EVALUATION OF A COMBINED CYCLE IN THE PECÉM II POWER PLANT

Vinícius Vilas Boas Soares[1], Waldyr Luiz Ribeiro Gallo[2]

University of Campinas, Energy Department, Campinas, São Paulo, Brazil

v202022@dac.unicamp.br, gallo@fem.unicamp.br.

ABSTRACT

The Pecém II power plant, located in São Gonçalo do Amarante, in the State of Ceará in Brazil, is a coal-fired thermal power plant with a 360 MW steam turbogenerator for power generation. The purpose of this study was to develop a technical study to implement two brand new gas turbogenerators of 431,2 MW each and two HRSGs (Heat Recovery Steam Generator Boilers), aiming to replace the existing coal-fired boiler and enhance the existing cycle efficiency by proposing a new (2x1) combined cycle using the existing steam turbogenerator currently in operation at the Pecém II plant. One of the main purposes of the new combined cycle arrangement proposed is to present a plan to reduce specific emissions of greenhouse gases such as CO2 and pollutants such as NOx, SOx, and CO per MWh generated, while using existing equipment and infrastructure to reduce the required investment and implementation lead time. The obtained results show that the installed capacity of the Pecém II plant can be increased from 360 MW to 1,216 MW and the cycle efficiency can be considerably enhanced by the combined cycle arrangement (from 35.4% to 59.7 %). Specific CO_2 emissions decrease from 900 kg CO_2/MWh to 361.93 kg CO_2/MWh when the coal plant is converted to a combined cycle that burns natural gas. A financial analysis to demonstrate the associated costs with new equipment acquisition, operation and maintenance, and daily consumption of natural gas with the new combined cycle was performed. Finally, it was calculated the required energy sales price to reach the investment break-even point in 15 years.

1 INTRODUCTION

According to the last Intergovernmental Panel on Climate Change (IPCC) report, to avoid climate change and limit global warming to well below 2ºC, as stipulated in the Paris United Nations Climate Change Conference (simply known as COP21), wide efforts in different segments of the market still need to be done in different countries in the world, (IPCC, 2021). The level of equivalent CO_2 emissions in each segment of the market can be seen in Figure 1, where it is possible to verify how much impact and CO_2 emissions are due to the energy segment:

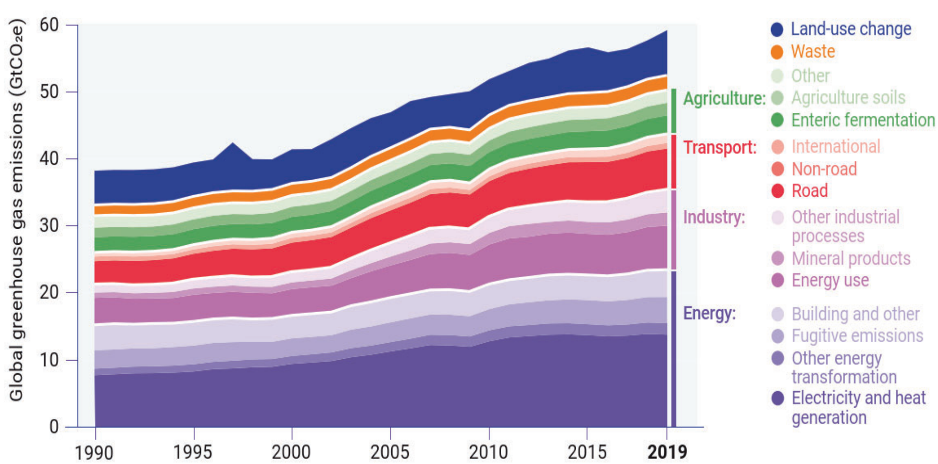

Figure 1: GHG emissions at the sectoral level. Sources: Takeshi Kuramochi *et al*. (2020).

https://doi.org/10.52202/077185-0169

In this sense, this study has considered the energy transition discussions and chose the Pecém II coal-fired power plant located in São Gonçalo do Amarante in the State of Ceará-Brazil, to analyze the replacement of mineral coal fuel by a combined cycle power plant composed of two new gas turbo-generators and two new HRSG to replace the present coal boiler while using the existent 360MW steam turbo-generator currently in operation at Pecém II power plant. Thus, the main objectives to be achieved under this article were:

- Propose the replacement of the coal fuel at the Pecém II power plant by natural gas in a new (2x1) combined cycle (to reduce the Pecém II power plant's CO_2 emissions).

- Use the existing steam turbine currently in operation at the Pecém II power plant in the new (2x1) combined cycle designed under this article, to use existing assets and infrastructure to reduce CAPEX and construction and installation lead time.

