UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA DE ALIMENTOS

PEDRO MEIRELLES VILLAS BÔAS

A CASE STUDY OF A SUCCESSFUL WOODCHIP PROJECT FOR AN ENERGY AUCTION FROM A STAKEHOLDER PERSPECTIVE: THE APPROACH USED AND UNDERLYING FACTORS

UM ESTUDO DE CASO DE UM PROJETO BEM-SUCEDIDO DE CAVACOS DE MADEIRA PARA UM LEILÃO DE ENERGIA SOB A PERSPECTIVA DAS PARTES INTERESSADAS: A ABORDAGEM UTILIZADA E OS FATORES SUBJACENTES

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Thesis presented to the School of Food Engineering of the University of Campinas in partial fulfillment of the requirements for the degree of Doctor of Science

Tese apresentada à Faculdade de Engenharia de Alimentos da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Ciências

Orientador: José Maria Ferreira Jardim da Silveira

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Dedicatória

Esse trabalho ficaria no campo das ideias não fossem duas pessoas me dando apoio incondicional.

Minha esposa, Lelé, que sempre acreditou que eu conseguiria fazer coisas que nem eu imaginava, me dando o chão para voar alto.

Meu pai, o amigo e matemático, que mesmo depois dos meus 40 anos de idade ainda está sempre ao meu lado, dando suporte e nunca pedindo nada além da minha felicidade.

De um nosso pai

Fez-se o início
E o que não mais era, agora se valia
Se talvez fosse, por um instante mais seria
Em seu ensaio, fez-se em mim eterno
E eu
Uma janela entre quadros,
uma síntese.

Depois de 28 anos é ainda mais verdadeiro...

Resumo

Os leilões de energia são comumente utilizados para a contratação de projetos de energia e são amplamente estudados sob a ótica do regulador.

No entanto, analisar os leilões da perspectiva do licitante é fundamental para determinar o impacto dos detalhes regulatórios nas receitas do licitante.

Neste estudo, analisamos um leilão público de energia em Roraima, um estado brasileiro com déficit de energia significativo e sem conexão à rede, onde muitos projetos foram bem-sucedidos na categoria de Produto de Energia não intermitente, tipicamente desfavorável para biomassa.

Usando a Programação Linear para maximizar as receitas dos licitantes, examinamos as fórmulas regulatórias que contribuíram para o sucesso desses projetos e comparamos os resultados da otimização com as receitas reais.

Nossa análise mostra que certos elementos regulatórios podem beneficiar os licitantes, permitindo que tomem decisões não convencionais de design de projeto.

Além disso, identificamos uma possível brecha na fórmula que pode ter o efeito contrário à intenção do regulador na categoria de Produto de Energia Renovável.

Nossas descobertas podem ajudar os licitantes a aumentar os lucros por meio da otimização e os reguladores a alterar as fórmulas se os objetivos não forem alcançados.

Este estudo traz a perspectiva muitas vezes negligenciada dos licitantes para os leilões de energia, acrescentando à literatura sobre o tema.

Palavras-chave: leilão de reserva de capacidade, inflexibilidade, perspectiva do licitante, biomassa, cogeração, sustentabilidade, otimização de lucro

Abstract

Energy auctions are commonly used to contract energy projects and are extensively studied from the regulator's perspective.

However, analyzing auctions from the stakeholders' perspective is critical to determine the impact of regulatory details on the bidder's revenues.

In this study, we analyze a public energy auction in Roraima, a Brazilian state with a significant energy deficit and no grid connection, where many projects were successful in the non-intermittent Power Product category, typically unfavorable for biomass.

Using Linear Programming to maximize bidders' revenues, we examine the regulatory formulas that contributed to the success of these projects and compare the optimization results to actual revenues.

Our analysis shows that certain regulatory elements can benefit stakeholders by allowing them to make unconventional project design decisions.

In addition, we identify a possible loophole in the formula that can have the opposite effect of the regulator's intent in the renewable Power Product category.

Our findings can help bidders increase profits through optimization and regulators to change formulas if objectives are not met.

This study brings the often-overlooked perspective of stakeholders to energy auctions, adding to the literature on this topic.

Keywords: capacity reserve auction, inflexibility, bidder perspective, biomass, cogeneration, sustainability, profit optimization

Sumário

1. Introduction

Energy auctions have been extensively studied. A quick search of the ScienceDirect database [1] reveals more than 11,000 research articles on this topic from the last two decades. So far, there is broad agreement in this literature that all design elements have a major impact on the trade-off between efficiency and effectiveness [2, 3] and on the energy transition toward decarbonization [4]. There is agreement that the choice of the design elements can determine whether these benefits will actually impact the results [5, 6], although some authors argue that the most important impact on various criteria and objectives comes from the structural features of the auctions as a whole and not necessarily from the design elements [7].

These studies take the point of view of the regulator who sets up the auction, and they analyze the results of the auction.

This raises a research question: "*What would the analyses and outcomes of the auction rules look like from the perspective of the stakeholder rather than the regulator, and what design would the stakeholder choose*?"

To explore this question, we take the perspective of a stakeholder in a particular auction where the analysis of the auction rules and subsequent design were based on the profitability of the project for the bidding project *prior* to the auction.

We focus on the 2019 energy auction in Roraima, a Brazilian state isolated from the national energy grid and with a significant energy deficit. As of 2021, there are about 250 isolated systems in Brazil, concentrated in the northern region, accounting for only 1% of the country's total electricity consumption but covering 40% of the territory [8].

The auction was mediated and regulated by a government agency, and its purpose was to replace and supplement the existing thermoelectric diesel power plants, which are expensive and polluting, with cleaner energy projects that can be called only when needed. To this end, certain special provisions were established to promote projects that provide energy only on demand, while allowing projects that require a fixed minimum consumption of fuel to participate via an inflexibility[1] declaration.

The government agency established a formula for what was called the "reference price," with some constants set by the regulator and some variables to be determined by the bidder. The formula aimed to equalize the prices of projects with and without inflexibility and to determine which projects would win the auction.

Since the formula was the key element in determining the winning bids, our methodology was to analyze in detail the variables that must be determined to maximize the profit for the bidder and then examine the consequences of these decisions.

Unlike some other studies of energy auctions, the analysis and design of some projects revealed most of the underlying elements of the formula used to set the reference price.

We believe that the same study and analysis can be applied to many auctions around the world under similar conditions.

This thesis was organized as follows.

In Section 2, we describe the context of this particular energy auction, its challenges, and some literature that addresses similar issues.

In Section 3, we make a brief review of the overall literature.

In Section 4, we describe our approach and perspective, as well as some terminology. In this section, we take a naive approach and look only for a design that can win the auction and whose annual revenue is at least equal to the internal rate of return of the investment. We also present the formula established by the regulator to determine the winners, which is necessary for the analysis in Section 00.

[1] In the context of energy auctions, *inflexibility* refers to the value of mandatory minimum electricity generation from a thermoelectric power plant that is not subject to the National Electricity System Operator's (ONS) rules for on-demand energy.

In Section 0, we take a very different perspective, namely a mathematical optimization for revenue of the energy provider, and discuss some of the results obtained and possible consequences.

In Section 5, we describe the results of the auction and our conclusions can be found in Section 6.

This thesis was the basis for the author's article published in the journal *Energies* [9]

2. Context of the auction

Isolated Systems

Isolated systems are places that, for technical or economic reasons, are not connected to the national power grid and are supplied by local power generation.

Almost every country has its isolated systems, in different conditions and sizes. The literature is full of examples such as in Russia, Japan, Canada, Colombia and many islands in the Caribbean and Indonesia.

Most of these isolated grids with local power generation are located on islands, in rural areas, or in remote regions with strong economic activities such as mining or onshore oil and gas exploration.

In areas far from main power grids, regional isolated grids powered by expensive diesel fuel are often the main source of electricity for industry and households. Another common feature of these systems is that governments usually subsidize the fuel [8].

Among isolated systems, islands[2] are particularly vulnerable in terms of energy security, as they often have limited capacity for energy sources and are often not connected to the energy grid [10, 11], and many solutions for such islands are sought using renewable sources [12].

Islands are often forced to invest in renewable energy to minimize their dependence on fossil fuel energy production [13].

In our case, the focus is on the northern region of Brazil, where the country's 250 isolated systems account for about 1% of national energy consumption and have historically been supplied by diesel power plants, an expensive solution based on complicated logistics and responsible for high greenhouse gas emissions.

Although many publications indicate that renewable energy is already a cost-effective solution, especially for economies dependent on expensive fuels,

[2] In the context of energy, an island or energy island can also mean an artificial island or an island on a platform that serves as a hub for power generation from surrounding offshore sources to interconnect them and distribute the power.

conventional power generation is still the main source of electricity for isolated systems, even in newer projects [8].

Auctions and Energy Auctions

Auctions have been used for millennia and remain the simplest and best-known means of price discovery in multilateral trading without intermediary "market makers" such as brokers and specialists. Their trading procedures, which simply process bids and offers, are a direct extension of the usual forms of bilateral negotiations [14].

Energy auctions, in particular, are demand-driven and the world's most popular system for promoting renewable energy. They have been evaluated according to various criteria, such as their effectiveness and efficiency [15].

Auction targets and their link to energy and environmental policy; hydraulic energy depletion

Energy auctions are critical to the sustainability of the power sector. They are used to award concessions for new power plants and contracts to meet current and future incremental demand.

In developing countries, whose energy matrix is mainly based on hydropower, the increasing energy demand requires an exponential growth of reservoirs, which is not feasible. In this way, the total capacity of hydropower to meet demand is depleted.

The construction of hydropower plants with insufficient reservoirs to meet current storage needs, along with the volatility of renewable energy sources, has increased the demand for distributed renewable energy sources.

Distributed renewable energy sources are not only about transitioning to a green energy supply, but also about supplying certain regions and enabling the necessary expansion of the economy and a reduction in prices.

The design of an energy auction by the regulator is critical to encourage not only an increase in energy production, but also the production of more renewable energy as a state energy and environmental policy.

Biomass and its importance

Biomass is a clean, renewable energy source. Its original energy comes from the sun, and plant or algal biomass can be replenished in a relatively short time. Trees, crops, and municipal solid waste are constantly available and can be sustainably managed.

When trees and crops are managed sustainably, they can offset carbon emissions when they absorb carbon dioxide through respiration. In some bioenergy processes, the amount of carbon that is reabsorbed actually exceeds the carbon emissions released during the processing or use of the fuel [16].

The case of Brazil

Brazil has historically relied on hydroelectric power plants that depend on large reservoirs that can be used year-round to minimize the impact of energy fluctuations caused by natural factors.

As a result, thermoelectric power plants played a supporting role in the portfolio of electricity generation sources, usually activated during periods of peak demand or severe drought, as these power plants were intended only to supplement hydropower. However, the thermoelectric power plants, which could be shut down when not needed, incurred high maintenance costs due to unexpectedly frequent and constant outages. The imbalance between energy supply and demand in 2001 led to a rationing decree [17].

The historical energy pattern in Brazil shows constant signs of depletion due to the difficulty of developing new power plants with storage capacity to meet increasing demand and the expansion of intermittent renewable energy sources. The combustion of biomass such as sugarcane, biogas, wood, beets, charcoal, vegetable oils and others represents the use of biomass in Combined Heat and Power (CHP) plants. These CHP processes are based on the simultaneous and sequential generation of electricity from mechanical energy and thermoelectric energy from the same primary source.

The energy auction in Roraima was primarily aimed at energy supply, since locally generated electricity is insufficient to meet demand, as Roraima State is characterized by a significant imbalance between consumption and generation of internal electricity [18]. At the same time, the auction aimed to allow power plants with renewable biomass, although no restrictions were set in terms of greenhouse gas emissions.

