Storage of Heat, Cold and Electricity

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Abstract: A promising energy storage system is presented based on the combination of a heat pump, a heat engine, a hot and a cold storage. It can be operated as a pure bulk electricity storage (alternative to Pumped Heat Electrical Storage (PHES)/ Compressed Air Energy Storage (CAES)) or as combined storage of heat, cold and electricity. Both variations have been evaluated using a steady state, thermodynamic model and two promising concepts are proposed: A transcritical CO_2 cycle for the pure electricity storage and a subcritical NH_3 cycle for combined storage of electricity, heat and cold. Parametric studies are used to evaluate the influence of different parameters on the roundtrip efficiency of the storage system.

Keywords: Dual Energy Storage & Converter · Electricity storage · Power-to-Heat · Reversible heat pump

Introduction

Storage technologies are bound to play an important role in the integration of renewable energy sources and in increasing the energy utilization efficiency in the upcoming years. The development of efficient and cost-effective storage technologies in all energy sectors is crucial to this task.[1] Along with the development of innovative electricity, thermal and chemical storage, the establishment of systems that can provide flexibility between energy forms will also gain importance.[2]

A promising storage system based on the combination of a heat pump, a heat engine, a cold and a hot storage is presented (Fig. 1). The system can be designed to serve as pure bulk electricity storage or a combination of heat, cold and electricity storage. The underlining operating principle is that during periods of excess electricity generation, a heat pump is operated to charge a hot and in some cases also a cold storage. In periods of excess electricity demand, the system can be operated in reverse as a heat engine, using the stored

temperature difference to generate electricity. This system variation is particularly interesting for bulk electricity storage in a power output range higher than 10 MW. It can be viewed as an alternative to Pumped-storage Hydroelectricity (PSH or PHES) and Compressed Air Electricity Storage (CAES), with the additional advantages of a higher energy density and the possibility of site-independent installation.

The first reports of this type of storage system can be found as early as 1924[3] and were continued in the 1970s[4] under the term 'reversible heat pumping'. In recent years, this technology has been the subject of several independent academic and industrial investigations with varying system specifications (working fluid, temperature levels, storing material, *etc.*). Most investigators named the system differently (*e.g.* ETES,[5] PTES,[6] CHEST,[7] TEES,[8] and others[9]), making the identification of relevant projects challenging.

The authors propose a thermally open variation of the technology, named Dual Energy Storage & Converter, where the two storage units can be used, not only as a means to store electricity but also to cover heating and cooling demands. This version offers additional flexibility between energy forms (power, heat and cold) and can be implemented in applications which possess a relatively high demand of all three energy forms during the whole year (*e.g.* food & beverages industry). A thermally open variation of the reversible heat pump has been previously considered for building applications using water storage for the high temperature side but no storage on the low temperature side.[10]

This work presents the evaluation process of different variations of the storage system by means of a simple thermodynamic tool. Two promising systems are selected and are shown in detail in terms of temperature–entropy diagrams.
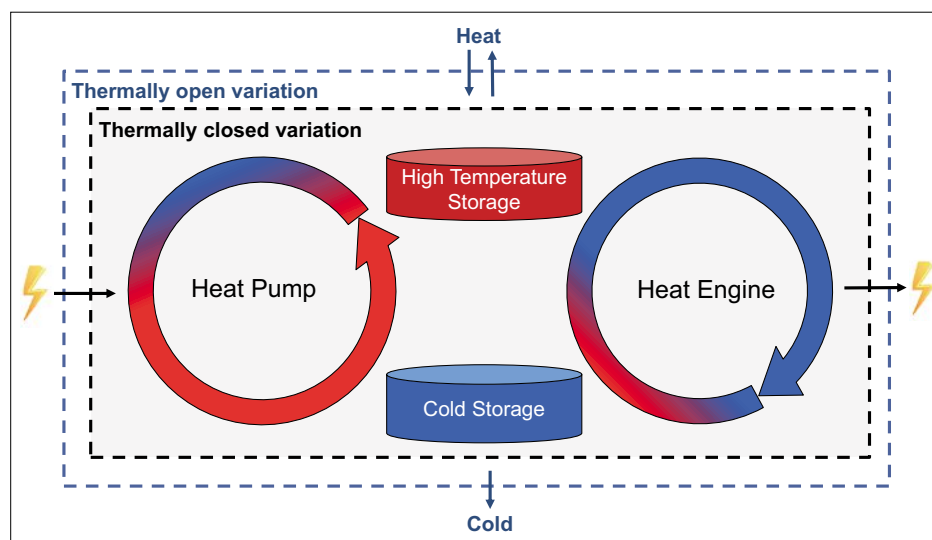
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Fig. 1. Schematic of the DESC process comprising a heat pump, a heat engine, a hot and a cold storage.

