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LUCAS LYRIO DE OLIVEIRA

Electricity generation in Brazil: social, economic, and environmental perspectives through statistical and optimization models

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Versão Corrigida

Tese apresentada à Escola Politécnica da Universidade de São Paulo para obtenção do título de Doutor em Ciências.

Orientadora: Prof.ª Dr.ª Celma de Oliveira Ribeiro

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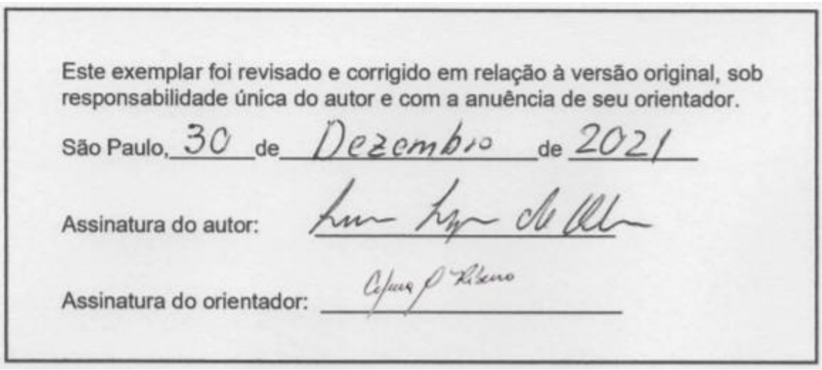

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To the ones who believe that prosperity is achieved through science and love.

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“Love is wise, hatred is foolish.”

(Bertrand Russell)

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Abstract

Depletion of fossil fuels, deforestation, climate change, industrialization of developing countries, population growth, interactions between society and energy vectors, and governments' efforts to guarantee affordable electricity prices to their populations are some of the factors that have motivated studies focused on the expansion of energy systems. These systems present complex factors and processes such as obtention of primary energy sources, energy conversion processes, market regulation, consumers' behavior, infrastructure costs, generation costs, and supply and demand uncertainties. Under this context, statistical and optimization-based techniques have enabled researchers to better comprehend the role that energy plays on society, economy, and environment. Taking Brazil as a case study, this thesis investigates alternatives for energy use expansion, particularly in the power sector. Risks related to generation and transmission costs are studied under the light of portfolio theory. Through a new modelling framework that integrates an agent-based model with a portfolio theory-based model, impacts of second-generation ethanol production and land use constraints for biomass cultivation are assessed with respect to bioelectricity generation. Moreover, a statistical analysis based on K-means algorithm and hypothesis testing is conducted to investigate relations between sugarcane expansion, which is the main source for bioelectricity generation in Brazil, and human development. Also, a hierarchical multi-period and multi-region optimization modelling framework capable of dealing with uncertainties on renewable generation and cost minimization is applied. Results point that the expansion of bioelectricity is preferred among other thermopower sources; however, limited availability of sugarcane bagasse may reduce its expansion, mainly under a scenario where second-generation ethanol is produced in scale. From the socioeconomic perspective, it is evidenced that sugarcane investors express preference to locate their mills where human development is higher but benefits from sugarcane activities to local population is unclear. Finally, it is shown that the use of renewable technologies in the power sector is beneficial for both the environment and economical spheres; however, emissions reduction targets will not be achieved without new policies to accelerate their expansion.

Keywords: Electricity supply; Brazilian electricity system; Generation expansion planning; Renewable energy sources.

Oliveira, Lucas Lyrio de. **Geração de eletricidade no Brasil:** perspectivas sociais, econômicas e ambientais através de modelos estatísticos e de otimização. 2021. X p. Tese (PhD) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2021.

Resumo

Esgotamento de combustíveis fósseis, desmatamento, mudanças climáticas, industrialização de países em desenvolvimento, crescimento populacional, interações entre sociedade e fontes energéticas, e esforços dos governos para garantir preços de eletricidade acessíveis para suas populações são alguns dos fatores que têm motivado estudos voltados para a expansão de sistemas energéticos. Esses sistemas apresentam fatores e processos complexos, como obtenção de fontes de energia primária, processos de conversão de energia, regulação do mercado, comportamento dos consumidores, custos de infraestrutura, custos de geração e incertezas na oferta e demanda. Nesse contexto, técnicas estatísticas e de otimização têm permitido aos pesquisadores compreender melhor o papel que a energia desempenha na sociedade, economia e meio ambiente. Adotando o Brasil como estudo de caso, esta tese investiga alternativas para a expansão do uso de energia, principalmente no setor elétrico. Os riscos relacionados aos custos de geração e transmissão são estudados à luz da teoria de portfólios. Através de uma nova estrutura de modelagem que integra um modelo baseado em agentes com um modelo baseado na teoria de portfólios, os impactos da produção de etanol de segunda geração e as restrições de uso da terra para o cultivo de biomassa são avaliados com relação à geração de bioeletricidade. Além disso, uma análise estatística baseada no algoritmo K-means e testes de hipóteses é conduzida para investigar relações entre a expansão da cana-de-açúcar, principal fonte de geração de bioeletricidade no Brasil, e o desenvolvimento humano. Também, uma estrutura de modelagem hierárquica de otimização multiperíodo e multirregional capaz de lidar com as incertezas na geração renovável e com a minimização de custos é aplicada. Resultados apontam que a expansão da bioeletricidade é mais vantajosa do que outras fontes termelétricas; entretanto, a disponibilidade limitada de bagaço cana de açúcar pode reduzir sua expansão, principalmente em um cenário onde o etanol de segunda geração é produzido em escala. Do ponto de vista socioeconômico, evidencia-se que os investidores canavieiros têm preferência por localizar usinas onde o desenvolvimento humano é maior, mas os benefícios da atividade para a população local não são claros. Por fim, é evidenciado que o uso de tecnologias renováveis no setor elétrico é benéfico tanto para a esfera ambiental quanto econômica; entretanto, metas de redução de emissões não serão alcançadas sem novas políticas para acelerar sua expansão.

Palavras-chaves: Fornecimento de eletricidade; Sistema Elétrico Brasileiro; Planejamento da expansão de geração; Fontes renováveis de energia.

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1 Introduction

1.1 Motivation

Brazil is a country with an extensive territory, with an area of 8.5 million km^2, and high regional heterogeneities with respect to social, economic, and environmental conditions. Availability of natural resources, logistic infrastructure, population size, human development, industrialization, agricultural activities, and climate conditions are factors that directly affect energy use and energy obtention. Therefore, regional aspects are important to be considered and challenge the energy expansion planning.

In addition to challenges imposed by regional specificities, Brazil is a developing country that is expected to experience a considerably rise in energy use. Particularly in the power sector, which is the focus of the present thesis, the Brazilian Energy Research Company – Empresa de Pesquisa Energética, in Portuguese – (EPE) estimates that electricity consumption will grow an average of 3.1% per year from 2019 to 2030 (EPE, 2020). In fact, data from the International Energy Agency (IEA, 2018) evidence that more developed countries tend to have higher electricity consumptions (Figure 1), suggesting that Brazil has great potential for demand increase.

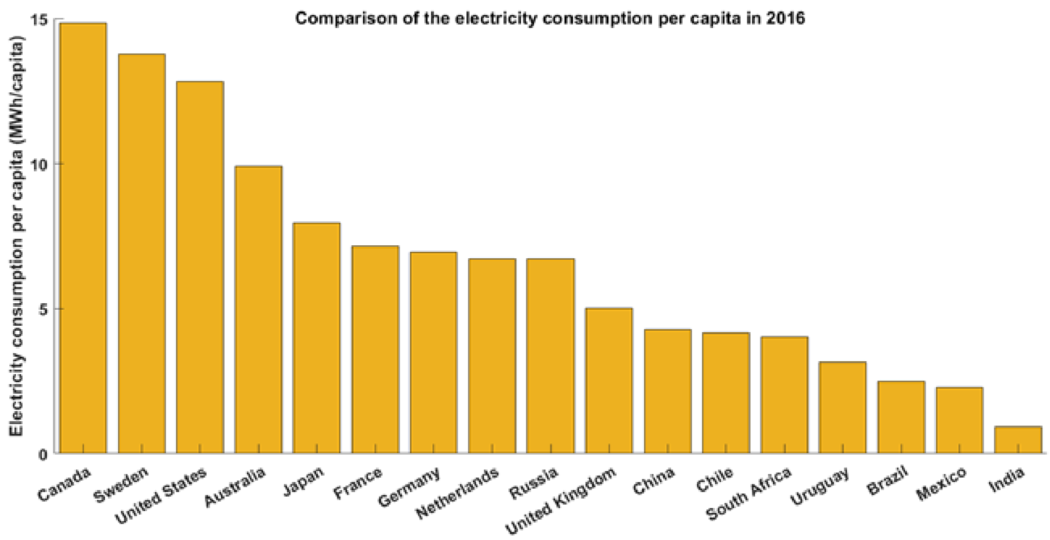

Figure 1- Electricity consumption per capita.
Source: IEA, 2018.

Undoubtedly, the growth in electricity demand will require new installed capacities to be built in the next years. Additionally, many of the existing powerplants in Brazil have already been operating for years, which means that in the midterm some of them will achieve their lifetimes and will have to be decommissioned. Therefore, new installed capacities will have to be enough to cover both the substitution of decommissioned powerplants and the supply expansion. Based on the starting operating data of power plants in Brazil (Aneel, 2019) and on average lifetimes of each generation technology, Figure 2 shows the estimated installed capacity in the country if no new investments are made. The adopted lifetimes are shown in Table 1.

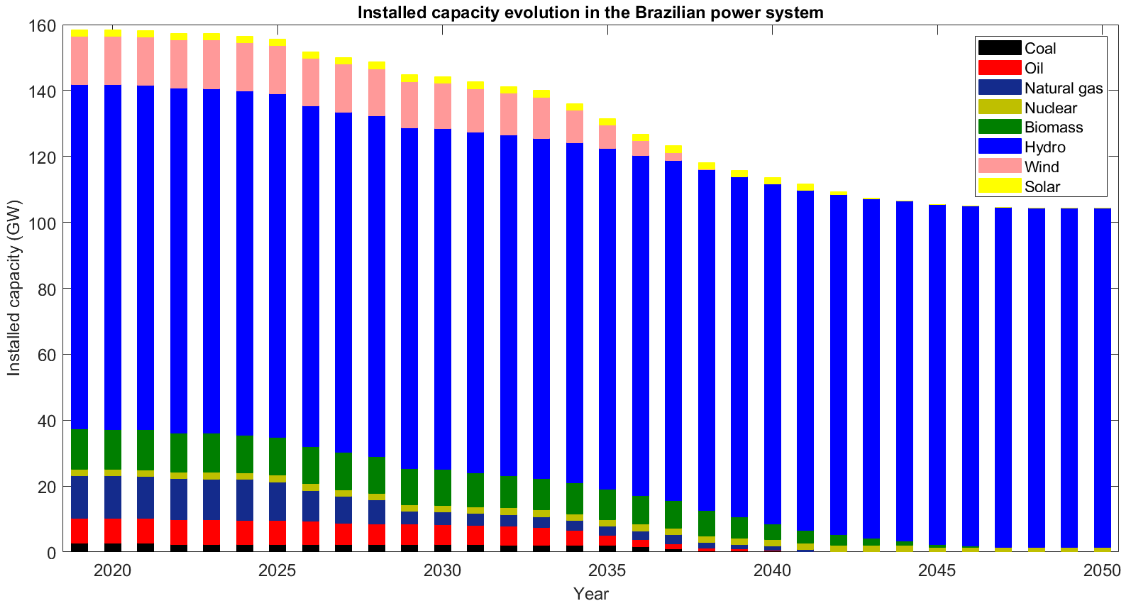

Figure 2 - Installed capacities evolution in the Brazilian power system.
Source: Based on Aneel (2019) and on references given in Table 1.

Table 1- Technologies' lifetimes.

Generation technology	Lifetime (years)	Source
Hydro	100	IEA, 2010
Wind	20	Abraceel, 2018
Solar	25	Cresesb 2014
Biomass	30	IEA and IRENA, 2013
Coal	25	EPE, 2007
Oil	25	EPE, 2007
Natural gas	25	MacDonald, 2010
Nuclear	60	Aneel, 2012

Aside from the requirements for new investments in the electricity supply capacity lays the need for expanding it in a sustainable way. It is important to highlight that one out of the seventeen sustainable development goals established by the United Nations (UN) is to “ensure access to affordable, reliable, sustainable, and modern energy for all” (UN, 2015). Therefore, investigating the relationship between electricity expansion and social, economic, and environmental spheres is required. Results from such investigations broader the knowledge in the energy field and can help society to shift to a better living. This motivates the research presented here.

1.2 Brazilian power sector

To meet its electricity demand, Brazil accounts with the National Interconnected System – Sistema Interligado Nacional, in Portuguese – (SIN), which is composed by four interconnected subsystems: North, Northeast, Southeast/Midwest and South. The expansion and maintenance of transmission lines allow exchanges of electricity from regions with excess production capacity to regions with electricity shortfalls, therefore increasing the security of supply (Silva et al., 2016). Figure 3 presents the SIN.

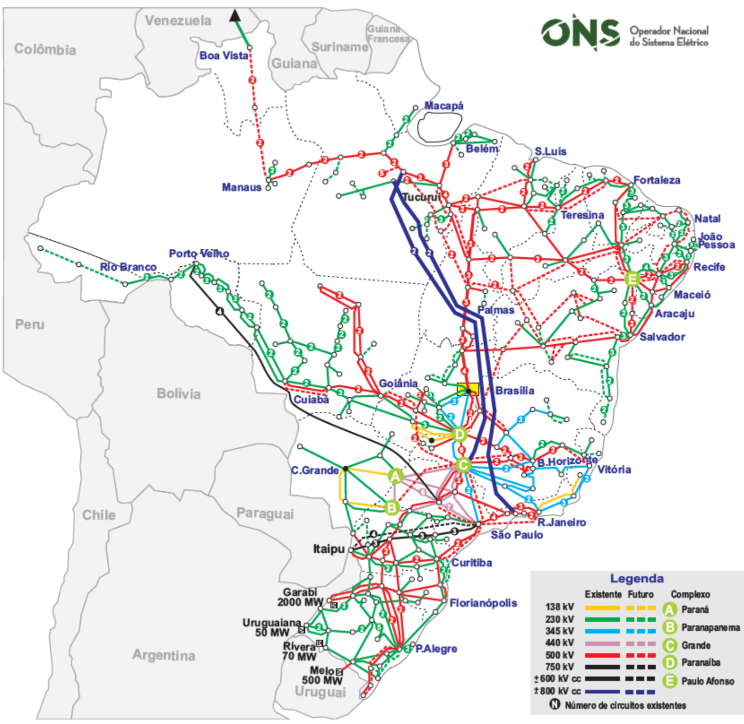

Figure 3 - Interconnected National System.
Source: ONS (2021).

