LCC evaluation of a High Efficiency Combined Cycle Plant Installed in Rio de Janeiro City with a TIC – Gas Turbine Air Inlet Cooling System Implementation

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Topics of interest:

- CCPP identification
- Technical paper objectives
- Methodology applied & specs
- Technical & Economic analysis
- Conclusion
- References

CCPP- Combined Cycle Power Plant Configuration

Fig. 1- CCPP

Figure 1 – Combined cycle power plant configuration

2 x 50% GT System - Aeroderivative Gas Turbines

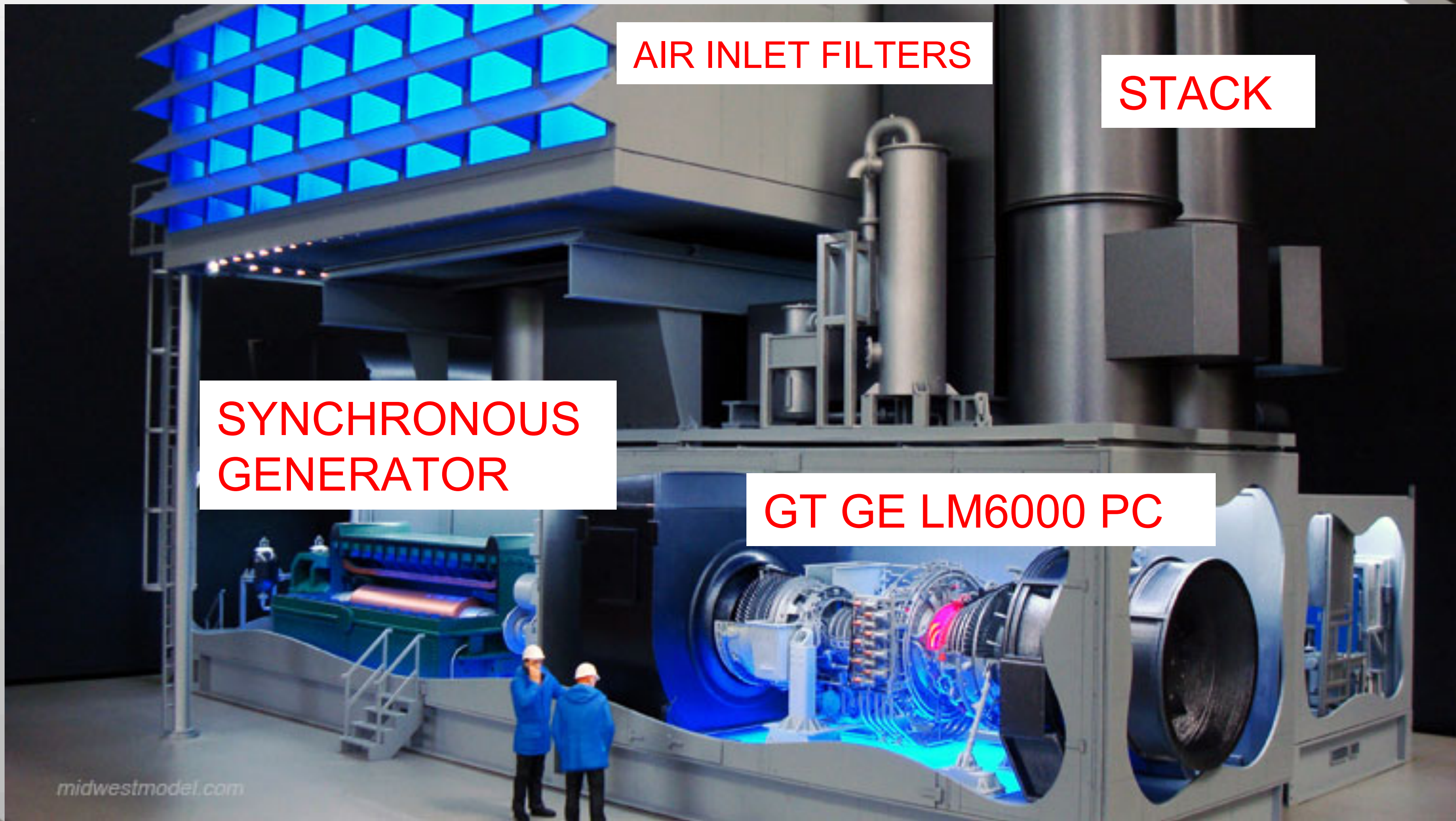


Fig. 2- GE LM 6000 PC package

2 x 50% GT System - Aeroderivative Gas Turbines

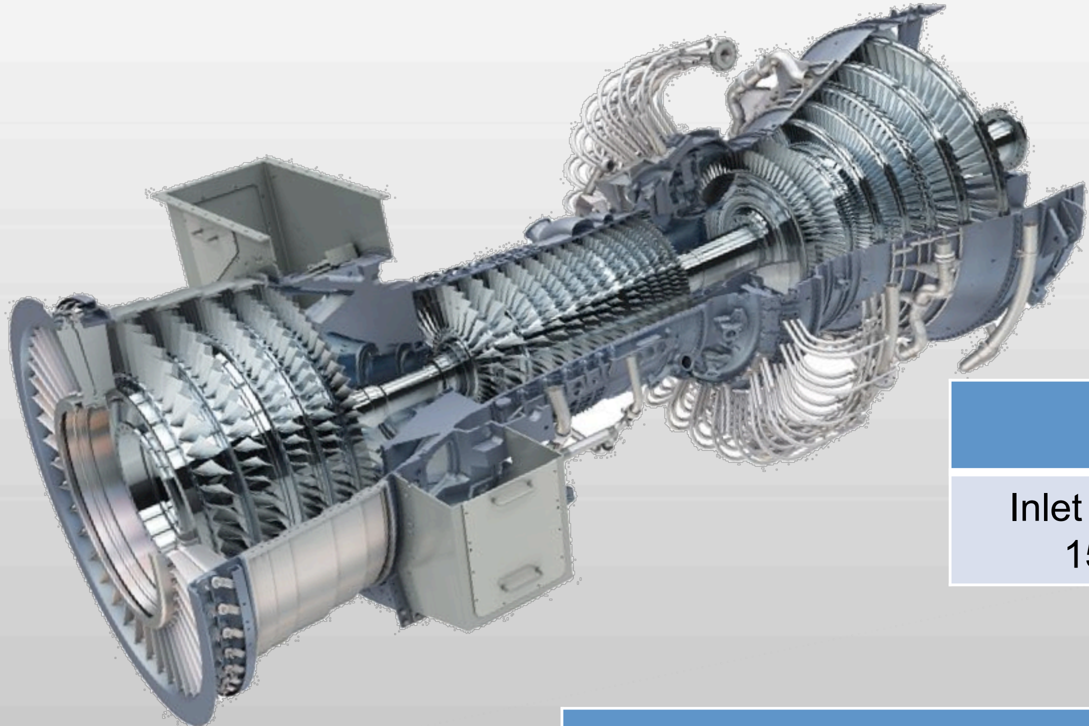


Fig. 3 – GT LM 6000 PC

ISO CONDITION		
Inlet Temp. 15 ^{o}C	RH 60%	Air Pressure 101,3 kPa

GT GE LM 6000 PC	DATA
AIR FLOW (kg/s)	115
POWER OUTPUT (ISO)	42
HEAT RATE (Btu/kWh)	8519
EFFICIENCY	40.5
EXHAUST GAS TEMP (^{O}C)	440

