

B. Modeling in off design considerations

Natural Gas Cycle

For the analysis under design conditions, the Siemens ST5-4000F 50 Hz frequency turbine was considered, but because the places where the plant is to be located is 60 Hz, a turbine with similar characteristics was chosen techniques but with different frequency.

The turbine chosen was the SGT6-5000F mainly due to its mass exhaust flow, exhaust temperature similar to the ST5-4000F and its frequency of 60 Hz, a summary of its technical specifications can be seen in Table 3.

TABLE 3
GAS TURBINE DESIGN PARAMETERS SIEMENS SGT6-5000F

Parameter	Siemens SGT6-5000F
Pressure ratio	18.90
Air flow (kg/s)	588.00
Exhaust temperature (°C)	598.00
Generator power output (kW)	250000.00

In the off design conditions the physical parameters of the 60 Hz turbine will be taken into account, in other words the model at the design point is with the characteristics of the 50 Hz turbine but in simulation conditions the 60 Hz has been taken.

The performance curves of the SGT6PAC-5000F gas turbine are those that will allow us to model the behavior in conditions outside of the design, for which the curves of [7] were modeled in second degree polynomial functions.

As already mentioned, the ambient temperature and atmospheric pressure are the two physical parameters considered for the evaluation of the plant in off design conditions. All the equations in this section will be a function of these two variables.

The performance curves considered were those of temperature and pressure, the curves in [7] were extracted and converted into functions.

The temperature at the outlet of the gas turbine as a function of the ambient temperature is defined by equation (11) and mass flow of exhaust gases at the outlet of the gas turbine as a function of local temperature is represented by the equation (12).

$$\begin{aligned} & (T_{OUT-OFF\ DESIGN})_T \\ & = 578 + 0.0049 \left(\frac{T_{IN-OFF\ DESIGN} - 15}{1.8} \right)^2 \\ & + 0.9599(T_{IN-OFF\ DESIGN} - 15), \end{aligned} \quad (11)$$

$$\begin{aligned} & (M_{G-OFF\ DESIGN})_T \\ & = 1 - 8(10^{-6})(T_{IN-OFF\ DESIGN} - 15)^2 \\ & - 0.0024(T_{IN-OFF\ DESIGN} - 15) \end{aligned} \quad (12)$$

Being $T_{OUT-OFF\ DESIGN}$ the ambient temperature in local conditions.

To take into account the influence of atmospheric pressure in off design conditions on the temperature of the exhaust gases the equation (13) is taken.

$$(T_{G-OFF\ DESIGN})_P = (T_{G-OFF\ DESIGN})_T + FC_T \quad (13)$$

where FC_T is the correction factor that is added to take into consideration atmospheric local pressure into the exhaust temperature. FC_T can be calculated with equation (14).

$$\begin{aligned} FC_T = & \frac{0.0454}{1.8} (P_{OFF\ DESIGN} - 14.696)^2 \\ & + \frac{0.4232}{1.8} (P_{OFF\ DESIGN} - 14.696) \end{aligned} \quad (14)$$

where $P_{OFF\ DESIGN}$ is the barometric pressure in local conditions.

The mass flow takes into account the influence of local atmospheric pressure with equation (19),

$$(M_{G-OFF\ DESIGN})_P = FC_P (M_{G-OFF\ DESIGN})_T, \quad (15)$$

where FC_P is defined as the correction factor for the mass flow that takes into account local atmospheric pressure conditions.

$M_{G-OFF\ DESIGN}$ is calculated with equation (16),

$$M_{G-OFF\ DESIGN} = \frac{1}{0.0688(P_{OFF\ DESIGN} - 14.696)}. \quad (16)$$

The power generated by the gas turbine in off design conditions is determined by the equation (17),

$$P_{GasTurbine-OFF} = C_{Pre} \times C_{Tem} \times 250000, \quad (17)$$

C_{Tem} and C_{Pre} are the correctors that takes into consideration the ambient temperature and the local atmospheric pressure respectively. C_{Tem} is defined by the equation (18),

$$C_{Tem} = \frac{2.414285(10^{-6})(Variation_T)^2 - 1.945088(10^{-3})(Variation_T) + 1}{1}, \quad (18)$$

being $Variation_T$ corresponds to the difference between the ambient and nominal temperatures as it can be seen in equation (19).

$$Variation_T = T_{ambient} - 15^\circ\text{C} \quad (19)$$

15 ° C is the nominal design temperature of the gas turbine.

