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A Techno-economic Model Of A Solid Oxide Electrolysis System

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Solid oxide cells can play a vital role in addressing energy and environmental issues. In fuel cell mode they are capable of producing electric energy at high efficiency using hydrocarbon fuels and in the electrolysis mode can produce hydrogen from steam or synthesis gas from a mixture of steam and carbon dioxide. The solid oxide electrolysis cells (SOEC) can operate at a wide range of conditions. A capable means by which to select operating conditions in the application of solid oxide electrolyzers is a necessity for successful commercial operation. Power and efficiency can be determined over a wide range of operating conditions by applying fundamental electrochemical principles to a SOEC system. Operating conditions may be selected based on power requirements or with efficiency as a priority. Operating cost for electricity which is a function of both power and efficiency can also be used to determine optimal operating conditions. Performance maps based on closed form isothermal parametric models for both hydrogen and natural gas fueled SOFC stacks have been demonstrated previously. This approach applied to a SOEC stack is shown. This model was applied to generate performance maps for a solid oxide cell stack operated in the electrolysis mode. The functional form of the model and the boundaries of the operating envelope provide useful insight into the SOEC operating characteristics and a simple means of selecting conditions for electrolysis operation.

1 Introduction

Solid oxide cells can play a vital role in addressing energy and environmental issues. As the demand for energy continues to increase, the need for technological solutions to provide energy at low environmental impact as well as mitigation and reuse of emissions becomes critical. Recent efforts to increase the use of renewable energy sources to provide green energy are hampered by the difficulty in efficiently storing energy to accommodate their intermittency. In that regard, SOEC technology offers a method to convert and store electrical energy in chemical form at an exceptionally high efficiency. The renewable energy can be stored in the form of hydrogen via the steam electrolysis process or synthesis gas via co-electrolysis of steam and carbon dioxide[1]. The synthesis gas from the co-electrolysis process can be further converted to common fuels such as methane and liquid fuels or chemicals. One such scheme of storing renewable energy in the form of liquid fuel using co-electrolysis technology is shown in Figure 1.

Not only does the high temperature electrolysis process convert steam and carbon dioxide at high efficiency, it can also operate over a wide range of conditions in endothermic, thermoneutral, or exothermic mode. The selection of operating condition largely depends upon availability of external heat, for example from solar concentrator[2] vs. wind energy, and power available depending on other load requirements. When external heat is available, the SOEC can be operated in endothermic mode at electrical efficiencies exceeding 100% and when external heat is not available it can be operated in exothermic mode to provide the heat of reaction in which case the electrical efficiency will be lower than 100% but the hydrogen or syngas production rate is higher. Thus, having the SOEC as the load allows tremendous flexibility in managing the distribution and storage of intermittency of renewable energy sources. Most previous economic analyses of high temperature electrolysis were life cycle cost analysis of full systems including the power generation cycle.[3–6] The cost of produced fuel, hydrogen or syngas, also depends upon the operating condition[3]. In this paper a methodology to derive a performance map of an SOEC as a function of the two main variables is presented. While what is shown is for a specific stack performance (i.e. area specific resistance) for the production of hydrogen, the map can easily be translated to production of syngas using stacks of any defined performance behavior. The performance map forms the basis for estimating the cost of fuel generated given the cost of electricity and capital cost of the stack and the balance of plant.

The electrochemical production rate, electrolysis efficiency and electrical power consumed by a solid oxide electrolysis system are not solely determined by stack characteristics but by operating conditions as well. These quantities can be determined by applying various operating conditions to a SOEC system experimentally. However, to gain a meaningful and comprehensive representation of the performance of a SOEC system one must formulate relationships among, elec-

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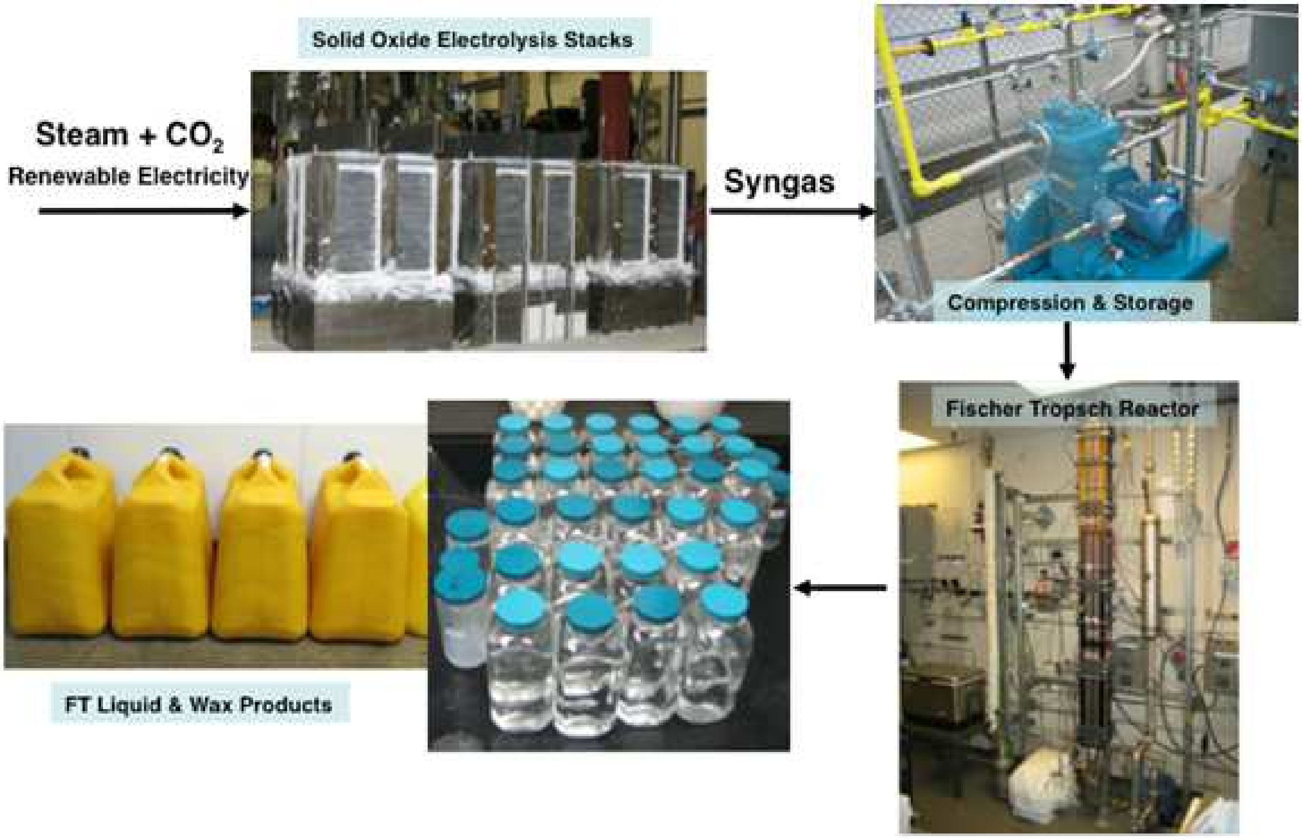