The auction is similar to that studied by Abbas et al [19] in terms of being isolated and based on steam turbine systems, but focusing on a chip cogeneration plant based on wood burning, and comparing fossil energy versus biomass energy (Marchenko et al. [20]). According to Tillman and Jamison [21], this cogeneration type is feasible and can be generalized to other regions of the country, as demonstrated by Nzotcha and Kenfack [22] in Cameroon and sub-Saharan region, and Madlener and Vogtli [23] in Basel and other Switzerland regions, as well as to other cases where government barriers to inflexibility plays an unnecessary negative role (Espinoza et al. [24]).

Biomass-based energy cogeneration is one of the most efficient and ecological alternatives emerging in the Brazilian economy, with the ability to supplement the Brazilian hydroelectric park. In Brazil, the role of biomass cogeneration has been limited to the production of sugarcane bagasse. Only 9 biomass cogeneration projects incorporate woodchips (202MW average contracted) and have been awarded in energy auctions out of a total of 156 biomass cogeneration projects (1.618MW average contracted), indicating that woodchips use 5.7% of biomass projects, or 12.5% of total energy contracted. Given that the cogeneration process is only used as a byproduct of sugar and ethanol production, it is worth noting that Brazil lacks an effective policy for biomass power generation.

Risks and opportunities

Isolated systems, including islands and the state of Roraima, could be integrated into the power grid in the future.

This is a risk that the bidder must take into account, as the power plant could then become obsolete due to lack of demand.

On the other hand, Roraima has many renewable reforestations that are underutilized, and winning such auctions encourages other projects. Even if Roraima is connected to the power grid, the plants can still be used as a small part of the power supply and the remaining wood can be sold.

The same reasoning applies to other places that are isolated systems where renewable forests that are underutilized or could be created.

Details of Roraima's Auction

Historical Background

Energy auctions in Brazil are a series of bidding processes in which the government encourages competition amongst proposals in order to deliver electricity for the future. Energy auctions are strictly governed by the National Electric Energy Agency (ANEEL) and occur within the framework of the Regulated Contracting Environment (ACR).

Although the energy auction in Roraima was primarily aimed at energy supply, it was also intended to enable renewable biomass power plants by establishing a "reference price" that would determine winning bids and in which inflexibility was one of the variables specified by the bidder. Inflexibility usually has a negative effect on the price that the bidder can offer, as we will show later.

A high degree of inflexibility may occur for two primary reasons: first, to secure a minimum quantity of raw materials in order to enter into long-term contracts with the raw materials suppliers; and second, *as in this study*, to be technically viable in order to provide the anticipated quantity of energy in the shortest time possible.

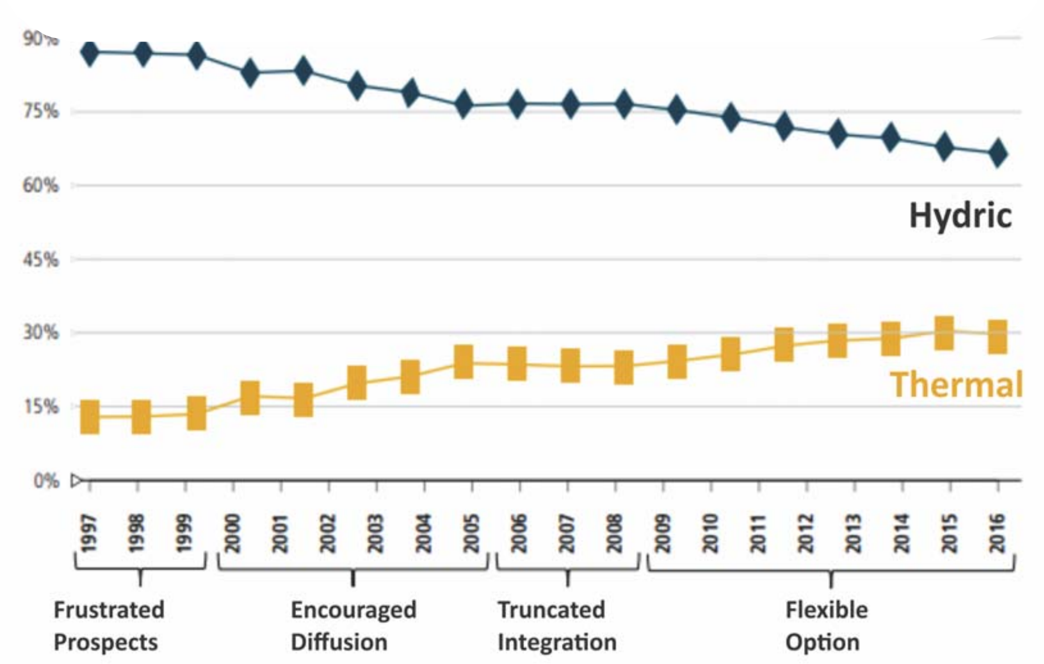
The majority of the energy auctioned in these processes is allocated to distributors. However, these auctions propose a strategy that ultimately benefits fossil-based initiatives at the expense of environmentally viable ventures such as biomass facilities. In particular, the restrictions imposed on the level of inflexibility allowed in auctions for biomass proposals, especially woodchips, appear to hinder the potential of biomass projects to compete with fossil projects[3].

The thermoelectric share in the installed capacity of the Brazilian system is shown below.

[3] The Environmental Impact Report and other additional and detailed information can be found at the site of the Government of Roraima.

Graph 1

Evolution of thermoelectric share in the installed capacity of the Brazilian electric system



Source: 2018 Election – Industry Proposals [26]

Brazil's electricity expansion was centralized before 2001, after demand increased. State-owned generation companies promoted energy supply. The energy supply and demand imbalance resulted in a rationing decree in 2001 [17]. In this context, the Electric Energy Crisis Management Chamber (GCE) was created. Ordinance No. 18 of 6/22/2001 of the Electric Energy Crisis Management Chamber – GCE established the Committee for the Revitalization of the Electric Sector Model to propose the model and correct current dysfunctions.

This Committee for the Revitalization suggested contracting reserve thermoelectric generation capacity. Such a reserve would protect the National Interconnected System (SIN) from potential shortages caused by higher than expected increases in demand, delays in the construction of already contracted plants, and delays in transmission reinforcement, among others. Furthermore, the reserve energy would boost thermoelectric improvement in the system, thus reducing hydrological noise and price volatility [25].

The recommendations of the Committee defined the Brazilian thermoelectric park as mostly composed of flexible units, reserve or emergency plants to complement hydraulic generation and no mandatory minimum generation. These are units with low fixed costs but high variable costs, and their long-term use results in high prices. The dominance of hydraulics, the broad National Interconnected System (SIN), and the configuration of water reservoirs influenced the choices for electrical system expansion. Much of the thermoelectric complementation were designed to be flexible, operating as a backup of hydro generation [26].

The thermoelectric participation was designed to supplement hydraulic generation by acting as a backup in adverse hydrological conditions, which is why its availability was designed to be flexible. Thermoelectric inflexibility refers to the percentage of contracted availability that the power plant must always generate, regardless of any dispatch[4] and merit order[5]. Thus, a thermoelectric power plant with 50% inflexibility creates half of its availability at all times, while a thermoelectric power plant 100% flexible only generates when sent in order of merit.

On the other hand, a flexible thermoelectric power plant is a variable fuel source, the availability of which is associated with a high degree of uncertainty about the time period and level of dispatch. The dispatchable sources are those whose generation time is independent of local weather conditions. Because they generate energy at a constant rate, thermal and hydroelectric plants are examples of dispatchable sources.

As Romeiro makes clear [27], since 2005, 18 auctions have been held using BCR[6] (Benefit-Cost Ratio) as a mechanism to select product availability. An average of more than 22 GW has been contracted in these auctions. The total includes 22% hydro, 16% wind, and 62% thermoelectric. The considerable challenges in acquiring an environmental license for the plants explain the minimal involvement of hydropower in these auctions. Given such limitation, less competitive sources were contracted until 2008, especially in the early auctions.

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[4] *Dispatch* means sending energy above the inflexibility level on request from ONS.

[5] The *Order of Dispatch* or *Order of Merit* is a procedure established by the regulatory authority to determine the order in which the power generators that have won the auction are called to dispatch when needed.

[6] Only in the context of energy auctions, *BCR* is measured in R$/MWh and in this paper we use it in the same meaning as Reference Price.

The most prevalent thermoelectric sources were fuel oil and diesel, followed by natural gas, coal, and biomass. Only six coal-fired thermoelectric plants won these auctions, but it was enough to sell more electricity than all 62 biomass-powered projects combined. By 2010, when wind energy became the most competitive source in the dispute, oil and diesel plants dominated and natural gas thermoelectric plants accounted for more than 5 GW of winning bids.

Despite the low fixed costs of all flexible power plants when dispatched, they result in significant variable operating costs, which are overestimated in the BCR since it assumes flexible thermoelectric power plants will only be used irregularly, overestimating low fixed costs.

Romeiro’s research also showed that additional flexible thermoelectric plants have been dispatched, increasing the share of thermoelectric generation in satisfying SIN load, which increased from less than 10% to 25% in 2012 and now accounts for approximately 30% of the total load.

As contracted flexible availability increasingly focuses on non-intermittent generation, the result is that BCR supports certain technologies and skews options in favor of flexible, dispatchable thermoelectric power plants with high variable unit prices.

Mechanisms of the Auction

Energy auctions are critical components for the sustainability of the Brazilian electricity sector, since they are the means by which concessions for new power plants and contracts to meet the future demands are processed. These auctions can be classified into two basic categories. The first consists of “quantity contracts” which are based on the provision of a fixed amount of energy at a fixed price. This type of auction is most commonly used in hydraulic energy contracts. The second is thermoelectric plant **“availability contract”** because it is intended to ensure the efficiency of the national hydrothermal system (which is the center of discussion in this paper).

The main feature of this category is the establishment of a fixed payment for the electricity producer, regardless of the amount of energy supplied. In these cases, the fixed portion covers the fixed cost of feeding the energy into the system, which may or may not be triggered by the feed-in. If the distributors are not fed in, they have to pay the variable cost of using the fuel, which means that in the end the consumer bears the cost.

It is always the consumer who pays. Fixed costs are the amount of insurance/security. Variable costs are the insurance effectively working. In both cases, it is under the population (the distributor is just an intermediary).

Precisely in this context, we can understand the goals of the 2019 energy auction in the state of Roraima. Roraima is the only Brazilian state that is not integrated into the National Interconnected System (SIN), as it currently relies on energy generated mainly by thermoelectric plants. Furthermore, all energy consumed in Roraima is generated locally or imported from other countries.

In Roraima, electricity generated locally is insufficient to meet demand. In 2018, Roraima had the second lowest electricity generation of all federated entities as it produced the equivalent to 0.05% of the country's electricity generation, while in the same year it consumed the equivalent of 0.2% of the national electricity consumption. Roraima State is characterized by a significant imbalance between consumption and generation of internal electricity [18].

The guidelines for conducting the Boa Vista Auction were established by the Ministry of Mines and Energy (MME) based on the publication of MME Ordinance No. 512/2018 of December 24, 2018. It was supplemented by the publication of MME Ordinance No. 134 of February 13, 2019, which amended various aspects of the previous Ordinance.

The auction categorized the registered bids into "Power Product" and "Energy Product". The power product corresponds to the solutions that allow load modulation and flexibility for variable operation to supply the maximum power required by the system. In this category, the product is separated into sub-products "Gas and Renewables" and "Other Sources". The energy product corresponds to the exclusive category of renewable sources, whose supply obligation is based on an annual energy output approved by the Energy Research Company (EPE).

To our knowledge, this is the first auction for an isolated system that behaves like an interconnected system, which is why renewable and other sources are distinguished.

Biomass cogeneration plants were usually a participant of the energy product auctions.

The energy product frequently deals with intermittent generation, especially when renewable sources are considered. The power product, on the other hand, deals with non-intermittent generation that occurs on demand. For example, solar energy usually is an Energy Product since it is intermittent, but when batteries are used, it becomes non-intermittent and can be a Power Product.

