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Research Article

Techno-economic analysis of the feasibility of a hybrid power plant with photovoltaic panels a water treatment station and compressed air energy storage. A case study: Casablanca-Morocco

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ABSTRACT

Due to the growth of population, the energy needs have increased. To address this rise of demand, the increase of share of renewable energy in the energy mix is the solution since it is a sustainable, unlimited and zero greenhouses' emissions source. However, these resources are characterized by their intermittency. To solve this problem, we need to store the additional energy. One of the most promising technologies is compressed air storage, it has proven useful to store energy during off-peak hours and to reproduce it during peak hours. This paper investigates the feasibility of a hybrid power generation system consisting of a photovoltaics system combined with a compressed air energy storage. The hybrid power system address to compare the system feasibility with and without the energy storage option. The hybrid system is intended to supply power to a water treatment plant. The analysis of the energy profile including consumption, generation, and storage, was performed. The influence of the air storage temperature on the levelized cost of storage and the dependence on the grid energy was studied. The effects of ambient temperature and compressor pressure ratio on various system parameters, such as mass air flow in and out, and system efficiency, have been investigated. The result shows that when the storage temperature is increased from 300 to 800°C, the levelized cost of storage benefit is 0.025$/kWh. The system efficiency decreased from 70% to 28% when increasing the pressure ratio from 2 to 30, while keeping the ambient temperature constant at 300°K. Conversely, it increased from 60% to 64% when raising the ambient temperature from 295°K to 320°K while maintaining the pressure ratio at 3.

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INTRODUCTION

Recently, the negative impact of greenhouse gas emissions on the environment and energy security has led to the need to increase the share of renewable energy in the global energy mix [1,2]. Due to the intermittent nature of renewable resources especially solar and wind energies, the integration of these technologies leads to a significant imbalance between energy production and consumption. Therefore, the power grid stability would be perturbed [3,4]. Energy storage is the most important way to solve this problem and ensure a continuous and stable energy balance, especially for off-grid systems [5,6]. Braff et al. [7] show that climate mitigation by integrating variable renewable energy with an energy storage system depends on many factors, especially the cost of storage for different technologies. Nowadays, there are many technologies for storing energy in different forms. The most widely used technology in the world is pumped hydroelectric storage, which has a high capacity. However, future development is limited by site selection, although there are many facilities that use the ocean as a lower reservoir [8]. After that, we found that the most preferred technology by scientists and engineers, especially for small plants, is battery, because it has fast response times and high efficiency compared to other technologies. On the other hand, the use of batteries is limited by their high cost [9], lifetime, and power to energy ratio [10]. Xing et al. [11] classified different types of batteries according to their performance scale: Lead-acid batteries range from 1MW-1.4 MWh to 36 MW -24 MWh, sodium-sulphur batteries range from 1 MW -7 MWh to 34 MW -245 MWh, and lithium-ion batteries range from 6 MW -10 MWh to 32 MW -8 MWh. After that, compressed air energy storage (CAES) technology has proved its large-scale utility among all these storage technologies [12]. CAES is a relatively mature energy storage technology that stores electrical energy in the form of high-pressure air and converts it into electrical energy when energy demand is higher than energy generation. It is characterized by high reliability, low energy storage cost, and low greenhouse gas emissions compared to other storage systems [13]. The combination of CAES with solar or wind power plants is a promising solution to the problem of intermittency renewable energy sources [14,15]. Today, there are two plants in the world using this technology for energy storage, the first one is called Huntorf (Germany, 321 MWel) and the second one is McIntosh (USA, 100 MWel) [16].

The first CAES generation is the diabatic or conventional compressed air energy storage system (D-CAES). In this system, air is compressed by compressors when energy demand is less than energy production, however a significant amount of thermal energy is released into the atmosphere. Conversely, the stored compressed air is fed into the turbines to regenerate power when demand is higher than production. This process requires an additional fuel to burn the compressed air stored in tanks or salt caverns before it is fed into the turbines. The heat losses during the charging process in addition to the fuel burned prior to the discharging process result in a significant reduction in overall efficiency to around 45-50% in addition to greenhouse-gas emissions. Subsequently, the D-CAES system was developed, made even more efficient by adding thermal energy storage (TES) system before entering a tank or salt cavern. This new device has the task of capturing the heat loss generated by the compressors and reusing it to burn fuel before the discharge process. This system is called advanced adiabatic CAES (AA-CAES). The improvements made have reduced greenhouse gas emissions and increased the overall efficiency of the system to 65-75%.

Liquid air energy storage LAES is a new concept of compressed air storage in which air is stored in the form of a liquid at cryogenic temperatures [17]. The process of the LAES system is the same as for the other derivatives. Except that the liquid air is stored in containers at near atmospheric pressure. During the discharge phase, the required energy is recovered by pumping, evaporating and expanding a liquid air stream through a series of turbines in an energy recovery unit (PRU) [18].

Kosowski et al. [19] designed a system consisting of an existing industrial plant using a CAES system as an energy and heat source for a system capacity of 30 MW. The study includes an analysis of technical and economic parameters to investigate the feasibility of the project. Some of the parameters were studied under three different scenarios; in the best scenario, the internal rate of return (IRR) achieved a value of 14.2% with a payback period of 10 years.

Matos et al [20] studied several business models for CAES systems. The analysis included two business models with Monte Carlo simulation (MCS). The first for energy storage of energy from renewable sources and the second for energy arbitrage.

Sadeghi [21] implemented a hybrid power system consisting of PV panels, CAES system, batteries, thermal energy storage, gas turbine, and molten carbonate fuel cells. The power plant is designed to meet the energy needs of 500 households in Iran. The peak load reaches 500 kW. The study includes the impact of various parameters on the levelized cost of energy (LCOE).

Cheekatamarla et al. [22] analyzed a storage system based on isothermal-CAES. The studied system is designed to supply energy to residential and commercial buildings. In the work, the influence of different parameters on the main performance and cost was studied.

The system studied in the paper by Bennett et al. [23] is an offshore isothermal CAES, and its efficiency and cost were analyzed. The site studied is located on the Atlantic coast of the United States near Virginia. The system capacity ranges from 10 to 390 MW. The results show that the system is capable of increasing the yield from 0.031$/kW h to 0.048$/kW h.

In this article, a brief introduction to the technology of compressed air energy storage and its derivatives is given. Followed by a description of the hybrid system studied and its operation. Finally, in the last part of this article, the results of the energy profile and the influence of the storage temperature, ambient temperature, and pressure ratio on the system performance are analyzed.

