs range calculated by EIA/DOE (EIA/DOE, 2016) for new generation resources in the United States is showed in the Table 5 below. The non-weighted average for a wind plant is USD 56.5/MWh or around R$226/MWh using the exchange rate in 31/12/2015. This value is smaller than the ones found in this study. This can be justified since the marginal generation price and the wind capacity credit in Brazil are usually higher than in the US. The wind capacity credits used in this study ranged from 31% to 48% while studies in US use around 25% (MILLIGAN AND PORTER, 2008; NREL, 2016).

Table 6: Levelized Avoided Costs range for different energy sources technologies in 2015



Plant Type	Range for Levelized Avoided Costs (2015 $/MWh) Minimum	Non-weighted Average	Capacity weighted[1] average	Maximum
Dispatchable Technologies				
Advanced Coal with CCS[2]	54.7	61.1	N/B	66.1
Natural Gas-fired Combined Cycle				
Conventional Combined Cycle	54.6	61.0	61.5	66.0
Advanced Combined Cycle	54.6	61.0	61.5	66.0
Advanced CC with CCS	54.6	61.0	N/B	66.0
Advanced Nuclear	54.9	61.2	61.4	65.8
Geothermal	54.4	56.9	56.6	60.7
Biomass	54.7	61.2	N/B	66.3
Non-Dispatchable Technologies				
Wind	50.2	56.5	53.7	62.8
Wind – Offshore	54.4	61.2	N/B	66.7
Solar PV[3]	51.7	67.1	67.4	78.1
Solar Thermal	49.0	66.8	N/B	80.3
Hydroelectric[4]	53.7	59.8	58.8	64.2

Source: EIA/DOE, 2016

This study used weekly marginal generation price for the LACE calculation. This is a significant limitation. Since hourly prices are not yet available in Brazil, it is not possible to capture the daily variability of production. The greatest possible discretization is weekly, the interval of PLD disclosure.

The wind energy generation data are simulated and not measured. The validation showed a good fit, however, it is a limitation for the study as it does not show the reality. Simulation data was needed since weekly generation data for the whole analyzed period was not available.

Another important limitation of this study is the CMO estimation. The study found a regression using the measured CMO from Southeast as the dependent variable and the simulated weekly wind generations in 2016 as the dependent variables. The CMO forecast should be done using a more sophisticated simulator that considers several factors such as fuel price estimation, hydrological and wind correlations, expected energy demand, etc. The wind generation contributes to just a small portion of the CMO.

8. CONCLUSIONS

This study found that the Port of Açu location has a great economic potential to develop wind energy projects if the avoided costs criteria is used in the energy auctions. This is true even if the avoided cost of transmission is neglected since the Port of Açu's minimum net economic value ($P_{5\%}$) is higher than the ones found in Northeast.

Rio de Janeiro is current suffering a serious economic crisis that can be alleviated if the renewable energy sector is developed in the region. Auctions provide governments with a market-based framework and an efficient allocation tool to meet policy objectives that should include the increase in investments in regions that need the most. This study results indicate that Rio de Janeiro state may suffer a high economic impact if the net value metric is used in the evaluation of competing renewable projects in the energy auctions and, therefore, is in line with federal government purposes.

Competitive tendering has become one of the preferred methods of contracting renewable energy generation capacity internationally. As of early 2015, at least 60 countries had adopted renewable energy tenders, compared to just six countries in 2005. Brazil was the first country to introduce both long-term electricity auctions (2004) and renewable specific auctions (2007) replacing its feed in tariff (FiT) scheme (HOCHBERG AND POUDINEH, 2018). As a pioneer, Brazil is a world reference in energy auctions programmes and is better able to propose new evaluation criteria that effectively accounts for the transmission costs and the time value of generation in relation to spot prices.

In 2014, Brazil adopted an adjusted minimum-price criteria in the A-5 auction introducing a “correction factor” which correlates the average spot price profile and the wind power plant’s production profile. When the plant generates mostly at times when the spot price is high, the adjustment will turn into a bonus, whereas when the plant generates mostly at times when the spot price is low, the adjustment will turn into a penalty (IRENA,2015). This criteria has similarities with the LACE calculation, however, the “correction factor” is just a small portion of the evaluation price since it is added to the ICB. This shows that Brazilian government is aware of the importance to develop public policies that are in line with the current participation of renewables in the energy mix and, therefore, an improvement in the current criteria is reasonable and possible.