CCPP- Combined Cycle Power Plant Configuration

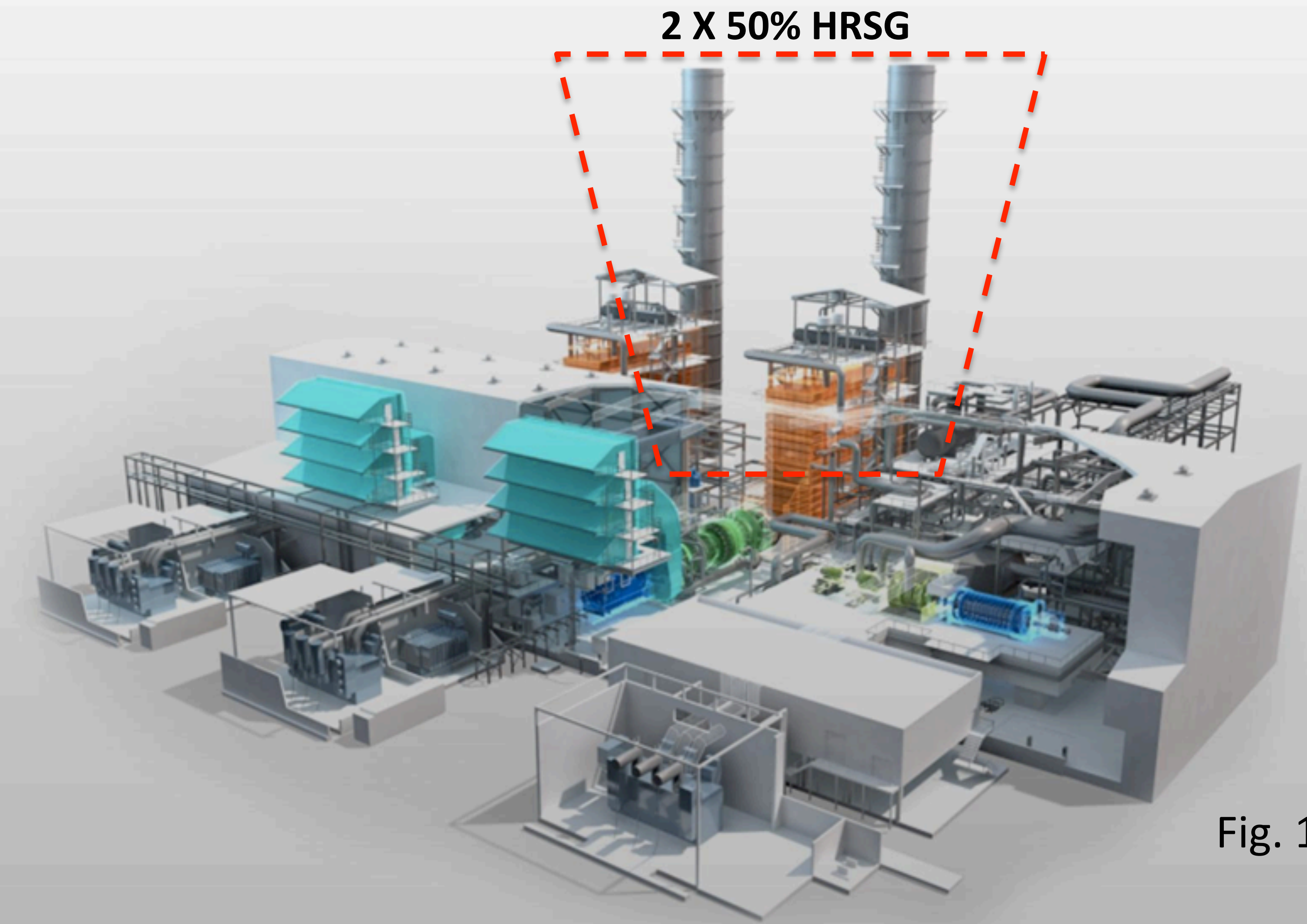


Fig. 1- CCPP

2 X 50% HRSG – Heat Recovery Steam Generator

Figure 4 – HRSG

HRSG	DATA
HP STEAM	@ 55 BAR
LP STEAM	@ 5 BAR

CCPP- Combined Cycle Power Plant Configuration

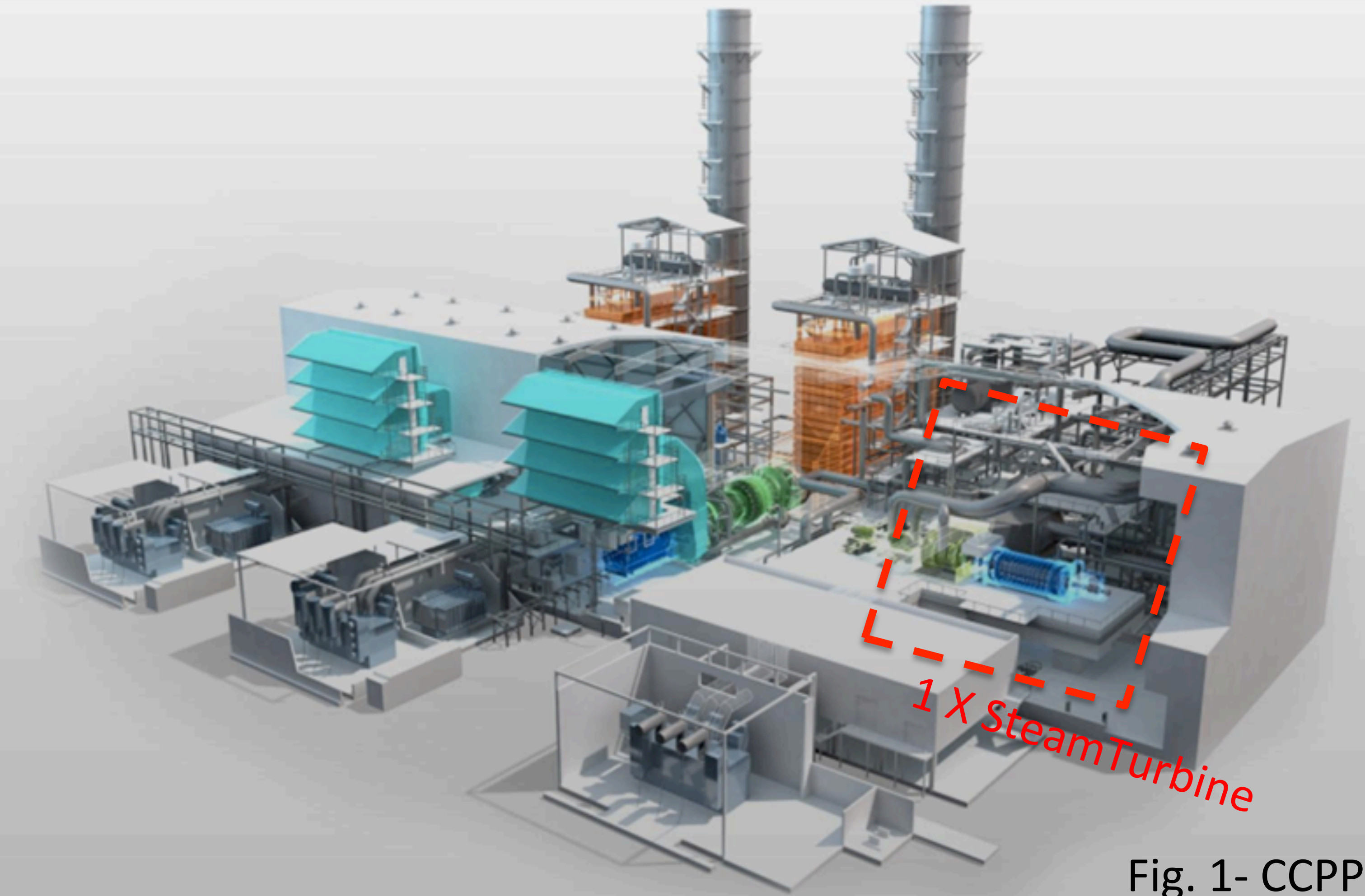


Fig. 1- CCPP

1 x 100% ST – Steam Turbine

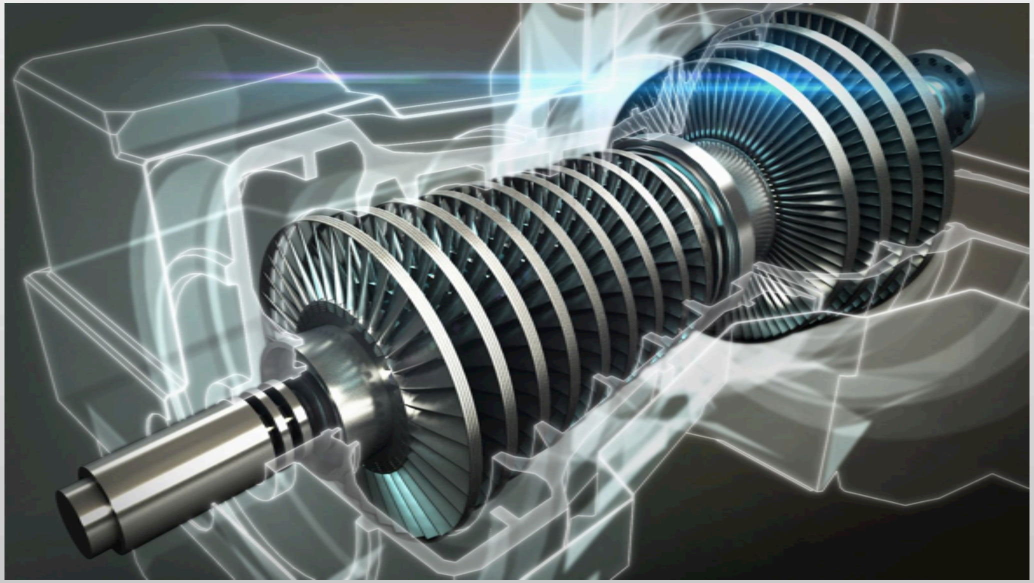


Figure 5 – ST – Steam turbine

STEAM TURBINE	DATA
POWER OUTPUT (MW)	26
EFFICIENCY (%)	38

GT performance evaluation

GT performance is expressed in terms of net power available on the GT output shaft and heat rate.

At GT 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 proportionally the GT output power.

GT performance evaluation

Each increment of 1 °C in the GT inlet air temperature results in a loss of 1% in GT output shaft power, and increasing in 0,031% the heat rate.

