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Influences of Input Parameters on the Energy Performance of the CAES-CPVTA System

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ABSTRAC

The use of compressed air, one of the alternatives to batteries as an innovative renewable energy (RE) storage solution, is characterized by remarkable stored energy density (kWh.m-³) and high reliability (days of operation) with no environmental impact. When the sun is shining brightly, the energy produced by the thermal air photovoltaic field is used to power the CAES (Compressed Air Energy Storage). The compressed air stored in the CAES tanks is used to drive a Compressed Air Motor (MAC) during periods of low or no solar irradiation. To get the best electrical and thermal performance from the air-cooled PVT, the compressed air from the CAES helps cool the photovoltaic cells as they heat up. Our work concerns both the development of a numerical model capable of simulating a Compressed Air Energy Storage (CAES) system fed by a CPVTA Air-Cooled Photovoltaic Thermal Field, and a system for cooling photovoltaic panels by recovering fresh air at the CAES outlet. In this paper, mathematical models are developed to estimate the relevant system parameters (energy consumed by the compressor, energy stored in the reservoir, energy produced by the MAC, mass flow rate used by the MAC and air motor efficiency). The study concludes with analyses of the influence of input parameters on the performance of the CAES-CPVTA system, such as: global solar irradiation, power of the photovoltaic panel field, number of compressor and MAC stages, air motor displacement and maximum and minimum stored pressure.

Keywords: *Solar radiation, Storage, Pressure, Energy, Photovoltaic, Thermal, Compressed air, Engine*

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I. INTRODUCTION

Solar energy storage is a reliable and effective strategy for controlling a large-scale direct-integrated CPVTA system, given the variability and intermittency of the solar renewable source. It also ensures smooth operation and continuity of power supply for stand-alone, off-grid sites (JIRAMA, in the case of Madagascar). In recent years, a great deal of scientific research has shown alternatives to batteries in the form of compressed air energy Storage (CAES) (Sidiki, 2018 ; Jubeh et al., 2012).

The aim of this article is to demonstrate the possibility of storing solar electrical energy in the form of compressed air using a CAES-CPVTA system, specifically by studying the influence of input parameters on the system's energy performance in Mahajanga's climate. The electrical energy produced by the thermal photovoltaic field powers the load and is simultaneously stored in the form of compressed air in a 200 L tank. The compressed air is then used to drive a 5 kW Compressed Air Motor (C.A.M.). Current technology offers two types of compressed air motor (vane type and piston type) (Hussein, 2010). However, we have chosen the piston-type MAC for this article. This technology converts pneumatic energy into mechanical energy on the motor shaft and electrical energy on the alternator shaft (Hussein Ibrahim et al., 2009). The result is a promising source of electricity, without the greenhouse gas emissions of combustion engines.

In addition, during high solar intensity, we record a drop in the CPVTA's electrical efficiency due to the rise in cell temperature (Pasera et al., 2024 ; Khaled, 2010). Automatic start-up of the pneumatic motor is therefore necessary to improve system efficiency. As a result, stored pneumatic energy will be converted into electrical energy, and some of this stored air, passing through the air motor at higher than atmospheric pressure, will be recovered for the purpose of cooling the CPVTA's photovoltaic cells. Hence the optimization of the system.

II. MATERIAL AND

Mathematical models of the system were introduced in order to study the parameters influencing the system. Figure 1 shows a schematic diagram of the model studied:

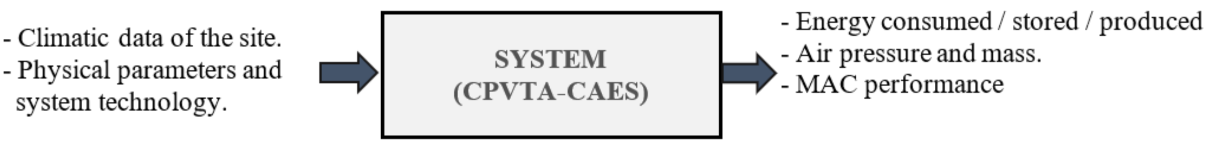

Figure1: System Modeling

2.1 Architecture of the System studied

Our system consists of a 50 m^2 field of Air Thermal Photovoltaic panels. This feeds a compressed-air storage system, featuring a 3 kW electric motor, 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) linked to a 5 kW alternator. The rest of the CPVTA's electrical power is sent directly to the load.

