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LCC EVALUATION OF A HIGH EFFICIENCY COMBINED CYCLE POWER PLANT INSTALLED IN RIO DE JANEIRO CITY WITH A TIC – GAS TURBINE AIR INLET COOLING SYSTEM

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Abstract. *The aim of this technical paper is to perform a LCC evaluation of a high efficiency 110 MW Combined Cycle Power Plant - CCPP operating in Rio de Janeiro City with the implementation of a TIC system for Gas turbine inlet air-cooling. GT – Gas turbine performance is expressed in terms of net power available on the GT output shaft and heat rate. In GT at nominal speed the air volume flow remains approximately constant, however, the mass flow will vary depending on the air inlet temperature and humidity. In accordance with GE performance chart for each increment of 1 °C in the GT incoming air temperature results in a loss of 1% in GT output shaft power, and increasing in 0,031% the heat rate. For a 10 years scenario, 2007-2016, using a special methodology, a temperature database was developed based on the collection of hourly temperature measurements of the automatic meteorological station of Seropédica - RJ, located in the industrial area of Rio de Janeiro City. In a previous technical analysis the AC – Absorption chiller – TIC– Turbine Inlet Cooling technology was elected as being the best technology to be applied. The estimated net electric power production would increase by 69.248MWh/yr. The payback period is 1.5 years and the net present value is 67.26 MUS$, considering the ANEEL electric power prices to Rio de Janeiro, Brazilian taxes, the ST power losses, the TIC total capital cost and TIC O&M costs during 20 years.*

Keywords: *Turbine Inlet Air Cooling System, Combined Cycle Power Plants, Aeroderivative Gas Turbines*

1. INTRODUCTION

The aim of this technical paper is to perform a LCC - Life Cycle Cost evaluation of a high efficiency 110 MW Combined Cycle Power Plant - CCPP operating in Rio de Janeiro City with the implementation of a TIC, gas turbine air inlet cooling system for GT.

Aeroderivative gas turbines are composed of an air compressor to pressurize the incoming air, a combustion chamber where chemical energy from fuel is converted in heat after being burned with air, and a HP and a LP expansion turbines responsible to convert thermal and pressure energy into useful mechanical energy. GT provides mechanical energy for driving the GT compressor shaft, and also to drive the electric generator. [1] [2] [6]

The GT performance is expressed in terms of net power available on the GT output shaft and heat rate, subtracting all losses and deratings. [2] [3] In GT at nominal speed the air volume flow remains approximately constant, however, the mass flow will vary depending on the air inlet temperature and humidity. Increasing the ambient air temperature lowers the density of the inlet air, thus reducing the mass flow through the GT, and decreasing considerably the output power. [2] [3]. Changes in the air inlet humidity have a negligible effect on the GT power output, therefore, it will not be considered. [2] [3]. It is important to observe that each machine has its own performance variation behavior.

In a previous technical analysis the AC – Absorption chiller – TIC technology was elected as being the best technology to be applied.

This technical study will determine the NPV for 20 years, considering the extra power provided by GT due to TIC application, price the electric power under ANEEL parameters [13], all costs involved for TIC system implementation, such as: acquisition, installation, commissioning and tests, the TIC system maintenance, and the ST power output reduction due to the AC - absorption chiller steam consumption.

According to ISO standard a GT power is informed by manufacturers considering: inlet air temperature =15 °C, air humidity = 60%, air pressure = 101,32 kPa at sea level, and zero losses. [1] [2]

For a 10 years scenario, 2007-2016, using a special methodology, a temperature database was developed based on the collection of hourly temperature measurements of the automatic meteorological station of Seropédica - RJ, located in the industrial area of Rio de Janeiro City. [11]

1.1 The combined cycle power plant

The CCPP consists of 2 x 50% configuration GT GE LM6000 PC, aeroderivative type, 42 MW (ISO) each, driving 2 synchronous generators, 1 x 100% configuration ST, 26 MW (ISO), driving 1 synchronous generators, 2 x 50% configuration HRSG, a refrigeration tower system, condenser, condensate pumps, deaerator, LP and HP feed water pumps, cooling water pumps, etc. The CCPP total delivery ISO power is 110 MW.