The methodology used in this study is relevant for other large interconnected systems in the world like China, Europe and Argentina. This type of system faces bigger challenges in allocates energy generation since they often aim to develop the energy potentialities of different regions at the same time that seeks for an optimized global cost.

The economic attractiveness of other renewable sources when a new criteria is used in the energy auctions needs to be assessed in future studies. Solar and biomass energy sources are great potentialities of Rio de Janeiro state that may be more economically competitive if avoided costs are taken into consideration. Not only Rio de Janeiro state can be seriously impacted if a shift in the current winner selection criteria takes place but all Southeast region, particularly, the coastal states of São Paulo and Espírito Santo.

9. BIBLIOGRAPHIC REFERENCES

Empresa de Pesquisa Energética (2016). Plano Decenal de Expansão de Energia. Available on: http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Decenal-de-Expansao-de-Energia-2026. Accessed in: 19 July 2018

Empresa de Pesquisa Energética (2018). Fontes. Available on: http://www.epe.gov.br/pt/areas-de-atuacao/energia-eletrica/expansao-da-geracao/fontes. Accessed in: 19 July 2018

CUNHA, D. A; FERREIRA, L. V. (2012). Impacts of the Belo Monte hydroelectric dam construction on pioneer vegetation formations along the Xingu River, Pará State, Brazil. Brazilian Journal of Botany, 35(2), 159-167. https://dx.doi.org/10.1590/S0100-84042012000200005

LATRUBESSE, E. M. et al. (2017). Damming the rivers of the Amazon basin. Nature, 546(7658), 363-369. DOI: 10.1038/nature22333

Operador Nacional do Sistema (2018). Histórico de Geração. Available on:

http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da operacao/geracao_energia.aspx. Accessed in: 19 July 2018

Portal Solar (2018). Available on: https://www.portalsolar.com.br/blog-solar/energia-solar/producao-de-energia-solar-fotovoltaica-pode-dobrar-em-2018.html Accessed in: 19 July 2018

CCEE (2018). Resultados Consolidados dos Leilões de Energia. Available on: https://www.ccee.org.br/portal/faces/acesso_rapido_header_publico_nao_logado/biblioteca_virtual?tipo=Resultado%20Consolidado&assunto=Leil%C3%A3o&_afrLoop=36065373116087&_adf.ctrl-state=el6jmd05e_18#!%40%40%3F_afrLoop%3D36065373116087%26tipo%3DResultado%2BConsolidado%26assunto%3DLeil%25C3%25A3o%26_adf.ctrl-state%3Del6jmd05e_22 Accessed in: 19 July 2018

Castro, G.M (2015). Avaliação do valor da energia proveniente de usinas heliotérmicas com armazenamento no âmbito do Sistema Interligado Nacional. 2015. Dissertação (Mestrado em Planejamento Energético) – Centro Tecnológico, Universidade Federal do Rio de Janeiro.

EIA (2013) Levelized Cost of Electricity and Levelized Avoided Cost of Electricity Methodology Supplement. Available on: https://www.eia.gov/renewable/workshop/gencosts/pdf/methodology_supplement.pdf Accessed in 19 July 2018

ROMEIRO, D.L; DE ALMEIDA, E.; LOSEKANN, L. (2015). The choice of dispatchable versus intermittent electricity generating technologies and the Brazilian case. 5th Latin American Energy Economics Meeting.

Operador Nacional do Sistema (2019). Apresentações reunião do PMO - Janeiro/2019. Available on: http://ons.org.br/Paginas/busca.aspx?k=PMO#k=PMO%20-%20Janeiro. Accessed in 25 Janeiro 2019

CARPIO, L.G.T; PEREIRA JR., A.O. (2006) Independent operation by subsystems: Strategic behavior for the Brazilian electricity sector. Energy Policy 34 (2006) 2964–2976

ANEEL (2018) Banco de Informação de Geração. Available on: http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm. Accessed in: 19 July 2018

Empresa de Pesquisa Energética (2018). Índice Custo Benefício (ICB) de Empreendimentos de Geração. Available on: http://www.epe.gov.br/sites-en/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-111/Metodologia%20de%20Calculo%20do%20ICB_R2.pdf. Accessed in: 19 July 2018

CEPEL (2001). Atlas do potencial eólico brasileiro. 2001. Brasília, 2001. Disponível em: <www.cresesb.cepel.br/publicacoes/download/atlas_eolico/Atlas%20do%20 Potencial%20Eolico%20Brasileiro.pdf>. Accessed in: 20 nov. 2018.

