Sustainable Futures 8 (2024) 100332

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Decommissioning of a fuel oil-fired thermoelectric power plant in Brazil - Economic feasibility under certain and risk conditions

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ARTICLE INFO

Keywords:
Decommissioning
Energy security
Energy transition
Decision making

ABSTRACT

The strategic analysis for the decommissioning of thermoelectric plants is seen as a trend for the coming years. The search for renewable alternatives should stimulate investment in other energy sources, reducing the number of thermoelectric plants in the energy generation system. However, few studies have dealt with the decommissioning of oil-fired thermoelectric plants. In this work, the methodology was applied under deterministic and stochastic conditions using methods of net present value (NPV), internal rate of return (IRR), discounted payback, capital asset pricing model (CAPM) and weighted average cost of capital (WACC). The results showed that the deterministic NPV was positive, ranging from R$101.30 million (pessimistic scenario) to R$109.73 million (optimistic scenario). The IRR was higher than the WACC of 10.55 %, ranging from 13.50 % to 13.68 % per year. For the Monte Carlo simulation, NPV was observed with 100 % certainty of viability and the probabilities of occurrence allowed more analysis of the risks involved than those obtained by deterministic methods. this study contributes to future decommissioning projects in Brazil, considering the scenario of stimulating renewable sources and the energy transition, helping managers make decisions about their projects. In addition, it helps guide public policies that can optimize the decommissioning process and strengthen the national energy sector.

1. Introduction

Looking at the history of the Brazilian Electricity Sector (SEB), it is possible to identify significant occasions for the inclusion of thermoelectric plants in order to meet the needs of expanding the supply of electricity in the National Interconnected System (SIN). Until the 2000s, the system was eminently hydroelectric, with marginal support from thermoelectric plants in situations of low affluence. As a result of the water shortage, there was a need to diversify the energy matrix through other energy sources, opting for regulated contracting of thermoelectric plants powered by fuel oil, accelerating generation capacity and balancing supply and demand for electricity, and encouraging the insertion of renewable sources [1-3]. With growing concern about the dependence on and problems caused by the use of fossil fuels for the environment, new ways of producing and consuming energy have been observed. Therefore, there is a great effort to develop more and more alternatives to meet energy demand with minimal externalities. This view directly affects the agents that operate using polluting sources, the

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https://doi.org/10.1016/j.sftr.2024.100332
Received 13 May 2024; Received in revised form 16 August 2024; Accepted 1 October 2024
Available online 6 October 2024
2666-1888/

thermoelectric power plants. For the *International Atomic Energy Agency* (IAEA), fossil fuel power plants are at the end of their operating cycles and will face permanent shutdown in the near future [4,5].

Therefore, this paper seeks to fill this gap by investigating the economic viability of decommissioning a fuel oil thermoelectric plant and identifying the main challenges and considerations associated with this process. In Brazil, the share of thermoelectric plants in total generation has been falling in recent years, especially with regard to oil-derived sources. While other sources of thermoelectric generation, such as natural gas, biomass, nuclear and coal, have shown growth, the share of plants powered by oil derivatives has fallen significantly. In concrete figures, between 2010 and 2020, the share of oil derivatives in total energy generation fell from 14.6 % to 7.8 %. In a shorter interval, from 2018 to 2019, electricity generation in gigawatt hours (GWh) from oil derivatives fell from 9293 to 6926, representing a drop of 25.5 % [6].

This change in scenario presupposes a trend and strategic vision aimed at reducing thermoelectric plants using oil-derived sources, which has led to the termination of energy supply contracts. In view of this, all that remains is for projects to plan for decommissioning, i.e. the final phase of their life cycle. For the business to be economically viable, it is essential that the assets outweigh the costs of the entire closure process. This process takes into account the facilities, location, initial investment, construction and all the operations involved in the project [7]. When making the decision to decommission, it is inevitable to have a period of negative cash flow, i.e. decommissioning projects prevent any revenue generation. In the future, such projects could lead to financial problems, which in turn directly impact the environment, among other socio-economic aspects, even affecting the workers who are part of the projects [5,8,9].

Currently, there are several reports and experiences on decommissioning in sectors such as oil, gas, wind, solar, mining, and especially nuclear power plants [10]. Studies of the nuclear sector have been the most significant, being common in South Korea, Russia and Germany [11]. For the Brazilian case, Monteiro et al. [12] developed a Novel management tool, including a mathematical model, for decommissioning cost estimation for power plants, and more recently Monteiro et al. [13] improved the decommissioning model by adjusting it for multiple reactors. Haggerty et al. [14] carried out planning studies for coal-based companies in the United States and found political instruments to be the main difficulty in decommissioning towards an energy transition. Another article that also presented decommissioning costs for coal was carried out by Qvist et al. [15] in Poland. For oil and gas, Raimi et al. [16] provided new cost estimates for decommissioning oil and gas wells in the United States.

The common characteristics of decommissioning projects generally involve large volumes of investment, environmental, economic, social and infrastructure impacts. These projects offer a strategic vision for fuel oil-fired thermoelectric plants, a scarce topic in national and international literature. In the coming decades, other projects will face closure due to their useful life cycles. Their tailor-made structures make decommissioning extremely complex and difficult to monitor [17,18]. Around the world, several countries have sought to strengthen laws and good practices for decommissioning projects. The Netherlands has included a master plan with circular economy principles [19]. In the UK, decommissioning plans integrate new renewable energy infrastructure [20].

