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**DESIGN OF OFF-GRID WIND-SOLAR HYBRID SYSTEM WITH  
AUXILIARY CAES SYSTEM**

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**Abstract**

*The generation of energy from a wind-solar hybrid system tends to be more effective and efficient compared to a system that uses only a renewable energy source. In nature these two sources are intermittent, having their peak generation at different times. By combining these two sources, they become complementary and their efficiency and generation are significantly increased. Aiming a reliable and effective way to address problems such as low power supply reliability, low voltage and frequent interruptions in remote areas, and this article demonstrates the study of the dimensioning of the implementation of a wind-solar hybrid system, presenting the components of the generation system and the dimensioning of the CAES system to feed a village without interruption in the city of Touros in the state of Rio Grande do Norte - Brazil.*

**Key words:** hybrid system, renewable energy, CAES system.

**1. INTRODUCTION**

Remote locations have a high cost in installation and maintenance of distribution lines. However, these facilities, despite the cost, do not perform well due to some factors that impair their operation such as: low reliability of the power supply, low power factor load and low voltage. Therefore, these remote facilities operate with frequent interruptions in the power supply.

Searching for a reliable, efficient and renewable way, this article presents the study of the implantation of a small hybrid energy system, composed by wind and photovoltaic generation, with a Compressed Air Energy Storage (CAES) method to feed a virtual village without power interruptions in the city of Touros, in the State of Rio Grande do Norte - Brazil.

A hybrid system that uses wind and photovoltaic generation makes it possible to meet the energy demand of consumers with greater efficiency than individual systems, that is, those systems that operate using only one source of energy to generate electricity.

Experiments carried out over the years have shown that winds are more intense at night and have a higher speed, whereas sunlight, in contrast, is more intense in summer, and its incidence is limited only during the day. For this reason, wind turbines and photovoltaic panels are complementary generators.

Dali et al. (2010) carried out an experimental test and evaluated the operation of a hybrid system of wind and photovoltaic energy connected to the electrical grid using an independent inverter capable of working in the connection mode to the grid and also in the autonomous mode as a generating micro-network. The interconnection system consists of photovoltaic emulators and wind turbines with converter interfaces.

Al-Badi (2011) evaluated the feasibility of using a hybrid wind / photovoltaic / diesel system to meet the load on Al Hallaniyat Island, and proved to be a technologically and economically viable option for rural electrification. The Electric Renewables software was used for its hybrid optimization model.

Denmark currently meets its electricity demand with 20% wind energy and combined heat and power (CHP) production accounts for 50%. Based on these data, Lund and Salgi (2009) evaluated the value of integrating the CAES system into future sustainable energy systems. Comparing to other storage systems, they concluded that, economically, CAES plants cannot solve the problems of excess electricity production on their own, but if this technology operates in the regulatory energy market, they may become viable.

A new CAES system is proposed by Jannelli, Minutillo, Lavadera and Falcucci (2014) for the storage of energy in a small-scale autonomous plant (central photovoltaic energy), designed to serve a radio station for telecommunications. The innovation inserted in the study refers to two perspectives: the first is the small-scale use of the CAES System integrated with a Thermal Energy Storage (TES) unit with inter-cooling compression and inter-heating expansion; the second is the production of cooling energy, obtained by cold air at the turbine outlet of the CAES system. For this reason, the storage system was defined as Small-scale compressed air energy storage system (SS-CAES System). It was concluded that the storage system had an efficiency of 57%.

Mason and Archer (2012) point to two CAES plants in operation, one in Germany with an installed capacity of 290MW, in operation since 1978; and a 110 MW plant of installed capacity, in operation in the state of Alabama, United States, since 1991. Both operates as peak demand energy, i.e. they buy low-cost electricity overnight to compress and store air in an underground reservoir. Thus, during the day, the system is prepared to generate electricity at times of peak demand. Compressed air is released from the reservoir to feed the plant, generating electricity at a more attractive price and without having to use air compressors as in the design of the conventional combustion turbine plant.