- Develop an Excel tool that allows real-time simulations of the new (2x1) Combined Cycle Heat Balance Diagram (HBD), providing all the relevant thermodynamic and transport properties of the fluids in each equipment inlet and outlet section.

- Develop the thermal design of the HRSGs and define all geometric parameters of each section, including tube diameter and bundle arrangement (staggered or in-line), pitch dimensions, number of tube rows, number of tubes per row, type and dimensions of the fins, heat exchange surface areas and maximum dimensions of the HRSG. The information mentioned above for HRSGs is relevant data to request quotes from a supplier and have a more accurate price range for this new equipment. The Excel tool developed for this study shall also be capable of simulating in real time all the HRSG calculations based on users' inputs.

- Compare the new combined cycle efficiency with the coal-fired cycle currently in operation at the Pecém II power plant.

- Develop financial analysis to demonstrate the economic viability of the project, considering a sales price for energy to be commercialized with the Brazilian GRID and reach the project breakeven point at the end of 15 years.

Ultimately, the new 2x1 combined cycle proposed in this study, which will replace the existing coal cycle currently in operation at the Pecém II plant, can be seen in Figure 2:

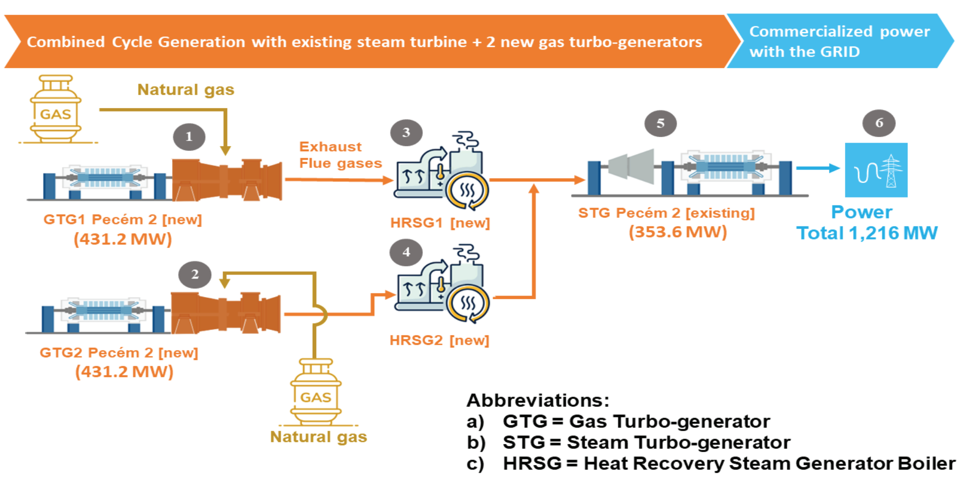

Figure 2: New (2x1) combined cycle with new gas turbogenerators and existing steam turbo generator at Pecém II power plant.

https://doi.org/10.52202/077185-0169

2 PREMISES

2.1 Pecém II Existent Steam Turbine

The Pecém Thermoelectric Complex contains a total of 3 steam turbogenerators powered by a mineral coal cycle, whereas 2x 360MW steam turbogenerators are from Pecém power plant I, with a total installed capacity of (720MW) and owned by the company EDP (2022). The Pecém power plant II owned by the company ENEVA (2022) has 1x identical steam turbogenerator as the ones from Pecém I, also with power output (360MW) in its generator terminals. In this paper, the implementation of the (2x1) combined cycle was exclusively contemplated for the Pecém II single steam turbogenerator owned by ENEVA. Nevertheless, it was assumed that the technical specifications for the steam turbines in both Pecém I (EDP) and Pecém II (ENEVA) plants are identical.

Table 1 contains technical data and inlet conditions for the existing steam turbines currently in operation at the Pecém I power plant. It is possible to see below that the required steam mass flow corresponds to 1,134 tons/h. As previously stated, the technical data for the Pecém I steam turbogenerator was identical to the Pecém II steam turbogenerator from ENEVA, which is the object of this study:

Table 1: Technical Information for Pecem I steam turbogenerator. Sources EDP (2022).

Description	Value
Inlet Steam Condition	Superheated
Inlet Steam Pressure	168.7 Kg/cm² (g)
Inlet Steam Temperature	537 ºC
Inlet Steam mass flow	1,134 tons/h
Power Output	360 MW
Original Manufacturer	Siemens

2.2 Pecém II 2x New Gas Turbines

Observing Table 1, it was necessary to choose a combination of gas turbines and HRSG boilers capable of producing steam at a temperature of at least 537ºC to meet the specified inlet conditions of the existing steam turbine. By analyzing the Heat Balance Diagram (HBD) in the Excel Tool developed for this present study, it was verified that the installation of two gas turbines in the new combined cycle would be required to fulfill the specified heat exchange flow for steam generation.

