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Advanced Strategies for Stationary Fuel Cell Systems (FCS)

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Relevance

Tri-generation Concept:

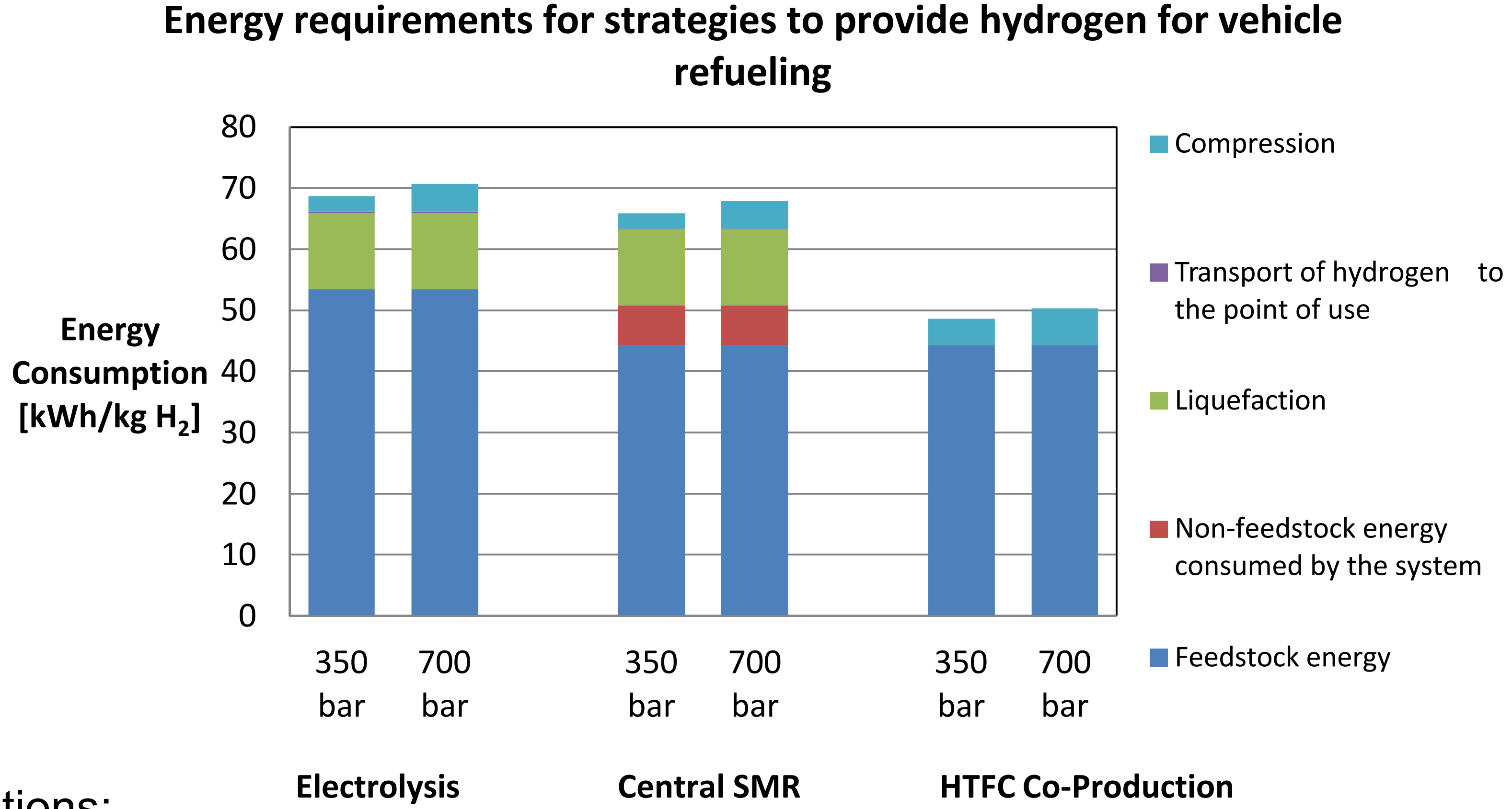
- Integrate clean electricity production of a high temperature fuel cells with local production of H_2 value-added product
- Excess H_2 for vehicles, merchant H_2, etc.
- Attenuate the “chicken-in-egg” problem of lack of H_2 refueling stations for initial H_2 fleet vehicles

Advantages:

- H_2 production is at the point of use averting emissions and energy impacts of hydrogen transport
- Use of fuel cell waste heat and steam as the primary inputs for the endothermic reforming process will use less fuel
- Schedule relative amounts to help with “dispatch-ability”
- Synergistic impact of lower fuel utilization increases overall efficiency (i.e. higher Nernst Voltage, lower mass transport losses, lower cooling requirement,…)
- Hydrogen and electricity transportation losses eradication.
- Potential capital cost reduction compared to centralized production by long-distance transport infrastructure exclusion.
- Securing fuel supply by using local feedstock.
- Less energy is needed to make and to transport H_2 to vehicles using high temperature fuel cell (HTFC) co-production compared with electrolysis or centralized steam methane reforming (SMR).

Relevance

Less energy is needed to make and to transport H_2 to vehicles using HTFC co-production compared with centralized electrolysis or centralized SMR.

