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Levelised Cost of Storage for Pumped Heat Energy Storage in comparison with other energy storage technologies

Andrew Smallbone[a,*], Verena Jülch[b], Robin Wardle[a], Anthony Paul Roskilly[a]

[a] Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[b] Fraunhofer Insitute for Solar Energy Systems ISE, Freiburg, Germany

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ABSTRACT

Future electricity systems which plan to use large proportions of intermittent (*e.g.* wind, solar or tidal generation) or inflexible (*e.g.* nuclear, coal, *etc.*) electricity generation sources require an increasing scale-up of energy storage to match the supply with hourly, daily and seasonal electricity demand profiles. Evaluation of how to meet this scale of energy storage has predominantly been based on the deployment of a handful of technologies including batteries, Pumped Hydroelectricity Storage, Compressed Air Energy Storage and Power-to-Gas. However, for technical, confidentiality and data availability reasons the majority of such analyses have been unable to properly consider and have therefore neglected the potential of Pumped Heat Energy Storage, which has thus not been benchmarked or considered in a much detail relative to competitive solutions. This paper presents an economic analysis of a Pumped Heat Energy Storage system using data obtained during the development of the world's first grid-scale demonstrator project. A Pumped Heat Energy Storage system stores electricity in the form of thermal energy using a proprietary reversible heat pump (engine) by compressing and expanding gas. Two thermal storage tanks are used to store heat at the temperature of the hot and cold gas. Using the Levelised Cost of Storage method, the cost of stored electricity of a demonstration plant proved to be between 2.7 and 5.0 €ct/kW h, depending on the assumptions considered. The Levelised Cost of Storage of Pumped Heat Energy Storage was then compared to other energy storage technologies at 100 MW and 400 MW h scales. The results show that Pumped Heat Energy Storage is cost-competitive with Compressed Air Energy Storage systems and may be even cost-competitive with Pumped Hydroelectricity Storage with the additional advantage of full flexibility for location. As with all other technologies, the Levelised Cost of Storage proved strongly dependent on the number of storage cycles per year. The low specific cost per storage capacity of Pumped Heat Energy Storage indicated that the technology could also be a valid option for long-term storage, even though it was designed for short-term operation. Based on the resulting Levelised Cost of Storage, Pumped Heat Energy Storage should be considered a cost-effective solution for electricity storage. However, the analysis did highlight that the Levelised Cost of Storage of a Pumped Heat Energy Storage system is sensitive to assumptions on capital expenditure and round trip efficiencies, emphasising a need for further empirical evidence at grid-scale and detailed cost analysis.

1. Introduction

A total of 7200 gigawatts (GW) of electricity capacity needs to be built worldwide to keep pace with increasing electricity demand while also replacing existing power plants expected to be retired by 2040 (around 40% of the current fleet) [1]. If future electricity systems are planned to use large proportions of intermittent (such as from wind, solar or tidal generation) or inflexible (*e.g.* nuclear, coal, *etc.*) electricity generation sources then an increasing scale-up of energy storage is necessary to match the supply with hourly, daily and seasonal electricity demand profiles. Reflecting this, the International Energy Agency [2] projects that 310 GW of additional grid-connected electricity storage capacity will be necessary in the United States, Europe, China and India.

To date, the economic and technical evaluation of how to meet this scale of energy storage has predominantly been based on the deployment of well-known technologies including batteries, Pumped Hydroelectricity Storage (PHS), Compressed Air Energy Storage (CAES) and Power-to-Gas (PtG) solutions. IEA [2] find that PHS and CAES can already reach the cost targets for widespread application in providing

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* Corresponding author.
E-mail address: andrew.smallbone@ncl.ac.uk (A. Smallbone).

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Nomenclature

A_t	annual cost of storage
c_{el}	cost of electricity
i	discount factor
n	system lifetime
Q	net heat flow
R	recovery value
T	temperature
t	year
W_{in}	amount of energy charged by the storage system per year
W_{out}	amount of energy discharged by the storage system per year
T_{amb}	ambient temperature
T_{hot}	temperature on the hot side of the PHES system
T_{cold}	temperature on the cold side of the PHES system
aCAES	adiabatic Compressed Air Energy Storage
CAPEX	capital expenditure
CHEST	Compressed Heat Energy Storage
CH_4	methane storage
dCAES	diabatic Compressed Air Energy Storage
GW	gigawatts
H_2	hydrogen storage
LCOE	Levelised Cost of Electricity
LCOS	Levelised Cost of Storage
Li-ion	Lithium-ion
ORC	Organic Rankine Cycle
OPEX	operational expenditure
Pb	Lead
PCES	Pumped Cryogenic Energy Storage
PHES	Pumped Heat Energy Storage
PSH	Pumped Hydroelectricity Storage
PTES	Pumped Thermal Energy Storage
PtG	Power to Gas
TRL	Technology Readiness Level
VRF	vanadium redox flow

