Inclusion of CO2 Transcritical Heat-Pump and Power Cycles in a Massive Electricity Storage System

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Abstract: Multi-megawatt thermo-electric energy storage based on thermodynamic cycles is a promising alternative to PSH (Pumped-Storage Hydroelectricity) and CAES (Compressed Air Energy Storage) systems. The size and cost of the heat storage are the main drawbacks of this technology but using the ground as a heat reservoir could be an interesting and cheap solution. In that context, the aim of this work is i) to assess the performance of a massive electricity storage concept based on CO2 transcritical cycles and ground heat exchangers, and ii) to carry out the preliminary design of the whole system. This later includes a heat pump transcritical cycle as the charging process and a transcritical Rankine cycle of 1 – 10 MWe as the discharging process.
A steady-state thermodynamic model is realized and several options, including regenerative or multi-stage cycles, are investigated. In addition preliminary transient simulations are performed. The first transient results show that the nominal efficiency is not obtained during the entire process. However substantial efficiency increase can be gained by using regenerative heat exchangers and two-phase and two-stage expanders.

1. Introduction

Thermo-electric energy storage (TEES) is a promising alternative to existing technologies that would allow widespread and large-scale electricity storage. It has a high energy density and is independent from geological or geographical constraints. During periods of excess electricity generation, a vapor compression heat pump consumes electricity and transfers heat between a low-temperature heat source and a higher temperature heat sink. The temperature difference between the heat sink and the heat source can be maintained for several hours, until a power cycle is used to discharge the system and generate electricity during peak consumption hours.
Mercangöz [1] gave references of thermo-electric energy storage studies as old as 1924 and described the general concept of this technology, based on two-way conversion of electricity to and from heat. He stated that the main challenges of TEES are to closely match the heat source and heat sink with the working fluid, and to find an optimum between roundtrip efficiency and capital cost. He analyzed a TEES system with transcritical CO2, hot water and ice as storage materials. The ABB Corporate Research Center [8-9] described a way to store electricity using two hot water tanks, ice storage and transcritical CO2 cycles. For similar systems, Morandin [10-12] defined a design methodology based on pinch analysis and calculated a 60% maximum roundtrip efficiency with turbomachinery efficiencies given by manufacturers.
Sensible heat storage with hot water tanks is often considered, since water has high thermal capacity, is very cheap and environmental-friendly. Latent heat storages based on phase change materials (PCMs) have also been widely investigated. The heat sink of the system can be either the ambient or ice. This second option ensures a constant low-pressure for the process that is favorable to turbomachines. A mixture of salt and water can be used to adjust the heat sink temperature between 0°C and -21.2°C (corresponding to the eutectic point with 23.3% of NaCl in the mixture) [10].
Different working fluids can be considered for the cycles. Desrues [13] presented a TEES process based on Argon in forward and backward closed Brayton cycles. Henchoz [13] analyzed the combination of solar thermal energy with TEES based on Ammonia cycles. Kim [14] reviewed current TEES systems and showed that using CO2 cycles instead of Argon Brayton cycles leads to a higher roundtrip efficiency even if the required temperature difference between the heat storages is much smaller. He also proposed an isothermal storage system based on CO2 cycles and liquid piston compressors/expanders. In parallel, underground thermal energy storage appears to be an attractive solution [15].

The purpose of this article is to introduce a new type of electro-thermal energy storage process for large scale electric applications, based on CO2 cycles and ground heat storage. The design of the TEES system is addressed here only from an energetic point of view and economic analysis are left for future works.

2. Thermodynamic cycle description

The investigated electro-thermal energy storage system is a massive storage concept that includes:

i-a hot reservoir made of a set of ground heat exchangers in a low diffusivity rock;

ii- a cold reservoir using either ice ($T_{cold} \leq 0°C$) or a phase-change material ($T_{cold} > 0°C$);

iii- two thermodynamic cycles both using carbon dioxide as a working fluid

All the components of each process are considered as open systems in steady state. The thermodynamic model is implemented in the Engineering Equation Solver (EES) software [16]. A detailed model has been developed and is extensively described in previous papers [17-18]. As a preliminary work, pressure losses are neglected. Simulation of the ground heat storage system will enable to estimate losses in that component and adjust cycle parameters.

