ENERGY PERFORMANCE STUDIES OF A PVT-AIR HYBRID SYSTEM WITH CAES : INFLUENCE OF INPUT PARAMETERS ON THE COMPRESSION SYSTEM

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ABSTRACT

In order to find the most efficient electrical-thermal energy cogeneration storage system, air compression and expansion, with their heat and cold recovery respectively, are currently very important research topics. The use of compressed air storage seems to be a promising solution in this field of energy storage, as it is characterized by a remarkable stored energy density (kWh.m^{-3}) and high reliability (days of operation) with no environmental impact. The aim of this work is to predict the performance of a thermal photovoltaic panel coupled to a compressed-air energy storage system (PVT-CAES) which produces electrical and thermal energy simultaneously from solar energy. The power produced over time by PVT photovoltaic panels is characterized by its fluctuation due to the fact that the sun is an unpredictable and highly fluctuating source. The study therefore focuses on the construction of a numerical model capable of simulating a CAES system powered by a PVT panel and a system for cooling a photovoltaic panel by using fresh air at the outlet (MAC: Compressed Air Engine) of the CAES. An analysis of the influence of key system parameters (PVT-CAES) such as: global solar irradiation, compression system volume flow rate, number of compressor stages and maximum permissible pressure was also carried out.

Keyword : - *Solar radiation, storage, energy, photovoltaic, thermal, compressed air, efficiency*.

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1. INTRODUCTION

In the spirit of energy transition, Madagascar, like many other countries, is also committed to changing its energy production model by moving towards renewable energies in general, and solar photovoltaics in particular. But like other renewable sources, the direct large-scale integration of solar photovoltaic energy poses a problem due to its intermittency and variability. One solution is energy storage. Until now, the most widely used electricity storage system has been batteries. Batteries convert chemical energy into electrical energy; they store electricity when charged, and release it when discharged. Despite their recognized high performance in recent years, they have a negative impact on the environment [1,2].

In recent years, a great deal of scientific research has shown alternatives to batteries in the form of compressed air energy storage (CAES) [3,4,5,6,7]. The aim of this article is to demonstrate the possibility of pairing a thermal air photovoltaic field with a compressed air storage system, specifically by studying the parameters influencing the compression system in Mahajanga's climate. In fact, the electrical energy produced by the thermal photovoltaic field is used in the compression system to compress the air that will be stored in a reservoir for later use.

2. METHODOLOGIES

Mathematical models (PVT-COMPRESSOR) have been developed to study compressor performance and the parameters that influence the system. A representative diagram of the model with its input and output parameters is given in figure 1 :

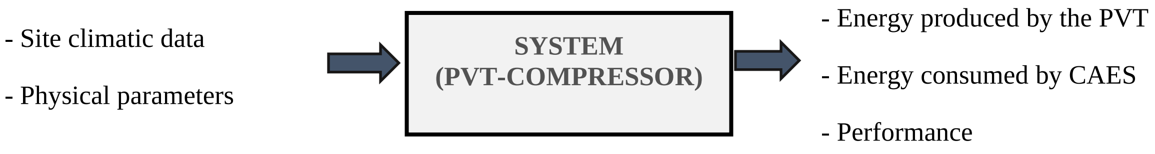

Fig -1 : System modeling

2.1 Architecture of the system studied

Our system consists of a 50 m field of Air Thermal Photovoltaic panels^2 (PVT) which feeds a compressed air storage system equipped with a 3 kW electric motor with a 200 L tank strong enough to withstand high pressures (70 bar to 200 bar) and an expansion system consisting of a compressed air motor (MAC) connected to a 5 kW to 8 kW alternator.