For the elaboration of this study, the SGT6-9000HL gas turbines from Siemens-Energy (2022) were selected. This gas turbine model was selected because its outlet exhaust flue gas properties (such as temperature, expected enthalpy, and mass flow) would attend to the required heat exchange flow by each HRSG to generate steam with the established conditions under Table 1. Moreover, the SGT6-9000HL turbines were also a good reference because many other modern (2x1) combined cycle power plants around the world are using or considering this equipment in their modernization projects. The Siemens Energy SGT6-9000HL gas turbine data sheet can be analyzed in Table 2 as follows:

Table 2: Heavy-duty gas turbine SGT6-9000HL (60 Hz). Sources: Siemens-Energy (2022).

Power Output	440 MW
Fuel	Natural Gas, LNG, Distilled Oil, other fuels on request
Gross Efficiency	> 43.2 %
Heat Rate	< 8,333 kJ/kWh (< 7,898 Btu/kWh)
Pressure Ratio	24.0: 1
Exhaust Mass Flow	760 kg/s (1,676 lb/s)
Exhaust Temperature	675 ºC (1,247 ºF)

https://doi.org/10.52202/077185-0169

2.3 Excel Tool – Pecém II Combined Cycle

The new 2x1 Combined Cycle and HRSGs' project, were designed using an Excel tool developed for this work, which uses equations from Ganapathy (2014), Ganapathy (1991), Rezaie (2019), and Moran et al. (2010), as well as gathered information for similar projects designed using the software GT PRO from Thermoflow (2023).

The Excel Tool can simulate several load points of the new 2x1 combined cycle in real time and provides valuable information such as the new cycle efficiency, power output, emissions, and equipment frame size to start quotes with suppliers. The Excel tool contains the following features:

1. Complete database for thermodynamic and transport properties for different fluids, such as:
    - Water/Steam, according to Tab (Water and Steam Data Base), using available information from Hans-Joachim Kretzschmar (2019);
    - Air as an ideal gas, according to Tab (Air as ideal gas Data Base), using available information from Moran et al. (2010) and Incropera (2011);
    - Natural Gas Data Base, according to Tab (Natural Gas Data Base), using available information from Thermoflow (2023) and EES (2023).
2. Visual Basic for Applications (VBA) code, which can automatically calculate:
    - Water/Steam enthalpy (h), entropy (s), Specific Heat at constant pressure (Cp), Specific Volume (v), Kinematic viscosity (ν), Prandtl Number (Pr), and Thermal conductivity (k) based on the fluid pressure and temperature;
    - Natural Gas Specific Heat at constant pressure, based on its temperature.
3. Complete Heat Balance Diagram (HBD) of the new 2x1 combined cycle, considering the existing steam turbine installed in the Pecém II power plant.
4. Design of HRSG sections and calculation of heat transfer between water/steam and flue gases of gas turbines.
5. HRSG thermal design, containing the water/steam and flue gases temperature profile for each heat exchanger section (economizers, evaporators, and superheaters).
6. HRSG construction design, specifying tube diameter, length, number of rows, bank arrangement, required surface area for heat exchange, and maximum dimensions of the HRSG, etc.

3 HRSG DESIGN CALCULATION

Using the Excel Tool developed for this present study, it was possible to obtain the HRSGs thermal and construction design. Therefore, the next sections present the obtained results which contain detailed information for the new 2x1 combined cycle and HRSGs considered in this study. All the information was later used to estimate the HRSGs' size and send requests for quotation to suppliers to get accurate price-range input for the financial analysis under this present study.

3.1 HRSG Thermal Design

In the Excel tool developed for this present study, the heat exchange between hot fluid (gas turbines exhaust flue gases) and cold fluid (water/steam) was verified. With available information from the Excel Tool calculation, Table 3 was created to summarize HRSG thermal design. It is worth mentioning that

https://doi.org/10.52202/077185-0169

the same calculation performed for HRSG1 can be also considered for HRSG2, since both HRSGs are identical.

Table 3: HRSG Thermal Design Performance Summary - Design case

Surface	Gas Temp		Wat/ Steam		Duty	Steam Press	Steam Flow	LMTD	U.A
	In/Out ºC		In/Out ºC		MW	Bar	ton/h	ºC	kW/ºC
HPS2	675.0	647.2	474.8	537.0	23.8	166.5	460,420.8	154.6	154.1
RH1	647.2	643.8	248.8	537.0	2.9	39.2	14,391.0	223.1	13.1
HPS1	643.8	609.9	412.6	474.8	28.9	166.5	460,420.8	182.7	158.1
HPS0	609.9	545.2	350.5	412.6	54.5	166.5	460,420.8	196.0	278.2
HPB1	545.2	399.6	340.5	350.5	120.2	166.5	460,420.8	113.8	1,056.3
HPE1	399.6	321.7	258.7	340.5	62.7	166.5	460,420.8	61.0	1,028.0
IPB	321.7	313.2	238.8	248.8	6.8	39.2	14,391.0	73.6	91.9
IPE	313.2	226.6	162.9	238.8	68.3	39.2	587,811.8	68.9	990.9

