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Evaluation of Protected Metal Hydride Slurries in a H_2 Mini-Grid

Hydrogen Technical Analysis Phase II Work in Progress

2003 Hydrogen and Fuel Cells Merit Review Meeting

Berkeley CA

May 19-22, 2003

TIAX, LLC
Acorn Park
Cambridge, Massachusetts
02140-2390

TIAX Ref: D0021
DOE Ref: DE-FC36-00GO10604

The hydrogen "Energy Station" concept has been proposed by DOE and others to facilitate the development of a hydrogen fuel infrastructure.

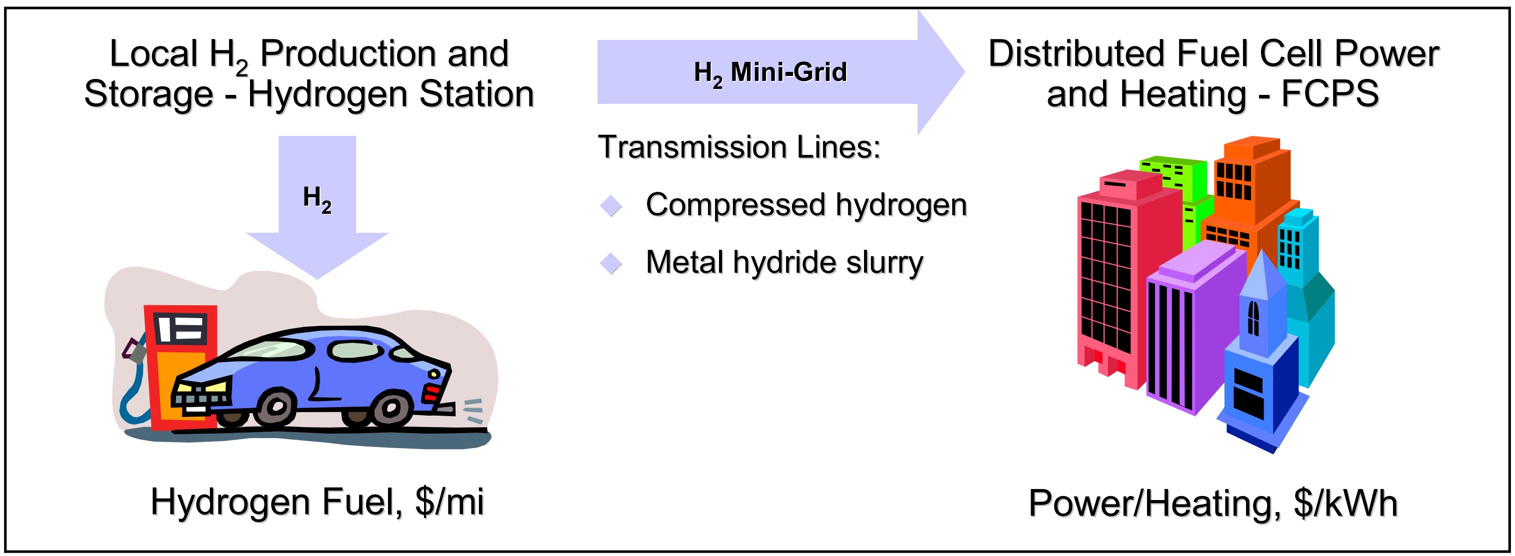
- Hydrogen is produced for stationary PEM fuel cell power systems (FCPS) and for fueling fuel cell vehicles (FCVs) at a hydrogen station
- Provides economies-of-scale and high utilization for hydrogen (H_2) production and storage equipment
- Opportunity for early revenue by supplying reliable power
- Helps solve "chicken and egg" problem for FCV/H_2 infrastructure

In addition, the Energy Station concept improves the commercialization of FCPS by lowering technical/economic risk compared to reformate-FCPS.

- Reduces risk of stack impurities poisoning
- Improves stack anode utilization
- Improves efficiency and reduces technical risk and cost of H_2 production
  - A single, larger reformer can operate base-loaded with H_2 storage
- Central hydrogen storage replaces need for battery
- Synergies with transportation developments

Distributed FCPS utilizing a H_2 Mini-Grid can provide all the benefits of a Hydrogen Energy Station and also provide cogen to buildings.