This factor is crucial because when energy security is discussed, we require non-intermittent energy so much that in the auction, the power product is auctioned first to ensure the security of the system, and the energy product is auctioned subsequently to meet the expected auction demand. At this point, inflexibility plays a vital role in the development of the project.

For the energy product, the price for energy generation would be substantially lower than the price for the power product. However, they were not compelled to generate on demand, but to supply an annual quantity of energy; there were no penalties in the BCR *formula* related to an inflexible part.

Key features of the Auction[7]

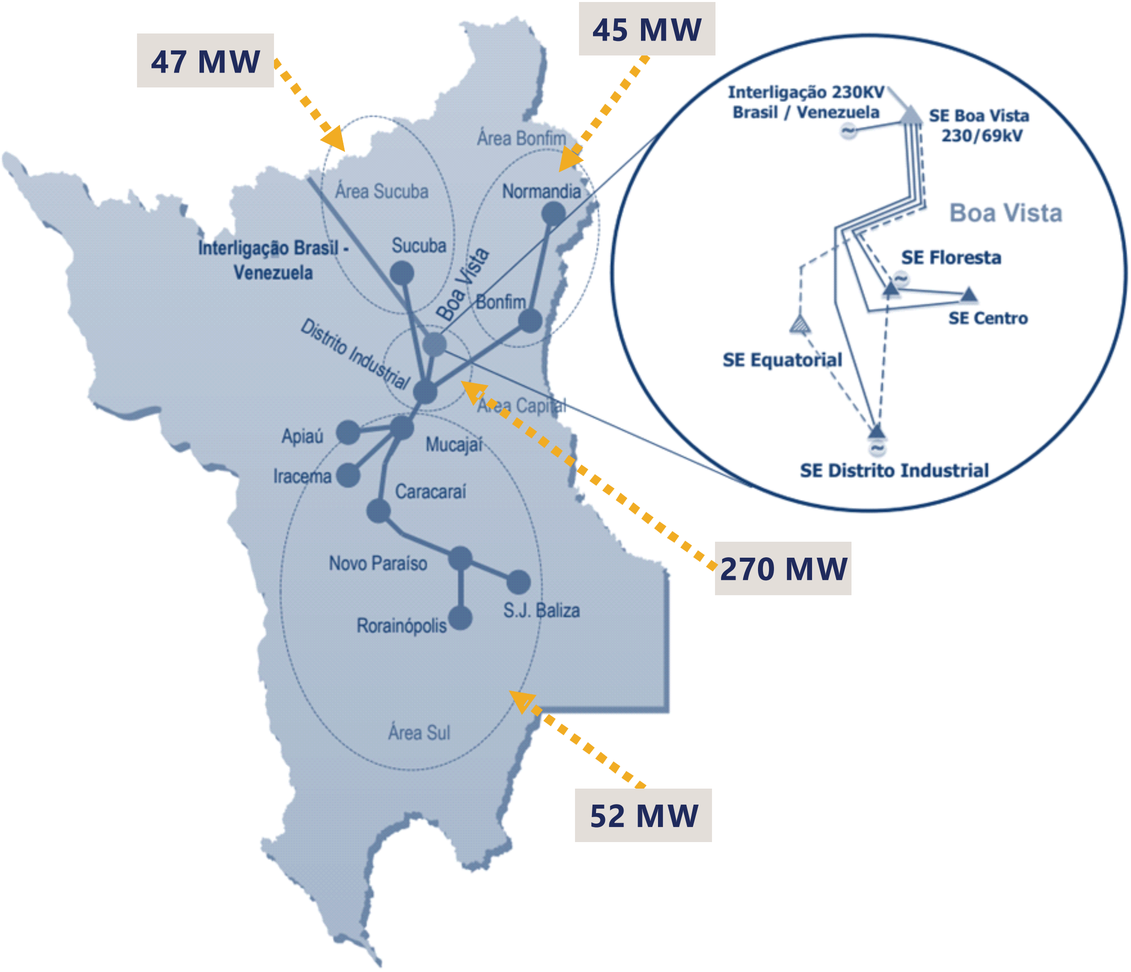
Main dates		
01/03/2019	**Project registration**	**Action Plan agreed in the Civil House/RR to conclude environmental licensing and start works and its compatibility with the concession expiry process in progress at ANEEL; Once the Installation License - LI is obtained, it will take about 18 months to complete the works.**
05/31/2019	**Conducting the Auction**	**Possibility of bringing forward the supply of electricity from January 1, 2021, provided there is flow capacity**
06/28/2021	**Start of electricity supply**	**Energy supply guaranteed for up to 15 years, regardless of the Manaus - Boavista Transmission Line or the connection to Venezuela**

Products

<table>
<tr><td rowspan="3">Power Product</td><td>Source</td><td>Term</td><td>Inflexibility</td><td>Description</td></tr>
<tr><td>Natural gas and renewables</td><td>15 years</td><td>Up to 50%</td><td rowspan="2">Supply solution characterized by load modulation capacity, with flexibility for variable operation, whose delivery commitment consists of power availability (MW), and the respective associated energy (MWh) at the times when it is called to operate, with the risk of seller the uncertainty of dispatch of the supply solution.</td></tr>
<tr><td>Any other</td><td>7 years</td><td>N/A</td></tr>
<tr><td rowspan="2">Energy Product</td><td>Source</td><td>Term</td><td>Inflexibility</td><td>Description</td></tr>
<tr><td>Renewables</td><td>15 years</td><td>N/A</td><td>Exclusively renewable primary energy source supply solution, whose delivery commitment consists of the annual energy production (MWh) resulting from the sale in the Auction.</td></tr>
</table>

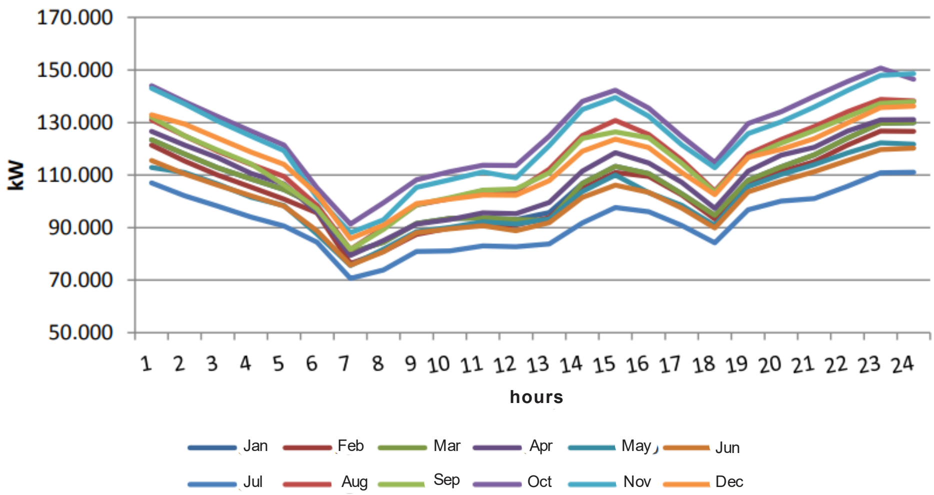
[7] Source: EPE-DEE-RE-086/2018-r1 (until Table 1)

Roraima electrical system substations - Picture 1



Source: EPE-DEE-RE-086/2018-r1

Boa Vista load curves in 2017 - Graph 2



Market data of Boa Vista Isolated System – Table 1

Year	Load (MWh)	Demand (kW)	Year	Load (MWh)	Demand (kW)
2019	1,310,602	229,762	2024	1,637,639	273,809
2020	1,370,870	238,568	2025	1,712,538	284,448
2021	1,435,513	247,368	2026	1,790,922	294,704
2022	1,499,742	256,130	2027	1,872,952	305,340
2023	1,566,949	265,095	2028	1,958,730	315,496

A supplier as an Energy Product does not need to generate when the agent demands it, but when it can. In this way, we can classify a solar plant with an expected MWh of R$250.00 as a plant that generates only when it is demanded; on the other hand, for solar energy with battery, for example, we must add the cost of the batteries, which are expensive. The same analogy applies to woodchip. The prices for a plant auctioned as an Energy Product in Brazil vary between R$ 130 MWh and R$ 300 MWh. In all power auctions, the prices are much higher. Energy Product implies lower Capital Expenditures and higher Operating Expenses; with Product Energy it is the opposite.

Further explaining the Reference Price or BCR and the parameters of the formula, the objective was to technically have a plant that can be activated at any time in a CHP cycle, since the price of the energy product can be around R$200/MWh and the auction for this product may not even take place.

Results of the auction

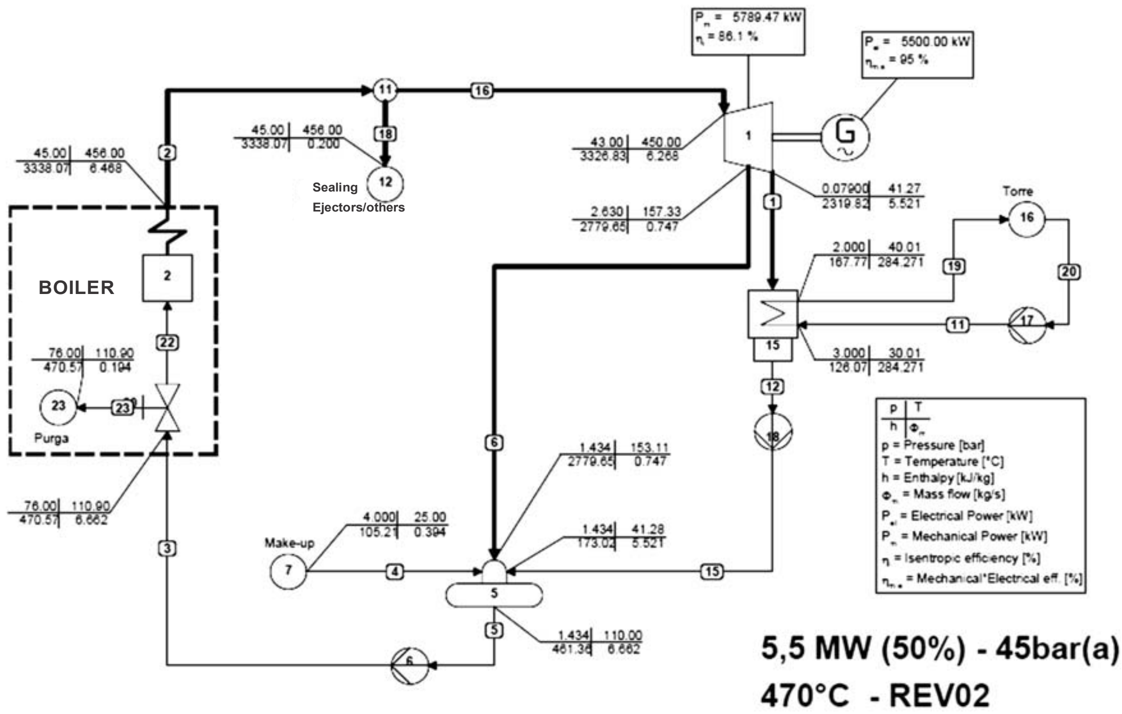
Of the 156 proposals submitted by various private actors, a total of 124 were eligible, representing 4.2 GW of capacity, with 53 projects (3.0 GW) eligible for the electricity product and 71 (1.2 GW) eligible for the energy product.