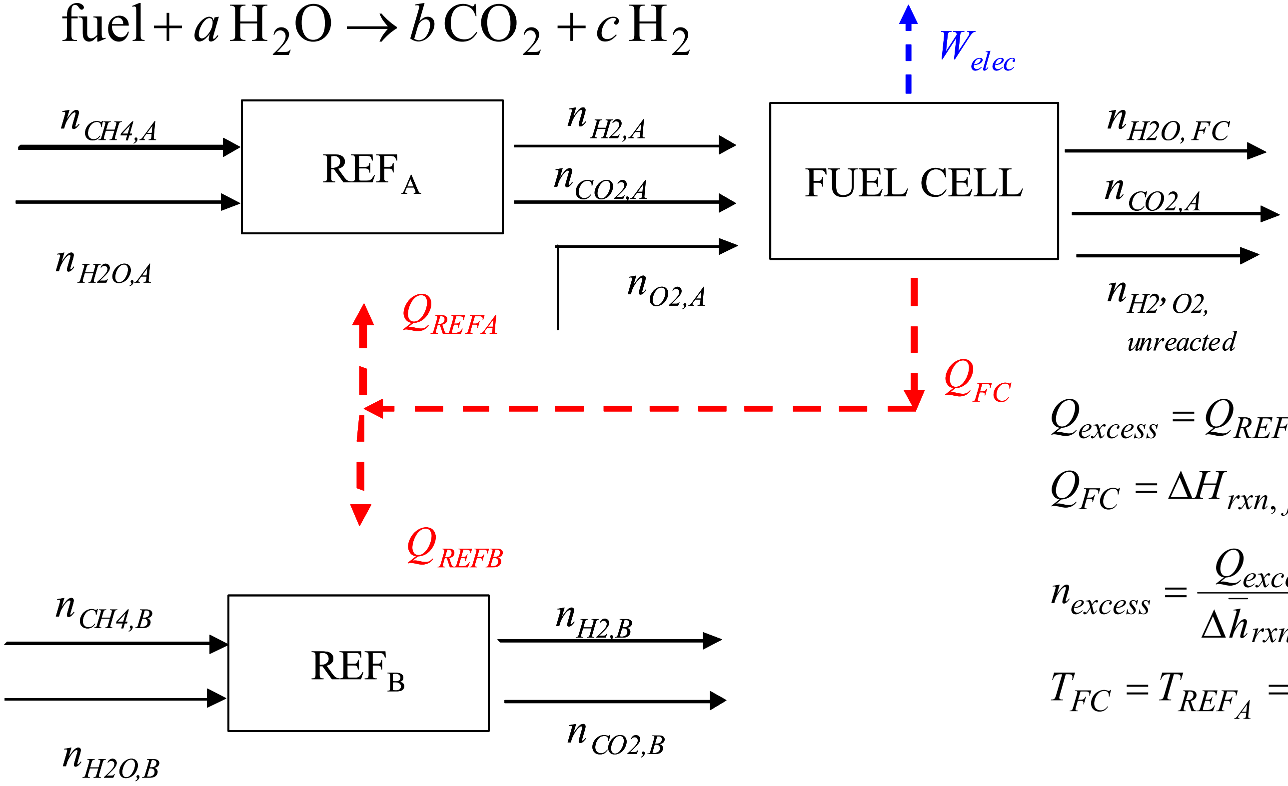


<u>Assumptions:</u>

- *SMR plant is located in Long Beach, CA and hydrogen is transported by a diesel-fueled truck to Los Angeles.*
- *Electrolysis plant located in Palm Springs, CA. 100% of electricity used is wind energy. Hydrogen is transported by diesel-fueled truck to Los Angeles.*

We derive the theoretical limit of excess H_2 from fuel cell electrochemical waste heat alone.

$$\mathrm{fuel} + a\,H_2O \rightarrow b\,CO_2 + c\,H_2$$



$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

$$\mathrm{SOFC}: O^{2-}\ \mathrm{carrier}$$

$$\mathrm{MCFC}: CO_3^{2-}\ \mathrm{carrier}$$

$$Q_{excess} = Q_{REF_B} = Q_{FC} - Q_{REF_A}$$

$$Q_{FC} = \Delta H_{rxn,fc} - W_{elec}$$

$$n_{excess} = \frac{Q_{excess}}{\Delta \bar{h}_{rxn,sr}} = \frac{\left(\Delta H_{rxn,fc} - W_{elec}\right) - Q_{REF_A}}{\Delta \bar{h}_{rxn,sr}}$$

$$T_{FC} = T_{REF_A} = T_{REF_B}$$

We derive the quantity of excess H_2 available (n_{excess}) from electrochemical waste heat (Q_{FC}). The steam reforming reactions can provide H_2 (A) for the fuel cell's anode or (B) for excess H_2 for vehicles, etc. For benchmarking a H_2 co-producing system against a standard system, we analytically separate the two processes – (A) and (B) -- in two "virtually" separate steam reformers – REF$_A$ and REF$_B$. REF$_A$ produces enough H_2 for the fuel cell to provide electric power. REF$_B$ produces excess H_2 for vehicles, etc.