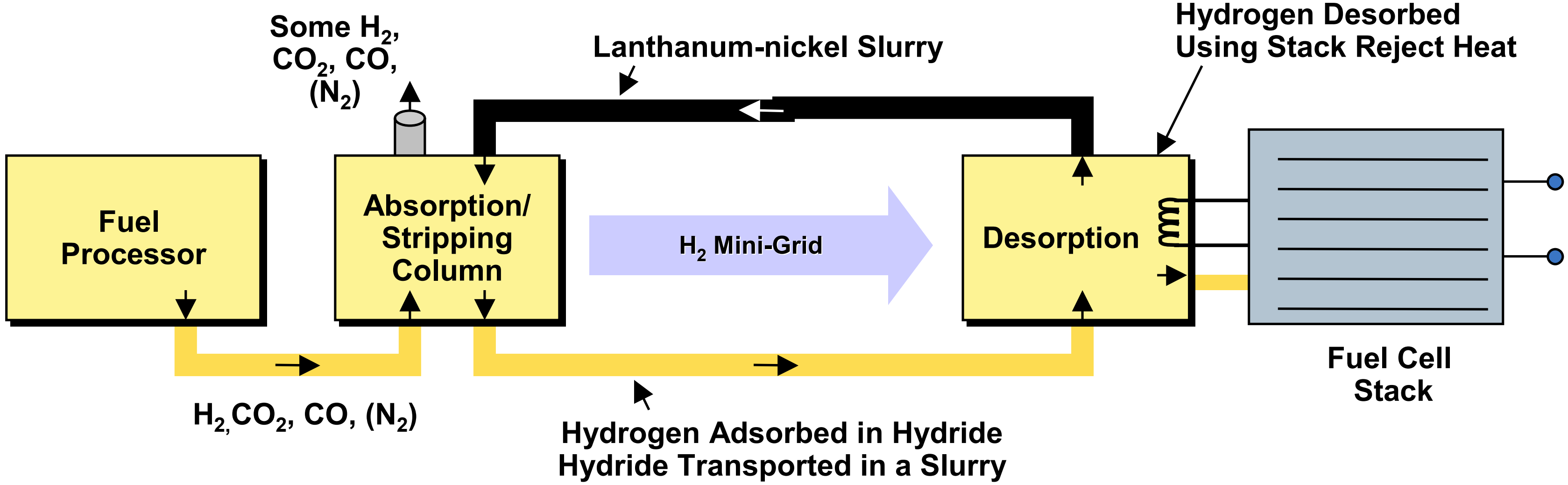
- Reduced technical risk and cost compared to distributed reformate-FCPS (see Energy Station Concept discussion)
- Fuel cell waste heat can be used for hot water or space heating in buildings (i.e. "cogen")
- Distributed FCPS utilizing a H_2 Mini-Grid are quiet and emissions free



However, the perceived safety of hydrogen transmission is a major barrier to it's implementation, especially in commercial/residential areas.

Metal hydride (MH) slurries are safer and are potentially more efficient and cheaper than compressed gas hydrogen (cH_2) transmission in pipelines.

Example: Fluorinated Metal Hydride Slurry Purification and Transmission



Potential Advantages:

- Safer than cH_2 storage/transmission - reduced permitting and right-of-way costs
- Excellent efficiency if dehydrogenation heat can be supplied by waste heat (e.g. fuel cell)
- Requires less space than low pressure cH_2 storage/transmission
- Convenient method of combined purification, storage, and transmission
- Protected (i.e. fluorinated) MH slurries can purify reformate streams at low cost

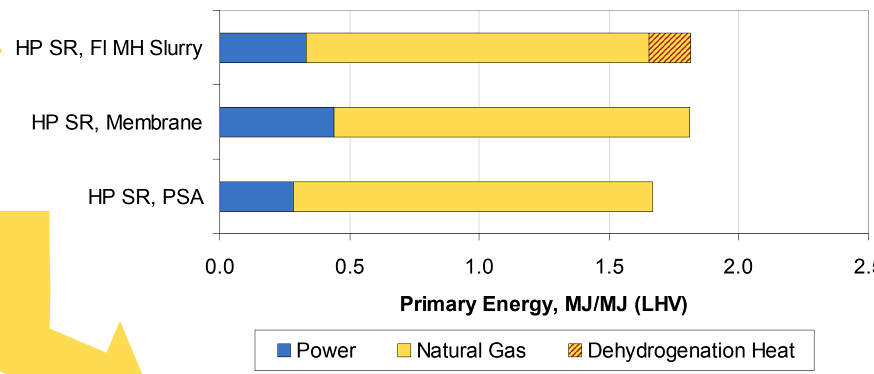
In Phase I, we identified fluorinated metal hydride (Fl MH) slurries as having potential to provide benefits as a purification and storage media.

