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Feasibility study of energy storage by concentrating/desalinating water: Concentrated Water Energy Storage

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HIGHLIGHTS

- Feasibility of energy storage by concentrating/desalinating water is studied.
- Energy density of CWES depends on the initial saline concentration.
- Trade-off relationship of cycle efficiency and energy density exists in CWES.
- Detrimental effects and energy loss reduce performance of CWES.

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ABSTRACT

The paper is to report the work on a preliminary feasibility study of energy storage by concentrating/desalinating water. First, a novel concentrated water energy storage (CWES) is proposed which aims to use off-peak electricity to build the osmotic potential between water bodies with different concentrations, namely brine and freshwater. During peak time, the osmotic potential energy is released to generate electricity.

Two scenarios of CWES are specified including a CWES system using reverse osmosis (RO) and pressure retarded osmosis (PRO), and a CWES system co-storing/generating energy and freshwater using "osmotic-equivalent" wastewater. A comprehensive case study is carried out with focusing on the configuration of CWES using RO and PRO. It is found that the limiting cycle efficiency of the CWES using RO and PRO is inversely proportional to the RO water recovery and independent of the initial salinity. Therefore, to balance the energy density and cycle efficiency of CWES, it is recommended to operate a system at lower RO water recovery with higher concentration of the initial solution. Detailed energy analysis of detrimental effects in mass transfer, e.g. concentration polarization and salt leakage, and energy losses of pressurisation and expansion of pressurized water, are studied. Finally, a preliminary cost analysis of CWES is given.

1. Introduction

Rapidly increase of the power generation from renewable energy sources has been achieved to reduce the usage of fossil fuels and the emissions of carbon dioxide [1]. By the year's end of 2014, renewables, mainly including the wind, solar PV and hydropower, account for an estimated 27.7% of the world's power generation capacity, enough to supply an estimated 22.8% of global electricity [2]. However, due to the unavoidable intermittence of the most renewable energy sources, there exists a great challenge in the power generation and load balance maintenance to ensure the stability and reliability of the power network. Electrical energy storage normally presents a process to convert electricity from grid or renewables into a form that can be stored for releasing back to generate electricity when needed. It provides the power management as an energy buffer to dispatch electrical energy in a flexible way [3]. With sufficient energy storage capacity, the total power generation capacity can be built to meet average electricity demand rather than peak demands [4]. Until now, there are mainly two commercialised bulk energy storage technologies, namely pumped hydroelectric storage (PHS) [5,6] and compressed air energy storage (CAES) [7]. As reported by the Electric Power Research Institute, PHS presents more than 99% of bulk energy storage capacity in the world and about 3% of global electricity generation, approximately an installed 127 GW in 2012 [8–10]. For CAES, there are two CAES plants in operation. The first utility-scale CAES project is the 290 MW Huntorf plant in Germany

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Nomenclature

Symbols

G	gibbs free energy, J
c	concentration, g/kg
q	mass flow rate, kg/s
x	mole fraction, mol/mol
R	gas constant, J K^{-1} kg^{-1}
T	temperature, K
γ	activity coefficient
ϕ	ratio of moles of two solutions
v	Van't Hoff factor, bar kg g^{-1}
Y	water recovery ratio
V	volume flow rate, m^3 s^{-1}
P	pressure, Pa
E	energy, J
π	osmotic pressure, Pa
η	cycle efficiency
J_W	water flux, L m^{-2} h^{-1}
A	membrane water permeability coefficient, L m^{-2} h^{-1} bar^{-1}
A_m	membrane area, m^2
B	membrane salt permeability coefficient, L m^{-2} h^{-1}
k	mass transfer coefficient, L m^{-2} h^{-1}
D	diffusion coefficient, m^2 s^{-1}
C_{OS}	modified van't Hoff coefficient, bar kg g^{-1}
S	membrane structure parameter, m
C	unit economic cost, $/unit

Subscripts/superscripts

mix, *M*	mixing
i	specie of salt
high	solution with high concentration
low	solution with low concentration
s	initial saline stream
B	brine
P	permeation
charge	operation of charging period
discharge	operation of discharging period
RO	reverse osmosis
PRO	pressure retarded osmosis
min	minimum
max	maximum

Acronyms

CWES	concentrated water energy storage
PHS	pumped hydroelectric storage
CAES	compressed air energy storage
RO	reverse osmosis
PRO	pressure retarded osmosis
MSF	multi-stage flash
MED	multi-effect distillation
TVC	thermal vapour compression
AD	adsorption desalination
MD	membrane distillation
FO	forward osmosis
HDH	humidification-dehumidification
ED	electrodialysis
MVC	mechanical vapour compression
CDI	capacitive deionization
RED	reverse electrodialysis
CAPMIX	capacitive mixing

using the salt dome for storage, which was built in 1978. The other is an 110 MW plant with a capacity of 26 h in McIntosh, Alabama.

However, current commercialised large-scale energy storage technologies are subject to geographic restrictions. A site for a PHS plant must be suitable for the construction of standing or dammed-up water reservoirs, and the capacity of the reservoir [11]. For building large-scale CAES plants, concerning the storage capacities up to several hundreds of megawatts, underground salt caverns, natural aquifers, and depleted natural gas reservoirs are potentially the most appropriate options [9]. The dependence on these specific geographic sites restricts the deployment of the large-scale energy storage systems of both PHS and CAES. In fact, installation of new PHS plants inclined since 90s due to the environmental concerns and scarcity of favourable sites [12]. And the potential for the further major PHS schemes would also be restricted [13]. Also, excluding storing the compressed air underground, it is challenge for CAES plants storing the compressed air above the ground to have bulk scale [14]. So the paper is to explore an alternative way for implementation of bulk energy storage.

A feasibility study of an innovative bulk energy storage by concentrating/desalinating water is conducted by employing technologies of desalination and osmotic energy generation. Since the mid-20th century desalination has been demonstrated to be a viable approach to broaden the current drinkable water supplies and has been widely and successfully used to produce freshwater in the Middle East and North African countries [15]. In addition, generation of osmotic energy, or salinity energy, from salinity gradients has been identified as a promising technology [16]. Similar to the reverse processes of lifting and releasing of water head in PHS, and processes of compressing and expanding air in CAES, desalination and osmotic energy generation are reverse processes to concentrate/desalinate and mix saline waters. Electricity is used to desalinate freshwater from saline stream and overcome the increased concentration difference. During mixture of the two streams, electricity is generated from the chemical potential between salinity gradients. Therefore, these two processes theoretically can be integrated to fulfil a cycle of charge and discharge to store electricity during off-peak and generate power during peak time. Moreover, compared to PHS and CAES, a significant advantage of desalination and osmotic energy generation is that freshwater can be produced with energy storage. It allows potential co-generation (or co-storage) of energy and freshwater in the hybrid system simultaneously. Additionally, the salinities can be stored in ambient temperature/pressure/height without geometric restrictions of CAES or PHS. Therefore, taking these potential advantages and the significant improvements on the osmotic energy generation technologies, a question arises: how about the performance of this new energy storage system?

The answer has not been found from the published studies yet. Only limited investigations focusing on a prototype using osmotic energy generator in thermal energy conversion have been envisioned. A process based on a closed-loop pressure retarded osmosis (PRO) has been recently proposed as an approach of transforming unusable low-grade thermal energy, such as waste heat, into electricity to the power network [17]. The process, also called an osmotic heat engine, enables a form of osmotic grid storage for available thermal energy and intermittent renewables [17–19]. It was estimated to be $\sim$ 1kWh/m^3 energy density of an osmotic battery at