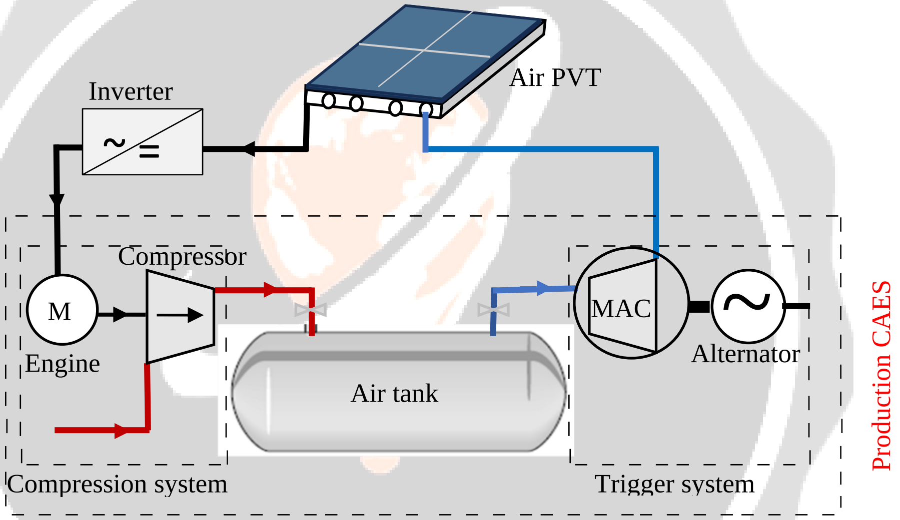

Fig -2: System configuration (PVT-CAES)

2.2 Global system modeling assumptions

Throughout this study, we will consider the following assumptions [3,6,7,8]:

- Air respects the properties of a perfect gas (air will be considered dry).
- Pressure losses in working fluids are neglected (CAES).
- Humidity in the system is negligible (CAES).
- The kinetic and potential energies inside the CAES are negligible.
- Gravity is negligible in the compression and expansion stage.
- Modeling is carried out dynamically, but some components are treated statically, since heat accumulation and mass are not taken into account for these components (CAES).
- Compression and expansion are polytropic transformations.
- The dead volume of the compressor is negligible.

2.3 Analytical model of the electrical power generated by the PVT field

In order to achieve high system efficiency (PVT-CAES), we have chosen the PVT as the power supply source. It is considered in this study as the system to be optimized thanks to the cooling of the cells. Thus, the electrical power produced by the PVT field is given by the expression [8] :

$$P_{PVT} = P_s.\eta_{réf}.\alpha_{sil}^{-1}.\exp\left[\beta\left(T_{cel} - T_{réf}\right)\right] \tag{1}$$

$P_s = \tau_v.\alpha_{sil}.G.S$ power absorbed by solar cells .

G et S are respectively the global irradiance received on the plane and the surface of the PVT field.

2.4 Compressor analytical model

The type of compressor chosen for the compression system is volumetric reciprocating piston, characterized by the compression ratio, the air delivery rate and the number of compressor stages. A very high compression ratio reduces the volume of stored air [3,4,5].

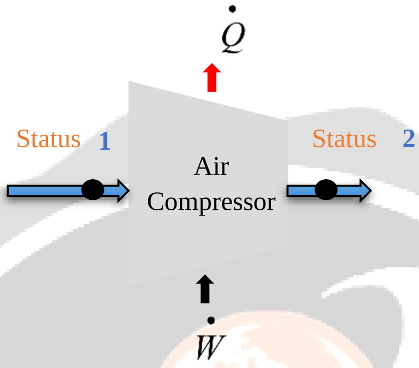

Fig -3 : Energy balance in the compression system

2.4.1 Energy required for compression

The energy required for compression is the work involved in transferring the compressor from state 1 to state 2 [3,4] :

$$E_{tr} = n_c \int_1^2 -pdV \qquad (2)$$

According to our assumptions: $pV^{n_c} = p_1 V_1^{n_c} = p_2 V_2^{n_c} = C$ (Laplace's law)

$$E_{tr} = -n_c \int_1^2 \frac{C}{V^{n_c}} dV = \frac{n_c}{n_c - 1}\left(p_2 V_2 - p_1 V_1\right)$$