Fig. 1 Fischer Tropsch process utilizing SOEC technology

trochemical production, power consumption and efficiency and present them clearly in terms of controllable operating conditions. The costs related to SOEC operation can be as important as the performance attributes of an electrolysis system. This work looks at the financial costs associated with up front capital as well as operational expense related to hydrogen production. However the context of this work could easily be reframed for the production of syngas. In certain situations it is feasible that the importance of resource consumption could be of critical importance, i.e. oxygen production in human space flight applications. It would be an easy task to modify the model at hand to account for resource cost rather than financial cost. This work provides a map of the performance of an SOEC system as well as a cost map associated with controllable operating conditions. Having a clear view of performance attributes and cost of operation would provide a greater opportunity for system optimization prior to capital investment. Such relationships have been developed previously for SOFC stacks[7–9]. These relationships for solid oxide systems operating in the electrolysis mode are addressed in the present work.

2 Stack Performance Model

The efficiency of a fuel cell stack is the ratio of the electrical power produced to the thermochemical power of the fuel consumed. In this instance fuel utilization is important and justifiably so due to the premium placed on fuel. Reactant utilization is however not a contributing factor in the electrolysis efficiency equation. In the electrolysis case efficiency is the ratio of the thermochemical power produced in the way of hydrogen production to the electrical power consumed. It has been shown that the efficiency (η_{stack}) of an electrochemical cell stack can be represented in terms of the operating voltage (V_{op}) and thermoneutral voltage (E_{tn})[10].

$$\eta_{stack} = \frac{E_{tn}}{V_{op}} \tag{1}$$

In equation (1) V_{op} is the only independent variable. Thermoneutral voltage, defined in equation (2) below, is the heating value (ΔH) of the reactant divided by the number of Faradays of charge required to completely consume this reactant. In the electrolysis mode the reactant is steam.

$$E_{tn} = \frac{\Delta H}{nF} \tag{2}$$

Steam utilization is defined below as the ratio of total current applied to the cell to stoichiometric current. It will be shown in equation (8) that steam utilization (U) is a function of steam flow rate, operating voltage and stack resistance.

$$U = \frac{I}{\dot{n}nF} \tag{3}$$

Given that inlet gas composition and stack resistance are known, the only independent variables that will affect power consumption and efficiency are operating voltage and steam flow rate. Stack resistance being a function of temperature is not considered as variable due to the assumption that the stack will operate close to isothermal conditions at the highest operating temperature possible with respect to stack life and balance of plant limitations. In the same approach covered previously for a SOFC system[7–9] relationships are developed between inlet reactant flow, steam utilization and operating voltage. With these relationships a closed form parametric model is created and used to generate performance and cost maps. These maps can then be used to optimize operating conditions.

The reactant flow rate can be expressed as an electrochemical term which represents the average current density (j_f) at which steam utilization is 100%.

$$j_f = \frac{\dot{n}nF}{A} \tag{4}$$

The driving potential V_f, which is the difference between the operating voltage V_{op} and the Nernst potential E_N, required to sustain full steam utilization current density can then be calculated using the stack area specific resistance.

$$V_f = j_f R'' \tag{5}$$

Here the term R'' represents the cell area specific resistance $(\Omega - cm^2)$, the steam flow rate (mol/s) is represented by $\dot{n}$. The term nF represents the number of Faradays (C/mol), and the cell area (cm^2) is represented by A. By using the term V_f as the driving potential to sustain full steam utilization several simple expressions can be parameterized with respect to steam utilization (U) and operating voltage (V_{op}).

2.1 Model Parameterization

When steam utilization is described in terms of fuel side electrode species concentrations[7] the Nernst potential can be rewritten as a function of utilization (U).

$$E_N(U) = E^o + \frac{RT}{nF} \ln \frac{U \cdot O_2^{1/2}}{1-U} \tag{6}$$

The average Nernst potential can then be calculated as follows.

$$\overline{E_N}(U) = \frac{\int_{U_o}^{U} E_N(U)dU}{U} \tag{7}$$

Integrating equation (6) yields a closed form solution for $\overline{E_N}$. While evaluating equation (7) is easily accomplished, obtaining the inverse function to solve explicitly for U is not possible. The need for solving for exit utilization (U) can be eliminated by developing a parametric representation in U and V_f rather than working with the true physical variables V_{op} and steam flow (V_f). Combining equations (4), (5) and (7) steam utilization can be expressed with the following equation.