Compact Size

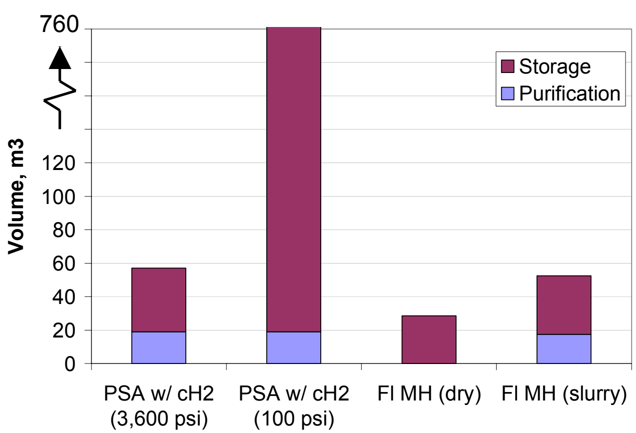
Excellent Efficiency

Low Capital Cost

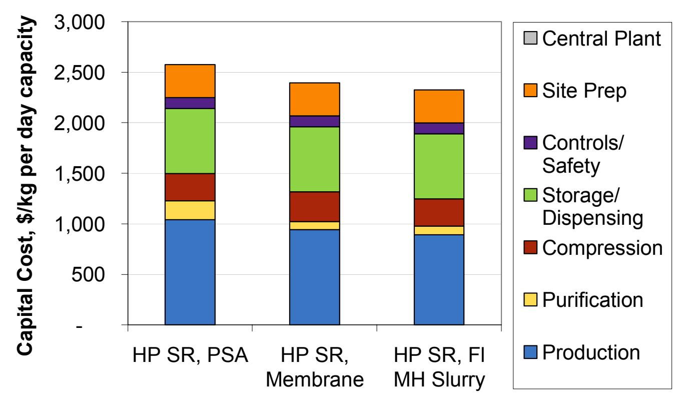
Primary Energy Efficiency



Purification and Storage Volumes



System Capital Cost



Legend: HP SR = high pressure (10 atm) steam reformer, Membrane = Zr-Ni metal membrane, PSA = pressure swing adsorption, LHV = lower heating value

Before FI MH can be used for H_2 purification, further development will be required to prove its feasibility and optimize its implementation.

- Current MH have low tolerance to impurities typically found in reformate streams, especially oxygen and carbon monoxide
- Fluorinated (or in some other way protected) metal hydrides should be able to demonstrate high tolerance to impurities
  - Researchers in Japan have shown a fluorinated surface layer will protect the MH from multiple impurities

Compound	Impurity Threshold, vol		Comment	Reference
	Fluorinated	Untreated		
Carbon Monoxide	<100 ppm	<10 ppm		Japan Metals and Chemicals
	<3000 ppm		Was shown by applying a particular fluorination method	Kogakuin University[1]
Carbon Dioxide	< 20%	<100 ppm		Kogakuin University[1] and Japan Metals and Chemicals
Oxygen	< 20%	<10 ppm	During MH storage: no surface oxidation was found after 15 day exposure to air	X.-L. Wang, S. Suda[2]