Else : $pV = mrT$ (perfect gas)

$$E_{tr} = \frac{n_c mr}{n_c - 1}\left(T_2 - T_1\right) \qquad (3)$$

$T_2 = T_1 \left(\tau_c\right)^{\frac{n_c - 1}{n_c}}$ with $\tau_c = \frac{p_2}{p_1}$ is the compression ratio of a polytropic transformation, then :

$$E_{tr} = \frac{n_c}{n_c - 1} m_1 r T_1 \left(\tau_c^{\frac{n_c - 1}{n_c}} - 1 \right) \qquad (4)$$

Thus the total energy per unit mass of air passing through the multi-stage compressor (N stages), which is characterized by the same compression ratio in each compressor stage, due to having a high efficiency is given by the formula :

$$E_c\left(\tau_c\right) = \frac{N_c n_c}{n_c - 1} r T_1 \left(\tau_c^{\frac{n_c - 1}{N_c n_c}} - 1 \right) \qquad (5)$$

The electrical power consumed by the motor of a multi-stage compressor is given by the expression [3,4] :

$$P_c\left(\tau_c\right)=\frac{\dot{m}\left(\tau_c\right)}{\eta_e\eta_{tr}\eta_c}E_c\left(\tau_c\right) \tag{6}$$

2.4.2 Compressor volumetric capacity

The volumetric capacity of the air passing through the compressor is defined as the ratio between the air mass flow rate and the compressed air density [3,4] :

$$\dot{V}\left(\tau_c\right)=\frac{\dot{m}\left(\tau_c\right)}{\rho_c}=\frac{P_c\left(\tau_c\right)}{\eta_e\eta_t\eta_c}E_c^{-1}\left(\tau_c\right) \tag{7}$$

P_c represents the variation in power delivered by the PVT energy source.

3. RESULTS AND DISCUSSION

For the simulations of the mathematical models studied (under MATLAB), we used meteorological data from the Mahajanga site : 15°43' Sud (latitude), 46°19' Est (longitude). The insolation data for the study site were taken from the ASECNA Mahajanga meteorological station over a 14-year period (2010 to 2023). The Page model was used to estimate global irradiation [9,10]. The mechanical and electrical (compressor) efficiency taken are around 98% and 75% respectively. Inverter electrical conversion is around 98%. The choice of relevant parameters influencing the system under study depends on the expected scale of the system [11]. Thus, our choice of references is set to run a 5 kW MAC for future use. Table 1 shows the limits and choice of some of the parameters used in this work.

Table 1: Limits of the parameters studied and proposed choice

Parameter studied	Limit	Choice	Unit
PVT field area	Variable	50	m^2
PVT field power	Variable	3	kW
Maximum stored pressure	5 - 500	200	bar
Reservoir volume	Variable	200	L
Number of stages (Compressor)	1 - 5	3	-
Charging time (tank)	Variable	1.8	h
Discharge time (Reservoir)	Variable	1	h
Product power (MAC)	1 - 12	5	kW
Efficiency (Compressor)	Variable	73	%

3.1 Simulation of the PVT air system

3.1.1 Average annual power output

Figure 4 shows the evolution of PVT electrical power, as an annual average, as a function of solar irradiance. Electrical power increases with irradiance, which also varies with the month of the year. In Mahajanga, average irradiance is highest in October (close to 1000 W.m^{-2}), while it is lowest in January (close to 700 W.m^{-2}). Similarly for electricity production, for a PVT field surface area of around 50 m^{2} , maximum power reaches 4.1 kW (in October) and 2.8 kW (in January).