PEREIRA, E.B (2009). Assessment of Solar and Wind Energy Resources in Brazil. National Institute for Space Research – INPE; Earth System Center – CST; Center For Weather Forecast and Climate Studies – CPTEC. FAPESP, IOP and RSC Workshop: Physics and Chemistry of Climate Change and Entrepreneurship February 27th, 2009.

CABRAL, A. (2015). Wind energy policy in Brazil: a discussion about technological autonomy and its impact on the reverse auction system. RDA – Revista de Direito Administrativo, Rio de Janeiro, v. 269, p. 225-254, maio/ago. 2015

DW (2018) Como o estado do Rio de Janeiro chegou à falência? Available on: https://www.dw.com/pt-br/como-o-estado-do-rio-de-janeiro-chegou-%C3%A0-fal%C3%AAncia/a-19344065. Accessed in: 22 July 2018

AMARANTE, O. A. C. et al. (2004) Atlas Eólico do Estado do Rio de Janeiro. Secretaria de Estado de Energia, da Indústria Naval e do Petróleo, RJ, 2004.

AMARANTE, O.A.C et al. (2001) Atlas do potencial eólico brasileiro. Ministerio de Minas e Energia Eletrobras. 2001

Port of Açu (2018). Website do Porto do Açu. Available on: www.portodoacu.com.br Accessed in: 22 July 2018

NAMOVICZ, C. (2013) Assessing the Economic Value of New Utility-Scale Generation Projects. Presented to the EIA LCOE/LACE Workshop July 25, 2013. Available on: https://www.eia.gov/renewable/workshop/gencosts/pdf/1_Namovicz.pdf. Accessed in: 21 July 2018

PARIENTE-DAVID, S. (2016). The Cost and Value of Renewable Energy: Revisiting Electricity Economics. IAEE Energy Forum. Available on: www.iaee.org/en/publications/newsletterdl.aspx?id=332 Accessed in: 21 July 2018

BENES, K.J; AUGUSTIN, C. (2016). Beyond LCOE: A simplified framework for assessing the full cost of Electricity. The Electricity Journal 29 (2016) 48–54. Energy Policy Institute's Sixth Annual Energy Policy Research Conference. http://dx.doi.org/10.1016/j.tej.2016.09.013

DE JONG, P.; KIPERSTOK, A.; TORRES,E.A. (2015) Economic and environmental analysis of electricity generation technologies in Brazil. Renewable and Sustainable Energy Reviews, 2015, vol. 52, issue C, 725-739. http://dx.doi.org/10.1016/j.rser.2015.06.064

SILVA, S.B.; DE OLIVEIRA; M.A; SEVERINO,M.M. (2010). Economic evaluation and optimization of a photovoltaic–fuel cell–batteries hybrid system for use in the Brazilian Amazon. Energy Policy 38 (2010) 6713–6723

CARDEMIL J.M.,COLLE S.A. Base de Dados SWERA Como Suporte para Análises Tecnico-Econômicas de Plantas Termo-Solares. III Congresso Brasileiro de Energia Solar—Belém; 2010.

BROWN, A. ET AL. (2016) Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results. Technical Report NREL/TP-6A20-64503 Revised August 2016

BEITER, P. ET AL. (2017) An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030 Technical Report NREL/TP-6A20-67675 March 2017

MULONGO, N.Y; KHOLOPANE,P. (2018). An Economic Competitiveness Analysis of Power Generation Plants. 2018 5th International Conference on Industrial Engineering and Applications.

MILBRANDT, A.; HEIMILLER, D.; SCHWABE,P. (2018) Techno-Economic Renewable Energy Potential on Tribal Lands. Technical Report NREL/TP-6A20-70807 July 2018

LEAL, F.I.; REGO, E.E; RIBEIRO, C.O. (2017) Levelized cost analysis of thermoelectric generation in Brazil: A comparative economic and policy study with environmental implications. Journal of Natural Gas Science and Engineering 44 (2017) 191-201. http://dx.doi.org/10.1016/j.jngse.2017.04.017

HIRTH, L. (2013). The market value of variable renewables: The effect of solar wind power variability on their relative price. Energy Economics Volume 38, July 2013, Pages 218-236. https://doi.org/10.1016/j.eneco.2013.02.004

MORAIS, R. C (2015). Aplicação do fator de valor na avaliação do benefício associado às novas fontes renováveis. Dissertação (Mestrado em Planejamento Energético) – Centro Tecnológico, Universidade Federal do Rio de Janeiro.