The lack of specific policies on the decommissioning of Brazilian thermal power plants leaves the environment with many uncertainties for the near future, where closure will be inevitable. Understanding the challenges aims to mitigate economic, social and environmental problems. Policies must consider technical, legal, economic, social and environmental issues [21]. According to Gitman [22], investment projects presuppose the existence of risks. It is therefore necessary to plan actions and use the best methods to analyze economic viability. In Brazil, no study has evaluated the economic impacts of decommissioning these thermoelectric plants. Understanding the potential economic implications, especially in a scenario with so many uncertainties, is indispensable for national operators and the results obtained can support companies that will soon be going through this process, as well as being a pathway for public managers and investors related to the electricity sector.

This article analyzed the economic viability of decommissioning a fuel oil thermoelectric plant in Brazil at the end of its energy supply contract. The Free Cash Flow for the Firm (FCFF) method was used to estimate the value of the plant. For decision making, under deterministic criteria, the Net Present Value (NPV), Internal Rate of Return (IRR) and Weighted Average Cost of Capital (WACC), indicated by Gitman [22], Lapponi [23] and Assaf Neto [24], were used. The risks and uncertainties involved in the project were measured using Monte Carlo simulation by evaluating the variables considered most critical within the model [25].

2. Material and methods

The study was carried out at a power station made up of two fuel oil-fired Thermoelectric Units (TPUs) in northeastern Brazil. Located in João Pessoa - PB, Brazil, it has an installed capacity of 342 MW and a site of 800,000 m^2. To analyze decommissioning, considering the risks and uncertainties, we used the Balance Sheet (BS), the Income Statement (IS), and the thermoelectric plant's management information for the period from 2010 to 2020. The values of the historical series were deflated by the National Consumer Price Index (NCPI). A decommissioning plan was drawn up to analyze the project and construct possible scenarios in order to obtain the residual value at the end of the contract. The cash flow projections (2021 to 2024) took into account the revenue estimates of the company's management. To determine the economic value, the Free Cash Flow for the Firm (FCFF) was applied, discounted by the Weighted Average Cost of Capital (WACC).

2.1. Financial statements

The raw BS and IS data was processed, classified and grouped into expenses and income in order to extract detailed information for each type of entry. The data was tabulated year by year, creating a historical cash flow series. The recommendations of Penman [25], Matarazzo [26], Salotti et al. [27] were followed. After a preliminary investigation of the plant, the Vertical and Horizontal Analysis technique was used, due to its ability to relate accounts and project scenarios [25,26]. All BS and IS accounts for the period from 2021 to 2024 were projected using the average of the last 5 years of operation, with the exception of the "other income/expenses" and "gross operating income" accounts, which took into account management's future projections.

The assets accounted for between 2010 and 2020 were classified and separated into classes. To estimate the useful life and depreciation rate of the assets, the National Electric Energy Agency (ANEEL) table was used using the straight-line method (Eq. (1)), in which depreciation occurs constantly over time [28].

$$D = \frac{1}{N}(P - S) \tag{1}$$

where, P represents the initial value of the asset, S is given by the residual value and N is the useful life of the asset. When calculating depreciation, it is necessary to include the asset's residual value, i.e. the value that the asset represents for the company even after it has been fully depreciated, representing the company's estimated receipt from future sales after the end of its useful life [28].

Due to the difficulty in estimating the residual value, it was assumed that the assets would have a value of zero. However, the estimated residual values were included in the decommissioning plan in 2024, at the end of the contract. During the analysis, due to the plant's strategic decision, from 2020 onwards all the amounts to be depreciated were adjusted at the end of the contract, leaving the balance at zero in 2025. The IS shows the plant's operating expenses, identifying how much the company spends to generate energy in each account: Energy purchased for resale; Transmission charges; Raw materials and inputs for production; Personnel (social charges, vacations, terminations, profit sharing, and other expenses); Administrators; Materials; Third-party services; Leases and rentals; Insurance; Donations and contributions; Provisions; Losses, disposal and decommissioning of assets; Recovery of expenses; Taxes; Amortization; and Miscellaneous expenses.

2.2. Firm's free cash flow (FCFF)

The FCFF is widely used in cases of going public, analyzing new investments, consultancies, mergers, spin-offs, buying and selling shareholdings and determining the "fair price" of a share. It consists of recording the inflows and outflows of a given investment, showing the company's operating profit after tax, reduction of investments in working capital, equipment, facilities and other assets of the company's operation. The method guarantees sophistication and reliability in estimating the value of the company, since it is based on a rate, reflecting the level of risk of the cash flow, as well as including important parameters such as the risk of the investment [29,30]. The structure of the FCFF is shown in Table 1. To estimate and evaluate the FCFF, revenue, investments in fixed assets and intangibles and the Working Capital Requirement (NCG) were accounted for, based on Matarazzo [26] and Penman [25]. Depreciation, despite being a cost or expense, should be added to the cash flow as it does not represent a cash outflow [24].

2.2.1. Decommissioning plan

The decommissioning plan was divided into four groups: assets (real estate, inventories and fixed assets); environmental costs (estimates for decommissioning); financial and tax costs; and legal demands (labor, tax, contract terminations and closure of the National Register of Legal Entities - CNPJ). Fig. 1 shows the decommissioning plan for planning and simulating three scenarios (pessimistic, more likely, optimistic) after the end of the energy supply contract. Among the plant's assets, property, plant and equipment were surveyed in accordance with the financial statements. Legal issues made it impossible to obtain a reliable value for the property, since the company did not provide clear information about the future of the development. The exclusion was deemed necessary to ensure that the study was conducted on the basis of reliable information available at the time of the analysis. Real estate was removed from the analysis because it involved strategic matters for the plant and specific legal discussions, making it difficult to analyze in the period. Inventories (fuels and lubricants) will be analyzed at the value represented in the plant's assets. The importance of the stock is measured in relation to the physical volume and its participation in the total investments made. Based on the data analysis, it was possible to select the most representative assets by applying the ABC curve method [24].