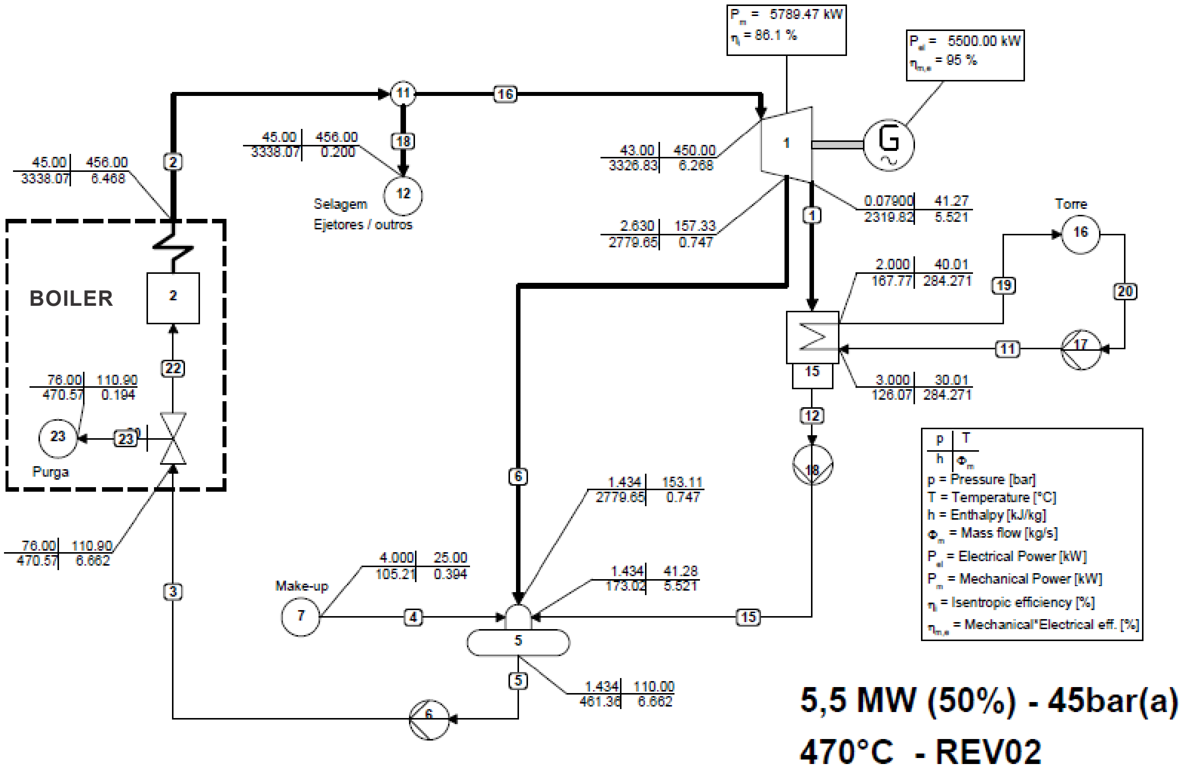
Seven of the nine winning projects in the subsequent phase were renewables under the Power Product scope, with a total installed capacity of 294 MW. Two winners in the Roraima region produce liquid biofuels on site, one also with photovoltaics and the other with biomass. A hybrid project with biofuels, photovoltaics and batteries has also won in Boa Vista.

A thermoelectric natural gas power plant is being built in Boa Vista, with fuel produced in the Amazon and completely flexible power generation. In addition, 4 projects based on biomass (woodchip) have been installed in Boa Vista and Bonfim, with a total of 40 MW, all coming from the same renewable forest owned by the stakeholder of this case study. This was the first time that a biomass cogeneration project won an auction under the Power Product scope.

The steady production of the declared capacity required some modifications to the existing boilers to make the project viable [28]. Figure 1 shows the schematic for the proposed boiler.

Figure 1 [28]





Compared to the government prospect of R$ 1,078 MW/h, the estimated investment of the winners was R$ 1.62 billion, with an average discount per MW/h of 22.7%. Roraima will generate 42.0% clean energy and 43.0% from natural gas. The Energy product winners based on natural gas or renewable sources have 15-year power trading contracts in isolated systems, while the other winners have 7-year contracts.

The stakeholder analyzed and designed a woodchip power plant project that won the Roraima Auction with an unfavorable reference price formula by avoiding its drawbacks to investigate whether the underlying ideas can be applied to similar projects, which is important because we are the largest eucalyptus producers in the world. We found that biomass projects can be competitive if they are allowed to operate with reasonable inflexibility.

3. Literature Review

There are many cases of cogeneration in Brazil and worldwide. In order to situate our case study, a brief review of previous papers is recommended.

International

Tillman and Jamison (1982) [29] studied and compared cogeneration and condensing systems. The study shows the greater profitability of wood when biomass is used in CHP systems. The study also shows that cogeneration systems are significantly more profitable than condensing systems in terms of operating costs, lower pollutant emissions, and thermal efficiency.

Gustavsson and Johansson (1994) [30] discuss and compare the processes of cogeneration in district heating systems with other energy sources to calculate and compare the associated economic and efficiency parameters. It is shown that cogeneration systems using biomass can compete with fossil fuels only if metrics are applied that are based on financial feasibility study methods and consider other additional benefits of using biomass, including least environmental impact.

Duval (2001) [31] discusses the degree of feasibility of plants using advanced biomass CHP technologies in Southeast Asia. The study estimates the results in terms of atmospheric emissions resulting from the deployment of advanced biomass CHP technologies in Indonesia, Malaysia, the Philippines, and Thailand. The results show that widespread adoption of biomass CHP technologies would lead to a significant decrease in pollutant emissions in the Southeast Asian region.

Wahlund, Yan, and Westermark (2002) [32] investigated a new approach to improve the performance of biomass-based CHP plants by conducting a case study between the municipalities of Skelleftea and Kraft in Sweden. The results show that technological improvements in CHP systems further improve the technical and financial viability of CHP plants by increasing their energy efficiency.

Mollersten et al. (2004) [33] investigate the impact of combining CO2 capture and storage as alternatives for combined heat and power generation from biomass in pulp and paper mills. The study suggests that CO2 reduction can be achieved if this gas is captured in a combined cycle integrated biomass gasifier. Such a technical configuration combines two desirable benefits, namely efficient energy conversion and a useful level of CO2 capture.

Krukanont and Prasertsan (2004) [34] evaluate the use of biomass residues from rubber trees in economies based on rubber production with high potential for energy production based on this type of cogeneration system. For this purpose, data from plants on a Thai peninsula were used. Specially developed mathematical models were used to determine the maximum cost as well as the ideal capacity of a CHP system in the region. The results show a consistent level of profitability for eight plants in the exposed region.

Madlener and Vogtli (2008) [35] studied a forestry project in the municipality of Basel, Switzerland, which proposed the implementation of a CHP system. The study consists in evaluating the feasibility of the project, which could be transformed into a schematic model, also with the aim of reproducing it in other regions of the Swiss territory. The study concludes, among other things, that the political, social and technical conditions are in place for the establishment of a cogeneration system capable of putting the residues of the regional forests to a useful and profitable use, i.e. generating income and financial benefits for local stakeholders.

Dong, Liu, and Riffat (2009) [36] conducted a detailed analysis of the development of biomass energy in CHP plants (small- and micro-scale) in the United Kingdom, based on technical and economic feasibility analyzes of the various CHP technologies that can be deployed in the United Kingdom.

The results show a large untapped potential for the construction of small-scale CHP plants that can use biomass in the UK. However, the study also highlights the need for continued development of research leading to improvements in CHP technologies to overcome both the technical and economic barriers most commonly encountered in CHP systems, which generally prevent greater uptake.

Espinoza et al. (2015) [37] discuss the social and cultural barriers, as well as public perceptions, that hinder further diffusion of CHP systems in the United States among wood sector producers. To this end, interviews were conducted with professionals and entrepreneurs to identify the main barriers cited by the industry. The main barriers include the high initial investment and the lack of government incentives.

Vieira et al. (2015) [38] conduct a case study to analyze the feasibility of implementing a biomass-based cogeneration system in the village of Cottown in Scotland. The potential for using local biomass in energy generation processes was investigated by assessing the heating value potential, availability, and technical and financial feasibility. The results indicate the large energy availability and high calorific value found in Phragnites Australis plantations on the banks of the River Tay, which could enable local strategies for the development of biomass-based thermal power plants.

Gholamian et al. (2016) [39] analyzed in great detail a novel cogeneration system including a biomass gasifier, a gas turbine, and a water heater. Therefore, exergetic analyzes were performed for each component of the system. The results show that the use of wood as biomass leads to energy efficiency up to 40.11%, with carbon dioxide emission of 4.99x10-2 t/MWh. The use of paper leads to an energy efficiency of up to 39.12% with an emission of 4.95x10-2 t/MWh.

Nzotcha and Kenfack (2018) [40] conducted a case study in Cameroon to investigate the capacity of the national wood processing industry to contribute to decentralized energy production. This study was based on the calculation and analysis of the techno-economic parameters of wood waste in CHP processes not only in Cameroon, but also with the aim of reaching conclusions that can be extrapolated to the entire sub-Saharan region.

The sensitivity analysis suggests an energy generation capacity of about 388 KWh per cubic meter of lumber. The study suggests that this type of cogeneration can generate up to 2,472 GWh of electricity in sub-Saharan Africa, assuming an estimated $2.5 billion is invested in the development of cogeneration systems in the region.

Abbas et al. (2020) [41] studied the different CHP systems for electricity and heat supply in isolated systems. For this purpose, the researchers carefully analyzed each type of CHP system technology in terms of efficiency and technological development status. It was found that steam turbine systems are the most suitable for biomass CHP systems due to their high efficiency and appropriate technological maturity.

Marchenko et al. (2020) [42] attempted to evaluate the effectiveness of biomass gasification plants in Russia, more specifically in the Irkutsk region, and compare them with other models of power and heat CHP systems. In the study, an economic analysis was carried out to compare the cost of electricity with other forms of energy production. The results of the calculations allow us to conclude that the cost of electricity using wood fuels is much lower than the cost of electricity generated in a diesel power plant, for example.

Therefore, in autonomous energy systems with low electricity consumption, energy supply by biomass gasification plants would prove to be a more suitable solution than the use of diesel power plants. In addition, it has been shown that wood-fired cogeneration plants can also successfully compete with coal- and gas-fired power plants as long as they use wood fuel that does not have penalty prices and is locally produced.

Gonzalez-Diaz et al. (2021) [43] studied the use of wood biomass in a gasifier. This study was based on calculations of efficiency indicators. The results show that it is possible to verify the existence of an enormous potential for energy production through a low-carbon cogeneration based on the use of wood in rural areas of developing countries.

National

Almeida et al. (2010) [44] conducted a study to analyze the characteristics of freshly slaughtered and stored pine patula waste preserved or uninfested by the wood wasp to enable a system for energy production. The method used was based on the Tillman method to calculate the lower heating value on a wet basis. The results show that the moisture value for the freshly slaughtered waste was 55.99%, while for the stored and wasp infested waste it was 26.20%. Moreover, the highest values for calorific value were 3,507.71 cal/g and 3,496 cal/g for residues from three months without wasp infestation and residues from one month with wasp infestation, respectively.

Seratto (2010) [45] investigates the technical and financial feasibility of a case study for the thermoelectric unit of Usina Santa Terezinha de Paranacity- PR, in order to take advantage of the unused capacity of the extraction and condensation thermogenerator system outside the shift and sugar season, by calculating economic and financial indicators such as IRR, NPV and payback, among others. The results show that the financial viability is achieved when the forest growing areas are up to 117.77 km away from the plant. The calculated payback reaches 10.49 years and the calculated NPV is R$ 10,489,586.13.

Gonçalves (2011) [46] studied the possibility of implementing a cogeneration system capable of generating heat to treat the pine wood nematode that causes the disease “pine wilt”, while allowing the generation of energy for sale to the public grid. A case study was conducted on a sawmill located in a district of Santarém, in the state of Pará, and the calculations of net present value, internal rate of return, amortization and sensitivity analyzes were performed. The results obtained show that one of the factors that most affect the economic viability of this type of projects is the reduced and insufficient operating time of these initiatives.

Santos (2011) [47] evaluated the economic feasibility of a biomass cogeneration system in a precipitated calcium carbonate factory located in the Midwest of Minas Gerais. For this purpose, the energy consumption and efficiency of the cogeneration system were analyzed using eucalyptus fuelwood biomass. The study shows the possibilities of energy self-sufficiency of the factory, indicating the total cost of the project in the order of R$2,585,00.00 to be recovered within 5 years.