We model SOFC polarization from 600 to 1000°C.

$$W_{elec} = n_e F V$$

$$V = V^{ideal} - \eta_{act} - \eta_{ohm} - \eta_{conc}$$

$$\eta_{ohm} = i \times \left(R_{anode} + R_{cathode} + R_{IC} + R_{electrolyte}\right)$$

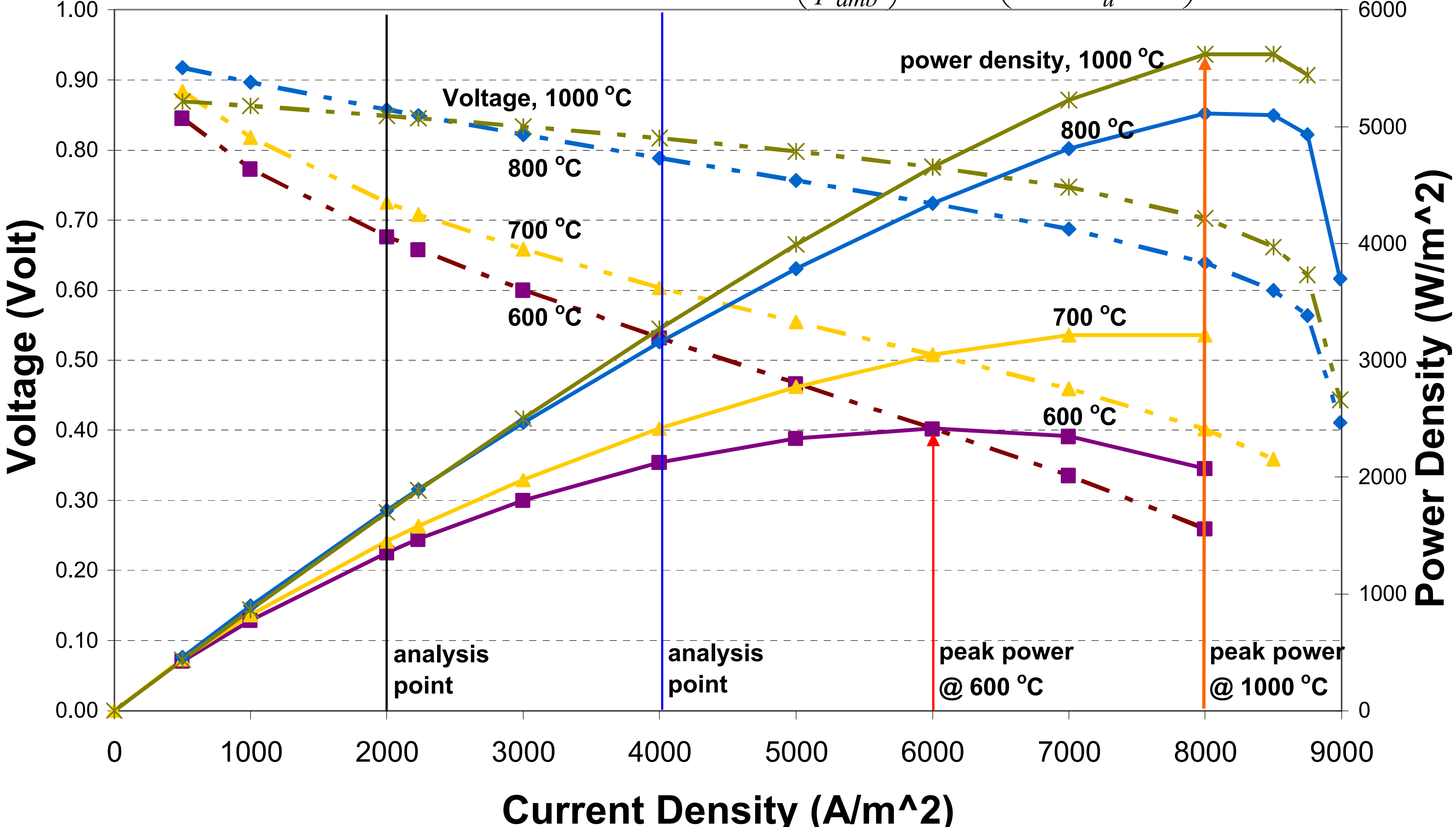
$$\eta_{conc} = -\frac{R_u T_{out}}{n_e F} \ln\left(1 - \frac{j}{j_L}\right)$$

$$\eta_{act} = \frac{R_u T_{out}}{n_e F} \sinh^{-1}\left(\frac{j}{2 j_{o,*}}\right)$$

