

Thermodynamic Models of High Temperature Stationary Fuel Cell Systems (FCS) Co-Producing Hydrogen (H₂)

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Background

Hydrogen Co-Production Integrated with Stationary Fuel Cell Systems (H₂-FCS) can provide H₂ with lower costs, fuel use, & emissions than other H₂ supply chains.

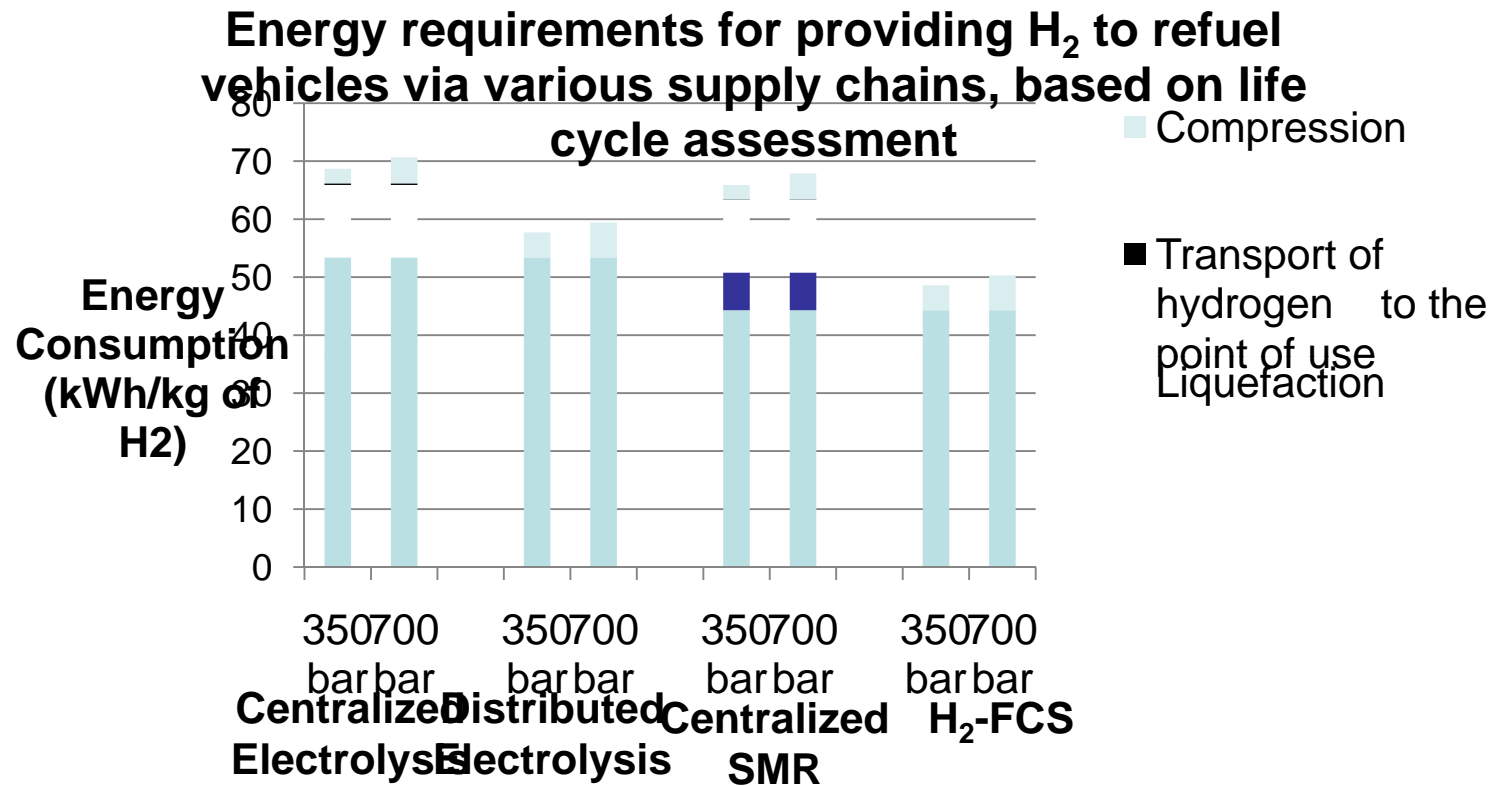
H₂-FCS Concept:

- A conventional distributed fuel cell system can provide clean electricity and recoverable heat to nearby buildings. This system can be re-designed to also provide excess hydrogen (H₂) for supplying H₂ vehicles or industry (merchant H₂).
- H₂-FCS can provide H₂ with lower costs, fuel use, & emissions.

Advantages of this Approach:

- H₂-FCS can supply H₂ locally, without the added H₂ transport infrastructure and related capital costs, energy use, and emissions seen with centralized production.
- H₂-FCS can supply H₂ in response to H₂ demand, and as a H₂ vehicle fleet grows. When H₂ demand is low, H₂-FCS can sell more electricity and heat instead, and thereby retain high system capacity utilization and lower costs.
- H₂-FCS can address the “chicken-or-egg” problem associated with a lack of H₂ refueling stations for initial H₂ fleets.
- H₂-FCS can improve fuel security by relying on local, widely-available feedstock.
- H₂-FCS can make H₂ with less additional fuel than distributed steam methane reforming (SMR) by reusing high temperature fuel cell waste heat to warm the endothermic steam reforming process to make excess H₂.
- Synergistic benefits include that a lower fuel utilization increases overall efficiency (i.e., higher Nernst Voltage, lower mass transport losses, lower cooling requirement and associated air blower parasitic load.)
- Less energy is needed to make and to transport H₂ to vehicles using H₂-FCS compared with centralized electrolysis, distributed electrolysis, or centralized SMR.

H₂-FCS consumes less energy to make and to transport H₂ compared with other H₂ supply chains.

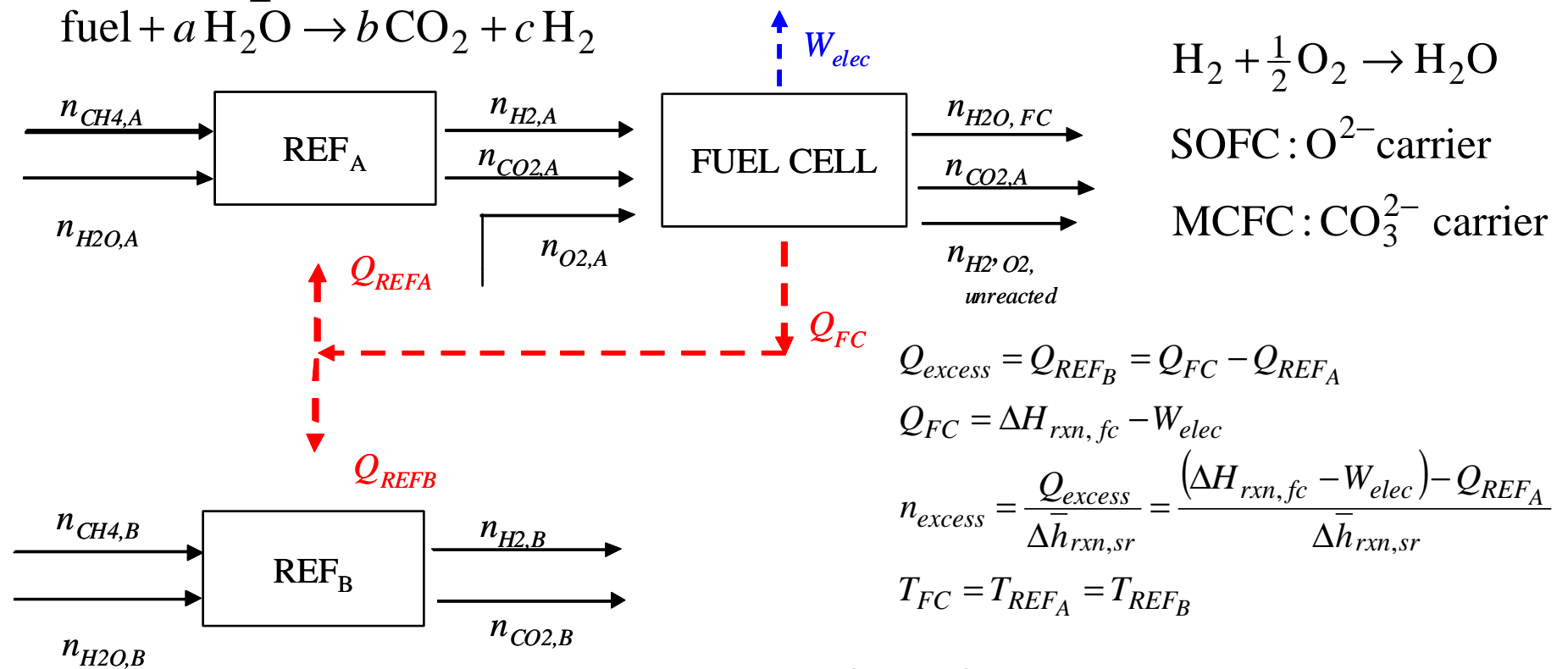


Assumptions:

- Centralized electrolysis plant is located in Palm Springs, CA. 100% of electricity used is wind power. H₂ is transported by diesel-fueled truck to Los Angeles (LA).
- Distributed electrolyzer is located at fueling station & consumes 100% wind power.
- Steam methane reforming (SMR) plant is located in Long Beach, CA; H₂ is transported by a diesel-fueled truck to LA.

Methodology

We reduce energy to make H₂ by using fuel cell heat for endothermic reforming. We derive the theoretical limit of excess H₂ from electrochemical waste heat alone.



We derive the quantity of excess H₂ available (n_{excess}) from electrochemical waste heat (Q_{FC}). The steam reforming reactions can provide H₂ (A) for the fuel cell's anode or (B) for excess H₂ production. For benchmarking a H₂ 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 H₂ for the fuel cell to provide electric power. REF_B produces excess H₂ (for vehicles, etc.)

We model SOFC polarization from 600 to 1000°C.

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

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

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

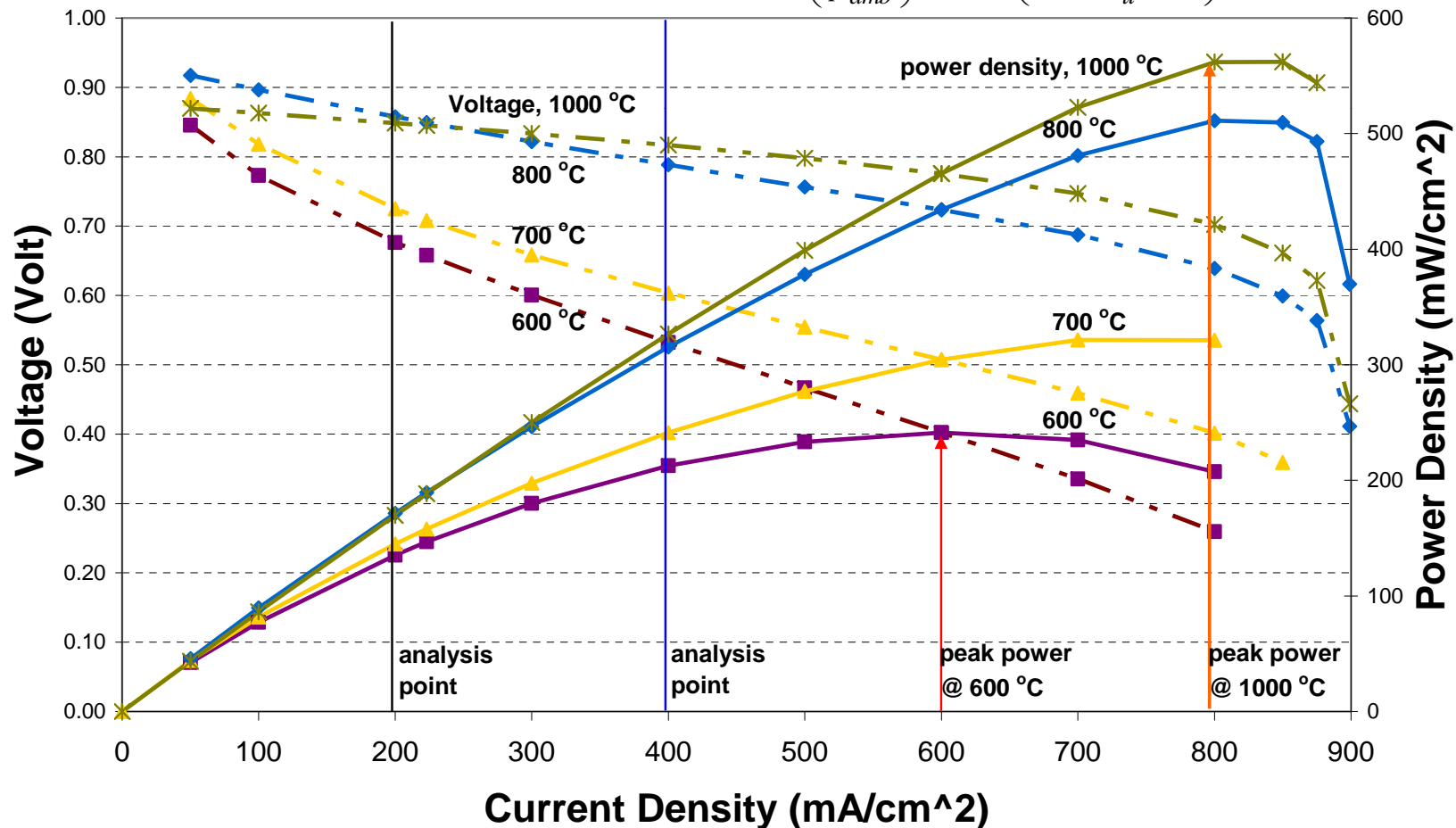
$$\eta_{conc} = -\frac{R_u T_{out}}{n_e F} \ln\left(1 - \frac{j}{j_L}\right)$$