The study by Furtado et al. (2012) [48] sought to assess the frequency of use and availability of forest biomass residues used in a cogeneration plant in Lagos, Santa Catarina State, between 2005 and 2009. For this purpose, analyzes of parameters such as moisture content, ash content, and calorific value were performed. The results obtained indicate that pine bark is more available, although the pine chips have a higher energetic efficiency.

The study of Pinheiro et al. (2012) [49] basically aims to investigate the results of the research and development program of Centrais Elétricas do Pará S/A – CELPA, entitled “Implantation of electricity generation systems to supply isolated communities in the Northern Region”, under the direction of the Federal College of Pará, in order to supply isolated communities with electricity through a decentralized system enabled by the direct combustion of biomass waste. The results indicate a monthly cost of approximately R$11,000.00. This type of system is described in the study as feasible as long as local labor and resources are used and sector policies are implemented to promote such a model.

The study by May et al. (2013) [50] on the feasibility of implementing sorghum-based power generation systems drew relevant conclusions when applying financial feasibility analysis. The results show that the cost of outsourced transportation of sorghum can vary so much from region to region that in some cases it is not feasible to use it as a primary energy source.

However, the data suggest that the use of desiccants can help reduce transportation costs. The analysis also estimates that the total production cost per hectare for the production of 35 tons of desiccant is R$3,393.93. Thus, considering the energy production per planted hectare of sorghum and the production costs, the business starts to cover the agricultural costs from R$ 27.79 MW.

Castro (2014) [51] had the task of quantifying the biomass stock of a eucalyptus forest and studying its feasibility in the processes of thermal and electrical energy production. For this purpose, a forest of Eucalyptus Urophylla X Eucalyptus Grandis with a cutting age of 79 months was studied. The energetic characteristics of the material and the performance of a cogeneration plant from carbonization gasses using a gas turbine with external combustion were considered. As a result, the high potential of waste from wood harvesting and charring for energy production was confirmed.

Dessbesell (2014) [52] studied both the environmental and economic aspects of producing pellets from sawdust in the Pardo River Basin. Samples were collected and chemical analyzes were performed, as well as calculations of indicators such as NPV, IRR, and others. The results confirmed the feasibility of the investment, with an NPV of R$4.72 million and an IRR of approximately 34.59%. It was also found that the pellets offer a biomass efficiency of up to 82.66% when drying tobacco.

Moraes and Zanella Júnior (2018) [53] attempted to propose a viable solution to reduce costs in companies that use steam generators, based on a case study of a company specialized in chicken protein production in rural Paraná. The findings obtained show that CHP systems require a longer payback period. In the case studied, a maximum payback period of 3 years and 8 months and a minimum payback period of 1 year and 7 months were found.

Ribeiro (2018) [54] conducted a long-term study to evaluate the technical and economic feasibility of energy production based on forest biomass, specifically in the form of eucalyptus wood chips, and to confirm the possibility that such an energy source could become a protagonist in the Brazilian energy matrix. A case study of a thermoelectric power plant with eucalyptus chips in the Viçosa- MG microregion was carried out, investigating capacities of 5, 10 and 20 megawatts

(MW) of gross installed capacity. A typical thermoelectric project with a capacity of 10 MW was also studied in a full commercialization scenario in the following scenarios: i) regulated market (ACR), ii) full commercialization in the free market (ACC) and iii) partial commercialization in both the regulated and free markets.

In all scenarios, the calculated ICBs remained within the average of the recent winners of the new energy auctions. However, in the free market, the risk is higher, but the NPV and IRR are higher (R$7.7 million and 20.4% p.a., respectively). Therefore, the work suggests that the expansion of forest biomass participation in the energy market depends largely on the readjustment of the criteria observed in energy auctions for forest biomass.

Deboni et al. (2019) [55] analyzed the quality of different types of forest residues and wood residues used for energy production in a cogeneration plant in the municipality of Lages, Santa Catarina State. For this purpose, the study evaluated 4,937 samples collected between 2005 and 2015. The results show that a mixture of sawdust, bark, and wood chips in cogeneration provides an improvement in fuel quality.

Nogueira (2019) [56] discussed the economic feasibility of siting a thermoelectric power plant in the municipality of Cachoeira do Sul RS given the significant amount of rice husks generated as waste in the local rice industry. For this purpose, the costs of rice production in the local mills were collected and this step was complemented by the calculations of IRR, NPV, among others, associated with the implementation of the project. The results show that the initial investment would be R$ 7.2 million. The identified financial indicators suggest the feasibility of the project and low environmental impacts.

Walker (2019) [57] investigates the economic feasibility of a continuous biodigestor associated with swine production. This involved developing a mathematical model and calculating economic-financial indicators. The results suggest that whether 1,000, 3,000, or 5,000 animal units are used, the returns achieved are positive. However, the conclusions suggest that the NPV is proportionally higher when 1,000 pigs are used.

Moraes and Abreu (2020) [58] conducted a long-term study to evaluate the degree of economic feasibility of using biodigestors to generate electricity with biogas produced by using waste from cattle, pigs, and poultry. For this purpose, indicators such as IRR, NPV, payback and others were calculated. All animal species were found to be promising, although pigs showed a higher technical return due to the higher daily production of biogas compared to the other animal species.

The study by Sales and Monteiro (2020) [59] aims to provide projections about the electric system and possible future scenarios. More specifically, projections were made for the years between 2027 and 2030, and the possibility of contracting energy and needed electricity was examined. The study contributes to the literature by proposing a new method for calculating the contribution of firm power to non-dispatchable water and renewable sources that allows the historical effect of flow to be included for run-of-river power plants.

The following tables summarize this review.

Table 2 - International Literature Review Table				
Year	**Author**	**Objective**	**Methodology**	**Results**
1982	Tillman and Jamison	Compare the technical feasibility between cogeneration and condensation systems.	Calculation and analysis of indicators for different projects	They point to the greater viability of cogeneration systems, as well as the strong viability of wood in this type of system.
1994	Gustavsson and Johansson	Compare different cogeneration processes in urban heating systems with other energy sources.	Calculation and analysis of indicators for different projects	They found evidence that biomass cogeneration systems are technically and economically more viable when other benefits such as reduced environmental impact are taken into account.
2001	Duval	To analyze the feasibility of implementing plants that use modern technologies of biomass cogeneration in Southeast Asia.	Estimation of atmospheric emissions from this type of plant in Indonesia, Malaysia, Philippines and Thailand.	They indicate a strong reduction in the emission of polluting gases in the Southeast Asian region with the implementation of modern biomass plants.
2002	Wahlund, Yan and Westermark	Investigate new techniques to optimize the performance of biomass cogeneration plants.	Case study situated between the municipalities of Skelleftea and Kraft in Sweden.	They indicate strategies that optimize biomass cogeneration systems in terms of energy efficiency.
2004	Mollersten et al.	Investigate the impact of the combination of CO_2 capture and storage processes as alternatives for the combined production of heat and energy in plants that use pulp and paper.	Calculation and analysis of indicators	They point to strategies that allow the capture of CO_2 within an integrated combined cycle biomass gasifier.
2008	Madlener and Vogtli	Propose the implementation of a cogeneration system to be replicated in Swiss territory.	Develop a schematic model that would be more viable on Swiss territory	They note the existence of political, social and technical conditions for the dissemination of cogeneration plants that use residues from regional forests.

Table 2 - International Literature Review Table				
Year	**Author**	**Objective**	**Methodology**	**Results**
2009	Dong, Liu and Riffat	Analyze the feasibility of spreading small and micro scale biomass power plants in the UK.	Calculation of technical and economic indicators	They show the feasibility of establishing small cogeneration plants in the United Kingdom, but reinforce the need to improve the technology used.
2015	Espinoza et al.	Evaluate the barriers of social, cultural and public perception that make it difficult to expand the cogeneration system in the US among producers in the timber sector.	Conducting interviews with experts and entrepreneurs	They indicate that among the main barriers identified are the high initial investment and the lack of government incentive policies.
2015	Vieira et al.	Analyze the feasibility of implementing a biomass cogeneration system in the village of Cottown in Scotland.	Calculation of technical and economic-financial indicators	They indicate the great energy availability and the high calorific value found in the *phragnites australis* plantations located on the banks of the River Tay.
2016	Gholamian et al.	Evaluate a biomass cogeneration system based on the use of a biomass gasifier, a gas turbine and a domestic water heater.	Carrying out calculations of exergetic indicators for each component of the system.	They show that the use of wood as biomass leads to an energy efficiency of up to 40.11%, with a carbon dioxide emission of 4.99 x10^{-2} t/MWh. The use of paper generates up to 39.12% of energy efficiency with an emission of 4.95 10^{-2} t/MWh.
2018	Nzotcha and Kenfack	Evaluate a case study in Cameroon to investigate the wood industry's capacity for decentralized energy generation.	Calculation and analysis of technical-economic parameters of wood residues in cogeneration processes.	The study suggests that this type of cogeneration can generate up to 2,472 GWh of electricity in Sub-Saharan Africa, provided that an estimated amount of US$ 2.5 billion is invested in the development of cogeneration systems in the region.
2020	Abbas et al.	Investigate the different cogeneration systems to supply electricity in isolated systems.	Comparison of different technologies applied in biomass cogeneration plants.	It was found that steam turbine schemes are the most appropriate for biomass cogeneration plants.

Table 3 - National Literature Review Table				
Year	**Author**	**Objective**	**Methodology**	**Results**
2010	Almeida et al.	Analyze the properties of freshly slaughtered and stored pine patula residues.	Application of the Tillman Method to calculate the net calorific value on the wet basis.	They demonstrate that the moisture value for the freshly slaughtered waste was equal to 55.99%, while that of stored and wasp-attacked waste was 26.20%.
2010	Seratto	Examine the technical and financial feasibility of a case study for the Thermoelectric Unit of Usina Santa Terezinha de Paranacity - PR.	Calculation of economic-financial indicators	They demonstrate that financial viability is achieved when the forest cultivation areas are located up to 117.77 KM from the plant. The calculated payback reaches 10.49 years and the NPV found was R$ 10,489,586.13.
2011	Gonçalves	Investigate the possibility of implementing a cogeneration system capable of generating heat to treat the pine wood nematode.	Carrying out a case study of a sawmill in a district of Santarém in the state of Pará, and carried out calculations of net present value, internal rate of return, payback and sensitivity analyses.	They indicate that one of the factors that most influence the economic viability of this type of project is the reduced and insufficient operating time of these initiatives.
2011	Santos	Evaluate the economic feasibility of a biomass energy cogeneration system in a precipitated calcium carbon plant, which is located in the center-west of Minas Gerais.	Calculation of energy consumption indicators and the efficiency of the eucalyptus firewood biomass cogeneration system.	They point to the achievement of energy self-sufficiency at the factory, with the total cost of the project quoted in the order and R$ 2,585,000.00 to be recovered within 5 years.
2012	Furtado et al.	Carry out a mapping of the frequency of use and availability of residues from forest biomass residues used in a cogeneration plant, between 2005 and 2009, in Lagos in the state of Santa Catarina.	Parameter analyses were carried out on moisture content, ash content, calorific value, among others.	They point to a greater availability of pine bark, despite the pine chip having a higher level of energy efficiency.
2012	Pinheiro et al.	Investigate the experience of the R&D Program of Centrais Elétricas do Pará S/A - CELPA.	Calculations of exergetic and economic-financial indicators.	They found evidence that biomass cogeneration systems are technically and economically more viable when other benefits, such as reduced environmental impact, are taken into account.