$$U = \frac{V_{op} - \overline{E_N}(U)}{V_f} \tag{8}$$

Which can be solved to obtain V_{op} as a function of U and V_f.

$$V_{op}(U, V_f) = \overline{E_N}(U) + UV_f \tag{9}$$

Average current density follows from Ohm's law.

$$j_i(U, V_f) = \frac{V_{op} - \overline{E_N}(U)}{R''} \tag{10}$$

While power density is the average current density (j_i) multiplied by operating voltage (V_{op}).

$$P_i(U, V_f) = V_{op} \cdot \frac{V_{op} - \overline{E_N}(U)}{R''} \tag{11}$$

Equations (1) and (8) require no parameterization. With these expressions a comprehensive set of performance maps can be generated which show efficiency, current density, power density and utilization in the independent variable space (V_{op}, V_f) representing operating voltage, area specific resistance, steam flow and composition. Parameterization in (V_{op}, V_f) is done simply for mathematical convenience. An example performance map of a SOEC stack operating at $800°C$, with an ASR of $1.0\ \Omega - cm^2$, is shown in Figure 2.

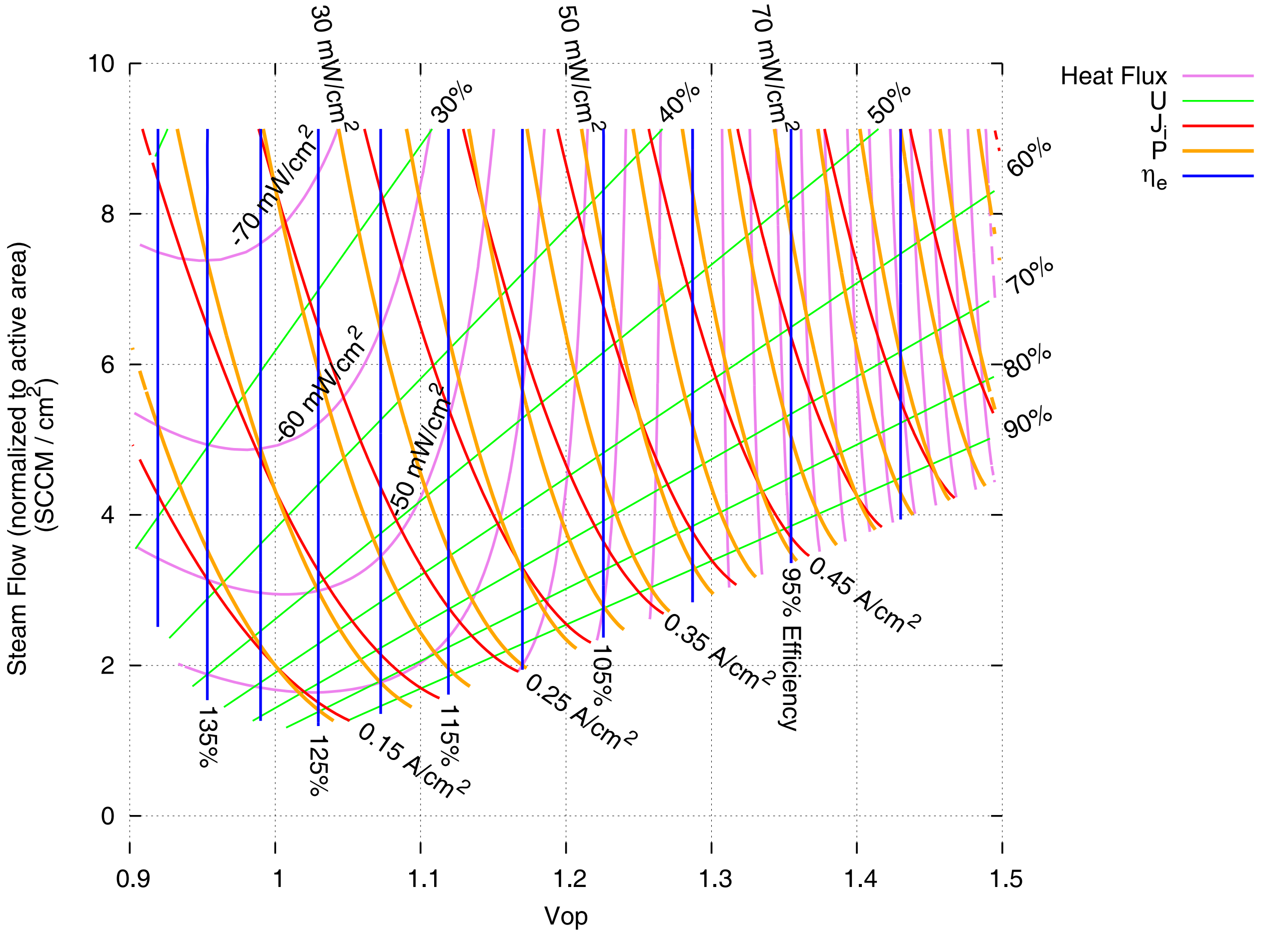

Fig. 2 SOEC Performance Map

3 Cost Model

The performance model along with mass and energy balances were used to determine the cost of major system components for a SOEC system with 25 kW electrolysis capacity. This system was comprised of four stacks of solid oxide cells each having 225 cm^2 of active area. The stack height at a given point in the (V_{op}, V_f) plane was determined by the total number of cells that would be required to consume 25 kW of electrical power at the power density obtainable at that given operating point. Stack cost was assumed to be $35 per cell-interconnect repeat unit within each stack. Air flow was calculated to maintain a 100°C temperature difference between the 900°C furnace chamber outlet and a constant 800°C stack air inlet. Energy required to heat the inlet streams from 25°C to 800°C was added to the energy needed to maintain a stack outlet temperature of 800°C. The energy required to maintain stack temperature will depend on how far above or below the operating voltage (V_{op}) is from thermoneutral voltage (V_{tn}). Steam flow rates are proportional to V_f as shown in equation (5).