C_{Pre} is defined by the equation (20),

$$C_{Pre} = 7.083344(10^{-2})(Variation_p) + 1 \quad (20)$$

Where $Variation_p$ is the difference between ambient and nominal atmospheric pressure as it can be seen in equation (21).

$$Variation_p = P_{ambient} - 1\ atm \quad (21)$$

Where 1 atm corresponds to the nominal pressure of the gas turbine.

Rankine Cycle

For off design model of the steam cycle, the Ganapathy off model [8] has been used because it does not require the details of the mechanical design details such as pipe size, length, density of the fins, etc.

For this method, initially calculations of three parameters are made: (i) the logarithmic temperature differential (equation (22)), (ii) the gas property accounting factor F_g (equation (23)), and (iii) the thermal conductivity of gases called K (equation (24)).

$$\Delta T = \frac{[(Tin_{gas} - Tin_{steam}) - (Tout_{gas} - Tout_{steam})]}{\ln[(Tin_{gas} - Tin_{steam}) - (Tout_{gas} - Tout_{steam})]} \quad (22)$$

$$F_g = \frac{C_p^{0.33} k^{0.67}}{\mu^{0.32}} \quad (23)$$

$$K = \frac{Q}{\Delta T (W_{gd}^{0.65}) F_g} \quad (24)$$

Being T the temperature, the suffixes *in* and *out* refer to the input and output respectively, while *gas* and *steam* are referring to the exhaust gases and the fluid of work respectively. C_p is the specific heat, k the thermal conductivity of the exhaust gases and μ is the viscosity of the exhaust gases.

Finally, Q is the heat that is transferred through the heat exchanger, ΔT the logarithmic temperature differential, W_{gd} the gas mass flow and F_g the gas properties accounting factor.

Once the values of ΔT , F_g and K are calculated at the design point, they are used in the iterations under off design conditions.

Fig. 2 shows the scheme that is used to obtain the off design condition in configurations and has been running for each hour of the day for both localizations considered.

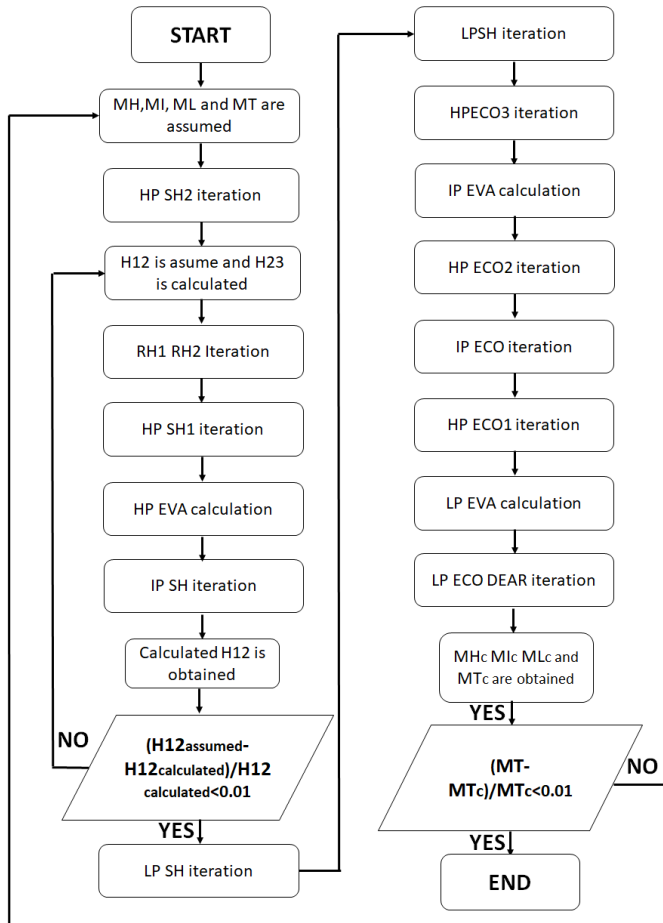


Fig. 2 Iteration Scheme Of NGCC

III. RESULTS

A. Design point

In this section a comparison between the results of this study and in Manente's [6] and Bravo's [10]. Table 4 shows the considered parameters in [6] that are evaluated in this paper.