Table 3 - National Literature Review Table

Year	Author	Objective	Methodology	Results
2013	May et al.	Evaluate the feasibility of implementing plants for the generation of energy based on sorghum.	Calculation of economic-financial indicators	They demonstrate that the costs of outsourced transport of sorghum can fluctuate significantly between regions to the point of making its use as a primary source of energy unfeasible in some cases.
2014	Castro	Quantify the biomass stock of a eucalyptus forest and investigate its viability in the processes of thermal and electrical energy generation.	Study of a 79-year-old *eucalyptus urophylla x eucalypto grandis* forest, and technical efficiency indicators were calculated.	They indicate the high potential for forest harvesting residues from carbonization in energy generation.
2014	Dessbel	Investigate both environmental and economic aspects related to the production of pellets based on sawdust in the Rio Pardo Hydrographic Basin.	Samples were collected and chemical analyses were performed, as well as calculations of indicators such as NPV, IRR, among others.	They confirm the feasibility of the investment with an NPV of R$ 4.72 million and an IRR of approximately 34.59%. It was also identified that in the curing of tobacco, the pellets provide a biomass economy in the order of up to 82.66%.
2018	Moraes e Zanella Júnior	Suggest a feasible solution to reduce costs in companies that use steam generators.	Based on a case study in which a company specialized in the production of proteins derived from chicken, which is located in the interior of Paraná.	They suggest that cogeneration systems need a longer payback time, and in the case studied the maximum payback found was 3 years and 8 months and the minimum of 1 year and 7 months.
2018	Ribeiro	Evaluate technically and economically the feasibility of producing energy based on forest biomass in the form of eucalyptus chips.	A case study of a eucalyptus chip thermoelectric plant in the micro-region of Viçosa-MG was used with calculations of efficiency indicators. A typical 10 MW thermoelectric project in a full commercialization scenario was also investigated.	They suggest that the expansion of forest biomass participation in the energy market largely depends on the readjustment of the criteria observed in energy auctions for forest biomass.
2019	Deboni et al.	Analyze the quality of different types of forest residues and wood residues used in energy generation in a cogeneration plant located in the municipality of Lages in the state of Santa Catarina.	Evaluated 4,397 samples collected in the interregnum between 2005 and 2015.	They show that a mix of sawdust, bark and chips in energy cogeneration implies improvements in fuel quality.

Table 3 - National Literature Review Table				
Year	**Author**	**Objective**	**Methodology**	**Results**
2019	Nogueira	Discuss the economic viability of a thermoelectric plant station in the city of Cachoeira do Sul-RS in view of the substantial amount of rice husks generated as waste in the local rice industry.	Estimation of rice production costs in local mills, this step being complemented by calculations of IRR, NPV, among others.	They point out that the initial investment would be R$ 7.2 million and that the identified financial indicators point to the feasibility of the project and low environmental impact.
2019	Walker	Investigate the economic viability of a continuous biodigestor associated with pig farming.	Development of a mathematical model and the calculation of economic-financial indicators.	
2020	Moraes e Abreu	Investigate the level of economic viability of implementing biodigestors to generate electricity from biogas produced by using waste from cattle, pigs, and poultry.	Calculations of indicators such as IRR, NPV, payback, among others.	They show that all species were promising, although pigs had greater technical profitability due to higher daily biogas production compared to the other species.
2020	Sales e Monteiro	Make projections about the electricity system and possible future scenarios concerning the years between 2027 and 2030.	Realization of statistical projections and suggestions of mathematical models.	They indicated new ways of calculating the contribution of firm power to non-dispatchable hydro and renewable sources.

4. Methodology

First, we describe how the stakeholder approached the bid, analyzing what was the deciding factor for being one of the winners. In this case, it was the reference price.

Second, we deepen the analysis using an optimization approach that uses Linear Programming to obtain a higher revenue that the bidder could have obtained.

Description of the approach and perspective

Motivation

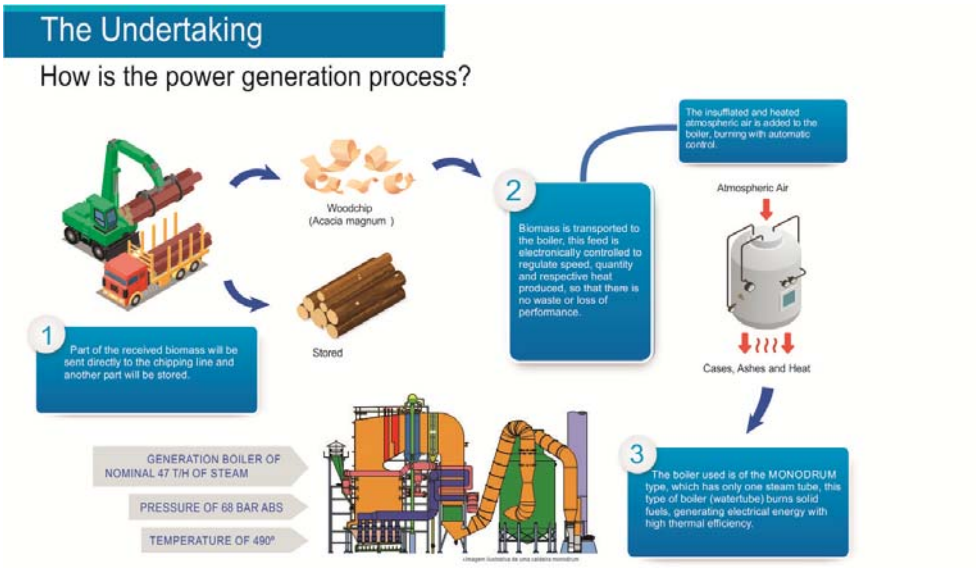
We examine how a particular woodchip power project won the 2019 auction in Roraima and is now operating three years later with a 15-year contract, even though the reference price formula was unfavorable for most biomass projects, and explain why it was unfavorable. This project is worth studying because the auction was preceded by an explicit analysis of the auction rules aimed at improving the benefits for stakeholders and avoiding the disadvantages of the reference price formula, which led to a better understanding of the stakeholders' perspective.

The underlying ideas may be applicable to similar projects to supplement hydropower plants by minimizing fluctuations in electricity generation, since Brazil is the largest eucalyptus producer in the world [60], the theoretical feasibility of which was analyzed by Ribeiro et al [61].

Acacia forest in Roraima – Picture 1:

Acacia forest in Roraima – Picture 2:

Schematics of the undertaking - Picture 3



Steam Turbine Model
Source: Technical Descriptive Memorial UTE Bonfim

4 The heat generated in the combustion chamber is absorbed by the water surrounding the chamber walls. The water changes from the liquid phase to superheated steam that drives a turbine that rotates at 9600 rpm and transfers energy to the generator through a speed reducer.

5 The generator, which is coupled to the turbine, uses mechanical energy to generate up to 10 MW of electrical energy.

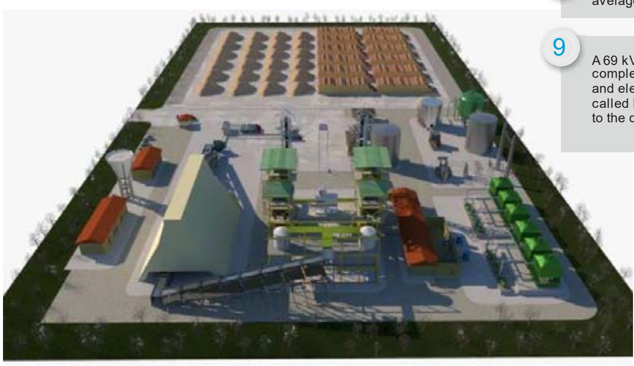
6 Gases from biomass burning will be retained in filters to ensure compliance with emission limits as determined by CONAMA Resolution No. 382/2006, Annex IV*

Emission limits for atmospheric pollutants from heat generation processes from the external combustion of wood derivatives, for thermal power between 10 and 30 MW.

7 Before the exhaust, a cyclone-type powder decanter will be installed. This will clean the particulate, so that at the exit of the chimney it does not exceed the current environmental determination.

8 The water for this process will come from an artesian well and its average consumption will be 40 m3/h for the boiler.

9 A 69 kV distribution line of approximately 25 km in length, complete with trusspole-type self-supporting metallic structures and electrical cables, connecting UTE Bonfim to the substation called Matá-Matá, to be built and subsequently transferred in part to the distribution concessioner.



3D design of the Bonfim Thermoelectric Plant (UTE).

With a thermal power of 10MW, the plant will produce energy for the public grid by burning plant biomass, which is a renewable source of raw material.rred in part to the distribution concessioner.

Source: https://femarh.rr.gov.br/wp-content/uploads/2022/10/RIMA_FINAL_BONFIM.pdf

Reference Price

The stakeholders owned an existing renewable reforestation (Acacia Mangium) of 22,275 ha that was originally intended for timber sales. However, the lack of electricity generation sources in Roraima could be exploited in a woodchip cogeneration project that would yield a much higher profit and solve a real challenge for the state.

The Reference Price, set by the Ministry of Mines and Energy [62] as mediator of the auction, is as follows. We quote:

Equation 1 – Reference Price

$$(1)\, P_{REF} = \frac{C_{other}}{f_c \times Pd_{\max} \times 8760} + \left(1 + \alpha \times \frac{F_{INFLEX}}{f_c}\right) \times C_{Fuel} + O\,\&\,M_{Var} + \left(1 - \frac{F_{INFLEX}}{f_c}\right) \times O\,\&\,M_{Var}$$

where

P_{REF} = Reference Price in R$/MWh;

C_{other} = Cost of Other Items, expressed in Reals per year (R$/year);

Pd_{max} = power availability of the supply solution in MW;

F_{INFLEX} = Under the Guidelines, the annual inflexibility factor associated with the inflexible energy amount, as defined by the proponent in the technical qualification process, which is limited to 50% (fifty percent);

f_c = 0.7;

α = 0.2 x f_c;

$O\&M_{Var}$ = Operation and Maintenance Cost of the Variable Portion, or Variable O&M, expressed in R$/MWh, and

C_{Fuel} = Fuel Cost, applicable both to inflexible generation and to generation above the declared Inflexibility, expressed in R$/MWh, with specific formulation for each type of fuel, that was presented in a Technical Report by EPE.

f_c and α are constants set by the regulatory authority that mediates the auction; all other items are set by the bidder before the auction begins and cannot be changed, except for item C_{other}, which can be changed during the auction.

In this case study, initially C_{other} was R$ 31,045,146.10 per year.

We now explain the components of the formula.

The Reference Price P_{REF} is intended to be an estimate of the future average electricity price effectively generated by each project participating in the Boa Vista and Connected Locations Auction, considering an annual period, and is measured in R$/MWh.

f_c is the capacity factor, as a dimensionless value or as a percentage, and Pd_{max} is the maximum available capacity. The product P_{REF}×8,760 can be defined as the maximum annual availability of the plant in MWh/year. Total annual revenues (TR) are divided into two components: fixed revenues (F_R) and variable revenues (V_R). Fixed revenues (F_R) are used to offset annual fixed costs, including the *costs of inflexible generation*, which are defined by the generator before signing the contract. These revenues exclude the costs resulting from dispatch contracts, where the power plant generates energy that exceeds inflexibility. It is worth noting that the declaration of inflexibility is only allowed for natural gas or renewable energy power plants, while the formula proposed in the Power product applies to all sources or technologies, such as diesel oil. However, in this case, it is considered as fully flexible generation.

Fixed revenues can be broken down into two parts: (i) the portion associated with fuel costs for inflexible power generation, F_R, in R$/year, and (ii) the portion associated with other items. The fixed revenues associated with fuel are composed of the product of the fuel cost C_{Fuel} in R$/MWh, the annual inflexibility factor F_{INFLEX} in percent, and the maximum annual availability of the power plant, i.e., the fixed revenues associated are $F_{INFLEX} \times C_{Fuel} \times Pd_{\max} \times 8{,}760$

Variable revenues (V_R), in turn, include the variable costs of the power plant resulting from the order of dispatch, i.e., the fuel cost C_{Fuel} and the operation and maintenance ($O\&M_{Var}$) costs of the variable portion, both measured in R$/MWh, or $V_R = O\,\&\,M_{Var} + C_{Fuel}$.

