# A Proposed Method for High Efficiency Electrical Energy Storage Using Solid Oxide Cells

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David M. Bierschenk, James R. Wilson, Elizabeth Miller, Emma Dutton and Scott A. Barnett
Department of Materials Science and Engineering
Northwestern University
2220 Campus Drive, Evanston IL, 60201, USA

Large-scale electrical energy storage is becoming increasingly necessary due to the continued growth of intermittent renewable sources such as wind and solar. However, currently available methods generally fail to meet at least one of the key storage-technology targets including cost, efficiency, storage capacity, and widespread availability. Reversible solid oxide cells (SOCs) have many desirable attributes for this application, but have not been widely considered due to their relatively low round trip efficiency. Here we show a novel reversible SOC storage chemistry where the fuel cycles between $H_2O$-$CO_2$-rich and $CH_4$-rich gases, enabled by operating at reduced temperature ($T$) and/or an increased pressure ($P$). The $CH_4$-forming electrolysis reactions require less heat energy input than the usual $H_2$- or CO-forming reactions, thereby allowing much-improved round-trip efficiency.

Figure 1 is a schematic view of the reversible fuel cell, operated in electrolysis mode (blue arrows) to chemically store energy in a fuel, and then in fuel cell mode (red arrows) to convert the fuel back to electricity.

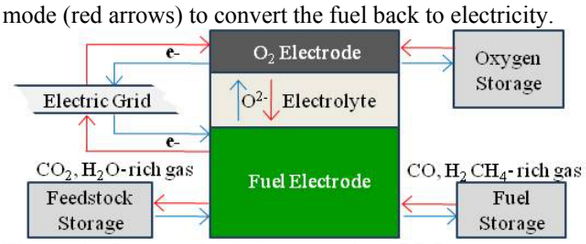


**Figure 1. Schematic of the reversible SOC.**

The maximum theoretical round-trip efficiency (η) of the process is given by the quotient of the fuel cell voltage ($V_{FC}$) and electrolysis voltage ($V_{EL}$)

$$\eta = V_{FC}/V_{EL}, \quad (1)$$

assuming a coulometric efficiency of unity. During electrolysis, the electrical energy input $zFV_{EL}$ (F is Faraday's constant and z is the number of electrons transferred) must match or exceed the thermal energy requirement ($\Delta H$) of the electrolysis reaction; otherwise, the device will cool (unless external heat is supplied). For electrolysis of $H_2O$ and $CO_2$ at 800°C, $\Delta H$ is 248.3 and 282.4 kJ mole$^{-1}$ respectively, requiring $V_{EL} \geq V_{TN} = 1.29$V for $H_2O$ (1.48V for $CO_2$), too high to yield an acceptable η in eq. (1). Here $V_{TN}$ is the thermal-neutral voltage. Thus, the maximum theoretical efficiency is:

$$\eta \leq V_{FC}/V_{TN} = zFV_{FC}/\Delta H, \quad (2)$$

This paper will show how $V_{TN}$ can be reduced and η increased, by utilizing less endothermic $CH_4$-forming reactions. Key parameters include temperature, pressure, and the compositions of the gas storage tanks. Calculations were done for an example condition where the feedstock, containing 8.2% C, 63.1% H, and 28.7% O (pt. 1 in Figure 2a), is electrolyzed to a fuel containing 10% C, 77% H and 13% O (pt. 2 in Figure 2a). These gas compositions are chosen, in part, to avoid the coke forming regions shown in Figure 2a. Gas constitutions were calculated using the Thermocalc SSUB database. For a normal electrolysis condition of $T$ = 800°C and $P$ = 1 atm, mostly $H_2$ and CO are produced by electrolysis resulting in a large $V_{TN}$ as shown in Figure 3. When $T$ is decreased to 600°C or $P$ increased to 10 atm, considerable $CH_4$ (13%) is produced (Figure 2b). As a result, $V_{TN}$ decreases substantially, to ≤ 1.1 V (Fig. 3). Note that these low $V_{TN}$ values are comparable to the Nernst potential, 1.03 - 1.08 V, such that net heat is produced by the cell in electrolysis mode.

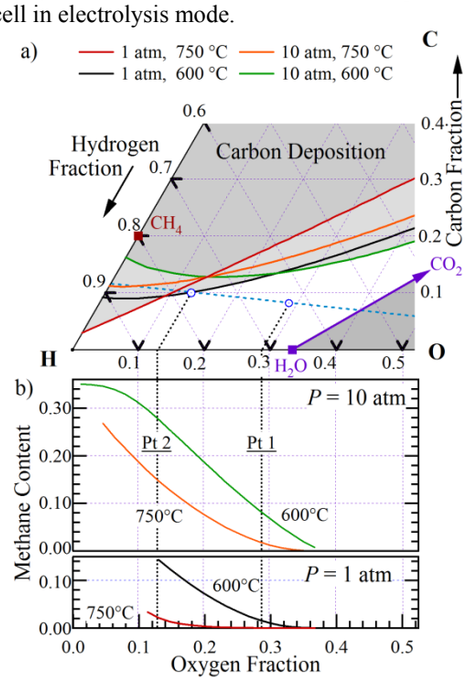


**Figure 2. (a) C-H-O ternary composition diagram section, with carbon forming boundaries indicated for various $T$ and $P$ values. (b) $CH_4$ content versus oxygen fraction for various $T$ and $P$.**

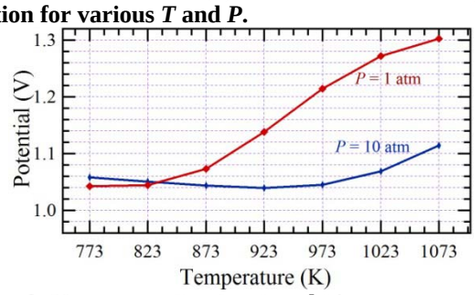


**Figure 3. $V_{TN}$ versus $T$ at $P$ = 1 and 10atm.**

Experimental results for anode-supported SOCs operated under the proposed conditions will be described. Briefly, Ni-YSZ anodes were found to provide good catalytic activity, such that measured product gas constitution matched well with the thermodynamic predictions. Operating SOCs produced the expected $CH_4$-enriched products.

The unique requirements on the SOCs for this application – producing useful current densities at the relatively low overpotentials needed for high efficiency – will be discussed. While this is challenging because of the relatively low $T$ = 600-750°C, pressurization helps to reduce cell polarization resistance.

Finally, balance of plant considerations will be discussed, including gas storage.

In summary, large-scale electrical storage is an important new application for which solid oxide cells appear to be well suited. However, much work remains to be done, posing interesting new challenges for the solid oxide fuel cell community.

ACKNOWLEDGMENTS

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