USE OF WASTEWATER TREATMENT PLANT BIOGAS FOR THE OPERATION OF SOLID OXIDE FUEL CELLS (SOFCs)

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PROJECT BACKGROUND

- Biogas from WWTPs is a readily available fuel source that when used in SOFC's is often considered 'carbon neutral'

- Biogas can be reformed to increase hydrogen concentration and reduce constituents that are harmful to SOFC technologies

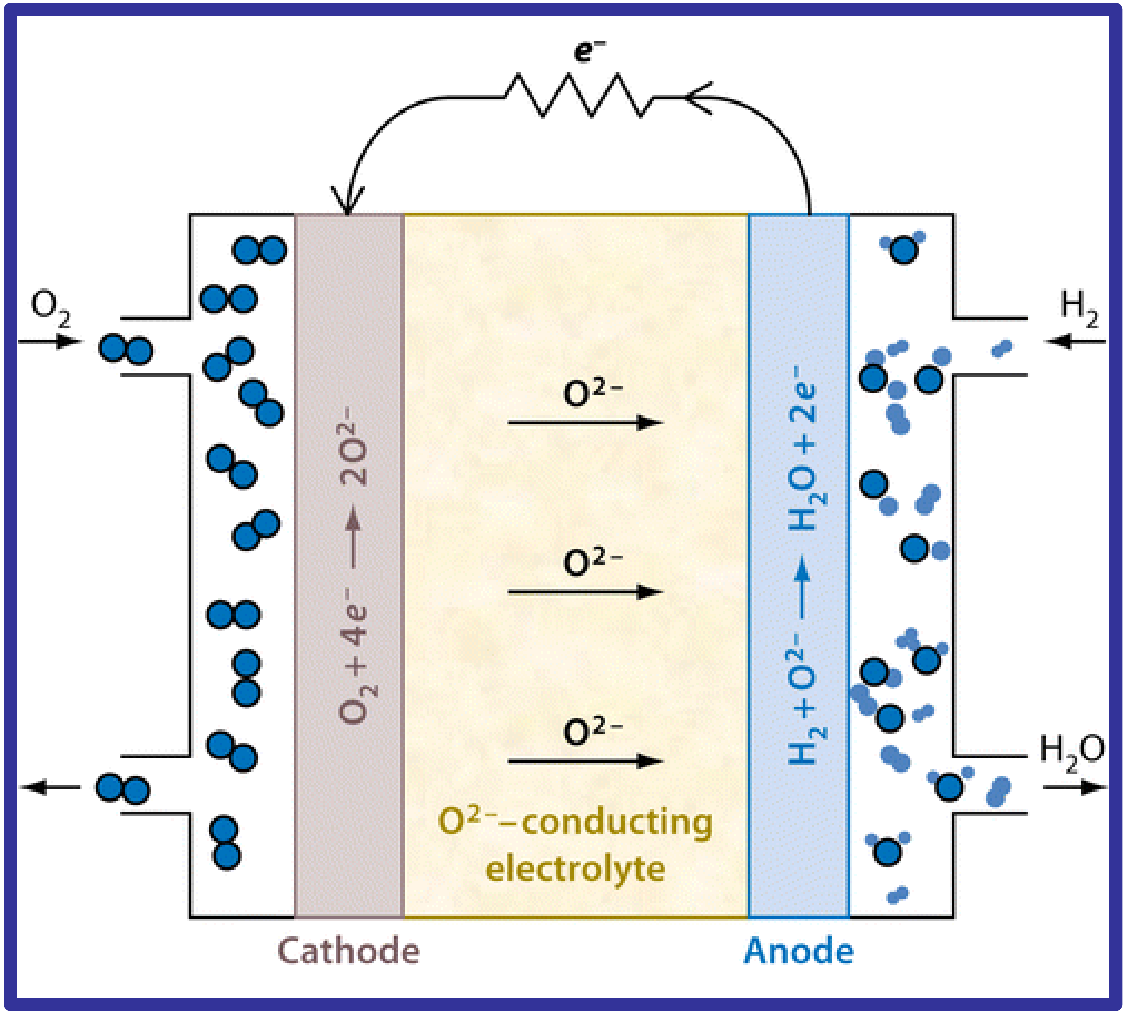
- Biogas that is variable in composition may damage or starve SOFCs

- Knowing typical and extreme concentration ranges is important

Kingston Ontario Application

- Utilities Kingston is taking pro-active measures to reduce its environmental footprint
  - The Kingston Ravensview WWTP currently processes approximately 19,000 m^3 of wastewater per day and uses over 4 million kWh per year of electrical power
  - The installation of a waste-to-energy system at the Kingston Ravensview WWTP could offset electrical needs as well as assist with the heat requirement of the anaerobic digesters, further reducing electrical needs
- This research project will result in the construction of a pilot scale plant at the Utilities Kingston Ravensview WWTP and a lasting relationship between the City of Kingston and renewable energy sources

FUEL CELL BASICS



- Anode material is: Ni-YSZ
- Cathode material is: LSM
- Solid electrolyte material is: YSZ

Catalysis in Solid Oxide Fuel Cells. **Annual Review of Chemical and Bimolecular Engineering.** JULY 2011, Vol. 2 **/ 10.1146**