This work introduces an alternative solution to address the high energy demand of water treatment plants. Previous articles have explored the use of energy storage in various types of facilities. The present article investigates the feasibility of integrating a photovoltaic power plant and a Compressed Air Energy Storage (CAES) system with a water treatment station. The study encompasses both technical and economic aspects. The novelty of this article lies in the examination of atmospheric conditions and their impact on the system's performance, particularly the ambient temperature. The results demonstrate significant changes in global efficiency as this parameter increases.

METHOD

Assumptions & Model Description

- The pressure drop in the Volume storage is around 20%.
- The compressor and turbine isotropic efficiency are respectively, 0.85 and 0.87%.
- The Thermal energy storage (TES) system efficiency supposed to be perfect.

Table 1. Power consumption by pump

Pump	Pump Power [kW]
Well Pump	15
Low-Pressure Pump	15
Booster	5.5
Wash pump	11
High-Pressure Pump	75
Treated Water Pump	15
Others	3.5

- The compressed air is stored in an underground cavern with a depth of 400 meters.

Our hybrid system consists of three parts: A water treatment plant, power generation facilities, and a storage system. The water treatment plant consists of several pumps that operate either independently or interdependently. The working hours of each pump are different, and the daily consumption profile is shown in Figure 1. Figure 2 illustrate the principle working of system during the different stages: production, storage and consumption. Table 1 describes the detailed consumption of each pump.

The methodology adopted in the present paper involves sourcing all data from existing literature and new data obtained from different sources such as the data on the annual capacity factor and data on the available space able to store compressed air.

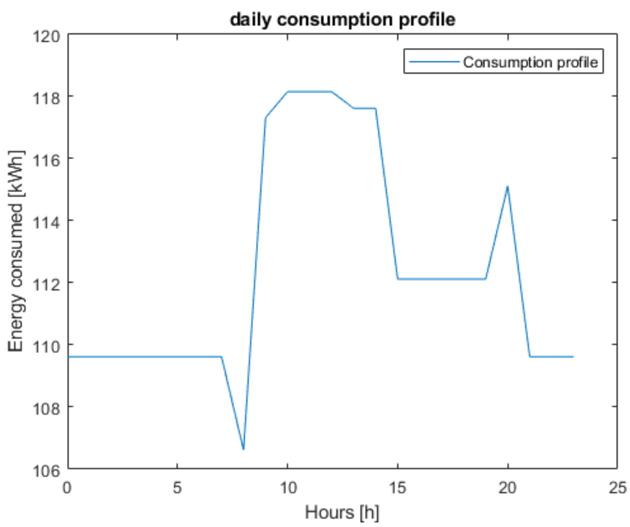

Figure 1. Consumption profile.

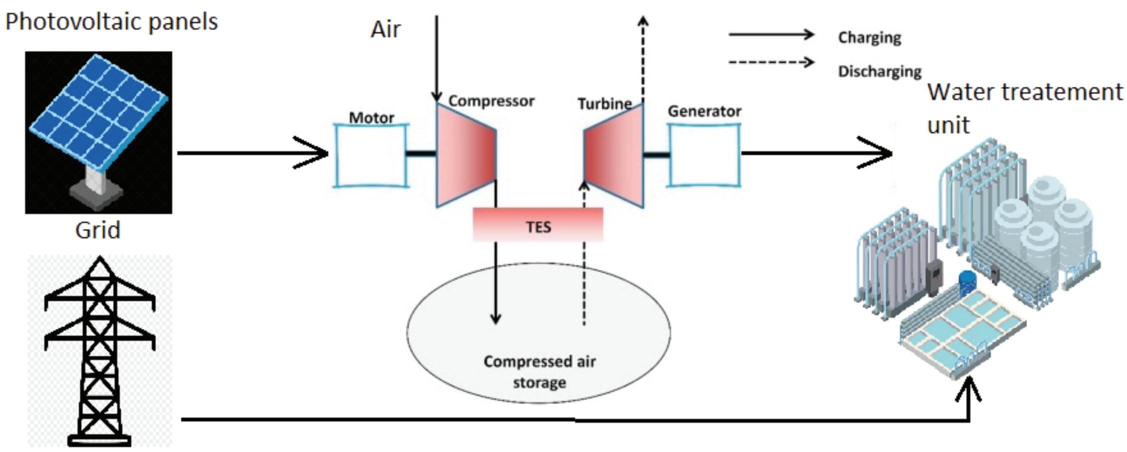

Figure 2. System principle working scheme.

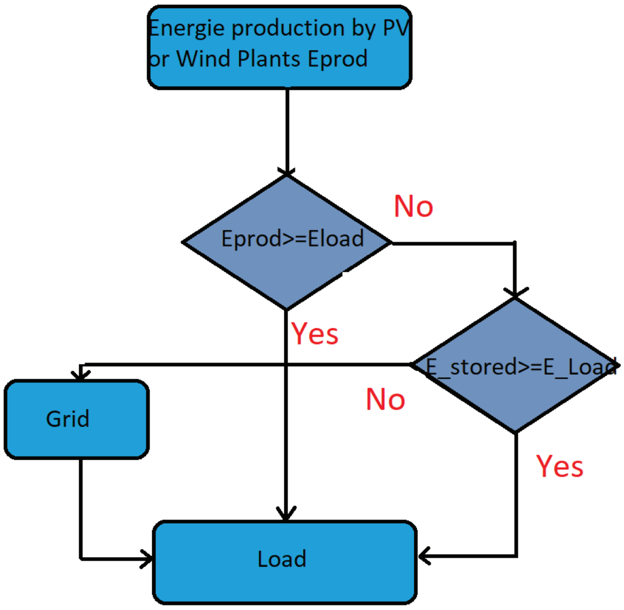

Figure 3. Model algorithm.

The well pump fills the first tank, which contains the untreated water. After the low-pressure pump, the water flows to the sand filter and the cartridge filter. In parallel, a wash pump and booster clean the sand filter as soon as the low-pressure pump is turned off. Once, the treated water leaves the second filter, a high-pressure pump sends it to reverse osmosis. In this step, the water pressure is very high, reaching 60 bar. After that, the treated water of the intended quality fills another tank via a pump for treated water, and the untreated or rejected water is returned to the reverse osmosis.

The power generation facilities may be solar or wind, and the power capacity must be designed according to the consumption profile. The peak consumption is about 118 kWh, therefore the power plant capacity is 140 kW (including all power losses). The working principle of the system is shown in Figure 3. The working principle can be divided into three states: First, when the produced energy is equal to or higher than the required energy, in this case no power grid is needed and the extra energy that is not used is stored.