arbitrage services, while battery technologies need considerable cost reductions to compete. Jülch [3] shows that the operation of the storage system has a vast impact on the LCOS. Zakeri et al. [4] calculate the lowest LCOS for PHS and CAES in providing energy arbitrage (5.4–7.1 €ct/kW h). Lazard [5] compare LCOS of several technologies in defined applications. They find that PHS can be competitive to fossil fuels at the transmission system level while batteries are starting to become competitive in frequency regulation. However, largely due to issues around commercial confidentiality, novelty of the solution and therefore a lack of technical data available in the public domain, the majority of such analyses have been unable to properly consider and have therefore neglected the potential of Pumped Heat Energy Storage (PHES). As such, despite its huge potential for delivering low-cost energy storage with a low footprint and high flexibility on the location of deployment, it has not been benchmarked or considered in a much detail as one might expect relative to competitive solutions.

The practical and theoretical aspects of a PHES system that come under the general term *Pumped Heat Energy Storage* (PHES) or *Pumped Thermal Energy Storage* (PTES) have been examined in a number of recent papers. The term *electricity* is sometimes used instead of energy. Pumped Cryogenic Energy Storage (PCES) is used to describe a system that stores energy at a temperature below ambient. In a review of recent literature, Steinmann [6] categorises PHES systems according to their thermodynamic cycle and working fluid: reversible Brayton cycle machines using a super-critical single-phase gas (air or an inert gas) and low- and high-temperature storage reservoirs; reversible trans-critical Organic Rankine Cycle (ORC) devices (often using CO_2) with ice and pressurised water storage reservoirs; and Compressed Heat Energy Storage (CHEST) systems [7] which use a conventional (but reversible) critical-region steam Rankine cycle with a latent-heat high-temperature reservoir and with the ambient environment as the low-temperature source. Recent literature describing PHES systems are generally variations on these three designs. A series of working prototypes of a Brayton-type device using thermally stratified (constant-temperature) storage were presented by Howes [8] who provides a simple theoretical and practical analysis, this analysis was considered in more detail by White et al. [9] and optimised by McTigue et al. [10]. These articles detail the development of, The work of Desrues et al. [11] also describes a very similar system. This type of constant-temperature storage design is the method studied in the present paper. Benato [12] describes the modelling of a PHES system which also operates in a similar manner, but which adds an electric heater to stabilise the charging temperature. The effects of varying bed characteristics and maximum cycle temperature are explored. The modelling predicts very low round-trip efficiencies for this configuration, and consequently specific energy costs which are higher than those used in the present analysis.

In [13] Thess formulates a finite-time thermodynamic model predicting the efficiency of PHES as a function of the temperature storage at maximum output power. Guo et al. [14] explore the performance of PHES and PCES machines using a finite-time thermodynamics approach, and develop the limiting efficiencies and the effect of varying parameters. Guo et al. [15] further derive expressions for the round trip efficiency and power output of a PTES system using a Brayton cycle. These three studies assume that the environment is used for one of the reservoirs. In contrast Frate et al. [16] examine the efficiencies for various working temperatures and fluids of a PTES system which uses a third reservoir at above ambient temperature as the cold source for a vapour compression heat pump (charging) component, with an ORC discharging section. This arrangement naturally leads to efficiencies of over 100% but the system is essentially the same as that analysed by other authors. Wang and Zhang [17] also describe a conceptually similar system producing efficiencies of over 100%, only in their case discharge occurs between the hot (charged) reservoir and a liquid natural gas store. Charging takes place via a CO_2 heat pump cycle, and discharge through cascaded CO_2/NH_4 Rankine cycles. Ni and Caram [18] conduct an analysis of a Brayton cycle PHES using discretised (stratified) storage using an exponential matrix method, and characterise the system round-trip efficiency and utilisation ratio as a function of a number of system design characteristics. Vinnemeier et al. [19] describe a system for integrating heat pumps into conventional thermal plants, giving bounds for efficiencies; the systems described here falling into the CHEST model category. Abarr et al. [20] develop a model for an ammonia-based PHES system with tube-in-concrete hot-store and ambient cool-store. This system's operation is slightly different to others studied in that it is primarily designed as a flexible bottoming-plant for a gas turbine generator, operating an asymmetric charge/discharge cycle.

To date, most of the work analysing PHES has been concerned with the engineering aspects of PHES storage devices. The theoretical studies (using conventional engine cycle analysis and/or finite-time thermodynamics) have the aim of determining limiting efficiencies, parameterised by working temperature range and other design variables. The small number of papers describing working prototypes examine practical designs for reducing irreversibilities, particularly in the compression, heat transfer and storage parts of the system. Only two papers move further into fully examining the economic aspects of PHES. Dietrich et al. [21] conduct a classical exergeoeconomic analysis of a hybrid CHEST-type system using an off-the shelf vapour-compression heat pump and a low-temperature ORC using butane, with ambient low-temperature source and a single daily charge-discharge schedule.