During the off-hours, the charging process consists of a transcritical heat pump cycle characterized by 6 main steps: the working fluid leaves the cold reservoir heat exchanger as a saturated vapour at $T_1 = T_{cold} - \Delta T_{min}$ and is internally superheated ($1 \rightarrow 2$) through a regenerator with a 5K pinch, before being adiabatically compressed ($2 \rightarrow 3$) with a mechanical compressor with isentropic efficiency of 0,85. At the compressor outlet, the fluid at $T_3 = (T_{hot})_{max} + \Delta T_{min}$ and supercritical high pressure P_3 is first cooled through the hot reservoir exchangers ($3 \rightarrow 4$) releasing heat to the ground, then subcooled through the regenerator ($4 \rightarrow 5$) releasing heat to the first flow. The fluid at a liquid state passes into an expansion valve ($5 \rightarrow 6$) to reach the low pressure and is evaporated through the cold reservoir exchanger ($6 \rightarrow 1$).

During the peak-hours, the discharging process consists of a transcritical Rankine cycle characterized by 6 main steps: the working fluid leaves the cold reservoir heat exchanger as a saturated liquid at $T_1' = T_{cold} + \Delta T_{min}$ and is adiabatically compressed ($1 \rightarrow 2$) in a feed pump with isentropic efficiency of 0,8. At the outlet of the pump, the fluid at a supercritical high pressure P_2' is first preheated through the regenerator ($2 \rightarrow 3$) with a 5K pinch, then heated further through the hot reservoir exchanger ($3 \rightarrow 4$) destocking heat from the ground. At the entrance of the turbine, the fluid at a defined temperature $T_4' = (T_{hot})_{max} - \Delta T_{min}$ is adiabatically expanded ($4 \rightarrow 5$) to the low pressure delivering a mechanical work with isentropic efficiency of 0,9. Finally, the fluid is cooled in the regenerator ($5 \rightarrow 6$) before being condensed through the cold reservoir exchanger ($6 \rightarrow 1$).

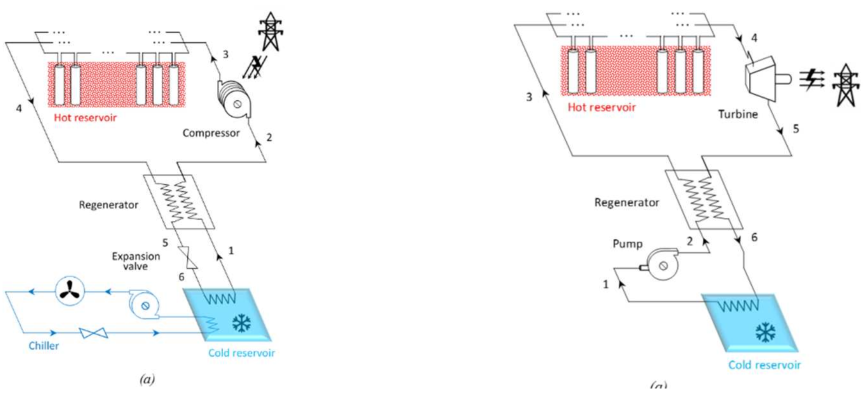


Figure 1: a) Charging process, b) Discharging process

3 . First results: Architecture Discussion

Based on the previous modelling, it is possible to carry out a parameter analysis of the system. Figure 2-a shows the efficiency of the system with respect to the temperature of the heat storages and architecture. It is possible to reach roundtrip efficiencies up to more than 50% with high storage temperatures and ΔT_{min}=1K, on condition that regenerator is used in heat-pump and ORC cycles. Detailed results can be found in [17]. In particular a very interesting configuration can be found in Figure 3-a. The value of ΔT_{min} has been discussed in an other paper [18]. Figure 2-a shows the interest of having an architecture with a two-stage turbine configuration of the ORC system. The parametric results allow the comparisons between non-regenerated and regenerated configurations. Up to 7% can be gained. We have also investigated the interest of having an architecture with a two-phase turbine configuration in the heat-pump system instead of the valve. A value of 75% of isentropic turbine efficiency has been chosen as an achievable goal. The parametric results allow the comparisons between non-regenerated and regenerated configurations. Up to 6% can be gained. Combination of two-stage turbine configuration of the ORC system and a two-phase turbine configuration in the heat-pump system with regeneration if each cycle is studied in Figure 2-b. A maximum value of 65% in efficiency could be reached with such a system.