The second case, when the production cannot cover the demand, the energy gap is covered by the storage system. The last case, when the sum of produced and stored energy cannot cover the demand, in this case the energy drawn from the grid to feed the load.

The principle operation of compressed air energy storage technology is based on 3 phases: Charging, storing and finally discharging. During the charging process, ambient air is compressed to high pressure by multistage compressors and, in the second stage, stored in a closed volume. When the stored energy is needed, the discharging process takes place, where this energy is converted into mechanical energy via multistage turbines [24]. The performance of this technology depends on several factors, such as the individual efficiency of each component, the ambient temperature, the pressure and temperatures of the stored air, the overall efficiency of the storage system is given in equation 1 [25]:

$$\eta_{CAES} = \frac{1 - \frac{T_0{}^{K*\eta_{turb}*\eta_{comp}}}{Ts}}{1 - \frac{T_0}{Ts}} \tag{1}$$

Where K is a function of pressure and T_0 is the ambient temperature. η_{turb} and η_{comp} are successively compressor efficiency and turbine efficiency. T_s is the storage temperature. During the compression phase, the compressor work can be calculated using the following equations: For an ideal gas,

$$PV = nR_tT \tag{2}$$

where P is the gas pressure, Pa; V is the volume of the gas m3 ; n is the mass of the gas, kg; Rg is ideal gas constant, J/(kg.°K); and T is a the gas temperature, °K.

$$W_{comp} = m_{air,in}C_p(T_2 - T_1) \tag{3}$$

$$\eta_{CAES} = \frac{T_2' - T_1}{T_2 - T_1} \tag{4}$$

For an isotropic compression: $PV^{\gamma} = Constant$. By using equation 2, the relationship between air pressure and temperature is deduced. Thus, $P^{1-\gamma}T^{\gamma} = Constant$. Therefore, the isentropic temperature at the outlet of the compressor becomes:

$$T_2' = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{5}$$

$$T_2' = T_1(\pi_c)^{\frac{\gamma-1}{\gamma}} \tag{6}$$

Where π_c is the compressor pressure ratio.

Therefore, the final expression of the efficiency can be given by the following equation:

$$\eta_{comp} = \frac{T_1(\pi_c)^{\frac{\gamma-1}{\gamma}} - T_1}{T_2 - T_1} \tag{7}$$

Thus, the temperatures at the outlet of the compressor is given by:

$$T_2 = \frac{T_1(\pi_c)^{\frac{\gamma-1}{\gamma}} - T_1}{\eta_{CAES}} + T_1 \tag{8}$$

Figures 4 and 5 represent the evolution of the outlet temperatures of the compressor as function of ambient temperature and compressor pressure ratio. The temperature at the outlet of the compressor is crucial for various parameters, particularly the temperature and pressure at

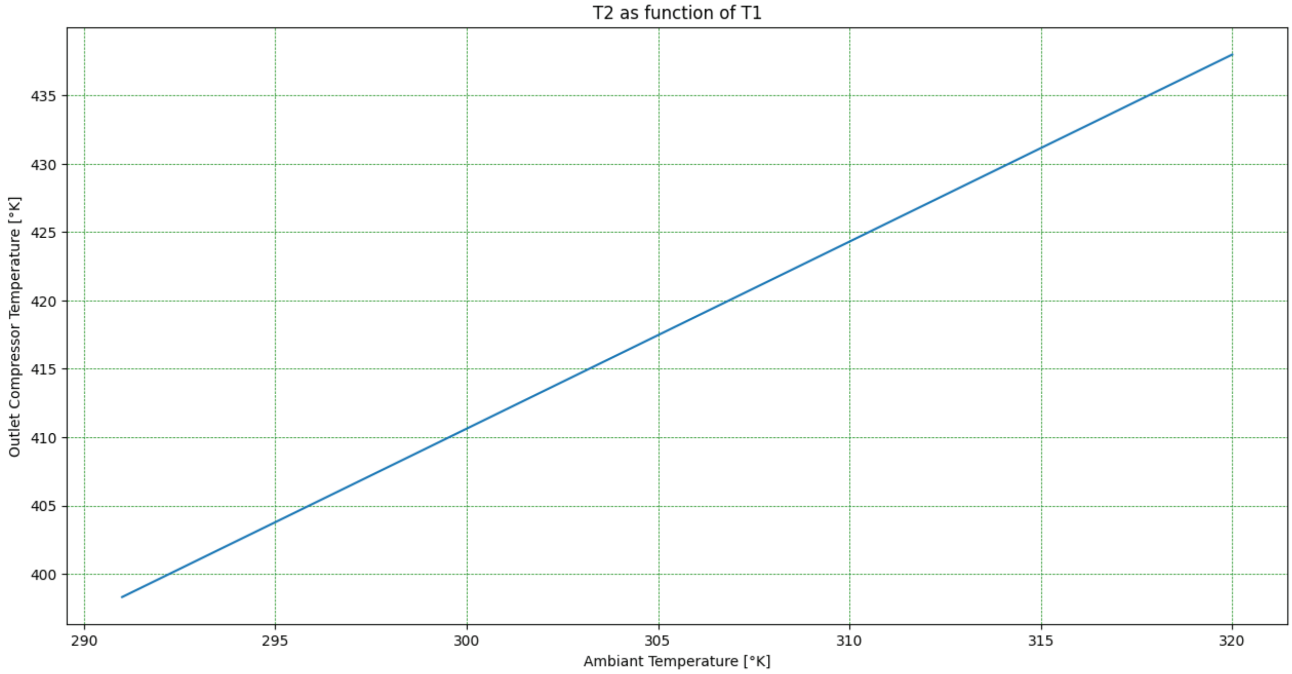

Figure 4. Effect of ambient temperature on the outlet temperature.

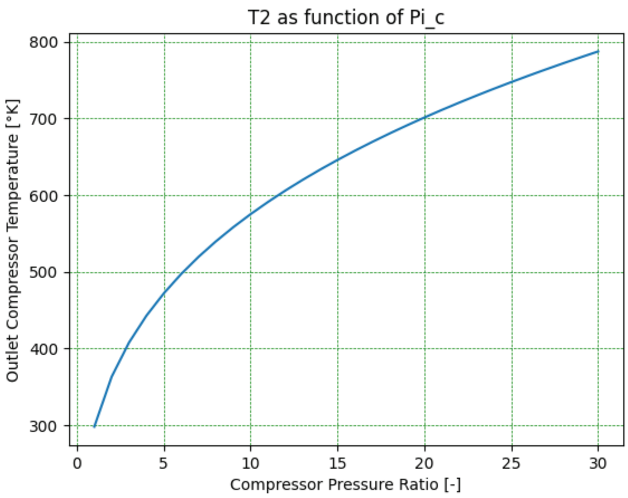

Figure 5. Effect of pressure ratio on the outlet temperature.

the volume storage, the turbine's inlet, and the power and energy output of the system. Consequently, it is essential to investigate the impact of ambient temperature and compressor pressure ratio on this parameter.

