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Integration of heat pumps into thermal plants for creation of large-scale electricity storage capacities

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HIGHLIGHTS

- Realistic round-trip-efficiencies are in range of 50–60% for different power plants.
- Efficient heat pumps are realizable at 300–600 °C and moderate internal recuperation.
- Trans-critical heat pumps are not generally superior to super-critical processes.
- Operation of heat pumps and electric heaters in series connection is promising.
- New thermodynamic assessment approach for PHES systems.

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ABSTRACT

Within Thermo-Electric Energy Storage (TEES) concepts, thermal plants are conceivable for reconversion of stored heat into electricity. By this means, new areas of application for existing thermal plants are established and the costs of the storage system are reduced. A promising TEES approach is Pumped-Heat-Electricity-Storage (PHES). In the present study, the thermodynamic potentials of the new concept of integrating PHES systems into different types of thermal plants for the creation of large-scale electricity storage units are assessed – based on exergetic quantities – including the discussion of technical aspects.

Using the environment as the heat source, recuperated heat pump designs are investigated with regards to the achievable efficiencies for different working fluids (CO_2, air and Argon) and the related processes (trans-critical/super-critical). The investigated maximum heat pump temperature range is between 50 °C and 700 °C. The heat pump designs are individually optimized concerning their remaining degrees of freedom. Finally, a combined characteristic diagram is provided, which allows to identify the most reasonable heat pump working fluid and process configuration referring to the boundaries of a specific storage concept. Electric heaters as a simpler method for power-to-heat conversion are assessed as well.

The results show that exergetic heat pump efficiencies of above 70% can be achieved if the maximum temperature of the provided heat is in the range of 300–600 °C while the minimum temperature is elevated. It is also shown that trans-critical cycle designs are not generally superior to super-critical cycle designs at these boundaries.

Based on the results of the heat pump analysis, the round-trip-efficiencies of different heat integration options into different types of thermal plants are estimated – the reachable efficiencies are roughly in the range of 50–60%. Finally, the application of heat pumps and electric heaters in series connection is assessed. Then, the round-trip-efficiencies of the storage concepts drop by a few percent points (2–5%) but the technical challenges of designing high temperature heat pumps are reduced.

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Nomenclature

Variables

a	specific work
B	energy
e	specific exergy
c	specific heat capacity
COP	coefficient of performance
$COEP$	coefficient of exergetic performance
E	exergy
ϵ	utilization factor
η	energetic efficiency
γ	recuperation rate
h	specific enthalpy
ν	volume flow ratio
m	mass
μ	exergy density
P	power rate
p	pressure
Π	pressure ratio
Q	Heat
T	temperature
t	time
$\tilde{T}$	thermodynamic averaged temperature
u	specific internal energy
$\dot{V}$	volume flow rate
ζ	exergetic efficiency

Abbreviations

C	Compressor or Carnot
crit	critical point
el	electric/electricity
eva	evaporation/evaporator
G	generator
HP	Heat pump
H2P	heat to power cycle
$lim+$	limit in direction of high values
$lim-$	limit in direction of low values
M	motor
P2H	power to heat cycle
RTE	round-trip-efficiency
s	isentropic
S	Storage
trip	triple point
T	turbine
WSC	water/steam cycle
+	upper part of the thermal potential
−	lower part of the thermal potential
∞	referring to environmental/ambient conditions

1. Introduction

1.1. Literature review

Worldwide, the share of renewable energy sources increases and induces a higher degree of volatility at the electricity supply side [1,2]. Adapting the more volatile supply side to the demand side needs the contribution of all market participants.

Conventional power plants are required to act more flexible to harmonize the supply side output [1,2]. Therefore, research is ongoing to extend the power plant capacities to variably respond on market demands. This refers to fossil-fired plants [3], but also to nuclear plants [4]. At the same time, fossil-fired plants are still improved with regards to energy efficiency and thereby contributing along with renewable sources to the environmental-friendly electricity generation. This can either be realized by improved plant designs but also by converting these plants into poly-generation systems. One example is the utilization of low-temperature waste heat of fossil-fired plants for heating purposes [5,6]. However, in some regions, as in Germany, fossil-fired power plants currently face the situation of being under-utilized because of regulations preferring renewable input [7,8]. The identification of additional areas of application could make these plants operate more economically. Also for renewable plants, as for solar thermal plants, intensive research and development is carried out referring to operational features. The integration of augmented thermal storage capacities [9–11], enabling the plant's power generation to be less dependent on the changing solar heat input is one focus. The target is to design solar thermal plants, which are capable for base-load operation [12].

Different authors point out that economic electricity storage systems are required as a further key component for proceeding to electricity grids with even higher degrees of integration of renewable sources [1,13–16]. Electricity is usually not stored directly but used to create a potential of another form of energy. This potential is preserved and reconverted into electricity when required (e.g. batteries → chemical potential/pumped hydro storage (PHS) → mechanical potential). An overview of the various concepts of electricity storage is provided in several studies, see e.g. [15,16]. The most relevant technological rating criteria for electricity storage concepts is the round-trip-efficiency. It is defined as the ratio between the electricity output during a discharging sequence and the input during a charging sequence. A comparison of the different storage technologies shows significant differences of achievable round-trip-efficiencies [15,16]. Nevertheless, further aspects of the storage technologies have to be considered. Systems with high efficiencies usually suffer from other disadvantages. For example, the application of pumped hydro storage (PHS) and compressed air energy storage (CAES) is bound to the availability of appropriate geological sites and materials for batteries are usually expensive. Therefore, storage technology of low efficiency is still considerable for economic application [16]. Apart from efficiency considerations, storage systems of different scale and response times are necessary to meet future demands [16].

One approach to create electricity storage capacities is the utilization of a power-to-heat cycle (heat pump) during a charging sequence in order to create a thermal potential. This potential is stored and later reconverted by a heat-to-power cycle (H2P) within a discharging sequence. In general, the minimum and maximum temperatures of the thermal potential can be above or below ambient conditions. This technology is usually known as Pumped-Heat-Energy-Storage (PHES) belonging to the category of Thermal Energy Storage (TES); if the temperatures are below ambient conditions, it is also referred to as Pumped-Cryogenic-Energy-Storage (PCES) [17,18]. Theoretical approaches are developed to estimate the potentials of this technology by means of the round-trip-efficiency; based on simple but very unspecific models, it can be shown that high round-trip-efficiencies require high differences in temperatures between the heat source and the heat sink [17,18]. Within recent years, different PHES concepts were developed. Four of them ([19–43]) are briefly introduced in Table 1 including characterizing values and features. These concepts have in common that they are investigated and developed beyond basic thermodynamic assessments. Significant differences between the