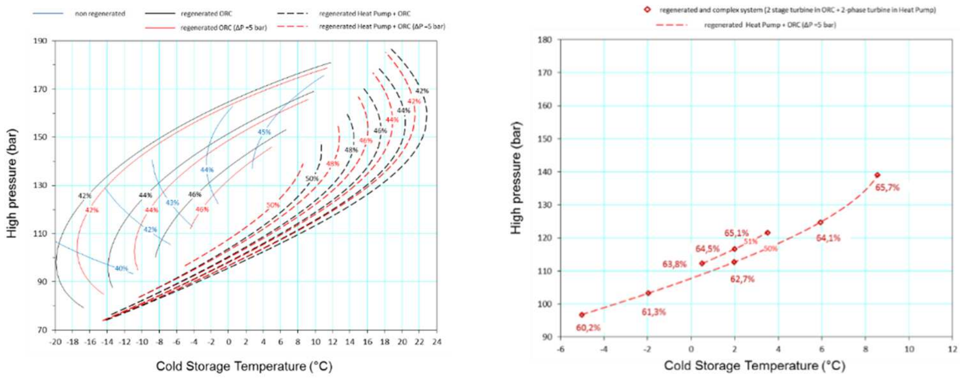


Figure 2 (a) Efficiency of the storage system: nominal and regenerative configurations; (b): two-stage turbine system and two-phase turbine system

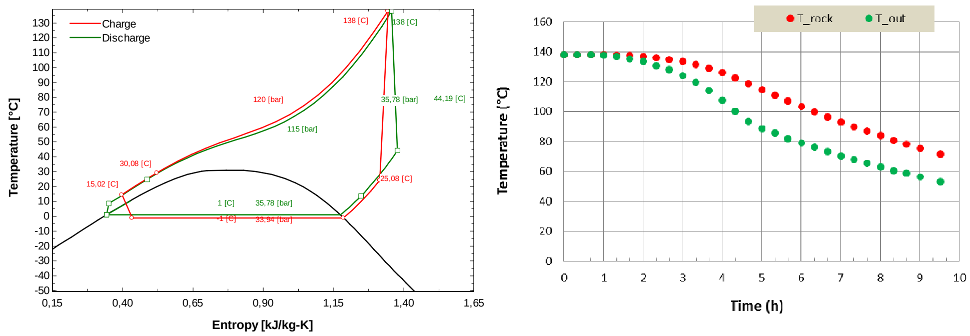


Figure 3 (a) T-S diagram for hot storage at 130°C and cold storage at 0°C; (b) Time evolution of temperature in the rock and in the fluid for the last column in a typical transient discharging process

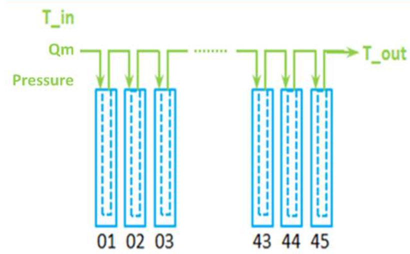
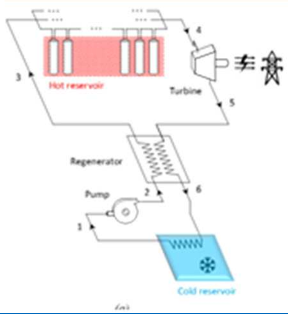
4. Ground Storage Model

The ground storage consists of vertical ground heat exchangers (geothermal exchangers). All geothermal exchangers have the same geometry and are set in a serial-parallel arrangement. A simplified ODE thermal model of the geothermal exchanger is established with a motivation to get a fast computing model for transient thermal simulation of the ground storage. The approximation assumes that the working fluid temperature in the geothermal exchanger results from a perfect (immediate) thermal homogenization of the working fluid inside the exchanger. The approximation is supported by (a) very high turbulence level (Reynolds number greater than 1E+5) and short residence time (65s) of the fluid inside the exchanger in the case of typical 12m long geothermal exchanger and 5kg/s sCO2 mass flow, and (b) the characteristic time associated with thermal conduction in the encasing rock is much larger than the one associated with the energy transport by convection in the fluid. In order to mitigate the hypothesis of an immediate thermal homogenization inside the geothermal exchanger, an efficiency coefficient EFF is taken in account to reflect the effective imperfection of the thermal exchange due to fluid dynamics in the exchanger. Thereby, only EFF proportion of the thermal energy input is considered under former hypothesis to be available for a thermal exchange with the fluid inside the geothermal exchanger, the encasing bedrock and as losses to the environment. The heat balance for the proportion (1 - EFF) of input energy not available for a thermal exchange with the fluid inside the heat exchanger provides the output temperature of the working fluid.
The implementation of the ODE model together with Comsol module *Heat Transfer in Solids* to compute the diffusive heat transfer in the encasing bedrock furnishes a complete numerical model for a time-