1.2 A schematic diagram of the CCPP system + TIC

Figure 1 presents theCCPP system schematic diagram to be installed in Rio de Janeiro City. The GT packages performance will be improved using 2 x 50% configuration AC- Absorption Chillers.

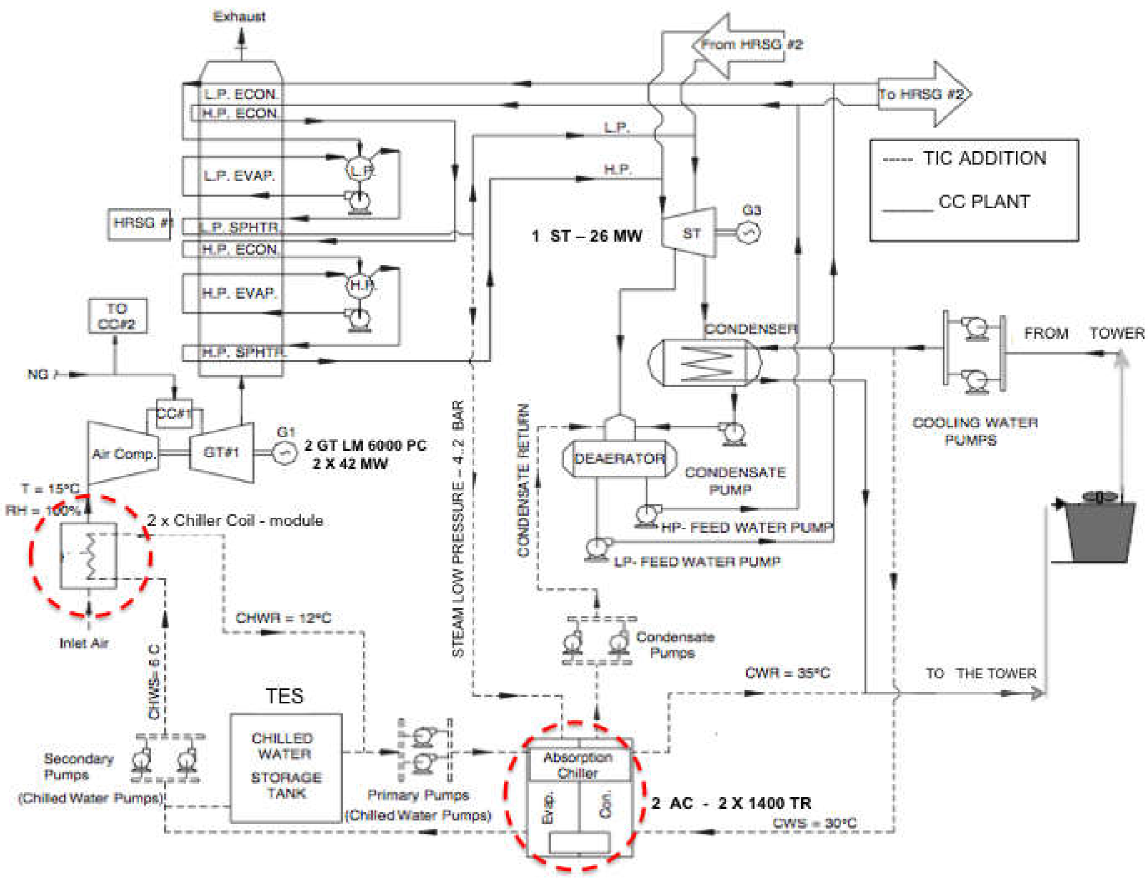


Figure 1 - CCPP and the TIC addition schematic diagram [6]

These chillers will produce chilled water. The AC – absorption chillers use heat input from a low-pressure steam (about 4.2 bar) from HRSG – Heat Recovery Steam Generator. The chilled water storage tank – TES will be installed between the AC and the chiller coil module. Chilled water pump system consists of two groups. The first one is a primary pump, which circulates chilled water between the chilled water storage tank and the AC. The second group is a secondary pump, which circulates chilled water between the TES - storage tank and the chiller coil module installed in front of GT air inlet filters.

