

Electronic supplementary information of “Pathway toward cost-effective green hydrogen production by solid oxide electrolyzer”

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1. Wind power capacity factor

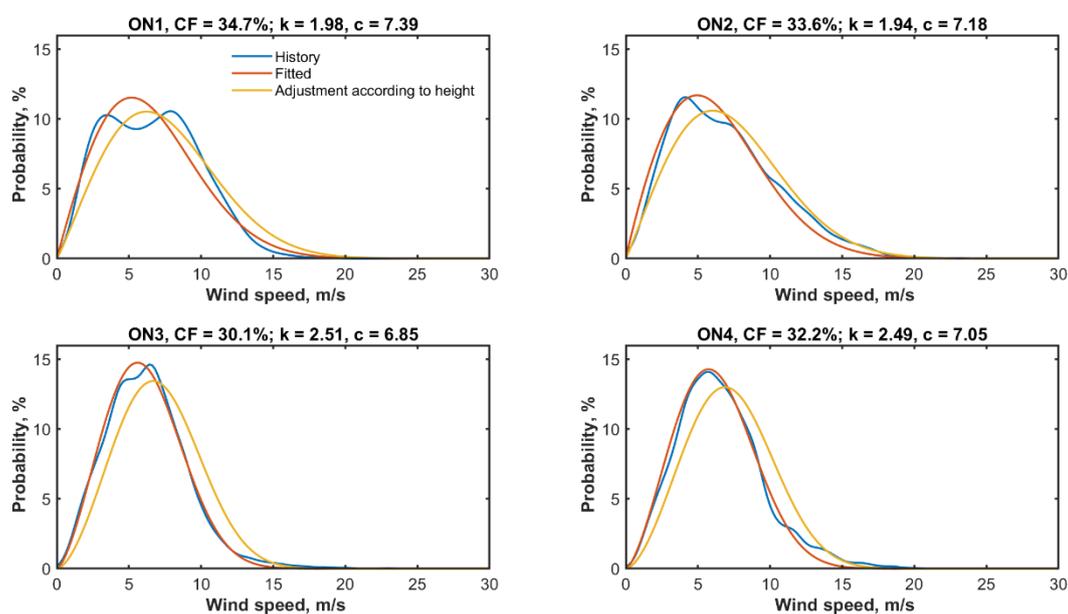


Fig. S1: Probability density of the wind speed for onshore location.

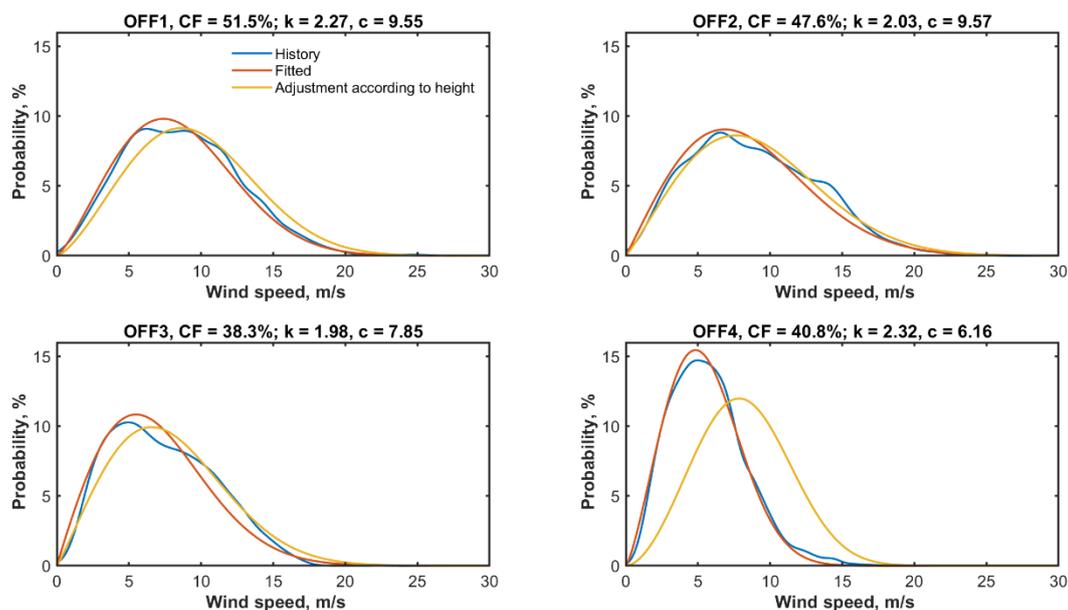


Fig. S2: Probability density of the wind speed for offshore location.