TABLE 4
INPUT PARAMETERS TO THE MODEL

Parameter	Value
Exhaust air flow (kg/s)	643.10
Exhaust temperature (°C)	600.00
High pressure section (bar)	99.95
Intermedial pressure section (bar)	14.93
Low pressure section (bar)	4.04
Pressure in the condenser (bar)	0.034
Pinch point (°C)	20.00
Approach point (°C)flow	5.00
Pump efficiency (%)	0.80
Inlet temperature in the high pressure steam turbine (°C)	540.00
Inlet temperature in the intermediate pressure steam turbine (°C)	530.00
Inlet temperature in the low pressure steam turbine (°C)	340.00
Efficiency of the high pressure turbine (%)	86.50
Efficiency of the intermediate pressure turbine (%)	90.89
Efficiency of the low pressure turbine (%)	93.29
Evaporator efficiency (%)	97.00

Table 5 shows a comparison between the results obtained with the thermodynamic model developed and Manente's model and model developed before in other paper that instead considered exhaust gases of the gas turbine as air.

TABLE 5
COMPARISON OF THE MODEL

	Model	Bravo [10]	Manente [6]
Power of the high pressure steam turbine	31881	31481	31680
Power of the intermediate pressure steam turbine	32062	31492	29330
Power of the low pressure steam turbine	72037	70960	76390
Total power	135980	133933	137400

It can be seen in table 6 that the actual model is more accurate compared with the realized before in the other paper that is because considering compounds of exhaust gases instead of just air.

TABLE 6
DEVIATION OF THE MODEL

Reference	Power generated (kW)	Deviation from the original model
Manente [6]	137400	-
Bravo [6]	133933	2.52%
Model	135980	1.03%

As observed in this table, the relative discrepancies between the results of the model and the reference [6] considered, in terms of power is almost just 1%, compared with the model before made [10] that gives us 2.5% approximately.

The values found in Table 3 correspond to the design point with the conditions of the parameters in Table 2 that belongs to Siemens SGT5-4000F that has a frequency of 50 Hz. The real conditions take into consideration Siemens SGT6 5000F whose frequency is 60 Hz. The turbine SGT6 5000F (Table 4) from Siemens was chosen because its mass flow of exhaust and the temperature of this flow is similar to that of SGT5-4000F.

B. Economic modeling

The economic parameters calculated were IRR, the NPV, the PayBack and the LCOE whose formulas are respectively defined in equations

(25), (26), (27) and (28).

$$NPV = -I_0 + \sum_{t=1}^n \frac{F_t}{(1+k)^t} \quad (25)$$

$$0 = -I_0 + \sum_{t=1}^n \frac{F_t}{(1+IRR)^t} \quad (26)$$

$$PayBack = \frac{I_0}{F} \quad (27)$$

$$LCOE = \frac{CC + O\&M + NG}{Et} \quad (28)$$

F_t is the money flows of each period t , I_0 is the investment made at the initial moment ($t = 0$), n is the number of time periods and k is the interest rate. CC is the capital cost of the plant, $O\&M$ is operation and maintenance cost NG is the natural gas cost and Et is the total energy generated in the life time of the plant. The investment cost of the power plant is defined per unit of energy defined by equation (29) extracted from [9].

$$\begin{aligned} \text{Investment per unit of energy} \\ = 370 + 10.3(10^4)(P)^{-0.438} \end{aligned} \quad (29)$$

Where P is the nominal power of the plant. Once the value of Investment per unit of energy is obtained, it is multiplied by P to obtain the total investment cost of the cycle as shown in equation (30).

$$\text{Power Plant} = P \times \text{Investment per unit of energy} \quad (30)$$

Operation and maintenance costs are defined as a percentage of the investment cost.

$$\text{Operation and maintenance costs} = \% \times I_0$$

The cost of maintenance with respect to the previous year increases by u , as can be seen in the formula (31)

$$O\&M_{year\ n+1} = (1 + u) \times O\&M_{year\ n} \quad (32)$$

C. Off design

Off-design conditions were made taking into consideration 8760 simulations for both places: La Joya and Majes. Taking into account ambient temperature and atmospheric pressure.

Meteorological real data was considered for both places that was registered in the years 2003, 2004 and 2005 for La Joya and in years 2017, 2018 and 2019 for Majes. Using the equations

Ambient temperature for La Joya and Majes considered for each hour of the year can be seen in Fig. 3 and 4 respectively.