Carvalho [31] classifies stock into three categories: A, B and C. Category A includes all the assets that require greater investment and, consequently, greater management. They generally have a low turnover and a highly significant stock volume. Category B contains assets that require less control. Finally, the items listed in category C are of low representativeness and do not require greater care. Fig. 2 shows the graphic classification of the ABC curve.

The environmental costs were calculated using specialized consultancy services and technical estimates provided by the company itself. Among them, a number of steps were observed in the cost-effectiveness analysis: decommissioning plan for submission to the environmental agency; environmental investigation of the soil and groundwater, groundwater monitoring, decommissioning report, and hazardous waste disposal. The estimates were included in the decommissioning calculation. In terms of taxes, there are particularities involving the land and legal obstacles with the state government. However, the credits and debits were collected from the available accounting data in order to estimate the impact of decommissioning. The plant has the Sudene benefit granted by the federal government, which reduces income tax payable by 75 %. However, there is a lot of uncertainty about the law that governs the benefit, leaving open the treatment to be given in cases of decommissioning of the enterprise. In a conservative scenario, accounts to be returned to Sudene should be included. Therefore, the benefit was not included in the decommissioning results.

The costs of legal proceedings were identified on the basis of reports from the plant's legal department, where it was possible to draw up three scenarios (probable, possible and remote) for all legal spheres. Also within this legal scope, it was identified that there will be no fines and/or contractual costs for ending operations. At the stage comprising the initial investment (2010), the income statement was not presented, so this information was collected based on the balance sheet for the period analyzed. During the study, percentage contingency values were included for direct and indirect costs, used through research in a report developed by Duke Energy, following the execution of numerous decommissioning plans [32].

2.3. Identification of risk and uncertainty in input variables

The analysis of decommissioning in a risky situation highlighted the opportunities and threats that influence the variables involved in generating the thermoelectric plant. To assess possible deviations in the model's evaluation results, Monte Carlo simulation was applied [33]. Freitas [34] recommends that the input variables correspond to the most critical points in the sensitivity analysis. The most significant variables affecting the viability of the project according to the data survey were: revenue, since generation depends on this variable; possible decommissioning scenarios; discount rate (WACC), since it directly affects the NPV; and the cost of raw materials, since it is the plant's main expense. The triangular distribution was used for each variable analyzed, requiring the entry of a minimum value, a most probable value and a maximum value [25,35].

2.4. Identification of the analysis variables or output variables

The Net Present Value (NPV), calculated using Eq. (2), represents the acceptance or denial of an investment project [22,23].

$$NPV = \frac{FC_t}{(1 + WACC)^t} \tag{2}$$

Table 1
Structure of the Firm's Free Cash Flow (FCFF).

(+) EBIT (operating profit)
(-) Taxes on EBIT (IR and CSLL)
(+) Depreciation
(-) Change in investments in fixed assets (property, plant and equipment and intangible assets)
(-) Variation in working capital requirements
(=) Firm's Free Cash Flow

Source: Assaf Neto [24].

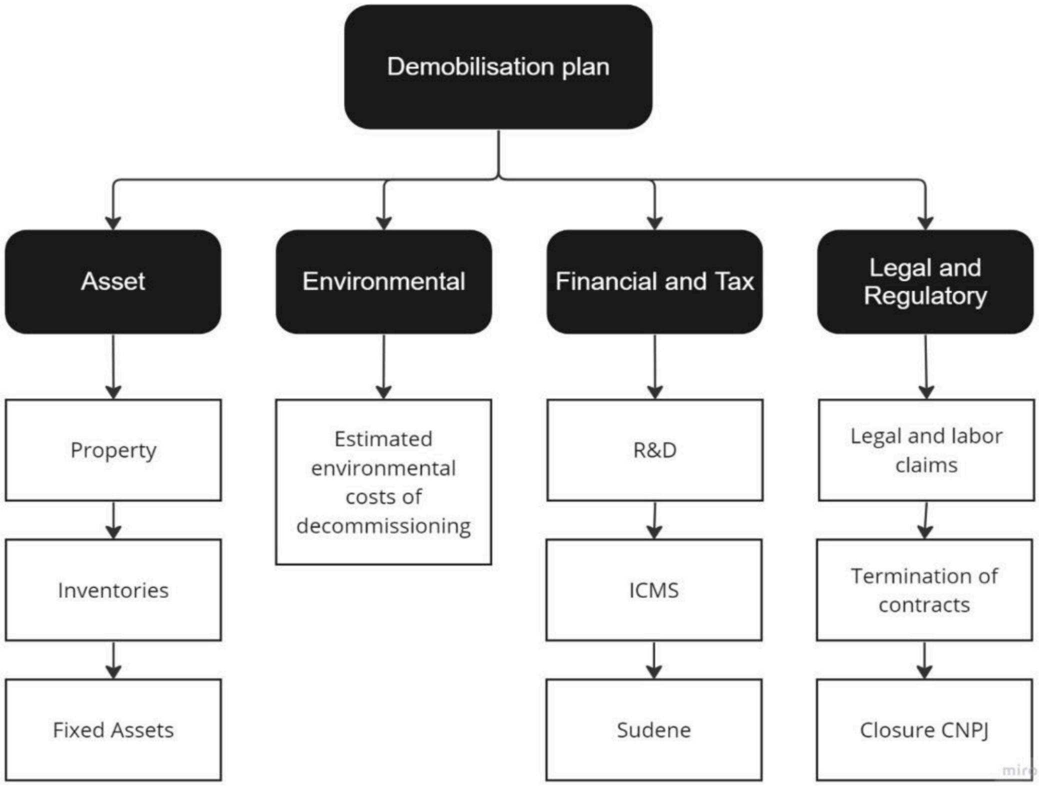

Fig. 1. Demobilization plan for the end of the concession contract in 2024.

