Applied Energy 211 (2018) 1060–1079

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimal design of solid-oxide electrolyzer based power-to-methane systems: A comprehensive comparison between steam electrolysis and co-electrolysis

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HIGHLIGHTS

- System design of solid-oxide electrolyzer based power-to-methane system comprehensively investigated.
- System performances with different operating modes of the electrolyzer deeply and intensively compared.
- Better system-level heat integration achieved by the co-electrolysis when operating with sweep air.
- System capacity significantly enlarged with the exothermic operating mode and electrical heating avoided.
- Significant heuristics derived for selecting critical design and operating variables.

ARTICLE INFO

Keywords:
Energy storage
Power-to-gas
Power-to-methane
Solid-oxide electrolyzer
Co-electrolysis
CO_2 utilization

ABSTRACT

Power-to-methane technologies have been regarded as a promising alternative to offer small- or large-scale, long-timescale (daily/weekly/seasonal) energy storage as well as the opportunity of utilizing CO_2. The performance of the core component, the electrolyzer, largely determines how well a power-to-methane system can perform, making high-temperature solid-oxide electrolysis attractive because of its inherent high electrical efficiency. More importantly, solid-oxide electrolysis uniquely allows co-electrolysis of steam and CO_2 for producing syngas, the composition of which can be readily, flexibly adjusted to synthesize different hydrocarbon fuels. In this paper, for both steam- and co-electrolysis, we comprehensively and comparatively investigate several critical design issues of a solid-oxide electrolyzer based power-to-methane system with fixed-bed methanation reactor and membrane-based methane upgrading: (1) system-level heat integration, (2) the impacts of operating variables (e.g., operating voltage, reactant utilization, anode/cathode feed ratio, and operating pressure of the methanation reactor and membrane) on system performances, (3) the competitiveness of the electrolyzer operation with pure oxygen production, and (4) the possibility of avoiding electrical heating, which is necessary for thermoneutral operation to heat up the electrolyzer feeds to the required temperature. To achieve this target, a multi-objective optimization platform with integrated heat cascade calculation is employed with experimentally-calibrated component models. The results show that, for both steam- and co-electrolysis, there is a trade-off between system efficiency and methane yield: pursuing a higher efficiency generally reduces the methane yield, which is a consequence of electrochemistry, stack cooling and system-level heat integration. Instead of sweep air, pure oxygen production is preferred only at small current density, which delivers the highest system efficiency but the lowest methane yield. When the electrolyzer operates exothermically, methane production and the total power consumption can vary in much wider ranges than those with the electrolyzer operating under thermoneutral mode, which leads to potential enhancement of operation flexibility and reliability. The co-electrolysis coupling with strongly-exothermic syngas methanation, in general, offers better heat-integration opportunity with sweep air, but less with pure oxygen production. In addition, several design heuristics, e.g., the operating pressure of the electrolyzer and methanation reactor, are concluded to potentially guide practical applications.

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https://doi.org/10.1016/j.apenergy.2017.11.050
Received 25 August 2017; Received in revised form 3 November 2017; Accepted 6 November 2017

Nomenclature

Abbreviations

AE	alkaline electrolyzer
AMPL	a mathematical programming language
CE	co-electrolysis
CPLEX	a commercial solver for large-scale (mixed-integer) linear programming problem
EES	engineering equation solver
EH	electrical heating
FP	fans, compressors and pumps
HEN	heat exchanger network
HER	hydrogen evolution reaction side
HHV	higher heating value
LCI	lifecycle indicator
MILP	mixed integer linear programming
MOO	multi-objective optimizer
OER	oxygen evolution reaction side
PEC	purchased equipment cost
PEME	polymer electrolyte membrane electrolyzer
PtM	power-to-methane
SE	steam electrolysis
SOE	solid-oxide electrolyzer
TPB	triple-phase boundary
VCH	vapor condensing heat

Greek symbols

η	efficiency, –

Mathematical symbols

$\Delta_r H^0_{298}$	standard enthalpy of formation, kJ mol^{-1}
$\dot{E}$	electricity consumption, kW
$\dot{F}$	molar flowrate, kmol K^{-1}
$\dot{m}$	mass flowrate, kg s^{-1}
A	membrane area, m^2
L	molar permeability, kmol m^{-2} h^{-1} bar^{-1}
M	syngas modular
R	gas constant, 8.314 J mol^{-1} K^{-1}
r	normalized rate constant, –
T	temperature, K
v	hourly space velocity, h^{-1}
Z	molar fraction, –