To cover all expenses related to maintenance and expansion of the grid, producers and distributors of electricity contribute with the payment of a tariff for the use of the transmission system, called Tarifa de Uso do Sistema de Transmissão (TUST). The TUST paid by each generator varies according to its location and the maximum amount of energy that can be injected into the grid, which in turn depends on the generator's installed capacity. TUST is comprised of two values: 1) a common value applied to all producers; and 2) a value that depends on the location of the producer. To stimulate investments in renewables, there is a reduction of at least 50% in the TUST value for electricity generation through wind, biomass and solar (Aneel, 2018).

Figure 4 shows regional shares of generation and demand in 2020, evidencing that electricity exchanges are indeed necessary. The dashed lines give the corresponding share of each subsystem demand in the Brazilian power system, while the solid lines represent the generation shares. In the North, generation share is higher than its demand share; in contrast, the South subsystem usually imports electricity from other subsystems. Subsystems Southeast/Midwest and Northeast vary between imports and exports.

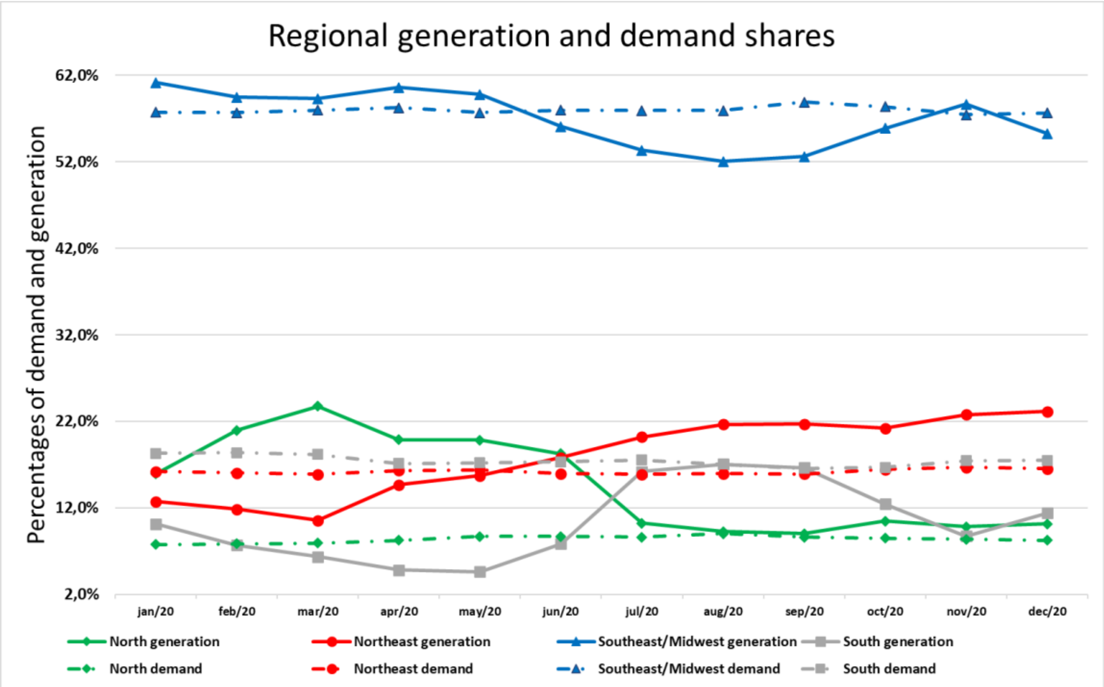

Figure 4 - Regional generation and demand shares in 2020.
Source: based on ONS (2021).

The agent responsible for the operation of the system is the National System Operator

- Operador Nacional do Sistema, in Portuguese - (ONS), which is an independent system operator that aims at defining operative conditions that minimize costs and guarantee security of supply requirements. To optimize the electricity dispatch to achieve the highest level of supply security at the lowest possible cost, ONS calculates how much thermal and hydroelectric energy should be produced in the short term to meet demand. The NEWAVE, which is a software based on stochastic dynamic programming model, is used for this calculation. NEWAVE is discussed in more detail in Pereira and Pinto (1991) and Rego et al. (2017).

One of the main features of the Brazilian power sector is the predominance of renewable generation sources. Brazil is the second largest producer of hydroelectricity in the world and hydropower plants provide approximately two-thirds of the electricity supply of the country. High shares of hydropower have advantages such as low greenhouse gas (GHG) emissions and lower generation costs. However, dependence on hydroelectricity exposes the electricity system to climatic risks, which are likely to be exacerbated by climate change.

Brazil frequently faces severe droughts that diminish the level of hydro reservoirs and forces the use of thermal power plants, at high economic and environmental costs, to ensure supply and avoid shortages and rationing. Particularly in the Northeast, periods of drought make imports of electricity from other regions necessary to meet its demand (De Jong et al., 2015).

In addition to the risks associated to unfavorable hydrological conditions, according to EPE (2021) about 60% of the Brazilian hydropower potential has already been tapped. About 70% of the remaining potential is in the Amazon and Tocantins-Araguaia basins where respectively 62.11% and 91.94% of their potential have environmental constraints (EPE, 2007). Also, these basins are in the North subsystem, far from the main load centers, and new powerplants there would come with the need for new investments in the transmission system. The hydroelectric plant Belo Monte, for instance, is situated in the North of Brazil. It is ranked the third largest hydropower plant in the world in terms of installed capacity (11.2 GW) and expanded the capacity of electricity exchange between regions. However, due to large distances covered by transmission lines, high energy losses are incurred in the process of transmitting electricity to other regions (De Jong et al., 2015). Moreover, the cost of building the line that brings electricity from Belo Monte to the Southeast of Brazil, which is the subsystem with highest consumption, is estimated to be R$ 8.5 billion (Banco Nacional de Desenvolvimento Econômico e Social, 2018). This is a significant additional cost, particularly when compared to the estimated plant construction cost of R$ 32.1 billion1 (Tribunal de Contas da União, 2016).

Still, most of the hydropower plants operate with reservoirs that can be used to control the electricity generation by saving energy during periods where rainfalls are abundant to use it during periods of adverse hydrological conditions. However, given the growth of the power system, it has become more difficult to build new hydropower plants with large regulation reservoirs. This means that new hydropower plants will likely generate power according to natural river flows, making generation capacity even more dependent on hydrological conditions and thus increasing supply risks (EPE, 2007).

The presented context highlights the need to diversify the sources of electricity in the Brazilian power system. As a result, to address the drawbacks from hydropower, the government has incentivized alternative energy sources, such as biomass, solar, and wind. From 2015 to 2020, solar power installed capacity went from only 27.2 MW to 3,290.9 MW (+11,998.9%). In the same period, biomass and wind installed capacities grew respectively 10.7%, and 123.1%, while hydropower grew 15.25%; however, if the power plant Belo Monte, which is a very peculiar and large project, is excluded, the growth of hydropower would be only 3.35% (Aneel, 2021). It shows that the Brazilian trend is indeed pointing to a decrease in hydroelectricity share.

Wind is the second most important generation source in the Brazilian system. In 2020 wind accounted for 9.7% of the electricity generation. It has also experienced a high increase in its installed capacity, going from 7,674 MW in 2015 to 17,120 MW in 2020 (Aneel, 2021). Due to better wind conditions, it prevails in the Northeast and South subsystems. However, conditions in the North region are also favorable for wind electricity generation and the region has experienced a growth of 277% between December of 2015 and December of 2020 (ONS, 2021).

Investments in wind bring the following benefits for the system: it helps Brazil to maintain its high share of renewables; it is a clean source; it presents low variable cost; and complement hydroelectricity in periods with unfavorable hydrologic conditions. Nevertheless, some aspects require attention: it introduces seasonality and intermittence in the supply; and it is difficult to forecast how much electricity will be generated through wind in the future, including in the short term, which makes the dispatch plan more difficult. Figure 5 shows the wind electricity generation in the country, evidencing the seasonality.

[1] Base year: 2018.

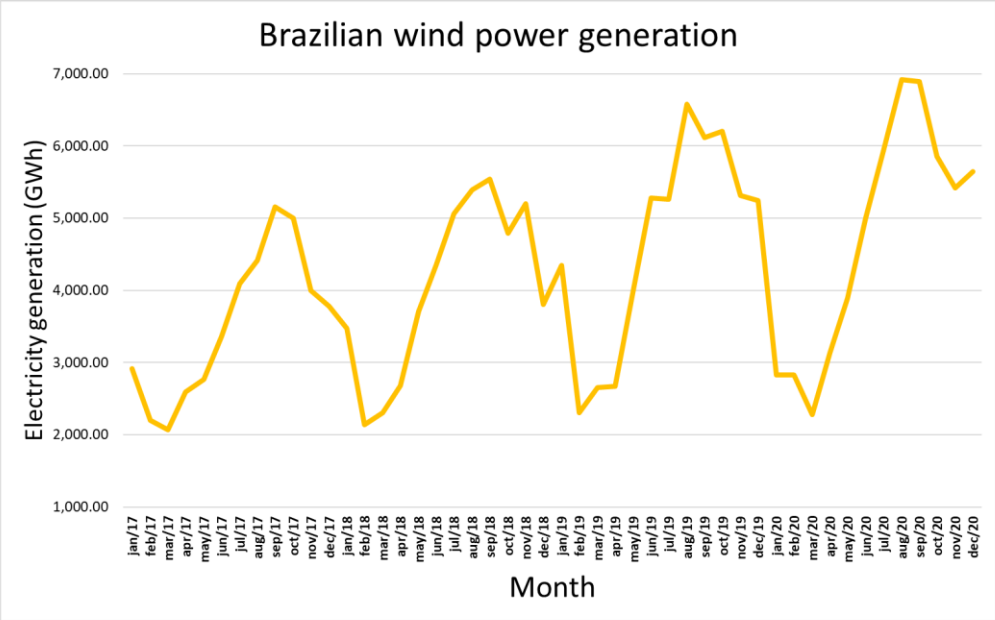

Figure 5 - Wind power generation.
Source: ONS (2021).

Biomass corresponded to 8.74% of the installed capacity in 2020. Different biofuels are used for electricity generation. Among them, sugarcane bagasse and black liquor are predominant. Table 2 shows the installed capacities by type of biofuel in 2020.

Table 2 - Bioelectricity sources.

Source	**Capacity (MW)**	**%**
Sugarcane bagasse	11,020	76.1%
Black Liquor	2,422	16.7%
Forest residues	590	4.1%
Biogas from urban residues	171	1.2%
Firewood	105	0.7%
Other	53	0.4%
Rice rusk	52	0.4%
Charcoal	36	0.2%
Elephant grass	32	0.2%

Source: Aneel, 2021.

Most of bioelectricity generation in the country occurs in the Southeast, mainly in the State of Sao Paulo. This is a result of the strong sugarcane industry in the region. Sugarcane is used to produce sugar and ethanol, and approximately 27% of its mass turns into bagasse (Neto and Ramon, 2002) that is burnt in boilers to produce heat and electricity. Table 3 shows the regional production of sugarcane in 2019 (IBGE, 2019).

Table 3 - Sugarcane production in 2019.

State	**Region**	**Tons of sugarcane**	**%**
São Paulo	Southeast	425,617,093	56.5%
Goiás	Midwest	75,315,239	10.0%
Minas Gerais	Southeast	72,968,836	9.7%
Mato Grosso do Sul	Midwest	52,245,291	6.9%
Paraná	South	41,658,888	5.5%
Mato Grosso	Midwest	23,319,052	3.1%
Alagoas	Northeast	18,702,251	2.5%
Pernambuco	Northeast	12,138,197	1.6%
Other	-	30,930,542	4.1%
Total	-	752,895,389	100.0%

Source: IBGE, 2019.

Although Sao Paulo is currently the state with the highest production, rising land prices and more strict environmental legislation have made it difficult to find new areas for cultivation. Therefore, the sector has expanded to frontier states, mainly in Mato Grosso do Sul, Goias, and Mato Grosso (Tomei et al., 2020).

Sugarcane refineries present advantageous characteristics for the power sector. Khatiwada et al. (2012) point that sugarcane refineries are located close to consumption centers, contributing then for lower transmission losses; harvesting occur during dry seasons, which help the system to complement hydroelectricity; low fuel (bagasse) cost; and they can operate in the base load during dry seasons. Also, it is a reliable non-intermittent energy source. Nevertheless, other sources are needed to complement sugarcane bioelectricity in the off-harvesting periods. This is evident from Figure 6, which shows the monthly bioelectricity generation in the country (including from other bioenergy sources than sugarcane bagasse).

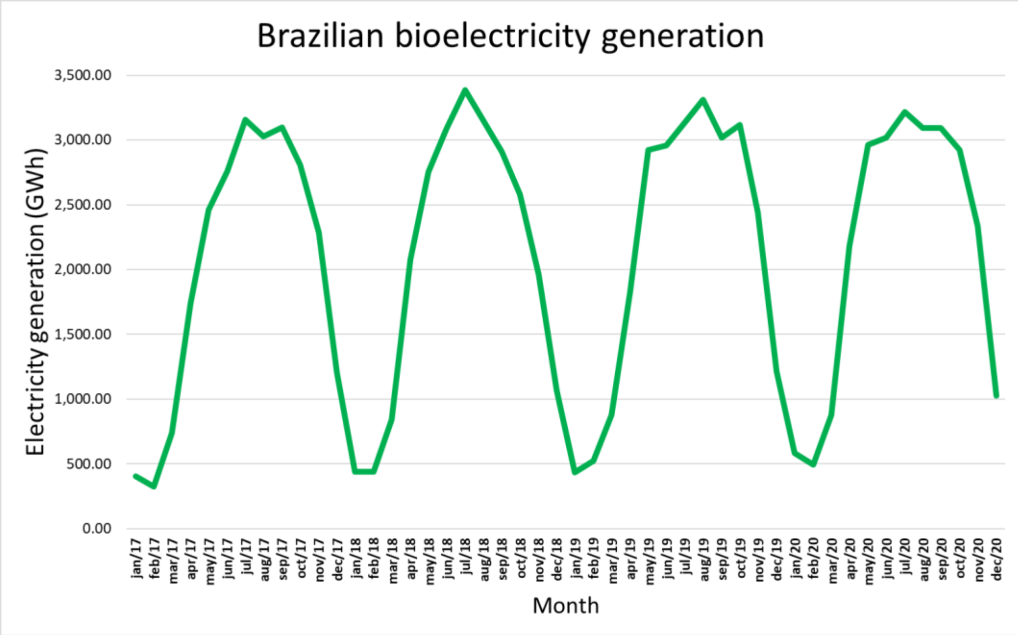

Figure 6 - Bioelectricity generation.
Source: ONS (2021).

The second most important source of bioelectricity in the country is a by-product from the pulp and paper industry, namely black liquor. In contrast to sugarcane, black liquor is not concentrated in one location. Instead, it is spread in the country according to the presence of pulp and paper industries. Table 4 shows the installed capacities of black liquor by region in 2020.