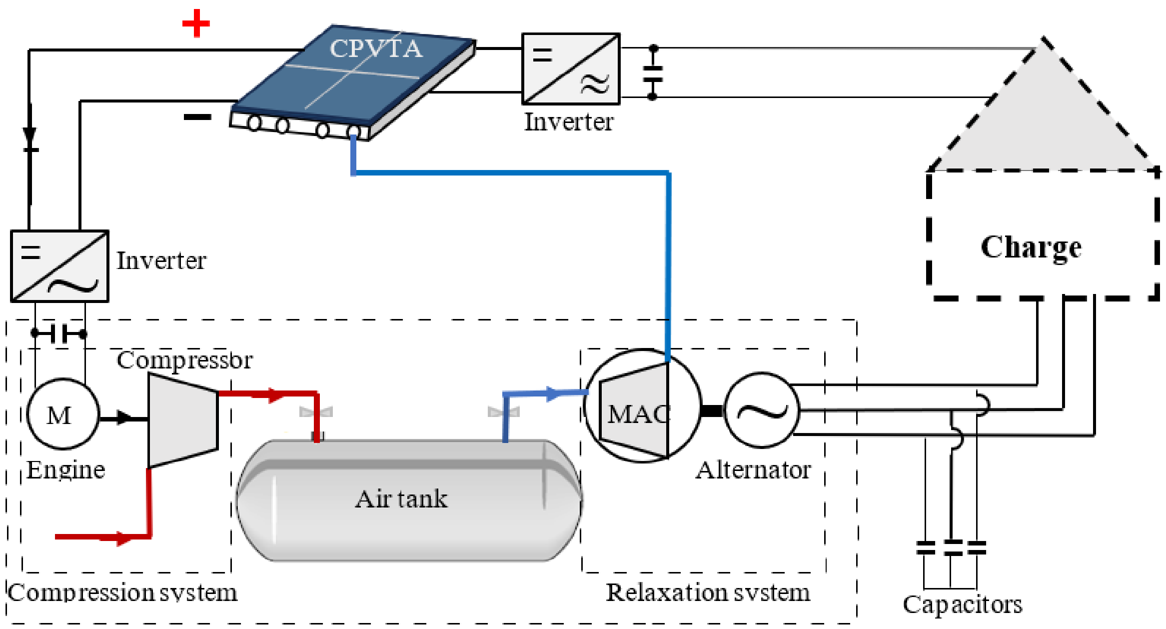

Figure2: System Configuration (CPVTA-CAES)

2.2 Global System Modeling Assumptions

Throughout this study, we will consider the following hypotheses (Sidiki et al, 2017; Bruno et al, 2019; Attoumane et al., 2024; Ibrahim, 2010):

- 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.
- Compressor dead volume is negligible. Electrical power produced by the CPVTA

2.3 Electrical Power Generated by the CPVTA

In order to achieve a high system efficiency (CPVTA-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 (Khaled, 2010):

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

Wit

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

G *et* S respectively represent the overall irradiance received on the plane and surface of the PVT field.

2.4 Energy Required for Compression

The energy required for compression has been determined from the work involved in transferring air from the compressor inlet to the outlet. 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 (Ibrahim, 2010; Sidiki et al., 2017) :

$$E_c\left(\tau_c\right) = \frac{N_c n_c}{n_c - 1} r T_1 \left(\tau_c^{\frac{n_c-1}{N_c n_c}} - 1\right) \tag{2}$$