Project Outline

- **Task 1**: Compile biogas variability data across North America to determine fuel composition
- **Task 2:** Determine the sensitivity of a SOFC to fuel dilution that is typically found in biogas produced by AD
- **Task 3:** Simulate expected system performance and GHG emissions when operating on dilute H_2
- **Task 4:** Conduct testing with simulated biogas reformate

Task 1

Biogas Variability

Lackey, J., A. Maier, P. Champagne* and B. Peppley (2015) *A Review of Biogas Composition and Uses in North America.* Waste Management and Research (*In Press*)

TASK 1: BIOGAS VARIABILITY

Voluntary survey of WWTPs in North America produced the following data:

Compound	# Urban Areas	Average	Standard Deviation	Median	Minimum	Maximum	Average Variability	Max Variability
Methane (CH_4)	16	63%	2%	63%	50%	69%	9%	28%
Carbon Dioxide (CO_2)	15	37%	4%	38%	24%	45%	14%	38%
Nitrogen (N_2)	13	1%	2%	0.3%	0.0%	9%	N/A	N/A
Oxygen (O_2)	12	0%	0.7%	0%	0%	3%	N/A	N/A
Hydrogen Sulphide (H_2S)	14	134ppm	186ppm	18ppm	0ppm	855ppm	258%	651%
Si Equivalence	11	12ppm	10ppm	10ppm	0.2ppm	38ppm	137%	340%

- Urban areas with populations above 150,000 in the U.S. and above 50,000 in Canada were solicited
- Data was reported from 16 different locations

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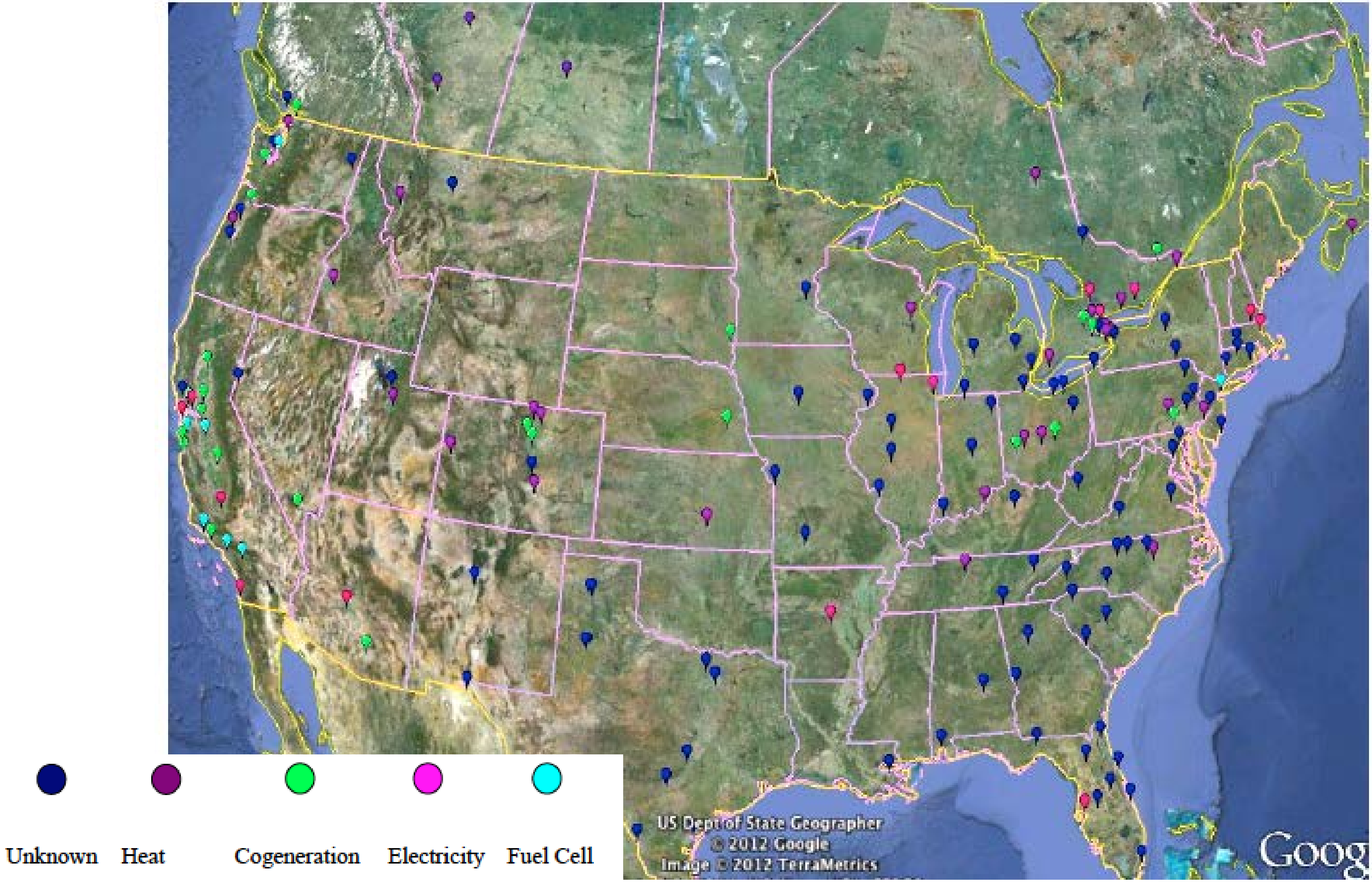
- CH_4 and CO_2 variability are not significant concerns
  - Lower variability than more poisonous compounds
- H_2S and Si compound variability are more troublesome