Figure 6 depicts the linear relationship between both temperatures as illustrated by Equation 8. It can be observed from Figure 7 that there is a significant increase in the outlet temperature of compression as the pressure ratio increases, compared to the increase observed with the rise in ambient temperature.

$$Energy_{stored} = W_{comp} t_{ch} \tag{9}$$

$$m_{air,in} = \frac{Energy_{stored}\eta_{comp}}{C_p(\pi_c^{\frac{\gamma-1}{\gamma}} - 1)} \tag{10}$$

During the storage phase, the following equation is used to compute the volume of air that can be stored, considering the available amount of energy generated by the solar plant. The air mass flow at the inlet of volume storage is given by:

$$m_{air,in} = v_{air}\rho_{air} \tag{11}$$

Where v_{air} and ρ_{air} are respectively, volume flow and density of air in m^3/s and kg/m^3. Since the gas density is proportional to the pressure, the following equation is used to calculate the evolution of density when the outlet compressor pressure changes.

$$P_2 = P_1 + \rho_{air} \tag{12}$$

Thus, using the relationship between density and pressure, the following equation is derived.

$$\rho_{air} = \frac{P_2 - P_1}{gh} \tag{13}$$

Therefore,

$$v_{air} = \frac{m_{air,in}gh}{P_2 - P_1} \tag{14}$$

It can be concluded that the air storage volume can be computed by multiplying the volume flow by the charging time.

$$V_{CAES} = 3600 v_{air} \tag{15}$$

$$V_{CAES} = 3600 \frac{m_{air,in} gh}{P_2 - P_1} \quad (16)$$

Using the assumption of pressure drop: P3 = 0.8P2,
Therefore: P3 = 0.8 π_c P_1,
using equation 23 we obtain for n = 1

$$T_3 = \frac{P_3 V_{CAES}}{nR} \quad (17)$$

$$T_3 = \frac{0.8\, \pi_c P_1 V_{CAES}}{nR} \quad (18)$$

By applying the mass flow conservation law, the mass air flow exiting the storage volume and entering the turbine is obtained by the following equation:

$$m_{air,out} = \frac{T_2}{T_3} m_{air,in} \quad (19)$$

In the last phase of storage, the power output of the turbine can be obtained using the same method as the compressor work. Thus, it can be expressed by the following equation:

$$W_{Turbine} = m_{air,out} \eta_{CAES} \frac{k}{k-1} T_3 (\pi_t^{\frac{k-1}{k}} - 1) \quad (20)$$

Therefore, it is deduced that the system efficiency.

$$\eta_{system} = \frac{W_{Turbine} t_{disch}}{Energy_{stored}} \quad (21)$$

Solar energy is the energy obtained from the conversion of solar radiation into thermal or electrical energy by solar panels [26]. Solar energy represents one of the cleanest technologies and is also an available energy source. The energy production of solar panels depends on several parameters, such as the material used to manufacture the panels,

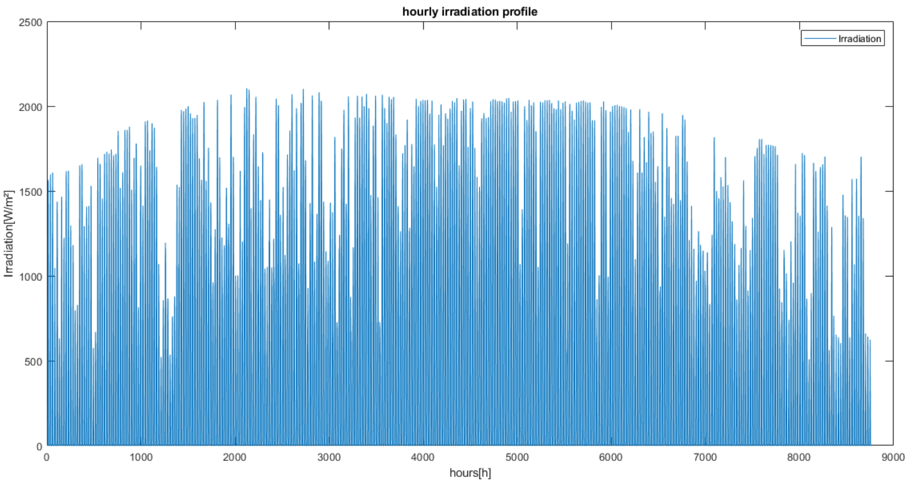

Figure 6. Hourly irradiation profile.

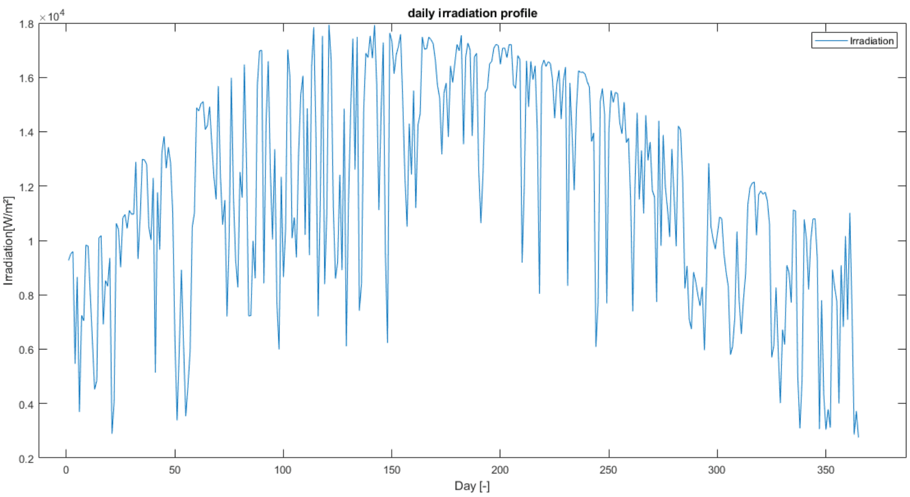

Figure 7. Daily irradiation profile.

orientation, tilt angles, and installation area. The energy output is given by equation 22. The hourly and daily irradiance profiles are shown in Figures 6 and 7. The data used in this paper was taken from the PVWATTS platform [27].

$$E = \eta_{PV} * G * A * PR * NH \tag{22}$$

Where: η_{PV} is the Solar Panel Efficiency [%], G is the Solar Irradiance [kWh/(m²·day)], A is the Panel Area [m²], PR is the Performance Ratio [-], and NH is the average number of sunlight hours per day.