Once the air flow is known, the heat exchanger and insulation were sized on the basis of their combined cost. Starting at an insulation thickness of 5 cm, heat transferred through the insulation was used to determine the temperature of the furnace chamber outlet. The heat exchanger area required is then calculated based on this new furnace chamber outlet and the air inlet flow rate. As insulation thickness increases heat exchanger area required decreases. Insulation thickness is iterated by 1 cm until a minimum combined cost for insulation and the heat exchanger is identified. The heat exchanger was assigned a cost of $\$400/m^2$. Insulation volume was a function of stack height (cell count) and thickness, and assigned a cost of $\$2180/m^3$. A total capital cost was taken as the sum of stack, heat exchanger, insulation, and a fixed balance of plant (BOP) cost of $\$500/kW$. The capital cost on a per kW basis was computed assuming full load operation 8600 hours/year ($98\%\ availability factor$) with a 5 year stack life, a 10 year BOP life and a 10% return on capital.

Operating costs included electrical power to feed the electrochemical reaction as well as the cost of natural gas to provide heat to the furnace chamber. The price of electrical power was set at $\$0.096/kWh$. A sensitivity study has shown that the price of fuel used to heat the furnace has a relatively small effect on the results of this analysis compared with the cost of electric power and total plant capital cost. This is because the relative amount of thermal to electric input is small over most of the operating envelope, and also due the the fact that over the common range of fuel prices natural gas is considerably lower cost than electricity on an equivalent energy basis. As hardware, electricity, fuel cost may vary it is important that realistic economic values be used when adopting a methodology such as this. Often economic data is proprietary and therefore difficult to obtain. The circumstance where the economic parameters presented here may be valid are rather specific, and particular values may not be widely applicable. The computation sequence is outlined in Table 1. Assumed cost factors are contained in Table 2.

Table 1 SOEC cost model computation sequence

1. Set parameters U,Vf
2. Compute Vop, j_i, power density, and efficiency
3. Size/Cost stack for 25kW target
4. Compute air flow for temperature requirements
5. Compute inlet steam flow from Vf
6. Size/cost heat exchanger and insulation
    - Cost insulation
    - Compute heat loss
    - Update chamber temperature
    - Size/cost heat exchanger
    - Increment insulation thickness until heat exchanger + insulation cost minimum is found
7. Calculate capital and component cost contribution $\$/kgH_2$ (stack, heat exchanger, insulation)
8. Calculate auxiliary heat cost contribution $\$/kgH_2$
9. Calculate electric power cost contribution $\$/kgH_2$

Table 2 SOEC cost model assumptions

1. Stacks: 15cm, 0.5 ohm-cm2, $35/repeat unit
2. Insulation: $\$2180/m^3$
3. Heat exchanger: $\$400/m^2$
4. Other BOP: $\$500/kW$
5. Fuel: $\$4/MMBTU$ (LNG)
6. Depreciation: stack 5 years, BOP 10 years, 10% continuous ROI
7. Duty factor: full load 8600 hours/year (98%)

4 Performance and Cost Maps

As can be seen in Figure 2 the domain is bounded to the right by high operating voltage and to the left by operating voltage below the steam inlet Nernst potential (E_N). Most of the lower boundary is due to the max steam utilization approaching 100%. It can be seen in Figure 2 that efficiency as a function of operating voltage decreases as operating voltage increases. Conversely the electrical basis electrolysis efficiency increases higher than of 100% when the stack is operated lower than thermoneutral voltage. Power density on the other hand increases with operating voltage. As can be seen in Figure 3 when the stack operating voltage is high the electrical power required to drive the electrochemical reaction is the dominant cost factor. When stack operating voltage is low capital costs shown in Figure 4 relative to production are high . Taking these competing factors into account one can determine a minimum cost of operation. The total cost to produce hydrogen in the given system is given in Figure 5. If cost is a primary concern then operating the stack at 1.1 V and at a steam utilization of approximately 20% would yield the lowest cost per unit produced for the given system.

Additional factors included in the cost buildup include the cost of fuel, Figure 6 the heat exchanger cost, Figure 7 and additional BOP cost, Figure 8 . It turns out in this analysis that the cost of insulation accounts for at most $\$0.007/kg$ of H_2 produced so that map is not shown.

5 Conclusions

A set of relationships combining specified operating and performance parameters for an SOEC system, such as steam flow rates, operating voltage and power density, was developed for a steam fed SOEC hydrogen production system. These were then combined with estimated costs of principal components and sized for specific system design criteria to obtain a cost/performance model. The model was used to map the performance of a stack and the cost elements for a given set of performance parameters across the operating space in voltage and specific steam flow rate $(V_{op}, SCCM/cm^3)$. Component