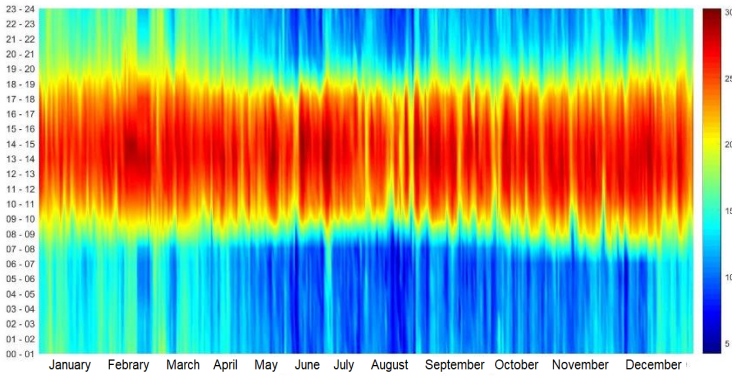


Fig. 3 Heatmap of air temperature of La Joya

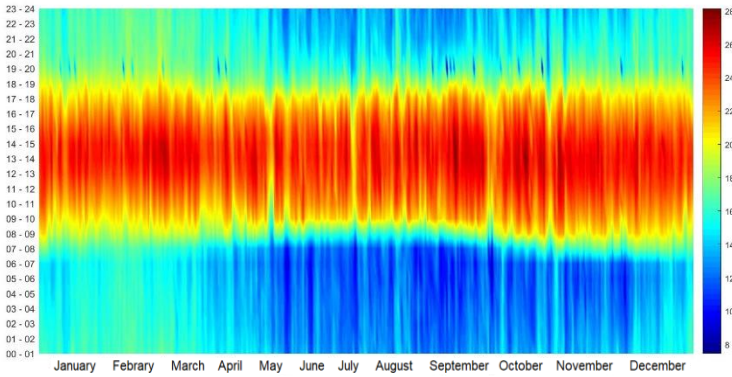


Fig. 4 Heatmap of air temperature of Majes.

For local atmospheric pressure equation (33) was taken into consideration

$$p = p_0 \left(1 - 0.0065 \frac{h}{288.15} \right)^{5.2561} \quad (33)$$

where, p_0 is nominal pressure (1atm) and h is the height of the place that is in meters above sea level. Table shows the results of pressure using equation (33).

TABLE 7
HEIGHT CONSIDERED

Location	Height (m.a.s.l)	Reference	Calculated pressure (kPa)
La Joya	1187	[11]	87854.09
Majes	1680	[12]	82704.22

Results of power generated for each hour of the year can be seen in Fig. 5 and 6 for La Joya y Majes correspondingly. Fig. 7 shows the energy generated for each month of the year for La Joya and Majes respectively.

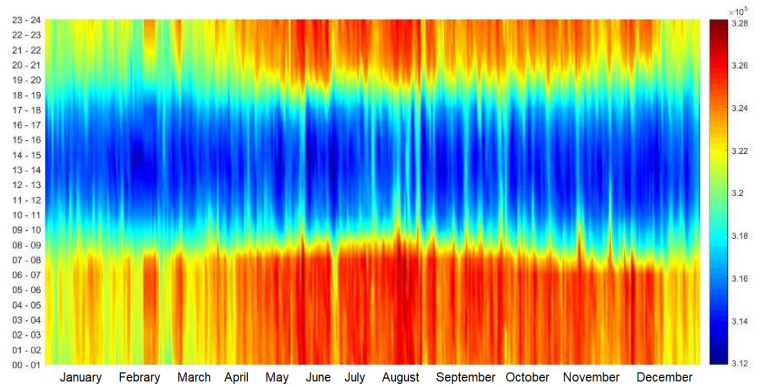


Fig. 5 Heatmap of the energy generated in La Joya.

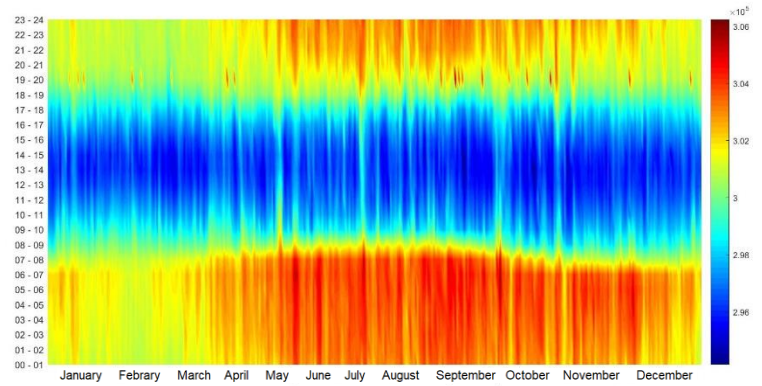


Fig. 6 Heatmap of the energy generated in Majes.