All the costs above are proportional to the variable generation period during the year, represented here by the larger value between the difference between the capacity factor f_c and the annual inflexibility factor F_{INFLEX} and zero. When the difference ($f_c - F_{INFLEX}$) is negative, it means that the power plant has received the financial value for the inflexibility of the fuel over the period of one year, but has not generated all the contracted energy related to this inflexibility. When this difference is positive, it is intended to reflect the portion of generation in the order of dispatch (or order of merit,) that is above the inflexibility.

We believe that the intent of the regulatory agency that issued this formula was to reduce inflexibility as much as possible while allowing energy buyers to use the expensive thermoelectric plants only when it is really needed.

To understand the implications of the formula, we need to rearrange the formula and then analyze it in more detail.

Analysis of the formula

After rearranging the formula to isolate inflexibility and assess its impact, the formula becomes:

Equation 2 – Reference Price

$$(2)\ P_{REF} = \frac{C_{other}}{f_c \times Pd_{\max} \times 8{,}760} + C_{Fuel} + O\,\&\,M - \frac{F_{INFLEX}}{f_c}\left(O\,\&\,M - \alpha \times C_{Fuel}\right)$$

All other constants and variables remaining the same, we see in the Equation 2 that the effect of inflexibility on the Reference Price depends on the sign of τ = (Variable O&M – *α**Fuel Cost). That is, the Reference Price increases with inflexibility when τ is negative and decreases when it is positive.

In auctions with fuel projects (excluding wind and hydro), Fuel Cost has historically been much larger than Variable O&M, the sign of the number τ= (Variable O&M – α*Fuel Cost) is negative and Inflexibility penalizes the Reference Price. For projects with zero inflexibility, this sign simply does not matter as the multiplying number is zero.

This means that a fossil fuel project with zero inflexibility can have a low reference price and win an auction because fuel costs and maintenance costs of the variable portion are independent factors in the reference price, although they depend on market prices.

With few exceptions, fossil fuel projects have low operating costs but high variable costs. As long as the energy generated is consumed only occasionally, the total cost to buyers can potentially be low, at least at the time of the auction and based on projected future energy use.

Inflexibility penalizes the reference price for almost all fuel projects, whether fossil fuel or biomass based. Inflexibility, however, is essential for the efficient and stable operation of certain biomass projects like ours.

Consequences for the stakeholder

In this case, however, declaring 50% inflexibility was the maximum allowed[8] and would result in a lower bid price if the declaration of Variable O&M and Fuel Cost was carefully chosen. Chosen is a key word here. Variable O&M and Fuel Cost are simply declared. The profitability of the project is entirely the responsibility of the bidder.

Also, in order to participate in the auction and win the bid, we needed to be able to produce energy at all times and still guarantee a minimum biomass flow to make the project profitable, and the 50% inflexibility was necessary for that.

So we declared the operation and maintenance cost as R$302.00/MWh, which was much *higher* than the actual cost, and a fuel price of R$85.00/MWh, which was much *lower* than the actual cost. Thus, the component (Variable O&M – *a**Fuel Cost) became positive and the inflexibility became an advantage since it allowed a lower reference price.

The reason why the formula was *favorable* in this case study is that our Variable O&M and Fuel Cost were incurred *together* and managed by the same energy provider and were not dependent on external market prices. In this way, it only mattered that both costs compensated each other in a profitable way, resulting in a positive difference for the number (Variable O&M – *a**Fuel Cost).

Unlike almost all fossil fuel based projects that have to buy fuel from third parties, our biomass was self-produced and we had control over the costs incurred. The above costs resulted in a positive value for the number (Variable O&M – Fuel Costs).

More importantly for our actions and analyses, sustainable energy matrices are no longer a matter of choice, but rather a matter of possibility and feasibility.

[8] According to article 6, §4, of MME Ordinance No. 512, of December 21, 2018, Power product supply projects whose primary sources are natural gas or renewables may declare inflexibility of annual generation limited to 50%.

This implies models based on systems that use low-carbon or renewable carbon to reduce the use of fossil fuels in energy production.

Biomass energy production has many advantages, first because it is based on renewable biological organisms, and second because it is well adapted to the biological conditions, soil and temperature in tropical developing countries, so it can be produced close to where it is consumed, generating income and jobs for local people;

We now perform a different analysis of Equation 2, but now under an optimization perspective.

Optimizing for profit of the energy provider

Let us review Equation 2:

$$(2)\, P_{REF} = \frac{C_{other}}{f_c \times Pd_{\max} \times 8{,}760} + C_{Fuel} + O\,\&\,M - \frac{F_{INFLEX}}{f_c}\left(O\,\&\,M - \alpha \times C_{Fuel}\right)$$

In this equation, the only control variables are $O\&M_{var}$ and C_{Fuel}, i.e., those are the *only* variables that the bidder can set the value *before* the auction begins. The bidder can also control C_{other}, that is defined before the auction, but that can be changed *during* the auction, so we consider it a constant.

The total annual revenue for the inflexible generation is equal to C_{other} plus C_{Fuel} times the inflexible generation (85 x 8,163 x 50% x 8760 = 3,039,084.90). This way, we change our initial declaration of C_{other} to R$ 34,084,231.00 (R$ 31,045,146.10 plus R$ 3,039,084.90).

Now suppose that for some reason the bidder believes that a certain value of P_{REF0} can win the auction, or at least is close enough so that during the auction C_{other} can be used to fine tune P_{REF}.

Let us define D_{OI} as the average energy dispatched per year above the inflexibility level, expressed as a percentage of the remaining maximum power available above the inflexibility level.

This variable D_{OI} is a *random variable* that will change significantly over the life of the contract and is essentially unknown, but for which the energy generator must be prepared for.

Since this additional energy dispatched is unknown, the bidder must be prepared for the worst scenario of no additional energy dispatched at all.

Under this perspective, a safe solution is to increase the initially declared C_{other} in order to cover all its fixed costs, including the operation at inflexibility level only, so this is why we change our initial declaration of C_{other} from R$ 31,045,146.10 to R$ 34,084,231.00.

Let us call P_{ED} the bidder's estimated revenue per year. It can be calculated as

$$P_{ED} = D_{OI} \times (1 - F_{INFLEX}) \times 8760 \times Pd_{\max}(O\&M_{\text{var}} + C_{Fuel}) + 8760 \times F_{INFLEX} \times Pd_{\max} \times C_{Fuel}$$

However, D_{OI} is essentially *unknown*. The only remaining parcel that can be maximized is the parcel multiplying D_{OI}, i.e. $(1 - F_{INFLEX}) \times 8760 \times Pd_{\max}(O\&M_{\text{var}} + C_{Fuel})$. The annual cost of operating at inflexibility level only should *not* be considered at all, since it is already covered by C_{other}.

In terms of Mathematical Programming, this problem can be stated as Linear Programming Program (LP), a very traditional and widely used tool in optimization.

Linear Programming is a mathematical optimization technique used to find the best possible solution to a problem with linear constraints and a linear objective function. It is a tool that allows decision makers to allocate limited resources as efficiently as possible. Linear Programming is widely used in fields such as economics, engineering, and operations research to solve problems involving the optimal allocation of resources.

The basic idea of Linear Programming is to represent a problem in terms of a set of linear equations and inequalities, and then find the optimal solution by maximizing or minimizing a linear objective function given these constraints. The constraints and objective function can be represented graphically as a system of linear equations and inequalities, and the optimal solution can be found by identifying the intersection of the feasible region with the objective function.

The advantages of linear programming include the ability to solve complex problems with many variables, the ability to optimize solutions in a systematic and quantitative manner, and the ability to incorporate various constraints and restrictions into the problem formulation. Linear Programming is also an important tool for decision making in the presence of uncertainty, as it allows decision makers to evaluate different scenarios and determine the best course of action.

This LP problem can be stated as

$$\begin{cases} \max(1-F_{INFLEX})\times 8760\times Pd_{\max}(O\&M_{\text{var}}+C_{Fuel}) \\ s.t. \\ \dfrac{C_{other}}{f_c\times Pd_{\max}\times 8760}+C_{Fuel}+O\&M-\dfrac{F_{INFLEX}}{f_c}(O\&M_{\text{var}}-\alpha\times C_{Fuel})\leq P_{REF0} \\ C_{Fuel}\geq 0,\ \ O\&M_{\text{var}}\geq 0 \end{cases}$$

As an example, in the case of the Uniagro Bonfim project, which were one of the projects under our analysis, the fixed parameters were

$$Pd_{\max}=8163,\ f_c=0.7, C_{other}=34084231, P_{REF0}=800,\ F_{INFLEX}=0.5, \alpha=0.14$$

Our LP problem is now

$$\begin{cases} \max 0.5\times 8760\times 8.163\times(O\&M_{\text{var}}+C_{Fuel}) \\ s.t. \\ \dfrac{0.5\times C_{Fuel}}{0.7}-\dfrac{34084231}{0.7\times 8.163\times 8760}+C_{Fuel}+O\&M-\dfrac{0.5}{0.7}(O\&M_{\text{var}}-0.14\times C_{Fuel})\leq 800 \\ C_{Fuel}\geq 0,\ \ O\&M\geq 0 \end{cases}$$

Since there are only two variables *O&M*$_{\text{var}}$ and C_{Fuel}, we can use the Simplex method[9], and the optimal result is *O&M* = 416.75 and C_{Fuel} = 0!

Replacing these values in the formula, we obtain exactly the desired value 800 for P_{REF0}.

The associated variable revenue for additional dispatch is 416.75 R$/MWh, quite above our actual value of 387.00 R$/MWh, resulting in R$ 29.75 for each MWh dispatched above the inflexibility level. The total fixed revenue also increased to R$ 34,084,231.00. In any case, regardless of the level of dispatch above the inflexibility, the price for the consumer would increase significantly.

Something is very wrong here! There must be serious errors, either in the model we have shown with its embedded ideas, or in the concepts behind the regulator's formula.

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[9] This method is available in Excel.

In any case, we have taken a more conservative approach to the values in or bid, $O\&M_{var}$ = 302 and *CFuel* = 85. These values cover the different scenarios, with sufficient profit.

The reasons why we did not pursue a more aggressive optimization approach are, first, that there was a possibility that the regulator ANEEL would suspect some kind of fraud behind the bid (which was *not* the case) and would stop the auction as soon as we declared a zero in fuel costs before the auction, even though all the rules were followed and the reference price would be a winning price; second, we did not want our total fixed annual revenues to be "excessive" or our fuel costs to be "too low," whatever that might mean.

Our interpretation is that the formula has a serious flaw. It regulates the price that is decisive for the auction and thus, in a sense, sets an upper limit for the reference price. However, as long as $O\&M_{var}$, C_{other} and *CFuel* can be freely chosen, and as long as the rules and the formula for the reference price are respected, there is nothing to prevent a bidder from applying the optimization models we propose, and reaching similar conclusions, regardless of what the final price paid by the consumer would be.

Our comments above are consistent with Matthew's [2] findings that "pre-qualifications and penalties drive realization rates, while technological banding or the pricing rules do not affect effectiveness."