2.5 Compressed Air Tank Volume

The air volume is expressed in terms of the maximum and minimum permissible pressures in the air motor, the desired autonomy and the maximum air flow rate to operate the motor (Ibrahim, 2010; Sidiki et al., 2017) :

$$V_{res} = \frac{P_a \dot{V}_{\max} a}{P_{\max\_MAC} - P_{\min\_MAC}} \tag{3}$$

2.6 Energy Stored in the Reservoir per unit Volume

The energy stored per unit volume is a function of the reservoir pressure and the subsequent use (expansion) of the stored air (Houssen, 2010; Sidiki et al., 2017) :

$$E_{st} = p_{st}\frac{k n_d N_d}{n_d - 1}\left(1 - \left(\frac{p_a}{p_{st}}\right)^{\frac{n_d-1}{n_d N_d}}\right) \tag{4}$$

2.7 Energy Generated by the MAC

The new MAC technology has shown two types of air motor. The vane MAC, which we won't use in this work, and the piston MAC, which we'll model later. The piston MAC, which converts compressed air into mechanical energy on the motor shaft and electrical energy on the alternator shaft, performs a two-stroke crankshaft revolution cycle (Houssen, 2010; Sidiki et al., 2017). There are three stages in the cycle: intake, expansion and exhaust, Figure 3.

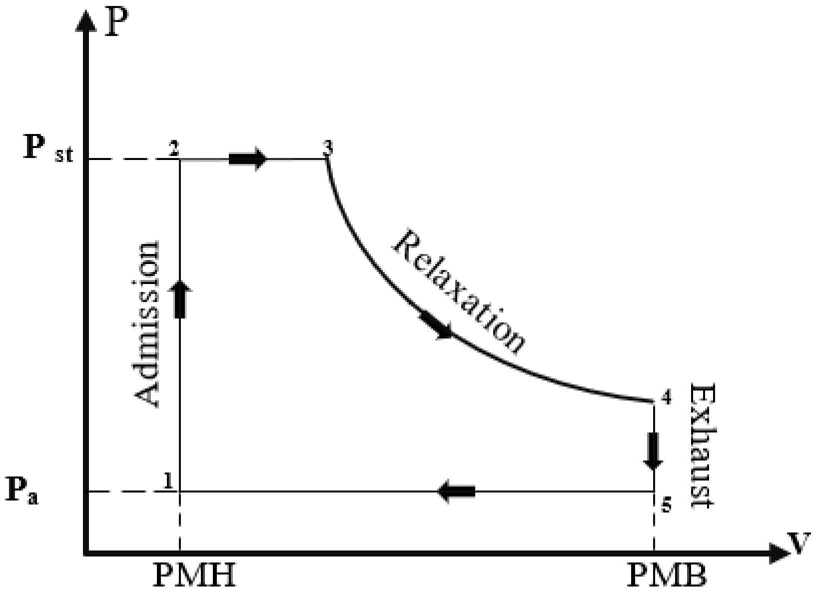

Figure3: Pressure/Volume (P-V) Diagram of the Air Cycle in the MAC

The energy produced by the MAC is represented by the work of the air motor's open cycle, which is the sum of the work of the three cycle stages:

$$W_M = W_{ad} + W_d + W_{ech}$$

By definition of work:

$$W = -\int pdV$$

- **Work Developed during Admission (1-3)**

During the admission phase, there are two transformations:

$$W_{ad} = W_{1-2}(\text{isochore}) + W_{2-3}(\text{isobare})$$

With:

$W_{1-2}(\text{isochore}) = 0$ for an isochoric transformation, thus :

$$W_{ad} = -p_2 \int_{V_2}^{V_3} dV = p_2 V_2 (1 - \alpha)$$

With:

$\alpha = \dfrac{V_3}{V_2}$ represents the volumetric ratio when air enters the cylinder.

- **Work developed during relaxation (3-4)**

During the relaxation phase, a transformation takes place:

$$W_d = W_{3-4}(\text{polytropique})$$

According to Laplace's law, $pV^{n_d} = p_3 V_3^{n_d} = p_4 V_4^{n_d}$, so:

$$W_d = -\int_3^4 pdV = \frac{p_3 V_3}{n_d - 1}\left(\beta^{1-n_d} - 1\right)$$

With :

$\beta = \dfrac{V_4}{V_3}$ represents the volumetric ratio as the air expands in the cylinder.

