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AN ALTERNATIVE SOLUTION BASED ON COMPRESSED AND LIQUEFIED AIR STORAGE SYSTEMS FOR REDUCING POWER OUTPUT VARIABILITY FROM PV SOLAR FARMS

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Abstract. *This work compares various compressed air energy storage (CAES) and Cryogenic Energy Storage (CES) systems as possible candidates to store energy from photovoltaic (PV) power plants with the goal to mitigate short-term voltage and frequency fluctuations due to cloud cover. Mitigating solar power variability and its direct effect on local grid stability is already a substantial technological bottleneck for increased market penetration of solar technologies in several communities around the world. In this context, forecast-assisted CAES and CES systems represent low-cost solutions for short-term variability that can be used to offset critical power ramp rates. We investigate the different thermodynamic and engineering constraints that affect the design of both CAES and CES systems. We show that CES systems provide more energy density; whereas CAES systems are more efficient in terms of capacity turnover. A combined system is proposed as a solution for short-term energy storage.*

Keywords: *Solar Variability, CAES, CES, Low-Cost Energy Storage*

1. INTRODUCTION

This work presents a discussion about different solutions for energy storage with the goal of mitigating solar power variability. There are different solutions for energy storage that have been under research such as Batteries (Zhu *et al.*, 2013; Singaravel and Daniel, 2013), Flywheel (Sebastian and Alzola, 2012), Pumped Hydroelectric Energy Storage-PHES (Margeta and Glasnovic, 2012), Capacitor (Mufti *et al.*, 2009), Superconducting Magnetic Energy Storage-SMES (Jin and Chen, 2012), Thermal Energy Storage (Kim *et al.*, 2013), Compressed Air Energy Storage-CAES (Safaei *et al.*, 2013; Raju and Khaitanb, 2012), and Cryogenic Energy Storage-CES (Ameel *et al.*, 2013; Li *et al.*, 2010b; Chen *et al.*, 2007) systems, just to name a few references.

Among the different solutions proposed, CAES and CES figure as two of the most important candidates, due to their large storage capacity, lower capital and maintenance cost, lifetime and environmental impact (Chen *et al.*, 2007). PHES is better than CAES and CES in terms of power output and duration as shown by Chen et al Chen *et al.* (2007), on the other hand, PHEs has ecological concerns and demands a huge amount of water during operation.

The first concept of CAES was conceived and patented during the 1940s and the first large scale plant was commissioned in 1978 (Giramonti *et al.*, 1978), in Huntorf, Germany, with the original idea of low cost energy storage during off-peak demand periods, permitting less fuel consumption than usual. The CAES process used in Huntorf can be described as follows:

1. The compressor is turned on using the surplus energy coming from a thermoelectric plant, during off-peak periods of demand;

2. Compressed air is stored inside underground tanks;

3. During demand-peak periods compressed air is reclaimed from the underground tank;

4. The reclaimed air passes through a combustion chamber before reaching the gas-turbine for expansion;

5. Energy is generated while air expands.

The combustion chamber is fuelled using natural gas, and this step is responsible for increasing the air temperature

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before the turbine, raising the process efficiency, but the quantity of gas used during this process is only one third the usual during normal operation of a gas turbine (Raju and Khaitanb, 2012).

The second CAES plant in operation was commissioned in 1991 in Mcintosh, Alabama. Both plants still in operation up today (Safaei *et al.*, 2013).

In terms of solar energy applicability, CAES original concept cannot be the same, one that it must not be combined with any fossil fuel cycle, instead of a combustion process for air heating it is used a thermal energy storage (TES) tank (this approach is so-called advanced adiabatic CAES, or AA-CAES); second that CAES has a different obstacle to overcome, mitigating solar power variability. Basically, the steps followed during a CAES applied for solar are:

1. The compressor is turned on using the surplus energy coming from a photo-voltaic plant, during over nominal power periods;

2. Compressed air is stored inside underground tanks;

3. Forecasting is used to detect ramp rates, and to determine the exact moment that the air will be recovered;

4. Air is reclaimed from the underground tank;

5. The reclaimed air passes through the thermal energy storage (TES) tank before reach the turbine for expansion;

6. Energy is generated while air expands.

The air receives a large amount of energy during the compression process expressed by temperature rising, and this energy can be stored using a static heat exchanger (TES), improving the process efficiency. The efficiency can reach 80 % if TES is combined with a compressor and a expansion train (Grazzini and Milazzo, 2008), comparing produced energy and spent energy. Solar heaters provide another good energy source for the TES. Kim et al. Kim *et al.* (2013) have suggested using CAES and PHES combination to reduce the efficiency deterioration due to the depressurization during the discharging process.