UECKERDT, F.; HIRTH, L.; LUDERER,G.; EDENHOFER,O. (2013) System LCOE: What are the costs of variable renewables? Energy 63 (2013) 61-75. http://dx.doi.org/10.1016/j.energy.2013.10.072

CRISTIAN RABITI, C.; GARCIA,H.E.; HOVSAPIAN, R.; KINOSHITA,R.A.; MESINA,G.L.; BRAGG-SITTON, S.M.; BOARDMAN, R.D. (2015). Strategy and Gaps for Modeling, Simulation, and Control of Hybrid Systems. Idaho National Laboratory INL ART Program Idaho Falls, Idaho 83415. Prepared for the U.S. Department of Energy Office of Nuclear Energy Under DOE Idaho Operations Office Contract DE-AC07-05ID14517

REICHELSTEIN, S.; SAHOO, A. (2015) Time of day pricing and the levelized cost of intermittent power generation. Energy Economics 48 (2015) 97–108. http://dx.doi.org/10.1016/j.eneco.2014.12.005

HEUBERGERA, C.F.; STAFFELL, I.; SHAHB, N.; DOWELL, N.M. (2017) A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks. Computers and Chemical Engineering 107 (2017) 247–256. http://dx.doi.org/10.1016/j.compchemeng.2017.05.012

BRUCK, M.; SANDBORN, P.; GOUDARZI, N. (2018) A Levelized Cost of Energy (LCOE) model for wind farms that include Power Purchase Agreements (PPAs). Renewable Energy 122 (2018) 131-139. https://doi.org/10.1016/j.renene.2017.12.100
ODEH, R.P.; WATTS, D.; FLORES, Y. (2018) Planning in a changing environment: Applications of portfolio optimisation to deal with risk in the electricity sector. Renewable and Sustainable Energy Reviews, 2018, vol. 82, issue P3, 3808-3823. https://doi.org/10.1016/j.rser.2017.10.089

AMARANTE, O. A.; SCHULTZ, D. J.; BITTENCOURT, R. M.; ROCHA, N. A. (2011) Wind / Hydro Complementary Seasonal Regimes in Brazil. DEWI Magazin Nr. 19, August 2001

SCHMIDT, J.; CANCELLA, R.; PEREIRA, A.O. (2014) Combing windpower and hydropower to decrease seasonal and inter-annual availability of renewable energy sources in Brazil, Discuss. Pap. Inst. Sustain. Econ. Dev. (DP-56) (2014).

DUTRA, R.M.; SZKLO, A.S. (2008) Incentive policies for promoting wind power production in Brazil: scenarios for the alternative energy sources incentive program (PROINFA) under the New Brazilian electric power sector regulation, Renew. Energy 33 (1) (Jan. 2008) 65-76.

BHATTACHARYA, A.; KOJIMA, S. (2012). Power sector investment risk and renewable energy: A Japanese case study using portfolio risk optimization method, Energy Policy, Elsevier, vol. 40(C), pages 69-80.

DELARUE, E.; DE JONGHE, E.; BELMANS, R.; D'HAESELEER, W., (2011). Applying portfolio theory to the electricity sector: Energy versus power. Energy Economics ,v.33, p.12–23, 2011.

NETO, D.P.; DOMINGUES, E.G.; COIMBRA, A.P.; DE ALMEIDA, A.T.; ALVES, A.J.; CALIXTO, W.P. (2017) Portfolio optimization of renewable energy assets: Hydro, wind, and photovoltaic energy in the regulated market in Brazil. Energy Economics 64 (2017) 238–250. http://dx.doi.org/10.1016/j.eneco.2017.03.020

JENKIN, T.; DIAKOV, V.; DRURY, E.; BUSH, B.; DENHOLM, P.; MILFORD, J.; ARENT, D.; MARGOLIS, R. (2013) The Use of Solar and Wind as a Physical Hedge against Price Variability within a Generation Portfolio. Technical Report NREL/TP-6A20-59065 August 2013

