

## Efficiency of unitized reversible fuel cell systems

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#### ABSTRACT

A pilot-scale unitized reversible fuel cell (URFC) system was installed in our laboratory (AIST) and its efficiency was comprehensively evaluated. This URFC system was composed of a proton exchange membrane (PEM)-based cell/stack and balance of plant (BOP) adaptable for both electrolysis (EL) and fuel cell (FC) operation modes. First, the efficiency of this URFC system was evaluated at both the stack level and system level. Next, the efficiency was also evaluated by considering the amount of recovered heat during EL and FC modes assuming combined heat and power (CHP) applications. Then, the calculated efficiency of the URFC system at each operation mode was compared with that of specialized devices of PEM electrolyzer and PEM fuel cell as reference standards. The comparison reveals that the stack performance of the operation modes of the URFC were comparable to that of the respective specialized device for EL and FC, whereas the system performance taking into account the BOP energy consumption requires improved efficiency for the FC mode of the URFC system. Finally, analysis of the system efficiency including heat recovery from the URFC system was used to evaluate quantitatively the potential of heat recovery, revealing that recovery and utilization of thermal energy are essential for improving the efficiency. It was identified that the round-trip efficiency of the system would be improved from 0.182 to 0.589 by utilizing thermal energy.

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#### Introduction

Attention is currently focusing on renewable energy as a countermeasure to the depletion of fossil fuels and to global warming. Renewable energy sources (RES) such as solar and wind have significant potential, but have major drawbacks related to their fluctuating and intermittent nature. When the proportion of power output from RES such as photovoltaic (PV) or wind power is considerably lower than the capacity of the

electricity grid network, the fluctuation of RES can be balanced by conventional power generation. In the recent rapid, widespread introduction of unstable RES (PV and wind power) implemented in numerous countries, the capacity of unstable RES might reach the limitation of grid balancing. This problem will be critical in small-scale grids in rural and island areas. Under these circumstances, energy storage is considered a solution for stabilizing the supply of electricity [1].

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Hydrogen is a unique storage medium for unstable RES because it offers many advantages for the storage of RES

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Nomenclature			$W_{BOP\_FC}$	total en
	Istack	stack current, A		(BOP) di
	i <sub>stack</sub>	stack current density, A $m^{-2}$		$(= (P_{P1} -$
	F <sub>BLW</sub>	flow rate of air supplied from air-blower, $m^3 s^{-1}$	W <sub>stack_EL</sub>	energy operat
		$(L \min -)$	W <sub>stack FC</sub>	energy
	F <sub>H2</sub>	now rate of circulating hydrogen, m <sup>2</sup> s <sup>-</sup> (L min <sup>-</sup> )	-	operat
	$P_{\rm H2}$	pressure of produced/supplied hydrogen from/to		
	л	stack, Pa (abs)	Greek Syr	nbois
	P <sub>BLW</sub>	power consumption of air-blower, w	$\Delta H_{H2_{cons}}$	, enthal
	P <sub>loss_AC/E</sub>	$_{\rm C}$ power loss related to AC-DC converter		operat
		(conversion eniciency of AC-DC converter: 0.85),		(handa)
	D	w	A 1.1	(KWII)
	r <sub>P1</sub>	for cooling water). W	ΔΠ <sub>H2_prod</sub>	oloctro
	D	nower consumption of nump 2 (circulation nump		and st
	1 P2	for electrolycic water) W		
	P	nower consumption of nump 3 (circulation nump	n -	stack of
	1 P3	for hydrogen) W	'Istack_EL	Table 2)
		heat loss to ambient during electrolysis operation.	note de EG	stack ef
	~1055_EL	J (kWh)	"Istack_FC	Table 2
	Qloss FC	heat loss to ambient during fuel cell operation, J	netack BT	stack ef
	2000_10	(kWh)	η <sub>eve FI</sub>	system
	Q <sub>rcvr EL</sub>	recovered heat from the stack with cooling water	ISYS_EE	Table 2)
		during electrolysis operation, J (kWh)	η <sub>svs FC</sub>	system
	Q <sub>rcvr_FC</sub>	recovered heat from the stack with cooling water		Table 2
		during fuel cell operation, J (kWh)	$\eta_{sys_{RT}}$	system
	T <sub>stack</sub>	stack temperature, K (°C)	$\eta'_{sys}_{EL}$	system
	t <sub>EL</sub>	operation time of electrolysis, s (h)	-	electrol
	t <sub>FC</sub>	operation time of fuel cell, s (h)	$\eta'_{sys}$ _FC	system
	V <sub>cell</sub>	cell voltage, V		fuel cell
	$V_{\text{cell\_avg}}$	average cell voltage calculated by dividing $V_{\rm stack} in$	$\eta'_{\text{sys }\_RT}$	system
		the number of cells in series, V		round-t
	$V_{\text{stack}}$	overall stack voltage, V		
	$W_{\text{BOP}\_\text{EL}}$	total energy consumption of balance of plant (BOP)		
		during electrolysis operation		
		(= ( $P_{P1} + P_{P2} + P_{loss\_AC/DC}$ ) × t <sub>EL</sub> ), J (kWh)		