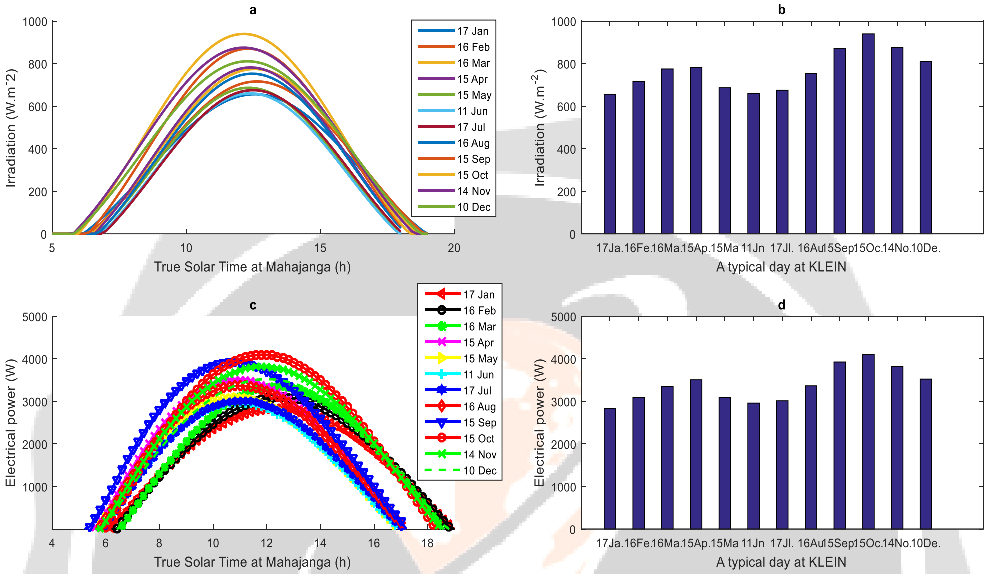

Fig -4: Average annual irradiation and power output on a typical day 2010-2023 (Mahajanga site).

3.1.2 Influence of overall illuminance on power

PVT power increases as the overall irradiation received over the PVT field area increases. At a surface area of 50 m^{2} and an irradiation of the order of 1000 W.m^{-2} , the power produced is of the order of 4.1 kW. For a very low irradiance of around 40 W.m^{-2} and the same surface area, the indicated power is 38 W. Illuminance therefore plays a key role in the PVT field's power output. In the absence of irradiation, the hybrid generator won't work.

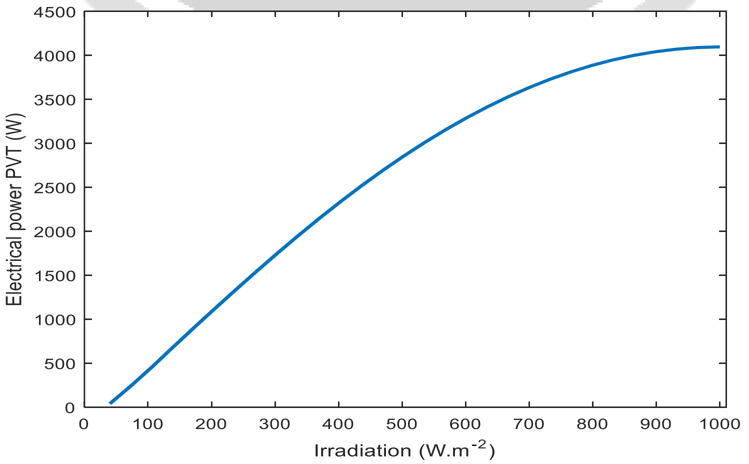

Fig -5 : Effect of solar irradiation on electrical output (Mahajanga site).

3.2 Compression system simulation

3.2.1 Influence of number of stages and compression ratio on energy consumption

Figure 6 shows the importance of the number of stages and the compression ratio in relation to compressor consumption. The red curve shows that with a compression ratio of 200 and a number of compressor stages N= 1, we need 900 kJ of energy to compress 1 kg of air. Unlike the yellow curve, with the same compression ratio and a number of stages N=5, to compress 1 kg of air we need 510 kJ of energy. A high-stage compressor can compress air with less energy consumed per unit mass of compressed air than a lower-stage compressor. But from 3 stages upwards, we notice very little variation. On the other hand, energy consumption increases as compressor outlet pressure rises.