dependent simulation of SeleCO2 geothermal exchanger. The numerical model calculates the temperature at the wall of the exchanger in contact with the encasing bedrock and the output temperature of the working fluid. The ODE model has been compared with a more physically-based CFD model and results show good consistency. The value of the efficiency coefficient EFF used by the ODE model must however be determined on basis of experimentally established references. In all present work using the ODE model to simulate SeleCO2 geothermal heat exchanger, EFF has been set to a value of 0,8.

5. Transient Coupling of Thermodynamic Cycles with the Geothermal Heat Exchangers

The thermodynamic machines reach within minutes if not seconds their stationary regimes when the kinetics of diffusive heat transfer in the ground storage is two to three orders of magnitude slower. The principle of transient coupling of thermodynamic cycles with geothermal exchangers is to calculate static behavior of thermodynamic machines on some specific points of the ground storage transient simulation. This first attempt of coupling strategy is described in Figure 4.

①	Transient simulation by Comsol using ODE simplified model of 45 geothermal exchangers in serial for 1200s time-step, for input temperature T_in = T_3', mass flow Qm and pressure “Pressure” = P_2'. Comsol model calculates the output temperature T_out = T_4' at the end of the 1200s time-step.	
②	Output temperature T_out = T_4' at the end of time-step transferred as input temperature for the EES model of thermodynamic cycles.	
③	Determination of mass flow and pressure for the next simulation period of geothermal exchangers so as to ensure optimum evolution on T-S entropy diagram. Calculation by EES model of input temperature T_in = T_3' for the next simulation period of geothermal exchangers.	
④	New input temperature, mass flow and pressure transferred as input parameters for the model of geothermal exchangers for the next 1200s time-step.	

⑤ Iteration for every 1200s time-step

Figure 4 First attempt of coupling strategy between thermodynamic cycles model & ground storage model

Preliminary results are presented in Figure 3(b), Figure 5(a), Figure 5 (b). They show temporal evolutions of interesting thermodynamic parameters: temperature, pressure, mass flow and consequently generated electrical power. These first results must be understood as a first attempt in the optimizing process, showing that off-design situations in the process must be taken into account, precisely. The required computational time is several hours long for transient simulation of typical 8h cycle of thermal charge or discharge. Thus it is difficult to use such coupling strategy in the design process, unless substantial progress is made to reduce the computational time.

6. Conclusion

The aim of this work is to assess the performance of a massive electricity storage involving CO_2 transcritical cycles and using the ground as a heat reservoir. The parametric study of the charging and discharging processes has shown roundtrip efficiencies up to more than 50% given by high storage temperatures and ΔT_{min} =1K with a regenerative systems and 65% with complex expansion processes.
In parallel, simulations of flow inside heat exchanger and within geothermal system are performed with a 3D approach. The first preliminary results show that such numerical tool is able to represent large off-design

conditions of the global system. Further work through the SELECO2 project will include turbomachinery and heat storage designs in order to have a more detailed overview of the system. Furthermore further transient simulations of the complete charging/discharging cycle, based on various different approaches (section 4) or 1D/2D model (faster model described in [19]), will be performed and confirm (or not) the efficiency value and the general interest of the device.