The usual application of CAES Plants is for operation continues to be responsible for the storage and generation of energy, innovating the use of the CAES system, this work seeks its application as an alternate generation. Compressed air is stored in the tank until there is a failure or need for scheduled stops in the power generation of the hybrid Off-Grid system.

## 2. METHODOLOGY

The studied village located in the city of Touros / RN has a consumption of approximately 300kWh / day or 9MWh / month. Generation of 50% of the total for the solar system and 50% for the wind system was considered. When the electricity supply is interrupted, the CAES system will start operating.

In the process of feeding loads in a normal generation period, i.e., without faults or scheduled maintenance, the load controller transfers the entire generation to the inverter, after having completely powered the CAES system, and the inverter directs the energy to all AC loads available in the system. In the event of a fault or scheduled maintenance on the generation system, the load controller blocks the flow of the system generation and activates the CAES system to supply the load. With the CAES system activated, it will supply some of the AC loads. Figure 1 shows the flowchart of the steps for sizing the system.

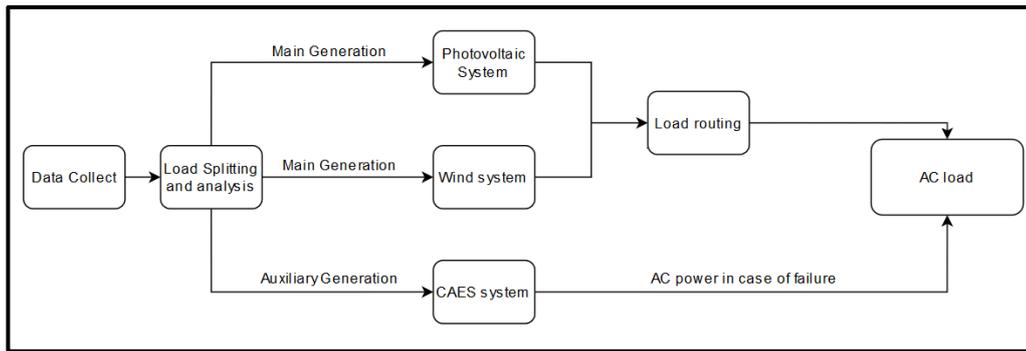


Figure 1 - Flowchart

To perform the sizing of the solar system, the simulations were performed by the PVsyst 7.0 software and the sizing of the wind system was done with the aid of the RETScreen software.

Compressed Air Energy Storage (CAES) is based on the use of electric compressors to compress the air accumulated in underground caves, which will be expanded in a separate turbine, connected to an electric generator to obtain energy (ALTMANN, 2018).

The diagram in Fig. 2 shows the diagram of the dimensioned CAES system, composed of two main parts, divided between the loading and unloading of the compressed air. The hybrid system provides the necessary energy for the operation of the electric motor, it drives a 3-stage compressor that is responsible for injecting compressed air, at a pressure of 30 bar, into an underground reservoir, which is maintained at a temperature 50 ° C and a maximum pressure of 30 bar. The compressed air is stored in the tank until a problem occurs in the power generation of the hybrid system, or due to the need for scheduled maintenance. It is at this moment that the CAES system starts operating and the compressed air presented in the reservoir is directed to the entrance of a gas turbine that produces shaft power in order to drive an electric generator. This is responsible for producing electricity and supplying the village of Touros-RN.