- **The Work Developed During the Exhaust**

During exhaust, two transformations take place:

$$W_{ech} = W_{4-5}\left(\text{isochore}\right) + W_{5-1}\left(\text{isobare}\right)$$

With , $W_{4-5}\left(\text{isochore}\right) = 0$, then :

$$W_{ech} = -p_1 \int_{V_5}^{V_1} dV = p_1 V_1 \left(\varepsilon_d - 1\right)$$

Where, $\varepsilon_d = \dfrac{V_m - C_y}{V_m}$, represents the volumetric compression ratio.

Finally, the work developed by the single-cylinder MAC is expressed as :

$$W_{MAC} = V_m \left[p_{st} \left[\frac{\alpha\left(\beta^{1-n_d} - n_d\right) + \left(n_d - 1\right)}{n_d - 1} \right] + p_a \left(\varepsilon_d - 1\right) \right] \tag{5}$$

2.8 Mass Flow Rate Used by the MAC

The mass flow rate required to turn a piston-type air motor is given by the expression (Ibrahim, 2010):

$$\dot{m}_{MAC}(\tau_d) = \rho_A \frac{W_{MAC}(\tau_d) N_{MAC}}{60(p_{st} - p_{s\_MAC})} \tag{6}$$

With : p_{s_MAC} , the motor output pressure, which may be ambient or other.

2.9 Pneumatic Piston Motor Efficiency

The efficiency of the piston MAC is given by the ratio between the energy produced by it and the potential power available in the mass flow through the compressed air motor (Houssen, 2010):

$$\eta_{MAC} = \frac{C_{MAC}\,\omega_{MAC}}{\dot{V}_{MAC}\,\Delta p_{MAC}} \tag{7}$$

III. RESULTS

We used the same characteristics of the CPVTA/compressor and the same meteorological data from the Mahajanga site: 15°43' Sud (latitude), 46°19' Est (longitude), which we have already dealt with (Attoumane et al., 2024), for the simulations (under MATLAB). Page's model was used to estimate the site's mean annual global irradiance (Attoumane et al., 2024; Benhammou, 2010). In Mahajanga, the maximum average irradiance value is in the month of October (close to 1000 $W.m^{-2}$), while it is very low in the month of January at close to 700 $W.m^{-2}$ (Attoumane et al., 2024). The same applies to electricity production: for a PVT field surface area of around 50 m2, maximum power reaches 4.1 kW (in October) and 2.8 kW in January (Attoumane et al., 2024). Inverter power conversion is around 98.5%. The choice of relevant parameters influencing the system under study (CPVTA-CAES) is set to run a 5 kW MAC for future use. Parameters influencing system energies, such as solar irradiation, air storage pressure and the number of MAC cylinders, were selected on the basis of a sensitivity analysis of key parameters. Table 1 shows the limits and choices of some of the parameters used in this work.

Table 1: Limits of the Parameters Studied and Proposed Choice (Attoumane et al., 2024)

Parameter studied	Limit	Choice	Unit
PVT field area	Variable	50	m^2
PVT field power	Variable	3	kW
Maximum stored pressure	5 - 500	200	bars
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	%
Yield (MAC)	Variable	32,24	%

3.1 Influence of Compressor Stage Number, Solar Irradiation and Pressure on Energy Consumption, Flow Rate and Compressor Efficiency

