18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (online)

ENC-2020-0222
ANALYSIS OF THE TECHNICAL AND ECONOMIC FEASIBILITY OF USING RESIDUAL HEAT FROM A GENSET IN AN ABSORPTION COOLING SYSTEM

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Abstract. *The constant increasing in the electricity price and its high cost at peak hours encourages the search for alternatives to reduce cost. A option is the use of a genset to supply electricity and use its exhaustion gases energy for thermal application. Currently, many companies already use gensets at peak hours to reduce the energy bill, however without using the exhaustion gases thermal energy. This work carries out a technical-economic feasibility analysis of a genset providing electricity and simultaneously using its heat from the exhaust gases as a thermal source for an absorption cooling system, operating full time and also only during peak hours, and comparing its operation cost against the current energy consumption cost of the Belem-Br international airport. The results showed that the cooling-generator system operating full-time and at peak hours proved to be economically unfeasible due to the current price of the diesel fuel. However, it was observed that the use of only the genset at peak times for electricity generation proved to be economically feasible, with a significant reduction in the electricity bill.*

Keywords: Cooling, Group generator, absorption cooling

1. INTRODUCTION

Due to the electricity, high price turns to be necessary to seek more economical alternative for the kWh acquisition and cogeneration is an option to reduce electricity costs. Being aware that energy for refrigeration system always is a major on electricity bills, it is natural to consider cogeneration systems where the residual heat from power generation is used to producing a cooling effect. Among so many ways to perform such cogeneration, one of them is the use of a compressed ignition genset to produce electricity and use its exhaustion gas heat as a hot source for an absorption refrigeration system (Junior, 2004).

(Silva, 2008) assembled one of these cogeneration prototype system. The engine fuel was landfill biogas and its mixtures with natural gas in a spark ignition generator set up and using the exhaust gases as energy source for an absorption refrigeration system with a cooling capacity of 15 kW. This cogeneration prototype system proved to be feasible and effective.

Seeking obtain a large capacity cogeneration cooling system, (Ferro, 2016) adopted a gas turbine to power generations and the heat in the exhaustion gas as a source for a large absorption cycle named ARCTIC, whose maximum nominal capacity is 2000 TR. The authors concluded that the absorption system has several advantages compared to vapor compression cycles, mainly because they use residual energy source.

Once the technical feasibility of a cogeneration with a power-absorption cooling was proved, the question about its economics was raised. Cruz et al. (2014) carried out a simulation study referring to the use of absorption refrigeration systems using thermal source the heat in a boiler exhaust gas from a steam power system. The authors found that the use of exhaust gases in an absorption refrigeration system proved to be an economically good alternative to reduce electricity costs. Compared to a compression system, annual savings of R$ 552,787.20 can be achieved.

Genset using a compression ignition engine consuming diesel fuel and using its waste heat to feed an absorption cooling system was tested by (Berndsen, 2007). A prototype was made to perform experimental energetic and exegetical analyzes based on the first and second laws of thermodynamics. According to the author, the experiment demonstrated the technical feasibility of using the exhaust gases from the engine as a heat source for the absorption cooling system.

The present work aims to verify if a large cogeneration with a compressed ignition genset being feed with the diesel and its exhaustion gas heat used to run a absorption cooling system is economical feasible under the regular Brazilian prices for fuel and electricity. The case study was performed at Belem International Airport.

2. THEORETICAL FOUNDATION

2.1 Heat recovery system

The main advantages of absorption cooling system are (Domingues, 2011):

- It has low electricity consumption compared to a compression refrigeration system;
- It generates very low noise;
- The heat recovered from any type of source can be used as an energy input;
- Do not cause damage to the ozone layer;
- They are economically attractive when the cost of fuel used as a heat source is between 12 to 20% of the cost of electricity.

The absorption cooling cycle have a few characteristics in common with the compression cooling system, however they differ in two details (Moran and Shapiro, 2002):

1º Instead of compressing the steam between the evaporator and the compressor, the refrigerant fluid vapor is absorbed by a secondary substance called an absorbent;

2º A process must be introduced in the absorption system to remove the refrigerant vapor from the liquid solution.

