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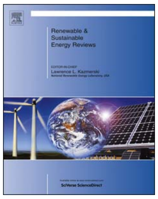

Thermo-mechanical concepts for bulk energy storage

Wolf-Dieter Steinmann

German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

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ABSTRACT

Grid scale electrical energy storage is considered facilitative for the increased deployment of renewable energy. Recent progress in the development of large scale thermal energy storage systems operated at medium and high temperatures has sparked the interest in the application of this technology as a storage sink for electricity. Life expectancies in the range of 20–30 years, low capacity-specific costs, a low environmental impact and flexibility regarding sites make thermo-mechanical energy storage a promising option for future bulk storage of electricity. A large number of concepts have been developed, which vary in storage efficiency, complexity and maturity. This paper provides an overview of the basic concepts for thermo-mechanical energy storage and describes various implementations and their characteristics. The utilization of waste heat, the combined delivery of heat and power during discharge and the integration of storage modules into power plants are described as additional options for some of these thermo-mechanical concepts.

1. Introduction

The limited flexibility of thermal power plants sparked interest in electrical energy storage early in the development of electricity networks. The availability of a storage option helps to reduce inefficient partial load or transient operation of thermal cycles. Highly efficient baseload power plants can be operated continuously; expensive and inefficient peak load capacity can be limited. In recent years, the increased share of electricity generated from solar irradiation or wind has shifted the focus to a different application area. Grid scale electricity storage is believed to facilitate the effective integration of energy provided by intermittent renewable energy sources [1–3].

This paper describes systems for grid scale diurnal storage of electricity. These systems should reach 10–500 $\mathrm{MW_{el}}$ and discharge times in the range of 4–12 h.

Pumped hydro energy storage (PHES) has the highest capacity of today's commercial electricity storage systems [4]. PHES facilities store off-peak electricity by moving water from a lower to an upper reservoir. During discharging water is released from an upper reservoir through a hydroelectric turbine into a lower reservoir, converting potential to kinetic energy and using this to generate electricity. The potential energy stored is defined by the elevation difference between the two reservoirs; a system with a height difference of 360 m has an ideal capacity of 1 $\mathrm{kWh/m^3}$. According to [5], the total global cumulative generating capacity of PHES is 127 MW, representing more than 99% of the total bulk storage capacity for electrical energy. While small facilities have capacities below 10 kW, the maximum size of a single facility is in the range of 4000 MW, the typical life expectancy is 50–60 years. The roundtrip efficiency, which is defined as

$$\eta_{\mathrm{roundtrip}} = \frac{\text{electric energy provided during discharging}}{\text{electric energy consumed during charging}} = \frac{W_{\mathrm{el,discharge}}}{W_{\mathrm{el,charge}}} \tag{1}$$

of PHES facilities is in the range of 75–85%. The costs of PHES systems depend strongly on location. Cost estimates for a 1000 MW unit range from 2000 \$/kW to 4000 \$/kW [5].

The main drawbacks of PHES are the geographic dependence and the environmental impact. Permitting processes often take several years. Usually, sites fulfilling the requirements of PHES plants are in remote areas with a low local electricity demand; the conditions for electricity generation of PV and wind are often less favorable at typical PHES sites. This requires the extension of the electric grid to connect source, storage and consumer.

2. Thermo-mechanical energy storage systems

Due to the specific tariff-structure, large-scale thermal energy storage systems became a viable option for concentrating solar thermal power (CSP) plants in Spain at the beginning of the 21st century [6,7]. The Andasol 1 solar thermal power plant with a nominal output of 50 $\mathrm{MW_{el}}$, which started operation in 2009, has a thermal storage unit

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Abbreviations: CAES, Compressed Air Energy Storage; CHEST, Compressed Heat Energy Storage; CHP, Combined Heat and Power; COP, Coefficient Of Performance; CSP, Concentrating Solar Power; HRSG, Heat Recovery Steam Generator; LAES, Liquid Air Energy Storage; ORC, Organic Rankine Cycle; PCM, Phase Change Material; PHCHP, Power to Heat to Combined Heat and Power; PHES, Pumped Hydro Energy Storage; PHP, Power to Heat to Power; PTES, Pumped Thermal Energy Storage

E-mail address: wolf.steinmann@dlr.de.