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

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

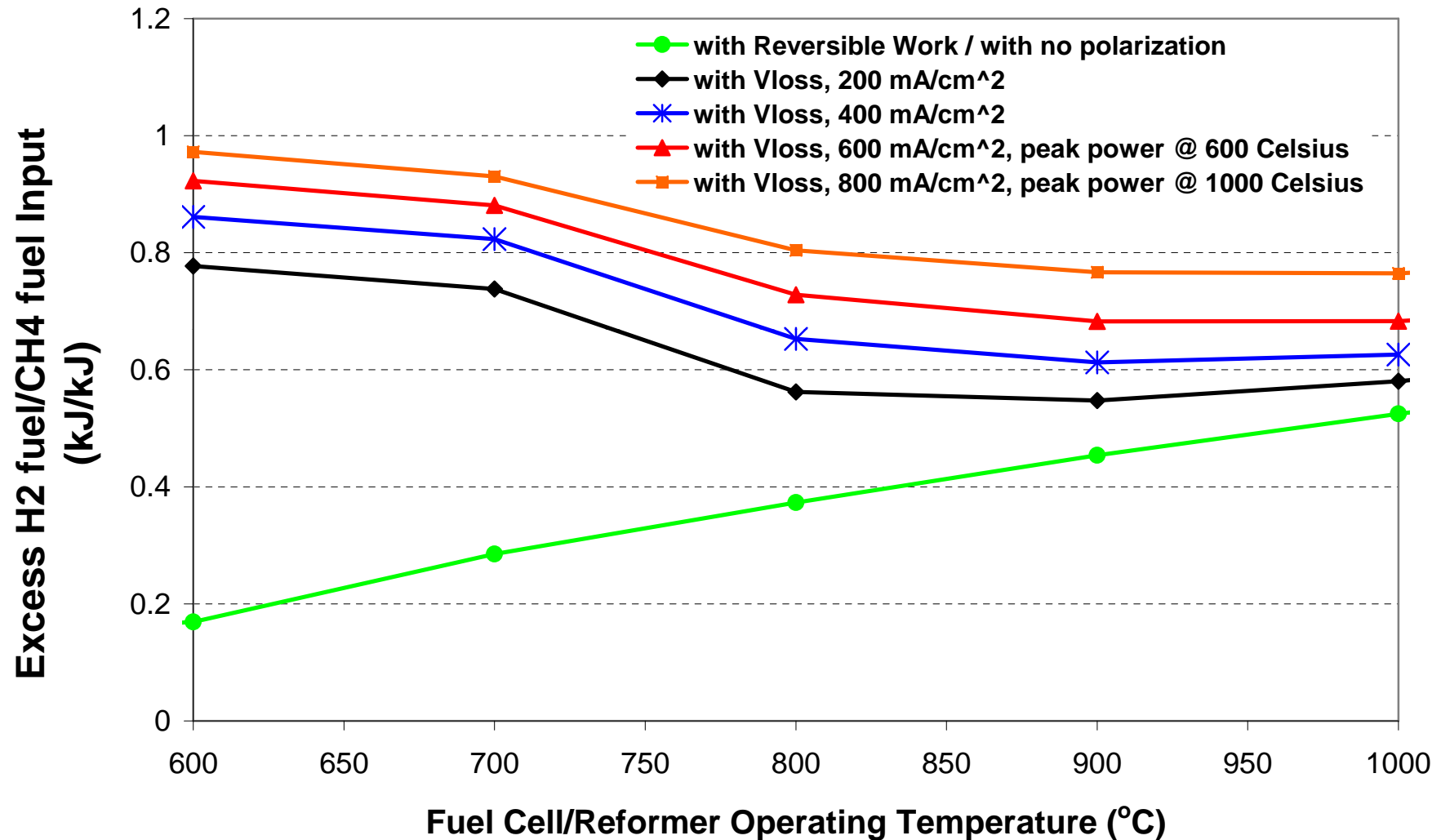
$$j_{o,cathode} = \gamma_{cathode} \left(\frac{p_{O_2}}{p_{amb}}\right)^{0.25} \exp\left(-\frac{E_{act,cathode}}{R_u T}\right)$$

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



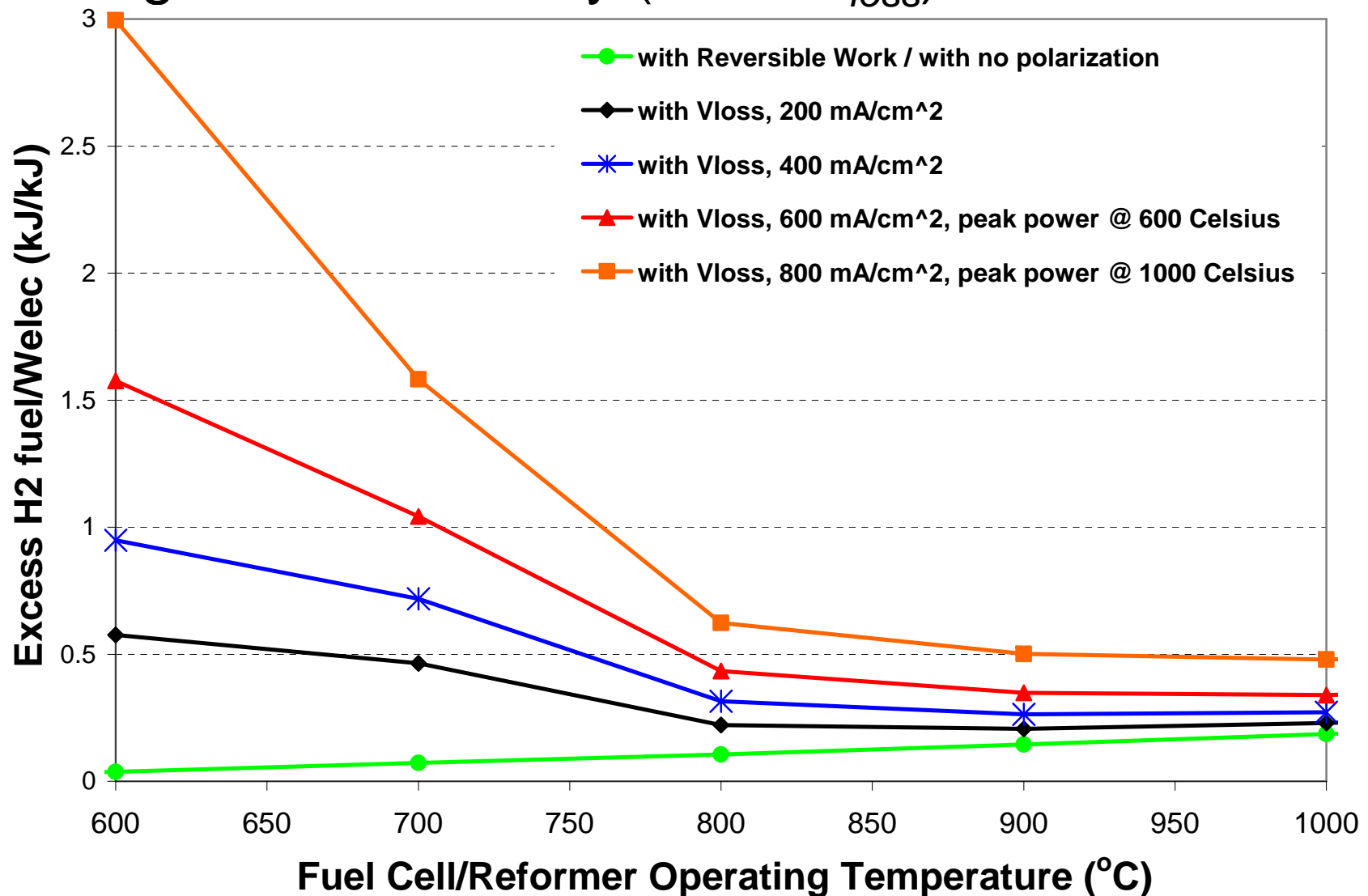
Results

Excess H₂ per unit of fuel input increases with increased irreversible work (i.e., with increased polarization).



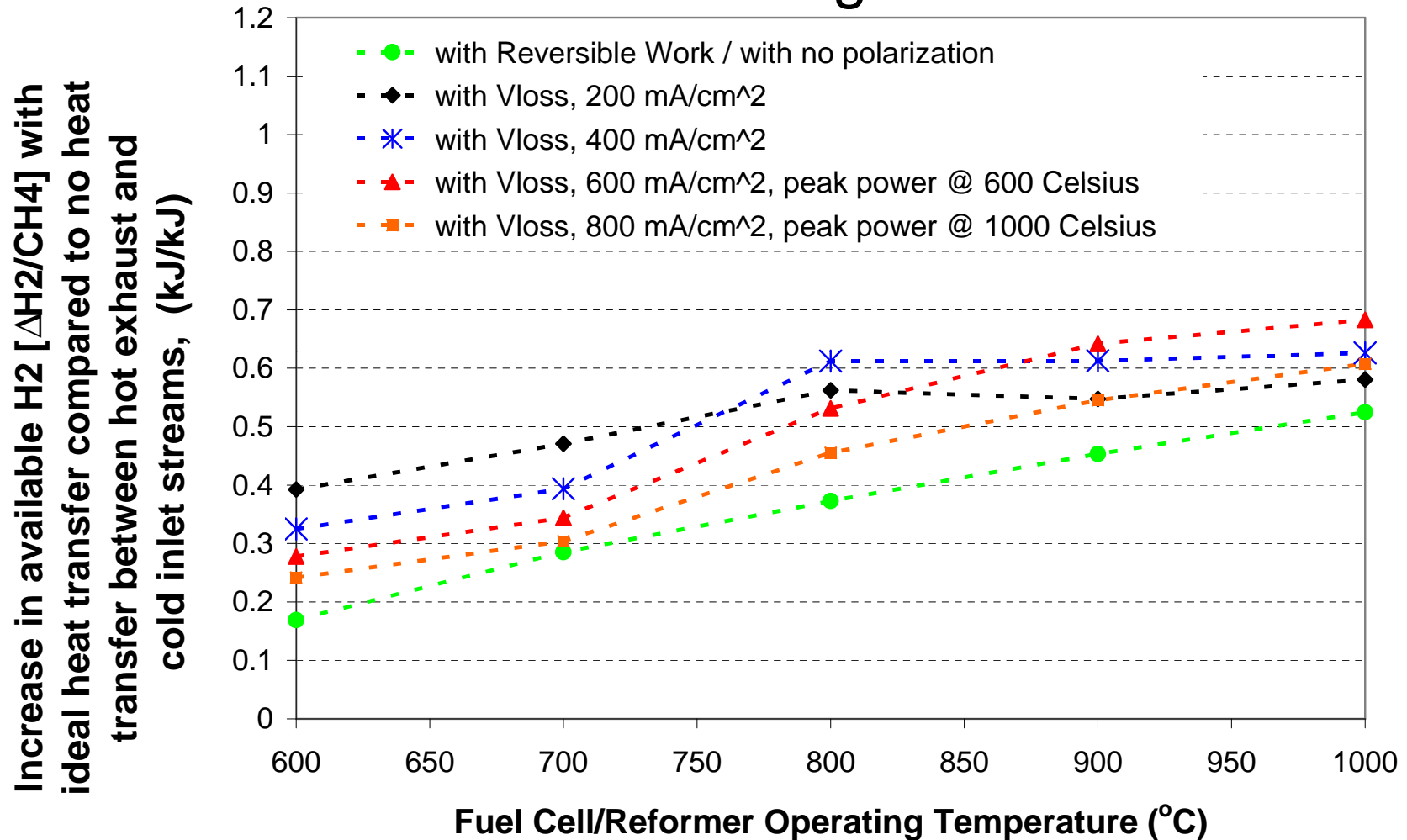
For reversible electrical work, the y-axis ratio increases with increasing temperature. For irreversible work, it decreases with increasing temperature. [SOFC polarization model supplies voltage losses (V_{loss}) at even current density increments (200 mA/cm²).]