The dashed lines in the schematic diagram are involving the TIC system specifically. As main components of the TIC system can be related: Two chiller coil modules, a TES – thermal energy storage (chilled water storage), two absorption chillers, two primary pumps, two secondary pumps, two chilled water control valves, a control system and the interconnection of the system components.

Table 1 presents the CCPP system components data.

Table 1 – CC system components data

Description	Data
Gas turbine	
Air flow (Kg/s)	115
Power output (MW) – ISO	42
Efficiency (%)	40.5
Heat rate (Btu/kWh)	8519
Steam turbine	
Power output (MW) – ISO	26
Efficiency (%)	38
HRSG	
HP – steam	@ 55 bar – 450 ^{o}C
LP - steam	@ 4.5 bar – 235 ^{o}C
CCPP	
Power output (MW) – ISO	110
Efficiency (%)	52.5

Figure 2. The chillingcoilmodule features installed in front of each GT air inlet filters. Each module consists of: a heat exchanger (chiller coil), a mist eliminator and a drain system.

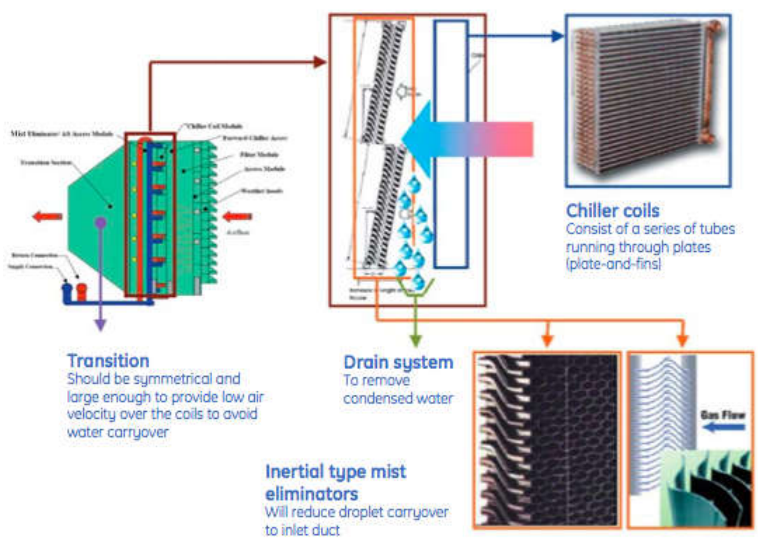


Figure 2. Chiller coil module components

2. RIO DE JANEIRO CITY – TEMPERATURE DATABASE ELABORATION[12]

For a 10 years scenario, 2007-2016, a temperature database was elaborated based on the collection of hourly temperature measurements of the automatic meteorological station of Seropédica, located in the industrial area of Rio de Janeiro City.

Tables 2A, 2B and 2C. The temperature weighted averages set up for each day of the year. [12]

Table 2A. Temperature weighted average records from the 1st to the 10th[12]