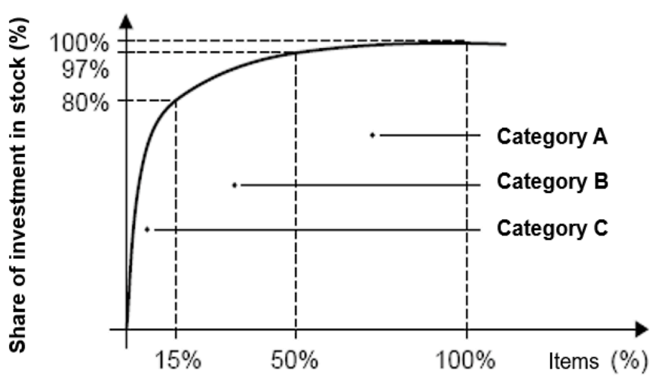

Fig. 2. Curve ABC
Source: Assaf Neto [24].

Where, FC_t is the annual cash flow over the total period and t is the total number of years and WACC is the discount rate. As a minimum required rate, the study used the Weighted Average Cost of Capital (WACC), Eq. (3), which is the minimum rate of return required by creditors and shareholders [24].

$$WACC = \left(\frac{E}{E+D}\right)Ke + \left(\frac{D}{E+D}\right)Kd(1-T) \tag{3}$$

where, E is the value of Equity, D is the value of Net Debt, Ke is the Cost of Equity, Kd is the Cost of Third Party Capital and T is the Marginal Tax Rate, 34 % in Brazil [36].

The Internal Rate of Return (IRR) is possibly the most widely used technique for detecting a project's value creation. In the NPV decision process, if the required rate is lower than the IRR, the project will be accepted (Eq. (4)) [22,24].

$$NPV = \frac{FC_t}{(1+IRR)^t} = 0 \tag{4}$$

2.5. Model simulation and analysis at risk

The risk analysis was carried out using Monte Carlo simulation, using Crystal Ball software. Monte Carlo simulation was used to simulate future scenarios based on stochastic variables whose values are randomly generated within a probability distribution that represents them [33]. The model's uncertainties, which are input variables, are returned to the NPV, WACC and IRR indicators selected as output parameters. Once measured, 10,000 simulations were carried out, generating a series of values for each analysis variable in order to obtain their simple and cumulative frequency distribution, descriptive statistics and sensitivity of the input variables. Once the probability distribution of the output variables has been obtained, a decision is made based on the information found, taking into account other relevant aspects of the project.

3. Results and discussion

Fig. 3 shows the proportion of the plant's existing assets and there is a large allocation to fixed assets (48.46 %), due to machinery and equipment, buildings and other assets. It has a high level of accounts receivable (15.62 %), cash and cash equivalents (14.30 %) which provide liquidity for operations, as well as stock (7.04 %) and other assets. In the process of exploring the costs of decommissioning, greater attention was paid to the plant's major assets (fixed assets and inventories), with a view to the plant's ability to generate cash by reversing possible losses at the end of the contract. Liabilities include obligations to shareholders in shareholders' equity (55.8 %), secondly taxes (federal, state, municipal, INSS, FGTS, fees, income tax and social security contributions) which represent 23.3 % and thirdly loans and financing (18 %).