Excess H₂ per unit of electrical work (W_{elec}) increases with a higher irreversibility (more V_{loss}).



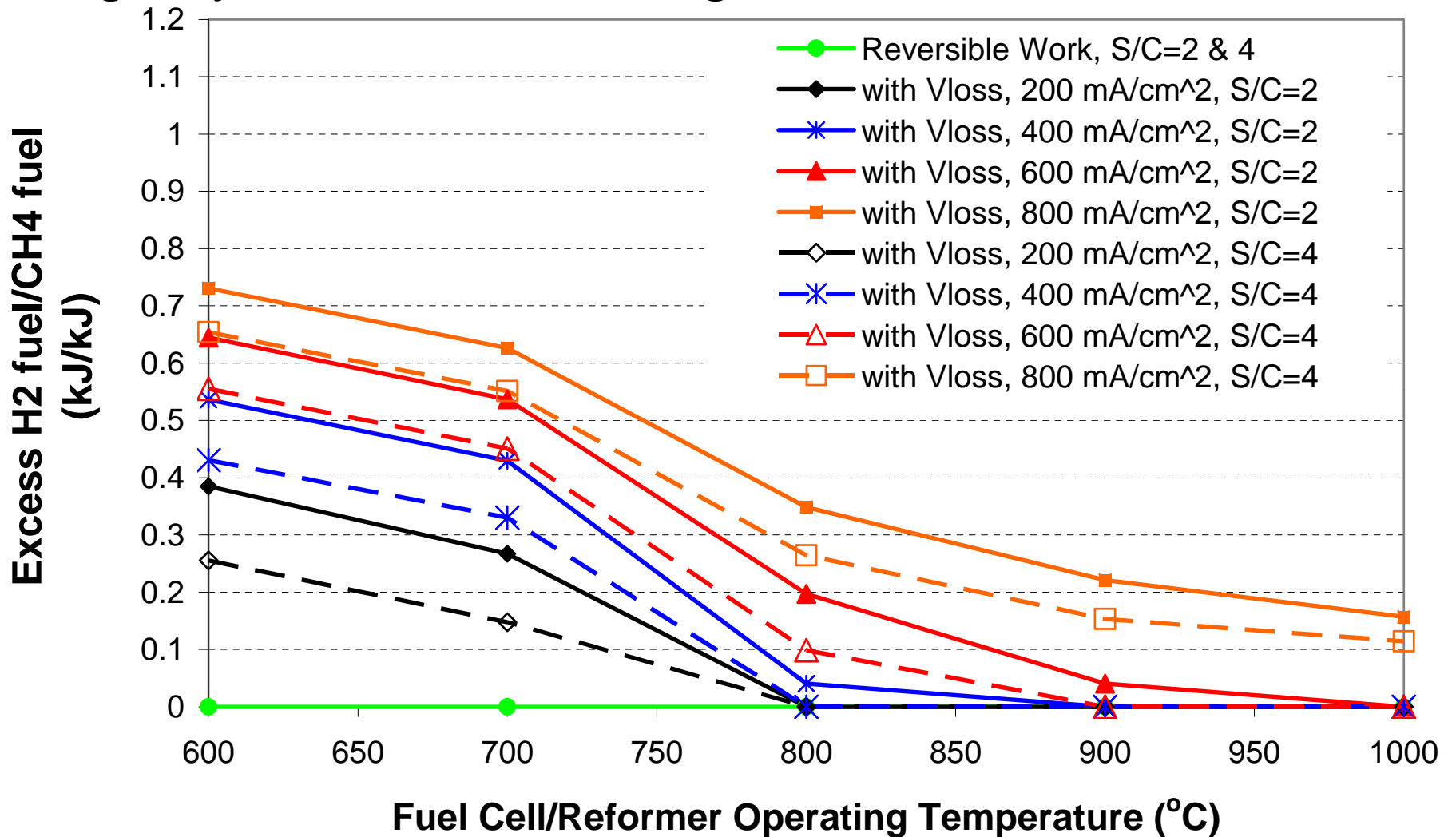
This trend occurs to a greater extent as temperature decreases, because as the temperature decreases in the range of 600-1000C, the polarization increases.

Excess H_2 is greater with more internal reuse of heat between hot outlet and cold inlet gases.



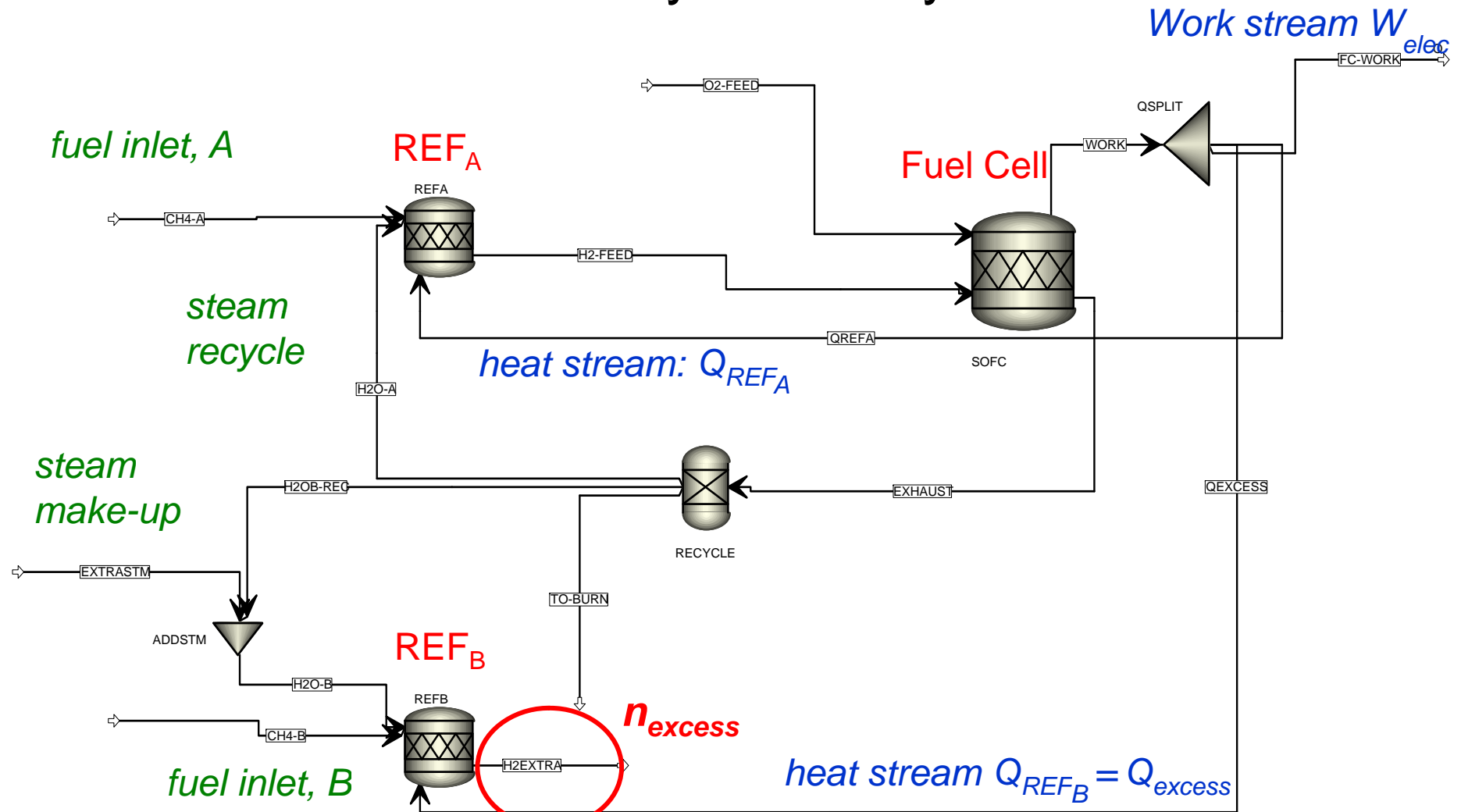
Excess H_2 is greater with (A) ideal heat transfer between hot fuel cell system exhaust gases (CO_2 , H_2O , H_2) and cold inlet gases (O_2 , CH_4 , H_2O) compared with (B) no heat transfer between hot exhaust and cold inlet streams. Excess H_2 depends upon the efficiency of heat exchange in preheating anode and cathode inlet gases.

Hydrogen yield declines at higher steam-to-carbon ratios.



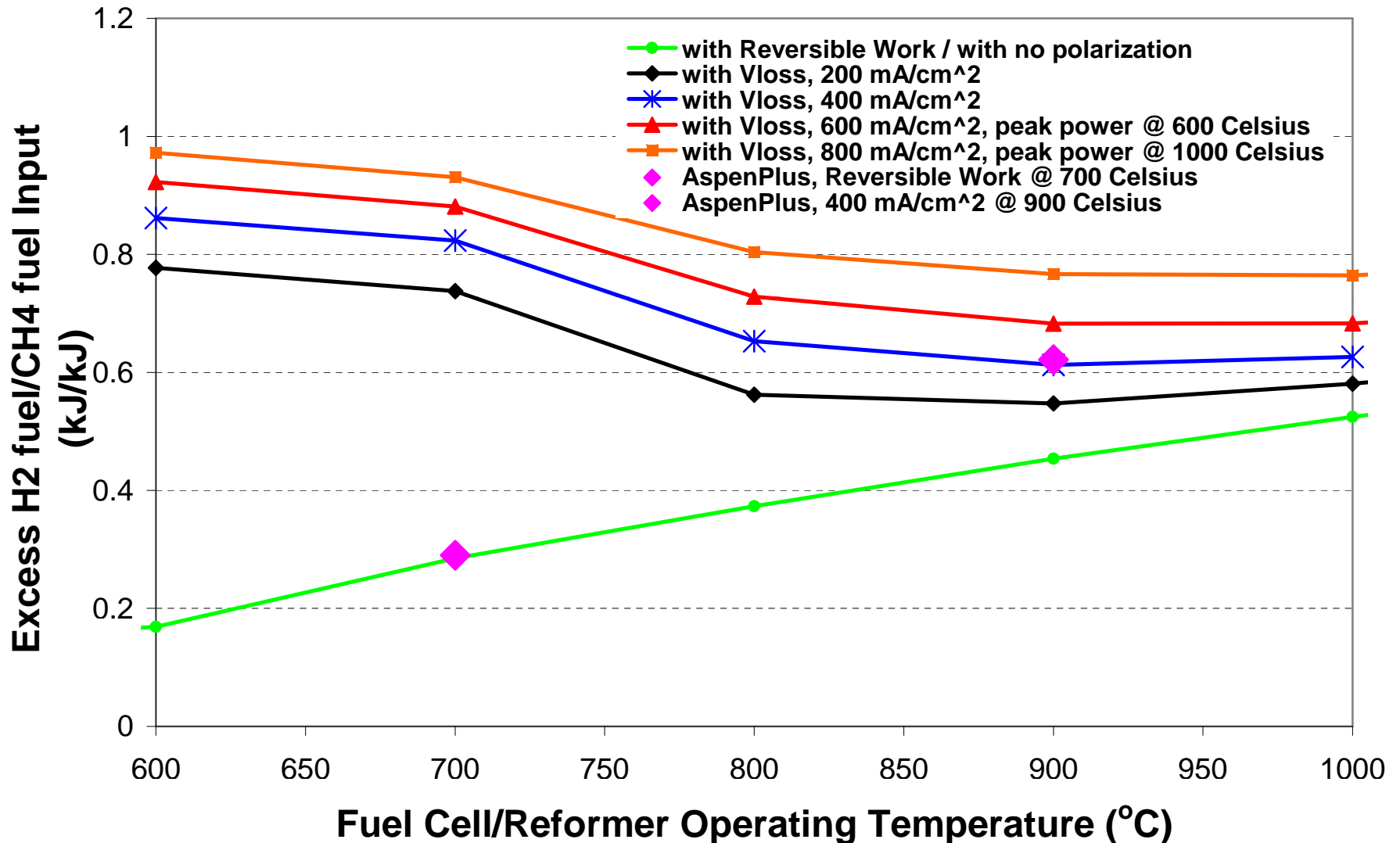
As the steam-to-carbon ratio increases, more water entering at ambient temperature must be heated up to produce steam. More available heat from the fuel cell stack is diverted for this purpose. Less heat is available for hydrogen co-production.

