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Practical Considerations related to a Large-scale Electricity Storage System using Transcritical Carbon Dioxide

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1. Introduction

1.1 Contextualization

Nowadays, the energy and its supply have become a critical challenge as resources are becoming scarcer. In particular, renewable energies have attracted more and more attention over the past years due to global warming concerns. Social pressure against conventional sources of energy such as nuclear plants also explains the raise of these environmentally friendly energies. However, given their intrinsically variable, unpredictable and thus unreliable nature, these energies cannot meet the energy demand alone. Therefore, new solutions need to be proposed to both ensure a safe and reliable energy supply while answering the aforementioned social expectations. The large-scale storage of energy is a very promising option, which has already been under investigation for many years. Indeed, the first Pumped Hydro Energy Storage system (PHES) was built in 1929 in the United States. Nowadays, PHESs and the Compressed Air Energy Storage systems (CAES) are the most mature and thus widely implemented technologies to store electricity on a large scale [1]. However, these two technologies suffer from serious drawbacks, such as the high site-dependency and the large initial costs. One possibility to avoid these drawbacks lies in the thermal conversion of electricity [2].

1.2 Presentation of the system under consideration

Pumped Thermal Energy Storage systems (PTES) are one kind of storage systems based on an electrical-thermal conversion [2]. In most PTESs, a working fluid follows a thermodynamic cycle clockwise to convert electricity into latent or sensible heat, which is then stored in a hot tank. Following this cycle anticlockwise enables to retrieve later the initially supplied electricity with a certain round-trip efficiency (RTT). Using a gas led to a very poor RTT (~6%) [2], while transcritical carbon dioxide (tCO2) shows a much higher potential. Indeed, Mercangöz et al [3] used tCO2 and managed to reach a 53% global efficiency for a 1MW power plant. Their choice for this working fluid is motivated by the excellent thermo-physical properties of tCO2. As for the storage medium, Mercangöz et al. [3] proposed to take water given its great economic, physical and environmental properties. Their set-up is introduced in Fig.1 and will be under consideration in this study.

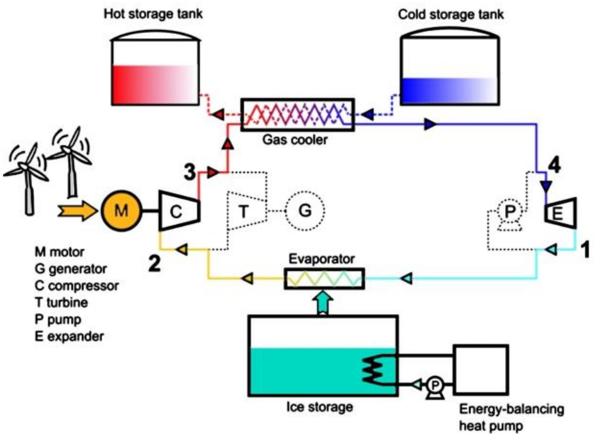

Fig. 1. Set-up used for the charging phase as suggested by Mercangöz [3]

1.3 Aims of the present study

Unlike previous studies, this work focuses on practical considerations to investigate the feasibility of this PTES. Moreover, it also aims at providing key figures to assess the potential of this technology.

2. Method

This second section starts with the method used in this study. This method is applied to develop a Python code that is then presented, before it is validated in the last part of this section.

2.1 The design-criteria based method

For this research, a methodology widely employed in materials engineering was chosen, namely the design-criteria method. According to this method, one or several criteria are first selected. Then, calculations are run to design a material, which is finally produced and tested to verify if its characteristics meet these criteria. This method is of particular interest because it is much better than simply guessing.

Regarding this technology, since it should compete with PHES and CAES, the criteria are the following [2,3]:

- ✓ An overall efficiency of at least 65% ;
- ✓ a work output of at least 10MW ;
- ✓ the total cost of the set-up should be at most equal to the one of the PHES and CAES.

Besides, using carbon dioxide and water enables to overrule any potential environmental concerns. With the aforementioned criteria, the following code was designed.

2.2 Presentation of the Python code

Based on the description of the set-up provided by Mercangöz et al. [3], a Python code was developed. It is coupled to the latest version of the REFPROP database in order to provide all the physical parameters necessary for the thermodynamic analysis. This database was chosen as it belongs to the most accurate ones. The working of this code has already been described [4]. In a nutshell, seven input parameters are given for the charging phase, which are either physical parameters - the minimum pressure- or industrial parameters that characterize the turbomachinery -isentropic efficiencies, pressure ratio and pressure drop. A similar routine also applies for the discharging phase. The calculations are then run to reach a RTT and a work output that are initially set as targets. Regarding the total cost of a set of input parameters for the charge and the discharge, it is evaluated afterwards and compared to those of the PHES and CAES technologies.