With the information available in Table 3, the fluids inlet and outlet temperature in each HRSG's section was determined, and a chart with the flue gases and water/steam temperature profile in each HRSG section was created, as demonstrated in Figure 3:

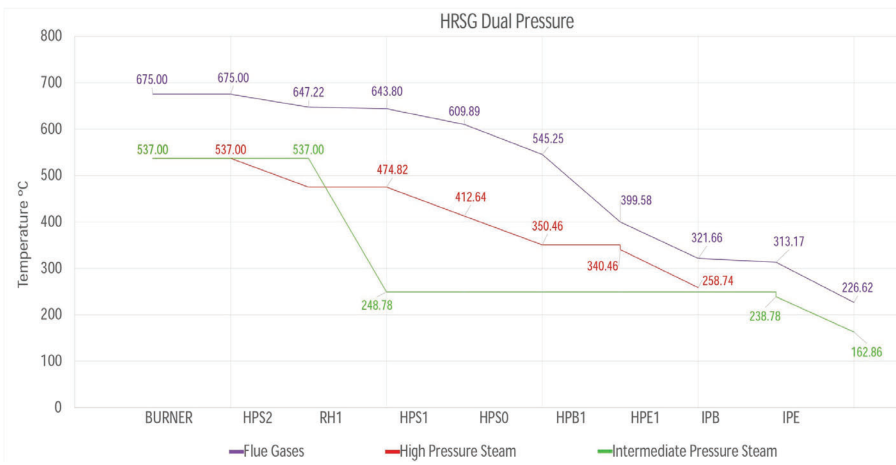

Figure 3: Flue gases and water/steam temperature profile in each HRSG section.

3.2 HRSG Construction Design

With the Excel Tool developed for this study, the HRSG construction design was also conducted, aiming to define the HRSG's bank of tubes arrangement, fins configuration, tubes' length and diameters, as well as calculating the convection (hi and ho) and overall (U) heat transfers coefficients to later evaluate the required heat exchange surface area for the HRSG's main sections (HPS2, RH1, HPS1, HPS0, HPB1, HPE1, IPB, and IPE).

Figure 4 below demonstrates the obtained results for the HRSG bank of tubes configuration, and its total surface area for heat exchange:

https://doi.org/10.52202/077185-0169

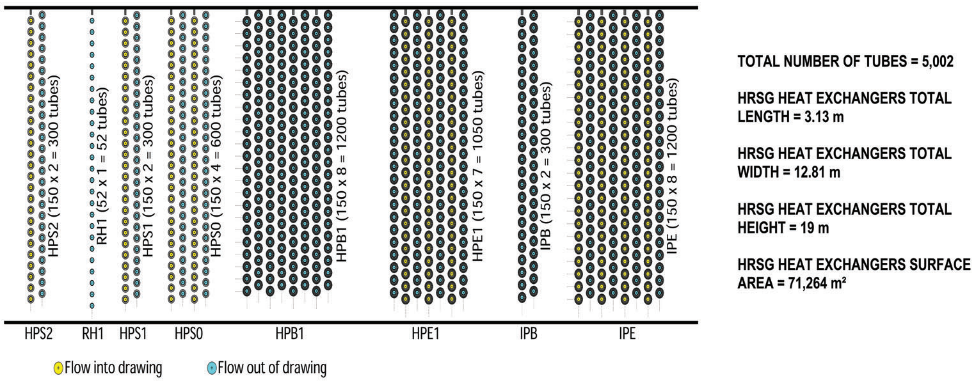

Figure 4: HRSG Sections, bank of tubes configuration.

4 NEW 2X1 COMBINED CYCLE VS EXISTING COAL FIRED CYCLE

This chapter focused on calculating the new 2x1 combined cycle proposed and comparing it with the estimated coal cycle currently in operation at the Pecém II power plant. For the new combined cycle, simulations in the Excel Tool developed for this study were considered, while for existing coal-fired cycle currently in operation, information available on ENEVA (2023) was used.

4.1 Cycle Efficiency

Existing Coal Fired Cycle

Valuable information from the Pecém II power plant was organized in Table 4, based on information provided by the power plant owners, EDP (2023) for Pecém I and ENEVA (2022) for Pecém II:

Table 4: Existing Coal Fired cycle information, Pecém II power plant. Sources: EDP (2023),ENEVA (2023a), ENEVA (2023b).