Task 1: Biogas Variability



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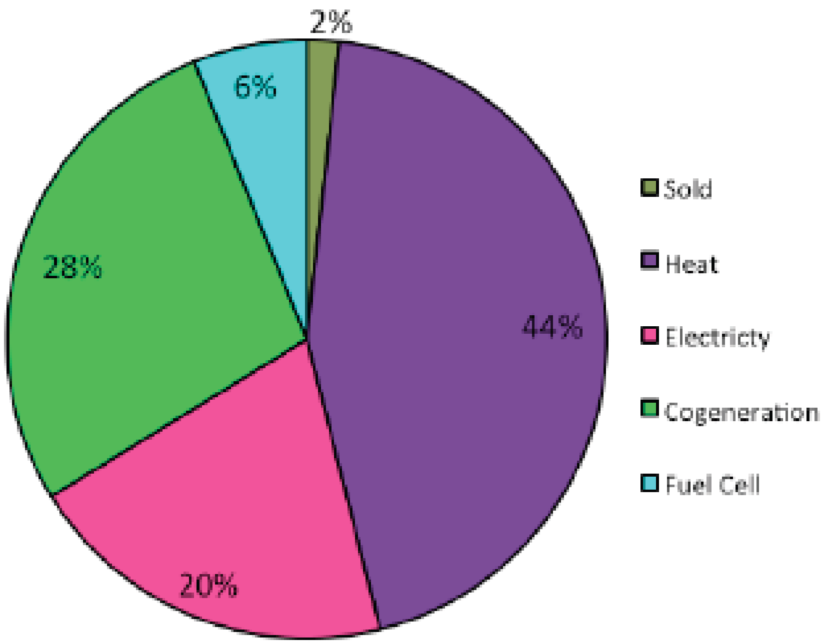
Task 1: Biogas Variability



- Few trends in biogas composition
  - Sociopolitical trends in some regions
- Heat is the predominent end use of biogas
  - Most prevalent in Northern states
  - Population trends with respect to biogas end use

Task 2

SOFCs Operating on Dilute H_2

TASK 2: SOFCs OPERATING ON DILUTE H_2

N_2, Ar and CO_2 were used as diluents at concentrations of 65%, 25% and 10% H_2 + 2.3mol% H_2O as steam + diluent

Cell Characteristics:

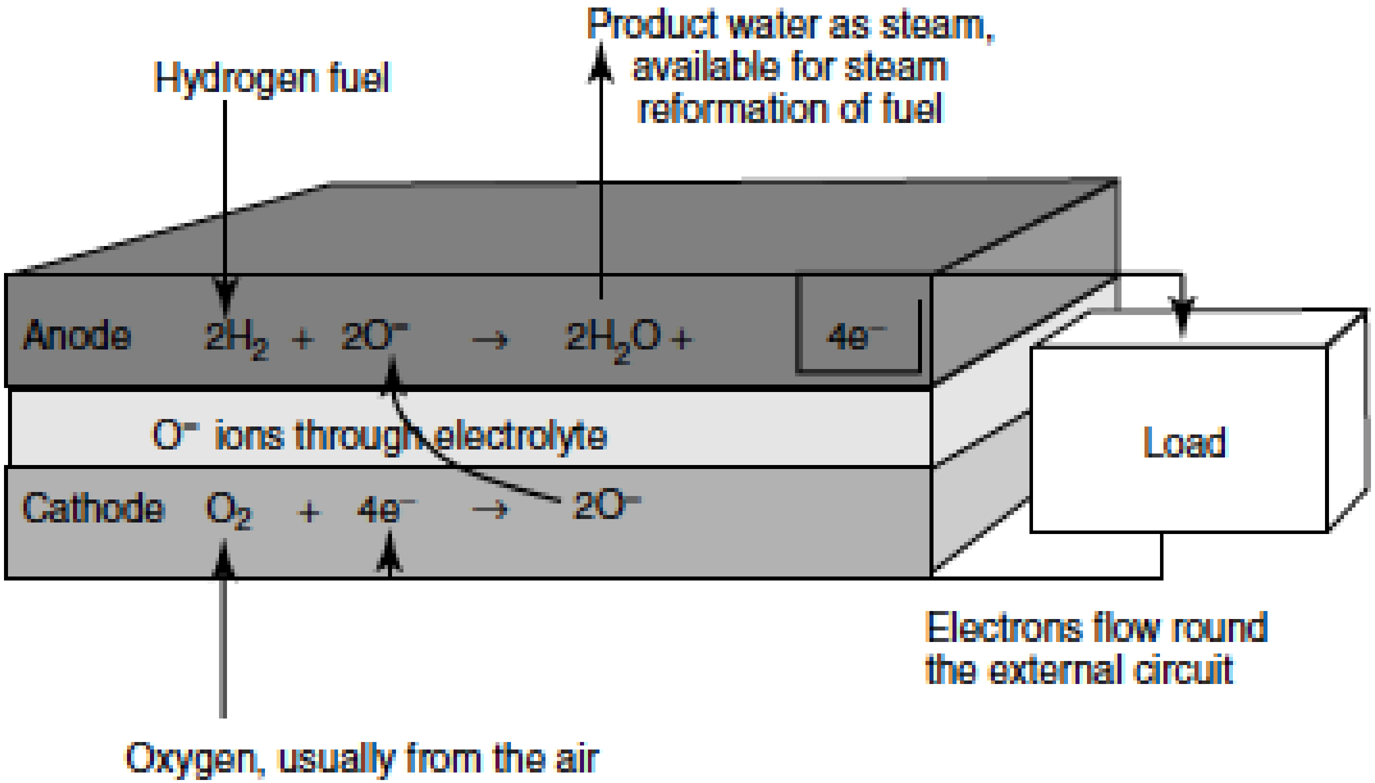
Ni-YSZ anode
LSM cathode
YSZ electrolyte