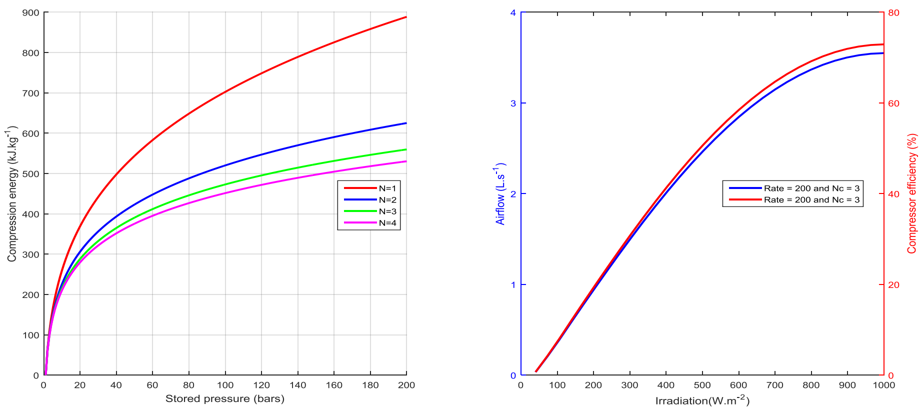

Figure4: Energy Consumption, Air flow Required and Compressor Efficiency

The red curve on figure 4, left, shows that with a number of compressor stages N= 1 and a compression ratio of 200, 900 kJ of energy is required to compress 1 kg of air. However, with the same characteristic (ratio= 200) but different number of stages (N=4), to compress 1 kg of air we need 525 kJ of energy (the purple curve). We also note that the air produced by the compressor increases as the radiation received on the surface of the PVT field increases. Thus, the blue curve on the right, with compression ratio = 200, irradiation G=1000 $W.m^{-2}$ and number of stages N=3, volume flow is of the order of 3.7 $L.s^{-1}$. On the other hand, for the same number of stages and compression ratio, but different irradiation (G= 100 $W.m^{-2}$), volume flow is 0.25 $L.s^{-1}$. For the red curve on the right, fixing all other simulation parameters, i.e. compression ratio (ratio=200), product volume flow (3.7 $L.s^{-1}$) and compressor stage number (N=3), efficiency increases as irradiation also increases. Indeed, we recorded an overall compressor system efficiency of 0.6% for irradiation G = 38 $W.m^{-2}$ and 73% for irradiation G = 1000 $W.m^{-2}$. So, a CPVTA with plenty of sunshine achieves a higher compression efficiency than one with less sunshine.