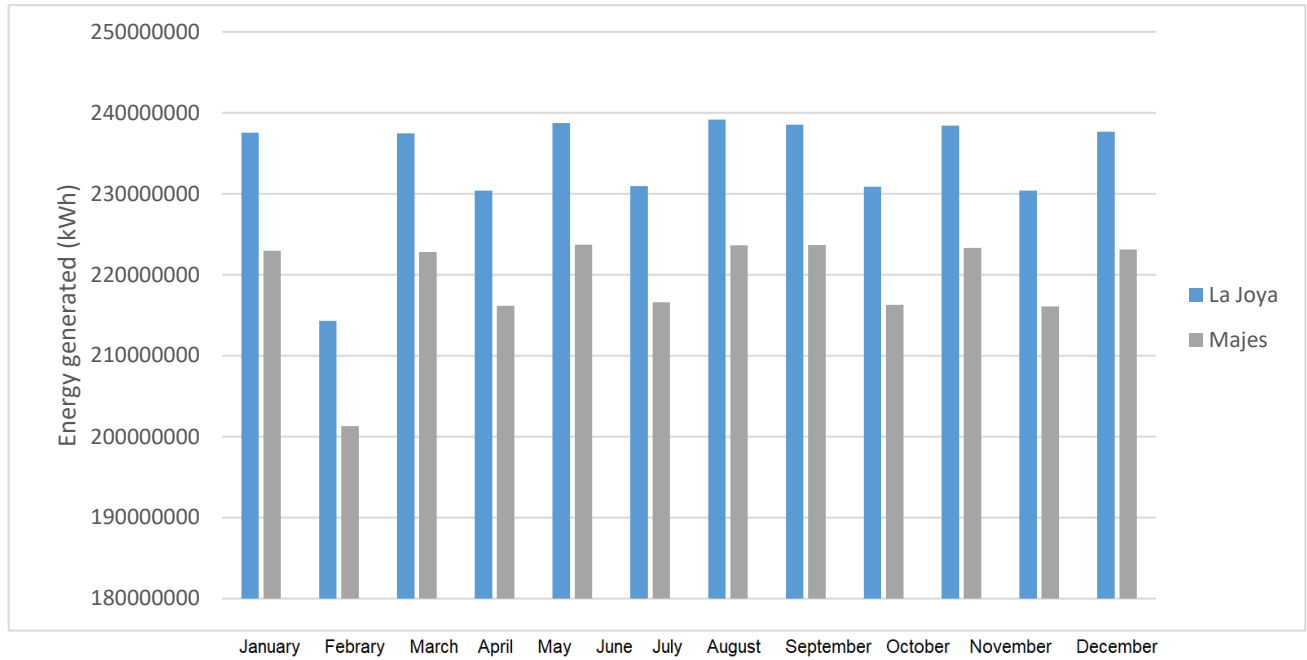


Fig. 7 Total energy generated

It can be noted in Fig. 7 as it is logical that the months when more energy is generated are the months of the seasons with lower temperatures that are autumn and winter being the largest months of July and May generation for La Joya and Majes corresponding. The months with the highest temperatures that are in the spring and summer seasons is the stage of the year that generates less energy being the month of February the month of lower generation, its lower generation is also due to the fact that this is the month with less days of the year.

Table 8 shows the total energy generated in many periods of time for La Joya y Majes.

TABLE 8
ENERGY GENERATED

Location	Average energy generated in a hour (kWh)	Average energy generated in a day (kWh)	Energy generated in a year (kWh)
La Joya	320124.64	7682991.36	2804291846.40
Majes	300187.23	7204493.52	2629640134.80

Table shows that the total energy generated in Majes is 2629665932 kWh and in La Joya 2804357790 kWh in a year being 6.64% more energy in La Joya compared to Majes.

D. Economic evaluation

This section describes the main economic indicators (VAN, IRR, PayBack and LCOE) for both locations.

Table 9 shows the economic consideration for both places.

TABLE 9
ECONOMIC VARIABLES CONSIDERED

Economic Variable	Value	Reference
Plant factor	0.80	Estimated
Availability factor	0.85	Estimated
Annualized factor	0.1175	Calculated
Plant life cycle (years)	20	Estimated
Natural gas cost (USD/MMBTU)	1.5572	[13]
Investment rate	0.10	Estimated
Electricity sale price (USD/MWh)	40	[14]

Considering table gives the results in table 10.