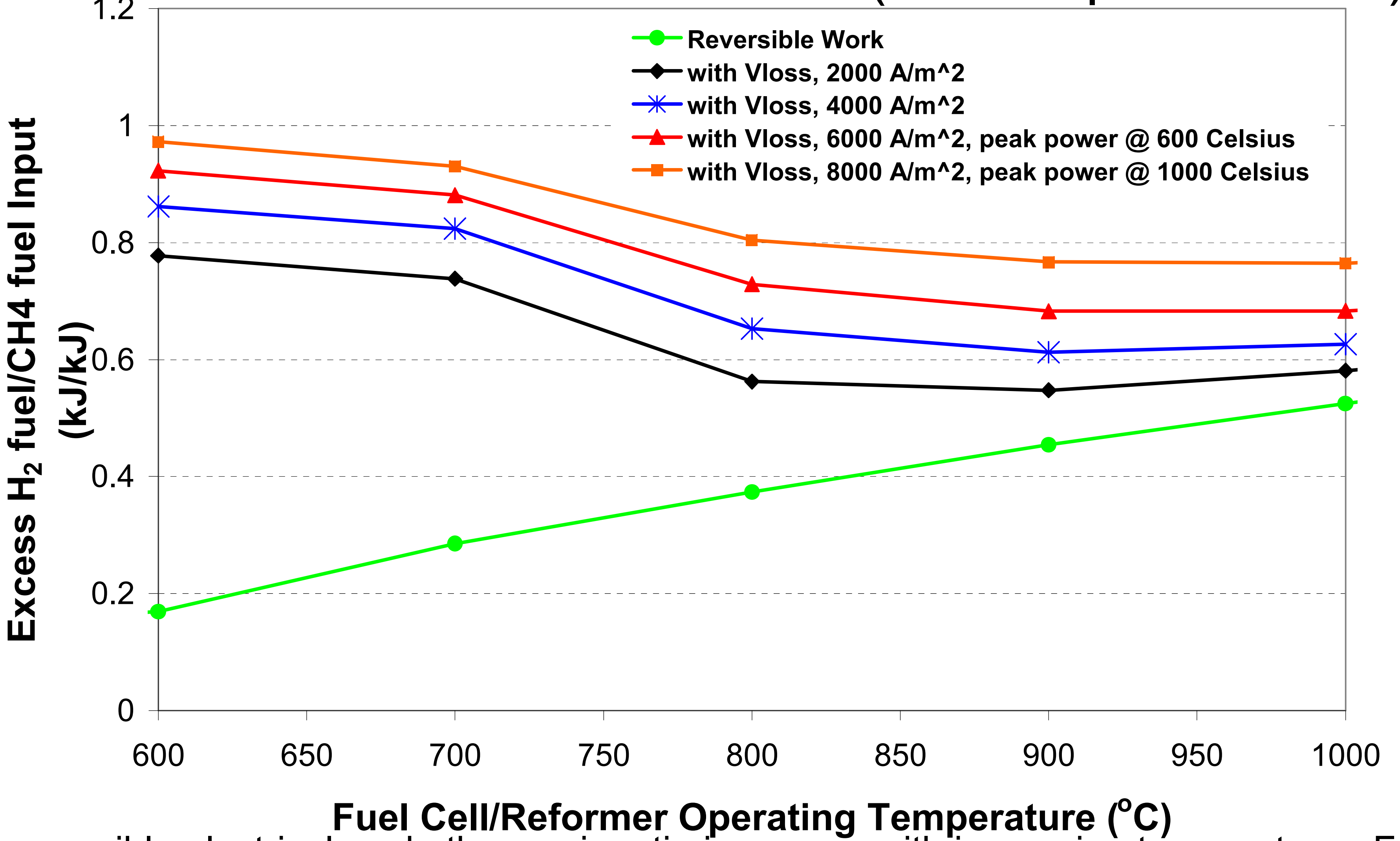
$$j_{o,anode} = \gamma_{anode} \left(\frac{p_{H_2}}{p_{amb}}\right)\left(\frac{p_{H_2O}}{p_{amb}}\right) \exp\left(-\frac{E_{act,anode}}{R_u T}\right)$$

$$j_{o,cathode} = \gamma_{cathode} \left(\frac{p_{O_2}}{p_{amb}}\right)^{0.25} \exp\left(-\frac{E_{act,cathode}}{R_u T}\right)$$

Includes constants published by Shaffer, B., M. Hunsuck, and J. Brouwer, 2008.