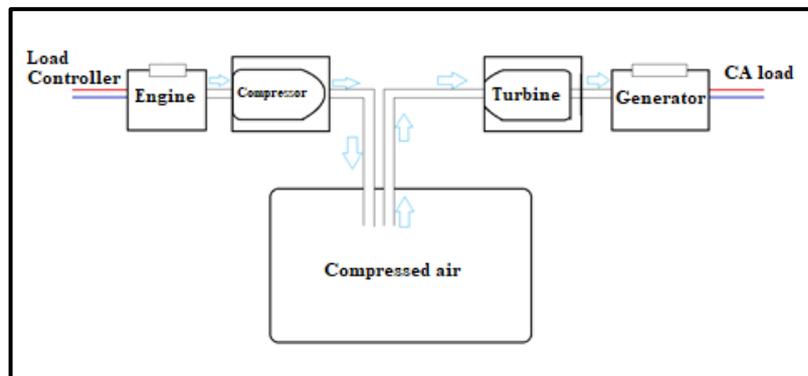


Figure 2– CAES system

### 3. SIMULATIONS

#### 3.1 Sizing the solar system

Understanding how the loss factors in photovoltaic systems impact generation is of paramount importance for their design in a correct and efficient way. Several factors must be taken into account, among which we have the dust / dirt that does not affect the production of the system immediately, but in the long run it can interfere, according to its quantity and the lack of correct cleaning of the photovoltaic modules; very high temperatures are factors of loss in the generation of the Photovoltaic System; in the process of conducting direct current energy there are losses that must be taken into account, the greater the distance, the greater the losses and in the same way the alternating current also has losses that must be considered, they also vary according to the distance and installation conditions. The following losses are usually considered for the design of a solar system, shown in Table 1.

Table 1- Loss of dimensioning for photovoltaic system

Losses	Value	Considered	Yield
Thermal losses	7.0% - 18%	12%	88%
Electrical mismatch	1.0% - 2.0%	1,50%	98,50%
Accumulation of dirt	1.0% - 8.0%	5%	95%
ohmic losses - AC	0.5% - 1.0%	1%	99%
ohmic losses - DC	0.5% - 1.0%	1%	99%
Inverter	2.5% - 5.0%	3,50%	96,50%
<b>Total Income</b>			<b>77,88%</b>

Considering only the angles of inclination of the modules being equal to or greater than the latitude of the location, the data and graph were obtained by the analysis of CRESESB, shown in Table 2. Through its analysis, it is concluded that the average amount of hours of peak sun that the city of Touros / RN receives daily is 5.8 hours / day.

Table 2 - Daily solar irradiation data from the city of Touros / RN (SOURCE: CRESESB, 2020)

Angle	Inclination	Average daily solar irradiation (kWh / m <sup>2</sup> . day)													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Set	Out	Nov	Dec	Average	Delta
Angle equals latitude	5 ° N	5.89	6.06	6.09	5.7	5.39	5.07	5.18	5.85	6.2	6.2	6.21	5.86	5.81	1.14
Highest monthly minimum	14 ° N	5.47	5.78	5.99	5.81	5.65	5.38	5.46	6.04	6.2	5.96	5.79	5.4	5.74	0.8

The simulations presented below were performed using the PVsyst 7.0 software. The proposed system has an annual consumption of approximately 110MWh. Generation was divided into 50% produced by the wind system and 50% produced by the solar system. Therefore, solar generation is 55MWh / year, that is, the solar system must have a daily production capacity of approximately 150kWh.

The city of Touros / RN, represented in Fig. 3, which has latitude coordinates: 05° 11 '56 "S and longitude: 35° 27' 39" W, has an average daily irradiation of 5.74 kWh / m<sup>2</sup> / day informed by CRESESB, shown in Fig. 3. The orientation of the modules was directed to the geographical north with a 15 ° inclination. The losses presented in Table 3 were considered for the simulation.

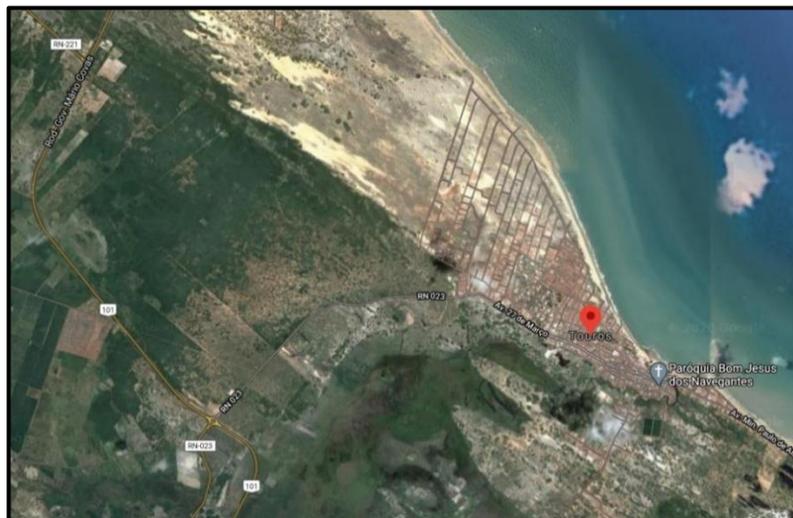


Figure 3– Touros City / RN  
 (SOURCE: Google Maps, 2020)