Day	1			2			3			4			5			6			7			8			9			10		
Month	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md
JAN	24	35	30	27	35	31	28	39	34	27	33	30	27	32	30	25	33	29	26	33	30	23	35	29	25	35	30	24	35	30
FEB	24	37	31	25	38	32	24	38	31	24	38	31	24	38	31	25	37	31	26	38	32	25	38	32	26	37	32	25	38	32
MAR	24	31	28	24	30	27	25	30	28	23	32	28	25	32	29	25	28	27	24	31	28	22	25	24	22	32	27	24	35	30
APR	23	32	28	24	30	27	25	29	27	24	27	26	23	29	26	23	31	27	21	29	25	21	30	26	22	33	28	23	30	27
MAY	18	28	23	19	30	25	18	28	23	18	30	24	18	31	25	18	31	25	20	30	25	21	31	26	20	26	23	19	25	22
JUN	21	27	24	21	26	24	17	22	20	17	26	22	16	30	23	22	28	25	21	32	27	22	32	27	23	28	26	20	22	21
JUL	19	26	23	18	26	22	18	29	24	18	31	25	17	30	24	17	30	24	18	29	24	18	25	22	19	24	22	19	22	21
AGO	14	29	22	17	29	23	17	32	25	19	35	27	21	22	22	12	24	18	13	29	21	16	25	21	18	23	21	16	28	22
SET	21	29	25	16	27	22	18	29	24	19	22	21	15	24	20	12	26	19	20	30	25	16	28	22	15	32	24	24	34	29
OCT	28	32	30	21	24	23	18	23	21	16	22	19	13	23	18	14	27	21	15	29	22	16	32	24	17	34	26	20	37	29
NOV	28	35	32	23	31	27	23	34	29	22	36	29	22	34	28	23	28	26	21	35	28	23	33	28	22	26	24	20	30	25
DEC	23	34	29	26	34	30	27	36	32	24	33	29	22	24	23	21	30	26	22	32	27	24	34	29	23	35	29	23	34	29

Table 2B. Temperature weighted average records from the 11th to the 20th[12]

Day	11			12			13			14			15			16			17			18			19			20		
Month	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md
JAN	25	37	31	26	35	31	25	36	31	24	37	31	25	37	31	26	35	31	21	31	26	22	30	26	22	31	27	23	32	28
FEB	25	35	30	24	38	31	24	39	32	26	35	31	26	29	28	24	28	26	22	29	26	23	28	26	23	28	26	24	32	28
MAR	25	34	30	27	33	30	25	33	29	25	34	30	25	35	30	25	35	30	24	36	30	25	35	30	23	35	29	23	36	30
APR	23	32	28	23	34	29	22	30	26	21	24	23	21	23	22	20	25	23	21	27	24	21	31	26	23	33	28	21	29	25
MAY	17	24	21	16	26	21	16	28	22	16	29	23	17	27	22	18	30	24	20	26	23	20	27	24	18	26	22	17	28	23
JUN	20	27	24	17	27	22	18	27	23	18	29	24	20	25	23	19	28	24	18	30	24	19	27	23	18	21	20	17	21	19
JUL	18	20	19	17	23	20	18	24	21	16	24	20	16	25	21	16	27	22	17	29	23	19	28	24	17	20	19	16	22	19
AGO	18	30	24	18	33	26	19	25	22	16	17	17	16	21	19	18	25	22	17	28	23	17	26	22	19	23	21	17	25	21
SET	24	36	30	21	27	24	18	29	24	16	33	25	18	35	27	22	30	26	19	22	21	20	30	25	19	28	24	22	32	27
OCT	24	36	30	19	30	25	19	41	30	21	26	24	22	29	26	20	32	26	22	32	27	23	30	27	21	37	29	23	29	26
NOV	20	29	25	20	34	27	23	33	28	20	24	22	19	23	21	18	25	22	16	27	22	17	28	23	16	32	24	20	33	27
DEC	23	36	30	25	36	31	26	34	30	24	30	27	23	28	26	20	28	24	21	32	27	21	33	27	23	31	27	24	32	28

Table 2C. Temperature weighted average records from the 21th to the 30th[12]

