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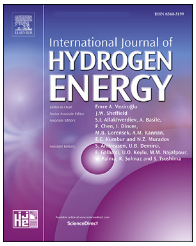

Optimal operation of a photovoltaic generation-powered hydrogen production system at a hydrogen refueling station

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ABSTRACT

As the popularity of fuel cell vehicles continues to rise in the global market, production and supply of low-carbon hydrogen are important to mitigate CO_2 emissions. We propose a design for a hydrogen refueling station with a proton exchange membrane electrolyzer (PEM-EL)-based electrolysis system (EL-System) and photovoltaic generation (PV) to supply low-carbon hydrogen. Hydrogen is produced by the EL-System using electricity from PV and the power grid. The system was formulated as a mixed integer linear programming (MILP) model to allow analysis of optimal operational strategies. Case studies with different objective functions, CO_2 emission targets, and capacity utilization of the EL-System were evaluated. Efficiency characteristics of the EL-System were obtained through measurements. The optimized operational strategies were evaluated with reference to three evaluation indices: CO_2 emissions, capacity utilization, and operational cost of the system. The results were as follows: 1) Regardless of the objective function, the EL-System generally operated in highest efficiency state, and optimal operation depended on the efficiency characteristics of the EL-System; 2) mitigation of CO_2 emissions and increase in capacity utilization of the EL-System required trade-offs; and 3) increased capacity utilization of the EL-System showed two opposing effects on hydrogen retail price.

Introduction

Due to the improved market penetration of fuel cell vehicles (FCVs), hydrogen demand is expected to increase in the near future. Major countries, including Japan, have established aggressive penetration targets for FCVs. For instance, 800,000 FCVs are expected to be on the road by 2030 in Japan [1]. Hydrogen-fueled FCVs require hydrogen infrastructure unlike battery-operated electric vehicles, which are plugged-in at home. As of 2017, 91 hydrogen refueling stations (HRS) have been constructed and are currently in service in Japan, and the number of HRS is expected to grow to 160 and 320 by 2020 and 2025, respectively. Other locations such as Germany or California in the United States have also set operational targets of 1000 stations by 2030 and 100 HRS by 2020, respectively [2,3].

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Abbreviations and nomenclature

FCV	Fuel cell vehicle
HRS	Hydrogen refueling station
ICEV	Internal combustion engine vehicle
WT	Wind turbine
PV	Photovoltaic generation
RES	Renewable energy resource
CAES	Compressed air energy storage
P2G	Power-to-Gas
VRE	Variable renewable energy
RES-HRS	RES-powered HRS
PEM-EL	Proton exchange membrane electrolyzer
EL-System	PEM-EL based electrolysis system
MILP	Mixed integer linear programming
LiB	Lithium-ion battery
BOP	Balance of plant
TOU	Time-of-use
LCOE	Levelized cost of electricity

Time steps

t, t'	Time step
nt	Number of time steps for the whole optimization period
nts	Number of time steps per hour

Variables

Obj	Objective function
COST	Total cost for the calculation period
ELh	Total hydrogen generation by the EL-System for the calculation period
CO2	CO_2 emissions, t-CO_2
GRID	Electricity supply from the power grid
EL	EL-System, consumption and generation
H2	Off-site reformed hydrogen (purchase)
HRS	Hydrogen refueling station
γ	Variable expressing operation of the EL-System (γ_1: binary, γ_2,γ_3,γ_4 : continuous)
δ	Binary variable expressing operation of the EL-System
LCOH1	Levelized cost of total supplied hydrogen
LCOH2	Levelized cost of generated hydrogen by EL-System

Parameters/constants

price	Price
dem	Demand
co2int	CO_2 emission intensity
pv	Photovoltaic generation
el_E^{bop}	EL-System, rate of electricity consumption by balance of plant to electricity consumption at rated operation
el_E^{low}	EL-System, rate of maximum electricity consumption in low operation state to electricity consumption at rated operation
η_{GRID}^{ad}	Conversion efficiency from AC to DC at interconnection to power grid
η_{el}	Efficiency of EL-System at rated load
$conv_{kWh}^{EMJ}$	Conversion factor of electricity from kWh to MJ
$conv_{Hm3}^{HMJ}$	Conversion factor of hydrogen from Nm^3 to MJ
w_i	Weather data, solar insolation
w_t	Weather data, ambient temperature
$\overline{()}, \underline{()}$	Upper and lower limits

Superscripts

ac	Alternative current
dc	Direct current
hrs	Hydrogen refueling station
bop	Balance of plant
dem	Demand
st	Storage level
lcoe	Levelized cost of electricity
init	Initial investment
lt	lifetime

Subscripts

E	electricity
H	hydrogen

Units

Cost, price	JPY (Japanese yen)
Electricity	kW, kWh
Hydrogen	Nm^3
CO_2	kg-CO_2

The main reason for public uptake of FCVs is CO_2 emission mitigation. FCVs can mitigate CO_2 emissions even though hydrogen is effectively a hydrocarbon material, because FCV well-to-wheel efficiency is higher than that of conventional internal combustion engine vehicles (ICEVs) [4]. Moreover, additional CO_2 mitigation can be achieved if hydrogen is produced from renewable energy resources (RES). Production and utilization of low-carbon hydrogen are thus critical if the growing FCV market is to contribute to the realization of a sustainable society.

High penetration of RES in power systems poses challenges to power system operation, because RES electricity generation is unstable and intermittent, and often severely affects the balance of supply and demand and operation of base load sources, such as through over-generation or "Duck curve" issues [5]. Furthermore, wholesale electricity prices may become negative, that is, utilities would need to pay consumers to use electricity [6]. Power systems need more flexibility in adapting to the challenges of RES [7,8]; otherwise, curtailing RES use may become necessary [9]. There are some possible options to increase grid flexibility, such as energy storage systems, demand response, and distributed energy resources, including fuel cells or electric water heaters. Energy storage systems include large-scale batteries, electric vehicles (vehicle-to-grid) [10], pumped hydro [11], or compressed air energy storage (CAES) [12,13]. One promising approach for hydrogen utilization of RES is Power-to-Gas (P2G) [14,15]. P2G produces hydrogen or methane from electricity produced by

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