The first CES system is dated from 1900 (Akhusrst, 2013), when the Tripler Liquid Air Company was formed to design a liquid air fuelled car for competing with steam and electric vehicles of those days. During the oil crisis in the 1970s the interest in cryogenic cars returned, and also in the end of 1970s it was evident the interest on air liquefaction as an energy storage system (Smith, 1977).

Up today, hydrogen and air/nitrogen are two of the promising alternatives (Sander *et al.*, 2012; Li *et al.*, 2010b) for being used as CES working fluids. In the literature (Li *et al.*, 2010b; Chen *et al.*, 2007), the term CES (Akhusrst, 2013), or LAES, generally is used to refer to energy storage of liquefied air. Li et al. Li *et al.* (2010b) prompted a review comparing Hydrogen and Air/Nitrogen for energy storage, concluding that even with similar efficiencies liquefied air is more competitive as an energy carrier in terms of capital costs. Recently, Akhusrst Akhusrst (2013) has published a summary report about using liquid air in the energy and transport systems, indicating the important potential of CES for these areas. According to this report, CES is already under demonstration (development stage 2 of 3), while CAES as applied for solar is only under research (development stage 1 of 3).

The CES efficiency during the air liquefaction process is punctuated to be between 11 % to 50 % (Li *et al.*, 2010b) according to the plant size. During the conversion to electricity, there is a huge potential for wasting energy to atmosphere due to the cryogenic temperature, generating a lower efficiency (up to 40 %). Looking forward solving this problem Chen et al. Chen *et al.* (2007) generate a patent to improve the conversion process, indicating a considerable advance, reaching more than 100 % (taking advantage of solar energy). Ameel et al. Ameel *et al.* (2013) accomplished simulations using the arrangement proposed by Chen et al. Chen *et al.* (2007) and concluded that the combined cycle proposed is very sensitive to the heat exchanger, compressor and turbine efficiency, reaching a maximum efficiency of 43.3 % without using any external source of energy, and 63.7 % considering an isothermal expansion at 400 K.

CAES and CES are considered open cycles, since air does not go through all over the thermodynamic cycle, as occurs in Brayton's thermodynamics cycle. Another important similarity is the large amount of back work required, because of the employment of compressors. In these type of systems, the overall efficiency drops very rapidly with a decreasing in compressor, turbine or heat exchangers efficiency, as observed by Ameel et al. Ameel *et al.* (2013). Here, we are not doing any quantitative analysis of efficiency, because the energy employed in the compressor is provided by a surplus source of energy and it would be wasted otherwise; only a qualitative analysis will be presented.

Comparing CAES and CES with the other candidates for energy storage, there is only one drawback of using these first two technologies: the response time is relatively low (Akhusrst, 2013). For a small scale storage, it can be solved using a CES / SMES combination (Sander *et al.*, 2012). For solar application, forecasting should be used to determine the starting time exactly.

In the following sections the solutions will be discussed in greater details.

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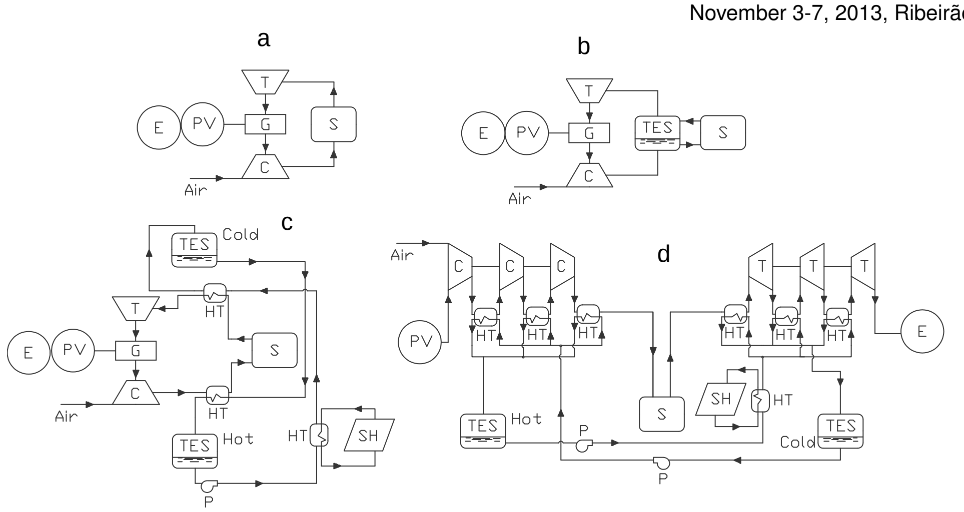