Methods

A simple steady-state thermodynamic tool has been developed for the scanning of different variations of the storage system shown in Fig. 1. The tool is based on Matlab[11] and extracts the thermodynamic properties from the NIST-REFPROP database.[12] It calculates the thermodynamic points describing the basic processes taking place during the heat pump and Rankine cycle (*e.g.* evaporation, expansion, condensation, *etc.*). Both the inefficiencies introduced by the machines and the exergy losses during heat exchange are considered but pressure drops and heat losses are neglected. The model was verified using independently calculated values describing the ABB concept with transcritical CO_2. It was subsequently used to carry out parametric studies of the systems considered and assess variations of the technology (working fluids, number of stages, *etc.*).

Results and Discussion

The main characteristics of the two system variations selected to be presented in this work are shown in Table 1. ETES is a bulk electricity storage concept developed by ABB[5] while DESC is a combined heat, cold and electricity storage concept developed by the authors.

The first thermodynamic evaluation was performed for the ETES system and can be seen in Fig. 2. The concept is based on transcritical CO_2 as working fluid for thermally closed cycles (see Table 1). The red line represents the heat pump cycle, the blue the Rankine cycle. Water is used for the sensible high temperature storage at 120 °C whereas ice is used for the low temperature storage at 0 °C. As seen in Fig. 2, the maximum operating pressure is 136.3 bar. The temperature levels and storage units are chosen to create an optimum match between the condensation/evaporation processes of the working fluid and the behavior of the storage media (water/ice) during charging/discharging. The ability to utilize water as the storage medium on both sides represents one of the biggest advantages of this variation of the reversible heat pump concept. The model was verified using independently calculated values provided by ABB. After the verification, the model was used to carry out parametric studies examining the influence of different parameters on the roundtrip efficiency of ETES. The parameters considered were: (i) temperature of hot storage, (ii) temperature of cold storage, (iii) ambient temperature, (iv) ΔT during heat transfer and (v) isentropic efficiencies of the mechanical components. Fig. 3 presents the results of