Figure 1 shows the difference between the two systems. The absorption system replaces the compressor in the vapor compression system by an absorber and a generator connected to each other by a pump. Similarly, to the compression system, in the absorption system the coolant circulates through the condenser, the expansion valve and the evaporator. In the absorber, the liquid water absorbs the coolant coming from the evaporator producing an exothermic liquid solution. To maintain the temperature as low as possible, water circulates through a heat exchanger in the absorber. The coolant-water solution leaves the absorber pumped to the generator raising the solution pressure (strong solution). In the generator, a heat is transferred from a high temperature source to the solution aiming to extract the refrigerant vapor from the solution (an endothermic process). The coolant vapor released from the solution goes into the condenser, as a weak solution, flowing through the following processes and returning to the absorber.

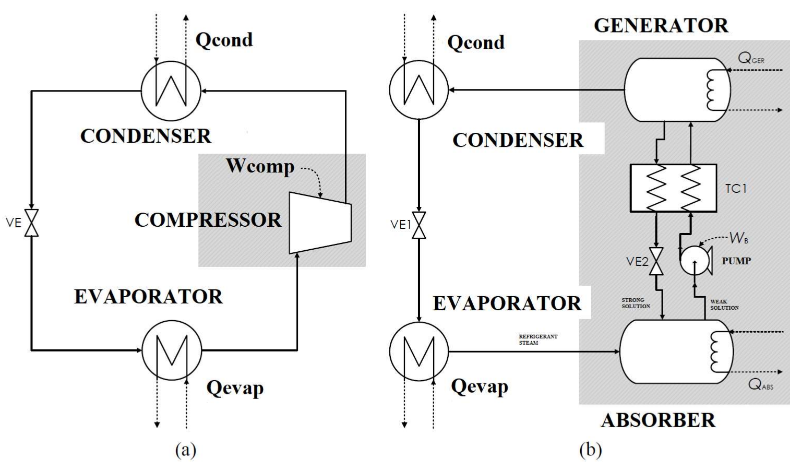

Figure 1. Basic configurations of compression (a) and absorption (b) cooling systems
Source: (Araújo, 2013)

2.2 Internal combustion engines

Compression ignition engines (CI) waste to the environment around 70% of the fuel energy in the form of heat (Domingues, 2011). Figure 2 locates the main points of thermal energy loss.

i. Energy in the exhaust gas;
ii. Cooling system for oil and water;
iii. Energy within the engine recirculation gas;
iv. Energy from the intake air cooling system, post compression.

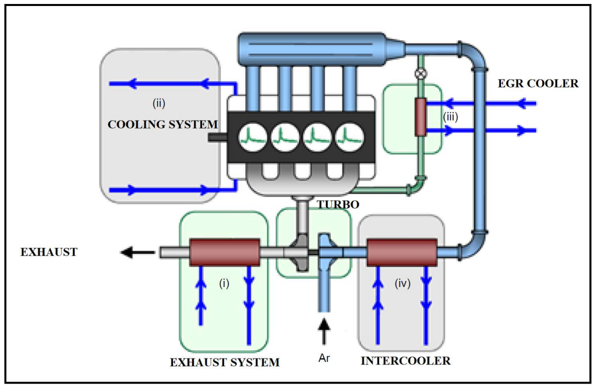

Figure 2. Main losses of thermal energy in internal combustion engines. Source Domingues, 2011.

Figure 3 shows the use and loss of energy in internal combustion engines. It can be observed that approximately 1/3 of the energy is used and 2/3 is lost due to exhaustion, friction, radiation, convection, cooling, among others, being just over 1/3 in the exhaust system alone.

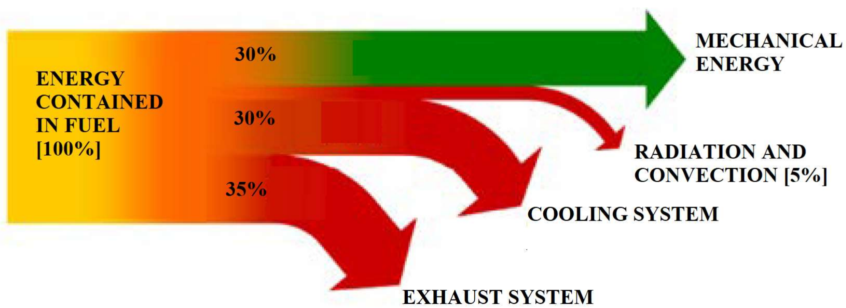

Figure 3. Sankey diagram showing the use and loss of energy in internal combustion engines. Source Domingues, 2011.