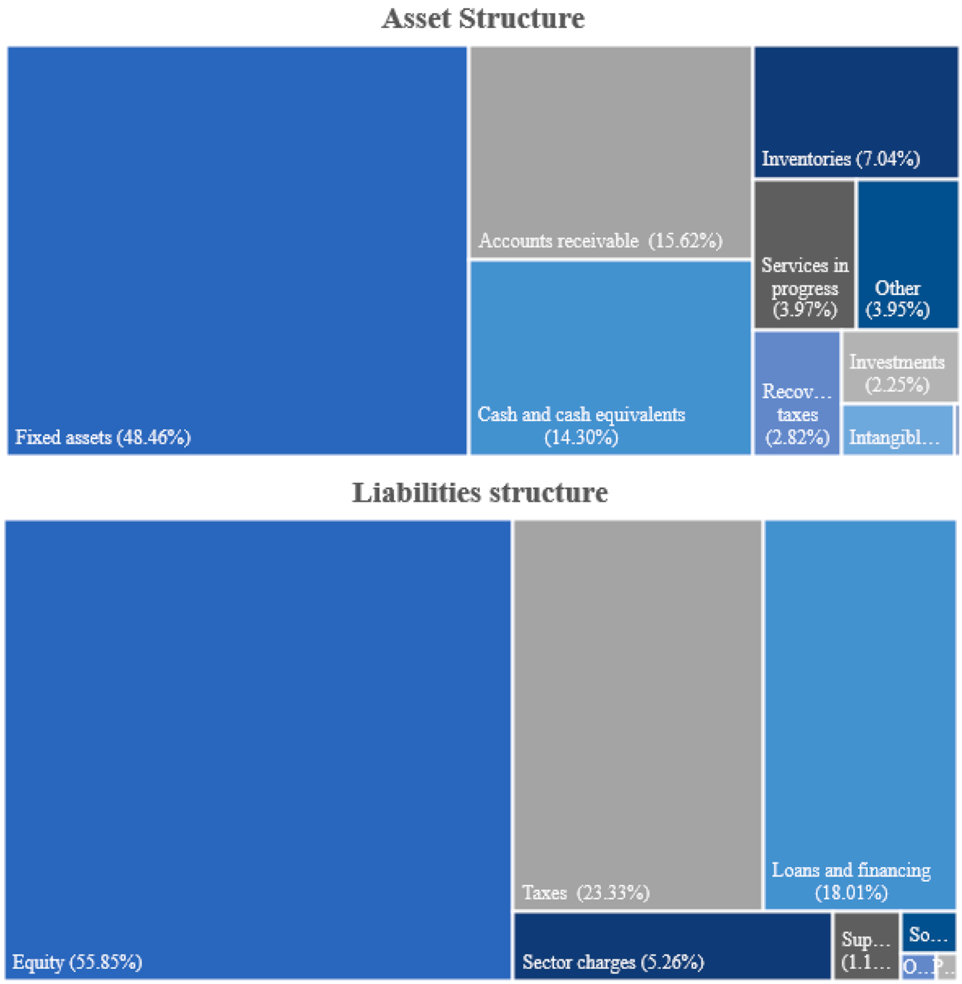

Fig. 3. Structure of the plant's assets and liabilities in 2020.

Fig. 4 shows the plant's revenue groups. The first group, "availability", represents a fixed revenue that the plant receives to cover fixed costs and another variable revenue whenever it is asked to generate energy. The latter revenue is earmarked for variable costs (O&M) and fuel purchases. Considering the period from 2010 to 2020, this type of revenue represented approximately 24 % of total revenue. The second group "dispatch" represents the amount of contracted energy that the generator is obliged to deliver during its operation, and the amount paid must cover the plant's operating costs (61 % of total revenue). As for "resale", the plant buys energy on the short-term market and resells it, earning 15 % of total revenue.

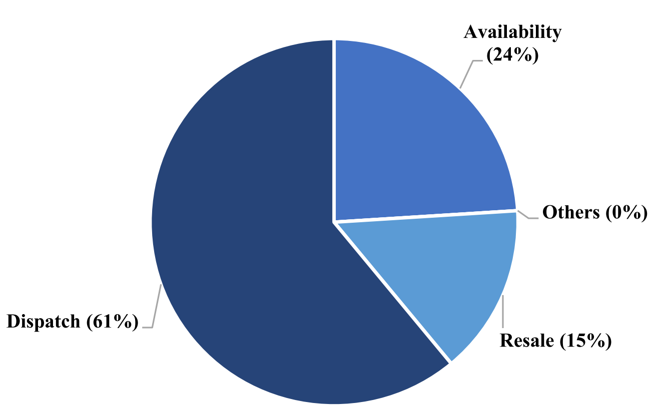

Fig. 4. Percentage distribution of revenue sources from 2011 to 2020.

Fig. 5 shows the evolution of annual depreciation from 2010 to 2019, considering all assets according to the ANELL table. In the period from 2020 to 2024, by strategic decision of the company, all assets were depreciated. The measure aimed to improve the final result of the income statement due to the large number of assets to be depreciated in 2025. In 2020, the Net Working Capital (NWC) was R$439,864,780.02 and the Current Liquidity Index (CLI) shows that the plant has R$3.86 (three reais and eighty-six cents) of assets and rights receivable for every R$1.00 (one real) of liabilities, consolidating the financial health of the enterprise. Table 2 shows the composition of the plant's fixed assets (Buildings; Machinery; Vehicles; Furniture and fixtures; and Software) from 2011 to 2024.

Table 3 shows the classification of assets in stock, by quantity, total cost, individual percentage for each asset class, accumulated percentage and ABC curve classification. The ABC method should be implemented through an asset sales policy, in order to establish priorities, management and stock control. Among the assets accounted for, machinery represents 79.15 % of all the investment made by the company. Classified as category A on the ABC curve, it has the greatest impact in terms of the company's budget. Category B includes buildings (physical structure), electrical materials (busbars, switches, circuit breakers, lighting, current transformers (CT), potential transformers (PT) and transformers) and software (acquisition licenses). It is estimated that only electrical materials will be traded in this category, as buildings and software cannot be traded or sold. Category C returned with various assets, including structures (towers), equipment, IT materials, tools, furniture, vehicles, utensils and other materials. Despite their low added

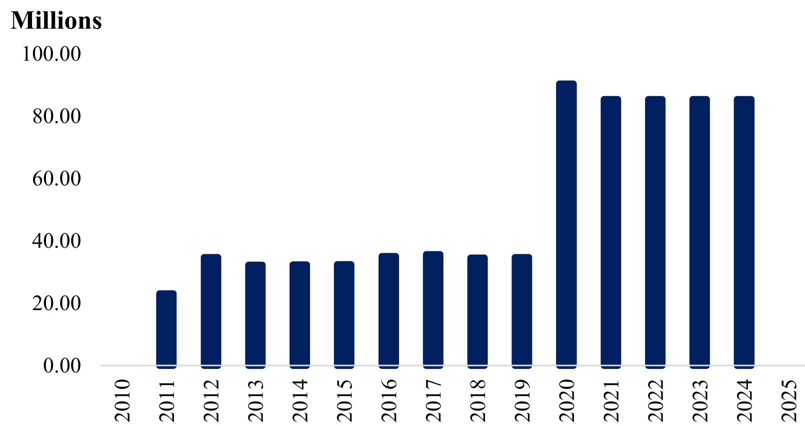

Fig. 5. Calculated annual depreciation from 2011 to 2024.

Table 2
Total assets grouped on the base date of December 31, 2020.