Figure 1. Schematic view of different CAES applied for solar energy (C = compressor, T = turbine, HT = heat exchanger, TES = thermal energy storage, S = storage tank, P = pump, SH = solar heater); (a) basic CAES, (b) CAES / TES, (c) CAES / TES with two tanks, (d) CAES / TES with compressor and expansion train.

2. CAES ARRANGMENTS

Fig. 1 (a) shows the basic form of a CAES system. The air compressor operates at high outlet temperature, and large amount of thermal energy gained by the air during the compression is wasted to the surroundings by natural convection inside the storage tank and in the piping, and as consequence of this fact the process has low efficiency. For a more efficient concept, it is necessary thinking about how to store the thermal energy wasted, and thermal energy storage (TES) appears to be a good and cheap solution for solve this problem. Fig. 1 (b) shows the basic CAES form complemented by a TES system. In this second approach, the thermal energy received by the air during the compression is stored in an insulated tank. This TES is constituted by a static heat exchanger, made with concrete and glass wool insulation (Steta, 2010); water is used as secondary fluid, but any fluid or solid with high heat capacity and density can be used; as an alternative for glass wool insulation, can be used any other similar low cost material. The efficiency is higher, but there is an additional cost due to the TES design. This system can be used for residential purposes by the high cost-benefit.

Using only one thermal tank can be ineffective because a high gradient inside the tank is needed to reach two completely different boundary conditions inside the tank: high temperature during the expansion (top side of the tank) and low temperature for storage (bottom side), and these conditions can be not totally reached. In many occurrences the air temperature arriving into the underground storage tank can be high, affecting adversely the process efficiency. Fig. 1 (c) presents a CAES / TES system using two tanks, one for the hot part and another one for the cold side, and a pump is used to connect them. In this version solar heaters are also used to improve even more the efficiency.

In order to reduce the compressor exit temperature and energy losses, for large scale processes is recommended using a train of compressors with heat exchangers inserted between each one for temperature decreasing and thermal energy storage. Fig. 1 (d) presents a CAES comprised by a compression and an expansion train and two TES tanks (hot and cold). It is the CAES solution to be applied in large PV solar plants, for example. The efficiency of the process increases when the number of compression and expansion stages increase, as shown by Grazzini and Milazzo Grazzini and Milazzo (2008), reaching 80 % of exergetic efficiency.

3. CES ARRANGMENTS

Fig. 2 (a) shows the basic form of a CES system. The liquefied air is reclaimed from a tank and pumped for the turbine using a cryogenic pump. During this process a large amount of energy is wasted to the surroundings by the air heat exchanger, and the efficiency is limited to about 40 %. In the scheme presented in Fig. 2 (a), liquefied air is provided from an external source.

Looking forward improving this approach, Li et al. Li *et al.* (2010a) proposed a combined system using CES and an expansion-Rankine cycle with propane, as shown in Fig. 2 (b). In this method the "cold" energy is not lost to the atmosphere as in the CES basic form (Fig. 2 (a)), it is transferred by the heat exchanger to the propane circuit, and afterward a turbine is used to recover this energy. Under ideal conditions the exergetic efficiency is up to 78 %. Another approach for taking advantage of the "cold" energy from the cryogenic tank was patented by Chen et al. Chen *et al.* (2007), and it can be schematically seen in Fig. 2 (c). At the same time that liquefied air is sent by a cryogenic pump from the tank to the turbine (expansion circuit), ambient air is sent back in a smaller proportion to the tank using a compressor; the compressed air passes through a heat exchanger to receive "cold" energy from the "expansion circuit" side, and following compressed air expands throw an expansion valve (Joule-Thomson valve) becoming liquid and entering into the tank (liquefaction circuit). If an external thermal source is used in the expansion circuit (heated water from a solar heater

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and/or compression process TES) the efficiency can reach more than 63 % Ameel *et al.* (2013), in which is very similar to the CAES efficiency. The liquefaction circuit side is essentially a liquefaction plant, but there is no net production of liquid because the recovering circuit mass flow is lower than the expansion circuit mass flow.