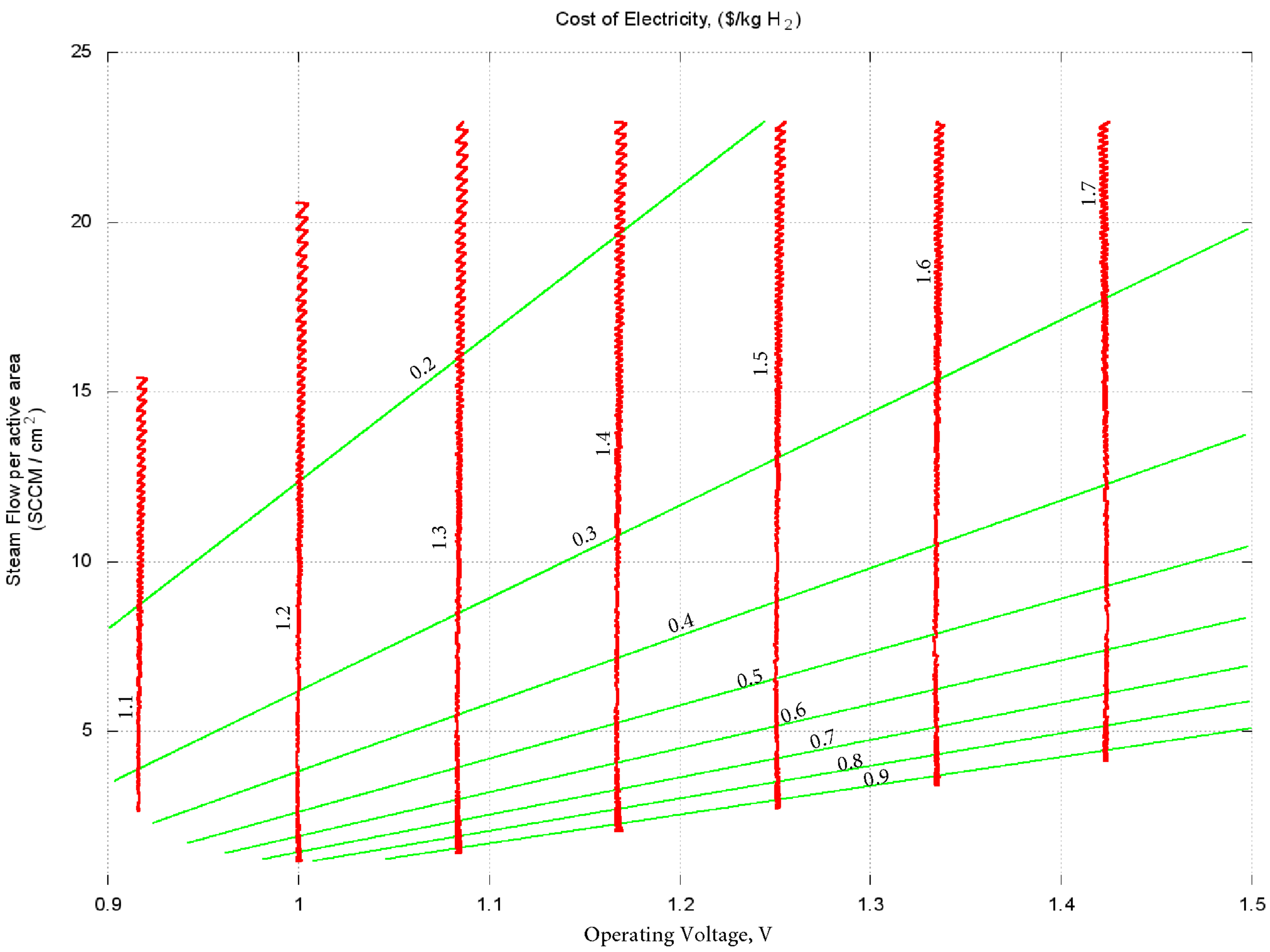

Fig. 3 Cost of electricity, $\$/kg$ of H_2 produced

sizing and cost estimates were used to obtain a prediction of total system capital cost. The cost per unit hydrogen produced for this set of assumptions was then calculated. A cost analysis framework is a useful tool to reveal opportunities for system optimization and cost minimization.

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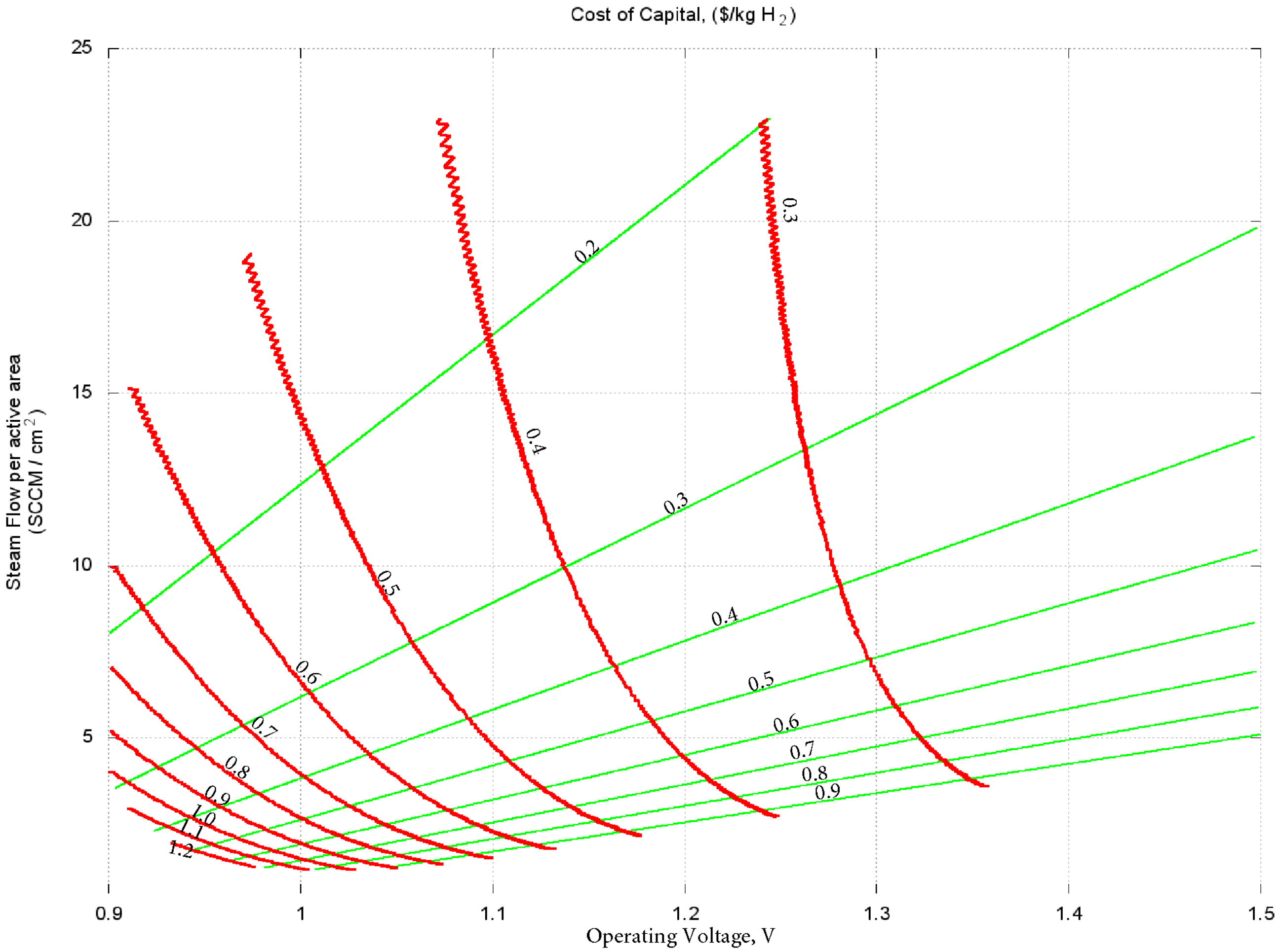