Assets	Total Value (R$)
Buildings	36,167,068.26
Machinery	658,003,273.10
Vehicles	270,333.32
Furniture and Fixtures	587,800.73
Software	31,832,243.04
Total fixed assets	726,860,718.45

value, these should also be traded and included in the planning.

Table 4 shows the three projected scenarios for the plant's decommissioning plan at the end of the contract (2024) and decommissioning scheduled for 2025. The Pessimistic Scenario (R$24.23 million), in which the sale of the assets as scrap and the high cost of dismantling; environmental costs for decommissioning and the sale of inventories for 20 % of the amount made available by the company (base = 06/30/2019) were computed. The Most Likely Scenario (R$35.62 million), consisting of the sale of assets for 10 % of the residual value (based on 12/31/2024); sale of inventories for 10 % (base = 06/30/2019); Best case scenario for environmental decommissioning costs. The Optimistic Scenario (R$53.60 million), in which the sale of assets considered the best scenario based on a study carried out by a specialized consultancy; sale of inventories for 20 % (base = 06/30/2019); considers an increase in payroll costs due to the greater demand for services internally.

Fig. 6 shows the FCFF, including depreciation by ANEEL (2010 to 2019) and for the duration of the contract (2020 to 2024), in millions of reais (R$ x10^6). The amounts accounted for in the period from 2021 to 2024 were the result of projections drawn up by the company for the cash flows considered, the average annual values of the cash flows resulted in around R$57.9 million. The FCFF represents the plant's result after discounting all operating obligations on net revenue, i.e. it shows the amount available in relation to debts contracted from third parties and equity. There are good levels of stability in this criterion for evaluating results, as the company has obtained a satisfactory operating result, even with a reduction in CAPEX investments, and historically little variation in the need for working capital. Table 5 shows the results of the economic assessment using viability indicators when analyzing the three decommissioning scenarios, covering the entire period (2010 to 2025). The NPV and IRR were calculated for the three scenarios.

The NPV ranged from R$101.30 million (pessimistic scenario) to R $109.73 million (optimistic scenario). The IRR ranged from 13.50 % p.a. to 13.68 % p.a. for the scenarios studied, inferring gains higher than the rate required by shareholders and creditors (WACC of 10.55 %), showing the contractual success of the venture in any scenario. It is worth noting that the business strategy of zeroing out depreciation in recent years, discounting capital less over time, contributes to a better economic assessment, given that the energy sales contract is in progress. Knowing the high degree of risk and uncertainty, 10,000 simulations were carried out with different probabilities of occurrence for each of the variables analyzed, enough to identify the sensitive parameters. Table 6 shows the variables in the stochastic model, assigning minimum, most likely and maximum values, opting for the triangular distribution.

Fig. 7 shows the participation of the variables analyzed in the composition of the NPV and IRR probabilities. Analyzing the NPV, the input value with the greatest impact was the Discount Rate (WACC), since it incorporates the project's capital costs, negatively impacting the estimated result by 44 %. Raw materials were also relevant to the plant's

Table 3
Classification and grouping of fixed assets using the ABC Curve method.

Assets	Number of Assets	Total Cost (R$)	Total Cost (%)	Accumulated (%)	Category
Machinery	1.683	575,291,163.96	79.15	79.15	A
Buildings	343	58,838,871.59	8.09	87.24	B
Electrical equipment	165	37,576,187.46	5.17	92.41	B
Software	9	31,862,966.18	4.38	96.80	B
Structures	2	11,317,971.01	1.56	98.35	C
Equipment	187	8,078,165.17	1.11	99.46	C
Computers	55 s	2,196,423.50	0.30	99.77	C
Tools	38	802,740.85	0.11	99.88	C
Furniture	36	280,583.57	0.04	99.92	C
Vehicles	3	270,333.32	0.04	99.95	C
Utensils	7	173,329.11	0.02	99.98	C
Air conditioning equipment	7	79,780.66	0.01	99.99	C
First aid supplies	4	56,236.15	0.01	100.00	C
Fire equipment	4	21,665.24	0.00	100.00	C
Miscellaneous	6	14,300.68	0.00	100.00	C
		726.860.718			

Table 4
Scenarios for the decommissioning plan at the end of the contract, December/ 2024, in millions of Reais (R$ x10⁶).

Description	Pessimistic	Most Likely	Optimistic
Total cost	−18.35	−8.46	−18.67
Environment	−0.51	−0.26	−0.26
Legal	−0.85	−0.85	−0.85
Personnel	−1.53	−1.53	−2.04
PDI	−2.85	−2.85	−2.85
Insurance	−0.85	−0.85	−0.85
Dismantling of Fixed Assets	−7.66	0.00	−7.66
Operating Expenses	−0.43	−0.43	−0.43
Contingency Indirect costs (5 %)	−0.74	−0.34	−0.75
Contingency Direct Costs (20 %)	−2.94	−1.35	−2.99
Total Revenue	45.36	53.95	86.63
Budgeted cash	41.27	41.27	41.27
Sale of Fixed Assets	–	10.64	41.27
Sale of stock	4.08	2.04	4.08
Taxes payable	−2.77	−9.87	−14.36
Net value	24.23	35.62	53.60

results, contributing 20 % negatively to the NPV. Positively, the variable with the highest degree of sensitivity highlighted the importance of revenue (36 %) in improving results. As for the decommissioning scenarios, the impact on the NPV was not significant (0.00 %).

Looking at the IRR, there was a significant share of revenue (64 %) in the computed value. On the other hand, Raw Materials negatively affected the result by 36 %. The Discount Rate (WACC) and the Decommissioning Scenarios made no contribution (0.00 %), which means there was no influence on the final viability of the project. By identifying which variables had the greatest influence on the NPV and IRR results, the Monte Carlo simulation made it possible to carry out various alternative occurrences in order to provide a probability distribution for managers' decision analysis.