Subscripts

i	species index
k	segment index
R	retentate flow
P	permeate flow
tot	total

1. Introduction

Due to the dynamic and intermittent nature of renewable energies and frequent mismatch of renewable-power supply and demand, energy storage has become a critical issue to deal with the increasing deployment of renewable energies, particularly wind and solar power. There have been many energy storage technologies available for short-timescale (second–minute) power quality regulation (e.g., sag compensation, power smoothing, grid stabilization, and frequency regulation) and long-timescale (minute–hour–day–month) bulk power management (e.g., load leveling, load following, power balancing, peak shaving and time shifting) [1]. These energy storage technologies can vary significantly with respect to storage capacity, power/energy density, round-trip efficiency, discharge timescale, performance degradation, durability and reliability, site versatility, modularity and scalability, operation complexity and flexibility, capital investment and maintenance cost, environmental impact, etc. [1,2]. Among these available technologies, only pumped-hydro and compressed-air energy storage have been deployed and operated for large-scale long-timescale (daily, weekly or seasonal) storage [3–5], while these two technologies suffer from either strict geographical constraint, very high capital investment, or low round-trip efficiency. Therefore, converting renewable electricity, whenever available, to easy-to-store/transport synthetic methane via power-to-methane technologies (PtM) has been considered as a promising choice for high-density, efficient, long-timescale energy storage [6–9], due to the existing infrastructure for methane storage and distribution. Particularly, storing renewable-derived chemicals [10,11] has been concluded as the only viable option to store electricity at a scale of over 10 GW h [12]. In addition to large-scale applications, medium- and small-scale power-to-methane technologies are also potential for the enhancement of chemical processes, e.g., biogas upgrading [13–15] and catalytic biomass-to-methane processes [16,17], or as an important element for the energy storage of district-level energy storage systems [18,19] to foster the flexibility in the low- and medium-voltage grid with renewable energies [20–23]. The multifunctional synthetic methane, also as an important energy carrier and commodity, can serve as a clean, renewable transportation/household hydrocarbon fuel, which may contribute significantly to forming a low-carbon or carbon-neutral society [24]. Therefore, various PtM systems are currently under intensive research, development and demonstration

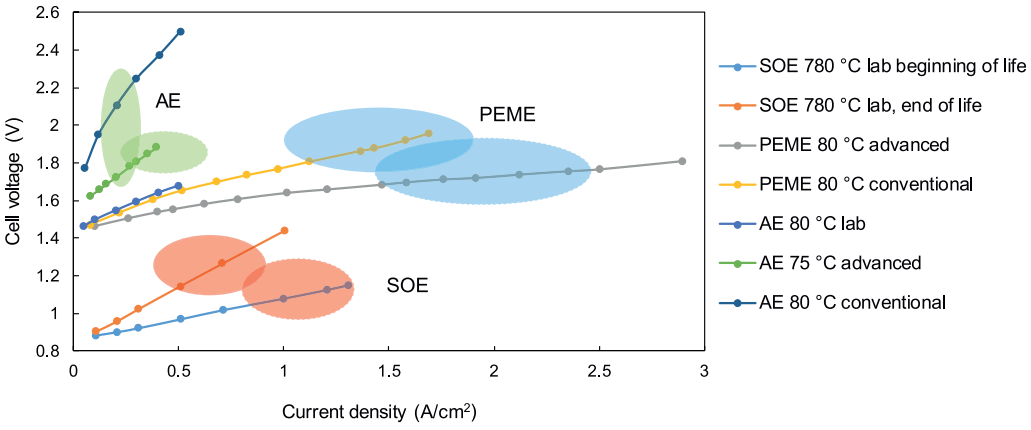

Fig. 1. Comparison of three different electrolysis technologies at stack level with typical operating conditions for today (solid eclipse) and future (dashed eclipse) performances (reproduced from [38] with permission of the author, AE – alkaline electrolysis, PEME – acidic proton exchange membrane based electrolysis, SOE – solid oxide electrolysis).