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, high fuel and oxidant utilization within fuel cell, and reuse of fuel cell electrochemical waste heat alone. It calculates excess H₂ available (n_{excess}).

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



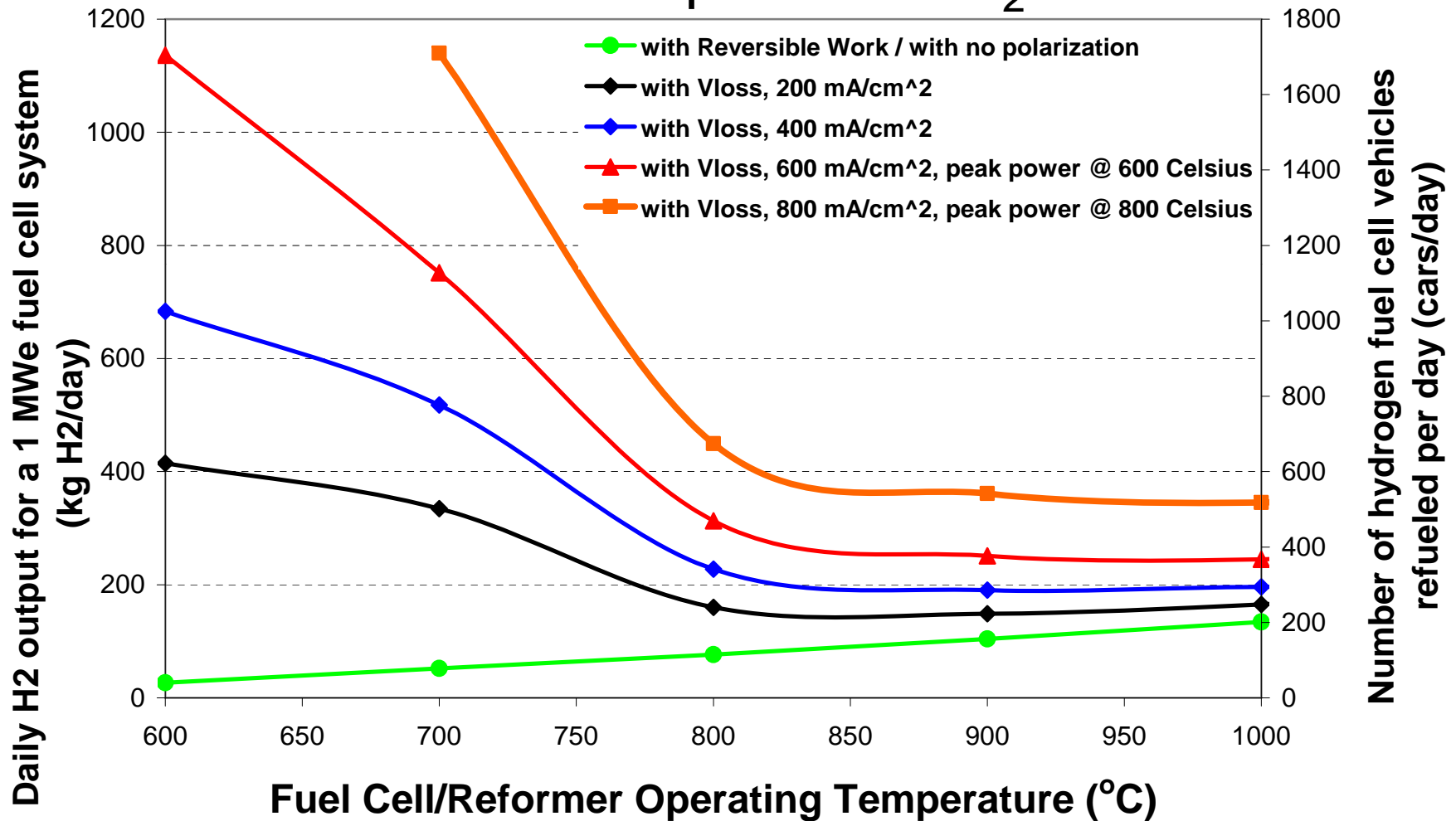
Results concur for reversible and non-reversible work, for different polarization levels (V_{loss}), and for different operating temperatures.

AspenPlus™ model fluid stream table shows results for excess H₂ moles from REF_B, and excess H₂/CH₄, which agree with analytical model.

	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	48.50112	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 400 mA/cm² and a fuel cell/reformer operating temperature of 900 °C

A 1 megawatt electric (MWe) fuel cell operating between 800 and 1000°C could make ~150 to 450 kg H₂ /day without added fuel consumption or CO₂ emissions.



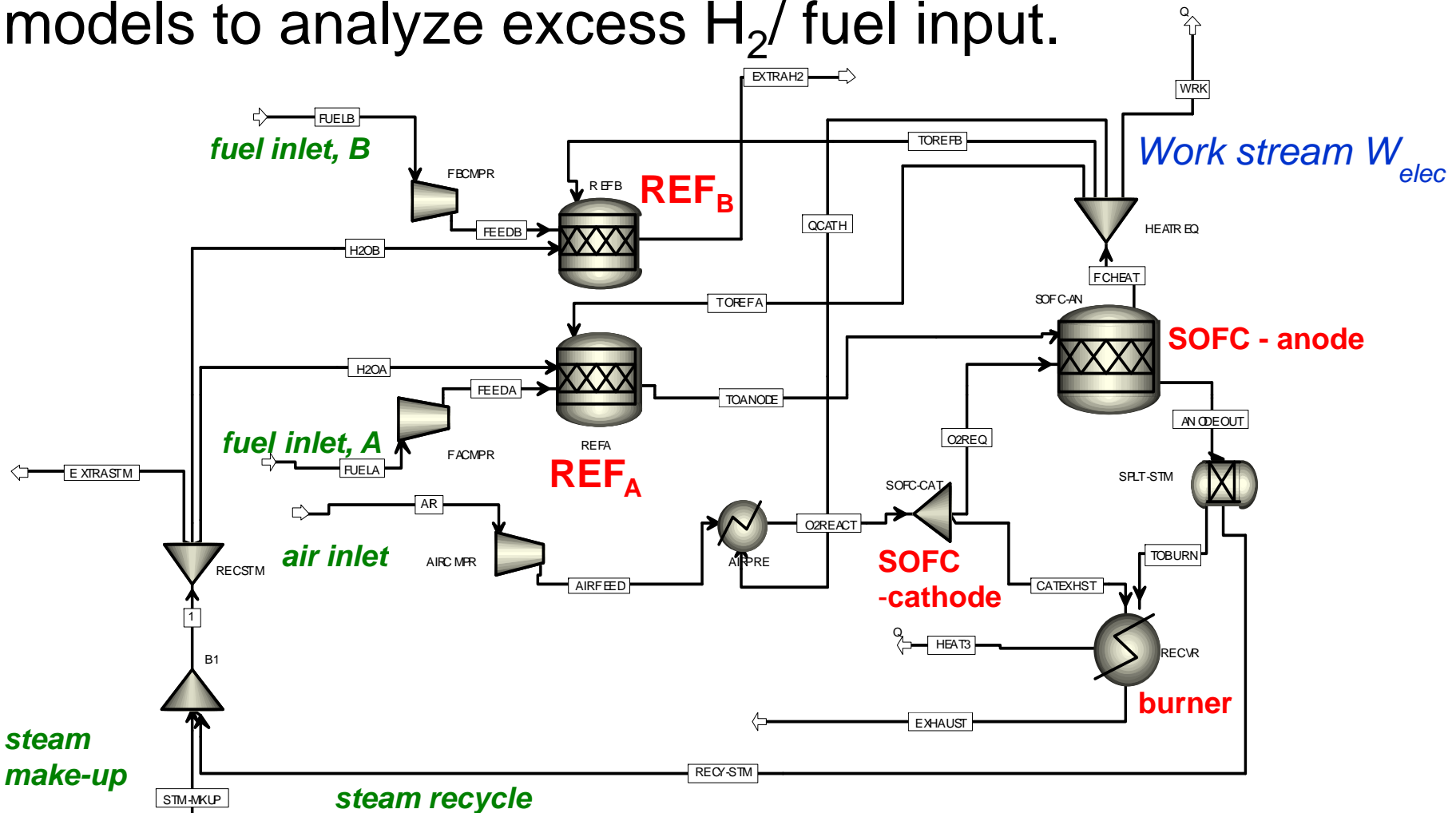
This equates to fueling between ~ 220 and 660 H₂ fuel cell cars per day.

Based on a fuel economy of 60 miles/kg H₂ ^[1] and an average annual mileage of 15,000.

^[1] http://www.fueleconomy.gov/feg/fcv_sbs.shtml

Methodology

We introduce increasing complexity into AspenPlus™ models to analyze excess H₂/ fuel input.



We enhance model fidelity to better analyze (A) preheating anode and cathode inlet gases, (B) reduced air compressor parasitic power for fuel cell stack cooling, (C) lower anodic fuel and cathode O₂ utilization rates, (D) ancillary loads (pumps, etc.), (E) heat exchanger loop designs, (F) recycle streams, (G) external and internal reforming, (H) thermodynamic cycle designs, and (I) operating conditions (steam-to-carbon ratio, etc.)

We derive excess H₂ from a H₂-FCS based on different operating conditions investigated in the scenarios below.

Scenario	Parameter Varied	Description	Values
A	Inlet stream temperature	Evaluate performance at the extreme inlet temperatures	<ol style="list-style-type: none"> 1. $T_{inlet} = T_{system}$ 2. $T_{inlet, fuel} = T_{ambient}$ 3. $T_{inlet, all} = T_{ambient}$
B	Steam-to-carbon ratio (S/C)	Compare stoichiometric S/C relative to excess steam	S/C = 2 S/C = 4
C	Pure oxygen as oxidant	Baseline case	S/C = 2
D	Air as oxidant	Compare impact of pure air as feed.	Air is 78% nitrogen and 22% oxygen by volume
E	Non-ideal cathode utilization	Compare the impact of inefficient oxidant utilization.	Utilization of oxygen at the cathode is as low as 25%.
F	Biogas fuel	Compare natural gas with a typical biogas feed stream.	Biogas is modeled as 65% CH ₄ , 32% CO ₂ , and 3% H ₂ O by mole fraction.

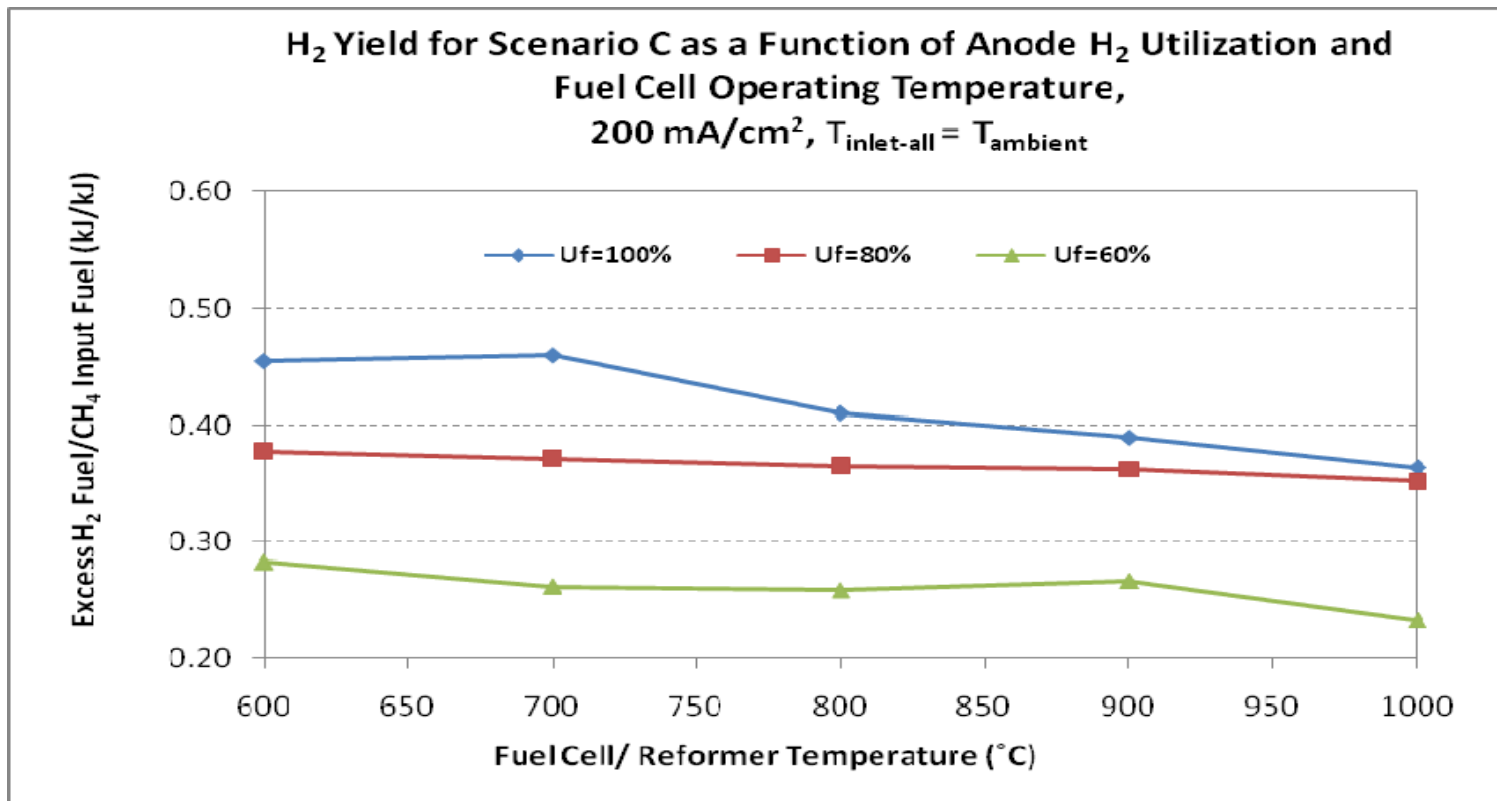
We conduct scenario analyses to determine the effects of changes in FCS operating conditions and greater FCS design complexity on the quantity of excess H₂ available from co-production. The table above summarizes key scenarios evaluated.