Fig. 8 shows the distribution of the output variables, where the frequency bars represent the left axis and the cumulative frequency curve characterizes the right axis. Gitman (2010) points out that the NPV result depends on the initial cost, the returns, their dates of occurrence and the rate required by the project's risk. The NPV varied between R $62.34 and R$260.31 with an average of R$157.02 and a standard deviation of R$29.43. The chances of the NPV being greater than zero was 100 %, ruling out the unfeasibility of the venture. The cumulative frequency provides the level of risk for each of its estimates, showing with a 73 % probability that the NPV will be equal to or less than R$175.95 on the projected histogram. For the NPV between R$140.00 and R$200.00 there is a probability of 64 %. Considering the worst case scenario estimated at R$101.30, the probability of occurrence was 97 %. The values calculated for the three scenarios were below the mean and median, indicating that there is a high chance that the result will be higher than computed.

The IRR varied between 12.78 % and 16.09 % with an average of 14.65 % and a standard deviation of 0.45 %, indicating that it was higher than the discount rate (WACC) of 10.55 %. This means that the project's rate of return was higher than the cost of capital, detecting that the project created value during the analysis period. Assaf Neto (2014) points out that in the NPV decision process, if the required rate is lower than the IRR, the project will be accepted. The projections show that at the end of the contract the IRR will be higher than the required rate, the WACC. The IRR calculated for the three scenarios (pessimistic, more likely and optimistic) was close to the mean and median, indicating a strong correlation and a 99.97 % chance of being above 13 %. The highest frequencies recorded indicate that for the IRR to be between 14.50 % and 15.00 % the chance is 42 % and based on the accumulated

Table 5
Economic evaluation indicators considering the FCFF with depreciation by ANEEL (2010 to 2020) and total depreciation of the assets at the end of the contract (2021 to 2025).

Indicators	Pessimistic Scenario	Most Likely Scenario	Optimistic Scenario
NPV (R$ x10⁶)	101.30	106.44	109.73
IRR	13.50 %	13.61 %	13.68 %

Table 6
Maximum, minimum and most probable values of the economic viability variables for estimating NPV and IRR, in millions of reais (R$ x10⁶).

Variables analyzed	Pessimistic	Most Likely	Optimistic
Revenue	245.65	415.86	553.47
Raw Material Cost	75.04	163.29	246.29
Discount Rate (WACC)	9.50 %	10.55 %	11.61 %
Decommissioning Plan Scenarios	10.40	45.40	67.96

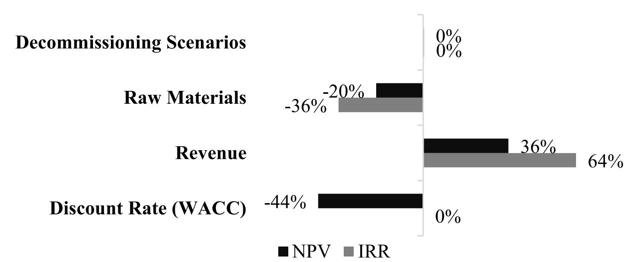

Fig. 7. Influence of the uncertainty variables in relation to the output variables NPV and IRR.

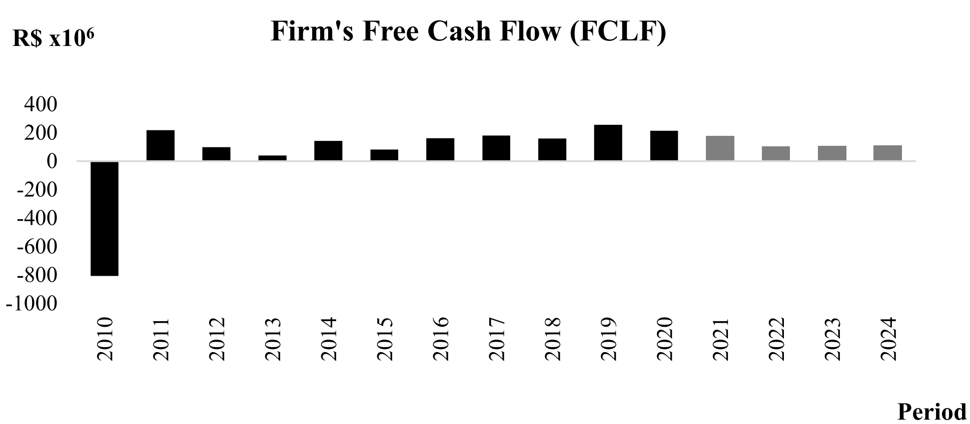

Fig. 6. The Firm's Free Cash Flow, with depreciation by ANEEL (2010 to 2019) and by the length of the contract (2020 to 2024), in millions of reais (R$ x10⁶), from 2010 to 2024.