2.3 Validation of the code

To validate the previously introduced code, a literature survey was conducted to find articles related to this PTES and which precise each physical state of the charge and the discharge. To the knowledge of the authors, the work of Mercangöz et al. [3] is the only one that fulfils these two requirements. Therefore, given the input parameters from their work, all the physical states of the charge and the discharge were calculated with our code. Then, our results were compared to those they had obtained. Table I summarizes both our results and the ones from [3] for the charging phase. In Table I, both the pressures and temperatures of the four states are presented since only two input parameters are needed when using the REFPROP database.

Table I : Comparison of the results with our Python code and those obtained by Mercangöz et al. [3]

State	Pressure in bar ([3])	Pressure (this study) in bar	Error (%)	Tempe-rature ([3]) in °C	Tempe-rature (this study) in C°	Error (%)
1	32.4	32.4	0	-2.8	-2.73	2.5
2	32.2	32.2	0	-3	-2.96	1.3
3	140	140	0	122.3	121.9	0.33
4	139.4	139.14	0.2	13.5	13.55	0.37

As for the three first pressures, no deviation is noticed because the same pressure ratio and the same pressure drop were used as in [3]. However, the final pressure at state 4 is slightly different from the one of [3] because this pressure was deduced from the entropy and the enthalpy of CO2 at state 4 thanks to the REFPROP database. Regarding the discharge, similar results were obtained. Overall, a maximal deviation of 2.5% was observed, which is mainly due to the approximations induced by the coupling of Python and the REFPROP database. Thus, it can be inferred that this code is valid and can be further employed.

3. Results

This section addresses the need for practical work, given that a solid theoretical background already exists [3]. Three considerations are herein proposed : a potentially limiting factor for the construction of this PTES, its total cost and an estimation of its size.

3.1 The mass flow rate of the working fluid as a potential industrial limitation

Firstly, as the RTT is always smaller than the unity, the amount of heat transferred during the discharge is smaller than the one during the charge. Therefore, the mass flow rate of CO2 during the charge is higher than the one during the discharge. Moreover, it appears from [3] that the mass flow rate of water is smaller than the one of CO2 for both phases. Consequently, the attention is focused in this section on the relation between the necessary mass flow rate of CO2 for the charge and the work output. The physical parameters are the same as in [3]. Regarding the first criterion introduced in section 2.1, i.e. the RTT, it takes four values : 65%, 70%, 75% and 80%. In case of the second criterion, namely the work output, it is varied from 10MW up to 1GW. These values of the RTT and the work output are chosen as they characterize the PHES and CAES technologies [2]. For each one of these values of work output, the necessary mass flow rate is computed. The results are reported on Fig. 2. In a seek of comparison, three values of typical industrial mass flow rates are added on the graph.

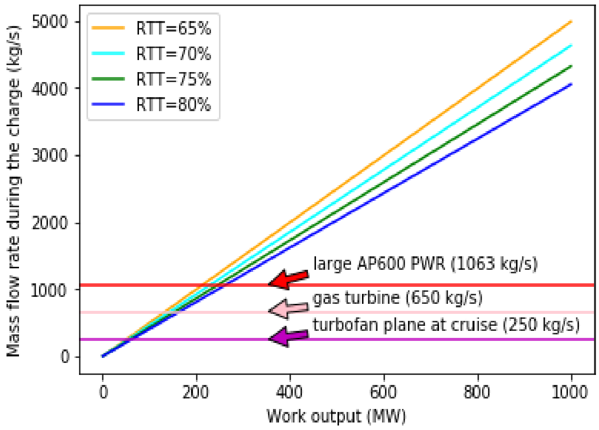

Fig. 2. Mass flow rates of the working fluid during the charge against the work output for different RTTs

We choose the mass flow rate of a large AP600 PWR (~1063kg/s) for a maximum reachable mass flow rate. Thus, he maximum work output of a PTES under the conditions of [3] is approximately 200MW. Consequently, when only considering the RTT and the work output, it follows that this PTES is able to compete with the CAES and with some PHESs.

3.2 The total cost as a function of the work output

Secondly, it is of particular interest to evaluate the costs of this technology. In particular, the increase in costs when increasing the work output is estimated here. The cost evaluation has already been lengthily described [4]. To summarize, the cost of each component of the set-up is calculated with the following procedure :

i) estimation of the purchase price of the component Cp ;
ii) estimation of its pressure factor Fp ;
iii) estimation of the corrected pressure factor Fp,c to account for the chosen material ;
iv) the total equipment cost of the component is thus deduced by multiplying Cp and Fp,c [4].