We derive excess H₂ from a H₂-FCS based on different operating conditions investigated in the scenarios below.

- Scenario A evaluates different levels of internal heat transfer within the system on hydrogen co-production.
 - Scenario A1 evaluates inlet reactant temperatures at the fuel cell/fuel reformer operating temperature (perfect heat transfer between hot exhaust gases and cold inlet gases.)
 - Scenario A2 evaluates the inlet temperature of the reactant fuel at ambient temperature, and inlet oxidant and water temperature at system temperature.
 - Scenario A3 evaluates conditions in which the inlet temperatures of all reactants are set to ambient temperature (no heat transfer between hot exhaust gases and cold inlet gases.)
- Scenario B evaluates excess hydrogen with respect to a stoichiometric steam-to-carbon ratio (S/C) (equal to two) and to excess steam (S/C = 4).
- Scenario C evaluates pure oxygen as the oxidant, with a stoichiometric S/C of two, and serves as a base case.
- Scenario D evaluates air as the oxidant.
- Scenario E evaluates non-ideal cathode utilizations, with the percentage of oxygen reacting at the cathode as low as 25%.
- Scenario F evaluates excess hydrogen from biogas fuel, derived from waste water treatment (WWT) plant anaerobic digester gas (ADG.) Biogas is modeled as 65% CH₄, 32% CO₂, and 3% H₂O by mole fraction.

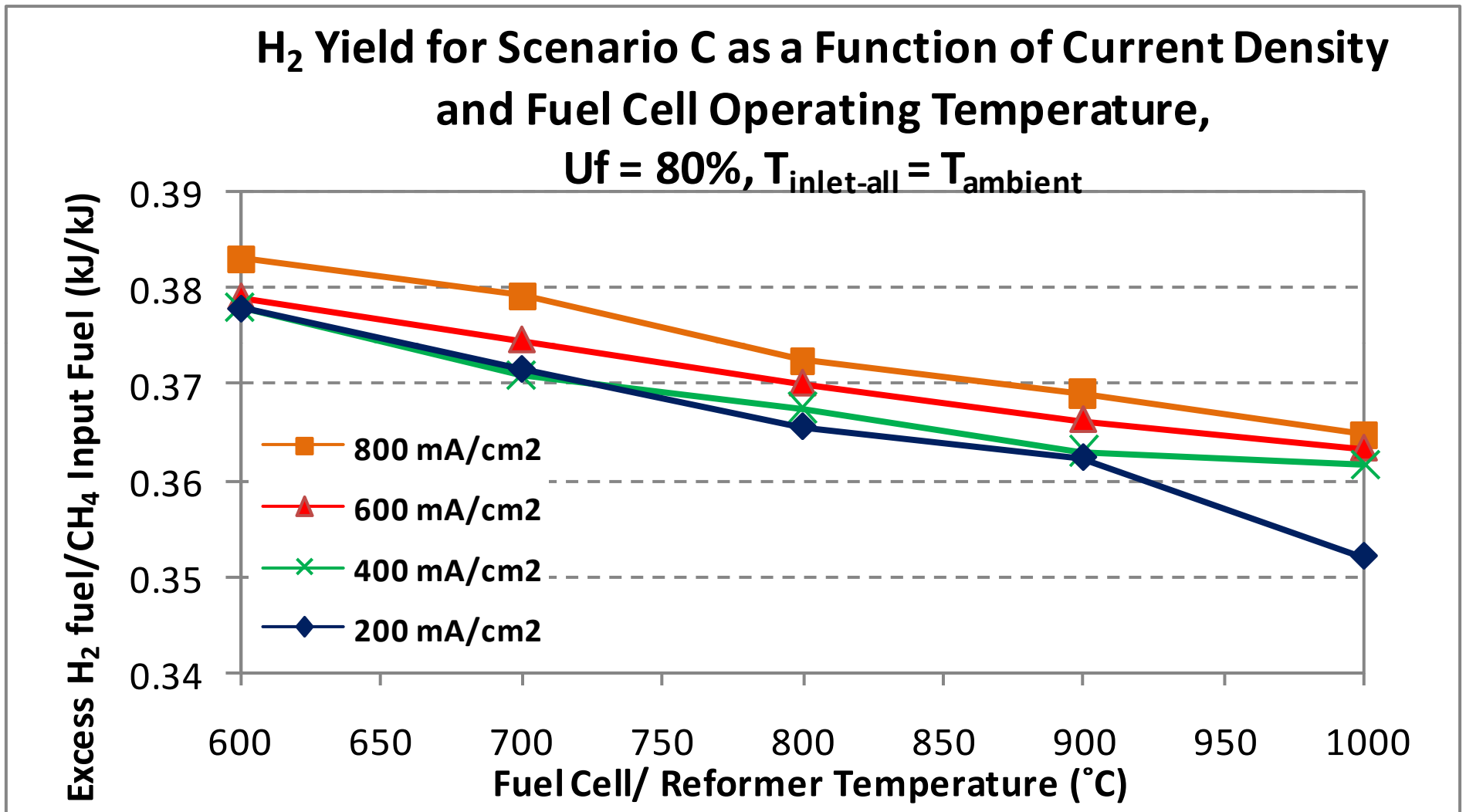
Results

Excess H₂ (from both “Reformer B” and the anode off-gas) per unit of methane increases with lower operating temperature and higher anode H₂ utilization.



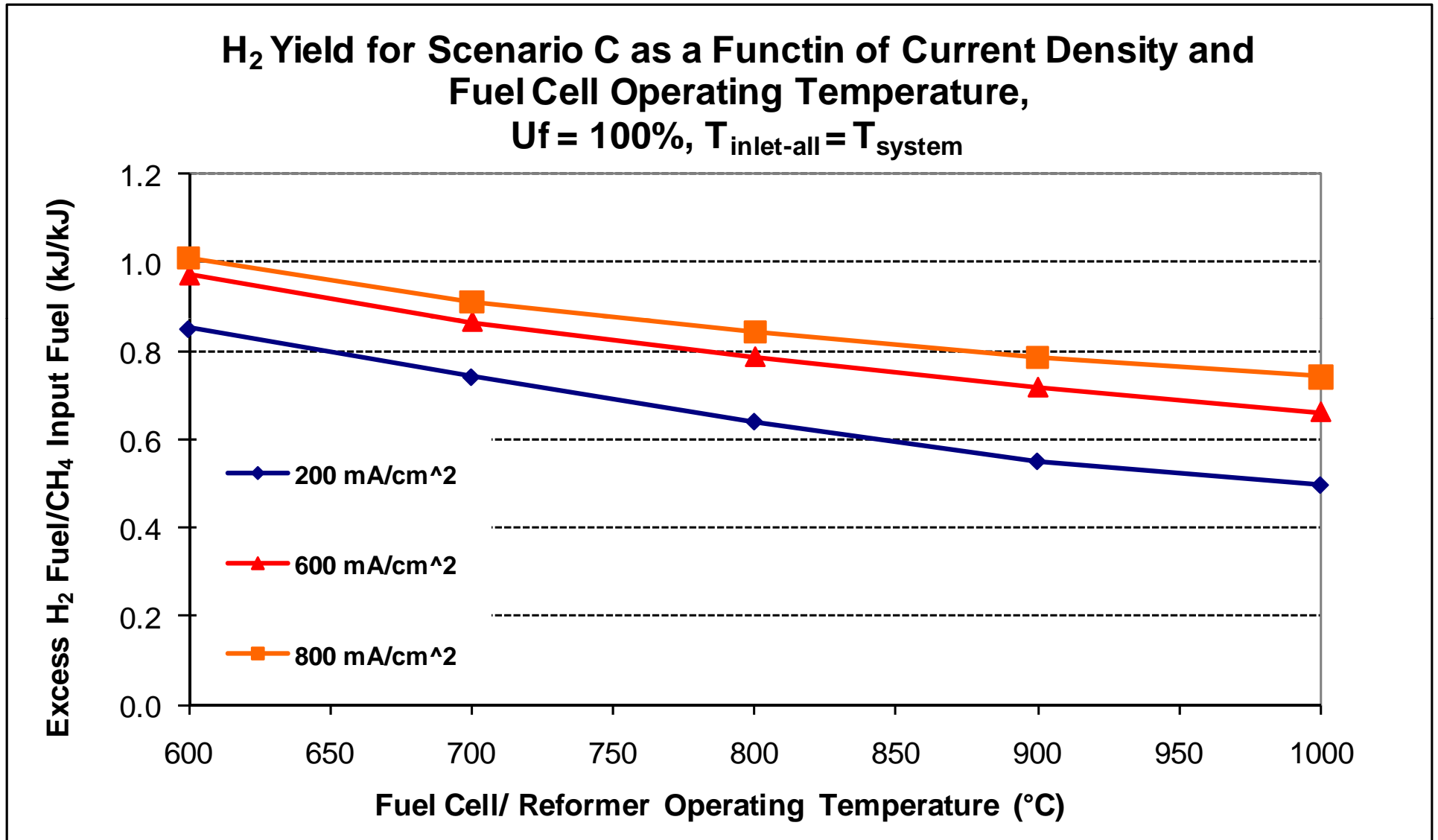
The y-axis ratio is referred to as the H₂ yield. At higher temperature, polarization losses are less, and less heat is available for hydrogen production, so H₂ yield is lower at higher temperatures. At higher utilization factors, the H₂ yield increases because more heat is available from the fuel cell stack, and this available heat increases the quantity of H₂ available at the outlet of Reformer B per unit of methane input. This increase in available H₂ at Reformer B offsets the lower quantity of H₂ from the anode off-gas.

As the current density increases, H₂ yield increases.