The liquefaction process used in this patented method was developed by Linde and Hampson (Sloane, 1900), so we are going to call it here as CES-Linde-Hampson method. The Linde-Hampson process is the simplest approach for liquid production, but it is a non efficient process and it requires a high pressure (20 MPa). A second approach more efficient for liquefaction is the Claude Method (Greenwood, 1919), comprised by a turbine for a parallel recovering, also increasing the production of liquefied air and working out at a lower pressure (4 MPa) and temperature. Fig. 2 (d) presents a CES-Claude approach. In this approach presented here, it is a self sufficient system that does not need any external source of liquefied air. The dashed line in Fig. 2(d) represents a circuit that is used just when liquefaction is the only current process. The by-passed air is under low pressure, and should be used in parallel with the high pressure circuit, during the recovering. The solution proposed (d) is a good solution in terms of solar plant, especially for remote locations.

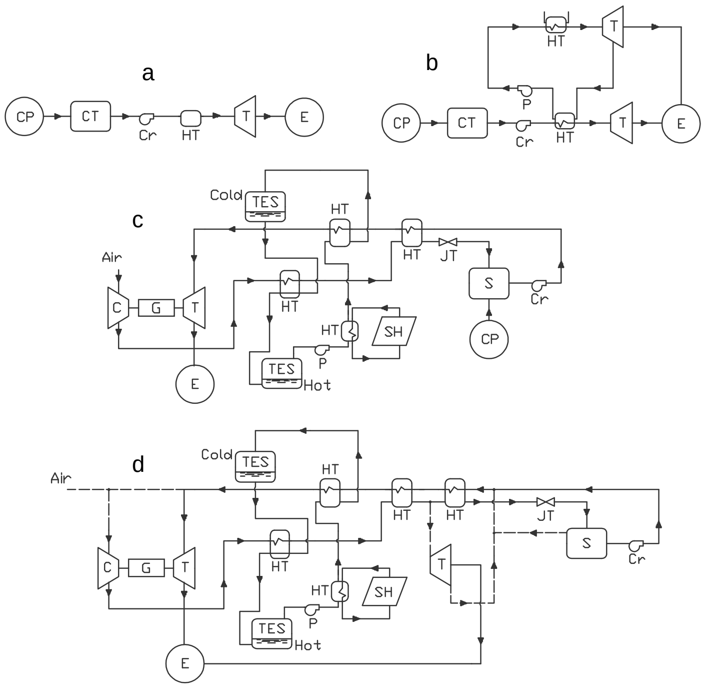

Figure 2. Schematic view of different CES applied for solar energy (C = compressor, CP = cryogenic plant, CT = cryogenic tank, T = turbine, HT = heat exchanger, TES = thermal energy storage, S = storage tank, P = pump, SH = solar heater, Cr = Cryogenic Pump, JT = Joule Thomson valve, dashed line = used if liquefaction is the only current process); (a) basic CES, (b) CES / expansion-Rankine-propane cycle, (c) CES-Linde-Hampson with recovering system Chen *et al.* (2007), (d) CES-Claude with recovering system.

4. CAES / CES solution

CAES and CES have different characteristics that make them attractive to work in the same circuit during the storage and recovering. Following will be shown a discussion regarding specific aspects of CAES and CES.

4.1 CES Self-pressurization and CAES depressurization

To validate the CAES model, an experiment was carried out using a 1/2 hp air compressor and a 1 gal tank for determining the characteristics during the discharging. Fig. 3 presents a comparison between the results obtained using the experimental apparatus and the work expected considering an efficiency of 70%.

The model used to predict the pressure decreasing works with good accuracy; only initial conditions were used for feeding the model. These model will be used later during the simulations.

As discussed before, one of the drawbacks in CAES is that during the recovering process is observed pressure decreasing inside the storage tank (Kim *et al.*, 2013). It was observed that the pressure decreasing has a representative impact on the work generated (Fig. 3), as expected.