IQBAL, M.; AZAM, M.; NAEEM, M.; KHWAJA, A.S.; ANPALAGAN, A. (2014) Optimization classification, algorithms and tools for renewable energy: A review. Renewable and Sustainable Energy Reviews 39 (2014) 640–654. http://dx.doi.org/10.1016/j.rser.2014.07.120

COSTA, O. L; DE OLIVEIRA, R. C.; REGO, E.E; STERN, J. M.; PARENTE, V.; KILEBER, S. (2017). Robust portfolio optimization for electricity planning: An application based on the Brazilian electricity mix. Energy Economics, Elsevier, vol. 64(C), pages 158-169. DOI: 10.1016/j.eneco.2017.03.021

LUZ, T.; MOURA, P.; DE ALMEIDA, A. (2018) Multi-objective power generation expansion planning with high penetration of renewables. Renewable and Sustainable Energy Reviews 81 (2018) 2637–2643. http://dx.doi.org/10.1016/j.rser.2017.06.069

NEA—Nuclear Energy Agency/ IEA—International Energy Agency/ OECD—Organization for Economic Cooperation and Development. Projected costs of generating electricity, edition; 2010.

NEA—Nuclear Energy Agency/ IEA—International Energy Agency/ OECD—Organization for Economic Cooperation and Development. Projected costs of generating electricity, edition; 2015.

OMEGA GERAÇÃO S.A (2017) Demonstrações Financeiras em 31 de December de 2017 e 2016. Available on: https://economia.estadao.com.br/fatos-relevantes/pdf/27459557.pdf. Accessed in 23 July 2018

ONS (2018) Histórico do Custo Marginal de Operação (CMO). Available on: http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/cmo.aspx. Accessed in 24 July 2018.

ONS (2018) Histórico de Geração. Available on: http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao_energia.aspx. Accessed in 24 July 2018.

CCEE (2018) Preço Horário Sombra. Available on: https://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/como_ccee_atua/precos/preco_sombra?_afrLoop=425494282219032&_adf.ctrl-state=80iv2zdpj_1#!%40%40%3F_afrLoop%3D425494282219032%26_adf.ctrl-state%3D80iv2zdpj_5 Accessed in 18 November 2018.

SÖDER, L.; AMELIN, M. (2008) A Review of Different Methodologies Used for Calculation of Wind Power Capacity Credit. Proceedings of the IEEE Power Engineering Society General Meeting; 2008, Pittsburgh, PA, 2008.

PUDARUTH, G.R.; LI, F. (2008) Capacity Credit Evaluation: A Literature Review. Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, DRPT 2008, Nanjing, China; pp. 2719–2724.

MILLIGAN, M.; PORTER, K. (2008) Determining the Capacity Value of Wind: An Updated Survey of Methods and Implementation. WindPower 2008; June 2008, Houston, Texas.

MILLIGAN, M.; PARSONS, B. (1999) A Comparison and Case Study of Capacity Credit Algorithms for Wind Power Plants. Wind Energy; Vol. 23, Iss. 3, 1999; pp. 159–166.

PEREIRA JR, A.O.; DA COSTA, R.C.; COSTA, C.V.; MARRECO, J.M.; LA ROVERE, E.L. (2013) Perspectives for the expansion of new renewable energy sources in Brazil. Renewable and Sustainable Energy Reviews 23 (2013) 49–59

IRENA (2018) Renewable Power Generation Costs in 2017. Available on: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf. Accessed in 13 January 2019.

EIA (2016) Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016. Available on: https://wecanfigurethisout.org/ENERGY/Web_notes/Technology%20Comparisons/Plant%20Economics%20-%20Supporting%20-%20Files/LCOE%202016%20-%20EIA%20%20Annual%20Energy%20Outlook%20%20Levelized%20Cost%20of%20New%20Generation%20Resources.pdf Accessed in 13 Janeiro 2019.

IRENA (2015) Auction design: Winner selection process. Available on: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_RE_Auctions_Guide_2015_5_winner_selection.pdf?la=en&hash=F45C1A24BD68F9AF3F52A264AF6C7B7E11940177. Accessed in 13 January de 2019.

HOCHBERG, M.; POUDINEH, R. (2018) Renewable Auction Design in Theory and Practice: Lessons from the Experiences of Brazil and Mexico. OIES Paper: EL 28. Oxford Institute for Energy Studies. DOI: https://doi.org/10.26889/9781784671068