Test Characteristics:

800° C
1 bar
80% Fuel utilization
20% Oxidant utilization

Jiang *et al*. Journal of the Electrochemical Society 2003, 150 (7) A942.

Task 2: SOFCs Operating on Dilute H_2



Larminie *et al. Fuel Cell Systems Explained* 2003, 2, 208.

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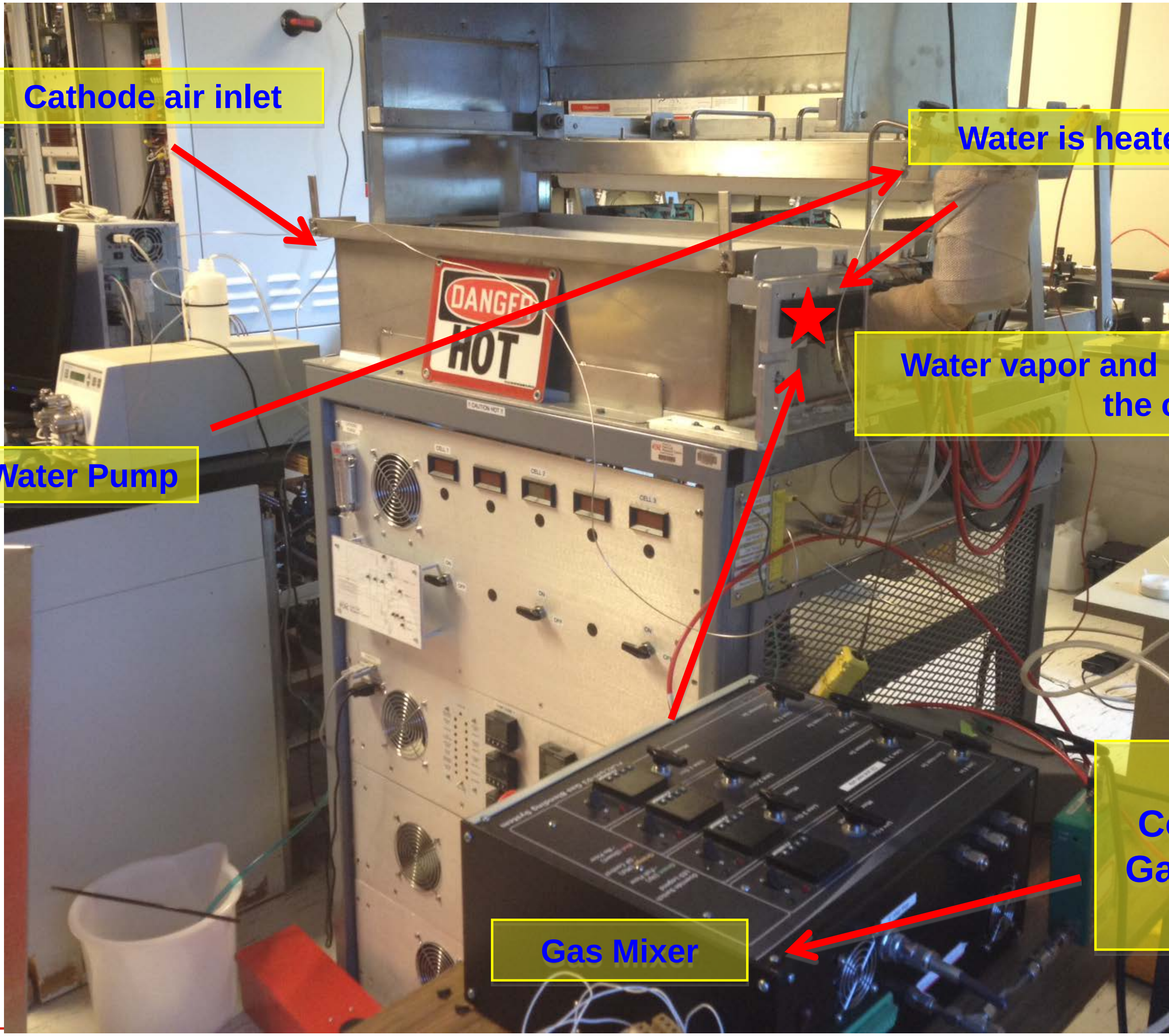