Table 4 - Black liquor in 2020.

Region	**MW**	**%**
South	771	31.8%
Midwest	659	27.2%
Northeast	586	24.2%
Southeast	352	14.5%
North	55	2.3%

Source: Aneel, 2021.

Aside from hydro, wind, and biomass, Brazil has a huge potential for solar power generation, and it is becoming more and more important for the system. According to Pereira et al. (2006), the values of incidence of solar radiation in any location of Brazil are higher than in most countries of Europe. Moreover, most of the Brazilian territory is in the intertropical region, which makes it favorable for solar generation during the whole year. Additionally, investment costs in this source have experienced a sharp decrease. This is evidenced from the observed average prices of electricity negotiated in auctions organized by the *Câmara de Comercialização de Energia Elétrica* (CCEE), with the aim of obtaining electricity to supply the Brazilian regulated electricity market. As a result, solar power is currently the source with highest growth rate among all other electricity sources. Figure 7 shows average prices closed in auctions from 2015 to 2019[2].

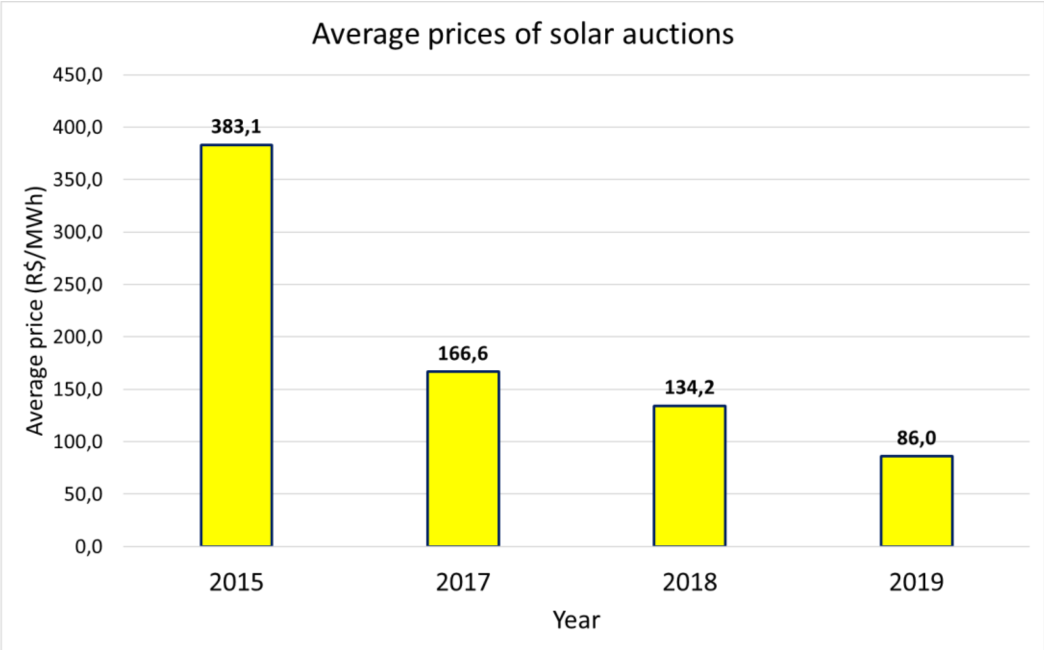

Figure 7 - Average prices of solar power negotiated in auctions from 2015 to 2019.
Source: based on CCEE, 2021.

Like wind power, solar energy presents advantages such as clean electricity production; low variable costs; it is a renewable source; and it complements hydroelectricity. However, it is an intermittent source and currently there is no low-cost batteries, therefore, solar supply in scale only occurs when there is sunlight.

Although most of the electricity is generated through renewable sources, fossil fuels have relevant shares in the electricity mix. Their presence in the system increases the security of supply and avoids shortages during dry periods. The following advantages make fossil fuel-based powerplants still important for the country: (i) they are usually located close to the main load centers, which contributes for lower transmission losses and transmission costs; (ii) they can be dispatched according to the hydrological conditions, therefore contributing for the

[2] Base year: 2021.

management of hydro reservoirs levels (ONS (2021)); (iii) thermal power plants have rapid dispatch response when variations in demand occur; (iv) in contrast with small hydro, solar and wind, they do not depend on intermittent weather conditions to generate power. Moreover, although large hydropower plants operating with sizeable reservoirs have rapid dispatchability, long term uncertainties in water availability mean that, at present, thermal power reserves are necessary for the security and reliability of Brazil's electricity system.

In contrast, fossil fuels-based powerplants have disadvantages that require attention and actions from policy makers. They are given as follows: (i) high variable costs due to the need for fuels acquisition; (ii) higher levels of GHG emissions when compared to renewables; (iii) environmental impacts and risks from fuel extraction and transport processes; (iv) economical risks associated with variations in international market prices; (v) fossil fuels can be depleted. In addition, the use of fossil fuels could make it difficult for Brazil to meet its Nationally Determined Contribution to reduce GHG emissions to 37% lower than in 2005 by 2025 (MME, 2015). Therefore, efforts to shift towards a more and more renewable-based system is needed.

Due to lower fuel costs if compared to other options, natural gas is responsible for most of the fossil fuel electricity generation. In 2020 it was the third most used electricity source after hydropower and wind (ONS, 2021). Nuclear energy is generated through two powerplants, Angra I and Angra II, located in the state of Rio de Janeiro, where a third powerplant, Angra III, is expected to be operating by 2026. Other fuels obtained from petroleum correspond to only 1.5% of projects under development, and there are not new projects related to coal (Aneel, 2021). Figure 8 shows the shares of installed capacities.

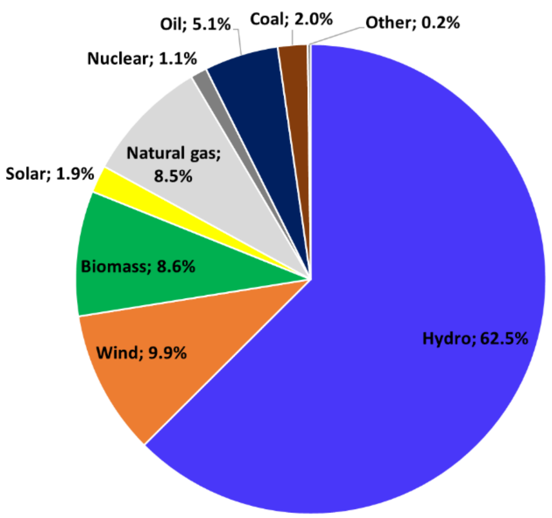

Figure 8 - Installed capacities shares.
Source: Aneel, 2021.

The shares of installed capacities presented in Figure 8 are not distributed equally across the country. Regional heterogeneity in installed capacity is evident from Figure 9. Thermopower sources are more predominant in the Southeast/Midwest, where the industrial sector is stronger, and in the Northeast, a region that suffers the most from droughts and therefore requires generation through fuel combustion. It is also noticeable the prevalence of wind power in the Northeast, which is the only subsystem in which hydropower does not represent most of the capacity.

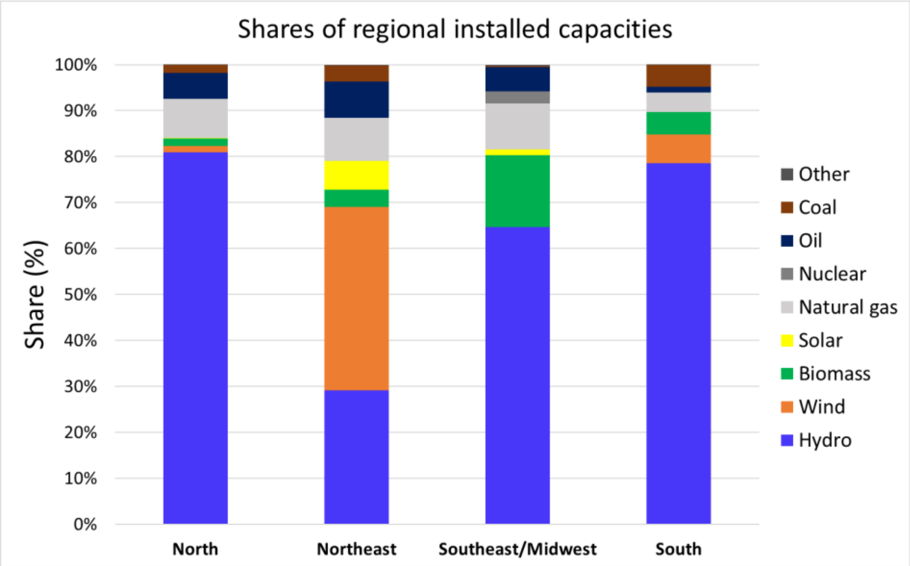

Figure 9 - Shares of regional installed capacities.
Source: Aneel, 2021

1.3 Objectives

The main objective of the present thesis is to apply optimization and statistical models to investigate which are the best alternatives for the Brazilian power sector expansion in terms of social, economic, and environmental impacts. Modelling frameworks based on portfolio theory are developed to define what are the generation technologies to be built in the next years, where and when to build them, and how much of each technology should be installed to supply the growing demand. Additionally, through the application of the clustering algorithm K-means and hypothesis testing, social aspects are investigated with regards to the expansion of sugarcane activity, particularly in municipalities of Mato Grosso do Sul, where sugarcane activity has grown. It is important to note here that sugarcane is strongly related with the power sector, being the main bioelectricity source of the country. Environmental impacts are analyzed with respect to the expected GHG emissions. Results from this work can contribute for designing new energy policies in Brazil. Moreover, improvements in current modelling approaches found in the literature expand the knowledge in the energy field and can be applied to other power systems than the Brazilian. Specific objectives are enumerated as follows:

- Obj1: Identify differences in solutions obtained through portfolio theory, applied to the Brazilian power sector expansion, when variance and conditional value at risk (CVaR) (Rockafellar and Uryasev, 2000) are adopted as risk measures.
- Obj2: Investigate impacts in the Brazilian electricity mix under scenarios where exploitation of natural gas pre-salt layers and bioenergy technological improvements reduce electricity generation costs.
- Obj3: Identify impacts of transmission constraints in the power expansion.
- Obj4: Develop a modelling framework integrating an agent-based model with a portfolio theory-based model to find shares of electricity generation technologies under different risk aversion policies.
- Obj5: Estimate impacts of land use constraints and the production of second-generation ethanol in the expansion of bioelectricity.
- Obj6: Assess the relationships between municipal human development and the presence of sugarcane activity in sugarcane expansion areas.
- Obj7: Develop a multi-period and multi-region electricity planning optimization modelling framework capable of dealing with electricity shortfall risks and cost minimization.
- Obj8: Assess if current government guidelines for the power system expansion is aligned with emission reduction targets (UN, 2015).

1.4 Structure of the thesis

This thesis is presented as a collection of four papers. Each paper address one or more of the objectives presented in Section 1.3. The introductory section gave the motivation and the context under the thesis development; Section 2 presents a literature review; Section 3 presents the methodology; Results and discussions are presented in Section 4; Final remarks are given in Section 5; References are given in Section 6; and appendices show the publications abstract as they were published or submitted. Table 5 summarizes the collection of papers.

Table 5 - Collection of papers.

Research article	Journal / Conference	Title	Objectives	Authors	Appendix
#1	Computer Aided Chemical Engineering	Insertion of Renewable Sources in the Brazilian Electricity Matrix: an Analysis through Portfolio Theory.	1-3	Oliveira[a]; Ribeiro[a]; Tomei[b]; Rego[a].	A
#2	Renewable and Sustainable Energy Reviews	Modelling the technical potential of bioelectricity production under land use constraints: A multi-region Brazil case study.	4-5	Oliveira[a]; Garcia[c]; Ribeiro[a]; Oller[d]; Rego[a]; Giarola[e]; Hawkes[c].	B
#3	Biomass and Bioenergy	Assessing the relationship between sugarcane expansion and human development at the municipal level: a case study of Mato Grosso do Sul, Brazil.	6	Tomei[b]; Oliveira[a]; Ribeiro[a]; Ho[a]; Montoya[f].	C
#4	International Journal of Electrical Power & Energy Systems	Analysis of electricity supply and demand intra-annual dynamics in Brazil: a multi-period and multi-regional generation expansion planning model.	7-8	Oliveira[a]; Ribeiro[a]; Qadrdan[g].	D

Filiation: [a]Department of Production Engineering, University of Sao Paulo; [b]Institute for Sustainable Resources, University College London; [c]Department of Chemical Engineering, Imperial College London; [d]Department of Chemical Engineering, University of Sao Paulo; [e]Department of Earth Science & Engineering, Imperial College London; [f]Independent Researcher; [g]School of Engineering, Cardiff University.

2 Literature review

2.1 Modern portfolio theory

In investment science, the portfolio problem deals with two conflicting investor objectives: to maximize expected return; and, to minimize the risks associated with the investment. Different investors usually have different tolerances toward risk and treat differently the trade-off between these objectives (Elton et al., 2009). The objective of the model originally proposed by Markowitz (1952) is to find a minimum risk portfolio of N financial assets, given limited capital. Risk is measured through variance of asset returns and the portfolio must achieve a minimum expected return. Let w_i represents the percentage of capital invested in asset i and $w = [w_1\ w_2\ ...\ w_N]' \in \mathbb{R}^N$. Given the expected return of asset i, $\bar{r}_i$, consider the vector $\bar{r} = [\bar{r}_1\ \bar{r}_2\ ...\ \bar{r}_N]' \in \mathbb{R}^N$. Letting Ω be the assets covariance matrix and

r_o denote the minimum expected return of the investor, the model is formulated as follows:

$$\min_{w} w'.\Omega.w \quad (1)$$

Subject to:

$$w'\,\bar{r} \geq r_o \quad (2)$$

$$w \geq 0 \quad (3)$$

$$\sum_{i=1}^{N} w_i = 1 \quad (4)$$

Although variance was originally adopted by Markowitz, other risk measures can also be applied (Artzner et al., 1999) and solutions can vary when different risk measures are adopted (Oliveira et al., 2018). The use of variance does not allow the assessment of extreme events i.e., those located in the tail of the probability density function, whose occurrences in the energy sector have high impacts over the whole economy. To assess these events, CVaR can be adopted as an alternative risk measure. CVaR is the expected loss above a given β-percentile of the probability distribution of the portfolio losses. Therefore, it is possible to minimize the loss when extreme events, located in the tail of the probability density function, occur. Solutions can vary when different risk measures are adopted. Figure 10 represents the CVaR. The following values from the probability distribution of a loss function are illustrated: mean value; maximum loss; value-at-risk for a confidence level of $1 - \alpha$; and the CVaR, which is the average of values greater than the value-at-risk.