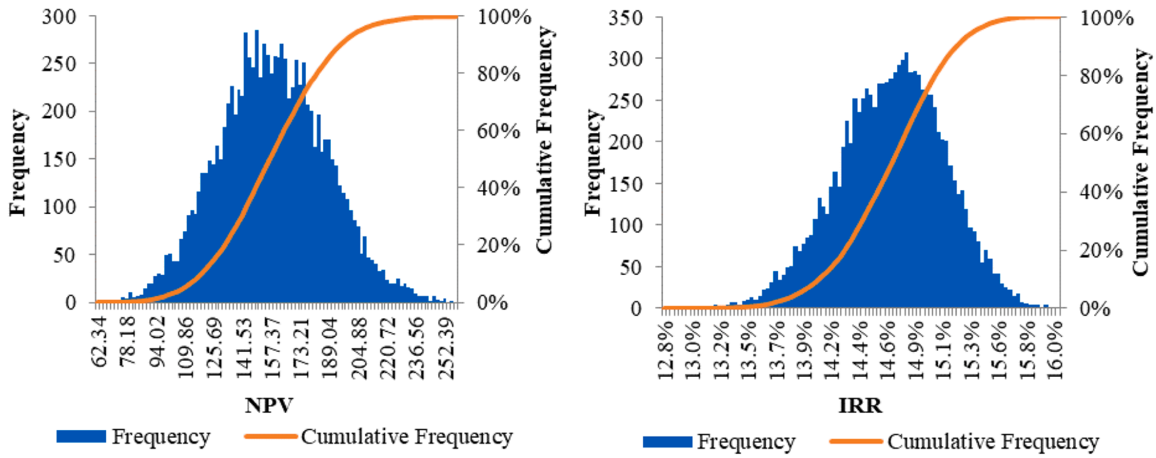

Fig. 8. Histogram of the frequency and cumulative frequency (%) of the Monte Carlo simulation of the economic viability of the thermoelectric plant, in millions of reais (R$ x10^6).

frequency the probability of it being equal to or <15 % was 72 %.

In Table 7, the statistical measures of mean, median, kurtosis and standard deviation indicate that the distribution of the NPV and IRR output values follows a normal distribution, since the mean and median values are close to each other. The standard deviation, which reflects the variation in estimates and is an important risk indicator for decision-making, indicated the IRR as the best parameter for assessing the degree of dispersion of the results. Analysis of the percentiles indicates that there is a high probability of the venture being economically viable, with a 10 % chance of the NPV and IRR already showing satisfactory results for the projected scenarios, being positive and higher than the discount rate (10.55 %), respectively.

4. Conclusion

This study evaluated the decommissioning of a fuel oil-fired thermoelectric plant using deterministic and stochastic analyses. According to the projected scenarios, the NPV and IRR indicators were calculated. The projected FCFF showed the success of the venture, portraying operating profit after taxes, investments in working capital, equipment, installations and other assets accounted for in the period. The NPV was positive, showing acceptance of the project, ranging from R$101.30 million (pessimistic scenario) to 109.73 million (optimistic scenario). The estimated IRR was higher than the discount rate (WACC) of 10.55 %, ranging from 13.50 % p.a. to 13.68 % p.a.

Table 7
Descriptive statistics of the output variables, NPV and IRR.

Statistics	NPV	IRR
Mean	157.02	14.65 %
Median	156.46	14.67 %
Standard Deviation	29.43	0.45 %
Kurtosis	2.86	2.95
Coefficient of Variation	0.1874	0.0304
Minimum	62.34	12.78 %
Maximum	260.31	16.09 %
Percentiles	NPV	IRR
0 %	62.34	12.78 %
10 %	119.20	14.06 %
20 %	132.01	14.28 %
30 %	141.12	14.42 %
40 %	148.72	14.55 %
50 %	156.44	14.67 %
60 %	164.18	14.78 %
70 %	172.60	14.90 %
80 %	182.21	15.03 %
90 %	195.03	15.21 %
100 %	260.31	16.09 %

The Monte Carlo simulation indicated with 100 % certainty that the results of the output variables, NPV and IRR, can be better than those obtained using deterministic methods in terms of economic viability. The variable with the greatest impact on the NPV was the discount rate, which affected it negatively. With regard to the IRR, revenue proved to be more relevant, contributing positively to the increase in the rate of return.

The conclusion is that despite the risk, and the possible discontinuation of the plant in 2024, from the point of view of the shareholders, there is a great capacity for financial gain and wealth generation. Although the study used robust methods (deterministic and stochastic) such as NPV, IRR, WACC and Monte Carlo simulation to assess the economic viability of demobilization, the approach still has limitations, especially in the accuracy of cost estimates due to external factors such as price fluctuations, regulatory changes and environmental costs. To improve cost models, future studies could develop dynamic models that integrate long-term forecasts for critical variables, using machine learning to adjust forecasts based on historical data. In addition, other studies could also quantify the environmental impacts associated with demobilization.

Another limitation of this study was the impossibility of including the value related to the property in the demobilization. This absence may have underestimated the economic return, but the results contribute to the orientation of the actors, because despite this, there was financial viability. Finally, this study contributes to future decommissioning projects in Brazil, considering the scenario of stimulating renewable sources and the energy transition, helping managers make decisions about their projects. In addition, it helps guide public policies that can optimize the decommissioning process and strengthen the national energy sector.

CRediT authorship contribution statement

Amadeu Junior da Silva Fonseca: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roberto Castro:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Dorel Soares Ramos:** Visualization, Validation, Supervision, Investigation, Formal analysis. **João Carlos de Oliveira Mello:** Writing – review & editing, Visualization, Validation, Investigation. **Luiz Célio Souza Rocha:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Camila Seibel Gehrke:** Writing – review & editing. **Edvaldo Pereira Santos Júnior:** Writing – review & editing, Validation. **Wilton Lima Sousa:** Writing – review & editing, Funding acquisition. **Luiz Moreira Coelho Junior:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

The authors are grateful for EPASA's financial support in the R&D; the National Council for Scientific and Technological Development - CNPq by Productivity Research Grants, n°: 310871/2021–2; Coordination of the Coordination for the Im-provement of Higher Education Personnel – CAPES; the MRTS Consultoria em Engenharia; the Thymos Energia, and the Federal University of Paraíba (UFPB) – Brazil.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2024.100332.

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