Day	21			22			23			24			25			26			27			28			29			30		
Month	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md	Min	Max	Md
JAN	23	35	29	24	35	30	26	36	31	26	36	31	24	36	30	25	34	30	26	36	31	26	38	32	25	38	32	24	36	30
FEB	24	36	30	23	35	29	26	35	31	28	33	31	25	35	30	25	36	31	25	35	30	25	35	30						
MAR	25	34	30	26	31	29	22	24	23	22	23	23	21	26	24	22	27	25	22	28	25	22	29	26	22	31	27	25	32	29
APR	21	27	24	20	32	26	22	28	25	22	26	24	20	25	23	17	26	22	17	26	22	18	23	21	16	26	21	17	26	22
MAY	18	29	24	20	31	26	25	28	27	19	21	20	19	22	21	20	27	24	20	25	23	17	21	19	17	24	21	18	24	21
JUN	18	25	22	17	24	21	17	26	22	18	28	23	15	29	22	18	29	24	18	31	25	16	29	23	18	31	25	20	27	24
JUL	16	25	21	16	27	22	16	28	22	21	30	26	20	24	22	18	19	19	18	20	19	17	21	19	16	23	20	16	18	17
AGO	18	28	23	17	32	25	17	31	24	16	34	25	17	30	24	17	29	23	20	22	21	17	19	18	16	21	19	17	25	21
SET	20	23	22	17	24	21	16	29	23	17	34	26	19	30	25	21	32	27	23	27	25	22	28	25	22	36	29	22	25	24
OCT	20	22	21	18	22	20	19	29	24	17	31	24	19	27	23	21	29	25	20	27	24	17	28	23	19	34	27	22	33	28
NOV	18	34	26	20	35	28	22	26	24	22	28	25	23	33	28	27	34	31	23	26	25	22	27	25	21	27	24	21	27	24
DEC	25	37	31	30	37	34	25	28	27	23	29	26	23	32	28	25	33	29	24	34	29	23	37	30	25	37	31	24	34	29

2.1 Each day thermal amplitude treatment

In one day the temperature and humidity can vary greatly. Comparing a large number of samples of the thermal amplitudes during the days, it was observed a relative number of hours for the maximum, minimum and average temperatures. With a small deviation is given: From 00:00 am to 8:00 am – minimum records, from 12:00 am to 6:00 pm – maximum records, and 9:00 am to 12:00 am / 7:00 pm to 11:00 pm – average records. [14]

Figure. 3 and fig. 4.The thermal amplitude during a typical day.

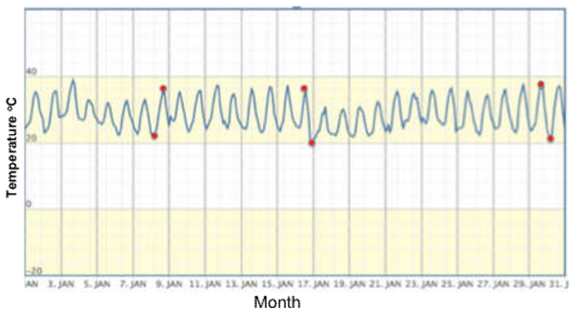


Figure 3. January month temperatures [12]

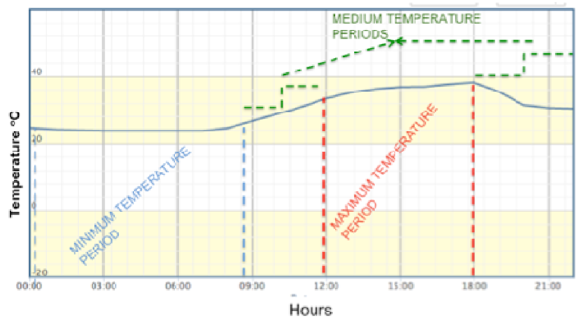


Figure 4. January15st thermal amplitude [12]

Therefore, for the same day, during the GT power calculation it will be considered the machine operating a few hours with maximum, minimum and average ambient temperatures.

3. GAS TURBINE SITE PERFORMANCE CALCULATION

The GT performance is informed by manufacturer in accordance with ISO specs, being:[1] [2]

- inlet air temperature =15 ^{o}C
- inletair humidity = 60%
- inletair pressure = 101,32 kPa at sea level
- and zero losses.