3. MATERIALS AND METHODS

3.1 Description of equipment used in the study

The equipment for the economic feasibility study, except for the absorption chiller, is already in operation at the airport under study. The actual cooling system is the chilled water plant (CWP) and the genset is the utility plant (UTP). The gensets are two Cummins models C1000D6 1250 kVA (1000 kW) as part of the airport emergency power which are used only in the absence of power by the local utility company and only one of the equipment is enough to keep the airport operational in the event of power outages. CWP and UTP systems are in the same building locating next to each other.

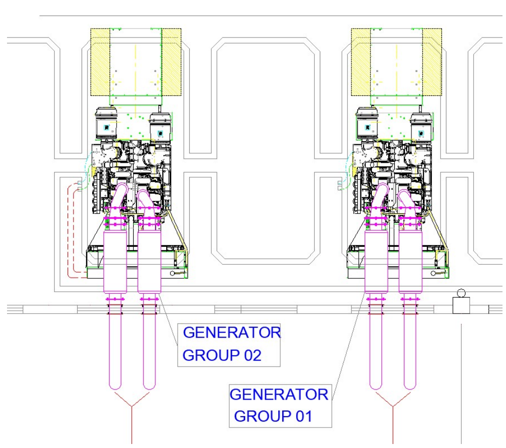

Figure 4. Scheme of the systems in the CUT. Own source

Table 1 shows the data for the turbo-compressed genset C1000D6. The values presented for exhaustion gas flow, and temperature are for the genset operating at 100% of the nominal load.

Table 1. Engine data provided by the manufacturer.

Parameters	Valor
Cylinders	12
Cylinders configuration, angle	V,50°
Compression rate	14:1
Displacement (liters)	30,5
Nominal speed (rpm)	1800
Fuel consumption 100% load (liters per hour)	262
Fuel consumption 75% load (liters per hour)	193
Fuel consumption 50% load (liters per hour)	134
Fuel consumption 25% load (liters per hour)	78
Inlet air flowrate (m^3/h)	4.824
Gas flowrate at 100% load (m^3/h)	13.200
Exhaust gas temperature (°C)	523,9
Maximum cylinder inlet pressure (kPa)	6,7

The genset fuel consumption was evaluated by measuring the volume in the fuel reservoir before and after the test. The mass flowrate supplied to the engine was calculated according to Eq. (1).

$$\dot{m}_c = {}^{V.\rho}/_{t}\,(kg/h) \tag{1}$$

Where V is the fuel volume consumed in liters, ρ is the fuel density and t is the fuel consumption time. The fuel power consumed in the genset was calculated according to Eq. (2).

$$P_c = \dot{m}_c\,.\,PCI_c \tag{2}$$

Where PCI_c is the fuel's lower heating value. The engine shaft power was calculated according to Eq. (3).

$$P_{shaft} = {}^{P_{el}}/_{\eta_g} \tag{3}$$

Where P_{el} is the electrical generator output power and η_g is the generator's efficiency. The power lost by the engine was calculated according to Eq. (4), which is the difference between the fuel power (P_c) and the shaft power (P_{shaft}).

$$P_p = P_c - P_{shaft} \tag{4}$$

The power within the engine exhaustion gas (P_e) the was calculated according to Eq. (5).

$$P_e = (\dot{m}_{ar} + \dot{m}_c).\overline{C_p}.(T_e - T_i) \tag{5}$$

Where $\bar{C}_p$ is the average exhaustion gas specific heat at constant pressure in the temperature range of T_e and T_i, exhaust gas and air inlet temperature respectively. The engine's efficiency was calculated by the electric output power divided by the fuel power, according to Eq. (6).

$$\eta_c = {}^{P_{el}}/_{P_c} \tag{6}$$

The CWP cooling system consists of:

1. Three 480 TOR centrifugal Chiller`s, one being a standby, having the 134A a coolant;
2. Four primary water pumps (PWP), one being a standby. Each PWP pumps 210 m^3/h of liquid water from airport terminal to the chiller evaporator;
3. Four chillers condensation (CCP), one being a standby. Each CCP pumps 330 m^3/h of liquid water from the chiller condensers to the cooling towers;
4. Four pumps of frozen water (FWP), two of them are standby. Each FWP pumps 320 m^3/h of frozen water from chillers or from storage tank to the passenger terminal (PT);
5. Three cooling towers of 480 TOR each;
6. One frozen water tank (thermal storage tank) with around 2000 m^3 capacity at approximately 6°C.

Figure 5 shows a schematic of the CWP and Table 2 shows the CWP's equipment nominal electric capacity.