2. Energy analysis

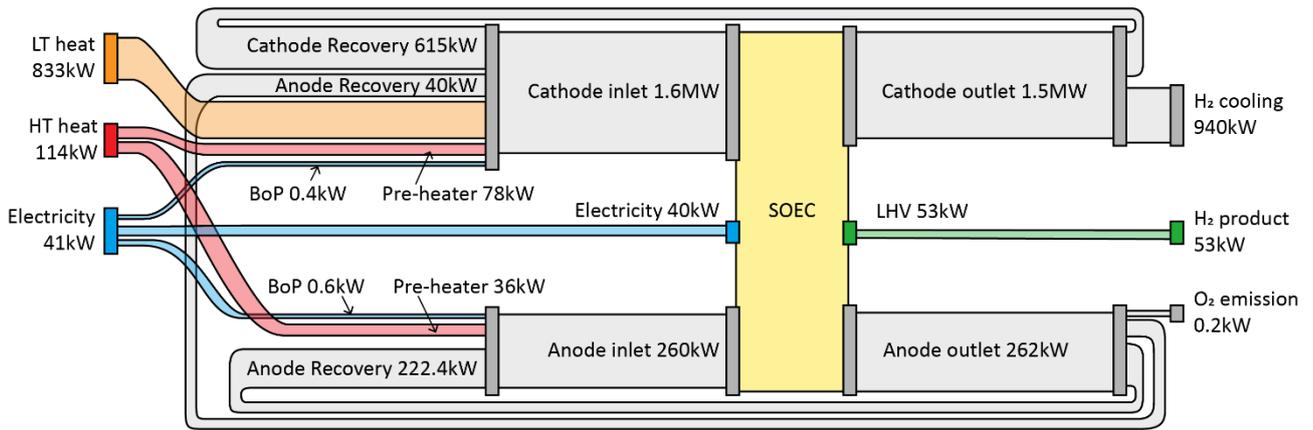


Fig. S2: Sankey diagram @stand-by

3. LCOH for different current density

After initial screening, four tests were selected under constant conditions for more than two kh. These tests confirmed stable degradation rates and potential commercial viability. Table S1 lists the durability of each cell. Cell A runs at -0.50 A/cm^2 and is electrolyte-supported [1]. Cell B–D are fuel electrode supported cells, operate at -0.75 , -1.00 , and -1.25 A/cm^2 , respectively [1-3]. Their degradation is fast at the initial stage, with DR1 values of 875, 20, 180, and 60 mV/kh. After initialization, degradation becomes stable, with DR2 of 6.0, 8.0, 6.6, and 55 mV/kh, respectively. The transition time t_s from initial rapid degradation to stable degradation are 0.05, 1.60, 0.70, and 1.25 kh, respectively. A virtual cell type, Cell E, is included for comparison. Its initial voltage and durability are predicted from the SOEC technology development trend [4]. Cell E operates at -1.25 A/cm^2 with minimal degradation (5 mV/kh). Fig. S3 illustrates the experiment data vs. PLA. The PLA fit the experimental data well, with the R2 for all cases greater than 0.998. Different degradation patterns result in a different lifetime. Assuming the V_{EoL} is 1.50 V and 8 kh operations per year, the lifetime of cell A–D is 9.6, 7.2, 5.4, 0.84 years. For the hypothesis Cell E, its lifetime is 12.5 years.

Table S1: Durability performance of each cell.