Table 3 - Losses considered in the simulation

Considered losses	Value
Thermal loss factor	29W / m <sup>2</sup> . K
Ohmic losses:	
-A.C	1.5%
-D.C	2.91%
- Transformers	1.1%
Module quality	0.3% / Year
MTTP power loss	0.1% / Year
Annual dirt loss	5% / Year
Annual module loss	0.72% / Year

### 3.2 Sizing of the wind system

The sizing of the wind system was carried out with the aid of the RETScreen software, prepared by the Government of Canada. The climatological data of the city of Touros were used the data presented by CRESESB, Brazilian Wind Atlas, World Wind Atlas and in NASA data software.

The losses presented by Table 5 were considered for the simulation. Considering a height of 50m, the following data and graph of the average seasonal wind speed were obtained, simulated by the CRESESB software, shown in Table 4

Tab. 4 - Seasonal average wind speed for the city of Touros / RN  
(SOURCE: CRESESB, 2020)

Atlas of Brazilian wind potential		Wind data at 50m height				
Greatness	unity	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Yearly
Average wind speed	m / s	8.08	7.12	9.23	9.19	8.41
Factor c		9.06	8.04	10.28	10.33	9.46
K factor		2.89	2.25	3.34	2.75	2.7
Power density	W / m <sup>2</sup>	463	379	640	703	546

Table 5- Losses considered in the simulation  
(SOURCE: RETScreen, 2020)

Considered losses	Value
Airfoil losses	2 years
Miscellaneous losses	6% / Year
Availability	98% / Year

### 3.3 Sizing of the Caes System

When the electricity supply is interrupted, the CAES system will start operating. The system was designed to supply 700KWh to the village for a period of 48 hours. With these two input variables, the input and output power of the electric generator was determined, given, respectively, by Eq. (1) and Eq. (2). The input power of the gas turbine is represented by Eq. (3).

$$Generator\ output\ power = \frac{Energy\ load}{time} \quad (1)$$

$$Generator\ input\ power = \frac{Output\ power}{\eta_{generator}} \quad (2)$$

$$Turbine\ input\ power = \frac{Output\ power}{\eta_{turbine}} \quad (3)$$

The calculation to determine the air temperature at the turbine inlet was made using the turbine expansion ratio ( $r_{EX}$ ) shown in Eq. (4), where  $P_{in,tur}$  and  $P_{out,tur}$  are the inlet pressures, 30bar and outlet pressure, 3bar. The reason for the specific heats is given by Eq. (5).

$$r_{EX} = \frac{P_{in,tur}}{P_{out,tur}} \quad (4)$$

$$K = \left( \frac{C_p}{C_n} \right)_{air} \quad (5)$$

The outlet temperature  $T_{out,turb}$  is obtained through Eq. (6), the air temperature value at the outlet equal to 20 ° C, or 293K, was adopted. The mass Vessel ( $\dot{m}$ ) of the turbine is given by Eq. (7), then found the value of the reservoir volume by Eq. (8), calculating the air as the ideal gas, we have the reservoir volume  $V$  expressed by Eq. (9)

$$T_{out,turb} = T_{in,tur} \left[ 1 - \eta_{turb} \cdot \left( 1 - r_{ex}^{\left[ \frac{1-k}{k} \right]} \right) \right] \quad (6)$$

$$P_{in,tur} = \dot{m} \cdot C_{p,ar} (T_{in} - T_{out})_{turb} \quad (7)$$

$$total\ air\ mass = \dot{m}_t \cdot periods\ (s) \quad (8)$$

$$V = \frac{m.R.T}{p} \quad (9)$$

The compressor consists of three stages, with the aim of raising the inlet pressure to 30 bars, at the end of the third stage. The compressed air at 30 bars is discharged into the underground reservoir. In the compressor analyzed there are two intercoolers, which have the function of reducing the compression work and the final temperature of the compressed air. Where, the 1st Intercooler is between the 1st and 2nd stage and the 2nd Intercooler is between the 2nd and 3rd stage.