Fig. 4 Cost of capital, $\$/kg$ of H_2 produced

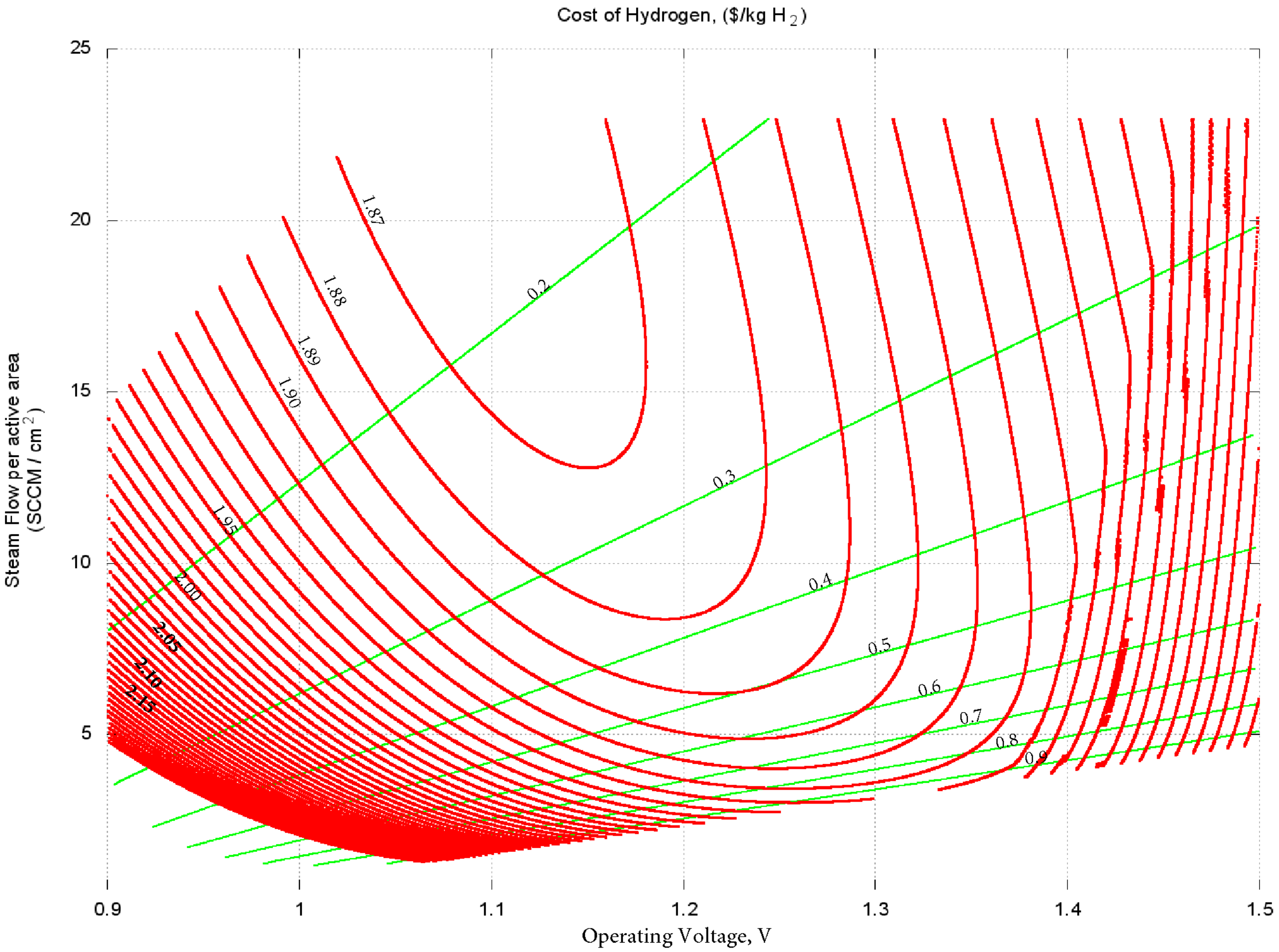

Fig. 5 Cost to produce hydrogen, $\$/kgH_2$