On the other hand, one of the most difficult obstacles in CES is the self-pressurization inside cryogenic tanks Thomas *et al.* (2011). Fig. 4 presents a graph indicating the pressure increasing for a closed mass control system (with fixed

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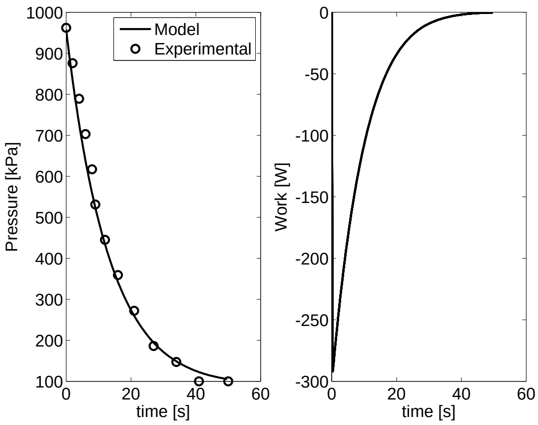

Figure 3. Left, pressure measurements during the discharging process of a CAES system and model validation; right, calculation of the work generated during the discharging process of a CAES system, considering an isothermal expansion.

density), when the temperature increases. This graph was plotted using the state equations for the air provided by Lemmon et al. Lemmon *et al.* (2000)

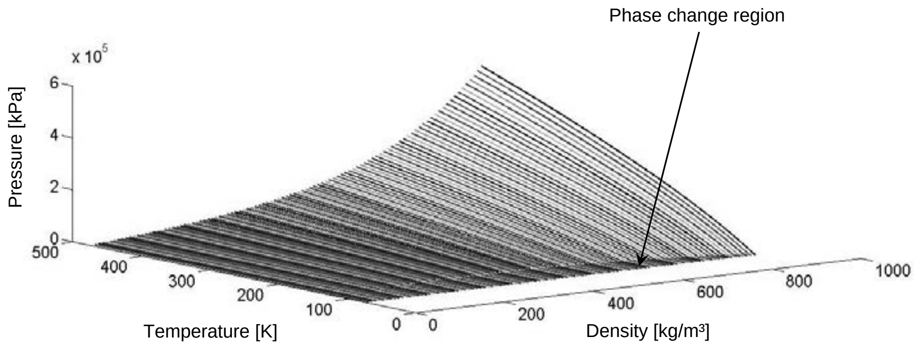

Figure 4. Self pressurization in function of temperature for fixed densities, it was considered the same temperature in all points inside the tank.

As consequence of these both concepts, it is possible using the quality of CES for self-pressurization for improving the CAES pressure decreasing during the discharging.

4.2 Energy density, energy storage rate and cool-down time

CAES has approximately 37 times (660 over $18 MJm^{-3}$) more energy density than CES Ameel *et al.* (2013), considering the same conditions during the recovering process. Due to the relatively small energy density, CAES system needs a larger storage tank at high pressure, and this explains why salt caverns are used as solution for storage; a CAES tank can be costly and not viable. Instead of CAES, CES system has a larger energy density at low pressure, which makes CES more attractive for energy carrier.

But CAES is not necessarily worse than CES in terms of energy storage rate. To prove this, consider 3 different ideal systems using the same tank size ($1\ m^3$): CAES, CES-Claude and CES-Linde-Hampson systems. Also, consider a hypothetical situation in which the compressor volumetric flow rate is $1\ m^3 s^{-1}$ for all systems (same output conditions). Claude liquefaction rate will be 0.14 m^3/s and Linde-Hampson 0.08 m^3/s; it is necessary 7 times (1 / 0.14) more time to store the same volume in a CES-Claude system, and 12.5 times (1 / 0.08) in a CES-Linde-Hampson, when compared with CAES system. CES-Claude would have 94.3 $MJ\ s^{-1}$, CES-Linde-Hampson 52.8 $MJ\ s^{-1}$ and CAES 18 $MJ\ s^{-1}$ energy storage rate. Considering that CES is subject to more losses due to the lower temperature than CAES, the order of magnitude in terms of energy storage rate will be similar for CAES and CES.