3.2 Influence of Storage Pressure, Autonomy and Site Irradiation on Stored air Volume

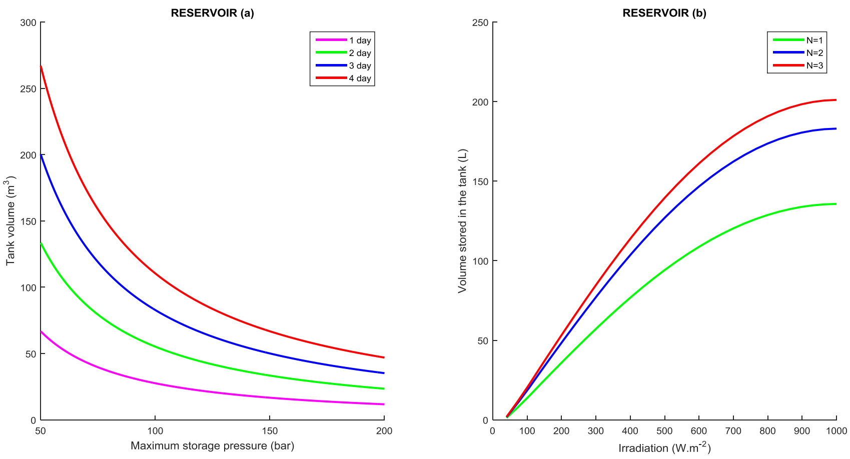

Figure5: Effect of Range and Pressure on Tank Volume

Figure 5 shows two possibilities for sizing the storage tank in relation to the air requirement. So, for tank (a), we see that the greater the number of days envisaged for air storage, the larger the tank. However, for an autonomy of 1 day with a maximum air flow from the reservoir $\dot{V} = 32,70\ L.s^{-1}$ and a storage pressure p = 200 bar, the volume of the reservoir must be of the order of V = 11.74 m^3. With the same flow rate and storage pressure, a 4-day autonomy requires a tank of V = 46.96 m^3 (red curve). The latter is enormous, and it will be complicated to install a tank with such a volume. For this reason, we propose the second, simpler sizing method (tank b). With a CPVTA surface area (S = 50 m^2), an irradiation of the order of 1000 $W.m^{-2}$, a tank charging time t = 1.38 h and a 3 kW compressor with a number of stages N = 3, the tank volume is of the order of 200 L. On the other hand, for the same parameters but a different number of stages (N = 1), the volume of stored air is 135.3 L. So, the tank will be recharged on a fairly regular basis using the CPVTA energy available from the site (Mahajanga), once the tank pressure is very low in order to get the best performance

3.3 Influence of Stored Pressure and MAC displacement on the Energy Produced by the MAC

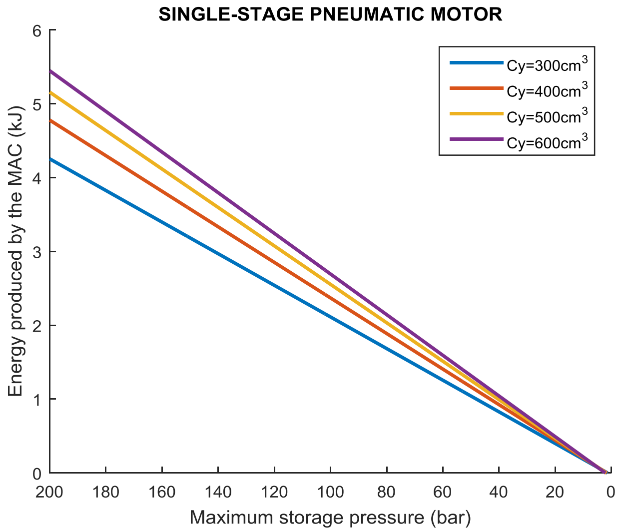

Figure 6: Effect of MAC intake Pressure and displacement on Engine Power output

Figure 6 shows that the energy of the air motor evolves linearly with the reservoir pressure. This is due to the volumetric compression ratio, which is constant at a motor angular velocity value $\omega = 125.66$ $rad.s^{-1}$. What's more, the energy produced increases as MAC displacement increases. Thus, with a storage pressure p = 200 bar and a displacement Cy = 600 cm^2, we have an energy output of the order of 5448 J. On the other hand, with the same pressure but a different displacement (Cy = 300 cm^2), the energy developed is 4254 J. Our results are in good agreement with those found in the scientific literature (Hussein Ibrahim, 2010).

3.4 Influences of Stored Pressure and MAC displacements on Air Mass Flow Rate

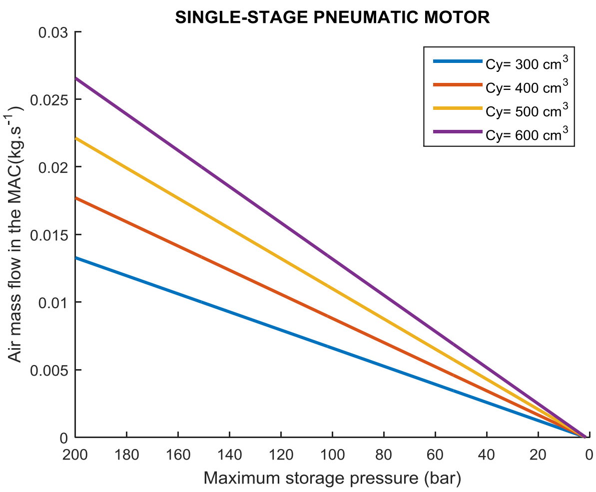

Figure7: Effect of Storage Pressure and Motor displacement on Air Flow Rate

Figure 7 shows that the air mass flow rate consumed by the piston MAC is also linear, and its magnitude depends on the increase in engine displacement. Thus, with an angular velocity fixed atω = 125.66 rad.s^{-1}, an air motor intake pressure of around 200 bar and a displacement of Cy = 600 cm^2, the mass flow required to turn the MAC is 0.027 kg.s^{-1}. On the other hand, with the same characteristics but a different displacement (Cy = 300 cm^2), the useful flow rate is of the order of 0.013 kg.s^{-1}.