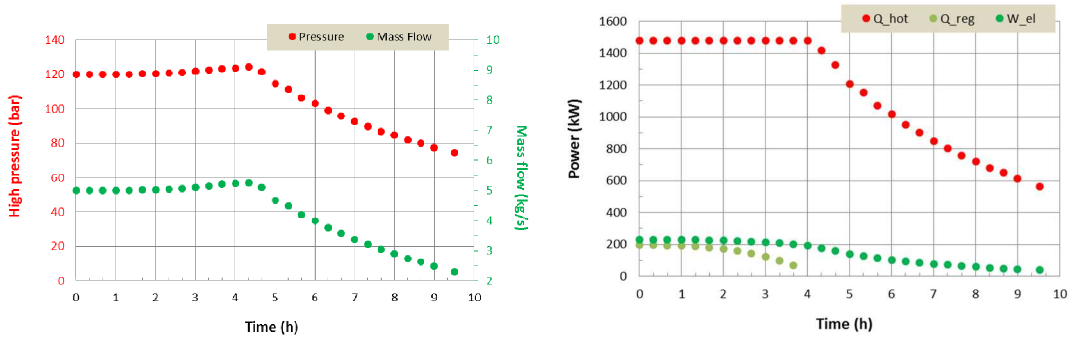


Figure 5 (a) Time evolution of (a) pressure, flow and (b) powers (hot storage, regenerator, electrical) in a typical transient discharging process

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References

[1] ENEA Consulting, Le Stockage d'Energie. 2012.

[2] Fujihara T, Imano H, Oshima K. Development of Pump Turbine for Seawater Pumped-Storage Power plant. Hitachi Review 1998 : 47 (5):199-202.

[3] Crotogino F, Mohmeyer K-U, and Scharf R. Huntorf CAES: More than 20 Years of Successful Operation. Proc of SMRI Spring Meeting,Orlando, Florida, USA, 15-18 April 2001.

[4] PowerSouth Energy Cooperative, CAES McIntosh Alabama.

[5] C. Bullough, C. Gatzen, C. Jakiel, M. Koller, A. Nowi, S. Zunft, Advanced adiabatic compressed air energy storage for the integration of wind energy, European Wind Energy Conference, 2004.

[6] Grazzini G, Milazzo A. Thermodynamic analysis of CAES/TES systems for renewable energy plants. Renewable Energy 2008;32:1998-2006.

[7] Mercangöz M, Hemrle J, Kaufmann L, Z'Graggen A, Ohler C. Electrothermal energy storage with transcritical CO2 cycles. Energy 2012; 45:407–415.

[8] Desrues T,Ruer J,Marty P,Fourmigué JF. A thermal energy storage process for large scale electric applications. Applied Thermal Engineering 2010;30(5):425-32

[9] Mercangoez M, Hemrle J, Kaufmann L. Thermoelectric energy storage system having two thermal baths and method for storing thermoelectric energy. Patent EP2241737

[10] Ohler C, Mercangoez M. Thermoelectric energy storage system and method for storing thermoelectric energy. Patent EP2182179.

[11] Henchoz S, Buchter F, Favrat D, Morandin M, Mercangoez M. Thermoeconomic analysis of a solar enhanced energy storage concept based on thermodynamic cycles. Energy 2012;45(1):358e65.

[12] Kim YM, Shin DG, Lee SY, Favrat D. Isothermal transcritical CO2 cycles with TES (thermal energy storage) for electricity storage. Energy 2013; 49: 484–501.

[13] Morandin M, Maréchal F, Mercangöz M, Buchter F. Conceptual design of a thermo-electrical energy storage system based on heat integration of thermodynamic cycles. Energy 2012;45:375-396.

[14] Morandin M, Mercangöz M, Hemrle J, Maréchal F, Favrat D. Thermoeconomic design optimization of a thermo-electric energy storage system based on transcritical CO2 cycles. Energy 2013; 58: 571–587.

[15] S. Laninia, F. Delaleux, X. Py, R.Olivès, D. Nguyen, Improvement of borehole thermal energy storage design basedon experimental and modelling results, Energy and Buildings 77 (2014) 393–400.

[16] S.A. Klein, Engineering Equation Solver. F-Chart Software, Middleton, WI, 2010.

[17] Ayachi F., Tartière T., Tauveron N., Colasson S., Nguyen D., Investigation of a massive electricity storage system by means of a geothermal heat transfer process involving CO2 cycles, ASME-ORC Conference, 2015.

[18] Ayachi F., Tauveron N., Tartière T., Colasson S., Nguyen D., Massive Thermo-Electric Energy Storage Based on CO2 Rankine Cycles and Ground Heat Storage, HEFAT Conference, 2016.

[19] E. Macchi, C. Colin, T. Tartière, D. Nguyen, N. Tauveron, Thermoelectric energy storage based on CO2 transcritical cycles: ground heat storage modelling, 1st European Seminar on Supercritical CO2 Power Systems, 2016.