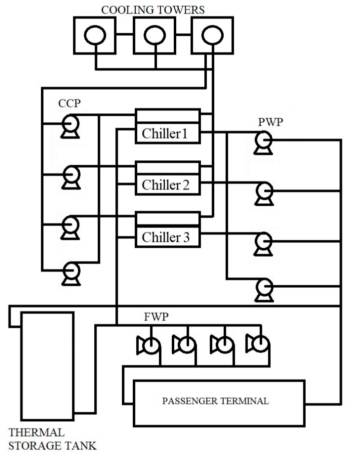

Figure 5: CWP scheme.

Table 2. Shows the CWP's each equipment electric capacity.

Equipment	Unitary Capacity	Number or units in operation	Total Capacity (kW)
Chiller	293.8	2	587.6
PWP	18.63	2	37.26
FWP	32.59	2	65.18
CCP	22.35	2	44.7
Cooling Tower	22.35	3	67.05
Total Operating at 100% Load			801.79

3.2 Current operation of airport systems

The cooling and emergency power system at Belem International Airport run as following: the two gensets C1000D6 operate only as emergency power in the event of a utility power failure. Only one genset is enough to attend airport electricity demand, except for the cooling system. The cooling system runs continuously for 21 hours a day varying only the chillers load according to the terminal thermal load. From 6 to 9 PM (demand peak hours), the cooling system is turned off and only the FWP pumps are kept on, using only the frozen water from the thermal storage tank. Using the capacity in Tab.2, one can verify that such procedure saves 2,209,83 kWh per day, generating monthly savings of R$ 190,450.92. Depending on the thermal load requested by the passenger terminal and the external climate, the use of the term accumulator can be extended beyond 9PM and can reach up to 11PM.

3.3 Airport electricity consumption in 2019

Figure 6 shows the average power demanded in each month (kW_{med}) from January to December 2019.

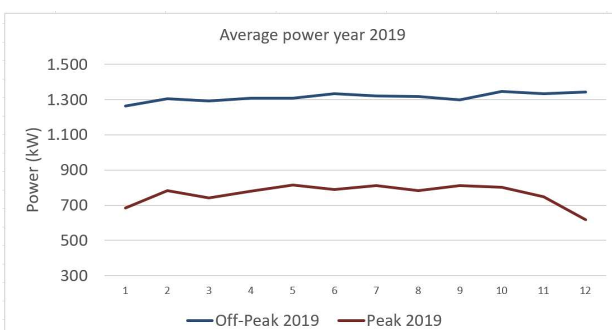

Figure 6. Average power year 2019.

Table 3 shows the average energy consumption in 2019 (kW) at peak and off-peak period. The utility invoice reports only the total energy consumed in the month. Peak and off-peak consumption was divided, adopting that for 255 days of the year, 3 hours a day were peak consumption and 21 hours of the same number of days were off-peak consumption. In the remaining 111 days, it was adopted 24 hours as off-peak. The power values in table 3 were used as a reference throughout this work. Peak and off-peak days were calculated month by month.

Table 3. Medium power in the year 2019

Airport Consumption	$\mathbf{kW_{med}}$
Off-peak Consumption	1313
Peak Consumption	763

The tariff modality applied to the airport is the green A4. Table 4 shows the prices for the kWh with taxes included for peak and off-peak periods.

Table 4. Energy price, taxes included.

Parameters	Value (R$)
Off-peak price (kWh) (with taxes)	0.50
Peak price (kWh) (with taxes)	3.84

3.4 Equipment used for energy measurement

To monitor the electrical energy consumption at CWP equipment, the passenger terminal and genset, the PowerPad 8335 three-phase power quality analyzer was used. It is equipped with 4 current inputs and 5 voltage inputs. Table 5 shows the information data for the PowerPad 8335.

Table 5. Powepad 8335 data

Electrical Characteristics	Value
Tension (RMS)	Phase-to-phase: 2,000 V Phase-to-neutral: 1,000 V Voltage ratio: up to 500 kV
Frequency (Hz)	40 – 69 Hz.
Harmonic	1º - 50º, Direction, Sequence
Current Accuracy	± 1% + 1 A
Voltage Accuracy	± 0,8% + 1V

The three-phase analyzer was connected directly to the system input or, in the case of the genset, to the output cables. It was connected to measure both voltage and current in the three phases. The equipment itself provides all the necessary data on power, energy consumed, current, voltage and several other parameters that are not applied to this study.