TABLE 10
ECONOMIC RESULTS

Location	VAN (USD)	IRR	PayBack (years)
La Joya	174,636,475.14	18.55%	5.12

Majes	127,247,104.32	16.35%	6.70
-------	----------------	--------	------

It can be seen in Table 10 all economic variables are advantageous in La Joya compared to Majes, having a NPV of 174636475.14 USD and 127247104.32 USD in La Joya and Majes correspondingly, which means 37.24% more in La Joya than Majes.

The IRR is higher in La Joya by 13.46% compared to Majes, being in 18.55% and 16.35% in La Joya and Majes respectively. The PayBack is 5 years 1 month and 14 days for La Joya, while for Majes it is 6 years 8 months and 15 days approximately which corresponds to a smaller PayBack in La Joya with respect to Majes of 23.58%.

Table 11 shows the LCOE calculated for both locations

TABLE 11
LCOE CALCULATION

Location	LCOE (\$/MWh)
La Joya	31.40
Majes	33.47

With Table 11 we can conclude that the cost per energy unit is higher in Majes compared to La Joya by 6.59%

IV. CONCLUSIONS

The performance was simulated considering the local meteorological conditions for the proposed combined cycle plant which indicates that, due to the ambient temperature and the local atmospheric pressure in the combined cycle, its performance has a significant impact, making it generate 6.64% more electricity in La Joya than in Majes.

It was possible to predict the performance of the gas turbine and the Rankine cycle based on the climatic variables having a greater plant efficiency in La Joya at 0.2414% with respect to Majes.

The economic variables were calculated considering the performance of the plant and thus calculating the total energy produced, obtaining a NPV, IRR and PayBack of USD 174636475.14, 18.55% and 5.12 years for La Joya and USD 127247104.32, 16.35% and 6.70 years for Majes. While the cost per unit of energy produced is 6.59% more expensive in Majes than in Joya, being 33.47 and \$ 31.40 / MWh respectively.

In addition, a performance pattern of the thermoelectric plant was obtained, which is reduced in summer and spring months due to the increase in air temperature, while in winter and autumn months the opposite effect due to the decrease in this It also

concludes that the hours of the morning and night are more productive than those of the day due to the change in temperature.

ACKNOWLEDGMENT

Thanks to the National Service of Meteorology and Hydrology of Peru (SENAMHI) for providing meteorological information necessary for this thesis.

REFERENCES

- [1] U.S. Energy Information Administration, International Energy Outlook 2016, 2016.
- [2] International Energy Agency, *Global Energy & CO2 Status Report 2017*, 2018.
- [3] *Decreto Legislativo N° 1002*, 2008.
- [4] F. R. Ponce Arrieta and E. E. Silva Lora, "Influence of ambient temperature on combined-cycle power-plant performance," *Applied Energy*, pp. 261-272, 2005.
- [5] Diario Oficial El Peruano, "Decreto Legislativo de Promoción de la inversión para la generación de electricidad con el uso de fuentes de energía renovable," *Decreto Legislativo N° 1002*, Mayo 2008.
- [6] G. Manente, S. Rech and A. Lazzaretto, "Optimum choice and placement of concentrating solar power technologies in integrated solar combined cycle systems," *Renewable Energy*, pp. 172-189, 2016.
- [7] Siemens Power Generation, Inc, *Siemens Gas Turbine SGT6-5000F Application Overview*, Orlando: Siemens AG, 2008.
- [8] V. Ganapathy, *Waste Heat Boiler Deskbook*, United States of America: The Fairmont Press, 1991.
- [9] Pequot, *Gas Turbine World 2018 GTW Handbook*, 2018.
- [10] H. J. Bravo, "Cylindrical Parabolic Trough Concentrator and Solar Tower comparison in an Integrated Solar Combined Cycle Power Plant," *ASME POWER 2019*, 2019.
- [11] Osinergmin, "Central Solar Repartición 20T," División de Supervisión de Electricidad, 2018.
- [12] Osinergmin, "Central Majes Solar 20T," División de Supervisión de Electricidad, 2018.
- [13] OSINERGMIN, *Presentación de información de precios y calidad de combustible gas natural correspondiente al periodo 01 de Julio de 2018 - 30 de junio de 2019*, 2018.
- [14] OSINERGMIN, *Audiencia Pública Exposición y Sustento de Criterios, Metodología y Modelos Económicos*, 2014.