5. Auction results

Below we can see the actual auction results:

Table 4 - Seller Summary

Owner	CNPJ	Supply Solution	C.E.G.	Connection Point	UF	Type	Source	Investment Value (R$)	Nominal power (MW)	Supplementary Capacity (MW)	Power Availability (MW)	Inflexible energy (MWm)	Reference Price (R$/MWh)	Total Inflex (MWh)	Fixed Revenue Other Items (R$/Year)	Fixed Revenue (R$/Year)
Power Product – Other Sources – POT-DF-2021-07																
OLIVEIRA ENERGIA GERAÇÃO E SERVIÇO LTDA	04.210.423/0001-97	MONTE CRISTO SUCUBA	UTE.PE.RR.044653-0.01	SUCUBA-69	RR	OLEOD	Diesel oil	126,983,750.00	42.255	0.000	38.116	0.000	1,059.17	0.000	11,875,801.00	11,875,801.00
Total								**126,983,750.00**	**42.255**	**0.000**	**38.116**	**0.000**		**0.000**	**11,875,801.00**	**11,875,801.00**
Power Product – Gas and Renewables – POT-GR-2021-15																
AZULÃO GERAÇÃO DE ENERGIA S/A	30.185.130/0001-07	JAGUATIRICA II	UTE.GN.RR.044619-0.01	BOA VISTA-230	RR	GAS	Natural gas	425,410,800.00	126.290	0.000	117.040	0.000	798.17	0.000	429,300,196.62	429,300,196.62
BRASIL BIO FUELS S/A	09.478.309/0001-66	BBF BALIZA	UTE.AI.RR.044586-0.01	SAO JOAO DA BALIZA-69	RR	HIBG	Biofuel + Biomass	97,416,022.00	17.616	5.000	13.310	6.655	670.00	875,105.880	2,456,914.14	35,784,017.46
BRASIL BIO FUELS S/A	09.478.309/0001-66	HÍBRIDO FORTE DE SÃO JOAQUIM	UFV.RS.RR.044589-4.01	BOA VISTA-69	RR	HIBG	Biofuel + Solar Radiation	537,759,883.00	56.218	36.300	51.420	25.710	825.00	3,380,762.160	6,069,352.91	168,995,463.74
ENERPLAN PONTAL PARTICIPACOES SOCIETARIAS S/A	17.184.806/0001-80	PALMAPLAN ENERGIA 2	UTE.BL.RR.044588-6.01	RORAINOPOLIS-34,5	RR	BIO	Biofuel	70,355,713.00	11.490	0.000	10.976	0.000	820.67	0.000	12,805,487.50	12,805,487.50
UNIAGRO COMÉRCIO DE ENERGIA LTDA	32.379.723/0001-30	BONFIM	UTE.FL.RR.044603-3.01	BONFIM-69	RR	BIO	Wood Chips/Waste	98,600,000.00	10.000	0.000	8.163	4.081	800.00	536,635.176	31,045,146.10	34,084,231.00

Owner	CNPJ	Supply Solution	C.E.G.	Connection Point	UF	Type	Source	Investment Value (R$)	Nominal power (MW)	Supplementary Capacity (MW)	Power Availability (MW)	Inflexible energy (MWm)	Reference Price (R$/ MWh)	Total Inflex (MWh)	Fixed Revenue Other Items (R$/Year)	Fixed Revenue (R$/Year)
UNIAGRO COMÉRCIO DE ENERGIA LTDA	32.379.723/0001-30	CANTÁ	UTE.FL.RR.044604-1.01	BONFIM-69	RR	BIO	Wood Chips/ Waste	113,500,000.00	10.000	0.000	8.163	4.081	800.00	536,635.176	31,045,146.10	34,084,231.00
UNIAGRO COMÉRCIO DE ENERGIA LTDA	32.379.723/0001-30	PAU RAINHA	UTE.FL.RR.044605-0.01	BOA VISTA-69	RR	BIO	Wood Chips/ Waste	76,500,000.00	10.000	0.000	8.163	4.081	754.00	536,635.176	28,742,592.37	31,781,677.27
UNIAGRO COMÉRCIO DE ENERGIA LTDA	32.379.723/0001-30	SANTA LUZ	UTE.FL.RR.044606-8.01	BOA VISTA-69	RR	BIO	Wood Chips/ Waste	76,500,000.00	10.000	0.000	8.163	4.081	754.00	536,635.176	28,742,592.37	31,781,677.27
Total								1,496,042,418.00	251.614	41.300	225.398	48.689		6,402,408.744	570,207,428.11	778,616,981.86

Grand total

Nominal power (MW):	293.869	Power Availability (MW):	263.514	Total Inflex (MWh):	6,402,408.744	Inflexible energy (MWm):	48.689
Supplementary Capacity (MW):	41.300	Investment (R$):	1,623,026,168.00	Supply Solution (No.):	9	Energy Lot:	0.1 Mwaverage

For the Uniagro projects that we helped develop, the reference price for the above operating and fuel costs was R$800.00 MWh for the Bonfim connection projects and R$754.00 MWh for the Boa Vista connection projects.

The Reference Prices of the winning projects are shown in the table below.

Table 5 - Reference Price (P_{Ref}) (R$/MWh)

	Oliveira	Azulão	BBF	BBF C	Enerplan B	Uniagro – Boa Vista	Uniagro – Bonfim	
P_{ref}	1,059.17	798.17	670.00	825.00	820.67	800.00	754.00	*R$/MWh*
Rf_{total}	11,875,801.00	429,300,196.62	35,784,017.46	168,995,463.74	12,805,487.50	34,084,231.00	31,781,677.27	*R$/year*
Rfother	11,875,801.00	429,300,196.62	2,456,914.14	6,069,352.91	12,805,487.50	31,045,146.10	28,742,592.37	*R$/year*
$P_{d.max}$	38.116	117.040	13.310	51.420	10.976	8.163	8.163	*MW*
F_{inflex}	0%	0%	50%	50%	0%	50%	50%	*Percentage*

	Oliveira	Azulão	BBF	BBF C	Enerplan B	Uniagro – Boa Vista	Uniagro – Bonfim	
f_c	0.7000	0.7000	0.7000	0.7000	0.7000	0.7000	0.7000	*Constant*
α	0.1400	0.1400	0.1400	0.1400	0.1400	0.1400	0.1400	*Constant*
$O\&M_{var}$	-	-	38.71	35.00	-	302.00	302.00	*R$/MWh*
C_{Comb}	1,008.36	200.00	571.67	723.41	630.41	85.00	85.00	*R$/MWh*
Total hours	8,760	8,760	8,760	8,760	8,760	8,760	8,760	*Hours/year*

According to project data

According to the auction system

RF_{other}: Fixed income linked to other items

$P_{d.max}$: Maximum available power

F_{inflex}: Annual inflexibility factor

f_c: Capacity factor

α: trade-off between fuel cost and flexibility for system operation.

$O\&M_{var}$: Operation and maintenance cost of the variable portion

C_{Comb} : Fuel cost

Total hours: Total hours for a year

For exercise purposes, if we exchange the value of the operation and maintenance costs with the value of the fuel costs (keeping the R$387.00 MWh indicated for the variable part), we obtain a reference price for the Bonfim project of R$976.70 and for the Boa Vista project of R$930.70 MWh, all other conditions remaining the same.

As an example, we can apply the same optimization to the BBF projects and show some interesting results.

As mentioned above the variable revenue can be expressed as $V_R = O\&M_{Var} + C_{Fuel}$.

The BBF projects both declare the following variable revenue:

BBF Baliza:
O&M$_{var}$ of R$ 38.71 MWh
C_{Fuel} of R$ 571.67 MWh
Variable Revenue of R$ 610.38 MWh
Total Annual Revenue: R$ 35,784,017.46
P_{REF}: R$ 670.00 Mwh

BBF Hibrido Forte de São Joaquim:
O&M$_{var}$ of R$ 35.00 MWh
C_{Fuel} of R$ 723.41 MWh

Variable Revenue of R$ 758.41 MWh
Total Annual Revenue: R$ 168,995,463.74
P_{REF}: R$ 825.00Mwh
The Total Annual Revenue for the inflexible generation is equal to C_{other} plus C_{Fuel} times the inflexible generation as mentioned above. So if we keep the same variable revenue to the projects and make C_{Fuel} equal to zero, and keep the same P_{REF}, we would have the following $O\&M_{\text{var}}$ and Total Annual Revenue:

BBF Baliza:
$O\&M_{\text{var}}$ of R$ 610.38 MWh
Total Annual Revenue: R$ 40,449,811.93
P_{REF}: R$ 670.00 Mwh

BBF Hibrido Forte de São Joaquim:
O $O\&M_{\text{var}}$ of R$ 758.41 MWh
Total Annual Revenue: R$ 191,805,119.26
P_{REF}: R$ 825.00Mwh

So with the same winning P_{REF}, BBF have won the auction they could be making an additional C_{other} of R$ 27,475,450.00 per year (BBF Baliza = R$ 4,665,794.47 and BBF Hibrido Forte de São Joaquim = R$ 22,809,655.53). In the 15 year contract we are talking about R$ 412,131,750.00.

This value is very revealing because it shows, for a winning project where the optimization model was not used, how much money could be lost in consumer efficiency if only the same P_{REF} equation was applied.

6. Conclusions

We chose not to examine the differences in carbon footprints between biomass and natural gas or diesel power plants, as these have been extensively studied in previous works. However, such effects should be considered in public policy because the decision to introduce reserve energy/electricity should take into account not only the financial social cost of the flexibility gain, but also the social cost of replacing a renewable energy source with a fossil one when both can solve the same problem (reserve/electricity). In addition, Duval [63] has shown that the use of biomass cogeneration reduces emissions, as compared to other carbon sources.

From the regulator's point of view, it is clear that the option of inflexible generation can be beneficial for the power producer, as it provides greater predictability in the management of fuels and power generation, as greater inflexibility is declared. As a result, inflexibility can translate to lower electricity generation prices, primarily due to lower fuel costs.

On the other hand, inflexible generation may penalize generation when the order of economic merit is applied by the regulator, which aims to match supply to demand through the sequential dispatch of plants with lower operating costs.

Now from the operator's point of view, the less inflexible the thermoelectric plants are, the more robust the optimization of system operation with the objective of minimizing the total cost to the electricity consumer.

Qualitatively, it is possible that a thermoelectric power plant with less inflexibility, even if it has higher fuel costs (which directly affects the higher price of its electricity generation), enables the system operator to generate more economically overall due to greater autonomy in portfolio management over a given period.

In addition, the regulator's argument for the Roraima auction [20] was that it must be taken into account that contracting inflexible generation has an impact on the maximum amount contracted in the Energy product, i.e., the more inflexible generation contracted in the Power product, the less energy can be contracted in the Energy product to avoid overproduction, which would lead to additional costs for the consumer.

Yet, only 48.69 MW of inflexible energy was contracted in the auction, representing 1/6 of the state's demand, and the regulator decided not to contract any energy product in the auction, so the expectation ended up being to generate energy via power product. This weakens the regulator's argument.

Although the intent of the regulator was to create a P_{REF} equation that would optimize the flexibility, they ended up with a completely different result. Expectations regarding future energy use, hydropower development, or even a future connection to the power grid were all wrong.

Another important flaw is that as long as the bidder can freely declare the costs $O\&M$ and C_{Fuel}, with no upper limitation to $O\&M$, the reference price can be adjusted to any number, subject only to the price that the bidder estimates that can win the bid.

Inflexibility aside, Uniagro Bonfim and Azulão projects have an almost identical P_{REF}, but the variable cost of Bonfim is almost twice the variable cost of Azulão. If only economic efficiency is considered, this is a distortion.

This is relevant only to point out that the PREF formula had an important flaw — namely, that as long as the bidder can freely declare the cost of *O&M* and C_{Fuel}, and there is no cap on O&M, the reference price can be adjusted to any number, subject only to the price that the bidder estimates that can win the bid.

This does not preclude the regulator from setting up special auctions for woodchip projects to feed into the grid. As mentioned earlier, Brazil is one of the largest producers of eucalyptus, and the switch from fossil fuels (including natural gas) to renewable energy is imperative with respect to the environment.

Inflexibility is essential for the development of woodchip cogeneration projects to ensure the flow and availability of biomass. In a scenario where the regulator has decided to penalize inflexibility, and where the project developer is doing both power generation and feedstock production, we can sometimes find a way to achieve very competitive prices by avoiding the penalty formula. The ideal, however, is that we do not have to find workarounds, but that the regulator establishes affirmative policies that allows it.

A future challenge for this work is to review the technical and economic parameters when and if the isolated system of Roraima is connected to the

National Interconnected System, and a future work is to perform a similar analysis for connected systems with renewable eucalyptus.

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