The compressor is powered by an electric motor with efficiency ( $\eta_{ME}$ ) 0.95 and the compressor efficiency ( $\eta_{comp}$ ) is 0.85. Both intercoolers cool the air to a temperature of 40 ° C (313K). The inlet temperature is 15 ° C (288K) and the inlet pressure in the first stage is 1.013 bar. For a given compression, the compression ratio  $r$  is given by Eq. (10):

$$r = \frac{p_{out}}{p_{in}} \quad (10)$$

Where  $p_{ent}$  and  $p_{out}$  are the inlet and outlet pressures, respectively, for the three stages. The outlet temperature  $T_{c,out}$  for each stage is obtained through Eq. (11), the mass flow of the compressor ( $\dot{m}_c$ ) is given by Eq. (12):

$$T_{c,out} = T_{c,in} \left[ 1 + \frac{1}{\eta_{comp}} \cdot \left( r^{\left[ \frac{k-1}{k} \right]} - 1 \right) \right] \quad (11)$$

$$\dot{m}_c = \frac{air\ mass}{filling\ period} \quad (12)$$

The compression work  $\dot{W}_c$  was determined by Eq. (13), later, adding the compression work of the 3 stages, there is the compressor's output power  $P_{out,comp}$ , where it was described by Eq. (14) and the input power of the compressor  $P_{in,comp}$  by Eq. (15).

$$\dot{W}_c = \dot{m}_c \cdot C_{p,air} \cdot (T_{out} - T_{in}) \quad (13)$$

$$P_{out,comp} = \sum \dot{W}_c \quad (14)$$

$$P_{in,comp} = \frac{P_{out,comp}}{n_{comp}} \quad (15)$$

Considering the Input Power  $P_{in,EM}$  of the compressor equal to the output power of the electric motor, we have Eq. (16)

$$P_{out,EM} = \frac{P_{out,EM}}{n_{EM}} \quad (16)$$

### 3.4 System operation in the event of a fault

In the process of feeding loads in a normal generation period, that is, without faults or scheduled maintenance, the load controller transfers the entire generation to the inverter, after having completely powered the CAES system, and the inverter directs the energy to all AC loads available in the system. In the event of a fault or scheduled maintenance on the generation system, the load controller blocks the flow of the system generation and activates the CAES system to supply the load. With the CAES system activated, it will supply some of the AC loads. The flowcharts of the system in normal and missing generation are represented in Figure 4 (a) and 4 (b) respectively.

The First Group is composed of the Health Post, market and home, the Second Group is formed by the School, Pharmacy and Public Lighting, Tab.6 presents the characterization of the components of each group.

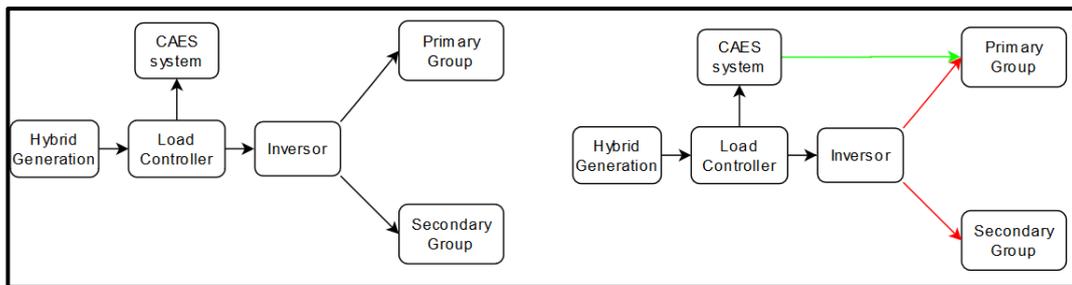


Figure 4 - Distribution flowcharts of the hybrid system: (a) normal and (b) missing