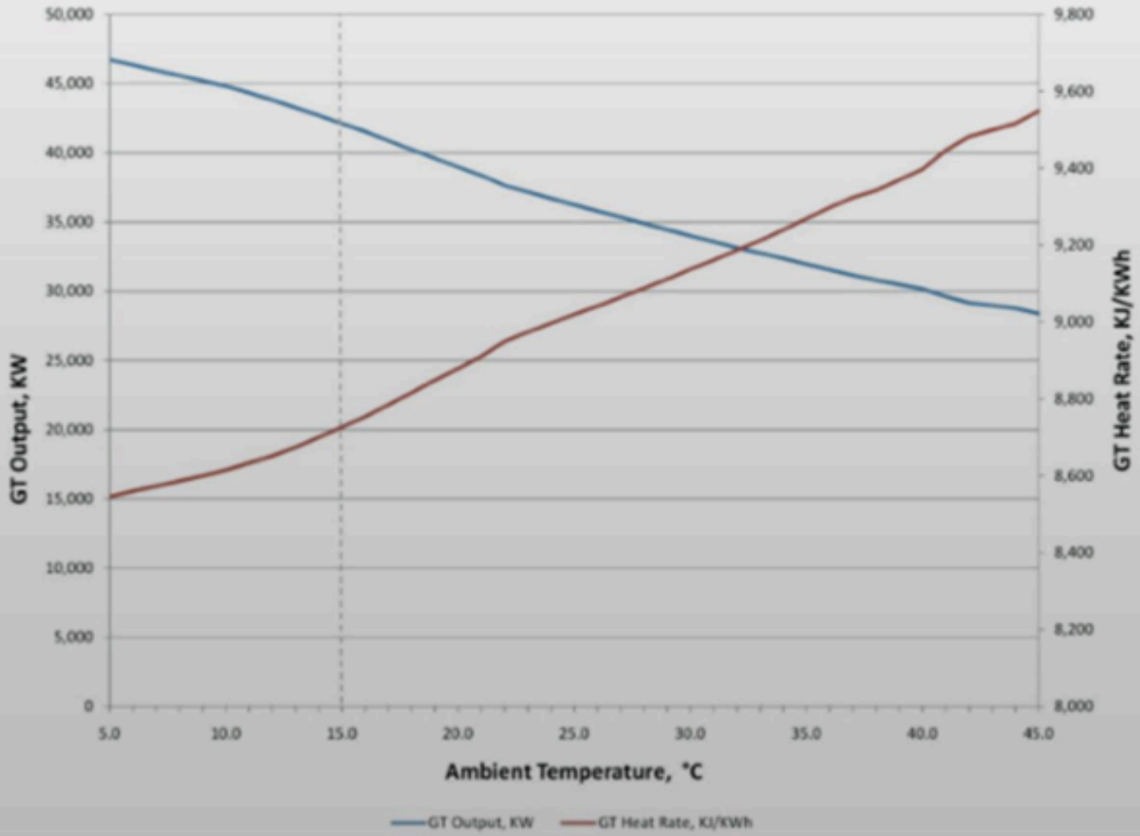
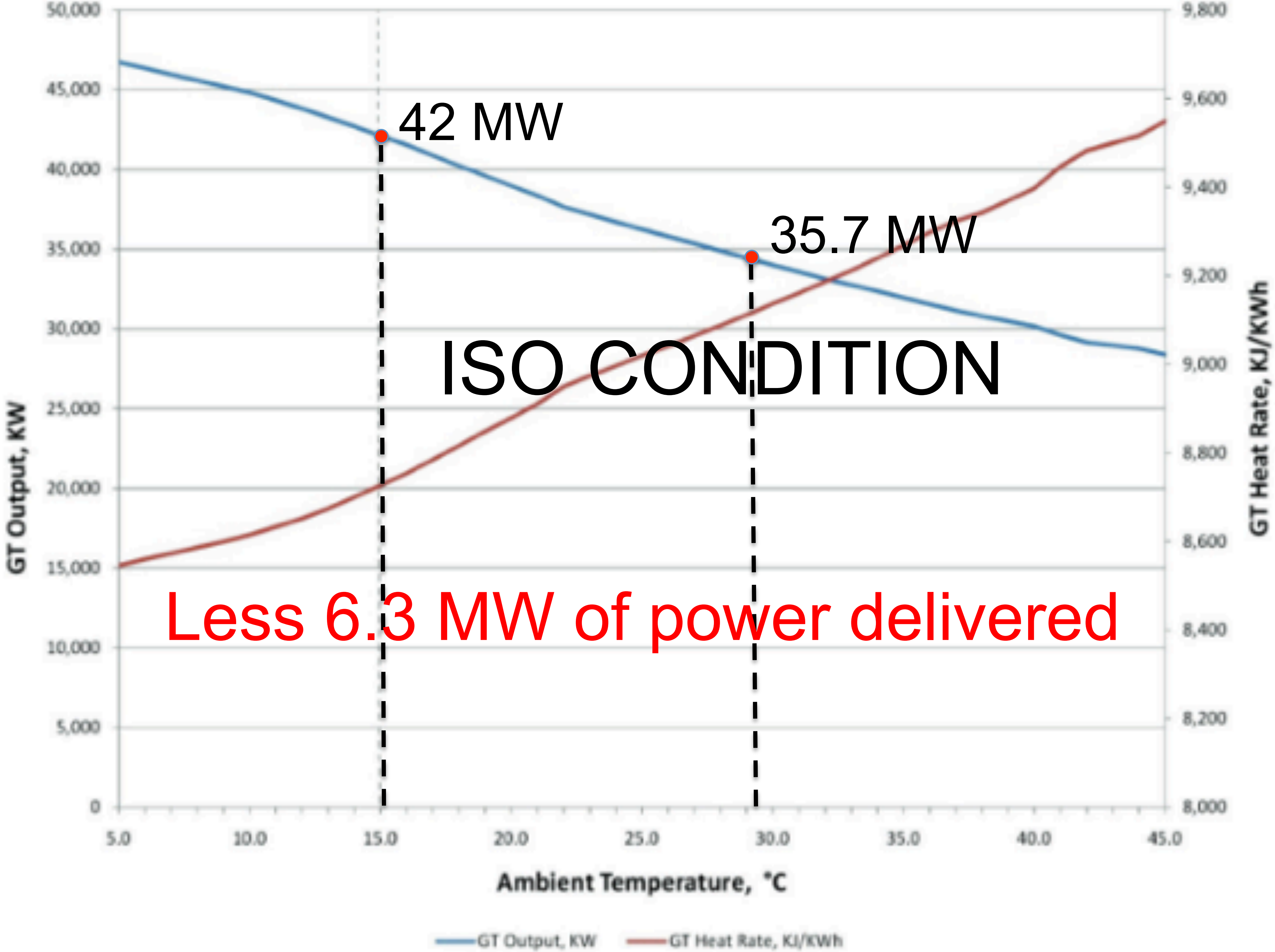


Figure 6 – LM 6000 PC Performance - Inlet Air Temperature x power chart


42 MW
35.7 MW
ISO CONDITION
Less 6.3 MW of power delivered
GT Output, KW
GT Heat Rate, KJ/KWh
Ambient Temperature, °C
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
9,800
9,600
9,400
9,200
9,000
8,800
8,600
8,400
8,200
8,000
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
GT Output, KW
GT Heat Rate, KJ/KWh

TIC technologies evaluation

Some TIC technologies were evaluated to determine the best solution to attend the CCPP system peculiarities.

✓Evaporative: wetted media, fogging, and wet compression;

✓Chillers: mechanical and absorption chillers w/ or without (TES);

✓LNG Vaporization;

✓Hybrid Systems: technologies combinations.

Absorption Chiller with TES was elected as being the best technology to be applied for GT inlet air cooling.

Temperature measurements methodology

For a 10-year scenario, 2007-2016, a temperature database was elaborated with the daily weighted average temperatures.

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 1 - Seropédica – RJ – 10 days Meteorological Weather Station data

Temperature measurements methodology

Figure 7 - Seropédica – RJ - Meteorological Weather Station

Temperature measurements methodology

A chart was plotted to determine the temperature behaviour during the day from 00:00 am to 11:59 pm.