Name	J , A/cm^2	T , $^\circ\text{C}$	V_{init} , V	DR_1 , mV/kh	t_s , kh	DR_2 , mV/kh	Ref.
Cell A	-0.50	830	1.00	875	0.05	6.0	[1]
Cell B	-0.75	780	1.02	20	1.60	8.0	[2]
Cell C	-1.00	800	1.09	180	0.70	6.6	[2]
Cell D	-1.25	800	1.12	60	1.25	55	[3]
Cell E	-1.25	800	1.00	-	-	5	-

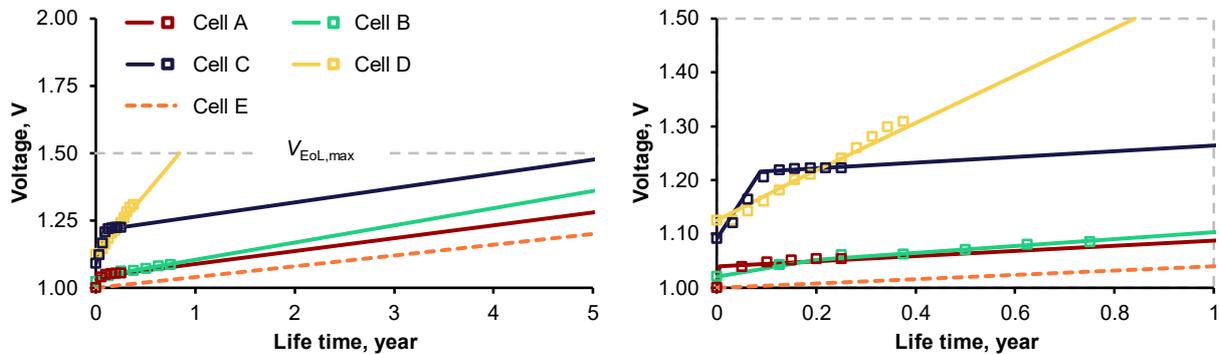


Fig. S3: Voltage development for each cell. The square is experiment data extracted from reference. Solid line is the PLA estimation. (b) is the zoomed-in image of (a).

The increase in current density will directly reduce the SOEC area and capital costs. Also, cell degradation and heat balance variation will result in additional replacement and capital costs. Fig. S4(a) compares the capital and replacement LCOH of each cell type. A trade-off between current density and degradation rate exists in the system design. Generally, low current density operation is undesirable. The capital cost is $\$0.82/\text{kg H}_2$, which is 34.4% higher than Cell C. Low current density operation is temporary for the industry today to ensure a long lifetime. However, it is better to run at a high current density to cut SOEC capital costs. The replacement cost of Cell C is $\$0.20/\text{kg H}_2$. Cell C is replaced at 1.42 V instead of 1.50 V, which means 31.2 kh of replacement. Optimization suggests an active replacement and avoids high power consumption at high voltage. Cell D is not mature and

needs to be replaced frequently, costing three times more than other cells. Nevertheless, if the technology develops and the degradation rate is lowered to 5 mV/kh, as with Cell E, the replacement cost would decrease to \$0.10/kg H₂, half of the others. Fig. S5 shows the LCOH of cells. Based on the available cell technology, the SOEC system with Cell C and -1.00 A/cm² has the lowest LCOH, 3.16 \$/kg H₂.

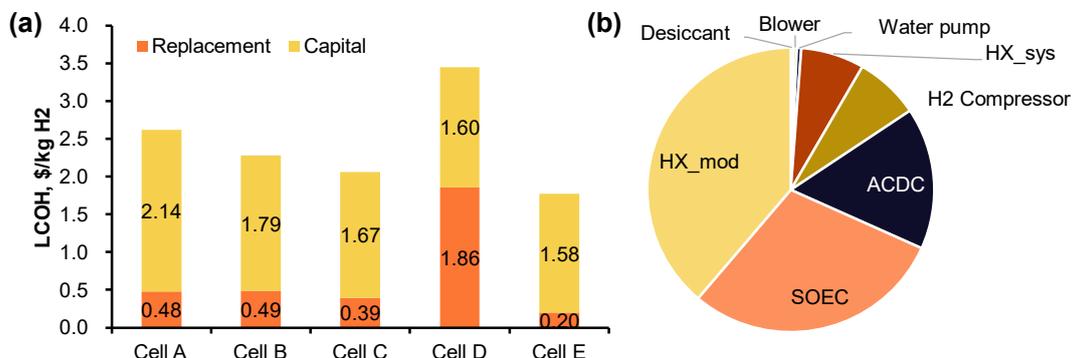


Fig. S4: Capital cost of the SOEC system. (a) Capital and replacement LCOH for each cell. (b) Pie chart of capital cost for Cell E.