Description	Value	Unit
Power Plant	Pecém II	-
Site Location	Ceará – Brazil	-
Fuel Origin	Imported from Colombia[2]	-
Specific Consumption	0.385	Coal: ton/MWh
Installed Power	365	MW
Average Power Guarantee with GRID	299	MWm
η_{coal} - Power Plant Efficiency[3]	35.4	%
Contract Type	CCEAR[4]	-
Beginning of CCEAR Contract	January – 13	-
Ending of CCEAR Contract	December – 27	-
Power Plant Fixed Revenue (nov/22)	96.6	MM$/year
CVU	62.8	$/MWh

1- Exchange Rate (1USD = 5 BRL), based on values from Brazilian Central Bank (2023).
2- Based on EDP (2023)
3- Average efficiency (2019, 2020, and 2021), based on ENEVA (2023a)
4- CCEAR: Energy Trading Contract in the Regulated Environment with Brazilian GRID

New 2x1 Combined Cycle

Based on Moran et al. (2010), the combined cycle efficiency (η_{cc}) can be obtained by the ratio of the net generated power by energy cost (heat entering the cycle through fuels), as represented in equation (1) below:

https://doi.org/10.52202/077185-0169

$$\eta_{cc} = \frac{\dot{W}_{GTG1} + \dot{W}_{GTG2} + \dot{W}_{STG}}{\dot{Q}_{NG-GT1} + \dot{Q}_{NG-GT2}} \tag{1}$$

Replacing values obtained in the heat balance diagram in the Excel Tool developed for this study, the result demonstrated in equation (2) below was achieved:

$$\eta_{cc} = \frac{431.2\ MW + 431.2\ MW + 353.6\ MW}{1{,}018.48\ MW + 1{,}018.48\ MW} = 59.7\% \tag{2}$$

Where:

- $\dot{W}_{GTG1}$ = 431.2 MW, net power output for new gas turbogenerator 1
- $\dot{W}_{GTG2}$ = 431.2 MW, net power output for new gas turbogenerator 2
- $\dot{W}_{STG}$ = 353.6 MW, net power output for existing steam turbogenerator
- $\dot{Q}_{NG-GT1}$ = 1,018.48 MW, heat inlet by natural gas firing in the gas turbogenerator 1
- $\dot{Q}_{NG-GT2}$ = 1,018.48 MW, heat inlet by natural gas firing in the gas turbogenerator 2

Comparing the existing coal-fired cycle (η_{coal} = 35.4%) in Table 4 with the combined cycle efficiency (η_{cc} = 59.7 %) from equation (2), it was observed that the new combined cycle can significantly improve the energy efficiency of Pecém II power plant with the new configuration proposed.

4.2 Emissions

Existing Coal Fired Cycle

Based on information available in ENEVA (2023c), Table 5 was created to present relevant information for Pecém II power plant emissions:

Table 5: Pecém II power plant emissions. Sources: ENEVA (2023c).

Emissions	Value	Unit
NOx	500	mg/Nm^3
SO_2	1,250	mg/Nm^3
Particulates	50	mg/Nm^3
CO_2	900	kgCO_2/MWh

As seen in Table 5 above, Pecém II has considerable Carbon Intensity (900 kg CO_2/MWh), and on top of that, pollutants emissions such as nitrogen oxide (NOx = 500 mg/N.m^3), sulfur dioxide (SO_2 = 1250 mg/Nm^3), and Particulates (50 mg/Nm^3).

New 2x1 Combined Cycle

To define the new 2x1 combined cycle emissions for both HRSGs' stacks, stoichiometric calculations of the combustion process using the mole fractions of each chemical element in the natural gas composition and references from similar projects running Thermoflow (2023) were considered. The composition of the flue gases for HRSG1 and HRSG2 is shown in Table 6 below:

Table 6: Flue Gases mass fraction of each constituent, for HRSG1 and HRSG2 stacks.

Products of combustion	Mole Fraction (%)	Mass Fraction (%)	Mass Flow (kg/h)
Flue Gases HRSG1 + HRSG2	100%	100%	5,472,000
Nitrogen (N_2)	75.10%	74.45%	4,073,980.29
Oxigen (O_2)	9.94%	11.26%	616,090.37
Carbon Dioxide (CO_2)	5.16%	8.04%	440,122.65
Water (H_2O)	9.80%	6.25%	341,806.69

https://doi.org/10.52202/077185-0169

Then, having the carbon dioxide CO_2 mass flow ($\dot{m}_{CO2} = 440{,}122.65$ kg/h) and the power output for the new combined cycle ($\dot{W} = 1{,}216$ MW), it was possible to calculate the Carbon Intensity as follows:

$$CI_{cc} = \frac{440{,}112.65\ \frac{kg\ CO_2}{h}}{1{,}216\ MW} = 361.93\ \frac{kg\ CO_2}{MWh} \tag{3}$$

Where:
CI_{cc}= Carbon Intensity for the combined cycle, given in kg CO_2/MWh.