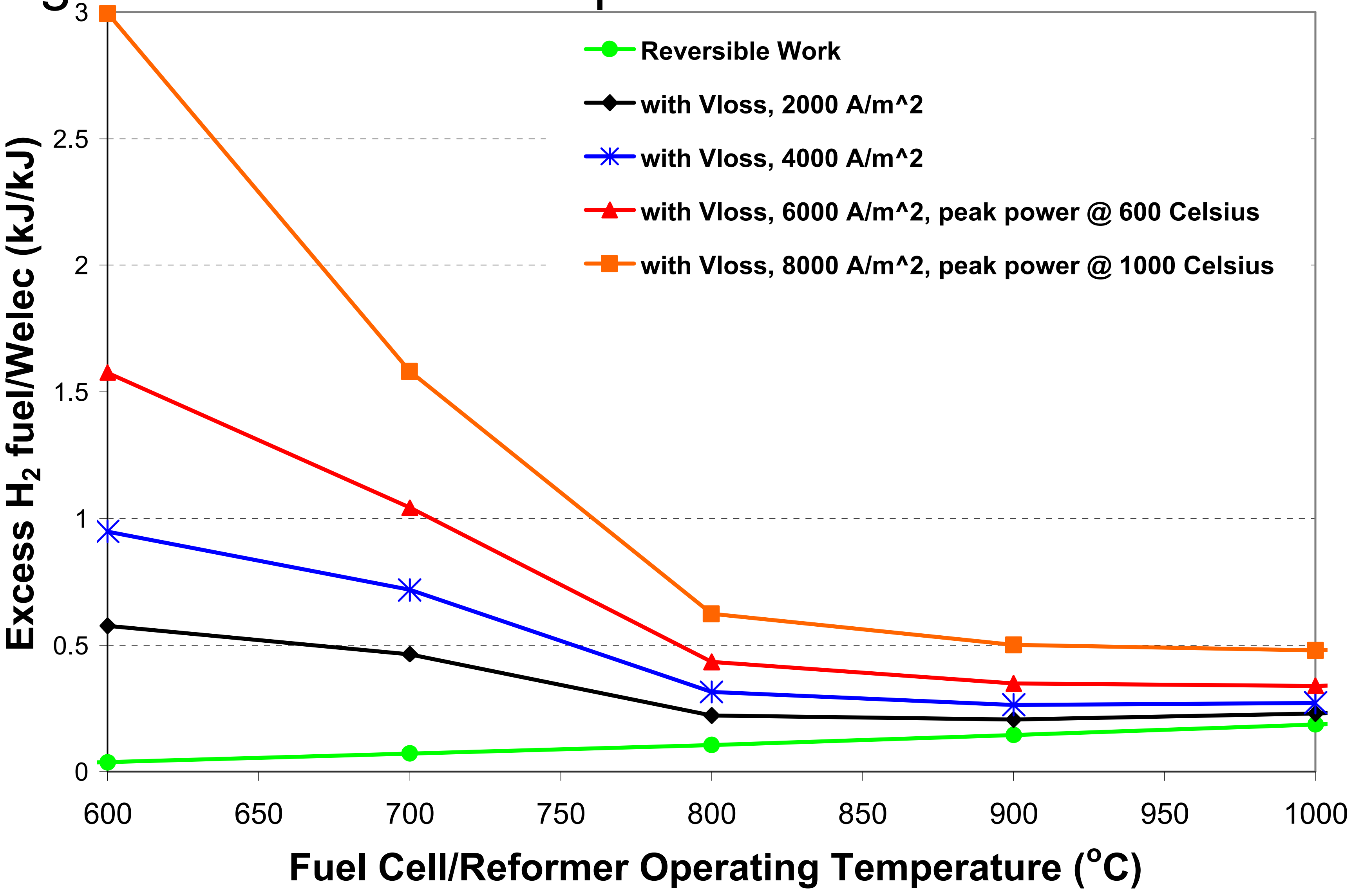


Excess H_2 per unit of fuel input increases moving from reversible work to irreversible work (ie. with polarization).