Table 6 - System components and demand

Component	Amount	Power (kWh / month)	Total power (kWh / month)
Average house	50	150	7500
Popular market	1	500	500
School	1	400	400
Drugstore	1	200	200
Health Center	1	300	300
Lighting poles	50	4.3	215
<b>Total (kWh / month)</b>			<b>9115</b>

## 4. RESULTS

### 4.1 Solar system

In order for the system to meet the minimum energy demand, a system was generated by simulation with the components shown below, in Tab. 7. It was found that the 126 modules must be built with a configuration of 18 modules in series and 7 series in parallel, shown by Fig. 5, interconnected with the available inverter inputs and the load controller. The simulation resulted in an annual production of 67.2MWh, with a minimum installation area of 260m<sup>2</sup>. Considering an additional solar production of

12.2MWh / year due to the system losses during the year and for feeding the air compression system to act as an auxiliary production system (storage).

Table 7 - Components of the simulated solar system

Component	Model	Technical information	Amount
Modules	CS6X-350P-FG / HE	350W - 32 V - Si-Poly	26
Inverter	Tauro Eco 50-3-D	50kW - 580 / 930v - Vinmax: 1000V	1
Charge Controller	Universal with MTPP	32 / 48V - 1000A	1

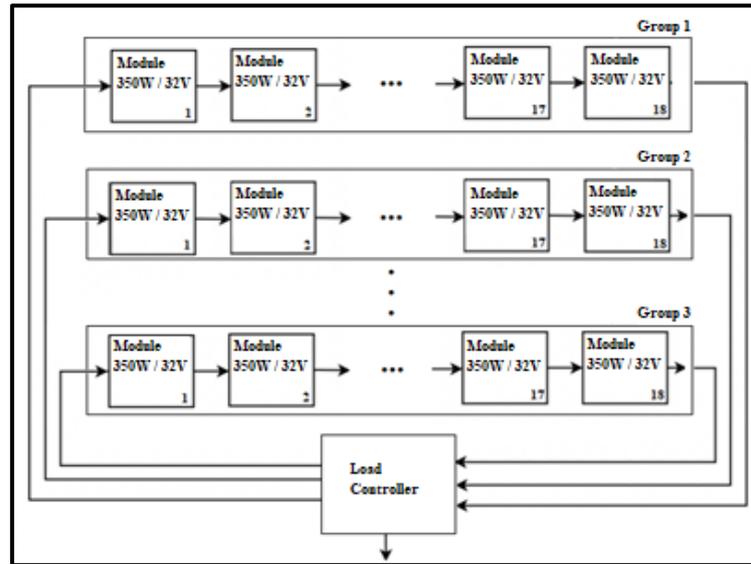


Figure 5 - Interconnection of the photovoltaic system modules

#### 4.2 Wind System

In order for the system to meet the minimum energy demand, a system was generated by simulation with the components shown below, in Tab. 8.

Table 8 - Components of the simulated wind system

Components	Model	Technical information	Amount
Wind Turbines	Bergey BWC	10kW - 36.6 m	2
Inverter	Powersync II	12 kW	1
Charge controller	FKJ-GT 20KW	AC380V-400V -100 A	1

From the simulation, it was found that the 2 model turbines, Bergey BWC, power 10 kW each must be used in the wind system. The simulation resulted in an annual production of 56.8 MWh, aiming at the best use of wind power, and the arrangement of the towers, attention should be paid to the distance restrictions between the turbines, as shown in Fig. 6. Through the simulation, the need for 2 turbines in the wind system for the village of Touros, and looking for the best locations in the towers, the distance of 5D (diameter of the turbine) was adopted, that is, 5 x 7, equal to 35 meters in the direction of the wind.