Table 1. Characteristics of technology variations presented in Figs 1–4

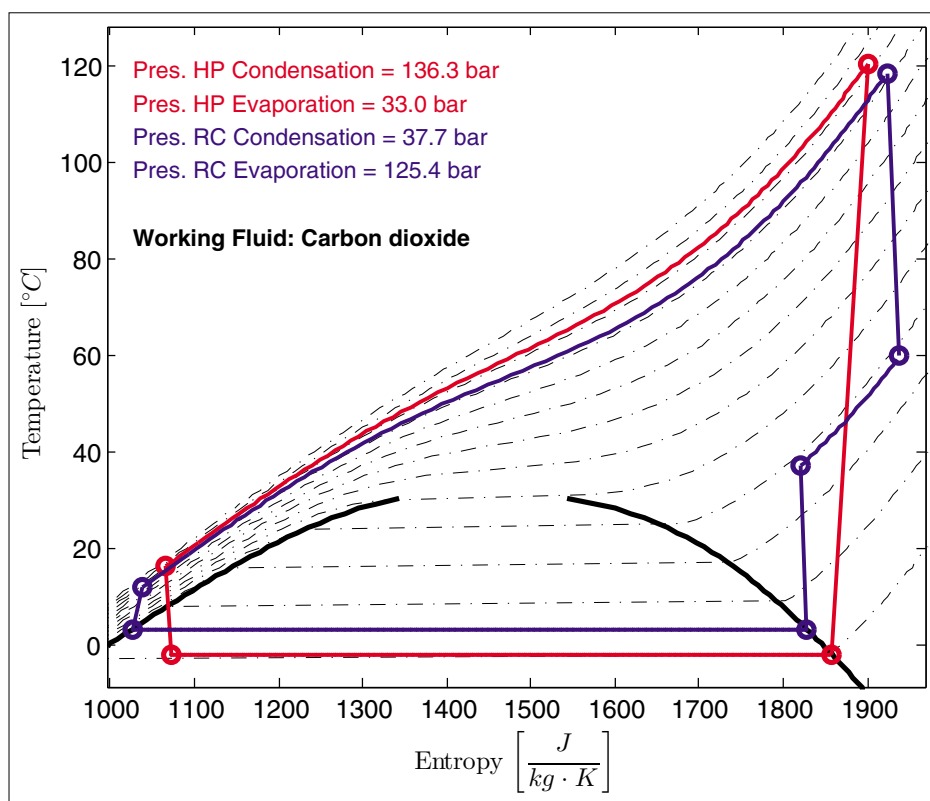| Name	Energy form		Working fluid	Storage units (hot/ cold)	Criteria for choice of T levels	Application
	Input	Output				
ETES	El.	El.	CO_2	Sensible / Latent (ice)	High roundtrip efficiency; water as storage material	Bulk electricity storage
DESC	El, heat	El., heat, cold	NH_3	Latent / Latent	Optimized for customer-relevant T levels	Heat, cold, electricity and storage, and supply

Fig. 2. Output of thermodynamic modeling for ETES concept with transcritical CO_2 as described in Table 1.
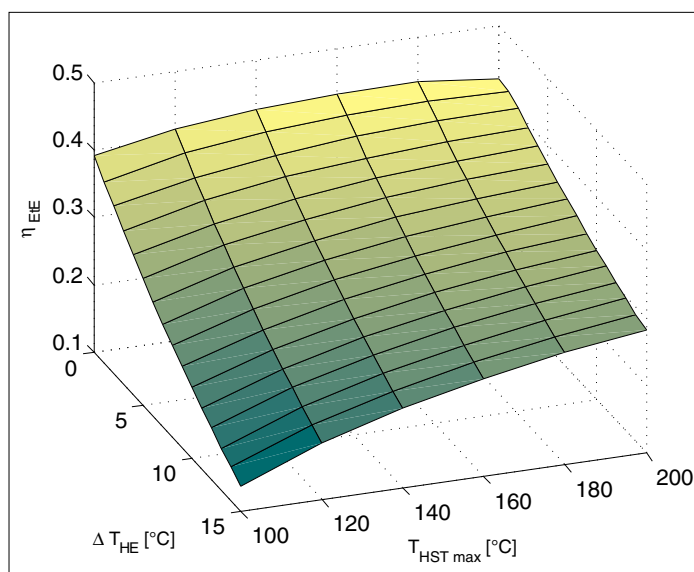

Fig. 3. Surface plot showing the roundtrip efficiency of the transcritical CO_2 system, η_{EtE}, as a function of the ΔT during the heat exchange and the maximum temperature of the high temperature storage T_{HST}.

one parametric analysis showing the evolution of the ETES roundtrip efficiency as a function of the maximum temperature of the hot storage and the ΔT during heat transfer. As expected, an increase in the heat exchanger ΔT results in a dramatic decrease in the ETES roundtrip efficiency η_{EtE}. In contrast, an increase in the maximum temperature of the hot storage results in an increase in the η_{EtE}.

The thermodynamic model was modified to describe the behavior of other reversible heat pump variations. Other working fluids were evaluated such as isobutane and ammonia. A promising variation for the combined storage uses NH_3 as a working fluid (Fig. 4). Similarly to Fig. 2, the red line describes the heat pump cycle and the blue line the Rankine cycle. Both processes comprise two stages providing the flexibility of charging/discharging the hot and the cold storage separately. Both the produced heat and cold will be stored in latent heat storage units to ensure an optimal match with the temperature profile of the subcritical cycles. The storage temperatures have been chosen at 0 °C and 95 °C because they represent two key temperature levels for industrial process heat and cold. Despite its toxicity, ammonia is a promising natural refrigerant with a very high enthalpy of vaporization. It has been used widely in refrigeration and there are already commercially available heat pumps that can deliver the temperatures required for this DESC variation. One big disadvantage is the high overheating during the heat pump operation which imposes challenges for the lubricant and induces mechanical stress on the components. The expansion processes during the heat engine mode take place in the two-phase region which imposes constraints on the choice of the expander. At the maximum operating pressure of 60 bar, even though not as high as the one demanded by the transcritical CO_2 cycle, it could still impose challenges in the component development and operation.