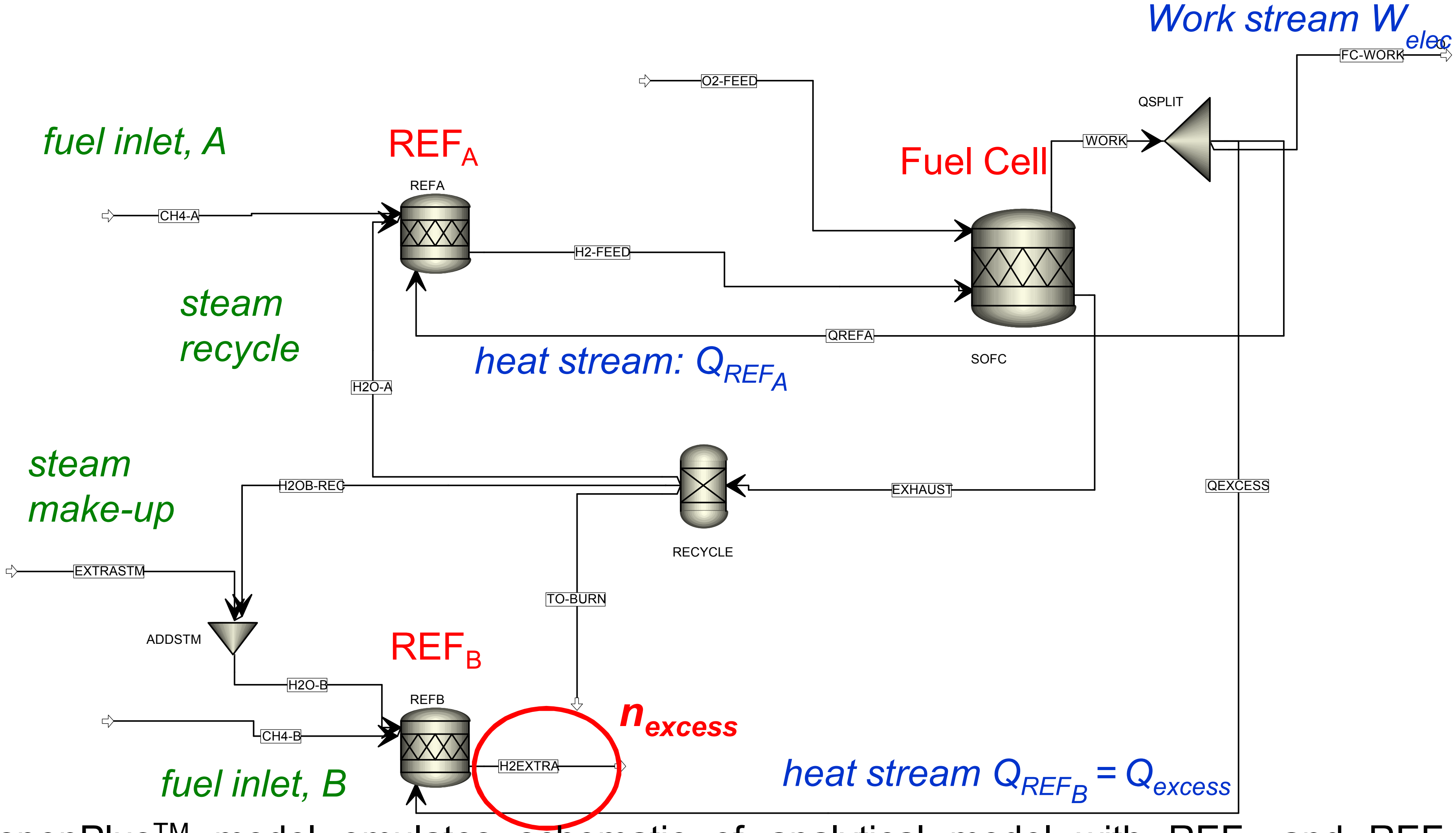


For reversible electrical work, the y-axis ratio increases with increasing temperature. For irreversible work, it decreases with increasing temperature. [SOFC polarization model supplies sampled voltage losses (V_{loss}) at even current density increments (2000 A/m^2).]

Excess H_2 per unit of electrical work (W_{elec}) increases with more irreversibilities (more V_{loss}). This trend occurs to a greater extent as temperature decreases.

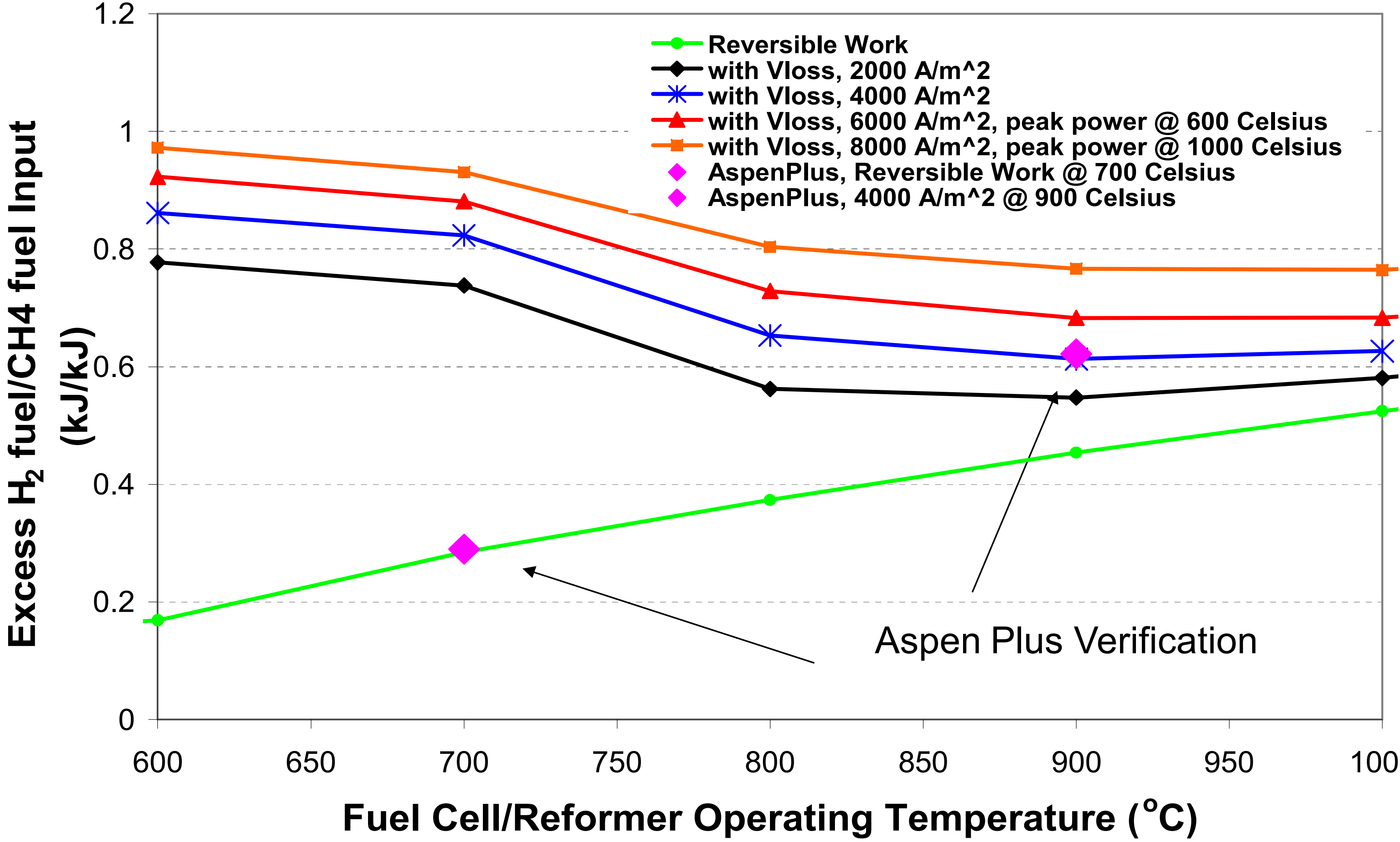


Our AspenPlus™ chemical engineering process flowsheet simulations verify our analytical models.



AspenPlus™ model emulates schematic of analytical model with REF_A and REF_B distinction, ideal heat transfer, 100% fuel and oxidant utilization within fuel cell, and reuse of fuel cell electrochemical waste heat alone. It calculates excess H_2 available (n_{excess}).

Our AspenPlus™ model results concur with our analytical model calculations.