It shall also be considered: [1] [2]

- input losses caused by: inlet filters, silencers and inlet plenum;
- output losses caused by: exhaust duct, silencers ducts and stack;
- gearbox losses when applied;
- mechanical losses;
- and others, depending on the GT features peculiarities.

Thus, to calculate the GT power on site conditionit shall be considered some deratings application and correction factors due to the changes of the ambient air temperature and humidity.

3.1 GT deratings

Table 3. Deratings to be applied in accordance with the GT packages - LM 6000 PC + direct drivensynchronous generator features. [4][5]:

Table 3. GT deratings[4][5]

Deratings	
Gearbox losses	NA
Inlet losses	1,00 %
Exhaust losses	2,00 %
Mechanical losses	0,5 %
Generator losses	0,5 %
Chiller coil losses	1 %

The GT LM 6000 output shaft speed é 3.600 rpm, allowing a direct driven with the synchronous generatorshaft,without requiring gearbox application.[7]

3.2 GT inlet air temperature and humidity changes

In GT at nominal speed the air volume flow remains approximately constant, however, the mass flow will vary depending on the air inlet temperature and humidity. Increasing the ambient air temperature lowers the density of the inlet air, thus reducing the mass flow through the GT, and decreasing considerably the output power. [2] [3]. Changes in the air inlet humidity have a negligible effect on the GT power output, therefore, it will not be considered. [2] [3].

Figure 5. GT output Power and Heat Rate x Air inlet temperature chart provided by General Electric manufacturer for GT LM 6000 PC.

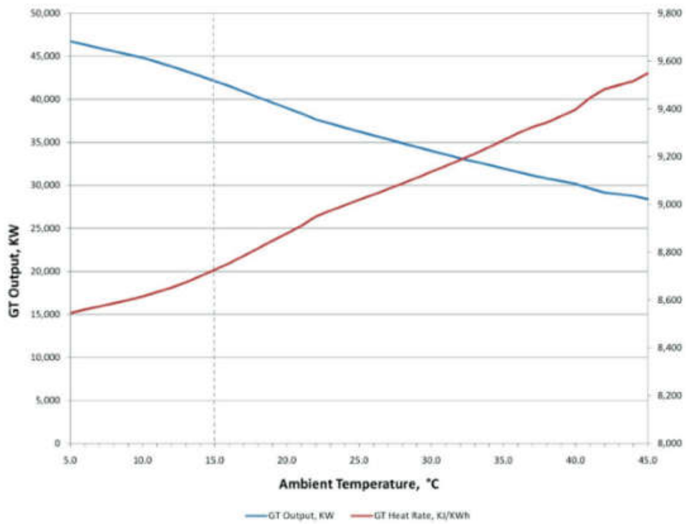


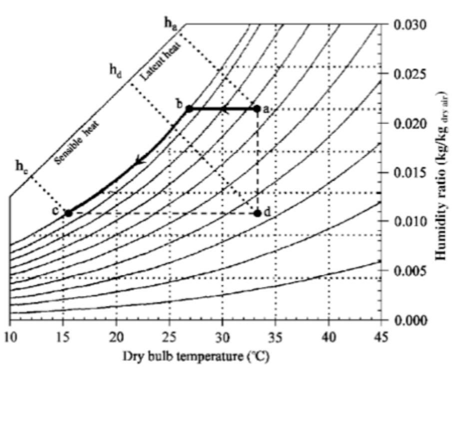
Figure 5. GT Performance - Function of Inlet Air Temperature - RH - 60%, no losses. [2]

In accordance to the GE GT performance chart above, for each increment of 1 °C in the GT incoming air temperature results in a loss of 1% in GT output shaft power, and the heat rate increases 0,031%. [2]