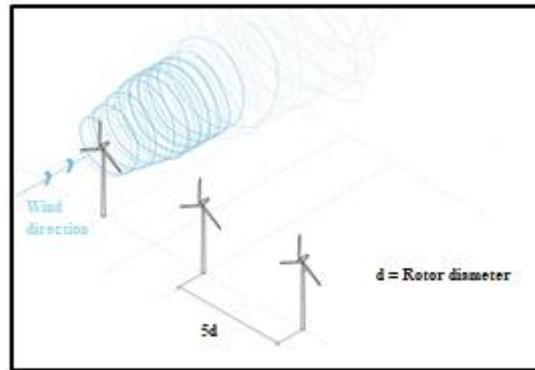


Figure 6- Distance between wind turbines.  
(SOURCE: Adapted from Camargo Schubert, 2020)

### 4.3 CAES System

Applying the mathematical model proposed in the dimensioning of the CAES System, Table 9 was constructed to present the results found.

Table 9 - Results of the mathematical model CAES system

Variable	Symbol	value
Power Charge	-	700 kwh
Period		48h
Generator Yield	$n_{generator}$	0.95
Generator output power		14.58 kW
Generator Yield	$n_{generator}$	0.86
Generator input power	-	15.35 kW
Turbine input power		17.89 kW
Inlet pressure	$P_{in,turb}$	30 bar
Outlet pressure	$P_{out,turb}$	3 bar
turbine expansion ratio	$r_{EX}$	10
Air cp	Cp	1.004 kJ / kg.k
ratio of specific heats		1.4
Turbine outlet temperature	$T_{out,turb}$	293 K
Turbine inlet temperature	$T_{in,turb}$	500K
Turbine mass flow	$\dot{m}$	0.0859 Kg / s
Initial air mass	-	14840, 67 kg
Temperature inside the reservoir	T	323 K
Pressure inside the reservoir	P	30 Bar
Air constant	-	287 J / kg.K
Reservoir volume		458.58 m <sup>3</sup>
1st stage compression ratio	$r_1$	5.53
2nd stage compression ratio	$r_2$	2,357
3rd stage compression ratio	$r_3$	2,272
Output temperature - 1st stage compressor	$T_{c,out}$	388 K
Output temperature - 2nd stage compressor	$T_{c,out}$	515 K
Output temperature - 3rd stage compressor	$T_{c,out}$	518 K
Compressor output power	$P_{out,comp}$	0.88 kW
Compressor input power	$P_{in,comp}$	12.8 kW
Electric Motor Input Power	$P_{in,ME}$	13.47 kW

For the CAES storage system, a pressure loss was considered every hour of operation, with a constant mass flow rate leaving 309.24 kg of air mass leaving the reservoir per hour. With the pressure drop in the reservoir over the hours, the power generated by the turbine decreases, however, the minimum working pressure at the turbine inlet is 11 bar.

With the reservoir volume of 458.58 m<sup>3</sup>, the pressure drops in the reservoir from 30 bar to the 11 bar turbine operating limit, takes 31 hours. Considering the efficiency of the turbine and generator, the final energy generated to supply the village is 359.28 kWh.

An alternative to make the pressure drop less severe in the reservoir and consequently increase the time of operation of the turbine and the energy generated, is to increase the volume of the reservoir. Table 10 shows the results considering an increase in the reservoir of 25%, 50%, and 75%.

Table 10 - Hours of operation and generated energy x size of the CAES system reservoir

Reservoir volume (m <sup>3</sup> )	Operating hours	Final energy generated in kWh
458.58 m <sup>3</sup>	31 h	359.28
573.22	38 h	442.54
687.87	46 h	533.37
802.5	48 h	575.87

## 5. CONCLUSION

The study of the application of the off-grid wind-solar hybrid system evaluated the implementation of the CAES system, instead of a storage system with batteries. Considering the pressure losses in the reservoir, the dimensioned CAES System will have the capacity to store enough energy to meet the needs of the village in case of failure for up to 31 hours.

For the supply of energy for 48 hours continuous, a new dimensioning must be carried out considering the increase in the volume of the reservoir and the use of a more powerful compressor. The storage system reservoir will take 8 days to fill.

The study also demonstrated that the CAES System is efficient to meet the Plant's energy demand when there is an interruption in the Off-grid System. The hybrid wind-solar generation are systems that work in different periods, allowing a better energy use of the region under study, which showed to have a great energetic potential.

Future work is needed for better modeling of systems and better accuracy together with an economic feasibility study.

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