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Nomenclature

$C_{capacity}$	capital costs dependent on capacity of storage system [\$]
C_{power}	capital costs dependent on power of storage system [\$]
$c_{power\ block}$	power specific costs of power block [\$/kW$_{el}$]
$c_{storage}$	capacity specific costs of thermal storage unit [\$/kWh$_{thermal}$]
C_{Total}	capital costs of storage system [\$]
Q_{fossil}	thermal energy provided by burning of fossil fuels [kWh]
Q_{hot}	capacity of hot reservoir of a PTES system [kWh]
$Q_{hot,\ min}$	minimum capacity required for hot reservoir of a PTES system [kWh]
Q_{cold}	capacity of cold reservoir of a PTES system [kWh]
$Q_{cold,\ min}$	minimum capacity required for hot reservoir of a PTES system [kWh]
p	pressure [bar]
P_{charge}	average power during charging process [kW]
$P_{discharge}$	average power during discharging process [kW]
s_{hybrid}	share of stored energy in total energy provided during discharging in a hybrid system, assuming a fossil-fuel-fired reference process [-]
$s_{hybrid40}$	share of stored energy in total energy provided during discharging in a hybrid system, assuming a fossil-fuel-fired reference process with a thermal efficiency of 40%[-]
$s_{hybrid60}$	share of stored energy in total energy provided during discharging in a hybrid system, assuming a fossil-fuel-fired reference process with a thermal efficiency of 60%[-]
T_{cold}	temperature of cold reservoir of PTES system [K]
T_{hot}	temperature of hot reservoir of PTES system [K]
$T_{max,\ Cycle}$	maximum temperature of thermodynamic cycle [K]
$T_{min,\ Cycle}$	minimum temperature of thermodynamic cycle [K]
$w_{AirStorage}$	volume specific storage capacity of air volume [kWh/m^3]
$w_{AirStorage,\ hybrid40}$	volume specific storage capacity of air volume for a hybrid system assuming a fossil fired reference cycle with a thermal efficiency of 60% [kWh/m^3]
$w_{AirStorage,\ hybrid60}$	volume specific storage capacity of air volume for a hybrid system assuming a fossil fired reference cycle with a thermal efficiency of 60% [kWh/m^3]
$W_{el,\ charge}$	electric energy required during charging [kWh]
$W_{el,\ discharge}$	electric energy delivered during discharge [kWh]
$W_{el,\ fossil}$	electric energy generated from fossil fuel
$W_{el,\ hybrid}$	electric energy generated from stored energy in a hybrid system during discharge [kWh]
$\eta_{1.\ Law}$	storage efficiency of hybrid system based on first law analysis [-]
η_{fossil}	thermal efficiency of fossil fired reference process [-]
η_{hybrid}	storage efficiency of hybrid system assuming a fossil fired reference process [-]
$\eta_{hybrid40}$	storage efficiency of hybrid system assuming a fossil fired reference process with a thermal efficiency of 40% [-]
$\eta_{hybrid40}$	storage efficiency of hybrid system assuming a fossil fired reference process with a thermal efficiency of 60% [-]
$\eta_{roundtrip}$	storage efficiency of an adiabatic system [-]
$\eta_{thermal}$	thermal efficiency of thermal cycle [-]
$\eta_{WasteHeat}$	storage efficiency of system using also waste heat from an external source [-]
κ	heat capacity ratio [-]
ψ	compression ratio gas turbine [-]

with a thermal capacity of 1 GWh which is cycled between 290 °C and 390 °C. More than a dozen similar solar thermal energy power plants with integrated storages have been built thus far. The thermal energy storage system of the Solana CSP plant near Phoenix generates 280 MW$_{el}$ during discharging for 6 h. While today's commercial storage systems for CSP applications use molten salt as the storage material, a variety of alternative concepts for large-scale storage at medium and high temperatures has been developed [8].

The characteristics of thermal energy storage systems also make them promising candidates for large-scale storage of electricity. There are no specific requirements regarding the geology of the site. The systems are designed for life expectancies in the range of 20–30 years. The required materials are abundant, the environmental impact is low. Capacity-specific costs of 15 \$/kW$_{thermal}$ have been defined as the goal of the ongoing development of thermal energy storage systems [9]. Although the required thermal capacity is 2–5 times the electrical energy storage capacity, the resulting costs are attractive.

Thermo-mechanical energy storage systems are based on transformations between mechanical and thermal energy. Internally, thermal energy storage might be combined with mechanical energy storage. The storage components are combined with standard components such as heat exchangers, compressors or turbines. Some of these components require modifications, other are identical to components used in the process industry or in power plants. While the capital costs of thermal energy storage units mainly depend on capacity, the costs of the other components are dependent on power. The costs of the resulting thermos-mechanical energy storage system depend on both capacity and power, comparison of different concepts requires the specification of both parameters. Thermo-mechanical energy storage concepts may be the basis for independent storage plants; some of these concepts may also be integrated into thermal power plants. Integration helps to reduce costs by the dual use of components and helps to ensure supply security.

2.1. Basic concepts

Three basic principles for thermo-mechanical energy storage can be distinguished:

- Compressed air energy storage (CAES), in which a volume is charged with pressurized air. This pressurized air is later used to operate an expander process during discharging. The expander process requires the addition of heat.
- Power to Heat to Power (PHP), in which a thermal energy storage unit is charged by electric energy. During the discharging phase, the heat delivered by the thermal storage energy unit is used to operate a thermal cycle. A modification of this concept is Power to Heat to Combined Heat and Power (PHCHP). Here, the storage unit provides not only energy for operating a thermal cycle, but also thermal energy for heating or process industry applications.
- Pumped Thermal Energy Storage (PTES), in which excess electrical

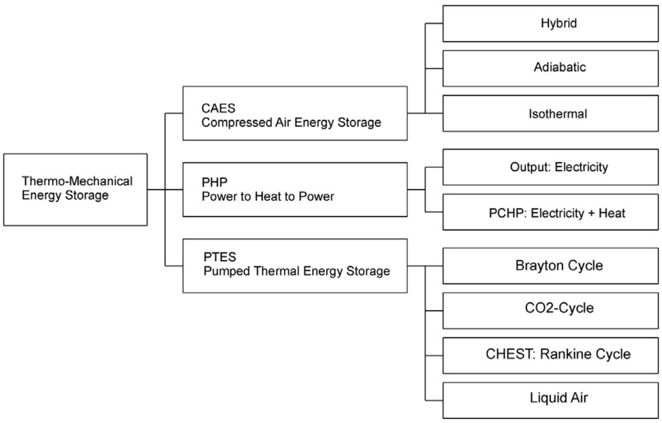

Fig. 1. Overview of concepts for thermo-mechanical energy storage.