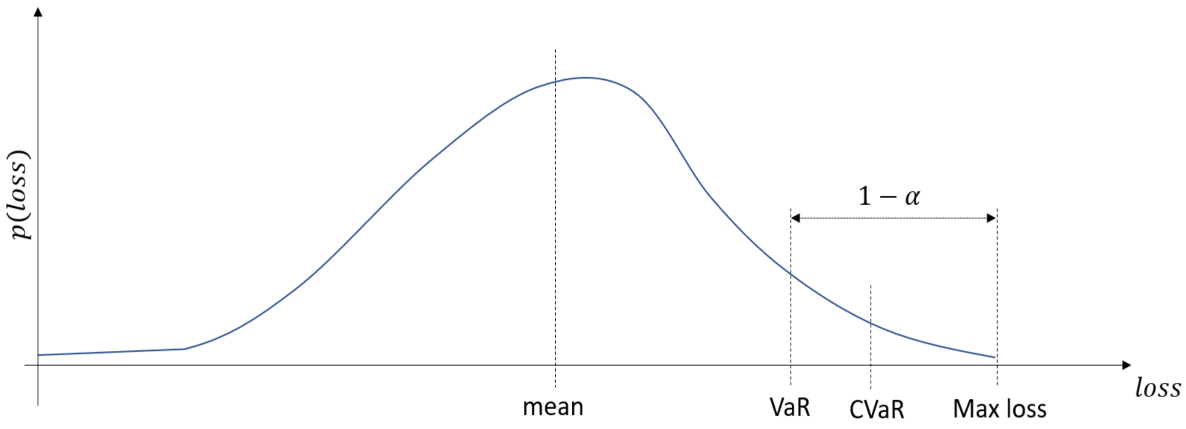

Figure 10 - Representation of the CVaR.
Source: Based on Sarykalin et al. (2008).

For a given confidence level β, let $\mathrm{f(w,y)}$ be the loss function depending on the decision vector $\mathrm{w} \in \mathrm{W} \subset \mathbb{R}^{\mathrm{N}}$, $\mathrm{p(y)}$ the probability density function of the random vector y, and $\zeta_\beta(\mathrm{w})$ the β-percentile of the portfolio, the CVaR function $\phi_\beta(\mathrm{w})$ is expressed as follows:

$$\phi_\beta(\mathrm{w}) = (1-\beta)^{-1} \int_{\mathrm{f(w,y)} \geq \zeta_\beta(\mathrm{w})} \mathrm{f(w,y)p(y)dy} \qquad (5)$$

The complexity of the optimization problem resulting from the use of CVaR as a risk measure can be reduced through the discretization of $\mathrm{p(y)}$ (Rockafellar and Uryasev, 2000). Based on Monte Carlo simulation, or historical simulation, a set of scenarios $\mathrm{Q} = \{1, 2, \ldots, |Q|\}$ is generated and the minimization of the objective function $\phi_\beta(\mathrm{w})$ can be approximated by the minimization of $\tilde{\mathrm{F}}_\beta(\mathrm{w}, \zeta)$. In the present thesis historical time-series were used to simulate scenarios, but other approaches could be applied. Equation 6 represents the approach.

$$\tilde{\mathrm{F}}_\beta(\mathrm{w}, \zeta) = \zeta + [(1-\beta)|Q|]^{-1} \sum_{\mathrm{q}=1}^{|Q|} \left[\mathrm{f}\left(\mathrm{w}, \mathrm{y_q}\right) - \zeta\right]^{+} \qquad (6)$$

Where $\mathrm{y_q}$ is the $\mathrm{q^{th}}$ simulated vector and $[\mathrm{t}]^{+} = \max\{0, \mathrm{t}\}$. The authors also show that through this minimization, the variable ζ assumes the estimated Value at Risk (VaR) of the resulting portfolio.

To solve the minimization problem through linear programming the authors considered auxiliary variables $\{\mathrm{z_q} \in \mathbb{R} : \mathrm{q} \in \mathrm{Q}\}$. Considering $|Q|$ scenarios and taking $\mathrm{z} =$

$[z_1\ z_2, \ldots, z_{|Q|}]'$, the final formulation is expressed below:

$$\min_{(z,\zeta)\in \mathbb{R}^{|Q|+1}} \left[\zeta + [(1-\beta)|Q|]^{-1} \sum_{q=1}^{|Q|} z_q\right] \quad (7)$$

Subject to constraints (2-4) and constraints (8-9).

$$f(w, y_q) - \zeta \leq z_q \text{ for all } q \in Q \quad (8)$$

$$z_q \geq 0 \quad \text{for all } q \in Q \quad (9)$$

Modern Portfolio Theory (MPT) is a widely used approach to identify optimal shares of power generation technologies in a power system. From an economic perspective, it is important to have an electricity portfolio with low expected cost and low risk. The application of MPT to decide upon the electricity portfolios allows the assessment of the trade-off between the expected cost of electricity and the associated risks (Awerbuch and Berger, 2003; Awerbuch and Yang, 2007; Kienzle and Andersson, 2008; Rombauts et al., 2011).

2.2 Modern portfolio theory applications

The planning of the electricity generation expansion must consider different types of uncertainties. For instance, time taken to build a power plant, future interest rates, environmental and social impacts, volatility of fuel prices, economic growth, technological improvements, amongst other factors, all affect the power sector. These factors are difficult to control and to forecast in the long term and, to manage uncertainties, a common approach in the electricity sector is the use of portfolio theory. This approach suggests that the agent responsible for energy planning must focus on the overall costs and risks brought by different strategies instead of focusing on individual generation sources (Kienzle and Andersson, 2008).

Bar-Lev and Katz (1976) were pioneers in the application of portfolio theory in the energy sector, and in 1976 they related this theory to the mix of fossil fuels. There were few follow-up studies until Shimon Awerbuch applied the approach (Jansen et al., 2006). Since Awerbuch and Berger (2003), MPT has been applied to reduce risks associated with costs and minimize the prices of electricity paid by final consumers.

Several other generation expansion planning models have been developed over the past years. Considering different characteristics of electricity generation sources, some issues that are commonly investigated include: energy dispatch, electricity shortfall risk, decarbonization, regional electricity supply/demand profiles, demand uncertainty, distributed generation, demand side programs, generation and transmission costs, economical risks, electricity markets and energy policies (Oree et al., 2017; Sadeghi et al., 2017; Odeh et al., 2018). Additionally, the modelling structure and assumptions vary between models.

In terms of temporal structure, both single-period and multi-period models can be applied to assist energy planners on the definition on how each generation technology should be expanded. For instance, Awerbuch and Yang (2007) applied a single period model to evaluate the energy matrix in Europe for the year 2020. The authors adopted the levelized generation cost of each technology and focused on the minimization of the cost per kilowatt-hour. On the other hand, as an example to contrast single period modelling approaches, Delarue et al. (2011) applied a multi-period portfolio theory-based model. Based on the 2008 Belgian load profile, the proposed model incorporated the time required to increase or reduce power plant generation. Results were discussed with regards to the importance of differentiating power and energy production, considering variable and fixed costs separately in multi-period settings.

Temporal structure of energy planning optimization models was explicitly studied by Merrick (2016). The author compared similar models that differ only with regards to temporal resolution and concluded that outputs diverge. In the present thesis, papers #1 and #2 adopt a single period optimization approach, while paper #4 enhances the analysis by explicitly incorporating daily and monthly variations on demand and supply in a multi-period setting.

Regional issues were discussed by Jansen et al. (2006). The authors applied the Markowitz model (Markowitz, 1952) to the Dutch generation mix under two scenarios for the year 2030: Strong Europe Scenario, where European integration proceeds with success in political, economic, and geographical spheres; and a Global Economy Scenario, where European integration is limited to the economic sphere. Results showed that the risk of a benchmark portfolio, based on the energy policy at the time of research, could be reduced by 20%. The authors highlighted that increase of generation from wind and biomass would be one of the main factors to contribute to this reduction.

Roques et al. (2010) incorporated both regional and temporal aspects of wind power outputs. They analysed the reduction of the hourly generation variability through installation of power plants in different countries and considered electricity exchanges between them. Using portfolio theory and considering regional generation profiles they identified areas that would minimize wind generation variability, assuming Austria, France, Germany, Spain and Denmark as possible producers. Due to better wind conditions, their results indicated a prevalence of generation in Spain and Denmark.

Rombauts et al. (2011), continuing the research of Roques et al. (2010), modelled transmission constraints and applied the model to three adjacent idealized countries considering different power plants installation regions in each country. In their model, they applied MPT to assess the expected hourly wind power generation and its standard deviation. Electricity exchange limits between two regions in the same country were assumed to be infinite. The model was applied under three scenarios: the first without transmission constraints, the second with no electricity exchange between countries, and the third allowing a finite capacity of electricity exchange. They concluded that different levels of transmission limits results in different hourly wind power variability.

The use of portfolio theory to analyse the Brazilian electricity generation mix was proposed by Losekann et al. (2013). Considering three different scenarios for CO2 prices, they compared their solutions with the mix estimated by EPE (2011). Although their results were close to the ones in EPE (2011), they concluded that it was possible to reduce risk. However, some important operational constraints, such as regional generation potential, regional renewable generations costs, transmission constraints and transmission and distribution losses were not incorporated into their model. Incorporation of these constraints is one of the contributions of the present thesis, particularly of papers #1, #2, and #4.

Based on the work of Losekann et al. (2013), Costa et al. (2017) applied portfolio selection theory to obtain efficient electricity mixes in Brazil using standard deviation as measure of risk. Taking both the expected cost and covariance matrix as uncertain parameters, this study proposed the use of robust optimization techniques to identify efficient energy matrices. The authors concluded that robust optimization could be used for energy planning to address uncertainty on parameters faced by traditional portfolio theory models.

Odeh et al. (2018) conducted a literature review and concluded that approaches that use portfolio theory lack spatial characteristics. Papers #1, #2, and #4 build on these studies by applying portfolio theory to the Brazilian electricity production mix and by considering regional, economic, and operational aspects. The models focus on regional production and transmission costs, considering transmission and distribution losses, different regional demands, and generation sources availability. Paper #1 and #2 deal with uncertainties on generation and transmission costs, while Paper #4 deals with the stochastic nature of renewable electricity generation.

Applications of MPT are also highlighted in the work of deLlano-Paz et al. (2017). The authors argue that efficient frontiers have been drawn for different purposes, including the consideration of economical and electricity production variables. Works focusing on economic variables usually consider expected financial returns and cost risks, while consideration of electricity production variables are usually incorporated to investigate strategies regarding expected electricity production and its variabilities (deLlano-Paz et al., 2017). In Paper #4 of the present thesis, it is proposed a modelling framework that relates expected costs and electricity deficit risks; therefore, it combines both economical and electricity production variables into a single model.

2.3 Integration of renewable sources

With growing efforts to reduce environmental impacts of human activities, renewables have been extensively studied. It is known that they present environmental advantages; however, some key challenges must be overcome to its further expansion. Through a literature review, Notton et al. (2018) pointed that the intermittent and stochastic nature of RES can result in high costs for an electricity system and concluded that uncertainty on generation requires the grid manager to take measures to control the balance between production and consumption, which implicates in extra costs for the system (integration costs). They argued that a good generation forecasting becomes more important when the share of renewables grows. Under this context, generation profiles of different renewable technologies, including regional conditions are important to be understood.

Monforti et al. (2014) developed a Monte Carlo approach to assess wind and solar complementarities in Italy. Results indicated strong negative correlation for local and national scales and evidenced that integration of these sources can enhance supply conditions and diminish electricity prices. Lopes and Borges (2014) assessed the impact that the exploitation of complementarities between wind and small hydropower plants have on the reliability of the Brazilian power system. The South region was taken as a case study. Monte Carlo simulation was applied to create representations of both generation and load profiles and reliability indexes were evaluated for two scenarios, one with and one without the presence of wind power generation. The authors concluded that it is important to consider spatial and temporal correlations between load and generation when integrating renewable energy sources to the system.

Schmidt et al. (2016a) applied an optimization model to define the optimal mix of solar, wind, and hydropower that minimizes the use of thermopower sources in Brazil. They considered a scenario where demand is twice the one occurred in 2013. Results showed that the use of solar, wind, and hydropower together can contribute to stabilize generation outputs and that an increase on current levels of thermopower installed capacity is not needed. Moreover, hydro expansion did not seem to contribute for diminishing requirements for thermal sources.

In a further study with focus in Brazil, Schmidt et al. (2016b) applied an optimization model with the objective of minimizing thermal generation and load shedding to study how the insertion of wind and solar power can enhance the stability of a hydro-based power system. Results showed that the addition of wind and solar power can improve the system stability, while the increase of hydropower would require more thermal backup capacity to protect the system against long drought periods. However, regional characteristics regarding electricity outputs from renewables were not considered.

The effect of wind power increase on the outputs' variabilities of a hydro-wind power mix in Brazil was also assessed by Schmidt et al. (2016c). The authors focused on wind speed and hydropower plants water inflows data from four states located in the Northeast and South of the country. Results showed that wind power deployment in the Northeast is preferable than in the South and that it can reduce seasonal variability of the hydro-wind joint production.

De Jong et al. (2016) estimated the maximum wind power share in the Northeast of Brazil. The authors concluded that higher capacity factors in the region and positive correlation with demand profile could allow wind penetration to achieve up to 65% of the region's generation, while hydroelectricity could represent the remaining 35%. However, Miranda et al. (2017) discussed the assumptions adopted by De Jong et al. (2016) and pointed that transmission limits and inflexibilities of power plants are the main reasons that could prevent 65% wind penetration in the region.

Advantages of offshore wind power in Brazil were evidenced by Silva et al. (2016), where the wind-hydro complementarity were investigated. Based on the analysis of historical precipitation, wind power density and turbine power, the authors argued that wind profiles in the North and Northeast regions present strong complementarity with the hydrological regimes of important basins in the country, while this effect is not evident in the Southern region. Nevertheless, offshore wind power is currently not cost-effective, and its deployment would need incentive policies from the government.

Dranka and Ferreira (2018) assessed future scenarios for the Brazilian power sector in 2050, including the possibility of achieving a mix with 100% of renewables. Results showed that complementarity between hydro and wind power is a key factor that contributes for obtaining high renewable shares. Overall installed capacities and costs would increase in the case where electricity is supplied only by renewables.

Hunt et al. (2018) assessed the hydrological conditions from 1931 to 2017 in Brazil and found that energy crisis tend to happen in drought periods. Additionally, the paper suggested that the Brazilian hydroelectricity generation follows a cyclic pattern with periodicity between 10 and 15 years. They pointed that electricity mix diversification through renewables and the use of pumped-storage technologies are alternatives that can improve supply reliability.

The Colombian hydro-based system is taken as a case study in the work of Zapata et al. (2018). By adopting a system dynamic modelling approach, they studied economic problems of having excess installed capacity, which implicates on idle power plants' fixed costs. On the other hand, they pointed that under capacity could result in electricity shortfalls and elevated electricity prices. The authors stated that, although counterintuitive, the increase on renewable sources in the country could contribute to increase supply security and to reduce the importance of thermal power sources and costs of the system.