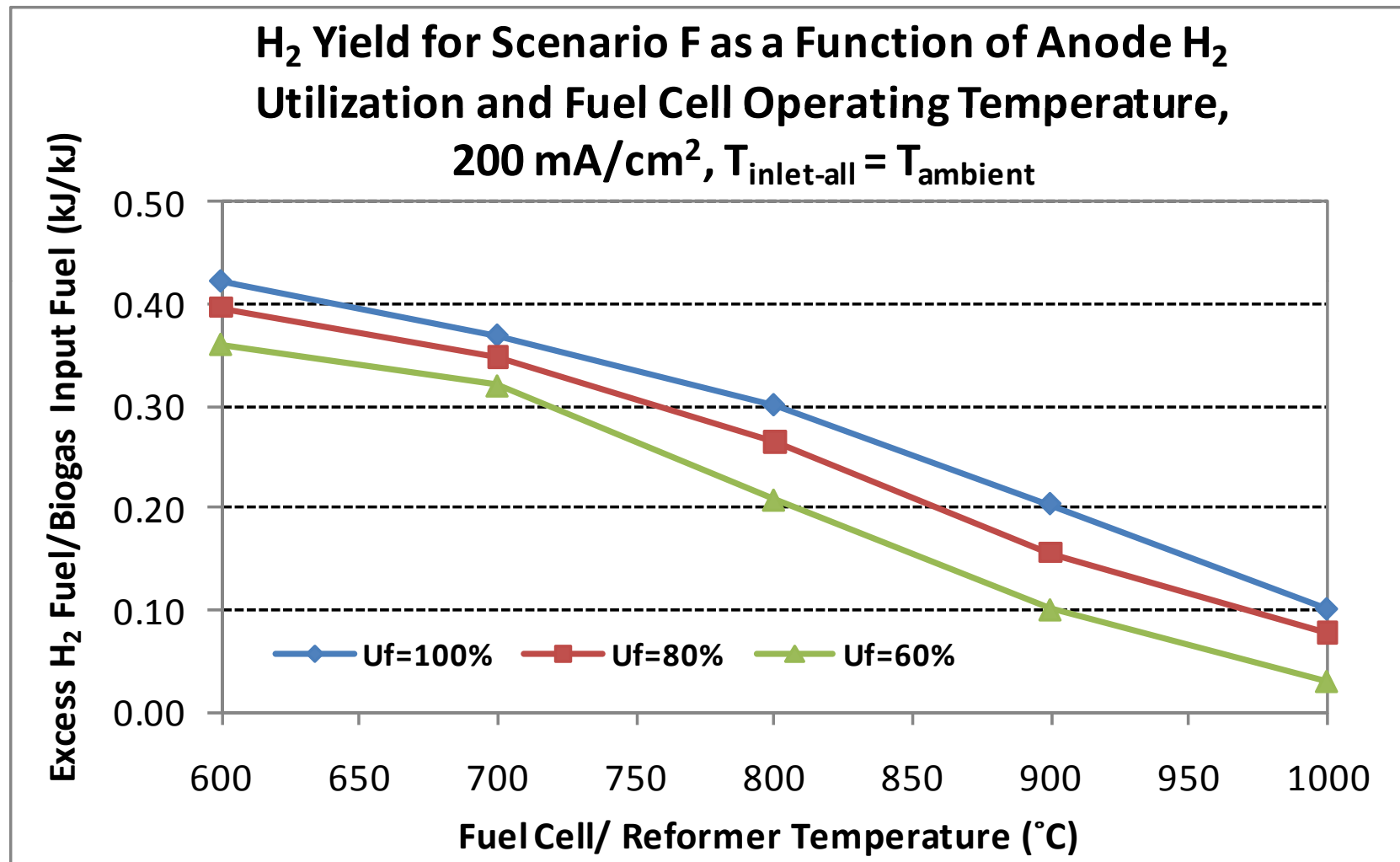
As the current density increases, the electrical efficiency declines, and the heat recovery efficiency and the hydrogen yield increases.

H₂ yield increases with greater internal reuse of available heat between hot outlet and cold inlet streams.



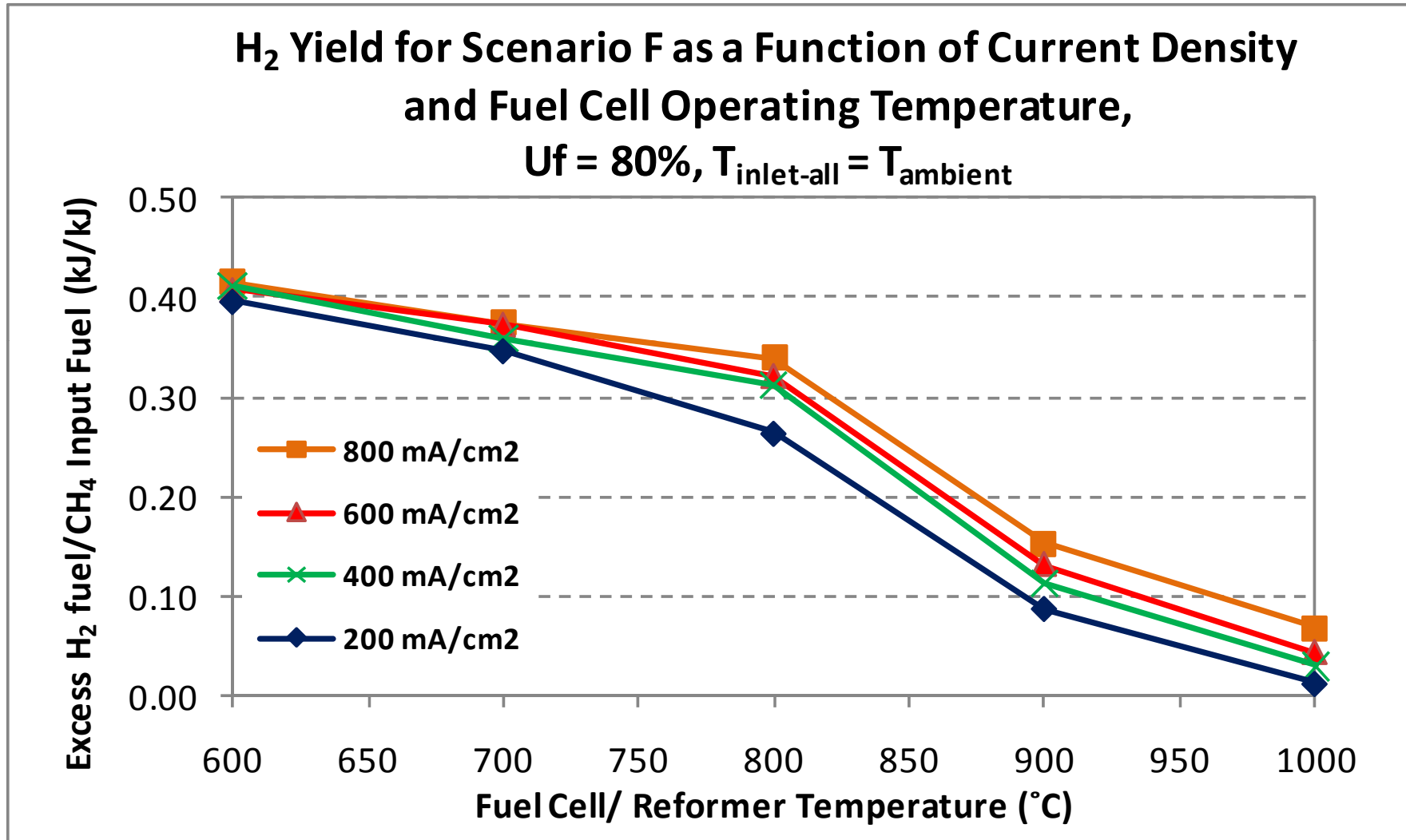
The efficiency of this heat transfer is potentially one of the most impactful variables determining hydrogen yield.

H₂ yield is typically lower with biogas fuel (compared to natural gas) due to the higher energy needs for upstream anaerobic digester gas (ADG) production.



The example results shown here assume that the ADG plant consumes 40% of the available energy in the resulting biogas fuel for running itself.

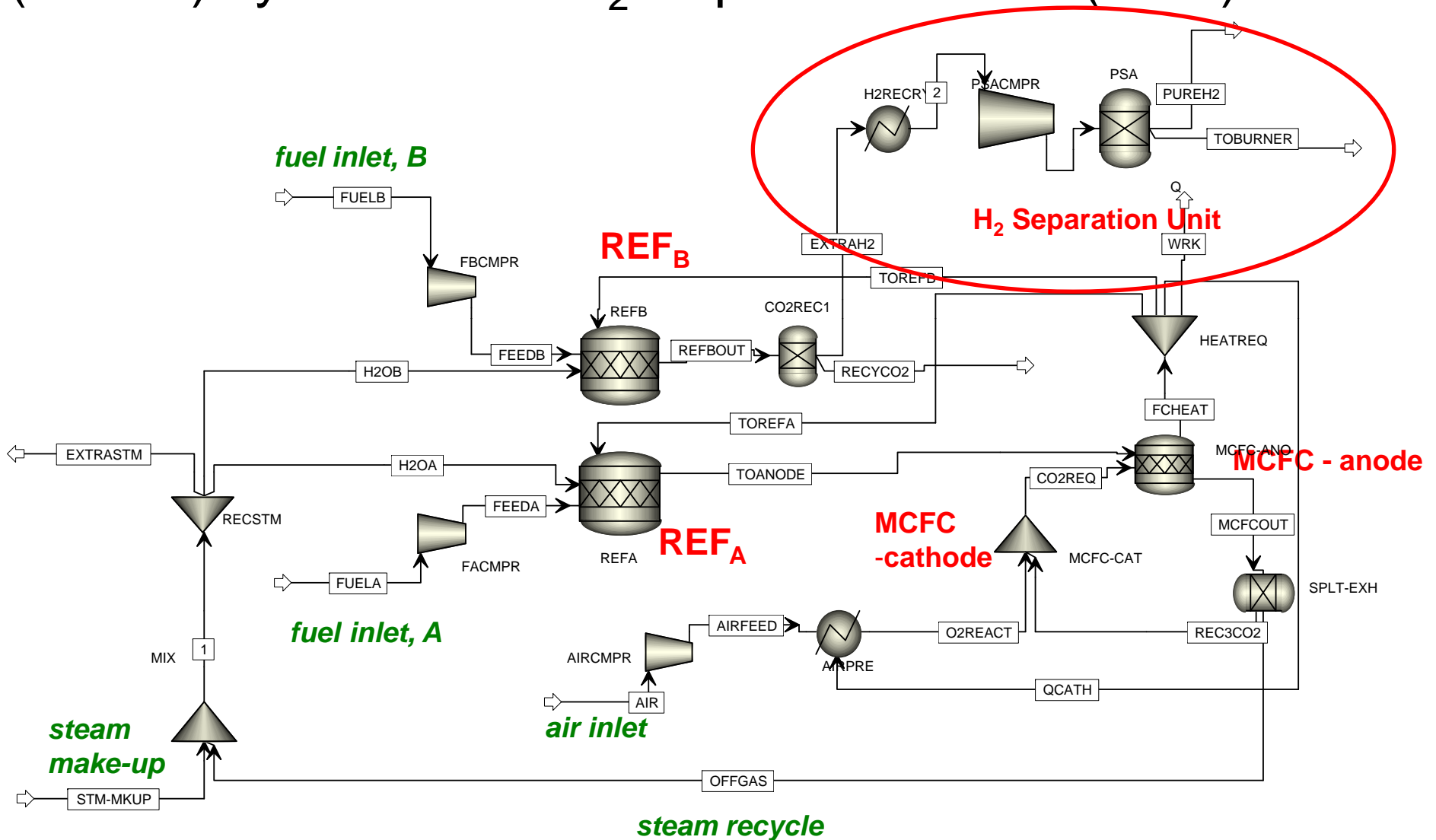
H₂ yield is lower for biogas due to higher upstream energy requirements.



H₂ co-production appears to be well matched to ADG fuel because high temperature heat (~800°C) can be used for steam reforming to make H₂ and low temperature heat (~40°C) can be used to heat the ADG process.

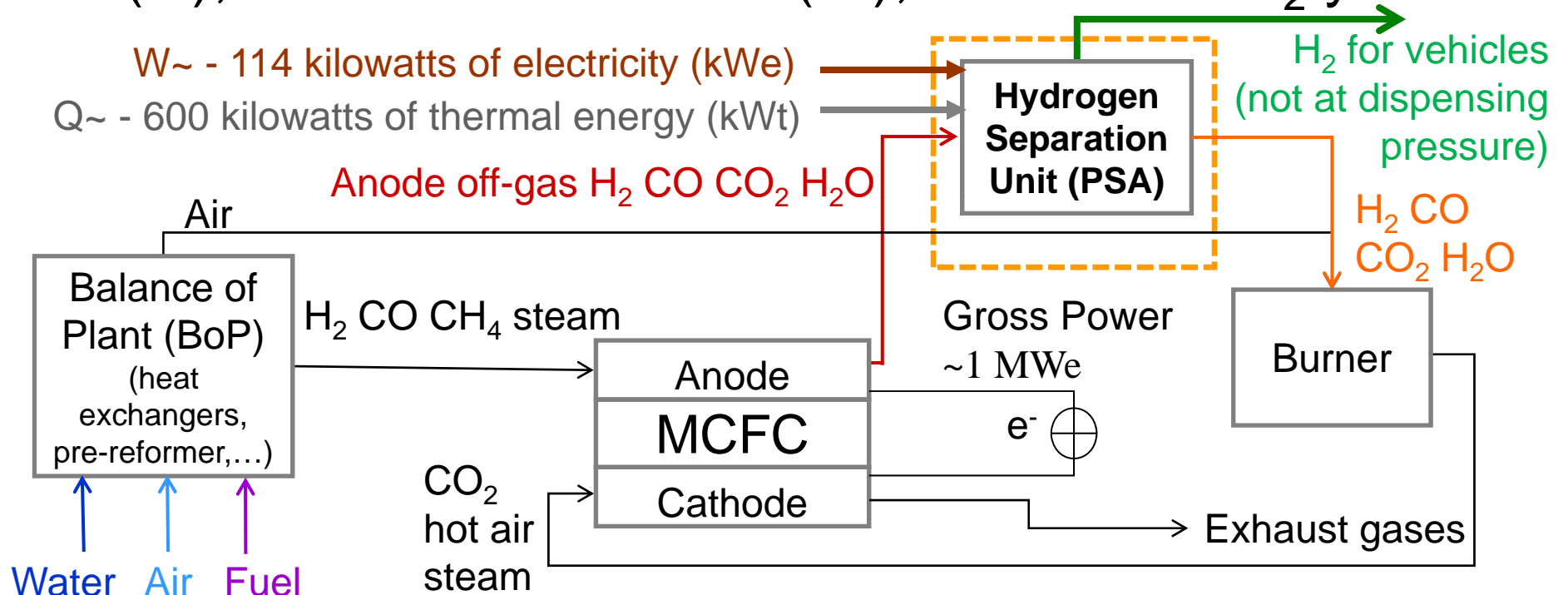
Methodology

We model the integration of Molten Carbonate Fuel Cell (MCFC) systems with H₂ Separation Units (HSU).