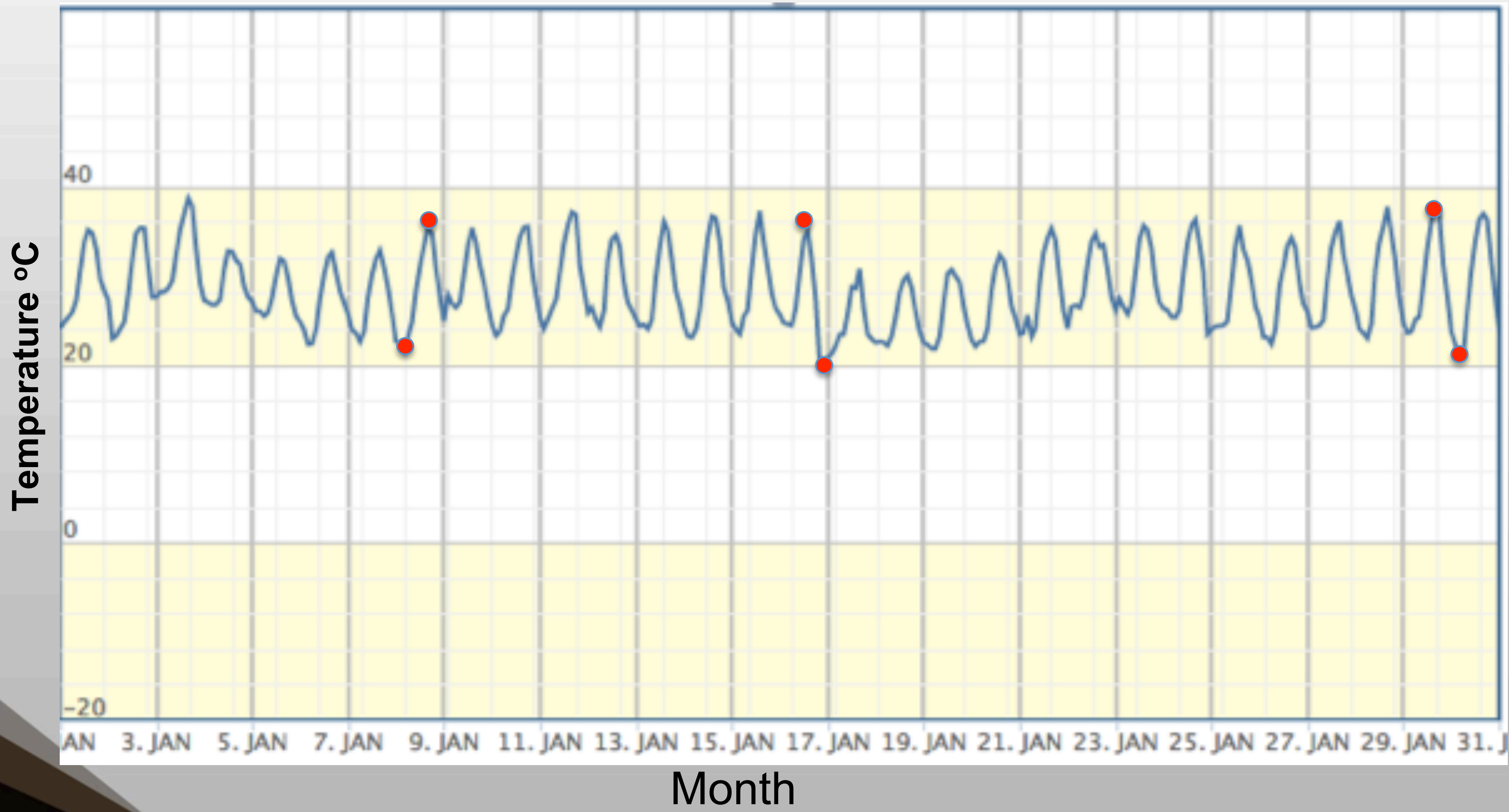


Table 2– Temperature variation during the day

Temperature measurements methodology

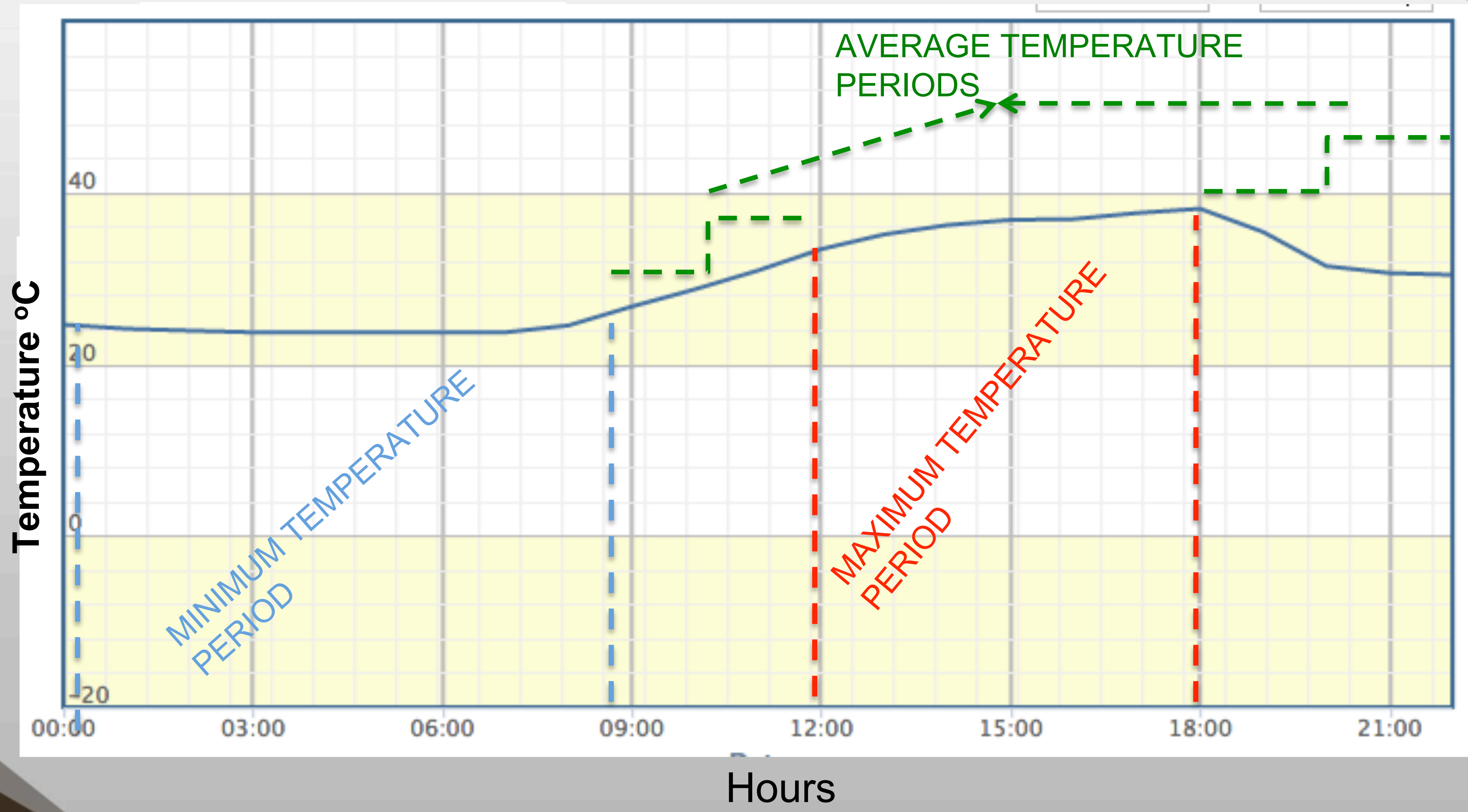


Table 3 -Temperature variation profile during the day

Temperature measurements methodology

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, being:

- From 00:00 am to 8:00 am – minimum records
- From 12:00 am to 6:00 pm – maximum records
- From 8:00 am to 12:00 am/18:00 pm to 12:00 pm – average records.

During the GT output power calculation, in one day the machine will be considered operating a specified number of hours at: maximum, average and minimum temperatures.