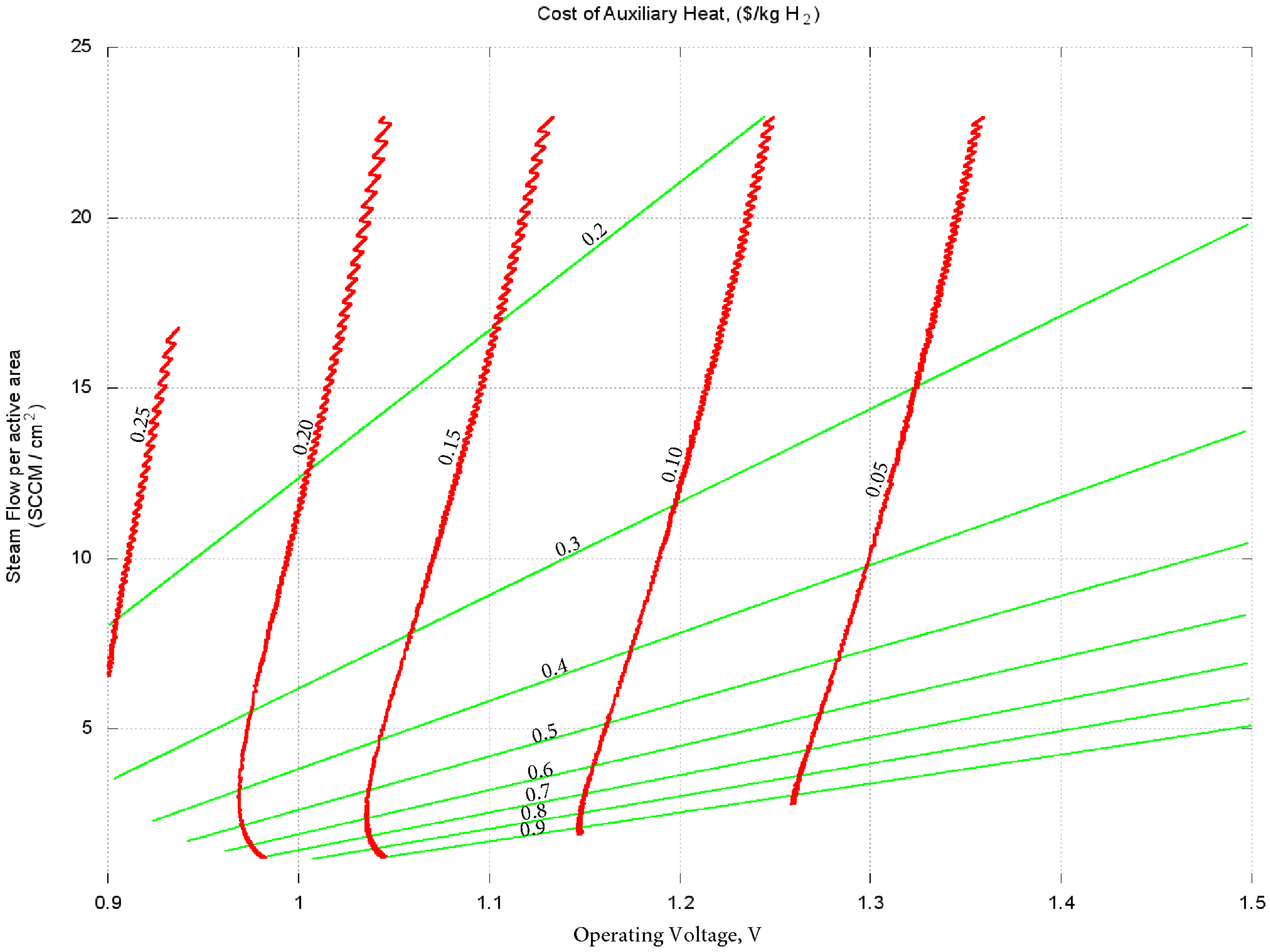

Fig. 6 Cost of fuel, $\$/kg$ of H_2 produced

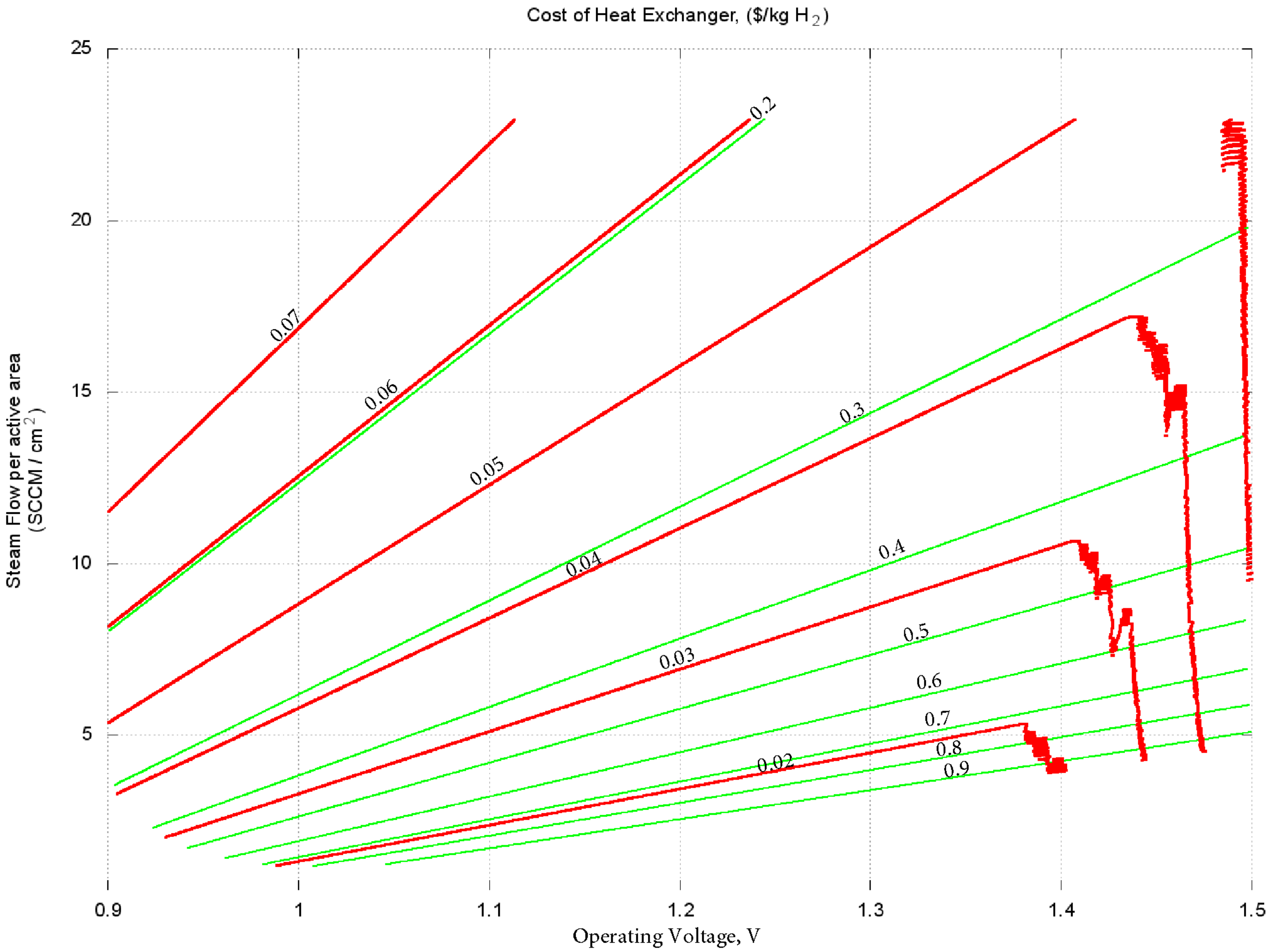