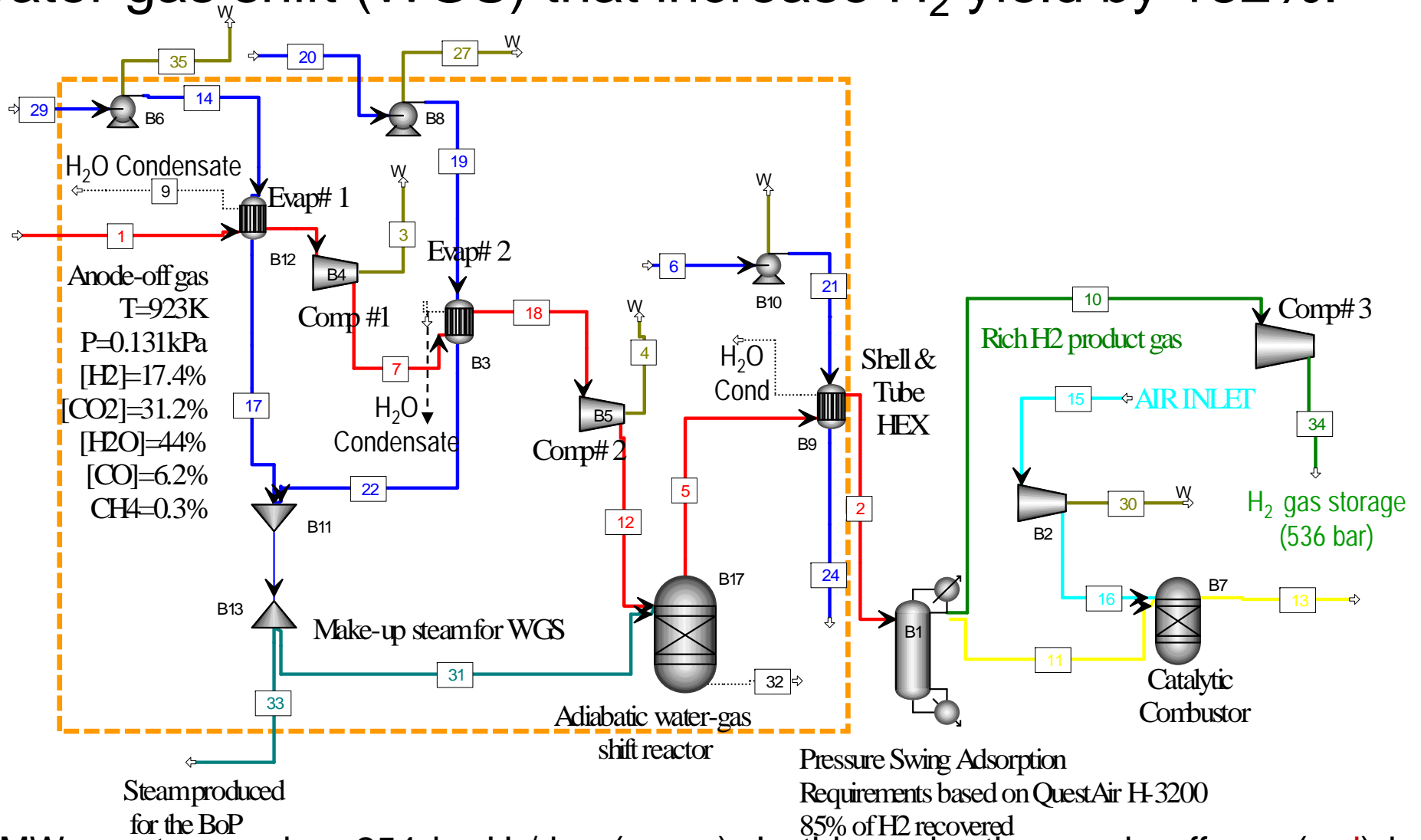
The HSU uses Pressure Swing Absorption (PSA) beds, based on 80% H₂ recovery and QuestAir H-3200 specifications. The 1 MWe MCFC operates with 60% H₂ utilization.

We evaluate cycle design configurations for thermally integrating HSU & fuel cell, with these goals: achieve required inlet temperature & pressure for PSA, reuse all heat (Q), consume less work (W), & increase H_2 yield.



H_2 yield for vehicle fueling (shown in green) increases when less anode off-gas H_2 (red) is burned for internal heat generation (orange). Heat from H_2 combustion can be displaced by internal reuse of available heat. The anode off-gas (red) must be cooled and compressed to reach the required PSA inlet temperature (~ 323 K) and pressure (~ 20 bar). We evaluate configurations where this available heat warms incoming water (blue), air (light blue), & fuel (purple), and displaces H_2 combustion at the burner (orange).

We identify HSU cycle designs with heat recovery & water gas shift (WGS) that increase H₂ yield by 132%.



1 MWe system makes 254 kg H₂/day (green). In this cycle, the anode off-gas (red) is cooled & compressed in series twice, cooled again, undergoes WGS to convert CO to H₂, & is cooled again before the PSA. Recovered heat makes BoP required steam (blue).

Results

This HSU design recovers 73% of the available thermal energy, with a compressor load of 11% of gross power.

Heat Recovery Devices

Heat Exchanger	Heat Recovered (kWt)
Evaporator #1	207
Evaporator #2	178
Post-WGS Heat Exchanger	51
Total	436

Compression Work Devices

Compressor	Outlet Pressure (bar)	Work Required (kW)	Comment
1	4	69	for PSA inlet
2	22	45	for PSA inlet
Subtotal		114	
3	537	32	for H ₂ storage
Total		146	

The anode off-gas has 600 kilowatts of thermal energy (kWt) available to recover between the anode outlet and the PSA inlet temperatures. The HSU cycle design shown here recovers 436 kWt of this heat (73%), which provides 91% of system-wide required steam. It requires 114 kW of compressor work (~11% of gross electric power) from compressors 1 & 2 to reach the required PSA inlet pressure (~21 bar.) This HSU design reduces compressor work by lowering compressor inlet gas temperatures. The H₂ delivery sub-system needs an additional 32 kW of compressor work to pressurize H₂ up to 537 bar for H₂ storage, to later dispense H₂ at 350 bar to vehicles. Total compressor load for the HSU and H₂ storage is about 15% of gross electric power.

The marginal increase in H₂ yield due to 1) displaced H₂ combustion alone is 102% (Case 2); 2) WGS alone is 15% (Case 3); & 3) both combined is 132% (Case 4.)

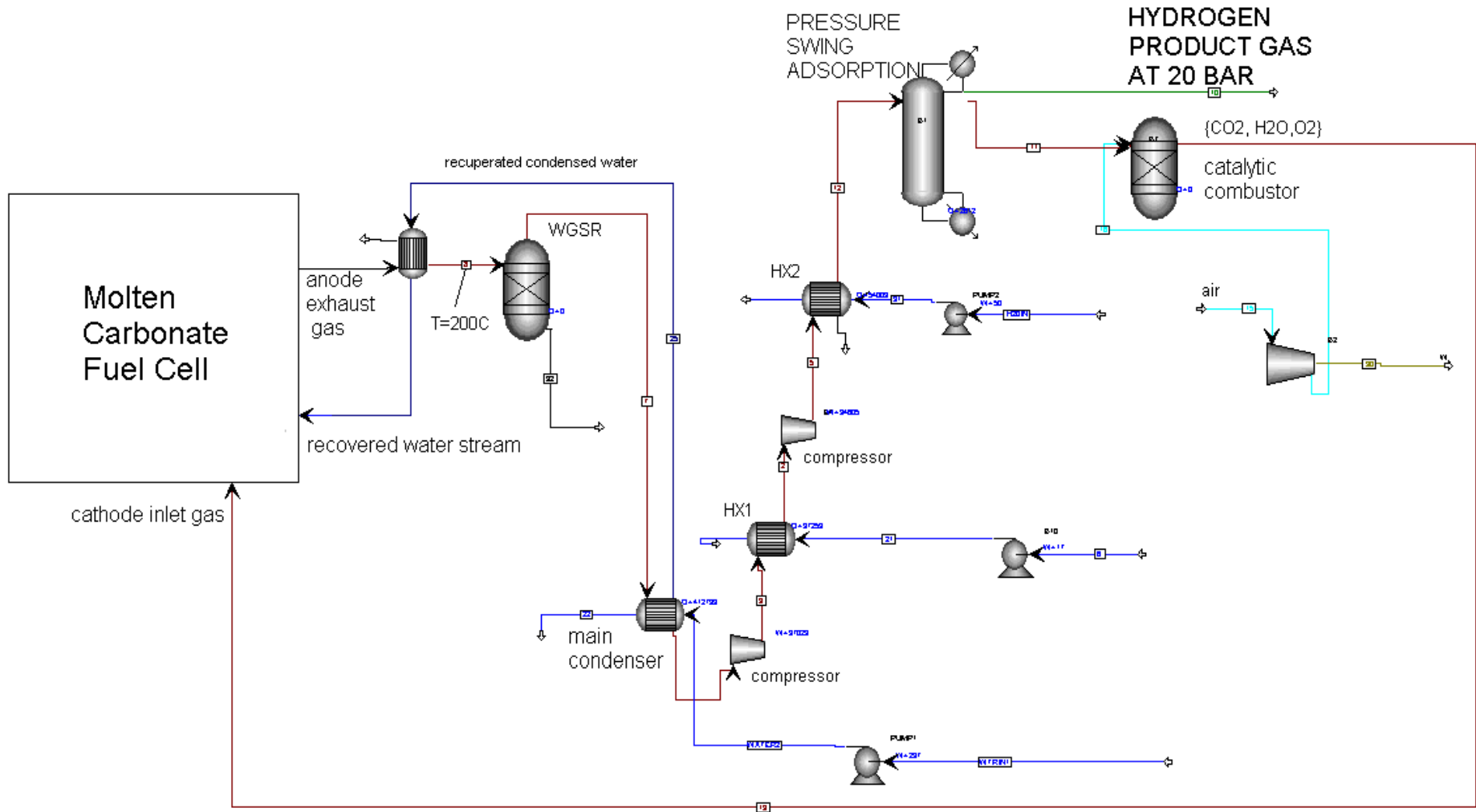
1 MWe Molten Carbonate Fuel Cell	CASE 1	CASE 2	CASE 3	CASE 4
H2 Co-production	Yes	Yes	Yes	Yes
Heat Recovery from the Hydrogen Separation Unit (HSU)	No	Yes	No	Yes
Water-Gas Shift	No	No	Yes	Yes
Fuel in @60% Utilization Factor [kgmol/s]	0.00312	0.00312	0.00312	0.00312
Methane LHV [kJ/kgmol]	800,800	800,800	800,800	800,800
Ein [kW]	2,500	2,500	2,500	2,500
Generated Gross Power [kW]	1000	1000	1000	1000
Thermal energy penalty to reach PSA levels [kW]	600	600	600	600
Heat recovered from HSU by steam production [kW]	0	435	0	435
Hydrogen potential before PSA [kgmol/s]	0.00151	0.00151	0.00173	0.00173
Hydrogen produced [kgmol/s]	0.00063	0.00128	0.00073	0.00147
Hydrogen potential before PSA [kg/s]	0.00302	0.00302	0.00346	0.00346
Hydrogen produced [kg/s]	0.00127	0.00257	0.00145	0.00294
Hydrogen produced [kg/h]	4.56624	9.2412	5.23152	10.5876
Hydrogen Produced [kg/day]	109.59	221.78	125.56	254.10
Marginal increase in H2 compared with base case (kg H2/day)	Basecase	112.19	15.96	144.51
H ₂ production increase (reference CASE 1: NO heat recv; NO WGS)	Basecase	102%	15%	132%

Without any HSU heat recovery (Case 1), the fuel cell system has a deficit of 123 kWt of required heat for the BoP. Heat released from the exothermic anodic reactions is consumed by reforming extra fuel. Consequently, to supply this deficit of heat, anode off-gas H₂ is burned, and H₂ yield for merchant H₂ or vehicles is only 110 kg H₂/day.