RESULTS AND DISCUSSION

This section would cover two areas of analysis. The technical side, in which technical behavior is examined. The economic part deals with the benefits of implementing this project. In the first part, we analyze the results of the simulation performed with MATLAB software. The results were obtained according to the algorithm cited in Figure 3. Figures 8 shows the energy profile including generation, consumption and storage of the hybrid system. The hourly profile provides more details about the energy profile and is clearer compared to the daily profile. Based on the daily profile, the amount of the possible energy that can be stored cannot be determined, especially in the case of solar energy, because the hours of solar radiation are very limited, so they can cover the entire demand of the day. Therefore, the energy storage amount is always next to the production and the storage energy cannot be calculated from the daily profile.

The daily profile is clearer to understand compared to the hourly profile. But without the hourly data, our results cannot be accurate. Figures 9 and 10 show, successively, the daily profile of the system coupled with solar panels with and without the storage option. From both figures, it can be seen that the energy production is highest in the middle of the year when the solar radiation is higher, especially

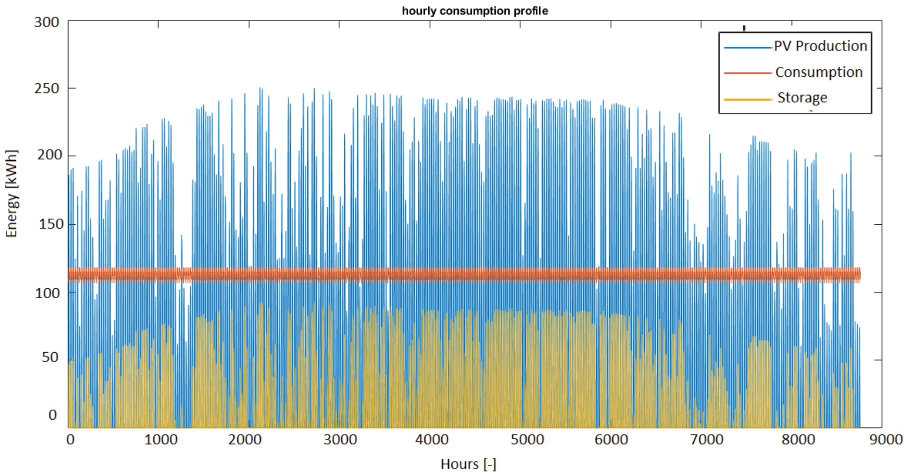

Figure 8. Hourly energy profile of the installation.

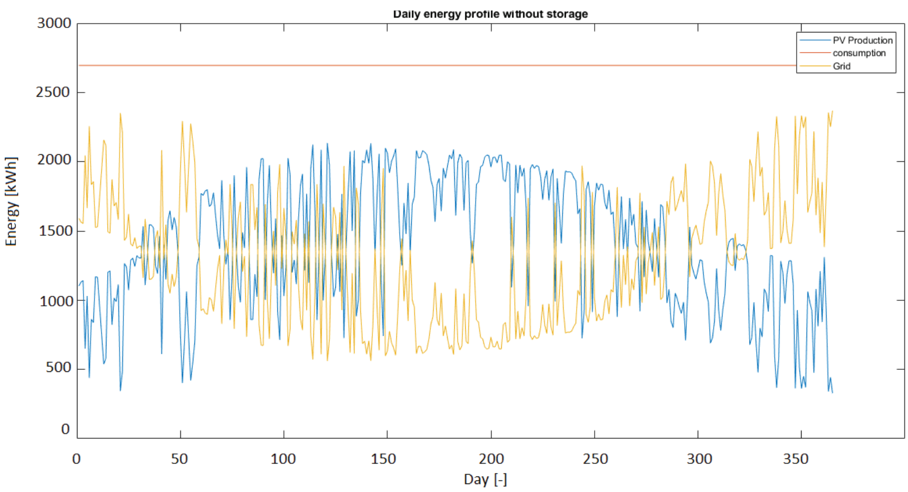

Figure 9. Daily energy profile of the installation without storage.

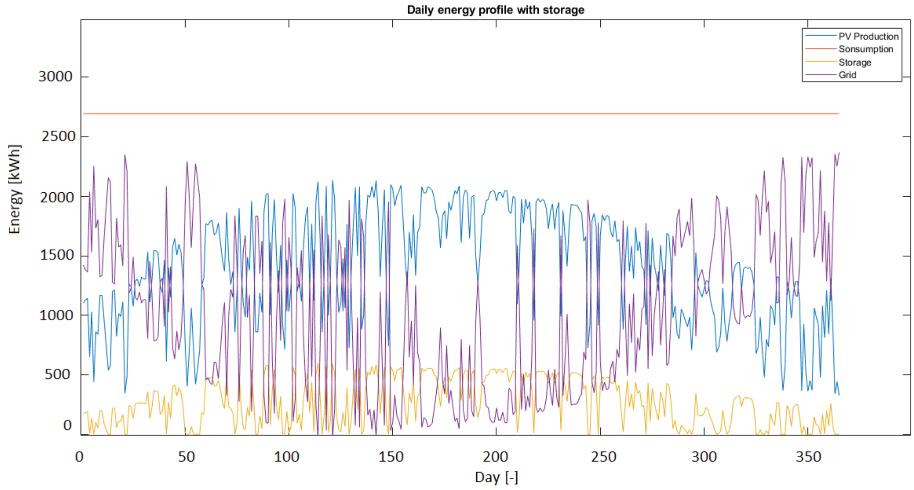

Figure 10. Daily energy profile of the installation with storage.

in summer. Since the production can supply the daily load and the load requires less electricity than the production at certain hours, the storage option is used to stabilize the energy balance and reduce the need for electricity grid usage. Therefore, the role of the CAES system is to reduce the dependence on the power grid.