3.5 Influence of Stored Pressure and displacement on MAC Piston Efficiency

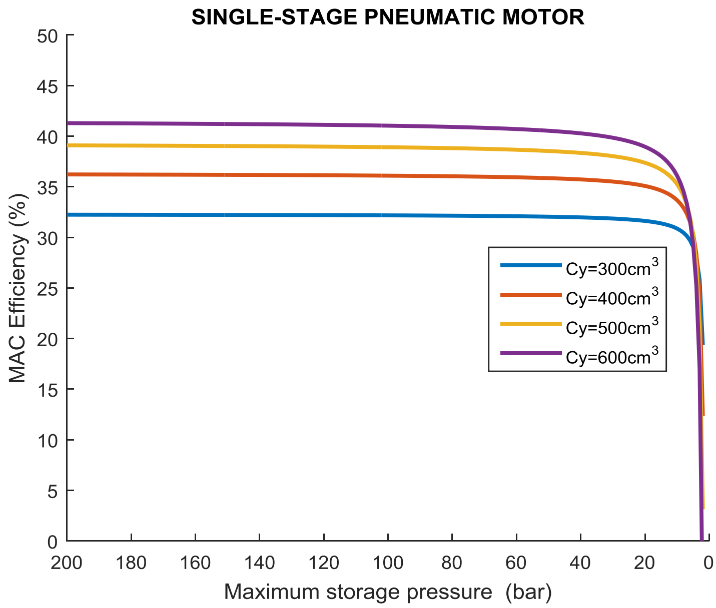

Figure 8: Effect of Storage Pressure and Motor displacement on MAC Efficiency

Figure 8 shows that the efficiency of the single-stage air motor is characterized by high reservoir pressures entering the motor and falling as the minimum pressure allowed to operate the MAC decreases. So, with an angular velocity fixed atω = 125.66 rad.s^{-1}, an air motor intake pressure of the order of 200 bar and a displacement of Cy = 600 cm^2, the efficiency of the single-cylinder MAC is of the order of 41.28%. However, with the same parameters but different displacement (Cy = 300 cm^2), the calculated efficiency isη_{MAC} = 32.24%.

IV. CONCLUSION

In conclusion, this study shows the possibility of combining a CAES with a single-cylinder piston air motor with a CPVTA, taking into account the key parameters (site environmental and technical) influencing the system (CPVTA-CAES). However, from the results of the influence analysis of the relevant input parameters of the system studied, it is clear that site insolation, the number of compressor stages, the maximum and minimum stored pressure, the tank volume and the displacement of the air motor play major roles in the study and sizing of the CPVTA-CAES. The simulations carried out provide satisfactory solutions. With high solar irradiation, the CPVTA operates at its rated power. As a result, we record good compressor efficiency and the volume produced is sufficient to fill our tank (200 L), provided that the number of compressor stages is correctly dimensioned (Nc = 3). Otherwise, compressor efficiency will be very low. As a result, we'll have a longer charging time. As a result, system efficiency (CPVTA-CAES) will be very low.

What's more, with a high storage pressure, a fairly large air reservoir and a slightly larger displacement, the MAC will produce electricity at its rated power at an enormous discharge time. As a result, the air motor's efficiency will be satisfactory. In our case, an irradiation (G =1000 W.m-2), a number of compressors (Nc = 3), a 200 L reservoir, a stored pressure (200 bar), a rotation speed (ω = 125.66 rad.s^{-1}) and a displacement (Cy = 300 cm^2), the efficiency of pneumatic conversion into electricity is of the orderη_{MAC} = 32.24%.

The next logical step in this work concerns a biodiesel engine coupled to a compressed air tank fed by a CPVTA, in order to raise awareness of the key parameters affecting the performance of the system studied (CPVTA-CAES-GEBD).

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