Case 4 meets PSA inlet needs, recovers 73% of heat, uses 11% of electricity, & increases H₂ yield by 132%.

Thermodynamic Characteristic of Stream	Aspen™ Flowsheet Fluid Stream Name and Number					
	HSU IN Anode- off gas	WGS IN	WGS OUT	PSA IN	PSA OUT	Burner OUT / Cathode Inlet Gas
	1	12	5	2	10	13
Mole Flow kgmol/sec						
O ₂	0	0	0	0	0.00E+00	0.00279
H ₂ O	0.003894	0.00046	0.000244	3.50E-05	0	0.00036
CO	0.000541	0.000541	0.000325	0.000325	0	0
CO ₂	0.002715	0.002715	0.002931	0.002931	0	0.00328
H ₂	0.001518	0.001518	0.001734	0.001734	1.47E-03	0
CH ₄	3.25E-05	3.25E-05	3.25E-05	3.25E-05	0	0
N ₂	0	0	0	0	0	0.01185
Mole Fraction						
O ₂	0	0	0	0	0	0.15267
H ₂ O	0.44755	0.087298	0.046295	0.006912	0	0.01968
CO	0.06216	0.102695	0.061692	0.064239	0	0
CO ₂	0.31205	0.515538	0.55654	0.579522	0	0.17976
H ₂	0.17451	0.288308	0.329311	0.342909	1	0
CH ₄	0.00373	0.006162	0.006162	0.006417	0	0
N ₂	0	0	0	0	0	0.64787
Total Flow kgmol/sec	0.0087	0.005266	0.005266	0.005057	0.001474	0.01829
Total Flow kg/sec	0.208354	0.14649	0.14649	0.142728	0.002971	0.57251
Temperature K	923.15	606.4986	527.5944	323.0022	333.0022	640.54
Pressure N/sqm	106799.8	2221836	2152888	2152888	2118414	101283
Vapor Frac	1	1	1	1	1	1
Liquid Frac	0	0	0	0	0	0
Enthalpy J/kgmol	-2.1E+08	-2.2E+08	-2.3E+08	-2.4E+08	1006438	-64421960
Enthalpy J/kg	-8948283	-8071116	-8240865	-8390823	499254.7	-2058156.6
Enthalpy Watt	-1864412	-1182339	-1207206	-1197605	1483.524	-1178320.3

We developed a further refined design called HSU 2, whereby the WGSR is placed prior to compression.



In HSU 2, more water is condensed out before the compression steps. These changes increase H₂ yield and reduce compressor load. In both HSU1 and HSU 2 designs, H₂ yield increases by shifting CO and H₂O into H₂ and CO₂ compared to the baseline case.

HSU 2 (Case 5) recovers 73% of available thermal energy, with a compressor load of only 7% gross power, & increases the H₂ yield by 172% to 298 kg H₂/day.

FUEL CELL (MCFC1000kW)	CASE 1	CASE 2	CASE 3
H2 Co-production	Yes	Yes	Yes
Heat Recovery from the Hydrogen Separation Unit (HSU)	No	Yes	Yes
Water-Gas Shift	No	Yes	Yes
Generated Gross Power [kW]	1000	1000	1000
Ancillary loads (compressors) [KW]	114	114	71
Thermal energy penalty to reach PSA levels [kW]	600	600	600
Heat recovered from HSU by steam production [kW]	0	435	435
Heat recovered from HSU by steam production [%]	n.a.	73 %	73 %
Hydrogen potential after WGSR (before PSA) [kmol/s]	0.00151	0.00173	0.00203
Hydrogen produced [kmol/s]	0.00063	0.00147	0.00173
Hydrogen produced [kg/day]	110	254	298
Marginal increase in H2 compared with base case (kg H2/day)	n.a.	144	188
H ₂ production increase (Benchmark: NO heat recovery; NO WGS)	n.a.	132%	172%

HSU 2 / Case 5 also achieves neutral net water balance.

Conclusions

Conclusions

According to model results, an idealized one megawatt-electric fuel cell system operating between 800 and 1000°C could make between ~150 to 450 kilograms of hydrogen per day (kg H₂/day), without added fuel use or CO₂ emissions from combustion to provide heat for the endothermic steam reforming reaction. This output rate is enough to refuel between 220 and 660 H₂ fuel cell cars per day.

The total excess hydrogen available per unit of inlet methane fuel increases with 1) decreasing fuel cell reformer operating temperature, 2) higher anode H₂ utilization, 3) Increasing current density, and 4) greater internal heat transfer.

At lower temperatures, polarization losses are greater, and more heat is available for hydrogen production, so H₂ yield is higher at lower temperatures.

At higher utilization factors, the H₂ yield increases because more heat is available from the fuel cell stack, and this available heat increases the quantity of H₂ available at the outlet of Reformer B per unit of methane input. This increase in available H₂ at Reformer B offsets the lower quantity of H₂ from the anode off-gas.

As the current density increases, the electrical efficiency declines, and the heat recovery efficiency and the hydrogen yield increases.

Conclusions

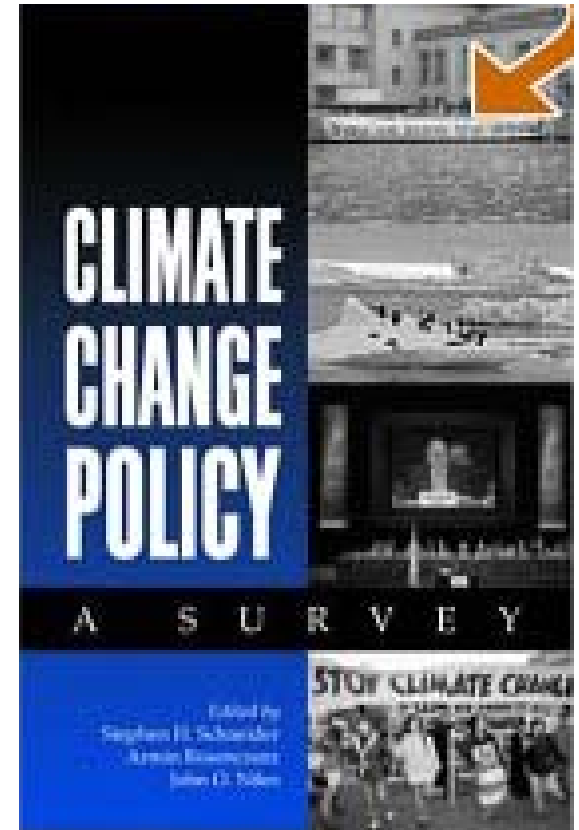
The quantity of excess H₂ available is very sensitive to the degree of internal heat transfer between cold inlet gases entering the system and hot anode and cathode off-gas streams. The lower the temperature of inlet streams, the more pre-heating they require, and the less heat is available for H₂ co-production.

H₂ yield is lower for biogas than for natural gas fuel due to the higher upstream energy requirements of biogas. Anaerobic digester gas (ADG) is well-matched to hydrogen co-production fuel cell system (H₂-FCS) because it can be employed to recover low-temperature heat (~40° C) from the H₂-FCS, which might otherwise go unused.

Our proposed hydrogen separation unit (HSU) design has been optimized to meet pressure swing absorption (PSA) unit inlet temperature and pressure requirements, recover 73% of available anode-off gas waste heat, consume only 7% of gross electricity, and increase H₂ yield by 172% to 298 kg H₂/day (compared with the base case with no heat recovery or WGS.) This design also achieves neutral water balance, and minimizes fuel consumption and CO₂ emissions by re-using available waste heat and minimizing losses.

Publications

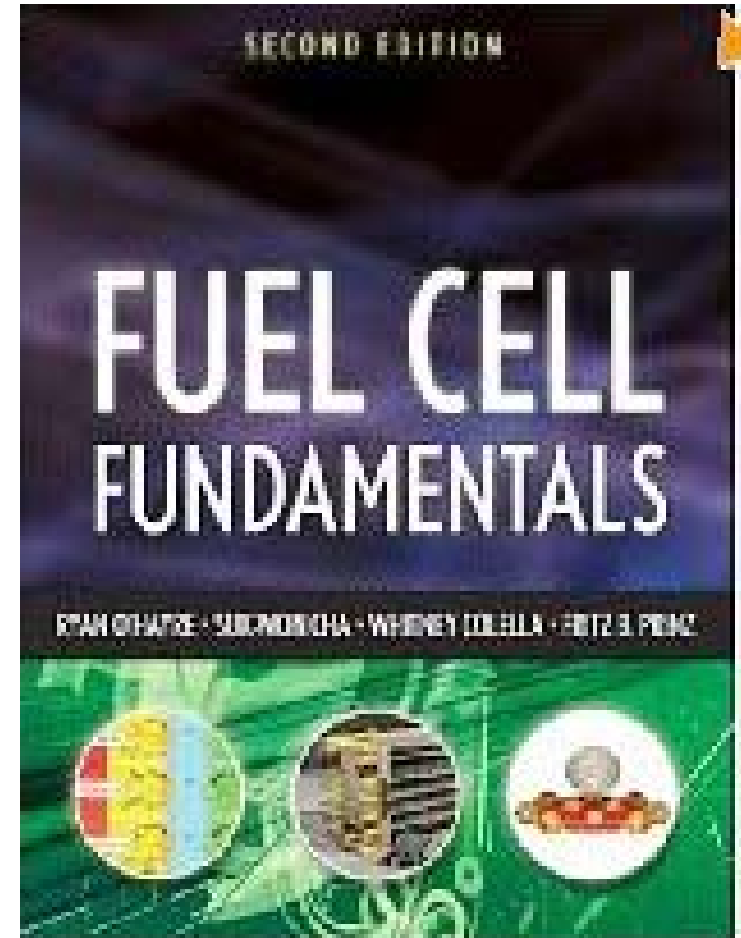
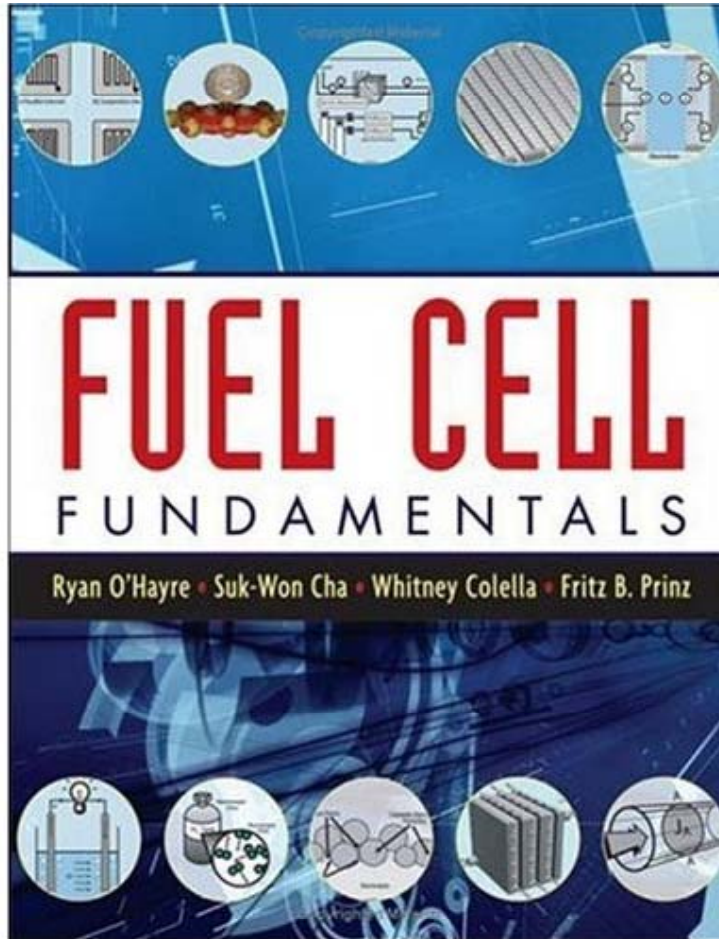
Climate Change Science and Policy educates policy makers and engineers on hydrogen and climate.



“**Designing Energy Supply Chains Based on Hydrogen** [To Mitigate Climate Change],” by W. Colella

Editors are Stanford University researchers: Stephen H. Schneider, Armin Rosencranz and Michael D. Mastrandrea

Fuel Cell Fundamentals educates engineers about fuel cells



This book is the first textbook on fuel cells, and includes solved problems and a solutions guide. The authors were Stanford researchers. The target audience is engineering students, senior undergraduates or graduate students. 1st & 2nd editions available.

Collaborators



**Aerel Rankin is a university student
who contributed to this work.**

Aerel Rankin is an M.S. candidate in Mechanical Engineering (ME) at the University of New Mexico. Aerel holds a B.S. in ME from the University of Washington. His educational focus is sustainable energy devices.



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