In order to select the technology of storage among others there are many keys that can be used. The levelized cost of storage represents an important key to selecting suitable, profitable, and efficient technology [28]. The mathematical expression of LCOS is given in equation 23 [29].

$$LCOS = \frac{CAPEX + \sum_{1}^{lt} \frac{(O\&M+Fuel)_{lt}}{(1+r)^{lt}}}{\sum_{1}^{lt} \frac{(Annual\ Energy\ Produced)_{lt}\eta_{CAES}}{(1+r)^{lt}}} \tag{23}$$

The economic part of this work is shown in the levelized cost of storage and grid dependence as a function of storage temperatures. Figure 11 show that the energy drawn from the grid decreases when the temperature of the air storage increases, because the ratio of ambient temperature and storage temperature directly affects the overall efficiency of the storage system, which means that the system losses are lower and therefore the energy drawn from the grid is reduced. Figure 12 shows the evolution of the levelized cost of storage as a function of storage temperatures. It can be seen that the average LCOS decreases as the CAES storage temperature increases. The lifetime of the CAES system is 25 years and the discount rate is 10% [12]. The average LCOS values decrease from about 0.2 to 0.175$/kWh when the storage temperature increases from 300°C to 800°C. In Figure 12, it can be observed that the LCOS decreases by 0.025$/kWh for a temperature increase of 500°C. Therefore, storing compressed air at high temperatures would increase the performance of the global storage system and decrease the energy storage prices. In addition, the turbine blades remain in operation longer. The LCOS of CAES system values obtained are competitive compared to the ones of Battery technology.

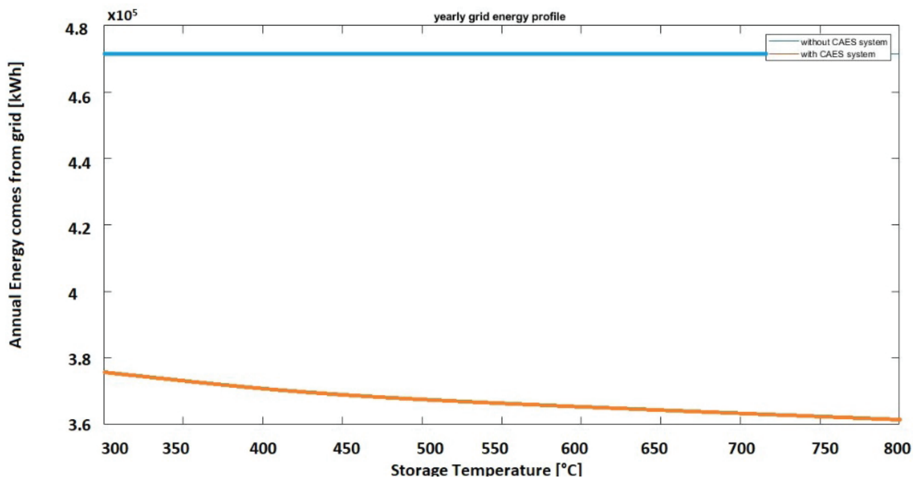

Figure 11. The influence of storage temperature on the energy profile.

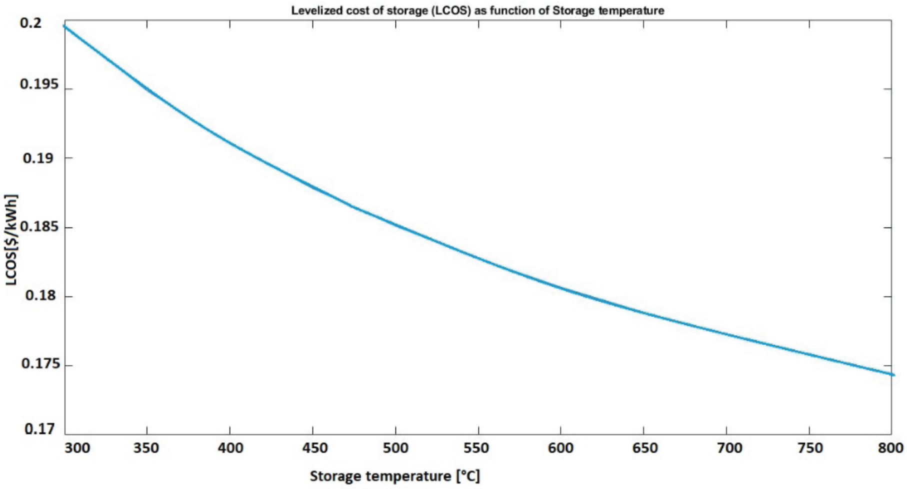

Figure 12. The influence of storage temperature on the LCOS.

Ambient Temperature Effect

In this section, the effect of ambient temperature is studied on different system parameters, including air mass flow at the inlet and outlet of the storage volume, the volume of storage that the underground cavern can accommodate based on the extra energy produced by the PV solar plant and compressed as air through compression. Finally, the power output of the system and the overall efficiency are examined. The working parameters of compressor pressure and turbine pressure ratios are 3 and 0.5, respectively. These parameters are selected after several simulations because they yield the best output results. The results of the simulations are obtained using data provided by an anonymous company, data from solar and wind websites, and the equations cited in the method section.

It can be observed from Figure 13 that the air flow in decreases by 8.6103 kg/year for each 5 K° of increase in ambient temperature.

Conversely, the air mass flow out increases by 36 kg/year with an increase of 1 K° in ambient temperature. This indicates that ambient temperature has a more significant impact on the air flow at the inlet of the cavern compared to the impact at its outlet (Figure 14).

The volume of storage should follow the same evolution as the inlet air flow mass according to equation 16, as illustrated in Figure 15.

The energy output of the turbine should follow the evolution of the air mass flow output, and Figure 16 demonstrates that evolution.

Figure 17 presents the evolution of storage efficiency as a function of ambient temperature. It can be concluded that installing the CAES system in hot places has a positive

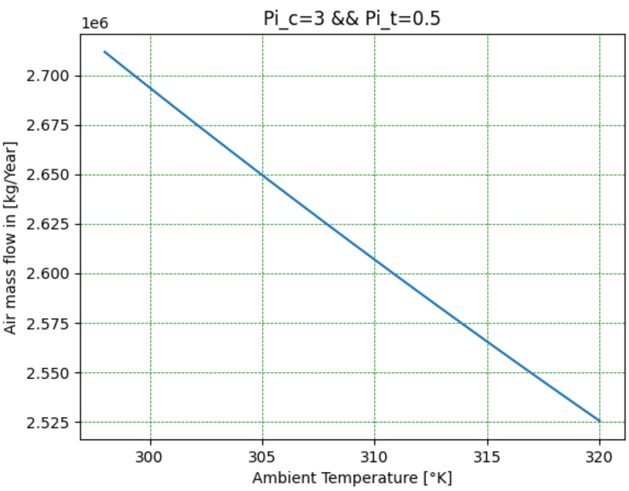

Figure 13. Effect of ambient temperature on the inlet air mass flow.