$W_{BOP_FC}$ total energy consumption of balance of (BOP) during fuel cell operation (= (P_{P1} + P_{P3} + P_{BLW}) \times t_{FC}), J (kWh)	plant	
$W_{stack\_EL}$ energy input into the stack during electroperation (= $V_{stack} \cdot I_{stack} \times t_{EL}$ ), J (kWh)	trolysis	
	ıel cell	
Greek symbols		
ΔH <sub>H2_cons</sub> enthalpy of consumed hydrogen durin operation calculated using amount and enthalpy of formation of hydrogen (HI (kWh)	ıg fuel cell l standard HV), J	
$\Delta H_{H2_{prod}}$ enthalpy of produced hydrogen during	5	
electrolysis operation calculated using	amount	
and standard enthalpy of formation of	hydrogen,	
J (kWh)		
$\eta_{stack\_EL}$ stack efficiency during electrolysis oper	ation (cf.	
Table 2)		
$\eta_{\text{stack}_{FC}}$ stack efficiency during fuel cell operation	on (cf.	
Table 2)		
$\eta_{stack_{RT}}$ stack efficiency of round-tip (cf. Table 2	2)	
$\eta_{sys\_EL}$ system efficiency during electrolysis ope	eration (cf.	
Table 2)		
$\eta_{sys\_FC}$ system efficiency during fuel cell operation	tion (cf.	
Table 2)		
$\eta_{sys\_RT}$ system efficiency of round-trip (cf. Tabl	e 2)	
$\eta'_{\text{sys}\_EL}$ system efficiency including heat recove	ry during	
electrolysis operation (cf. Table 2)		
$\eta'_{\text{sys }\_FC}$ system efficiency including heat recove	ry during	
fuel cell operation (cf. Table 2)		
$\eta'_{\text{sys }_{RT}}$ system efficiency including heat recove	ry for	
round-trip (cf. Table 2)		

output; 1) hydrogen can be produced with water electrolysis from intermittent RES (e.g., PV and wind power), 2) produced hydrogen can be stored in numerous forms (e.g., compressed, liquefied, metal hydride) without self-discharge over time, 3) carbon-free electricity production can be achieved using a fuel cell, and 4) system power (kW) and stored energy (kWh) can be independently optimized.

According to literature [2–7], hydrogen utilization systems have been extensively studied for several decades. Up to now, the major component of such systems has been a small-scale distributed energy system typically consisting of an RES, water electrolyzer, hydrogen storage apparatus, and a fuel cell. PVs and wind turbines are most common RES for these systems. The lower operating temperature of proton exchange membrane fuel cells (PEMFCs) (~80 °C) enables excellent start-up performance, a simplified BOP, and a compact total system. However, also due to low operating temperature, PEMFCs are sensitive to impurities in the hydrogen. Power production by a fuel cell introduced into a hydrogen utilization system can be supplied by stored pure hydrogen. Consequently, PEMFCs are promising candidates as power production devices in hydrogen storage systems.

In general, a hydrogen utilization system is connected to either an AC-grid or a local DC-bus [2–5]. Although the operation strategy depends on the specific purpose of the system, there must be no overlap time between the electrolysis (EL) operation mode and fuel cell (FC) operation mode regardless of the type of application. Proton exchange membrane (PEM) electrolyzers and PEMFCs both use a common proton exchange membrane (PEM) as the electrolyte, and have a similar cell/stack design. From the technical viewpoint, it is possible to establish a unitized cell/stack of these two electrochemical devices. A unitized reversible fuel cell (URFC) based on PEM has been studied for several decades [8–11] as an energy device for space [12–14] or terrestrial applications [15,16]. As an energy-conversion device in stationary systems, URFCs have

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