Results concur for reversible and non-reversible work, for different polarization levels (V_{loss}), and for different operating temperatures.

AspenPlus^{TM} model's partial stream table shows results for excess H_2 moles from REF_B, and excess H_2/CH_4, which agree with analytical model.

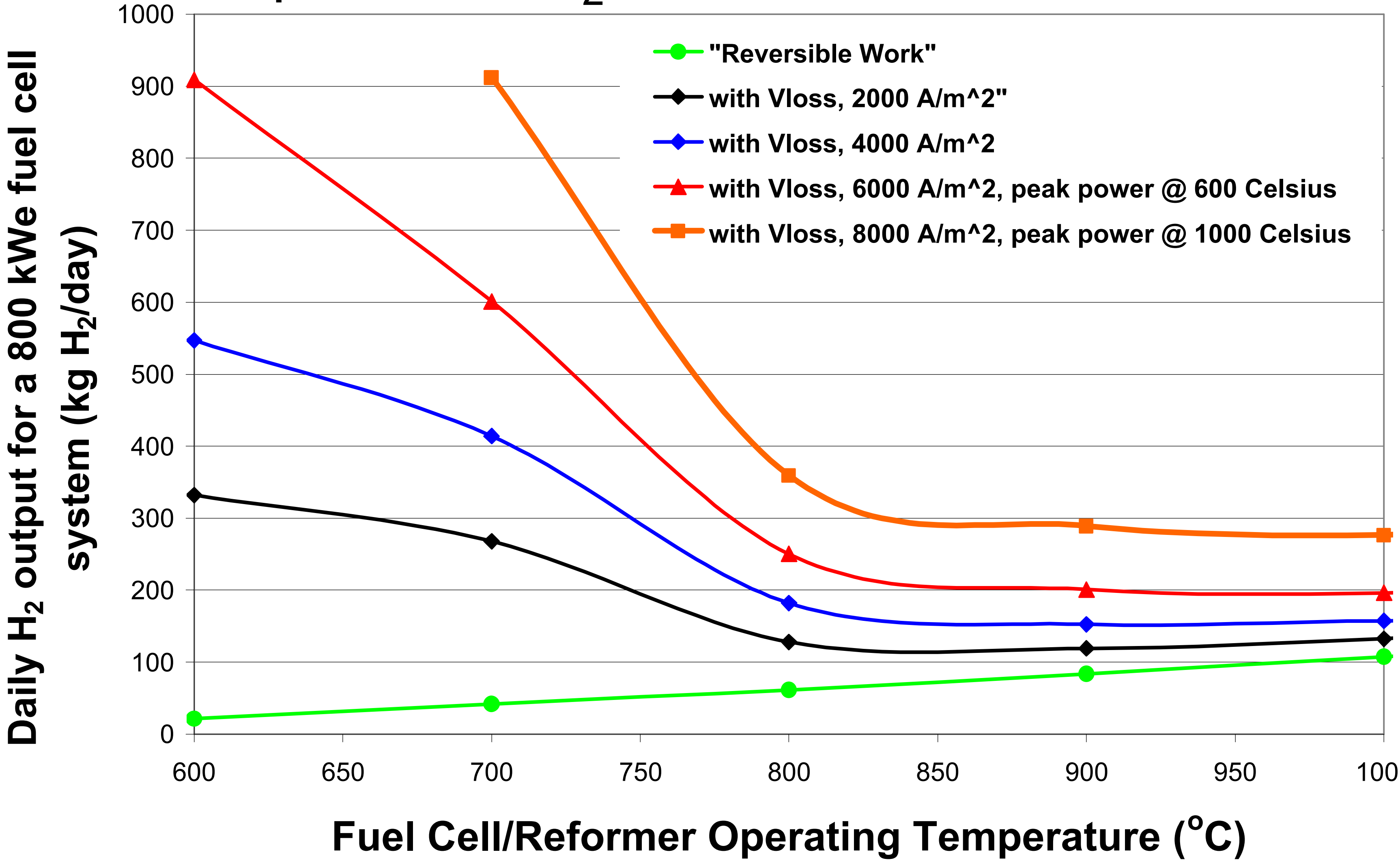
n_{excess}

Excess H_2 fuel/CH_4 fuel input (kJ/kJ)

	CH4-A	CH4-B	H2-FEED	H2EXTRA	H2O-A	H2O-B	H2OB-REC
Mole Flow (kmol/hr)							
CH4	0.25	0.22	0	0	0	0	0
H2O	0	0	0	0.56	0.5	1	0.5
CO	0	0	0	0	0	0	0
CO2	0	0	0.25	0.22	0	0	0
H2	0	0	1	0.874	0	0	0
O2	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0
Total Flow kmol/hr	0.25	0.22	1.25	1.66	0.5	1	0.5
total Flow kg/hr	4.01	3.51	13.02	21.52	9.01	18.02	9.01
Total Flow cum/hr	24.38	21.31	121.94	161.47	48.77	97.54	48.77
Temperature, K	1173.15	1173.15	1173.29	1173.15	1173.15	1173.15	1173.15
Pressure, bar	1	1	1	1	1	1	1
Vapor Frac	1	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0	0
Molar Enthalpy, kJ/kmol	-22855.56	-22855.56	-49352.94	-103436.06	-208462.8	-208462.8	-208462.8
Mass Enthalpy, kJ/kg	-1424.9102	-1432.5422	-4738.1855	-7978.8039	-11568.4129	-11568.4129	-11568.4129
Enthalpy Flow, kW	1.5872	1.3967	17.1364	47.6955	28.9532	57.9063	28.9532
Excess H2 fuel/total CH4 fuel Input	0	0	0	0.62175	0	0	0
Molar Entropy, J/mol-K	-6.65256	-6.65256	49.9988	40.50112	6.40152	6.40152	6.40152
Mass Entropy, J/gm-K	-0.4184	-0.4184	4.8116	3.09616	0.37656	0.37656	0.37656
Molar Density, kmol/cum	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mass Density, kg/cum	0.16	0.16	0.11	0.13	0.18	0.18	0.18
Average MW	16.04	16.04	10.41	13	18.02	18.02	18.02