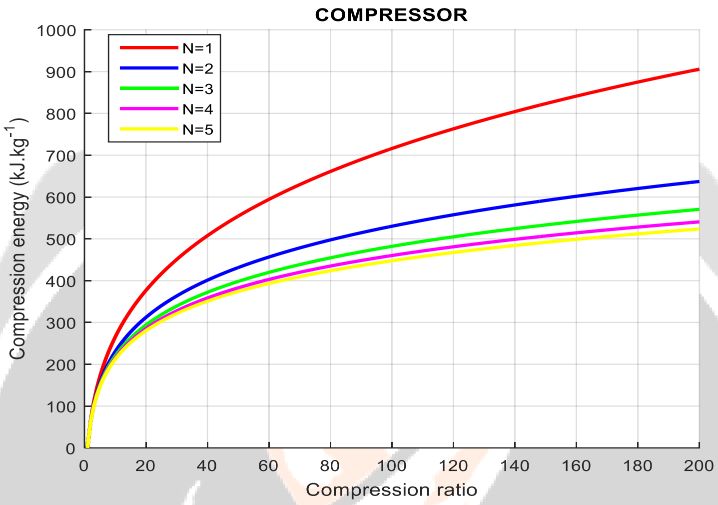

Fig -6: Influence of number of stages and compression ratio on the energy required for compression.

3.2.2 Influence of stage number on volume flow rate

Compressor volume flow and compressor delivery pressure characterize the performance of a compressor. Figure 7 shows that as storage pressure increases, the amount of air delivered decreases. And the quantity of air increases as the number of compressor stages increases. Thus, for a compression ratio of 200 and a number of stages of N=1, the air flow produced is of the order of 0.0025 $m^3 .s^{-1}$. On the other hand, with the same compression ratio and 5 stages, the air flow is 0.0045 $m^3 .s^{-1}$.

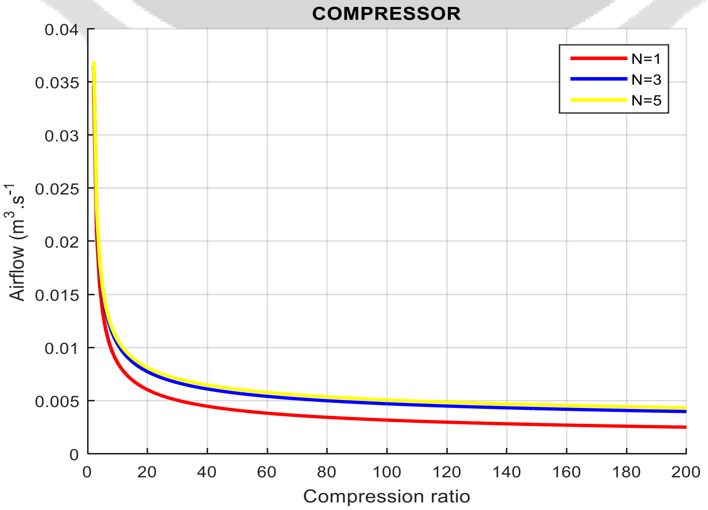

Fig -7: Effect of number of stages and compression ratio on volume flow rate

3.2.2 Influence of solar radiation on volume flow rate

In Figure 8, we can see that the compressed air flow rate produced by the compressor follows the same pattern as the PVT field power curve in Figure 5. The air produced increases as the compression ratio decreases and the radiation received on the surface of the PVT field increases. Thus, the red curve (rate=2) at irradiation G=1000 $W.m^{-2}$ and a number of stages N=3, the volume flow rate is of the order of 0.03 $m^3 .s^{-1}$. On the other hand, for the same irradiation and same number of stages but different compression ratio (ratio=200), the volume flow rate is of the order of 0.004 $m^3 .s^{-1}$ (blue star curve).