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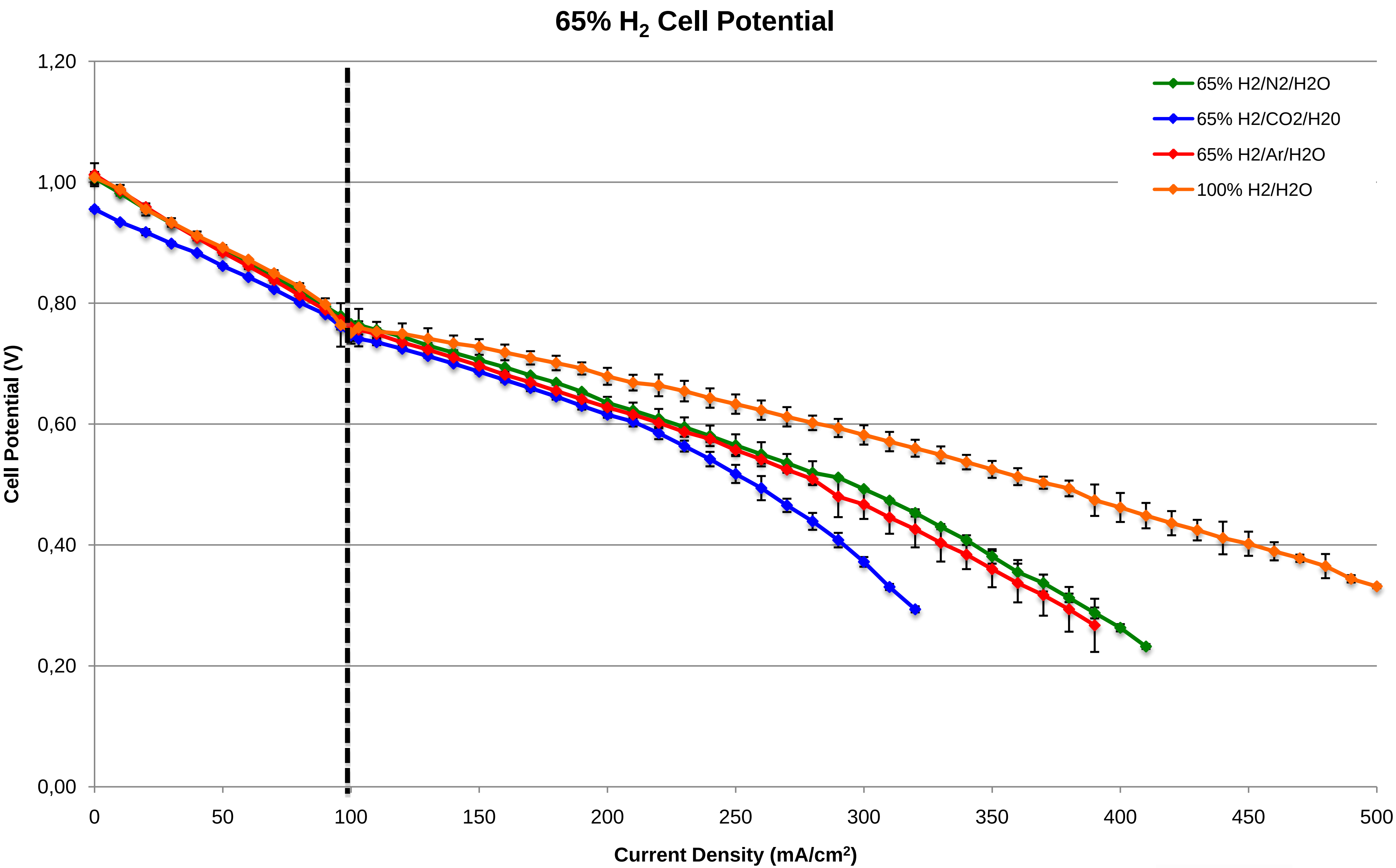