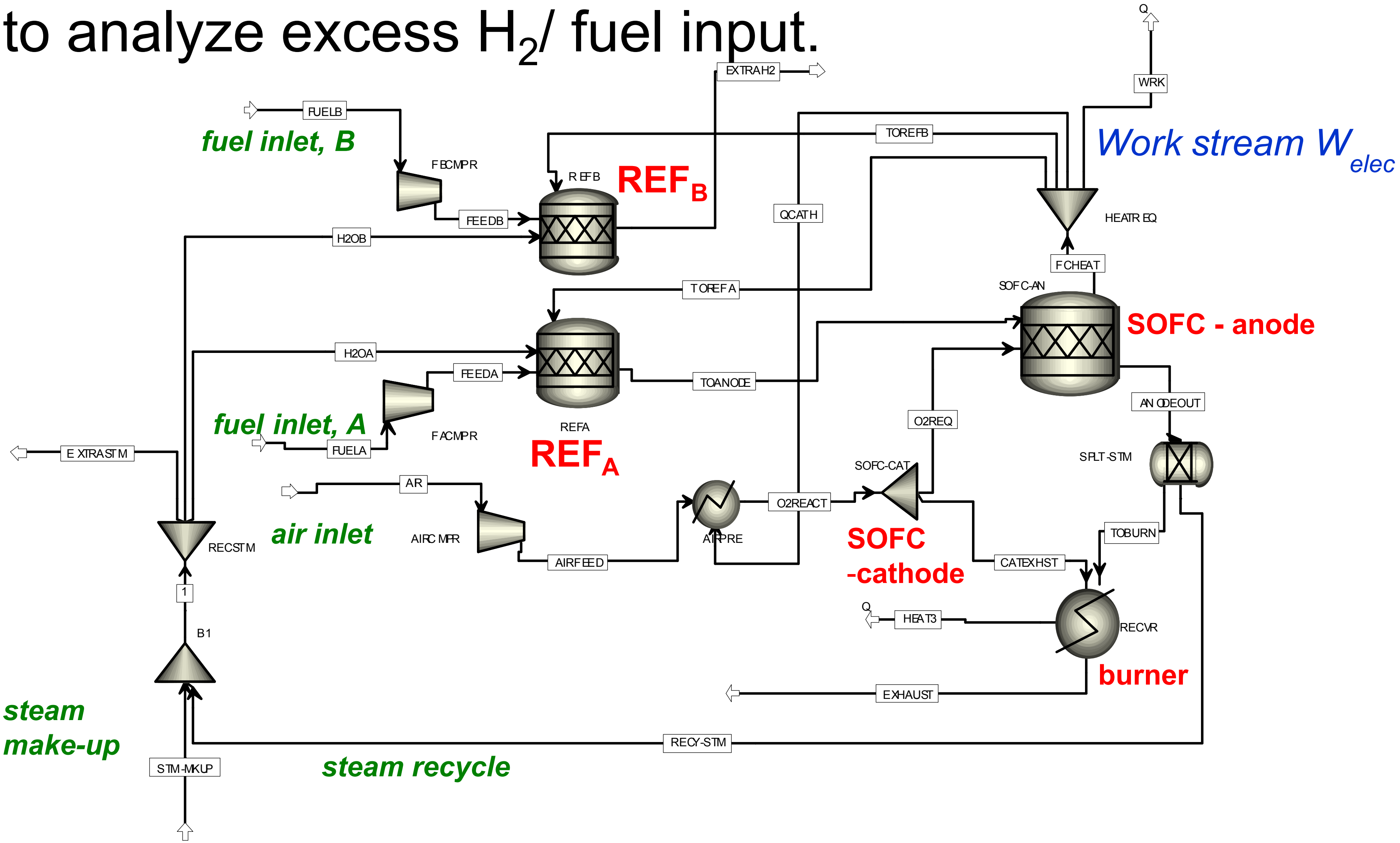
Table shows example data for a power density of 4000 A/m^2 and a fuel cell/reformer operating temperature of 900 °C

An 800 kWe fuel cell operating between 800 and 1000ºC will tend to make ~100 to 350 kg H_2 /day without added fuel consumption or CO_2 emissions.



An 800 kWe fuel cell can theoretically make >900 kg H_2 /day without added fuel or CO_2.

We introduce increasing complexity into Aspen models to analyze excess H_2/ fuel input.



We enhance SOFC model fidelity to better analyze the effect of lower fuel utilization rates at the anode, ancillary loads (compressors, pumps, etc.), heat exchanger loop designs, recycle streams, and more complicated thermodynamic cycle designs.