4. LOAD CALCULATIONS AND COOLING SYSTEM DIMENSIONING

4.1 Cooling load calculation

The inlet air-cooling system, with absorption chiller (AC), will be dimensioning to cool the GT inlet air mass flow temperature from 32 °C to 15 °C. Thus, whenever the temperature is lower than 32 °C the air temperature will be even lower than 15 °C, allowing GT power incremental gains of 1% in each degree. The air-cooling shall be limited to 8°C due to the risk of ice formation on the GT Inlet Guide Vanes (IGV). Therefore, a control valve should be installed on the adduction header in order to provide the chilling system with the required turndown capability. [4] [8][9] [10]



During the GT air-cooling process the air is cooled by rejecting its heat to the chilled water. As the air temperature drops, its relative humidity will rise until 100%. It consists of two steps, which are latent heat (a–d) and sensible heat (d–c) [6], as shown in Figure 6.

The necessary total cooling load can be calculated by using the energy balance formula as follow: [6]

$$Q_{CL} = m_{air}[(h_a - h_c) - hf_{g,c}(\omega_a - \omega_c)][6] \quad (1)$$

Being,

Q_{CL} - Cooling load (kW)
m_{air}- Air mass flow (kg/s)
h_a- Inlet specific enthalpy – point a (kJ/kg)
h_c- Outlet specific enthalpy – point c (kJ/kg)
$hf_{g,c}$= Latent heat of vaporization of water(kJ/kg)
ω - Humidity ratio

Figure 7. Simulation of the air enthalpies and humidity ratios.

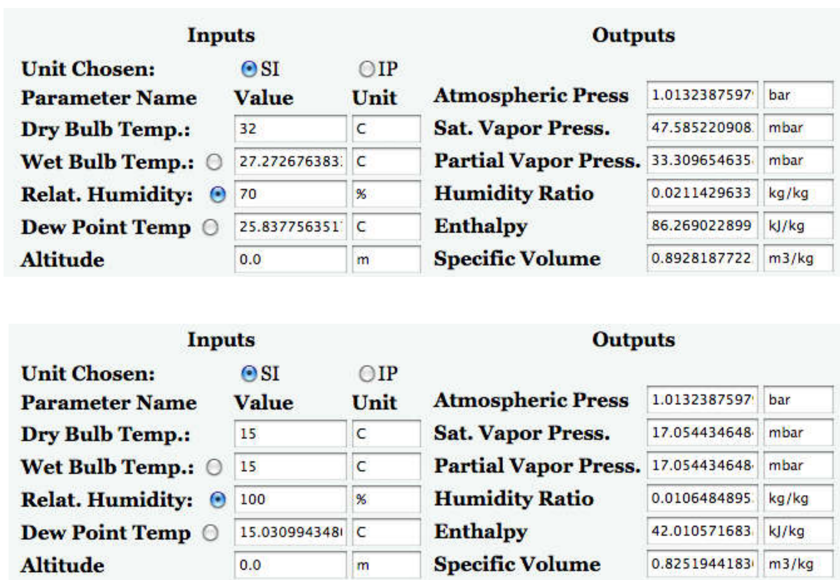


Figure 7. Air Enthalpies& humidity ratios simulation

4.2 Absorption chiller dimensioning simulation

Table 4. THERMOFLOW® software simulation of the AC - absorption chiller machine capacity.

Table 4. Absorption chiller dimensioning

Description	Unit	Value
Mass flow rate to be cooled at GT inlet (M_a)	Kg/s	115
Air temperature – site condition – RH = 70 %	^oC	32
Enthalpy – Inlet air - h_a	kJ/kg	86.26
Air temperature after coil	^oC	15
Enthalpy – air after cooling – RH = 100 % - h_c	kJ/kg	42.20
Heat to be removed per machine - Q_{CL}	kW	4.560
Heat to be removed per machine - Q_{CL}	TR	1.420
Total heat to be removed per machine – 2 machines	TR	2.800

Enhancing the operational flexibility it will be applied 2 x 50 % configuration, 1.400 TR absorption chiller machines.