Comparing equation 3 with the Carbon Intensity for the existing coal-fired cycle (CI_{coal} = 900 kg CO_2/MWh) as previously shown in Table 5, it is possible to see that, the new 2x1 combined cycle has the potential to decrease GHG emissions by 59.78%. Moreover, it is also important to mention that the new 2x1 combined cycle can avoid SO_2 emissions, which is an undesirable pollutant in coal-fired thermal power plants.

5 FINANCIAL ANALYSIS CALCULATION

In this chapter, the costs related to the acquisition of new equipment (2x gas turbogenerators and 2x HRSGs), new demand for fuel (natural gas) to keep the power plant in operation and the associated costs of operation and maintenance (O&M) for the new combined cycle configuration (2x1) will be discussed.

5.1 New Combined Cycle Cost

To define the 2x gas turbogenerators (GTG1 and GTG2), and 2x Heat Recovery Boiler Steam Generators (HRSG1 and HRSG2) cost estimate with new equipment acquisition, references from World (2022), PEACE tool from Thermoflow (2023), and request for quotation with suppliers were considered.

Another cost considered was the operation and maintenance of the new combined cycle (2x1) proposed for the Pecém II power plant, to guarantee the maintenance, modernization, and supply of parts for the turbogenerators. The cost estimate considered was the amount foreseen in the O&M public contract of UTE Santa Cruz, located in Rio de Janeiro, which has an installed capacity of 350 MW, signed between the companies Furnas Centrais Elétricas S.A. (owner of Usina Santa Cruz) and Siemens Energy, Furnas (2020).

For this present study, an Energy Trading Contract in the Regulated Environment with the Brazilian Grid (CCEAR) with contract term of 15 years was considered, since according to CCEE (2022), it is a common period for this type of combined cycle power plant and projects participating in the Reserve of Capacity power auction.

Using the Heat Balance Diagram in the Excel Tool developed for this study, it was verified that by operating with full load for 4380 hours per year, the new combined cycle would consume 869,799,228 m^3/year of natural gas for both gas turbines. Subsequently, using references from Cegás (2023), it was observed that, the natural gas sales price average for 2023, considering taxes, was around (3.42 R\$/m^3 = 0.684 U\$/m^3). Therefore, with the abovementioned data, the natural gas consumption cost per year was defined in the financial analysis of this study. The main results obtained in the financial analysis developed in Excel Tool can be assessed in Table 7 as follows:

https://doi.org/10.52202/077185-0169

Table 7: Results financial analysis new 2x1 combined cycle.

Description	Values in (USD)
Annual Costs	
Annual Loan Payment 2x Gas Turbogenerators	$ 15,784,523
Annual Loan Payment 2x HRSGs	$ 7,892,261
Annual Cost Natural Gas Consumption	$ 595,474.699
Annual Cost O&M Turbogenerators	$ 31,522,929
Annual Income Taxes	$ 8,469,218
Annual Revenues	
Annual Revenue Electricity Sale (Full Load Operation)	$ 254,835,949
Annual Fixed Revenue for Availability in the GRID	$ 432,200,000
Required Energy Sales Price (Break-Even 15 years)	
Energy Sales Price	47.85 $/MWh
Average Annual Cash Flow (Revenues-Costs)	
Annual Cash Flow	$ 27,892,319

1- Exchange Rate (1USD = 5 BRL), based on values from Brazilian Central Bank (2023).
2- For new equipment acquisition (2x Gas Turbogenerators + 2x HRSGs), a loan with French Amortization System (Price) was considered.
3- For the Annual Fixed Revenue for Availability in the Brazilian GRID, it was considered the value for the existing steam turbogenerator plus estimates for 2x new gas turbogenerators based on information of similar projects from ENEVA, as described in the interactive spreadsheets available on ENEVA (2023b).

The financial analysis performed using the Excel tool shows that to cover the loan payments for the new equipment and the fixed annual operational costs related to natural gas consumption and O&M maintenance services, an energy sales price of around $47.85/MWh would be required to achieve a break-even point at the end of 15 years.

It is important to note that the energy sales price of $47.85/MWh would only cover the costs associated with the proposed new combined cycle, operating 4,380 hours per year for 15 years. Therefore, it would still be necessary to consider that the energy sales price to be presented in the power auction public bidding can be increased to improve the plant's annual free cash flow.