Another important consideration is regarding the cool-down time; Chou et al. Chou *et al.* (1995) for example accomplished several tests for Joule-Thomson cryocoolers and found a cool-down time of 25 seconds for a 20.69 MPa of compressing pressure. For solar application, where the variability will require a fast transient response, this cool-down time will play an important role for determining the process efficiency.

Focusing on PV solar plants and considering the above mentioned, CES system presents good features for long-time

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storage, because it has more energy density at lower pressure, and CAES can be used as short-term storage, mainly during cloudy days because of the faster transient response.

4.3 CAES / CES basic design

Fig. 5 presents a new method for energy storage, combining CAES and CES systems. Comparing this approach with Fig. 2 (d) is difficult to realize the difference between both designs; the only visual modification is the addition of another tank, the CAES tank, but the conceptual idea is completely different. This solution allows different operational processes. A simplified control algorithm is also presented for this system (Fig. 6) considering a cloudy day and a clear sky day; one example of the basic operations is described below for a cloudy day:

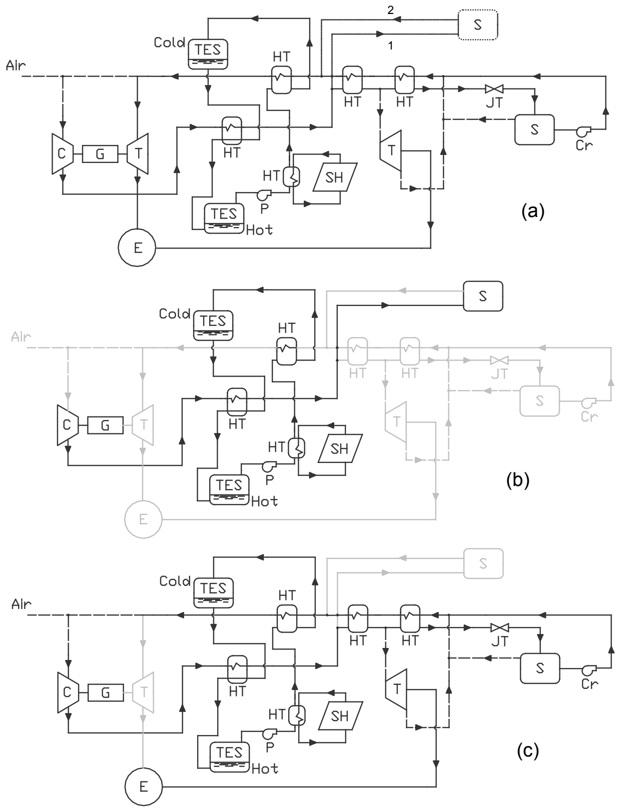

Figure 5. (a)Schematic view of different CAES / CES-Claude; (b) Schematic view of different CAES / CES-Claude, highlighting the CAES; (c) Schematic view of different CAES / CES-Claude applied for solar energy, highlighting the CES; (C = compressor, T = turbine, HT = heat exchanger, TES = thermal energy storage, S = storage tank, P = pump, SH = solar heater, Cr = Cryogenic Pump, JT = Joule Thomson valve, dashed line = used if liquefaction is the only current process); proposed method.

1. Surplus energy from the PV solar plant turns the compressor on, and the compressor feeds the CAES tank; only a part of the circuit operates, see Fig. 5(b);

2. Afterwards, if energy is not required by the recovering system and the CAES tank is fulfilled, the CES system starts to liquefy the air; only a second part of this circuit operates, see Fig. 5(c).

3. During the recovering all parts of the system works out, but in a new way; instead of using the line number 1 to store energy from the CAES system, it is used for increasing the pressure during the discharging process using the cryogenic circuit. The valves were not represented for simplification (Fig. 5(a)).

As an alternative approach, the control algorithm can be inverted for cloudy days; the liquefaction plant starts to operate storing liquefied air; during the self pressurization phenomenon, liquid can be transferred to the CAES tank; if both tanks are full, energy should be generated without using any forecast.