Li et al. (2019) argued that hydro-photovoltaic complementarity is important for the system operation; however, strong variations on water flows and solar generation makes the complementarity advantages uncertain. The authors considered uncertainties in the streamflow and solar generation and proposed the use of a multi objective stochastic optimization model to maximize the total generation and supply guarantee rate in the Longyangxia power plant operation. They concluded that consideration of uncertainties can improve the system operation.

Han et al. (2019) evaluated wind, solar and hydro complementarities. The authors proposed new indices to measure variabilities of combined power generation and characterized generation profiles. An area located in the North of China was adopted as a case study, where hourly data from 2014 was used to validate the applied methodology. Results showed that shares of each source can be adjusted to improve system stability.

Bianco et al. (2019) assessed both positive and negative consequences of renewables expansion and highlighted that it contributes to achieve environmental sustainability and reduce dependence on fossil fuels; however, variability on energy supply still represented an important issue that challenges the system operation. An analysis of how the integration of batteries impacts renewables share is presented by Duan et al. (2020). The authors studied the Alberta system in the United States and pointed that the use of batteries was only economically attractive under a carbon tax higher than \$200/tCO_2, but future costs reductions could foster their adoption.

From the literature, it is evident that great research efforts have been made to support the shift towards a clean global electricity production. Yet, results vary from research to research, indicating that this is a topic that requires further investigation. The present thesis contributes with the literature by presenting new modelling approaches focusing on electricity costs, economical risks, social impacts of bioenergy expansion, GHG emissions, and electricity shortfall risks.

2.4 Sugarcane expansion and human development

Under the necessity of mitigating GHG emissions in the energy sector, bioenergy from sugarcane emerges as a clean alternative to fossil fuels. With a production of around 736 Mt/year Brazil is the largest producer of sugarcane in the world (Silalertruksa and Gheewala, 2018). It is responsible for 45% of sugar global exports and is the world leader in ethanol production from sugarcane (International Sugar Organization, 2020). Additionally, the country has a relevant role in biofuels adoption, pioneering the flex fuel technology, which enables vehicles to run on ethanol or gasoline (or a mix between them).

To incentivize the use of biofuels, the Brazilian government has created bioenergy-oriented policies. For instance, from 2015 on it was established that gasoline must contain 25% of ethanol (Ministério da Agricultura, Pecuária e Abastecimento, 2015). Additionally, in 2017 it was created the RenovaBio program, which grants carbon credits to biofuels distributors with the objective of expanding the use of renewable energy, and to achieve emissions reduction targets established in the Paris Agreement (Presidência da República, 2017). Therefore, sugarcane production in the country is expected to grow further.

The Southeast of the country, mainly the state of Sao Paulo, is the main producing region. In 2019, around 67% of the national production was in the Southeast (57% only in Sao Paulo) (IBGE, 2019). Nevertheless, growing demand, more strict legislations, and more expensive land in the Southeast have led sugarcane farmers to seek for other investment areas (Tomei et al., 2020). This shift is illustrated in Figure 11. Taking the period from 2010 to 2019, it is seen that the highest Southeast production share occurred in 2010, with around 70% of the production, while in the Midwest, the highest share occurred in 2019, with around 20% of the national production. The growing production trend in the Midwest is also evident from the figure.

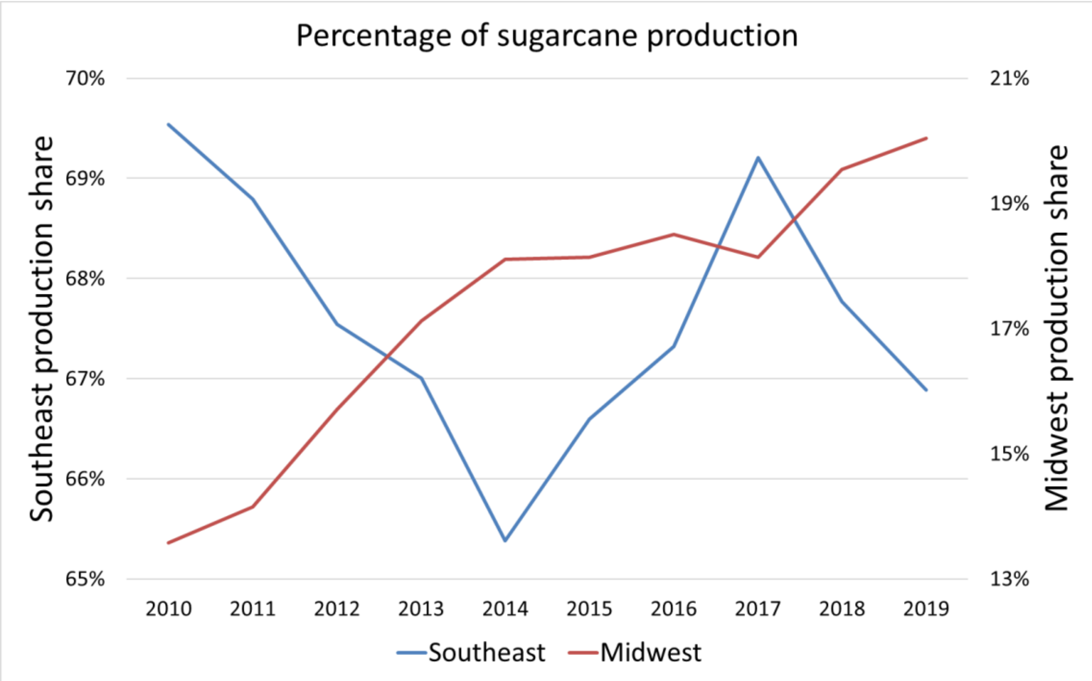

Figure 11 - Percentage of sugarcane production in the Southeast and Midwest.
Source: (IBGE, 2019).

With respect to the power sector, the use of sugarcane bagasse to produce bioelectricity has been shown to be economically attractive (Oliveira et al., 2018 and Oliveira et al., 2020). However, impacts on the social sphere need to be investigated when the question is if sugarcane expansion is indeed a sustainable alternative for Brazil. As the sector has been well established in the state of Sao Paulo, social aspects there have already been investigated and benefits and drawbacks from sugarcane cane activity have been documented in the literature; however, impacts of its expansion to frontier regions still need to be understood (Tomei et al., 2020).

With focus in the sugarcane evolution in the state of Sao Paulo, Chagas et al. (2011) developed a dynamic panel model to assess the effect on tax revenues. The authors argued that the presence of the sector induces higher public expenditures due to pressures from migratory workers and health hazards caused by burn-offs and other practices. Nevertheless, the value per hectare of sugarcane is higher than of most other crops and, therefore, it can provide higher incomes that are partially captured by municipal tax revenues. This enables greater amounts of public expenditures to improve health conditions. Additionally, the number of jobs were evaluated, and it was evidenced that the activity generates more jobs per hectare. However, it is important to highlight that in 2002 the government of Sao Paulo determined that burn-offs of straw to enable manual harvesting had to be gradually reduced, achieving total elimination by 2021 (Assembleia Legislativa do Estado de São Paulo, 2002). The law induced higher levels of harvest mechanization, contributing for both reduction of health hazards and number of jobs. This may invalidate the analysis of the authors for the current and future states of the sector.

Machado et al. (2015) studied the impacts of the presence of sugarcane in municipalities of three important production states in Brazil. The authors considered illiteracy rate, human development index, Theil index, percentage of poor people, connection to the grid, connection to the sewer system, child mortality and life expectancy as social indicators and showed that, overall, municipalities with sugarcane activity tend to have better performance. However, beneficial effects were found to be different between the studied states.

Discussions presented in the work of Machado et al. (2015) suggested that relations between human development and sugarcane activity evidenced in traditional producing municipalities may not be realized in the same way in expansion areas. Such effects are studied by Assunção et al. (2016). The authors applied both fixed-effect panel data and synthetic control method (Abadie et al. (2010); Abadie and Gardeazabal (2003)) to relate the sector with economic and social indicators. They evidenced that the presence of the sector contributes for the growth in population, GDP per capita, and GDP; increases the number of firms and jobs; improves financial services; reduces deforestation; and increases productivity of other neighboring agricultural activities. However, as part of the employment corresponds to migrated works, benefits for local population remained unclear.

Although, Chagas et al. (2011), Machado et al. (2015), and Assunção et al. (2016) evidenced benefits from the sugarcane sector, there are also works that point to negative impacts. Novo at al. (2010) examined the land competition between dairy and beef, and sugarcane producers. It was discussed that sugarcane investors are willing to pay more for land, which causes land prices to increase. Also, investors of other agriculture crops search for cheaper land regions, causing land use change. Moreover, policies to incentivize biofuels prevails when compared to other activities, giving competitive advantages for sugarcane in comparison to other important agricultures.

In a more recent work, Postal et al. (2020) confirmed concerns of local stakeholders with regards to rising land prices caused by the sugarcane expansion. Through a survey conducted in municipalities of 5 states in the Centre-South of Brazil, they could identify 5 out of 17 variables considered in the study in which a considerable part of the stakeholders are concerned with: (i) inflation; (ii) decrease in biodiversity; (iii) poor air quality caused by excessive number of trucks, burn-offs, and bad smell of vinasse (a by-product from the sugarcane processing); (iv) deforestation; and (v) land concentration.

Overall, the literature indicates that the relation between human development and the presence of sugarcane is an ongoing discussion. Under this context, paper #3 of the present thesis proposes a new methodology based on the assessment of human development dimensions (health, education, and income) and the presence of sugarcane refineries in Mato Grosso do Sul. The methodology, results and discussions are given in the next sections.

3 Methodology

The present section describes the adopted methodological approaches for each of the four papers that compose this thesis. Although methodologies vary from one to another, all of them are based on quantitative analysis. In paper #1 portfolio theory was applied to deal with uncertainties in electricity generation and transmission costs. Paper #2 proposed the application of an agent-based model integrated with a portfolio theory model to investigate the bioelectricity expansion potential in Brazil. In paper #3 hypothesis testing was applied to assess if municipalities of Mato Grosso do Sul with sugarcane mills presented higher improvements in indicators related to education, health, and wealth dimensions than those where mills were not established. Additionally, the clustering algorithm K-means was applied to group municipalities with regards to their human development performance, and the groups were compared with respect to the presence/absence of sugarcane refineries. Finally, in paper #4 a careful data analysis of electricity supply and demand profiles were presented, and an integrated multi-period/multi-region modelling framework that deals with deficit risks and cost minimization was proposed. Detailed descriptions of each methodology are given throughout this section.

3.1 Methodology: paper #1

To address objectives 1, 2, and 3 (see Section 1.3), a portfolio theory model that finds efficient electricity generation portfolios with respect to expected total cost (sum of generation and transmission costs) and cost risk was proposed. The impact of the adopted risk measure on obtained solutions was evaluated by the application of two versions of the model: the first version considered CVaR as the risk measure, while the second minimized variance.

To assess how reductions on costs of electricity generated through natural gas and biomass can affect the electricity mix, four scenarios were studied: (i) the first is the business-as-usual (BAU) scenario, where generation costs given by industry experts were considered; the second assumed that electricity generated through natural gas was 20% cheaper than the BAU; the third assumed that bioelectricity was 20% cheaper than in the BAU; and the fourth assumed that both bioelectricity and natural gas were 20% cheaper. Additionally, the effect of transmission constraints was studied by comparing solutions where electricity exchanges respect the transmission infrastructure, with solutions obtained when no transmission constraints are considered.

The linprog and quadprog tools from the MATLAB software was used to solve the optimization problem.

3.1.1 Model description: paper #1

Sets:

R: set of Brazilian regions {North; Northeast; Southeast/Midwest; South}.

S: set of energy sources {old hydro; new hydro; wind; biomass; natural gas; oil; coal; old nuclear; new nuclear}.

$\boldsymbol{S_{th}}$: subset of thermopower sources {biomass; natural gas; oil; coal}.

Q: set of simulated scenarios for generation and transmission costs. This set is only used for the model version that minimizes the conditional value at risk.

X: set of feasible solutions for the optimization problem.

Parameters:

$\boldsymbol{\mu_{inv}^{s}}$: expected value of the investment cost of source $\boldsymbol{s}$ (R$/MWh).

$\boldsymbol{\sigma_{inv}^{ss'}}$: covariance between investment costs of sources $\boldsymbol{s}$ and $\boldsymbol{s'}$ (R$/MWh)^2.

$\boldsymbol{\tau_{inv}^{sq}}$: simulated investment cost of source $\boldsymbol{s}$ under scenario $\boldsymbol{q}$ (R$/MWh).

$\boldsymbol{\mu_{OM}^{s}}$: expected value of the operation and maintenance cost of source $\boldsymbol{s}$ (R$/MWh).

$\boldsymbol{\sigma_{OM}^{ss'}}$: covariance between operation and maintenance costs of sources $\boldsymbol{s}$ and $\boldsymbol{s'}$ (R$/MWh)^2.

$\boldsymbol{\tau_{OM}^{sq}}$: simulated operation and maintenance cost of source $\boldsymbol{s}$ under scenario $\boldsymbol{q}$ (R$/MWh).

$\boldsymbol{\mu_{fuel}^{s}}$: expected value of the fuel cost of source $\boldsymbol{s}$ (R$/MWh).

$\boldsymbol{\sigma_{fuel}^{ss'}}$: covariance between fuel costs of sources $\boldsymbol{s}$ and $\boldsymbol{s'}$ (R$/MWh)^2.

$\boldsymbol{\tau_{fuel}^{sq}}$: simulated fuel cost of source $\boldsymbol{s}$ under scenario $\boldsymbol{q}$ (R$/MWh).

$\boldsymbol{\mu}_{ltc}^{r}$: expected value of local transmission cost of region $\boldsymbol{r}$ (R$/MWh).

$\boldsymbol{\sigma}_{ltc}^{rr'}$: covariance between local transmission costs of regions $\boldsymbol{r}$ and $\boldsymbol{r'}$ (R$/MWh)².

$\boldsymbol{\tau}_{ltc}^{rq}$: simulated local transmission cost of region $\boldsymbol{r}$ under scenario $\boldsymbol{q}$ (R$/MWh).

$\boldsymbol{\beta}$: adopted confidence level for CVaR.

$\boldsymbol{ctc}$: transmission cost term applied to all generators (common transmission cost), regardless their locations (R$/MWh).

$\boldsymbol{\alpha}^{s}$: renewable transmission cost reduction factor for source $\boldsymbol{s}$.

$\boldsymbol{U}_{r}^{s}$: maximum electricity generation by source $\boldsymbol{s}$ in region $\boldsymbol{r}$ (MWh).

$\boldsymbol{L}_{r}^{s}$: minimum electricity generation by source $\boldsymbol{s}$ in region $\boldsymbol{r}$ (MWh).