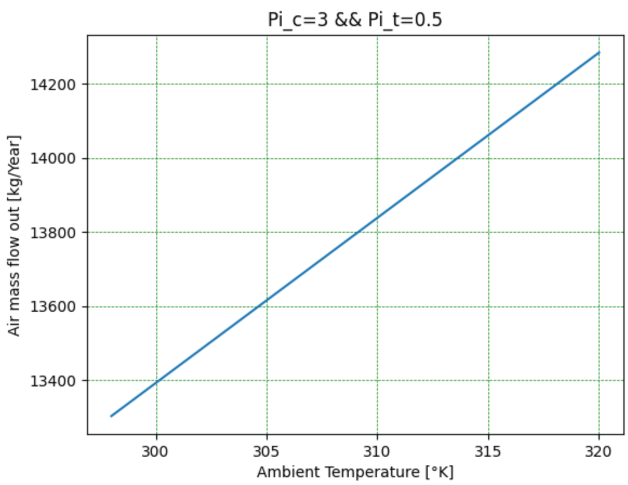

Figure 14. Effect of ambient temperature on the inlet air mass flow.

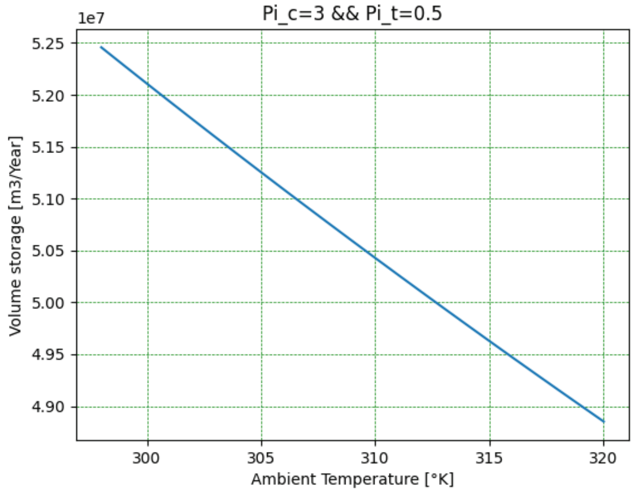

Figure 15. Effect of ambient temperature on the volume storage.

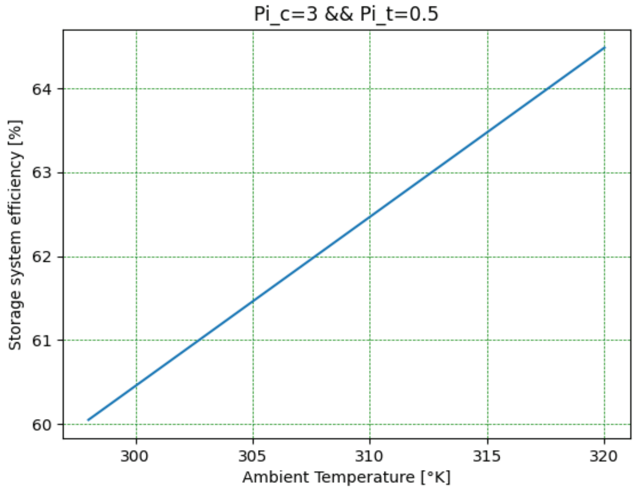

Figure 17. Effect of ambient temperature on the system efficiency.

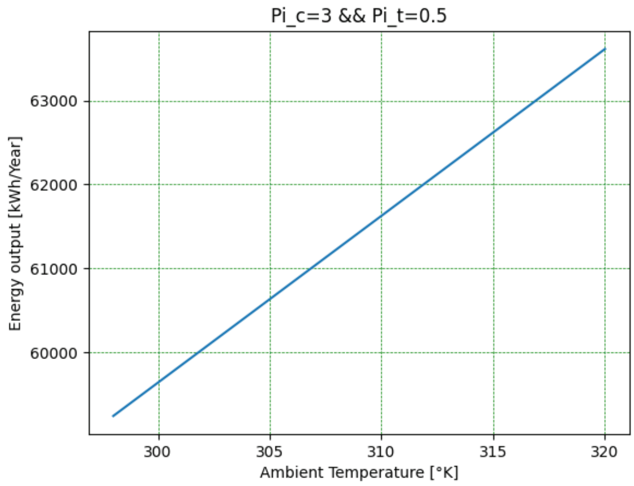

Figure 16. Effect of ambient temperature on the turbine power output.

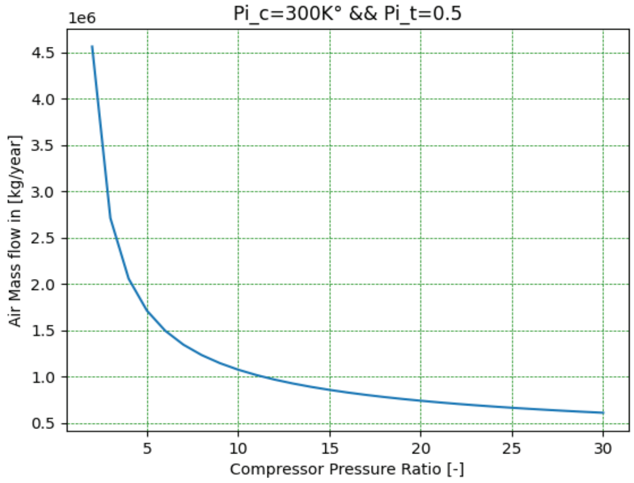

Figure 18. Effect of pressure ratio on the inlet air mass flow.

impact on the global efficiency, with the system gaining around 4% when the temperature increases from 25°C to 47°C. However, the highest temperature also has a negative effect on other parameters, such as the air flow mass at the inlet of the storage volume.

Compressor Pressure Ratio Effect

In this section, the effect of the compressor pressure ratio is investigated on the same system parameters studied before. The working parameters of ambient temperature and turbine pressure ratio are 300°K and 0.5, respectively.

These parameters are selected after several simulations because they yield the best output results.