Plants in current operation can be adapted for using this solution, for example: using a small CES tank is possible improve a CAES plant in terms of depressurization during discharging. CES plants used for renewable resources, as solar, should also be analyzed for using CAES as a back up source of energy, since there is a low cost involved in the

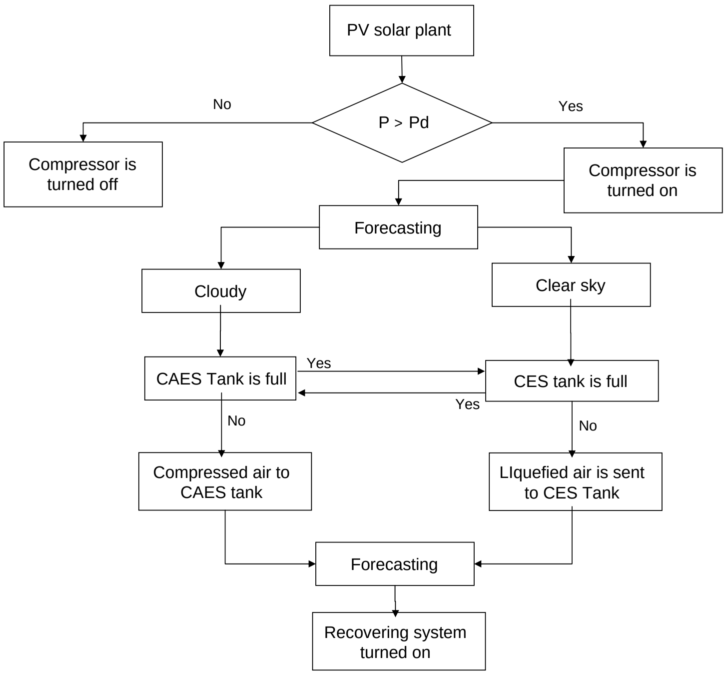

Figure 6. Basic control algorithm to work with the new proposed CAES / CES system (P = Power, Pd = minimum surplus power).

construction of the additional parts, providing a good solution during cloudy days. Other benefit of this approach is the possibility of maintenance in parts of the circuit without stopping the other one.

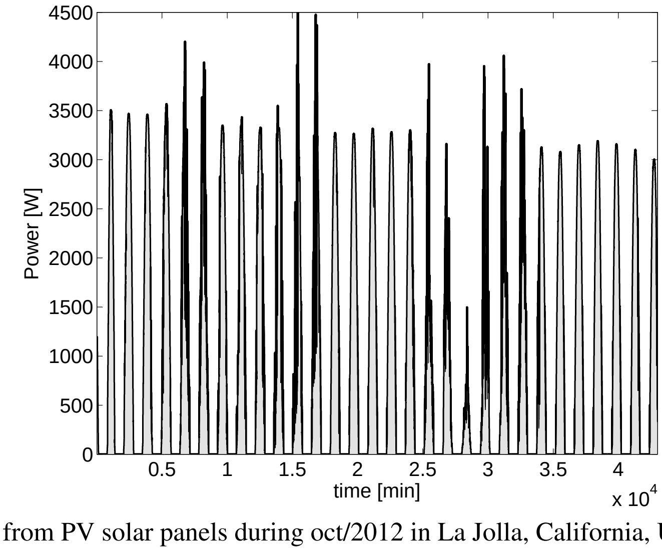

Figure 7. Power provided from PV solar panels during oct/2012 in La Jolla, California, USA, for a time step of 1 minute

4.4 CAES / CES simulation

Following will be briefly presented a CAES / CES simulation using the methodology shown in this work. Consider a PV solar power plant with peak capacity of 4500 W that provides 1500 W of power output for a determined application. Fig. 7 presents a month of data from october/2012 of La Jolla, San Diego. The time step is 1 minute. A CAES / CES system (see Fig. 5) is working integrated with PV solar panels, as presented by the algorithm presented in Fig. 6. The compressor used is a 2.4 kW, volumetric flow of 4.3 cfm and 4MPa of peak pressure. The CAES tank is a 10 gal of volumetric capacity and the CES tank is a 1 gal. The CAES discharging time calculated is 4 minutes, generating an average of 400 W at 70% of efficiency.