$\boldsymbol{Th}_{r}$: minimum amount of thermoelectricity, which is the sum of bioelectricity, natural gas, coal, and oil, produced in region $\boldsymbol{r}$ (MWh).

$\boldsymbol{\nu}_{r}$: percentage of electricity loss during the electricity distribution within region $\boldsymbol{r}$.

$\boldsymbol{\varphi}_{rr'}$: percentage of electricity loss during transmission from region $\boldsymbol{r}$ to region $\boldsymbol{r'}$.

$\boldsymbol{T}_{rr'}$: maximum electricity exchange between regions $\boldsymbol{r}$ and $\boldsymbol{r'}$ (MWh).

$\boldsymbol{D}_{r}$: electricity demand in region $\boldsymbol{r}$ by 2026 (EPE, 2017).

$\overline{\boldsymbol{\mu}}_{total\,cost}$: maximum tolerated expected total cost.

<u>Decision variables:</u>

$\boldsymbol{x}_{rr'}^{s}$: amount of electricity produced through source $\boldsymbol{s}$, in region $\boldsymbol{r}$, to be sent to region $\boldsymbol{r'}$ (MWh).

$\boldsymbol{\psi}_{s}$: total amount of electricity produced through source $\boldsymbol{s}$ (MWh).

$\boldsymbol{\theta}_{r}$: amount of electricity produced in region $\boldsymbol{r}$ that incurs on the tariff for the use of the transmission system (MWh).

$\boldsymbol{z}_{q}$: auxiliary variable associated with scenario $\boldsymbol{q}$.

$\boldsymbol{\zeta}$: variable that assumes the value-at-risk when CVaR is minimized.

<u>Objective function:</u>

The objective function for the version of the model that minimizes variance is given by expression 10, while the objective function for the version that minimizes the conditional value at risk is given by expression 11.

$$\min_{\psi,\theta}\left(\sum_{s=1}^{|S|}\sum_{s'=1}^{|S|}\left(\psi_s\psi_{s'}\left(\sigma_{inv}^{ss'}+\sigma_{OM}^{ss'}+\sigma_{fuel}^{ss'}\right)\right)+\sum_{r=1}^{|R|}\sum_{r'=1}^{|R|}\theta_r\theta_{r'}\sigma_{ltc}^{rr'}\right) \qquad (10)$$

$$\min_{\zeta,z}\left(\zeta+\frac{1}{|Q|(1-\beta)}\sum_{q=1}^{|Q|}z_q\right) \qquad (11)$$

<u>Constraints:</u>

The first and second constraints are only applied for the case where CVaR is minimized. This approach follows the optimization methodology proposed by Rockafellar and Uryasev (2000).

$$\sum_{r=1}^{|R|}\sum_{r'=1}^{|R|}\sum_{s=1}^{|S|}x_{rr'}^{s}\left(\tau_{inv}^{sq}+\tau_{OM}^{sq}+\tau_{fuel}^{sq}\right)+\sum_{r=1}^{|R|}\theta_r\left(ctc+\tau_{ltc}^{rq}\right)-\zeta-z_q\le 0 \qquad (12)$$

$$z_q \ge 0 \qquad (13)$$

The following constraint guarantees that the transmission tariff reduction factor is applied for the electricity produced in each region.

$$\theta_r=\sum_{r'=1}^{|R|}\sum_{s=1}^{|S|}\alpha^s x_{rr'}^{s} \qquad (14)$$

The following constraint is used for calculating the total amount of electricity produced by each source.

$$\psi^s=\sum_{r=1}^{|R|}\sum_{r'=1}^{|R|}x_{rr'}^{s} \qquad (15)$$

Upper and lower amounts of electricity production are established according to the Brazilian regional infrastructure and availabilities of natural resources.

$$\sum_{r'=1}^{|R|} x_{rr'}^{s} \leq U_{r}^{s} \qquad (16)$$

$$\sum_{r'=1}^{|R|} x_{rr'}^{s} \geq L_{r}^{s} \qquad (17)$$

A minimum production of thermoelectricity is established in each region to ensure system reliability.

$$\sum_{s \in S_{th}} \sum_{r'=1}^{|R|} x_{rr'}^{s} \geq Th_{r} \qquad (18)$$

Transmission infrastructure must be respected (only under the scenario in which exchange limits are considered).

$$\sum_{s=1}^{|S|} x_{rr'}^{s} \leq T_{rr'} \qquad (19)$$

After transmission and distribution losses are discounted, demand must be attended.

$$\nu_{i} \left(\sum_{r=1}^{|R|} \sum_{s=1}^{|S|} \varphi_{rr'} x_{rr'}^{s} \right) \geq D_{r'} \qquad (20)$$

The expected cost is limited from above.

$$\sum_{r=1}^{|R|} \sum_{r'=1}^{|R|} \sum_{s=1}^{|S|} x_{rr'}^{s} \left(\mu_{inv}^{s} + \mu_{OM}^{s} + \mu_{fuel}^{s} \right) + \sum_{r=1}^{|R|} \theta_{r} (ctc + \mu_{ltc}^{r}) \leq \bar{\mu}_{total\,cost} \qquad (21)$$

3.1.2 Datasets: paper #1

To represent the Brazilian electricity sector, input data was gathered from documents of national electricity sector agencies, interviews with professionals from the sector, and from the grey and academic literature. These are described below.

Upper and lower generation bounds were estimated according to data from Eletrobras (2017), Aneel (2017), Cresesb (2001), EPE (2007), and operational data from ONS (2017), and exchange limits were obtained from EPE (2017).

Expected values and standard deviations for operation and maintenance, fuel and investment costs were based on interviews with experts from the sector, and on Awerbuch and Yang (2007). Fuel costs covariance matrix was also based on Awerbuch and Yang (2007). Values of the TUST for each region were estimated according to Aneel (2015).

Energy losses during the energy flow in transmission lines between subsystems were assumed to be equal to 5%, and estimated values of distribution losses within the subsystems were based on Aneel (2016).

To guarantee feasibility of the solutions during the peak hours, the estimated average demand was multiplied by a peak load factor. Average demand was estimated according to the electricity load forecasted from EPE (2017), and the load factor according to operational data from ONS (2017).

3.2 Methodology: paper #2

In paper #2 a new modelling framework based on a soft link between a multi-sectoral Brazilian integrated assessment model and an electricity portfolio optimization model was proposed for the estimation of electricity demand, biofuels availabilities, GHG emissions, and optimal electricity portfolios with respect to expected costs and its associated risk. Additionally, impacts of both land use constraints and the production of second-generation ethanol in the expansion of bioelectricity were evaluated. The models were applied for a horizon from 2020 to 2050 with time steps of 5 years, and similarly to Oliveira et al. (2018) four regions were considered.

The first model, namely Modular Energy Systems Simulation Environment (MUSE), is an agent-based model developed by researchers at Imperial College London (MUSE, 2021). The model was used to simulate the aggregate capacity, CAPEX and OPEX by technology per agricultural commodity; activity and emissions by technology; energy crops and residues supply (biofuels); land use allocation and corresponding emissions; future demand of agricultural, forestry, and bioenergy commodities; electricity demand by sector, region, and time step; and maximum potential of bioelectricity production. The simulation was based on policy frameworks; cost by technology; efficiencies by technology; emissions by technology; existing stock by technology and retirement (decommissioning) profiles; forward macro-drivers; land use demand; and land use constraints.

The second model is an enhanced version of the model presented in Oliveira et al. (2018). Model improvements are listed as follows:

- solar power was included.
- the constraint that a minimum amount of thermoelectricity must be produced was substituted by a constraint in which a minimum ratio between thermopower sources and renewables must be respected. This is an improvement since it ensures that the more renewable installed capacity, which increases generation uncertainty, the more thermopower sources are needed for system reliability.
- As the model was applied for multiple points in time, it was considered that the amount of electricity generated by source and region in each time step must be at least equal to the generation occurred in previous time steps. It ensured that existent powerplants were not idle.
- It included a learning rate for the cost of solar power by assuming that for every doubling in solar generation its cost was reduced by 20%.

The linprog tool from the MATLAB software was used to solve the optimization problem.

Regarding risk aversion, the optimization model was applied under a risk-taking perspective, in which expected cost was minimized, and a risk-averse perspective, in which the cost CVaR was minimized. Two scenarios were considered for the assessment of the impact of second-generation ethanol in the bioelectricity potential: a scenario in which its production is economically attractive, and a scenario in which it is not produced.

The models were linked in a way that electricity demand and biomass availability estimated through MUSE were sent to the portfolio optimization model; then, based on generation costs of each energy source, their availabilities, and regional electricity demand the optimization model provided electricity portfolios that yield minimum expected cost and minimum risk. Solutions obtained by the optimization model were sent back to MUSE and GHG emissions for the power sector were estimated. This approach allowed the evaluation of how the Brazilian power sector should be expanded until 2050, and what are its estimated emissions. Figure 12 illustrates the link between the two models.

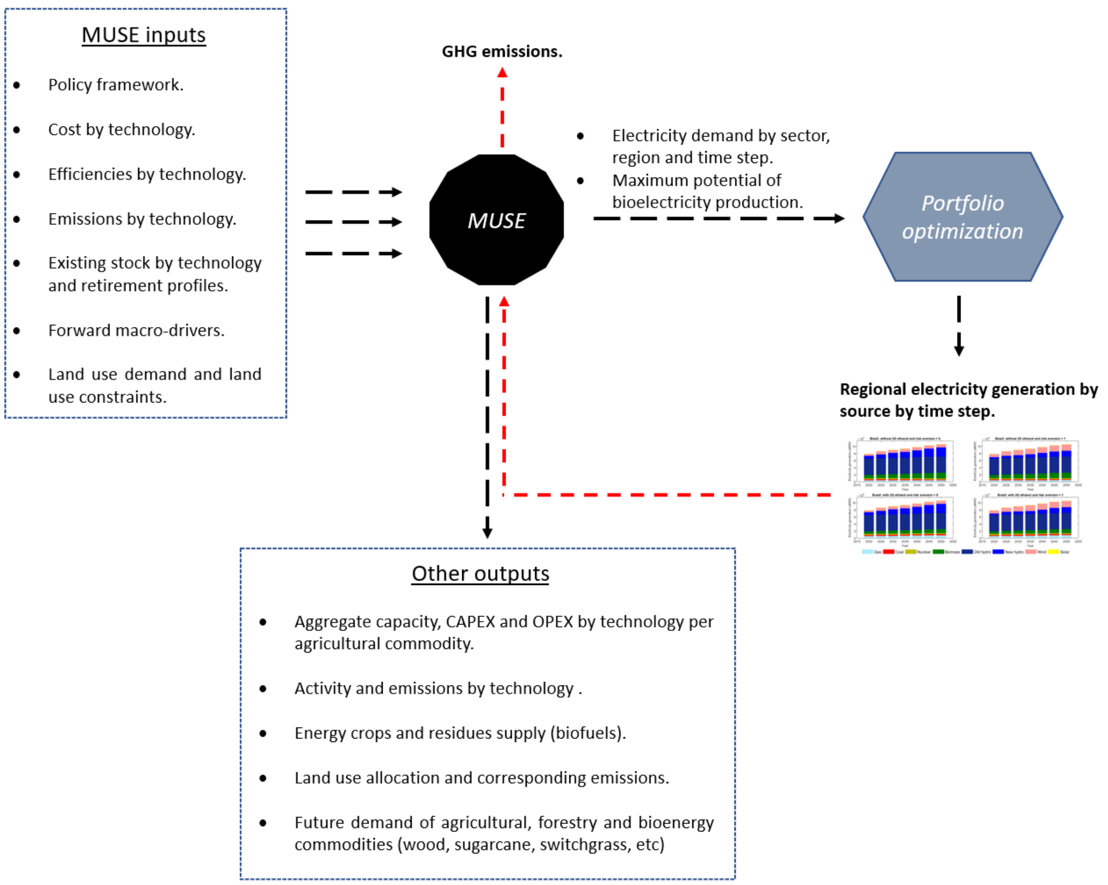

Figure 12 - Soft link: Muse and Electricity Portfolio Optimization Model.

3.3 Methodology: paper #3

To assess the relationship between human development and sugarcane expansion, paper #3 presented a methodology built on the UN human development index (UN, 2018), and the Paulista Social Responsibility Index (Seade, 2016). Taking municipalities of Mato Grosso do Sul (MS) as a case study, the methodology comprised the following five steps: (i) identification of municipalities in MS with aptitude for sugarcane; (ii) assessment of land use in MS; (iii) identification of sugar mills; (iv) assessment of municipal human development; (v) clustering and assessment of municipalities according to their performances with respect to indicators related to health, education, and wealth.

The identification of municipalities with aptitude for sugarcane cultivation was based on the Sugarcane Agroecological Zoning from Embrapa (Embrapa, 2009). According to Embrapa (2009) cultivation of sugarcane is not feasible in approximately 92% of the Brazilian territory. Through this assessment, it was found that 57 out of 79 municipalities in MS are favorable for its cultivation. By this first analysis, it was defined that these 57 municipalities were the focus of the research. The exclusion of municipalities not apt for sugarcane ensured that municipalities with protected areas that could also prevent other economic activities and distort the analysis were not included; not apt areas tend to be concentrated in the eastern of the state, which can present different socioeconomic characteristics that also could distort the analysis; and polices recommendations regarding the bioelectricity sector would be flawed for municipalities where sugarcane cultivation is not allowed.

The assessment of land use in MS enhanced the understanding of the agricultural land use in the state. Based on data from IBGE (2019), and Lapig (2020) shares of planted areas of different crops and pasture area in 2015 could be evaluated, and predominant activities in each municipality were identified.

The presence of sugar mills and the date when they started operating in the municipalities were identified through online sources, namely UDOP (2019), Aneel (2019) (the Brazilian Electricity Regulatory Agency), and on websites of members of UNICA (the Brazilian Sugarcane Industry Association) and BioSul (the Association of Bioenergy Producers in MS). Data regarding the year when they were built was used to relate human development and sugarcane activity in different periods.

Municipal data related to health, wealth, and education conditions were gathered for the assessment of municipal human development. Perinatal mortality rate, child mortality rate, mortality rate of people aged 15 to 39 years old, and mortality rate for people aged 60 to 69 years old represented the health dimension. Average annual electricity consumption per residence, average annual electricity consumption per consumer in rural areas and public services, industry and commerce sectors, GDP per capita, and average remuneration of active formal employees represented the wealth dimension. Finally, the education dimension was represented by school attendance of children aged 4 to 5 years old, average score of 5th grade students in mathematics and Portuguese national tests, average score of 9th grade students in mathematics and Portuguese national tests, and age-grade distortion rate of high school students. To enable the analysis over time, the data were collected for the years 2007 and 2015.

The data were collected from Semade (2019), DATASUS (2018), Ministério do Trabalho (2018), and INEP (2018).