4. RESULTS AND DISCUSSION

4.1 Case study

Three case studies were carried out: the first was using a genset for 24 hours generating power and supplying heat from exhaust gas to the absorption cooling system. The second case, the use of the genset with absorption system only at peak hours. The third case, only using the genset during peak hours. The values compared with the electricity amount bought under the regular procedure: without genset for the year 2019.

Initially measurements of electricity consumption were performed at various times of the day both at genset and CWP. Table 6 shows the consumption made at the cooling system at full load during the measurement period of 48 hours for the chiller and for CWP, both at peak and off-peak hours. During off-peak hours, only FWP pumps were switched on.

Table 6. Consumption in measured (kW_{med})

Parameters	**Values ($\mathbf{kW_{med}}$)**
Chiller Consumption CWP (kW_{med})	292
Peak Consumption CWP (kW_{med})	41
Off-Peak Consumption CWP (kW_{med})	700

The test on the genset was carried out in the peak period for 03h12 minutes from 17h55 to 21h07 hours. During this test, all loads from the airport and runways borders were taken into account. Due to the schedule, the CWP load was not taken un account. Table 7 shows the results of this test with the generator setup.

The rate of energy content within exhaust gas was calculated using Eq. 5, where the $\bar{C}_p$ was adopted as 1.049 kJ/kg-K and the air inlet temperature was 298 K. The temperature of the exhaust gases was obtained using Eq. 7 (Silva, 2019).

$$T_g = 250 + 2{,}81 \times P \quad (7)$$

Where P is the percentage of the maximum power of the genset used in the test and T_g is the exhaustion gas temperature degree Celsius. The obtained temperature was 430 ºC, thus providing the thermal power of the exhaust gas as 671 kW.

Table 7. Results from generator setup test during peak period.

Parameters	Value
Test time	03:12
Power generation kWh (test time)	2.052
Average power kW_{med}	641
Fuel consumption (liters)	546
Fuel cost (R$/L)	4.68
Fuel cost (R$) (test time)	2.555
PCI (kJ/kg)	42.200
Average fuel power (kW)	1706
Exhaust gas power (kW)	671
Lost power, friction, cooling, radiation (kW)	394
Efficiency, Energy used / Energy available from Fuel (%)	37.6
Cost of kWh (R$)	1.24

Table 8 shows the distribution of the different forms of energy in %.

Table 8. Distribution of powers.

Parameters	Value (%)
Losses on exhaustion	39.3
Transferred to the generator	37.6
Other losses	23.1
Total	100

As shown in Tab. 7, the demand for energy, without CWP during an hour was 641 kWh. As shown in Tab. 6, CWP demands 700 kWh. Running both genset simultaneously the total energy required during the off-peak hours can be meet: 1300 kWh. CWP consumes approximately 54% of the energy supplied to the airport. According to the genset manufacturer, the fuel consumption for the 641 kW, interpolated in Tab. 1, was 167 l/h. The consumption measured in this work was 171 l/h: 2% offset.

To assess operation parameters of an absorption chiller coupled to the genset, data from the literature was used, according to Tab. 9. It presents the typical operating characteristics for single and double stage chiller using indirect burning of H2O-LiBr (ASHRAE, 2006). This table was used to calculate the cooling capacity that can be obtained using the exhaust gases from the genset.

For 671 kW of thermal energy in the exhaust, and using the COP of 1.2 in Tab. 9, the heat in the exhaust gases rejected by the generator group would generate, at best, 828 kW (235 TOR, refrigeration ton) cooling using a double-acting absorption chiller.

The chiller consuming an electrical power of 292 kW produces a cooling power of 1700 kW (480 TOR). Therefore, the energy contained in the exhaust gases is not enough to replace an electric chiller with an absorption one. Two gensets operating simultaneously would have the thermal power in the exhaust gases to allow for this replacement.

Table 9. Chiller characteristics by simple and double step absorption

Parameters	Simple effect	Double effect
Cooling Steam Consumption (kW/ kW)	60 to 80 kW	0,78 to 0,81 kW
COP	0,7 to 0,8	1,1 to 1,2
Hot water inlet temperature	115 ºC to 132 ºC	188 ºC

4.2 Results evaluation and discussion

Three economic analyzes were carried out:

1. Absorption chiller + generator for 24 hours;
2. Absorption chiller + generator for 3 hours (tip);
3. Generator for 3 hours (tip).

Table 10 shows the total consumption of one month of use without the genset and without an absorption cooling system to be used as a reference.