With further advancements in SOEC cell technology, the LCOH can be further reduced to 3.10 \$/kg H₂ with Cell E. Overall, improving current density and lifetime is critical to lowering hydrogen production costs and profitability. Fig. 4(b) illustrates the pie chart of the uninstal cost on Cell E. When operated at a high current density, the SOEC capital cost can be reduced from 50.5% (Cell A, -0.5 A/cm²) to 25.3% (Cell E, -1.25 A/cm²). Desiccant and heat exchangers are the most expensive units in the SOEC system. Desiccant involves a series of pressurized and adsorption units, which result in 26.4% capital cost. The heat exchanger network is responsible for 38.7% of capital cost, 6.0% for the system, and 32.7% for the module. There are 179 modules included in the system. Duplication of small heat exchangers significantly increases construction costs.

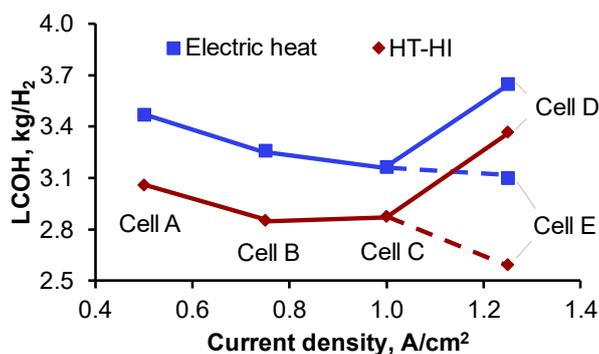


Fig. S5: LCOH of each cell type with and without HT-HI.

Heat integration can faster the commercialization of green hydrogen. The high temperature heat integration (HT-HI) with free waste heat is used here. As shown in Fig. S5, LCOH is saved by 8.9 ~ 16.4% with H-HI. Cell B is the most profitable cell with HT-HI and only \$0.03/kg H₂ lower than Cell C. In the future, a stable Cell E with high current density shows 9.2% lower LCOH than Cell B. HT-HI even change the optimal V_{EoL} .

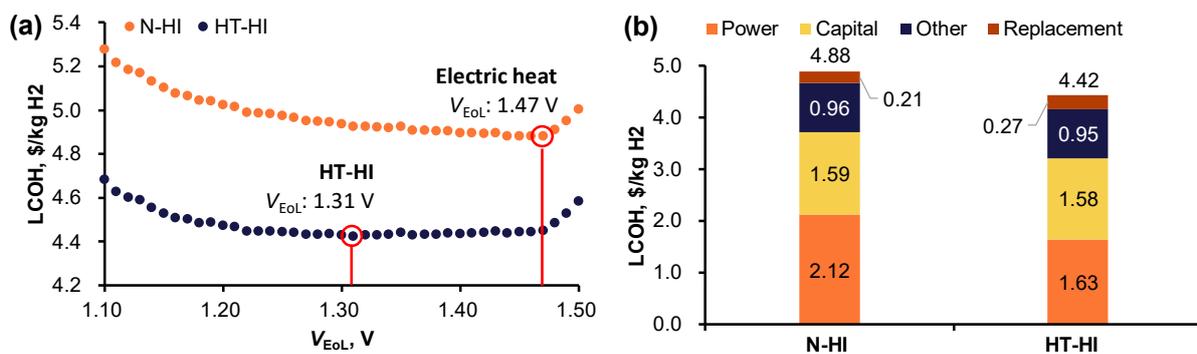


Fig. S6: (a) LCOH of Cell E with different V_{EoL} and (b) bar chart of Cell E LCOH at optimal V_{EoL} w/o HT-HI.

LCOH of Cell E with different V_{EoL} is shown in Fig. S6(a) and LCOH at optimal V_{EoL} is shown in Fig. S6(b). Without HT-HI, the optimal V_{EoL} is 1.47 V, replacement after 94 kh of operation. The operation cost is \$1.92/kg H₂, in which \$0.41/kg H₂ is used for heating. With HT-HI, the optimal V_{EoL} decreased to 1.31 V, resulting in a lifetime of 62 kh, 65.9% of the formal one. Saving heating costs motivate more frequent replacement but only increases \$0.07/kg H₂ replacement cost. \$0.55/kg H₂ is saved on electric power cost, which is 28.6% of the LCOH for no waste heat scenario. As a result, with HT-HI, the LCOH is saved by \$0.51/kg H₂.

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- [4] Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) Addendum to the Multi - Annual Work Plan 2014 - 2020 2018.