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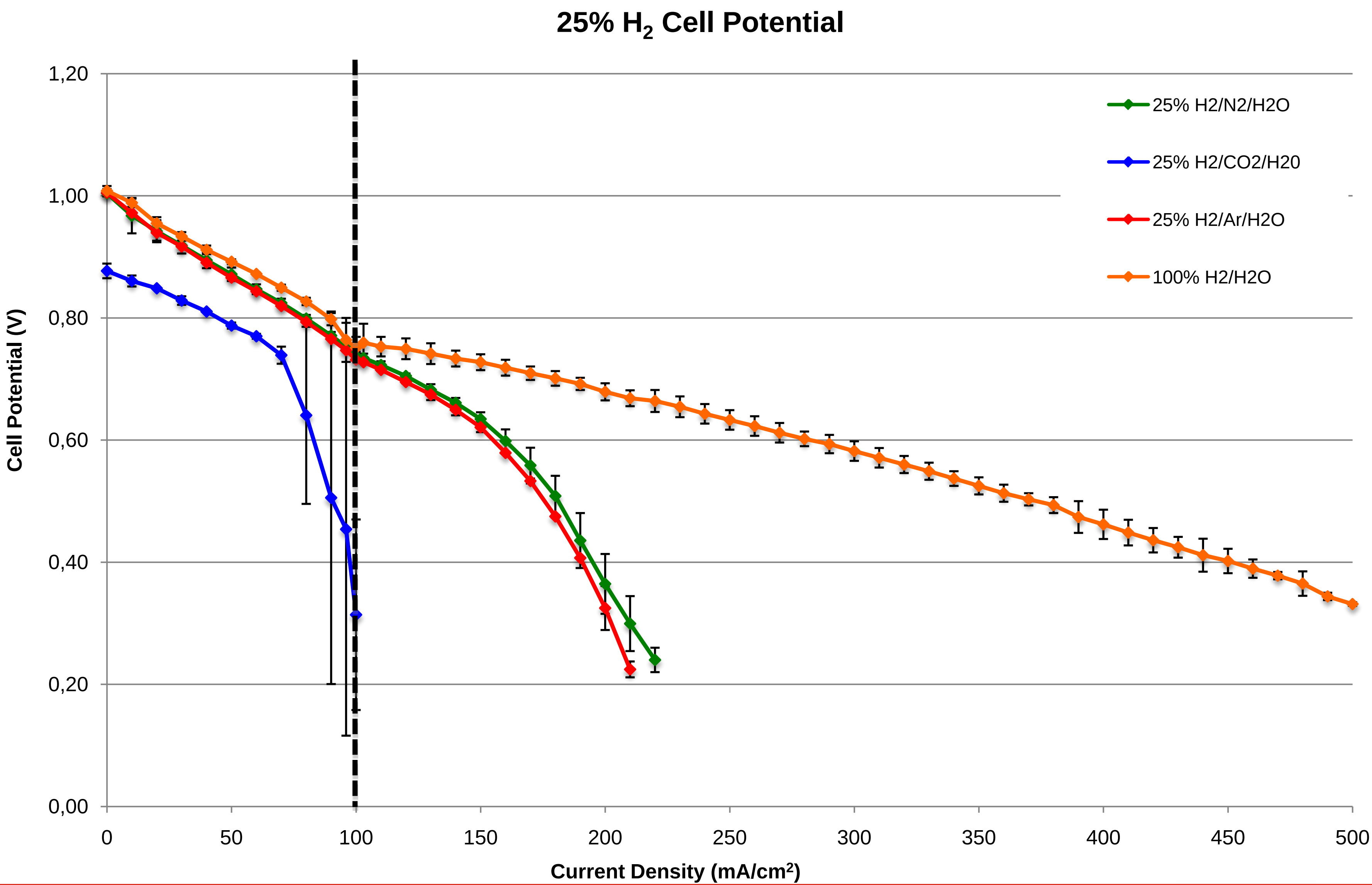

TASK 2: SOFCS OPERATING ON DILUTE H_2

- Dilute H_2 tests were designed to assist with the prediction of cell performance when operating on simulated WWTP biogas reformate
- The water-gas shift (WGS) reaction can produce or consume H_2 depending on the reactants

$$CO + H_2O \rightleftarrows CO_2 + H_2$$

- Contributes to decreased cell performance in the presence of CO_2 as a diluent

Task 3

SOFC System Simulation

TASK 3: SOFC SYSTEM SIMULATION

- Model developed to simulate system performance using dilute H_2 data
- Empirical model was incorporated into the computer simulation developed in UniSIM

$$V = C_1 + C_2 \ln\left(\frac{\bar{P}_{H_2}\,\bar{P}_{O_2}^{0.5}}{\bar{P}_{H_2O}}\right) - C_3 i + C_4 \ln\left(1 - \frac{\bar{P}_{CO_2}}{P_{Total}}\right)$$