Conclusions

A promising energy storage system is presented. It can be operated as a pure bulk electricity storage (alternative to PHES/CAES) or as combined storage of heat, cold and electricity. Both variations have been evaluated using a steady state, thermodynamic model and two promising concepts are being proposed: A transcritical CO_2 cycle for the pure electricity stor-
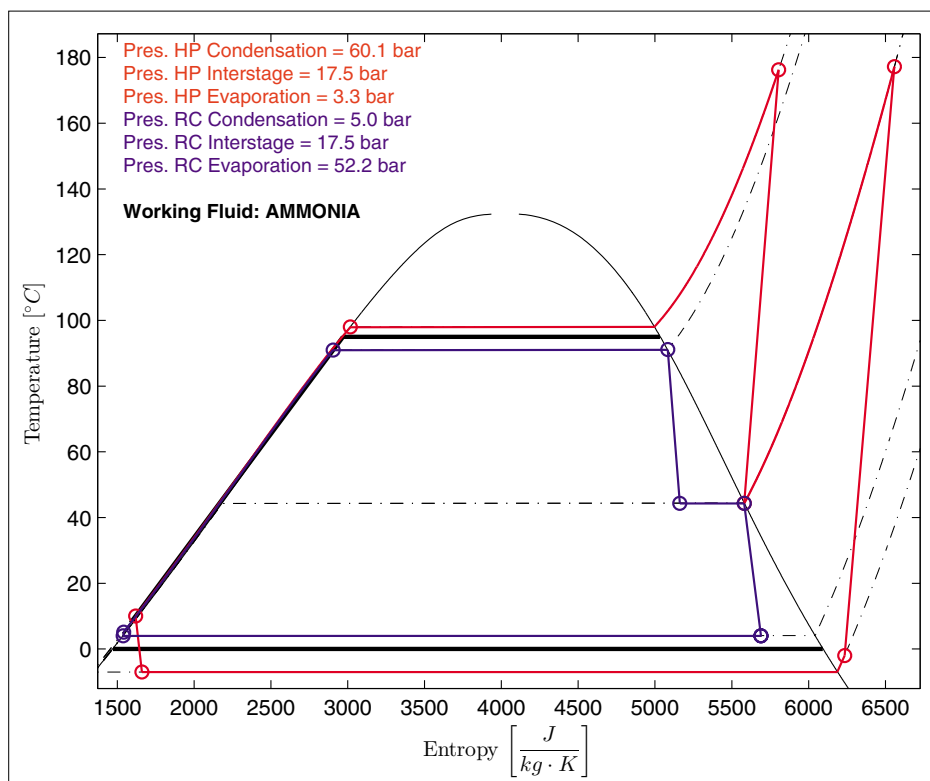

Fig. 4. Results of thermodynamic evaluation for DESC concept with subcritical NH_3 as described in Table 1.

age and a subcritical NH_3 cycle for combined storage of electricity, heat and cold. The CO_2 system has a maximum operating temperature of 120 °C and can be combined with water as a storage medium on both the hot and cold sides, which offers a valuable simplicity to the ETES system. The NH_3-based DESC system on the other hand can be integrated in a large number of industrial applications which require cold at 0 °C and heat at ~95 °C. The high heat of vaporisation of NH_3 and high energy density of the latent heat storage units increase system compactness. The developed steady-state thermodynamic tool is suitable for a first scanning/evaluation of different storage systems variations. It can also be successfully used to perform parametric studies and find optimal operation points. For a more detailed estimation of the system potential, the tool has to be extended to capture transient phenomena and to include pressure drops and heat losses.

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