Fig. 7 Cost of heat exchanger, $\$/kg$ of H_2 produced

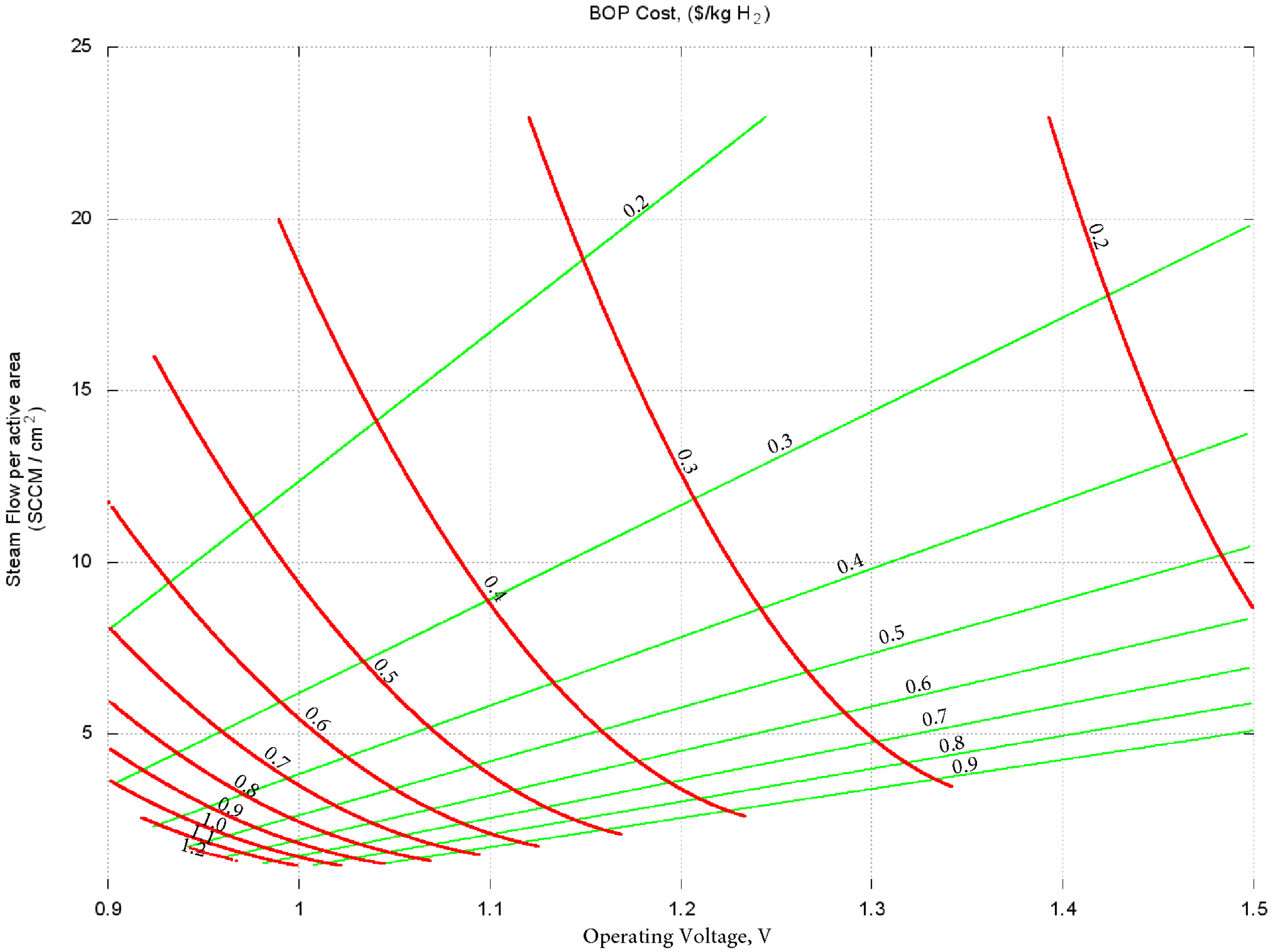

Fig. 8 Cost of BOP, $\$/kg$ of H_2 produced