Parameter	Parameter Value
C1	0.9130 V
C2	0.0168 V
C3	0.0016 kΩcm^2
C4	0.0229

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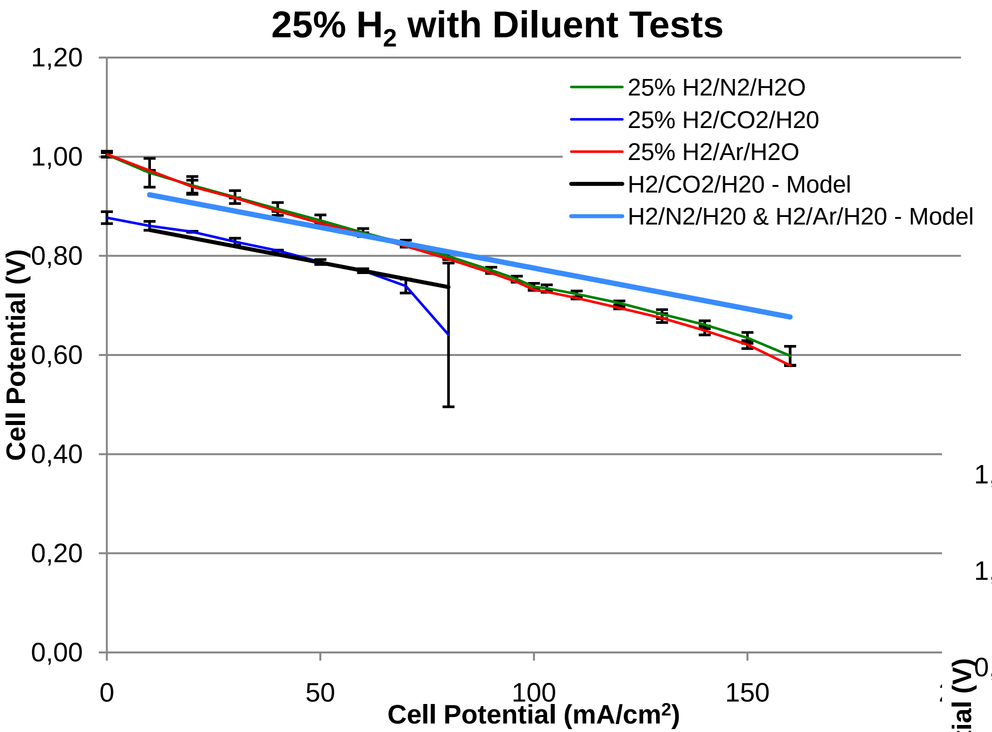
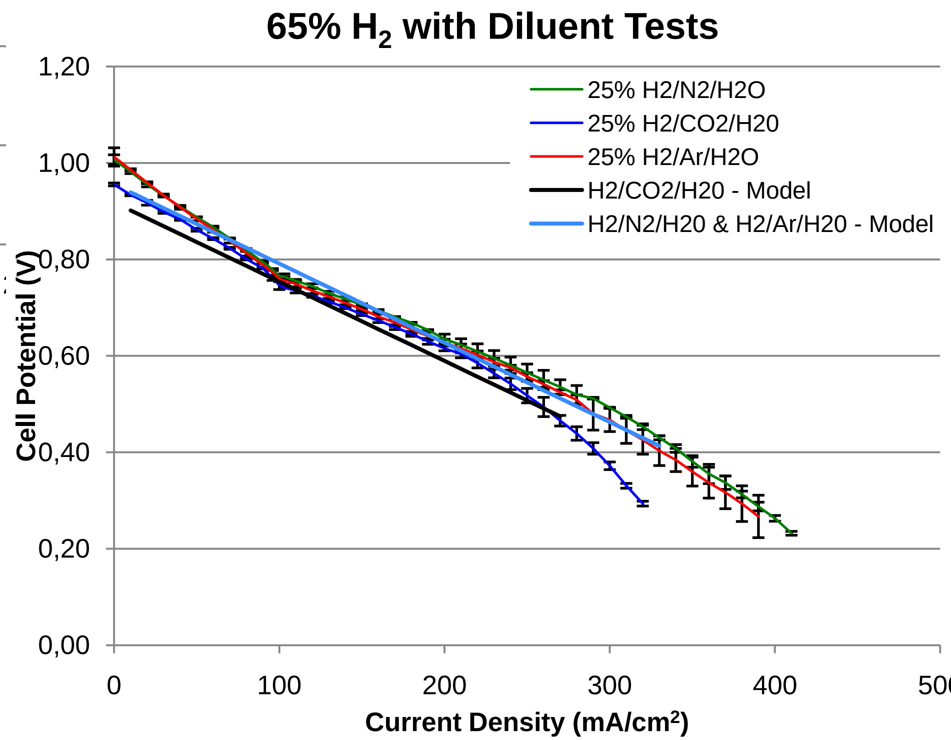




Task 4

Operation on Simulated Biogas Reformate

DATA COLLECTION

AD-derived WWTP biogas: 58-70% CH_4, 30-43% CO_2 and 1.2-7.1% N_2 with trace quantities of H_2S, O_2, H_2O, CO and Si compounds

Autothermal Reforming:

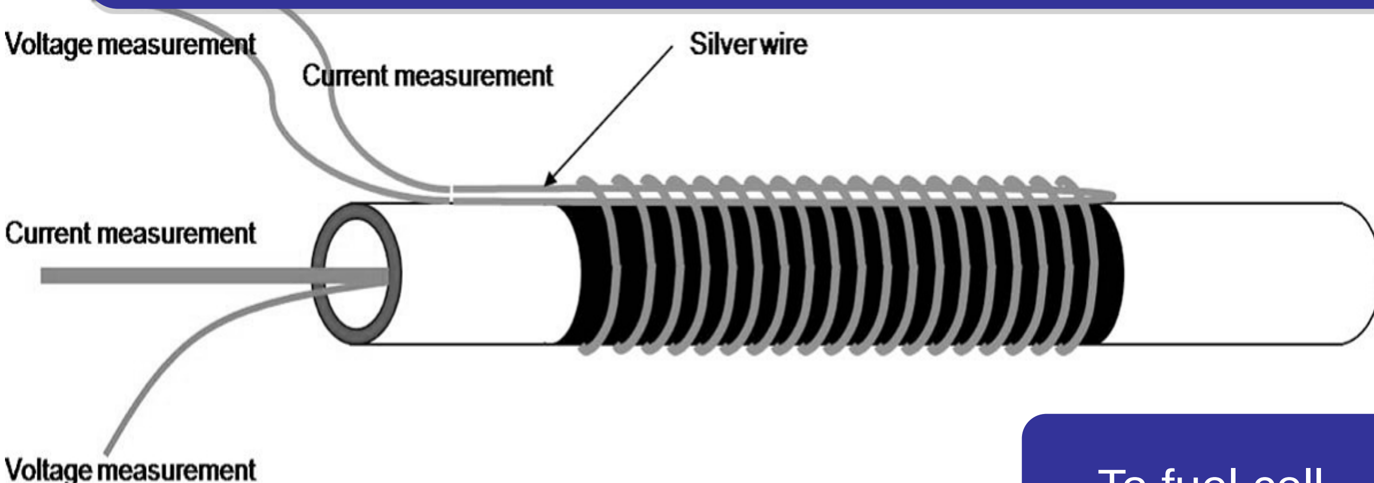
$$2CH_4 + O_2 + CO_2 \rightarrow 3H_2 + 3CO + H_2O$$