For all indicators, the min-max feature scaling was applied so that the minimum value was equal to zero and maximum value equal to one. Then, the following four groups were defined: (i) all 57 municipalities; (ii) municipalities without a mill (n=37); (iii) all municipalities with a mill (n=20); (iv) municipalities that established a mill between 2007 and 2015 (n = 12). To check if the groups of municipalities with sugar mills, or where sugar mills were established within the studied period, improved their relativized indicators (min-max feature scaling), paired t-tests were applied to test for mean differences between 2007 and 2015 values. This part of the methodology provided the answer for the question "Do municipalities with mills experienced higher socioeconomic improvements than those without?".

Additionally, a clustering analysis based on the K-Means algorithm was done to answer the question "Do municipalities that have better socioeconomic conditions tend to have mills?". Therefore, based on the 12 adopted indicators, the K-Means was applied to cluster the municipalities in two groups: the group with better human development and the group with worse human development. After the clustering, boxplots were built and evaluated to check if the separation of better and worse municipalities was achieved. Finally, the amounts of municipalities with and without mills in each group and year were analyzed.

3.4 Methodology: paper #4

The methodologies presented in papers #1 and #2 enabled the achievement of objectives 1-5 (see Section 1.3). Through models that consider different regions and yearly temporal resolution it was addressed questions regarding uncertainties on generation and transmission costs, risk measures, transmission infrastructure, land use/land use change, and impacts from different bioenergy technological routes in the power sector. Nevertheless, under the context where the shift towards a low carbon economy is a global compromise, expansion of renewable sources with variable generation profiles within a year is required. Therefore, the use of higher temporal resolution models is needed to investigate the implications of renewables share increase.

In paper #4 electricity generation and demand profiles were explicitly considered in a multi-period and multi-region optimization modelling framework. Regional resolution was maintained the same as the adopted in papers #1 and #2, while temporal resolution was defined after a careful data analysis based on historical operation of the national grid (ONS, 2021) and demand forecasting from EPE (2020). The study covered the period from 2020 to 2035 with yearly time-steps. To introduce generation and demand profiles, 3 seasons were considered for each year, a representative day was considered for each season, and 5 periods were considered for each representative day. Figure 13 represents the temporal structure.

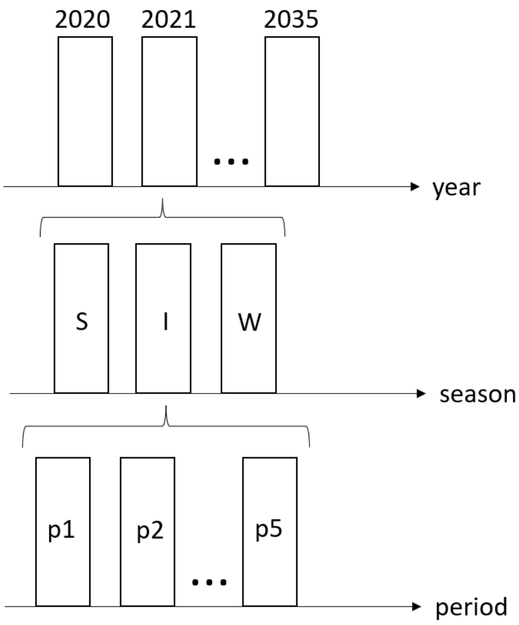

Figure 13 - Temporal structure.
Source: based on paper #4.

The applied approach combines two different models: the first model is based on portfolio theory and deals with renewable generation uncertainties, and the second model is a least cost optimization model. For the first model, scenarios for technologies capacity factors and availabilities were generated through Monte Carlo simulation, and regional installed capacities that minimize the CVaR of the electricity deficit, under the constraint that the expected supply cost could not be higher than a given limit, were calculated. By varying the expected cost limit, it was obtained the so-called efficient frontier. The second model takes the optimal installed capacities provided by the first model and calculates regional electricity generation by technology that minimizes the supply cost under a scenario where capacity factors are deterministic and equal to historical averages. Figure 14 illustrates the modelling framework.

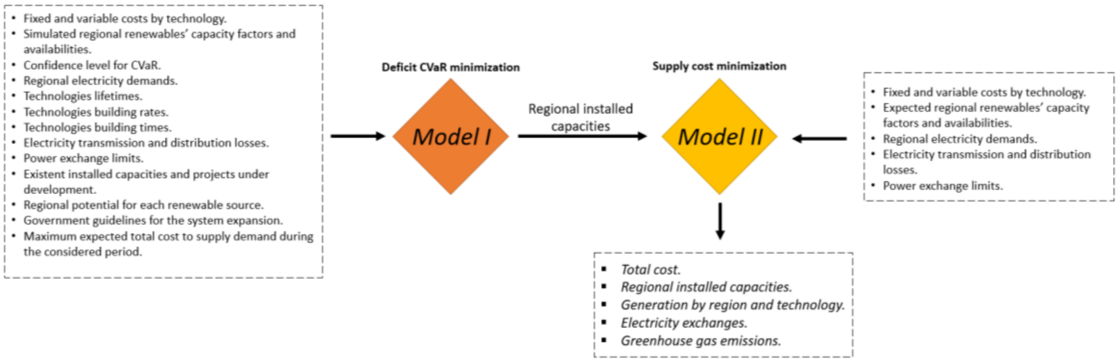

Figure 14 - Electricity deficit and cost minimization framework.
Source: paper #4.

The models were implemented in the IBM ILOG CPLEX software, solved through the dual simplex solver, and processed with Intel(R) Core (TM) i7-8550U CPU with 16 Gb of RAM memory. Each solution of the first model was solved in about 30 minutes and the second model in about 20 seconds.

4 Results and discussion

4.1 Results and discussion: paper #1

Results from the first paper evidenced that the choice of risk measure has direct impact on the solutions of portfolio theory models. When variance is adopted as risk measure, it is observed that thermopower sources expansion are greater than solutions obtained through CVaR minimization. In the analysis, it was highlighted that the reason for that is because variance minimization is concerned with minimizing deviations from the expected cost of the portfolio; therefore, if their inclusion results in variance decrease, thermopower sources with high expected costs are included in the solutions. On the other hand, CVaR is concerned with reducing the mean value of the $\boldsymbol{\beta}$% worst cases, which makes high expected cost sources less attractive.

The following fictitious example illustrates this analysis: take energy sources A and B, where the generation cost of source A follows a uniform distribution with minimum and maximum values equal to 120 R$/MWh and 180 R$/MWh, and the generation cost through source B is deterministic and equal to 500 R$/MWh. If variance is adopted as risk measure, the portfolio where 100% of the electricity is generated through source B is efficient, as it is the only portfolio that results in a variance equal zero (minimum). However, from the CVaR perspective the efficient solution would be to produce 100% of electricity through source A, as in the worst-case scenario it would result in an electricity cost of 180 R$/MWh (lower than 500 R$/MWh).

Overall, optimal expansion of the Brazilian power sector with respect to expected cost and its associated risk was given mainly by renewable sources. Bioelectricity prevailed among other thermopower sources, and its expansion reduced the need for fossil fuels to ensure security of supply. In the BAU scenario and under the adoption of CVaR as risk measure, the average electricity generation mix was composed by 39.0% of old hydro, 25.9% of new hydro, 20.8% of wind, 12.2% of biomass, and 2.1% of nuclear. This result highlights the important role of wind and biomass to reduce dependence on hydropower and to maintain the predominance of renewables in Brazil. From the variance perspective, the electricity mix was composed by 39.1% of old hydro, 21.2 of new hydro, 21.8% of wind, 7.4% of biomass, 5.2% of coal, 3.2% of natural gas, and 2.1% of nuclear.

From the sensitivity analysis, no significant difference was observed when bioelectricity cost maintains 20% lower than in the BAU scenario. This reduction would only maintain the observed predominance of bioelectricity among other thermopower sources. In contrast, the scenario where natural gas is 20% cheaper than in the BAU scenario revealed an augmented share of this source in the system. Under CVaR as risk measure, natural gas represented an average of 2.9% of the generation, while bioelectricity share was reduced from 12.2% to 9.3%. When variance was adopted as risk measure, natural gas share was increased from 3.2% to 4.9%, while bioelectricity was reduced from 7.4% to 6.8%.

The research revealed that if bioelectricity expansion is not realized, natural gas would be the best thermopower alternative from the economic perspective. Additionally, the predominance of bioelectricity raised questions regarding the impacts of limited potential for bioelectricity expansion, land use change, impacts of agriculture efficiency increase, biomass technological routes, and policies to ensure the attractiveness of investments on bioelectricity.

With respect to the impacts of transmission constraints, no expressive differences were observed when comparing solutions obtained through the model where they are considered and through the model where they are not. It is important to note though that a single period optimization model was applied based on average costs and average yearly generation and demand; therefore, supply and demand variations within a year that could increase requirements of electricity exchanges were not considered. A multi-period analysis relating transmission infrastructure and variations on regional supply and demand was left as suggestion for future works.

4.2 Results and discussion: paper #2

Results obtained through MUSE suggested that the production of second-generation ethanol would not impact electricity demand. For both scenarios, it was estimated that demand in 2050 will reach 989 TWh, a growth of 85% if compared to 2015. The highest increase was given in the Southeast region where demand would achieve 236.2 TWh, corresponding to around 52% of the Brazilian consumption. As the country develops, it is expected that 4.25 MWh per capita will be demanded, representing a growth of 63.5% when compared to 2015.

MUSE also enabled a sectorial analysis and results indicated that the industrial sector will correspond to the highest demand increase in absolute values, followed by residential, transport, refinery, agriculture, and commercial sectors. This is presented in Table 6.

Table 6 - Sectorial electricity consumption (TWh).

Sector	2015	2050	Δ%
Agriculture	18.4	45.8	149%
Residential	128.4	282.0	120%
Commercial&Public	141.2	153.6	9%
Industry	188.5	369.1	96%
Transport	2.9	55.4	1,810%
Refinery&Energy	55.1	83.0	51%
Total	*534.5*	*988.9*	*85%*

Regarding land use, it is expected a reduction on the harvest area. The peak occurs in 2020, with an area 292 Mha. In the scenario where second-generation ethanol is not produced, improvements on agriculture efficiencies would reduce land demand to 230 Mha by 2050. For the case in which the production of second-generation ethanol occurs, areas for energy crops would be reduced and 225 Mha would be occupied by agriculture. As a result, part of the land would be available for natural vegetation regeneration.

The production of second-generation ethanol would also impact the potential for bioelectricity production. The Brazilian potential in 2050 would be reduced from 21.1 aGW to 11.3 aGW in case second-generation ethanol is produced. The reason for that is that the use of bagasse to produce ethanol would require lower amounts of sugarcane to meet biofuels demand and, part of the bagasse that could be burnt in boilers to produce electricity would be destinated to ethanol production.

Regional bioelectricity potentials estimated from MUSE's sugarcane and black-liquor demand outputs, electricity demand forecasting, and exogeneous inputs regarding other electricity generation technologies were sent to the electricity portfolio optimization model. For each scenario, the expansion of the power sector was investigated under two different risk aversion policies: (i) risk-taking policy, which aims at obtaining electricity generation shares that yield the minimum expected cost; and (ii) risk-averse policy, which is concerned with cost risk minimization.

Regardless the risk policy, results suggested that optimal expansion of the power sector is given predominantly by renewables, mainly through hydro and wind powerplants. The main difference when comparing the electricity mix in 2050 under different risk strategies is that more wind power (+34.45 TWh) and less hydropower (-35.51 TWh) are generated under the risk-averse policy. This result reflected high uncertainties of capital costs incurred in the building process of a hydropower plant.

Among thermopower sources it was observed that bioelectricity prevails. Nevertheless, if second-generation was produced, more natural gas was used to substitute the decrease in the bioelectricity potential. Therefore, although the production of second-generation ethanol is beneficial from the perspective that it contributes for liberating more land to be regenerated with natural vegetation, it increases the use of fossil fuels, leveraging electricity prices and GHG emissions.

4.3 Results and discussion: paper #3

From the initial assessment it was found that 57 out of 79 municipalities of Mato Grosso do Sul (MS) present areas apt for sugarcane cultivation. Among them, those located close to protected areas, natural vegetation and important watercourses present lower proportions of suitable areas. Overall, areas with aptitude vary between 0.05% to 97% of the municipalities. Those municipalities that do not present aptitude for sugarcane activity were excluded from the analysis.

In 2015, land use in MS was dominated by pasture, followed by soy and maize crops. Sugarcane occupied around 0.52 Mha, representing 6% of the apt areas. This result suggests that the state still presents great potential for sustainable investments in the sugarcane industry.

However, it is likely that if such investments continue to grow, existent crops will need to be shifted to other locations. Therefore, new studies are needed to investigate impacts of land use change caused by sugarcane expansion.

Presence of sugarcane refineries were identified in 20 out of the 57 considered municipalities. From these 20 refineries, 8 were established before 2007, and 12 between 2007 and 2015. Based on the establishment year of these refineries and on values of the 12 considered municipal socioeconomic variables, the applied paired t-test (see Section 3.3) did not reveal a clear relationship between the presence/absence of refineries and improvements on socioeconomic conditions in the studied period.

After the hypothesis testing, the clustering algorithm K-means was applied to assign municipalities in two groups for each considered year: better and worse groups with respect to their human development. Through visual analysis (boxplots), it was verified that the algorithm succeeded in identifying these groups. Following the analysis, the relation between the group in which municipalities were assigned, and the presence of a refinery was assessed.

Results obtained show that municipalities with better socioeconomic conditions are more likely to present sugarcane refineries. However, it was found that those municipalities in which a refinery was established between 2007 and 2015 already had better performance in 2007. This result indicates that the sugarcane industry may not improve human development, but instead, among other local characteristics, investors tend to choose more developed locations to build their refineries.

4.4 Results and discussion: paper #4

When comparing installed capacities obtained from the model that deals with the trade-off between electricity deficit risk and expected cost, no expressive differences were observed for the minimum risk solution and minimum expected cost solution. The main difference is that for risk-averse solutions more CCGT and oil powerplants were built. This happens because, as CCGT and coal generation do not depend on environmental conditions, the expansion of these powerplants contributes to ensure demand attendance under scenarios where renewable generation is lower.

When the strategy is based on minimizing the expected cost, the model points to 294.34 MW of total installed capacity by 2035, with CCGT and oil corresponding for respectively 21.66 MW and 3.52 MW. Nevertheless, if electricity deficit risk is minimized, total installed capacity is increased to 309.77 MW, with CCGT and oil corresponding to 26.32 MW and 14.56

MW. In this case, the stronger increase of oil is a result from both its lower fixed annual costs, and its role of attending demand only under unfavorable renewable generation periods and peak demand hours; therefore, high variable costs incurred during adverse renewable scenarios are compensated by its lower fixed cost.

