Total Energy for the SOEC and SOFC

Mark C. Williams* and Randall S. Gemmen*

* U.S. DOE National Energy Technology Laboratory, Morgantown, WV 26501

*mark.williams@keylogic.com

Abstract

The Solid Oxide Fuel Cell (SOFC) Program at the National Energy Technology Laboratory (NETL) managed by the U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) is currently developing low-cost SOFC and Solid Oxide Electrolysis Cell (SOEC) systems. This paper develops the Total Energy (TE) (kilowatt-hours per kilogram hydrogen, kWh/kgH₂) for the SOEC and SOFC. The Total Energy includes heat input, exergetic flows, enthalpy of vaporization, pressurization, heat loss, area specific resistance, etc. The SOEC Total Energy developed at NETL, as it would happen, correlates well with the Idaho National Laboratory (INL) proven SOEC performance of forty-five kilowatt-hours per kilogram hydrogen at twenty bars, 1.3 volt and 725°C. Total Energy is necessary for designing, predicting, and planning for SOEC and SOFC performance and cost.

Introduction

The SOFC and SOEC technologies are expanding globally and finding new market opportunities in a variety of applications. The technology has not been fully developed and has a promising future. The amazing versatility and applicability of the solid oxide technology is astounding as solid oxide fuel cells are developed as a source of efficient, low-cost electricity from natural gas for distributed power generation, as reversible cells, and as SOEC to produce hydrogen. The technology has many applications in data centers, distributed generation, microgrids, hydrogen production, hydrogen energy storage, telecom backup markets, telecommunications, banking, combined heat and power (CHP), absorption chillers, power to chemicals and fuels, ships, vehicles, drones, sensors, and others (1, 2).

The SOFC and SOEC technology also finds applications in national defense, space programs and world health initiatives due to uniqueness in its suitability for in-situ resource utilization and oxygen separation and compression for life support. Because of the diversity of applications, fuel flexibility, hybridization with renewable resources and hydrogen production (when operated in reverse mode), it offers national competitive and energy security advantages in the global energy environment as it utilizes non-noble and non-strategic materials resources abundant in the United States.
Development

Total Energy is the key performance indicator necessary for designing, predicting, and planning for SOEC and SOFC performance and cost. INL has developed the concept for all electrolyzers and presented it as shown in Figure 1 (3).

![Figure 1 INL Total Energy Performance for Electrolysers](image)

The Total Energy of 33.6 kilowatt-hours per kilogram hydrogen at lower heating value (LHV) shown in Figure 1 is simply the value for providing the complete $\Delta H^r$ through voltage. It is only the thermodynamic lower (ideal) limit if one does not provide heat from outside and operate at atmospheric pressure. The actual lower limit occurs at essentially zero current (all losses essentially zero) is based on the OCV(T). That is, the true lower limit is at the Carnot temperature when $\Delta G$ equal zero.
The SOEC Total Energy includes heat input, exergetic flows, enthalpy of vaporization, pressure drop (function of velocity and diameter), radiative heat loss (function of temperature) pressurization, area specific resistance, etc. (2). All in the units of joule/mole (J/m) hydrogen. The non-design specific aspects of Total Energy are straightforward and are not dependent on a specific configuration of the SOEC. Total Energy is always negative but is sometimes plotted positively as shown in Figures 1 and 3. The the heat of vaporization, exergetic flows, and enthalpy of reaction (when it is included) are negative. ASR (area specific resistance) is positive. J, the current, is negative when operating as an SOEC. All the parasitics are negative since they increase SOEC power input requirements.

For \( 0 \geq J \geq J_{TN} \), heat must be added for electrolysis to occur. It is not free. At any particular \( J \), \( Q \) is calculated from JASR and \( \Delta S \) (Figure 2). At \( TN \), \( Q = 0 \). \( J \), JASR and \( \Delta S \) are always negative.

If \( Q \) is free, it is omitted from the TE Equation. At any particular \( J \), \( Q \) is still calculated from JASR and \( \Delta S \).

For \( J_{TN} \geq J \), heat must be removed. JASR includes \( Q \). Starting with the TE Equation, \( Q \) can be shown explicitly. At any particular \( J \), \( Q \) is calculated from JASR and \( \Delta S \).

**Results**

The NETL SOEC Total Energy calculated using the above equation correlates well with the INL proven forty-five kWh/kgH\(_2\) Total Energy performance at twenty bar and 1.3 volt (see Figure 3). The Total Energy prediction at twenty bar and 1.3 volt is close to proven Total Energy performance of INL. The thirty-five kWh/kgH\(_2\) Total Energy Hydrogen and Fuel Cell Technology Office (HFCTO) Design Point is a SOEC near-term performance expectation.
target. Using externally supplied $Q$ and $\Delta H_{\text{vap}}$ would lower the INL proven Total Energy of forty-five kWh/kgH$_2$ at twenty bar and 1.3 volt by five kWh/kgH$_2$. Thermoneutral operation for water splitting without heat addition, $Q$, may be holding development back if high ASRs are tolerated.

Figure 3 SOEC Total Energy (Total Energy plotted positively)

The Total Energy for the SOFC is given by:

$$TE = 26801 \left( \frac{V}{1000} \right) + \frac{\left[ -\Delta H_{\text{vap}}(T) - e_f(T) - Q_{\text{loss}}(T) - RT \ln \left( \frac{P_T}{P_1} \right) - \Delta P_{\text{loss}} \right]}{2} \frac{1}{60^2} \tag{1}$$

The development of the Total Energy for SOFC is analogous for SOEC. The constant 26801 ampere-h/kgH$_2$ is introduced here for the number of electrons equal two to simplify.

The voltage is given by:

$$V = (OCV(T) + JASR - \frac{RT}{nF} \ln \frac{X_{H_2O}^{0.5} X_{H_2}^{0.5}}{P^{0.5} X_{O_2}^{0.5}}) \tag{2}$$

The absolute value of Total Energy is around twenty kWh/kgH$_2$ for SOFC and forty kWh/kgH$_2$ for SOEC. One must use positive $J$ for the SOFC. Power changes sign through $J$. One still calculates Total Energy like the SOEC, but conceptually it is how many kWh are produced from
a KgH2 rather than how many kg H2 are produced with a kWh of H2 fuel. Heat of vaporization and \( \Delta e \) must change their sign. Then, after the two sign changes, all the parasitics remain negative since they lower SOFC power output.

**Conclusions**

The SOEC Total Energy developed by through the Solid Oxide Fuel Cell SOFC Program at NETL, as it would happen, correlates well with the Idaho National Laboratory proven SOEC performance of forty-five kilowatt-hours per kilogram hydrogen at twenty bars, 1.3 volt and 725°C. Total Energy is a key performance indicator necessary for designing, predicting, and planning for SOEC and SOFC performance and cost.

**Disclaimer**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference therein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed therein do not necessarily state or reflect those of the United States Government or any agency thereof.

**References**

2. Overview of Nuclear-Hydrogen Demonstrations supported by INL, INL/CON-21-63552.