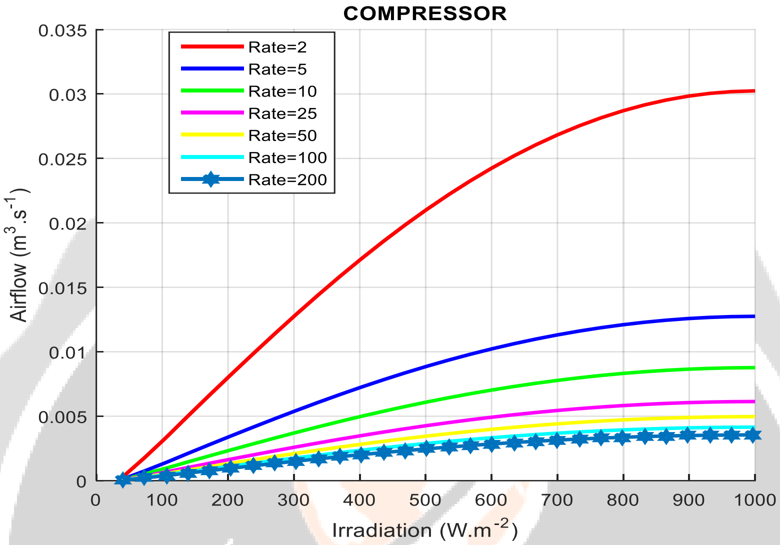

Fig -8: Effect of illumination and compression ratio on volume flow rate

3.3 Influence of solar irradiation on compressor efficiency

In Figure 9, by setting all other simulation parameters, i.e. compression ratio (ratio=200), product volume flow rate (0.004 $m^3 .s^{-1}$) and number of compressor stages (N=3), efficiency increases with increasing irradiance. Indeed, we recorded an overall compressor system efficiency of 0.6% for an irradiation of 38 $W.m^{-2}$ and 73% for an irradiation of 1000 $W.m^{-2}$.

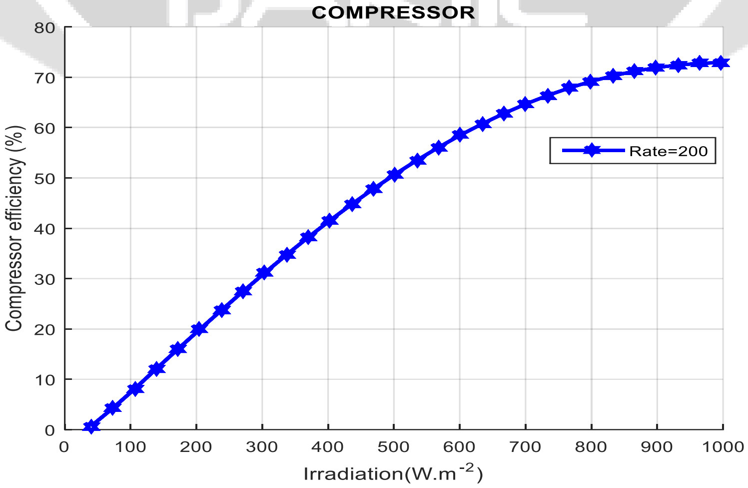

Fig -9: Overall compressor efficiency as a function of solar irradiance

4. CONCLUSION

The system studied demonstrates the possibility of coupling a positive-displacement piston compressor with a PVT hybrid system. For the sensitizations of the influencable parameters, we note that solar irradiation, the number of stages and the pressure delivered by the compression system, play an essential role on the system's performance. All simulations were carried out using Mahajanga's environmental parameters. We chose the month of October because it is the most sunny, with an estimated average annual irradiance of around 1000 $W.m^{-2}$. The next logical step in this work is to study the pressurized air tank and the CAES expansion module, to check the effect of the parameters that can be influenced, in order to properly size the PVT-CAES system.

6. REFERENCES

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