Figures 18 and 19 illustrate that the mass air flow at the inlet and outlet of the storage volume follows a similar evolution. This similarity arises because both air flow masses

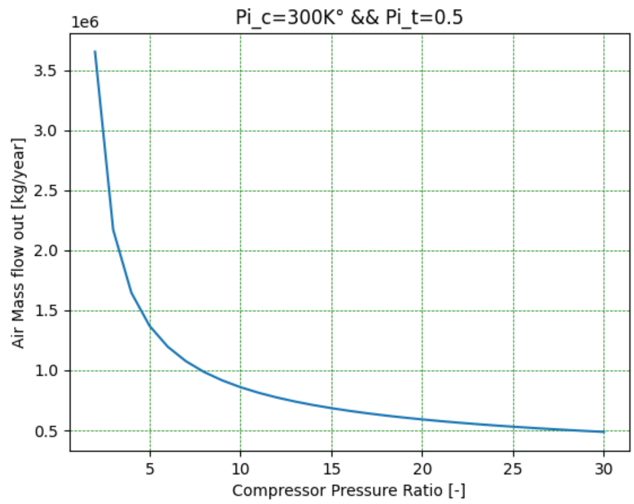

Figure 19. Effect of pressure ratio at the outlet air mass flow.

are influenced by the temperature ratio ($\frac{T_2}{T_3}$), and the pressure ratio affects the two temperatures in the same manner.

Figure 20 illustrates the evolution of air volume. The decrease in storage volume can be justified by its proportionality to the air mass flow at the inlet. Therefore, the volume of air stored must follow the same evolution as the inlet and outlet mass flow.

There is a significant decrease in the energy output of the turbine once the compressor pressure ratio reaches 5, as illustrated in Figure 21. Figure 22 shows the evolution of storage efficiency as a function of pressure ratio. It can be concluded that working with a high-pressure ratio lowers the CAES system efficiency.

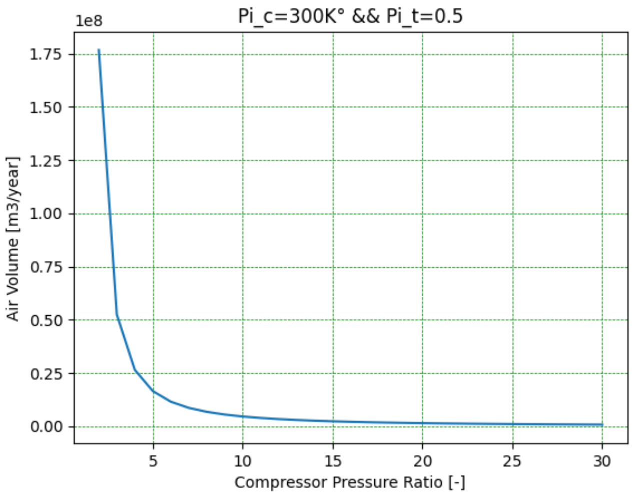

Figure 20. Effect of pressure ratio on the volume storage.

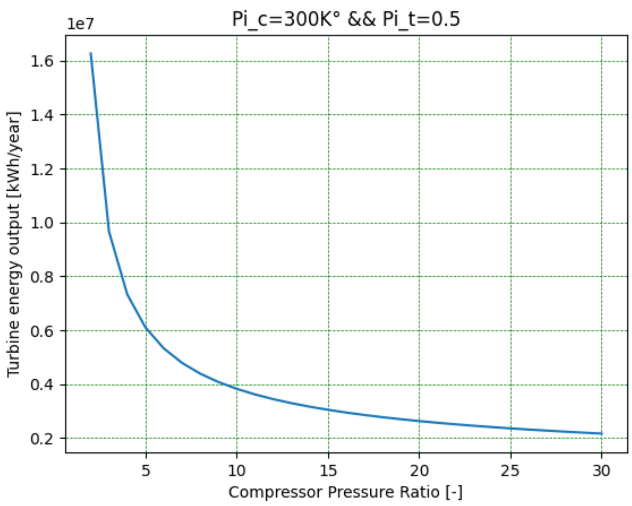

Figure 21. Effect of pressure ratio on the output turbine power.

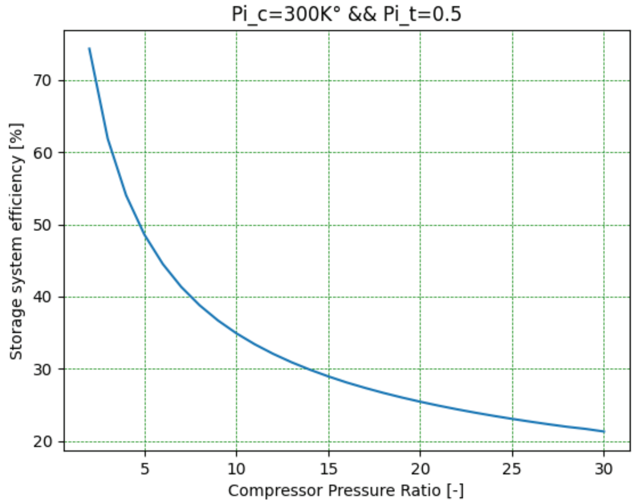

Figure 22. Effect of pressure ratio on the system efficiency.

CONCLUSION

This paper investigates the feasibility analysis of a hybrid system consisting of PV panels as the energy source, a water treatment plant as the load, and a compressed air energy storage as the storage system. The impact of air temperature storage on the levelized cost of storage and energy sourced from the grid was analyzed. The analysis also included the daily and hourly energy profile of the hybrid system and provides a comparison between the system with and without energy storage system according to the algorithm model mentioned in the method section. The analysis of other parameters that affect the performance of the hybrid system, such as the air storage temperature, pressure ratio and ambient temperature. The comparison of solar energy with wind energy as energy sources would provide an overview of which technology could reduce the levelized cost of energy or storage. Ultimately, the development of thermal storage systems could improve the efficiency of compressed air energy storage technology.

NOMENCLATURE

K	Function of pressure, -
T_0	The ambient temperature, K°
η_{turb}	Compressor efficiency, %
η_{comp}	Turbine efficiency, %
T_s	The storage temperature, K°
P	The gas pressure, Pa
V	The volume of the gas, m^3
n	The mass of the gas, kg
R_g	The ideal gas constant, J/(kg.K)
T	The gas temperature, K°
π_c	The compressor pressure ratio, -
η_{CAES}	System efficiency, %
W_{comp}	Compressor work, W
W_{turb}	Turbine work, W

v_{air} Air volume flow, m^3/s
ρ_{air} Density of air, kg/m^3
η_{PV} The Solar Panel Efficiency, %
G The Solar Irradiance, $kWh/(m^2 \cdot day)$
A The Panel Area, m^2
PR The Performance Ratio, -
NH The average number of sunlight hours per day, sunlight hours/day
O&M Operation and maintenance cost, \$/kWh
CAPEX Capital cost, \$

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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