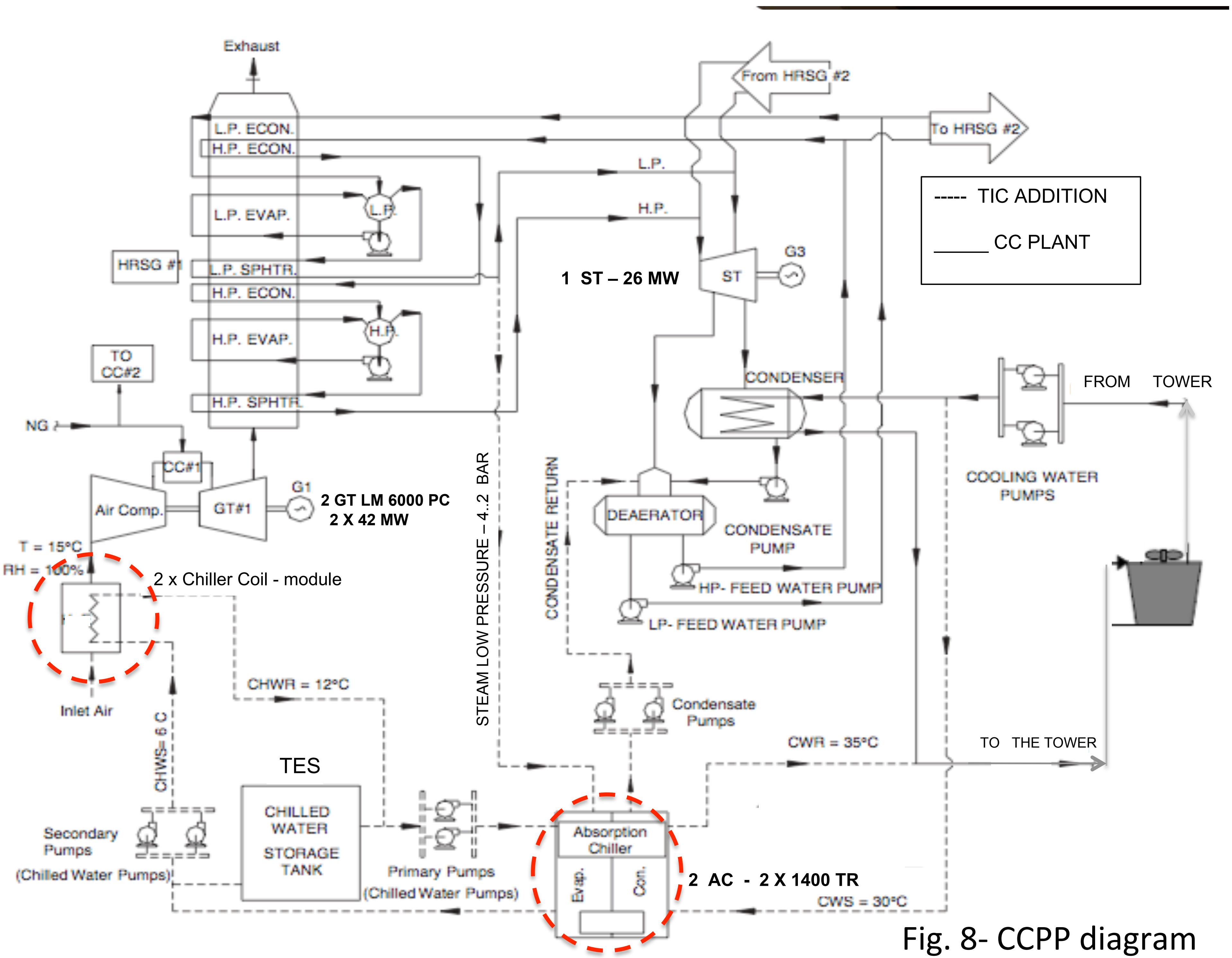


Fig. 8- CCPP diagram

TIC Dimensioning – Coil installation

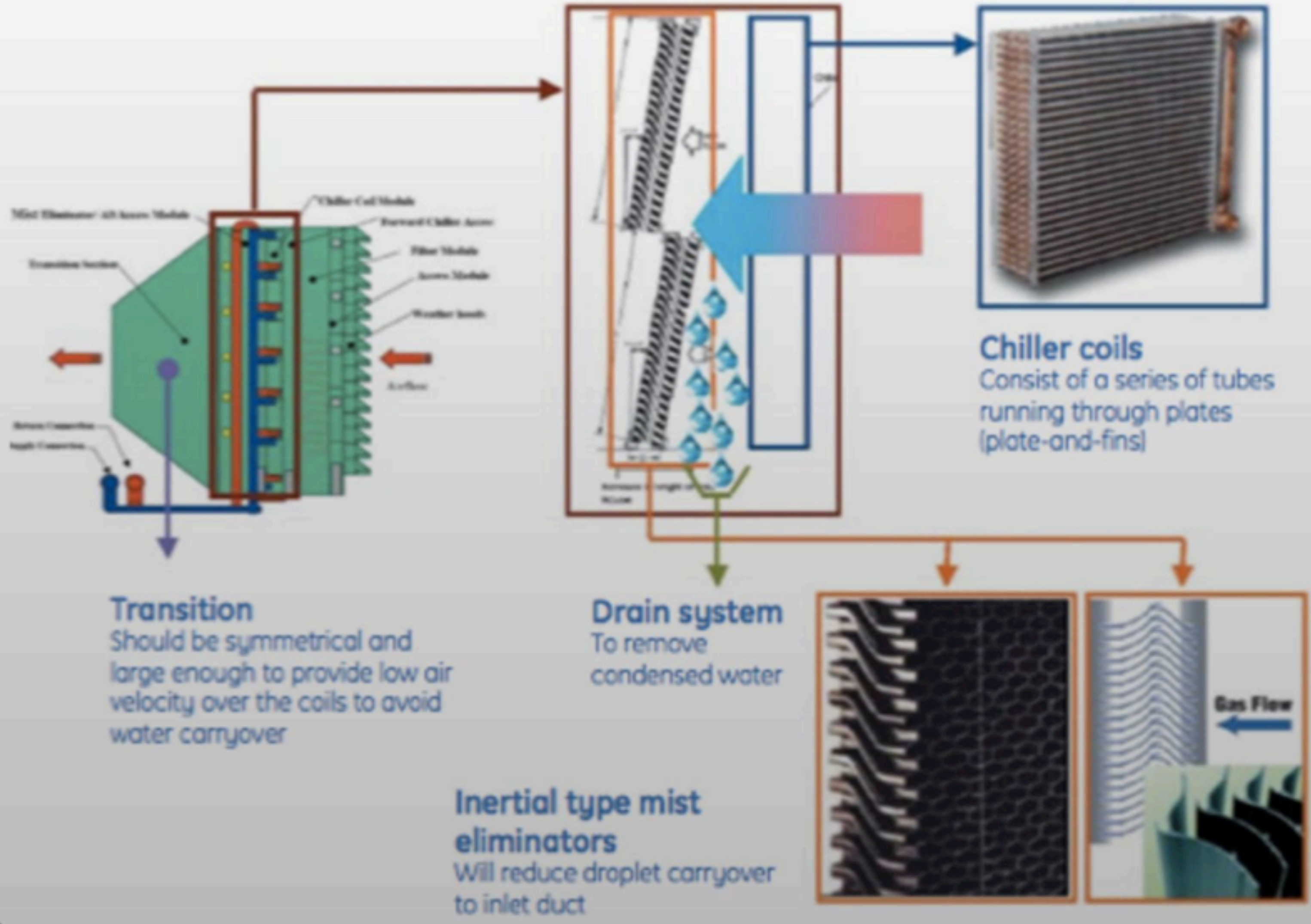


Figure 9 – TIC coil installation

TIC dimensioning - 2 x 50% AC machines

Figure 10 – YIA Single Stage Absorption Chiller – 1,400 TR

Cooling load calculation

The air inlet cooling system, with absorption chiller (AC), will be dimensioned to cool the GT inlet air mass flow temperature from 32^{o}C to 15 ^{o}C, assuming an air average relative humidity of 70%.