The energy sales price of $47.85/MWh, which will guarantee coverage of the costs of new equipment in 15 years, demonstrated competitiveness when compared to recent winning natural gas projects in Brazilian power auctions in the last 4 years, as illustrated in Table 8:

Table 8: Recent winning projects with natural gas fuel in New Energy and Reserve of Capacity power auctions in Brazil. Sources: CCEE (2022).

Company	Project	Year	Fuel	Power Output (MW)	CVU ($/MWh)
Global Participações em Energia S.A	Manaus 1	2022	Natural Gas	160.87	88.8
ENEVA S.A	Azulão IV	2022	Natural Gas	284.07	88.8
ENEVA S.A	Azulão	2021	Natural Gas	284.30	111.15
Petrobras	Termorio	2021	Natural Gas	994.08	120
Portocém	Portocém I	2021	Natural Gas	1,535.00	98.07
Centrais Elétricas Bacaraena	Bacarena	2019	LNG	592.29	37.79

https://doi.org/10.52202/077185-0169

6 CONCLUSIONS

This paper could demonstrate and propose a new 2x1 combined cycle for Pecém II, an existing coal-fired power plant located in São Gonçalo do Amarante in the state of Ceará Brazil. The study presented the Pecém II repower, with installed capacity increase by application of a new 2x1 combined cycle using the existing steam turbine current in operation and State-of-the-art gas turbo generators with high performance and efficiency.

It was possible to propose a new configuration capable of, decreasing the environmental impact, saving CAPEX when compared with a new green field project, and expediting the equipment installation and project commissioning lead time, while reusing existing infrastructure at the power plant.

An Excel tool was developed to simulate the Heat Balance Diagram (HBD) of the new cycle, as well as performing the thermal and construction design of the new HRSGs proposed for waste heat recovery coming from flue gases in the exhaust of gas turbines.

Flue Gases and Water/Steam heat exchange, and their temperature profile in each HRSG's section were defined in Figure 3. Eight sections (4 superheaters, 2 evaporators, and 2 economizers) were considered for the dual-pressure HRSGs proposed as illustrated in Figure 4.

The new 2x1 combined cycle has proved to be more efficient than the existing coal-fired cycle (59.7% for the new 2x1 combined cycle Vs 35.4% for the existing coal-fired cycle). Furthermore, the new cycle can substantially reduce GHG and pollutant emissions, going from 900 kg CO_2/MWh plus a high concentration of NOx, SO_2, and particulates with the existing coal-fired cycle, to 361.93 kg CO_2/MWh and decrease in the intensity of pollutants and particulates with the new 2x1 combined cycle proposed.

In addition to thermodynamic parameters, economic considerations play a crucial role in determining the viability of the new cycle. Therefore, Table 7 presents the main results obtained in the financial analysis conducted in the Excel Tool developed for this study. The Cost-Benefit Index (CVU), expressed in $/MWh, has yielded satisfactory results, which demonstrated competitiveness when compared to recent winning projects in the Brazilian power auctions, especially when considering projects participating in the Reserve of Capacity modality.

Considering the new combined cycle operating full load for 4,380 hours per year, with the energy sales price of 47.85 $/MWh, it would be possible to reach the new project break-even by the end of 15 years, a common period for new CCEAR contracts for power supply in the Brazilian National GRID.

Besides enhancing the cycle efficiency, reducing the carbon intensity, and eliminating Sulfur Dioxide (SO_2) in the Pecém II power plant, the new 2x1 combined cycle proposed would considerably increase the installed capacity in the region (going from the actual 360 MW to 1,216 MW). Therefore, the new cycle can ensure power supply reliability for Ceará state, which will be a key industrial region in Brazil in the next years based on National Power expansion plans published by the Department of Mines and Energy.

7 NOMENCLATURE

Symbols

A	External Surface Area	(m^2)
CI	Carbon intensity	(kg CO_2/MWh)
$\dot{m}$	Mass flow rate	(kg/s)
$\dot{Q}$	Heat Transfer rate	(W)
$\dot{W}$	Rate of work or power	(W)
U	Overall heat transfer coefficient	($W/m^2.°C$)
η	Efficiency	(%)

https://doi.org/10.52202/077185-0169

Notations and Abbreviations

CCEAR	Energy Trading Contract in the Regulated Environment with the Brazilian Grid
CCEE	Brazilian Electric Energy Trading Department
CVU	Unit Variable Cost
GHG	Greenhouse Gas
GT	Gas Turbine
GTG	Gas turbogenerator unit
HBD	Heat Balance Diagram
HPB	HRSG Section, High Pressure Boiler
HPE	HRSG Section, High Pressure Economizer
HPS	HRSG Section, High Pressure Superheater
HRSG	Heat Recovery Steam Generator
IPB	HRSG Section, Intermediate Pressure Boiler
IPCC	Intergovernmental Panel on Climate Change
IPE	HRSG Section, Intermediate Pressure Economizer
LNG	Liquified natural gas
O&M	Operation and Maintenance
RH	HRSG Section, Reheat Superheater
ST	Steam Turbine
STG	Steam turbogenerator

Subscript

cc	Combined Cycle
coal	Mineral Coal Fuel
year	One year, 365 days

8 REFERENCES

Bank, Brazilian Central (2023). Quotes and newsletters. url: https://www.bcb.gov.br/estabilidadefinanceira/historicocotacoes. (accessed: 2023-31-12).