Regardless the strategy towards deficit risk, all considered renewable technologies were expanded at the upper limit established by the Brazilian government energy research company (EPE (2018) and EPE (2020)). Results also suggested that the available hydropower potential in Brazil will be completely tapped by 2030; therefore, from 2030 to 2035 new hydropower plants would only be built to substitute those that will achieve their lifetimes (decommissioned plants). Other renewables will not achieve their available potentials. Table 7 presents the installed capacities in the initial year (i.e., 2020), and in 2035 for the minimum risk solution (risk-averse policy), and minimum expected cost solution (risk-taking policy).

Table 7 - Installed capacities under different risk policies (GW).

	2020	**2035**	
Technology	***Initial year***	**Risk-averse policy**	**Risk-taking policy**
Hydro	*109,3*	131,6	131,6
Wind	*16,4*	57,9	57,9
Solar	*3,1*	42,6	42,6
Biomass	*15,4*	19,3	19,3
CCGT	*9,2*	26,3	21,7
OCGT	*6,5*	12,1	12,4
Oil	*9,5*	14,6	3,5
Coal	*3,6*	2,1	2,1
Nuclear	*2,0*	3,3	3,3
Total	*174,9*	309.8	294.3

Impacts of regional demand and environmental conditions were also captured by the model. Government guidelines regarding wind building rates in the country resulted in its expansion only in the North and Northeast, where better environmental conditions are found. Therefore, although the Southeast/Midwest and South also present conditions that make wind deployment economically feasible, its expansion does not occur in these regions. In contrast, competitive solar capacity factors in the Southeast/Midwest and South, limitations on solar building rates in the country, and lack of wind expansion resulted in solutions in which solar expansion only occur in these regions. This is an important result, as it suggests that government guidelines for renewables expansion are too tight and can difficult the shift to a cleaner electricity matrix.

Installed capacities outputs from the first model were used as inputs for the second model, which aimed at finding the least cost expansion strategy. For the second model it was considered deterministic capacity factors, estimated through average historical values. Then, solutions for different risk strategies were compared with respect to technologies generation shares, and emissions.

Overall, results suggested that requirements for fossil fuel-based electricity generation are stronger between 18:00 and 23:59 hours. This result reflects the fact that in this period there is no solar generation, and more electricity consumption is observed. With regards to the amount of renewable generation, no difference was observed when comparing risk policies. The main difference is that for the risk-averse strategy more generation through CCGT, and less generation through OCGT, is observed. This is because more CCGT installed capacity is built for the minimum risk solution, and its variable cost is lower than OCGT.

Finally, for each analyzed solution it was estimated the amount of CO2 emissions. Results indicated that power sector emissions in 2035 will be increased by around 84% when compared to 2020. Therefore, under current government guidelines, the power sector will not contribute for the achievement of the Brazilian NDC of the Paris agreement. This is an important result, revealing an urgent need for energy policies oriented to accelerating renewables expansion in Brazil.

5 Final remarks

Under the light of optimization and statistical models, this thesis aimed at investigating environmental, social, and economic issues related to the energy sector in Brazil. The thesis was structured as a collection of four papers, in which new methodological approaches were proposed to address relevant energy-related questions. Specific objectives were presented in Section 1.3, while Section 1.4 indicated which are the objectives addressed by each paper.

Although each paper focused on different objectives, the four papers are related to each other. The thesis began with paper #1, where a single period model based on portfolio theory was applied. In paper #2 an enhanced version of the model presented in paper #1 was proposed, and an agent-based model was integrated to the modelling framework. Results obtained from paper #1 and paper #2 revealed that, from both the economic and environmental perspectives, bioelectricity is more attractive than other thermopower sources. This result motivated the study presented in paper #3, which focused on the relation between municipal human development and sugarcane activity (main source of bioelectricity in Brazil). Finally, a multi-period optimization modelling framework that considered regional monthly and daily electricity supply and demand profiles were presented in paper #4. Results and contributions of each paper are summarized as follows.

In paper #1 it was shown that models based on portfolio theory are sensitive to the risk measure. It was concluded that for power sector expansion planning models the adoption of CVaR is more adequate than variance. Through the investigation of different scenarios regarding natural gas and bioelectricity prices it was concluded that the expansion of bioelectricity is the best alternative among all other thermopower sources. In case bioelectricity generation is limited, it was found that natural gas is the best alternative to complement electricity supply and ensure that demand attendance is achieved. Lastly, results from paper #1 indicated that transmission constraints do not significantly change optimal solutions for electricity mixes in Brazil. However, as a single period model was applied, seasonal variations on generation and consumption that could stress transmission lines were not considered, and further investigation on the impacts of transmission constraints was left as suggestion for future works.

In paper #2 it was studied how availability of biomass impacts the power sector. The paper proposed a new modelling framework that integrates an agent-based model developed by researchers at Imperial College London with an enhanced version of the portfolio theory-based model presented in paper #1. Under different risk policies, investment routes in the sugarcane sector were analyzed with regards to the production of second-generation ethanol and its impact on the bioelectricity potential in Brazil. Also, land use, and land use change were evaluated for each investment scenario. Results indicated that if second-generation ethanol is produced in scale, the bioelectricity potential of the country would be reduced. In this case, more electricity would be generated through natural gas, which would imply in more GHG emissions from the power sector. Nevertheless, it was also found a positive environmental effect from second-generation production: it would result in more land availability, liberating current agriculture areas for natural vegetation regeneration. With respect to the risk policy, it was shown that under a risk-taking strategy more hydropower plants would be built, with a concomitant reduction in wind power. Under a risk-averse policy the opposite occurs.

In paper #3 the sugarcane activity was studied with respect to the social dimension of sustainability. From the research, it was identified papers that focused on socioeconomic impacts from the sector in traditional producing municipalities. Nevertheless, only few studies on impacts of the activity on expansion areas were found. Therefore, taking the state of Mato Grosso do Sul (one of the states where sugarcane production has expanded), as a case study, the paper proposed a methodology comprised by 5 steps: (i) identification of suitable areas for sugarcane cultivation; (ii) analysis of current land use; (iii) identification of municipalities where refineries operate; (iv) selection of human development-related indexes; (v) assessment of the relationship between sugarcane activity and human development. Results revealed a great potential for sugarcane cultivation expansion, and that current land use is dominated by pasture, maize, and soy crops. Also, it was found that investors seek for more developed municipalities to locate their refineries, but no clear positive effect from the sector was identified for local people. This result indicates that new policies need to be put in place to ensure that municipalities and their residents capture potential socioeconomic benefits from the sugarcane activity.

In paper #4 a multi-period and multi-region modelling framework was proposed to evaluate the Brazilian power sector expansion. The methodology was able to capture regional electricity supply and demand profiles. In the study, a portfolio-theory that deals with expected cost and electricity shortage risk minimization was applied to define which, when, and where each generation technology should be expanded to cover demand growth, and to substitute powerplants that will be decommissioned when they achieve their lifetimes. Then, based on installed capacities provided by the first model, a least cost optimization model was applied to estimate the expected generation by each technology and the resulting GHG emissions. Moreover, current government guidelines were evaluated with regards to the accomplishment of emissions reduction targets. Results suggested that renewable sources are attractive from both the environmental and economic perspectives. Nevertheless, it was found that renewable expansion limitations established by the government are too tight and may difficult the country to achieve it compromise. The models indicated that hydropower potential will be completely tapped by 2030, and that wind, solar, and biomass could help the country to maintain high shares of renewables. To ensure security of supply during unfavorable periods for renewable generation, installation of natural gas plants was found to be the best alternative among the considered fossil fuel-based powerplants.

Overall, methodologies and analysis applied through this work provide useful results and insights for both academics and energy planners. Nevertheless, it is important to highlight some limitations of the proposed models. In papers #1 and #2 it is proposed single period optimization models based on average yearly demands and generation; therefore, the importance of the transmission system to ensure demand attendance during low renewable generation periods could not be assessed. Moreover, the role of thermopower sources to supply demand during peak demand periods could not be explicitly investigated.

Temporal aspects were included in paper #4 to complement the analysis conducted in papers #1 and #2. Nevertheless, it also presents opportunities for further improvements. Storage technologies such as pumped hydro systems, use of batteries to store energy during higher renewable generation periods, and energy storage through hydrogen production were not considered. Also, the possibility of electricity trading with neighboring countries were not modelled. Finally, increasing temporal resolution to consider technologies ramp-up times can enhance the analysis. These improvements are left as suggestions for future works.

Additionally, the energy sector is under constant transformation and more research is needed to foster sustainable growth. Suggestions for future works are summarized as follows: (i) analysis of power sector expansion through models that consider energy storage technologies, including pumped storage hydroelectricity, batteries that absorb solar energy, and hydrogen production through electrolysis; (ii) development of models with more granular temporal and regional resolutions; (iii) investigation of potential benefits from hybrid power plants; (iv) further investigation on impacts of renewable expansion in socioeconomic conditions; and (v) policy designs aimed to fostering sustainable energy obtention and use.

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Appendices

Appendix A – paper #1

Mario R. Eden, Marianthi Ierapetritou and Gavin P. Towler (Editors) Proceedings of the 13th International Symposium on Process Systems Engineering – PSE 2018
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Insertion of Renewable Sources in the Brazilian Electricity Matrix: an Analysis through Portfolio Theory

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Abstract

The insertion of renewable sources in the world energy matrix is a promising pathway to reduce greenhouse gas (GHG) emissions in the future. Brazil is one of the leaders in the use of renewable energy, pioneering new biofuel technologies and presenting an electricity matrix based on hydroelectric power. Due to its vast territory, Brazil presents a high heterogeneity regarding natural resources availability and socioeconomic conditions, resulting in regions with different electricity supply and demand profiles. Hydropower, biomass and wind power account respectively for 61.40%, 8.77% and 6.71% of the Brazilian total installed capacity. However, the high dependence on hydroelectricity exposes the country to risks associated with variations on the hydrological regimes. The renewable alternatives to hydroelectricity in the country - biomass and wind power - can increase the reliability of the system and the choice of the optimal power mix is a challenge.
This study analyzes the optimal Brazilian electricity mix based on a portfolio model considering regional supply and demand characteristics. The main drivers to analyze the problem are the generation and transmission costs and the regional supply and demand. At an aggregate level, the results show that bioelectricity is the most economical option among the thermal sources. The results motivate the analysis of land use for biomass crops, the development of new technologies to increase the harvest productivity and establishment of policies to attract investments on bioelectricity.

Appendix B – paper #2

ELSEVIER

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Modelling the technical potential of bioelectricity production under land use constraints: A multi-region Brazil case study

Lucas Lyrio de Oliveira [a, 1], Iván García Kerdan [b, e, f, 1], Celma de Oliveira Ribeiro [a], Claudio Augusto Oller do Nascimento [c], Erik Eduardo Rego [a], Sara Giarola [d], Adam Hawkes [b]

Abstract

In Brazil, bioelectricity generation from sugarcane bagasse and black liquor is regarded as a sustainable electricity supply option. However, questions regarding land use, investment decisions, and demand for paper, ethanol and sugar make its future role uncertain. The aim of this paper is to present a novel modelling framework based on a soft-link between a multi-sectoral Brazilian integrated assessment model (MUSE-Brazil) and an electricity portfolio optimisation model (EPOM). The proposed framework is capable of dynamically simulating sectoral electricity demand, regional bioenergy production under land use constraints and optimal power sector technological shares in each of the electricity subsystems. Considering Brazil under a 2 °C carbon budget, two scenarios based on economic attractiveness of producing second-generation ethanol have been investigated. Under the scenario where second-generation ethanol is not produced, outputs indicate that by 2050, Brazil would increase sugarcane and wood production by 68% and 49% respectively without causing direct or indirect deforestation. Agriculture intensification is evidenced as an alternative for reducing land use disruptions. Bioelectricity share is projected to remain around 9–10%. However, if second generation ethanol becomes cost-effective, thus limiting bagasse availability, the share of bioelectricity production would decrease to approximately 7.7%, with natural gas-fired plants playing a stronger role in the future power system expansion, causing an increase on electricity sector emissions.

Appendix C – paper #3

ELSEVIER

Biomass and Bioenergy
Volume 141, October 2020, 105700

Research paper

Assessing the relationship between sugarcane expansion and human development at the municipal level: A case study of Mato Grosso do Sul, Brazil

Julia Tomei [a], Lucas Lyrio de Oliveira [b], Celma de Oliveira Ribeiro [b], Linda Lee Ho [b], Luis Guillermo Montoya [c]

Abstract

Brazil has a long history of sugarcane development and since the 2000s has undergone a significant increase in land cultivated with sugarcane. Policy-driven demand and a growing international market mean that sugarcane cultivation in Brazil is expected to increase in the coming years. Rising land prices and strengthened environmental legislation in São Paulo state – where the bulk of production occurs – have led farmers and investors to seek new land to cultivate. As a result, the Centre- West region, including the state of Mato Grosso do Sul, has become an epicentre for sugarcane expansion in Brazil. While the social, economic and environmental impacts of sugarcane have been well documented for the state of São Paulo, much less is known about these impacts in new sugarcane frontier regions. This paper addresses an important gap in the literature through an assessment of the relationship between human development and presence or absence of a sugar mill in municipalities in Mato Grosso do Sul. Drawing on the UN Human Development Index and the Social Responsibility Index of São Paulo, this paper develops a method to examine the relationship between the presence of sugarcane processing mills and human development at the municipal level in Mato Grosso do Sul. The paper finds evidence that municipalities with a mill perform relatively better in terms of human development than those without, but that municipalities with mills already performed relatively better than those without. This raises important questions about how are and where the socio-economic benefits of sugarcane materialise.

Appendix D – paper #4

ELSEVIER

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Analysis of electricity supply and demand intra-annual dynamics in Brazil: A multi-period and multi-regional generation expansion planning model

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Abstract

The use of renewable energy sources in electricity systems has become an important strategy to reduce greenhouse gas emissions in the power sector and to avoid depletion of natural resources. However, uncertainties on renewable power generation, diurnal and seasonal variability, technology costs and regional resources availability are factors that have challenged their large-scale adoption. In this context, studies have been focused on how to best integrate different generation technologies with regards to costs and security of supply. Taking the Brazilian electricity system expansion as a case study, this paper proposes a new hierarchical modelling framework that integrates two electricity planning optimization models: (i) a portfolio theory-based model that deals with the trade-off between security of supply and expected supply cost and (ii) a deterministic least cost model that finds the amount of electricity to be produced by each generation technology. The proposed approach can provide information regarding expected total supply cost, electricity deficit risks, capacity expansion and expected greenhouse gas emissions. Additionally, current government guidelines for renewables expansion are discussed with respect to the Brazilian targets for emissions reduction. Results point to a slight increase in renewables share from 82.4% in 2020 to 85.3% in 2035; however maximum established building rates for renewable generation projects are shown to be very tight and may hamper the achievement of emissions reduction. Overall, it is shown that renewable technologies are attractive for both the environmental and economic spheres, but fossil fuels will continue to play an important role for meeting demand.