The air cooling shall be limited to 8°C due to the risk of ice formation on the GT Inlet Guide Vanes (IGV).

Cooling load calculation

Figure 12 shown the air is cooled by rejecting its heat to the chilled water. Its relative humidity will rise until 100%. Two steps:

- latent heat: (a - d)

- sensible heat (d-c)

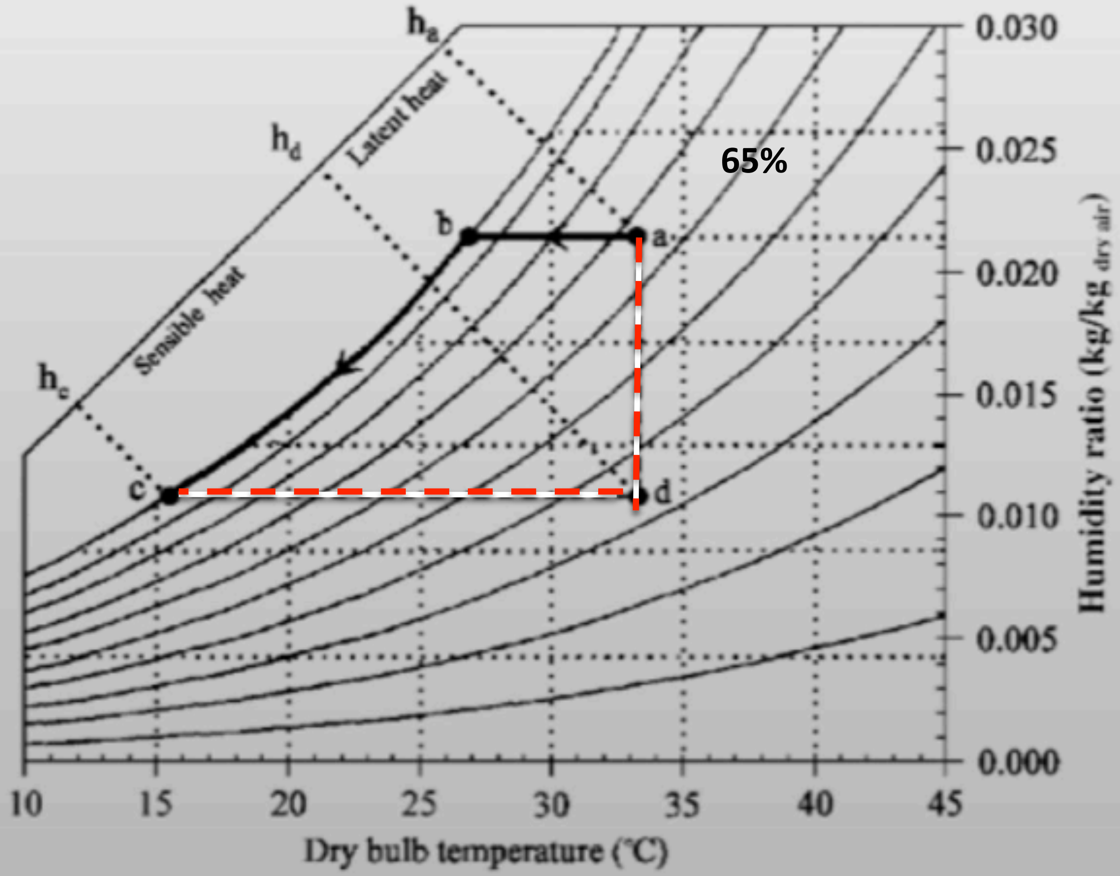


Figure 11 – Psichrometric chart

Cooling load calculation – Psychrometric simulation

Enthalpies & Humidity ratio calculation as given:

Inputs			Outputs		
Unit Chosen:	◉SI	○IP			
Parameter Name	Value	Unit	Atmospheric Press	1.0132387597	bar
Dry Bulb Temp.:	32	C	Sat. Vapor Press.	47.585220908	mbar
Wet Bulb Temp.: ○	27.272676383	C	Partial Vapor Press.	33.3096554635	mbar
Relat. Humidity: ◉	70	%	Humidity Ratio	0.0211429633	kg/kg
Dew Point Temp ○	25.837756351	C	Enthalpy	86.269022899	kJ/kg
Altitude	0.0	m	Specific Volume	0.8928187722	m3/kg

0.0211

86.26

Figure 12 – Enthalpy calculation – 32 ºC RH 70%

0.0106

42.02

Inputs			Outputs		
Unit Chosen:	◉SI	○IP			
Parameter Name	Value	Unit	Atmospheric Press	1.0132387597	bar
Dry Bulb Temp.:	15	C	Sat. Vapor Press.	17.054434648	mbar
Wet Bulb Temp.: ○	15	C	Partial Vapor Press.	17.054434648	mbar
Relat. Humidity: ◉	100	%	Humidity Ratio	0.0106484895	kg/kg
Dew Point Temp ○	15.030994348	C	Enthalpy	42.010571683	kJ/kg
Altitude	0.0	m	Specific Volume	0.8251944183	m3/kg

Figure 13 – Enthalpy calculation – 15 ºC RH 100%

Cooling load calculation

The total cooling load can be calculated by using energy balance as follows:

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

Being,

Q_{CL} = Cooling load (kW,RT)

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 (kg of moisture/kg of dry air)

Cooling load calculation – THERMOFLOW®

DESCRIPTION	UNITS	VALUE
Mass flow rate to be cooled at GT inlet (M_a)	Kg/s	115
Air Temperature at site condition at 70% RH	ºC	32
Enthalpy of inlet air - h_a	kJ/kg	86.26
Air Temperature after cooling	ºC	15
Enthalpy of the air after cooling at 100% RH- h_c	kJ/kg	42.20
Total heat to be removed	TR	1.297
Total heat + 10% margin	TR	1.426
Total heat - 2 machines	TR	2.800

Table 4 - AC- Absorption Chiller capacity simulation

➢ Technical analysis

Chilled water system capacity

The chilled water capacity can be calculated by using the heat transfer formula:

$$\boxed{Q_{cw} = M_{cw} * Cp_{cw} * (T_{cw2} - T_{cw1})} \quad (2)$$

Being,

Q_{cw} = Heat load available for Cooling (kW,RT)

M_{cw} – mass of chilled water (kg/s)

Cp_{cw} = specific heat of chilled water (kJ/kg ^{o}C)

T_{cw1}= Chilled water inlet temperature (^{o}C)

T_{cw2}= Chilled water outlet temperature (^{o}C)

➢ Technical analysis

Chilled water system capacity - THERMOFLOW®

$$Q_{cw} = M_{cw} * Cp_{cw} * (T_{cw2} - T_{cw1})$$

1 TR	3,52 KW
Cp_{cw}	4,2 kJ/kg ºC

T_{cw1}	12 ºC
T_{cw2}	6 ºC

DESCRIPTION	UNIT	VALUE
Mas flow rate for 1 TR	Kg/s	0.139
Flow rate for 1 TR	M^3/h	0.502
Flow for 1.426 TR	M^3/h	716
Total Flow + 5% margin	M^3/h	752
For 2 GT application	M^3/h	1.500

Table 5 – Chilled water capacity calculation

TIC total capital cost

ESTIMATE AIR CHILLER SYSTEM TOTAL CAPITAL COST			
Equipment	Unis	Price	Total
Absorption chiller (1400 TR)	2	$1.250.000	$2.500.000
Transition piece, Chiller coil, Inertial type mist eliminator, Drain system	2	$910.000	$1.420.000
Chilled control valve	2	$450.000	$900.000
Chilled water primary pumps	2	$500.000	$1.000.000
Chilled water secondary pumps	2	$250.000	$500.00
TES - Chilled water storage	1	$3.840.000	$3.920.000
Control system	1	$1.100.000	$1.200.000
Miscellaneous-Installation			$2.860.000
		Total	$14.700.000

Table 6 - TIC system total capital cost

➢ Technical analysis

TIC auxiliary power consumption

Table 7 estimates the TIC auxiliary power consumption

AIR CHILLING POWER CONSUMPTION	
EQUIPMENT	KW
ABSORPTION CHILLER (1400 TR)	36
CHILLED WATER PRIMARY PUMPS	190
CHILLED W. SECONDARY PUMPS	26
TOTAL	252

Table 7 – TIC auxiliary power consumption

➢ Technical analysis

Steam turbine power losses

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. It is a very conservative calculation.

Economic Analysis

The LCC analysis considers for a 20 years period the extra electric power delivered with the TIC implementation and all involved costs for its application, including the TIC O&M costs.

The analysis is based on 18% Brazilian tax rate, 15% interest rate.

Economic Analysis

PREMISES & RESULTS		
INTEREST RATE - BRAZIL		15%
EXCHANGE - DATE: 01/08/2017 US$ / R$		3,1154
MWH PRICE (PLUS TAXES) - RJ - ANEEL	R$628,00	$201,58
LIFE TIME SERVICE	YRS	20
ST LOSSES + AUXILIARY ELECTRIC LOAD (MWH)	p/yr	17.243
TIC CAPITAL COST+ INSTALLATION+COMISSIONING+TESTS	6 months	$14.070.000
GT SYSTEM AVAILABILITY		0,95
TIC SYSTEM O&M COST PER YEAR		$965.000
CC EXTRA POWER DELIVERED PER YEAR	MWH	69.248
NET PRESENT VALUE (NPV)		$67.263.511
INVESTMENT PAYBACK PERIOD	YR	1,5

Table 8 - Economics analysis

Conclusion

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

TIC implementation allows the GT system runs 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$.

➢ References

[1] Doom, T. R., 2013. “Case studies on the government’s role in energy technology innovation – Aeroderivative Gas Turbines”. In American Innovation Council.

[2] Kurz, R., 2005. “Gas turbine performance”. In Thirty-fourth Turbomachinery Symposium. San Diego, Califórnia, USA.

[3] Josef, P., 2005. “Performance monitoring for Gas Turbine”. In GE Orbit 65 Seminar. Florence, Italy.

[4] Brooks, F. J., “GE Gas turbine performance characteristics”. GE Power Systems. Schenectady, NY. GER-3567H.

[5] Bejan, A., Tsatsaronis G., and Moran M., 1996. Thermal Design & Optimization Book.

QUESTIONS?