CCEE (2022). Leilões. url: https://www.ccee.org.br/mercado/leilao-mercado. (accessed: 2022-11-05).

Cegás (2023). TABELAS DE TARIFAS ANTERIORES. url: https://www.cegas.com.br/tabela-de-tarifas-atual-3/ . (accessed: 2023-31-12).

EDP (2022). UTE Pecém. url: https://brasil.edp.com/pt-br/o-que-fazemos/geracao/ute-pecem. (accessed: 2022-12-31).

ENEVA (2022). Pecém II. url: https://eneva.com.br/nossos-negocios/geracao-de-energia/pecem-ii/. (accessed: 2022-12-31).

— (2023a). 2021 Sustainability Report. url: https://eneva.com.br/en/sustainability/sr2021/. (accessed: 2023-31-12).

— (2023b). Planilhas Interativas. url: https://ri.eneva.com.br/informacoes-financeiras/planilhas-interativas/. (accessed: 2023-31-12).

— (2023c). ENEVA Relatório de Sustentabilidade 2019. url: https://eneva.com.br/wp-content/uploads/2020/09/Eneva_Relatorio-Sustentabilidade.pdf. (accessed: 2023-31-12).

EES (2023). Engineering Equation Solver. url: https://fchartsoftware.com/ees/. (accessed: 2023-12-31).

https://doi.org/10.52202/077185-0169

Furnas, Eletrobras - (2020). Contrato de serviços de manutenção, implementação de melhorias e fornecimento de pças para as Unidades Geradoras da UTE Santa Cruz. url: https://www2.furnas.com.br/arqtrab/ddppg/editais/GCMA/ArqPublicacao/LIGSA000142020CA.pdf. (accessed: 2022-31-12).

Ganapathy, V. (1991). *Waste Heat Boiler Deskbook*. Fairmont Press. isbn: 9780881731224. url: https://books.google.com.br/books?id=FfZqzgEACAAJ.

— (2014). *Steam Generators and Waste Heat Boilers: For Process and Plant Engineers.* Mechanical Engineering. Taylor & Francis. isbn: 9781482247121. url: https://books.google.com.br/books?id=0fGsBAAAQBAJ.

Hans-Joachim Kretzschmar, Wolfgang Wagner (2019). *International Steam Tables*, 3rd Edition. isbn: 978-3-662-53219-5. doi: https://doi.org/10.1007/978-3-662-53219-5. url: https://link.springer.com/book/10.1007/978-3-662-53219-5.

Incropera, F.P. (2011). *Fundamentals of Heat and Mass Transfer*, 7th Edition. John Wiley & Sons, Incorporated. isbn: 9781118137253. url: https://books.google.com.br/books?id=5cgbAAAAQBAJ.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Moran, M.J. et al. (2010). *Fundamentals of Engineering Thermodynamics*. Wiley. isbn: 9780470495902. url: https://books.google.com.br/books?id=oyt8iW6B4aUC.

Rezaie, Ali (2019). "Thermal design and optimization of a heat recovery steam generator in a combined-cycle power plant by applying a genetic algorithm". In: Energy 168, pp. 346–357. issn: 0360-5442. doi: https://doi.org/10.1016/j.energy.2018.11.047.

Siemens Energy (2022). SGT6-9000HL (60 Hz) Heavy-duty gas turbine. url: https://www.siemens-energy.com/global/en/home/products-services/product/sgt6-9000hl-heavy-duty-gas-turbine.html. (accessed: 2022-12-31).

Takeshi Kuramochi Michel den Elzen, Glen P. Peters (2020). "Emissions Gap Report 2020". In: UNEP, UNEP Copenhagen Climate Centre (UNEP-CCC), pp. 1–128. url: https://www.unep.org/emissions-gap-report-2020.

Thermoflow (2023). GTPRO Thermoflow. url: https://www.thermoflow.com/. (accessed: 2023-31-12).

World, Gas Turbine (2022). Gas Turbine World 2018 GTW Handbook. url: https://gasturbineworld.com/shop/annual-handbook/2018-handbook-volume-33/. (accessed: 2022-31-12).

 https://doi.org/10.52202/077185-0169