Table 10. Current energy cost

Parameters	Value (R$)
Day off-peak cost (21h)	13,786
Day peak cost (3h)	8,789
Cost off-peak month (31 days)	438,826
Peak month cost (21 days)	184,584
Total cost month	623,411

The first analysis took into account the replacement of a 292 kW (480 TOR) electric cooler with an absorption cooler and the use of the generator set for 24 hours. Tthe power required outside the peak (1313 kW_{med}) is approximately equal to the sum of the average test power of the generator set (641 kW_{med}) plus the average power of the CWP (700 kW_{med}), minus the power of the CWP (41kW) in peak, which is equal to 1,300 kW. Value close to the average consumption of 2019. When removing an electric cooler (292 kW_{med}) from the average consumption of 1313 kW_{med}, the generator sets will have to provide 1008 kW, for 21 hours outside peak hours and 3 hours during peak hours.

To reach such capacity (1008 kW), two generator sets are needed to operate simultaneously, each with an average power of 504.0 kW, which means 50.4% of the maximum load. Interpolating on the tab. 1, fuel consumption must be 135 l/h. Using Eq. 7, the temperature of the exhaust gases must be 391 ºC, providing a thermal energy in the exhaust gases of 631 kW.

631 kW of cooling power (180 TOR) are generated in each absorption chiller. Operating two generator sets in parallel provides 1262 kW of cooling power (358 TOR), far below the current 1700 kW (480 TOR) provided by the electric chiller. Regarding the energy cost, as shown in the Table. 11, the total cost in the month was R$ 909,792, higher than that obtained in the Table. 10, turning it to be economically unfeasible.

Table 11. Energy cost used with absorption chiller more two group generators for 24 hours

Parameters	Values (R$)
Cust (24h)	30,326
Total cost per month	909,792

In the second analysis, only one genset would be used, since the average power at this moment is approximately 641 kW. The use of an absorption chiller only during peak hours proved to be unfeasible because at this time the term accumulator is used, so there is no consumption of electricity to produce cooling, making the use of the absorption chiller unfeasible.

The third assessment, which is the use of the genset during peak hours. Table 12 shows that the cost of this option as R$ 450,253 monthly with the use of the genset during peak hours against the R$ 623,411 of energy provided by utility company. The savings can reach R$ 124,979 per month. This third analysis became feasible due to the price of energy supplied by the utility at peak times which is 3.84 R$/kWh, while that of the genset is 1.24 R$/kWh.

Table 12. Energy cost using the genset during peak hours.

Parameters	Values (R$)
Day off-peak cost (21h)	12,601
Day peak cost (3h)	2,304
Cost off-peak month (31 days)	401,852
Custo mês fora de ponta (21 days)	48,400
Total cost month	450,253

Figure 7 shows a summary comparing the results found.

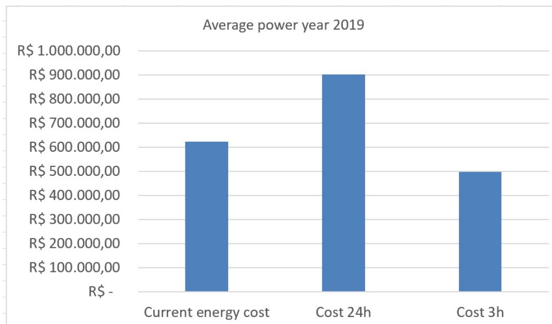

Figure 7. Average power year 2019.

In this work, the cost of the genset and cooling systems maintenance was not taken into account because these costs are regularly carried out according to the manufacturer and regardless of the genset period of operation. The cost of a new absorption refrigeration equipment was also not used in the analysis, since only energy costs made its use unfeasible.

5. CONCLUSION

The analysis shows that using an absorption chiller taking advantage of the heat of the exhaust gases for the generation of cold is not an economically feasible alternative due to the electricity price generated by the genset when compared to the electricity supplied by the utility company outside the peak hours 1,24 x 0.50 R$/kWh. However, it was observed that the use of the genset during peak hours is economically feasible, since the price of kWh sold by the utility company during peak hours is 3.1 times higher than the price of electric diesel generation.

6. ACKNOWLEDGEMENTS

To Electrical Engineer Alex Takashi and INFRAERO Electrotechnical Technicians for the support given at the facilities. To the support of the Maintenance Manager Mr. Peralta and INFRAERO for the support and availability of the infrastructure for study.

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