4.3 Estimation of the chilled water system capacity

Table 5. THERMOFLOW® software simulation based on the heat transfer formula: [6]

$$Q_{cw} = M_{cw} * Cp_{cw} * (T_{cw2} - T_{cw1}) \quad [6] \qquad (2)$$

Being,

Q_{cw} = Heat load available for Cooling (kW,RT) = 2.800
M_{cw} – mass of chilled water (kg/s) – in progress
Cp_{cw} = specific heat of chilled water (kJ/kg ^{o}C) = 4.2
T_{cw1}= Chilled water inlet temperature (^{o}C) = 12
T_{cw2}= Chilled water outlet temperature (^{o}C) = 6
1 TR = 3.52 kW

Table 5 – Chilled water capacity simulation [5][6]

Description	Unit	Value
Mass flow rate for 1 TR	Kg/s	0.139
Volume flow rate for 1 TR	M^3/h	0.502
Volume flow for 1.420 TR + 10% margin	M^3/h	752
Total Volume flow – 2 machines	M^3/h	1.500

4.4 Steam Turbine output power losses estimation

The AC needs a constant (4.2 bar) low-pressure steam, with a mass flow rate of 3.5 kg/s (4.5kg/h-RT) in accordance with AC manufacturer specs. THERMOFLOW® software simulation result indicates that the ST power output decreases by around 1.82 MW (7% of the ST total output power) due to the low pressure steam consumption by the AC - Absorption Chiller. This is a very conservative calculation.

5. TIC CAPITAL COST AND AUXILIARY POWER CONSUMPTION

Table 6.TIC implementation total capital costs. It comprises all items foreseen due to TIC acquisition, including the procurement, installation, erection, commissioning and tests.

Table 6. TIC system total capital cost

Equipment	Unit	Price (MUS$)
Absorption chiller machine	2	2 x 1.25
Transition piece Chiller coil Inertial type mist eliminator Drain system	2	2 x 0.91
Chiller water control valve	2	2 x 0.45
Chilled water pumps - primary	2	2 x 0.5
Chilled water pumps - secondary	2	2 x 0.25
TES – Chilled water storage tank	1	3.92
Control system	1	1.2
Installation, commissioning, tests	-	1.4
Miscellaneous		1.46
Total capital costs		14.7

The total TIC auxiliary power consumption is 234 kW

6. GT -EXTRA POWER CALCULATION & ECONOMIC ANALYSIS

Table 8. General parameters, premises and LCC result.

Table 8. General parameters application and the LCC evaluation results

Premises & LCC Evaluation Results		
Interest rate - Brazil		15 %
Currency exchange rate-Real /US$	08/01/2017	3,11
MWH Price - Rio de Janeiro + taxes	ANEEL – R$ 628,00	$201.58
Life time service	Years	20
ST losses + Auxiliary electric load	MWH per/year	17.243
TIC capital cost – Installation, commissioning, tests		$14,700.000
GT system availability record		95 %
TIC system O&M cost	Per year	$965,000
CCPP extra power delivered	Per year	69.248
Net Present Value (NPV)		$67,263.511
Payback period	Year	1.5

7. CONCLUSIONS

LCC evaluation results show that TIC - turbine inlet air-cooling system application on GT system is feasible and very attractive. Nowadays, the AC – absorption chiller technology can be considered as a reliable alternative with several successful applications worldwide.

With TIC implementation the GT system can run always in base load condition, high efficiency mode, extending the GT life cycle, increasing the GT maintenance intervals, and also reducing air effluent emissions.

The estimated net electric power production would increase by 69.248MWh/yr. The payback period is 1.5 years, and the net present value is 67.26 MUS$.

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9. RESPONSIBILITY NOTICE

The authors, P. R. Cruz, D. J. N. M. Chalhub and M. A. F. Costa are the only responsible for the printed material included in this paper.