Steam Reforming

$$4CH_4 + O_2 + 2H_2O \rightarrow 10H_2 + 4CO$$

Simulated biogas reformate mixture was developed using UniSim software:

66.7% H_2, 16.5% CO_2, 16.2% CO and 0.7% N_2

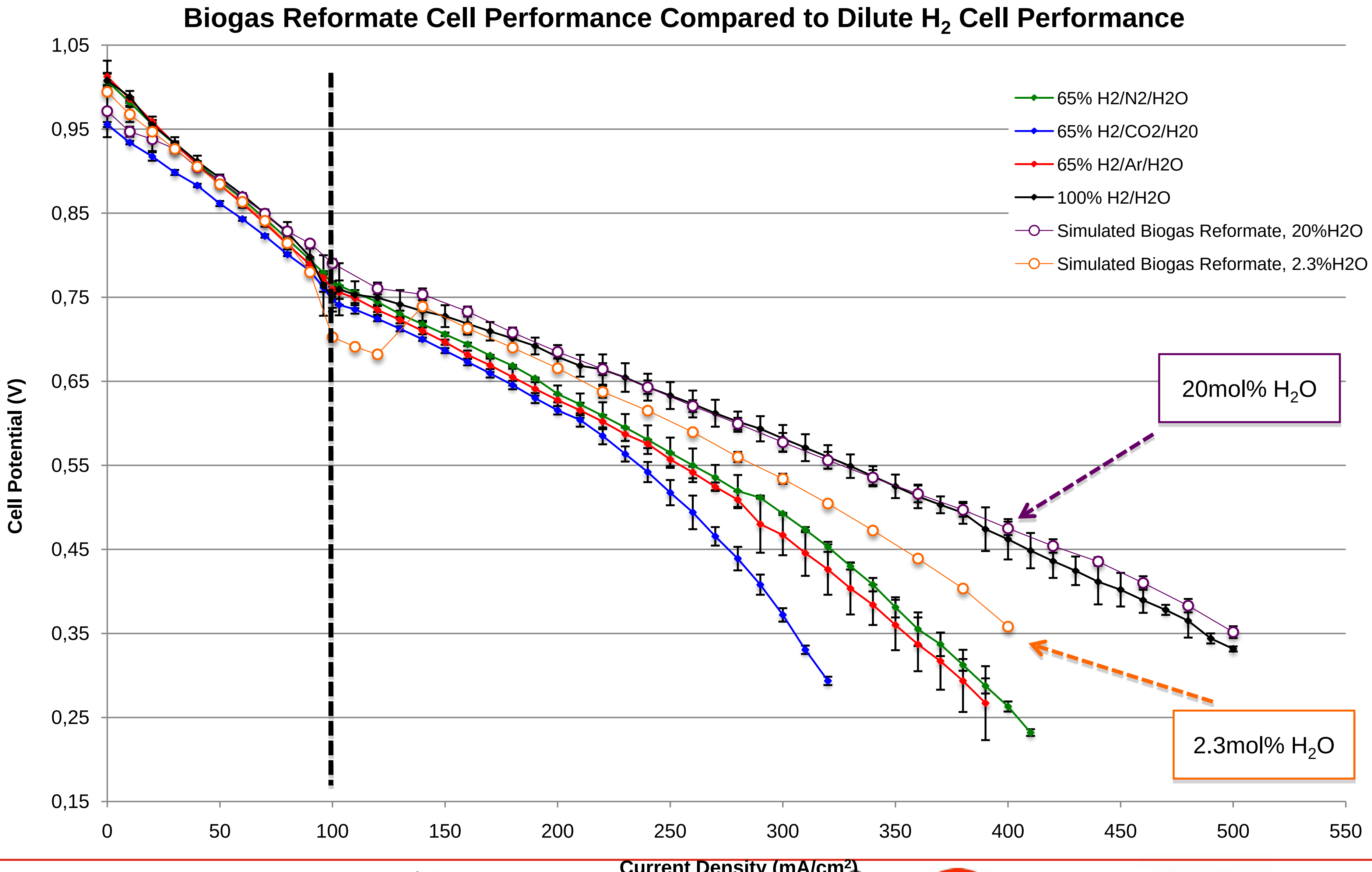


Addition of H_2O at 2.3% or 20mol% of total fuel flow rate

To fuel cell

Song *et al*. Journal of Fuel Cell Science and Technology 2010, 7, 97.

TASK 4: OPERATION ON SIMULATED BIOGAS REFORMATE



Task 4: Operation on Simulated Biogas Reformate

- Increased cell performance when operating on the simulated biogas reformate mixture is due the forward WGS reaction producing H_2 in the presence of CO and H_2O

- Tests conducted with 20mol% H_2O showed increases in cell performance that can be attributed to the presence of additional H_2O

  - Increased reaction rate:

$$K = \frac{[CO_2][H_2]}{[CO][H_2O]}$$

Conclusions

- Biogas composition is variable from site to site
- Dilution testing helped understand the cell performance decreases that occur when H_2 concentration decreases
  - Recommendation: Conduct tests using CO as a diluent gas
- Dilution model predicted system performance and efficiency when dilute H_2 was used as a fuel
  - Recommendation: Adapt to simulation to predict performance of a pilot scale system; include thermal efficiency
- Simulated biogas reformate tests showed good cell performance
  - Recommendation: Complete pilot scale testing at Ravensview WWTP

Questions?

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