Looking at Fig. 7 there is a period of time with predominance of cloudy days and some clear days. During cloudy

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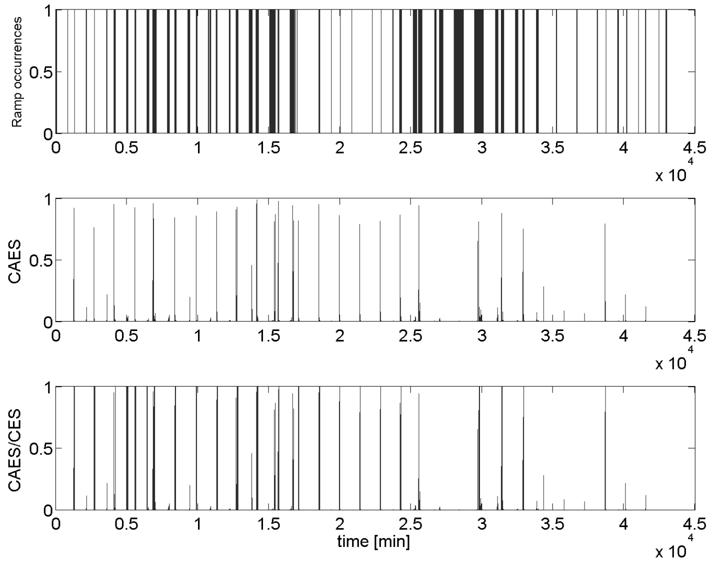

Figure 8. Top: ramp rates occurrences below the minimum provided power of 1500 W normalized to the unity; middle: CAES discharging occurrences, normalized per event by the maximum of 400 W of providing energy; bottom: CAES / CES discharging occurrences, normalized per event for 400 W

days, it was observed ramp rates occurrences below 1500 W; at the moment of these ramp rates, the system will discharge compressed air generating power. The number of ramp rates occurrences are presented in the top side of Fig. 8, and for each one event the power required is normalized for the unity. The middle graph in Fig. 8 is presenting the occurrences considering that only a CAES system would be operating, and each one event normalized to the maximum capacity of 400 W provided. The bottom graph in the Fig. 8 is representing the number of occurrences for the case in which the CAES / CES system is operating.

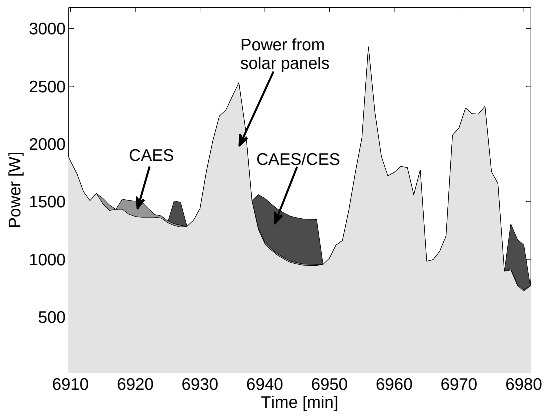

Figure 9. Simulation presenting CAES and CAES/CES working during a ramp rate demand

It is possible to notice that there is a considerable increasing in the number of occurrences and in the magnitude of these events for the CAES / CES simulation. This difference is due to the fact that the capacity of CAES for storing energy is rapidly saturated, and it not occurs with CES. During high variability days, CAES system works for more events than CES system because of the algorithm used (Fig. 6); the CAES has a faster response during transient time, and should be preferred in this situation.

The number of occurrences will be different if the output power is more or less than 1500 W. During the basic project design, the designer should optimize the system to verify the actual improvement of using it.

Fig. 9 presents a simulation for CAES and CAES/CES during a ramp rate demand, considering that both systems are working separately with the solar panels. It is more evident that CAES works out during a lower range time than CAES / CES, and the power provided by CAES/CES is higher. This difference in intensity can be seen also in the Fig. 8.

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5. CONCLUSION

In this paper alternatives for short-term storage are discussed for mitigating PV solar variability. Today, there is a currently discussion about which energy storage system provides the best solution for renewable sources and a combination of CAES and CES is proposed as a new concept.

A basic control algorithm is presented to the proposed method, and using this one the CAES / CES system generates a larger number of recovering occurrences than CAES, also with higher intensity.

An optimization is required during the basic design phase to determine the cost-benefit of using this system for the plant's operational conditions, defining basic characteristics such as tank size, mass flow, power and range time, which it is not the scope of this work.

The low cost for converting a CES plant in a CAES / CES plant should be considered in renewable plants with large intermittency, as solar plants. Also CAES / CES system can be used to improve the CAES depressurization during discharging; other benefit is the relatively long-term storage of CES, using less space than the natural caverns used for CAES.

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