The total cost of the set-up is then calculated by summing the cost of each one of its components, before the Levelized Cost Of Electricity is obtained thanks to (1) :

$$LCOE = \frac{C_{TCI} + \sum_{p=1}^{n} \frac{C_{TPC}}{(1+i)^p}}{\sum_{p=1}^{n} \frac{M_{el}}{(1+i)^p}} \quad (1)$$

The LCOE is a crucial parameter since it enables the comparison of electricity producing systems on a coherent and consistent basis. In Equation (1), C_{TCI} refers to the Total Capital Investment Cost, C_{TPC} the Total Production Cost, M_{el} the annual electricity generation, i the annual interest rate taken to be 7% and n the economic lifetime of the PTES, which is supposed to be 20 years.

The two first costs are functions of the total cost [4], as expressed in (2) and (3) :

- ✓ $C_{TCI} = 1.4278 * C_{tot}$ (2)
- ✓ $C_{TPC} = 0.13 * C_{tot}$ (3)

The annual electricity generation is a function of the annual operating hours and of the work output, as described in (4) :

$$M_{el} = 0.9 * 365 * 24 * \dot{W}_{net}^{elec} \quad (4)$$

Consequently, Equation (1) becomes :

$$LCOE = 0.00036 * \frac{C_{tot}}{\dot{W}_{net}^{elec}} \quad (5)$$

The conditions of validity of the previous equation are :

- No cost of land : a PTES can be built in the controlled area of a nuclear power plant, that is left free by law;
- No royalties or working capital cost [4] ;
- The total cost of the working fluid ($0.00835/kg for CO_2) and the storage medium ($0.0005/kg for water) is negligible, which is the case here.

Using Equation (5) and the physical data from [3], the LCOE of the PTES is evaluated and displayed on Fig.3 as function of the work output. This work output is comprised between 1MW and 200MW since the previous section highlighted this maximum admissible value for the work output. The LCOE was computed for a 53% RTT as in [3].

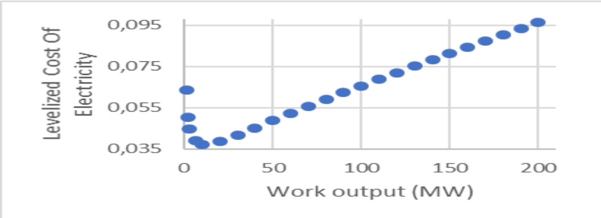

Fig. 3. LCOE against the work output

This last figure shows a certain work output for which the LCOE is minimum. This behaviour was also observed for other roundtrip efficiencies. However, the work output leading to a minimum LCOE is quite low, of the order of magnitude of a few MW. Besides, it is particularly relevant to compare the LCOE of this PTES with the ones of the PHESs and the CAESs. Typical LCOEs of for these two technologies are summarized in Table II.

Table II : LCOE of the PHES and the CAES

Technology	LCOE ($/kWh)
PHES	0.188-0.274
CAES	0.192

From the previous table, it appears that this PTES shows exhibits a lower LCOE than the two other large-scale existing technologies. This is very promising since the PHES and the CAES can store more electricity. Indeed, if this system can actually store more than 200 MW, it will be able to compete with the PHES and the CAES without presenting their main drawbacks.

3.3 Preliminary calculation for the sizing

Finally, this section tackles the sizing of the PTES described in [3]. Among its several components, the two tanks containing the storage medium appear to be the unwieldiest ones. Therefore, estimating their size enables to have a first idea of the total size of the set-up. Their size is directly linked to the amount of heat stored. For mass flow rates ranking from 1MW up to 200MW and a 70% RTT, the following correlation for the heat stored was obtained :

$$\dot{Q}_{stored} = 6.0606 * \dot{W}_{out} \quad (6)$$

Knowing that approximately 45 liters of liquid water can store 1kWh of energy, Eq. (8) gives the tanks volume in m3 needed to retrieve the work output $\dot{W}_{out}$ (kW) with a 70% RTT :

$$V_{tanks} = 0.067 * \dot{W}_{out} \quad (7)$$

Thus, the total volume of the two tanks is 6700 m3 in order to retrieve a 100MW work output from this PTES with a 70% RTT.

4. Conclusions

This paper addressed the need for practical considerations in order to have a first insight on the design, feasibility, potential and design of a new PTES. Throughout this study, it appears that this system is limited by the CO2 mass flow rate of the charging phase. However, this PTES can certainly compete with CAESs and with small-size PHESs. Moreover, economic considerations have also been raised, especially the evaluation of the LCOE, which happens to be close to the ones of PHESs and CAESs. As for the design of this set-up, the volume of water tanks has also been evaluated in order to estimate the size of the whole set-up.

Since the system introduced in [3] is a priori not optimal, further work should include an optimization part. This would enable to draw conclusion on the potential of this PTES to compete with PHESs.

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