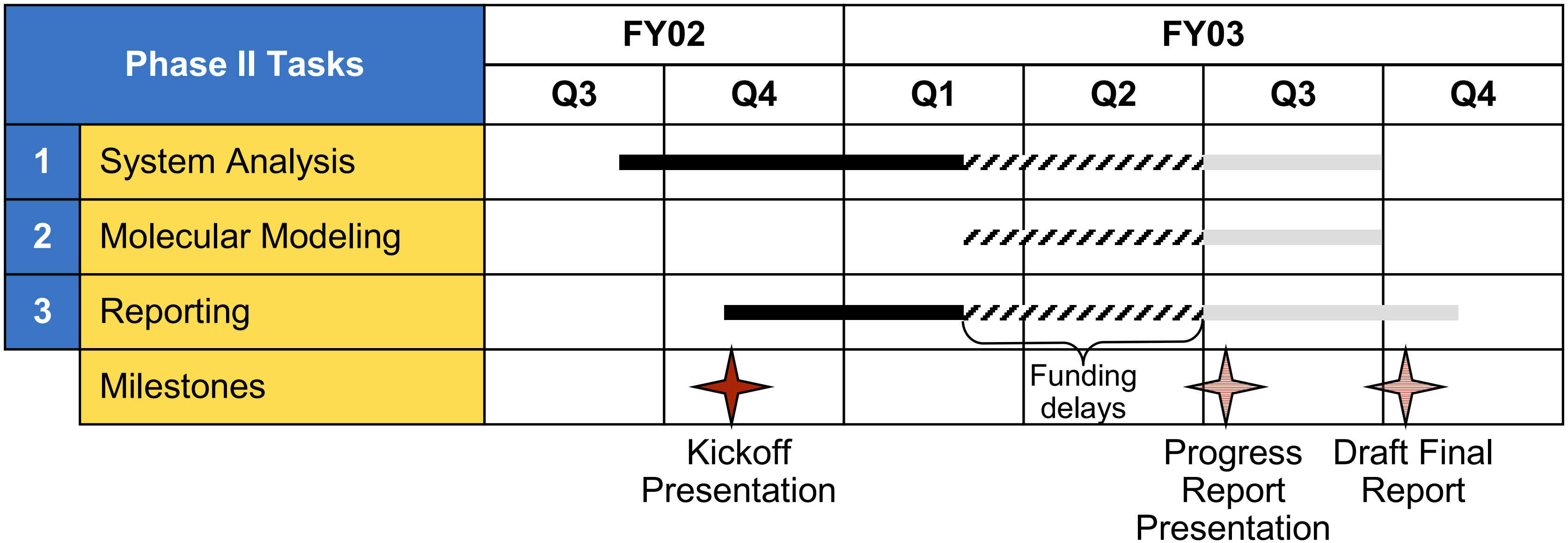
[1] Personal communication with Pr. S. Suda of Kogakuin University

[2] Stability and Tolerance to Impurities of the Fluorinated Surface go Hydrogen-Absorbing Alloys, Journal of Alloys and Compounds 227 (1995) 58-62.

The purpose of Phase II is to evaluate the feasibility of using FI MH slurries for purification and transmission in a H_2 Mini-Grid concept.

- Assess the viability of using fluorinated (or otherwise treated) metal hydrides for the purification of carbon monoxide-containing hydrogen streams
  - Using computational modeling to help fully characterize the limitations of fluorination and identify alternative technologies
- Assess the attractiveness and viability of using fluorinated metal hydride slurries in a hydrogen distribution system (H_2 Mini-Grid)
  - Including both vehicle refueling stations and building combined heat and power systems
- Establish research and development (R&D) objectives for the development of hydrogen distribution systems using fluorinated metal hydrides
  - Identify key barriers and possible development paths
  - Contingent on a positive outcome from above

We will accomplish this project's objectives in two key tasks: (1) analysis of FI MH slurries in a H_2 Mini-Grid and (2) molecular modeling of FI MHs.



- The work to date has been slowed due to funding delays, but we are on schedule to finish by the end of this fiscal year
- We are less than 40% through the total budget

In Task 1, we will analyze the potential cost and performance of H_2 Mini-Grid concepts for integrated fueling and power systems.

Subtasks to Task 1: System Analysis
Subtask 1: Evaluate metal hydride slurry purification, storage and dispensing apparatus for Integrated Systems (fueling and power)
Subtask 2: Develop hydrogen fueling system designs
Subtask 3: Develop fuel cell power system designs
Subtask 4: Determine cost of electricity (COE), hydrogen costs, energy use, and GHG* and other emissions for H_2 Mini-Grid concepts and stand-alone systems
Subtask 5: Reporting

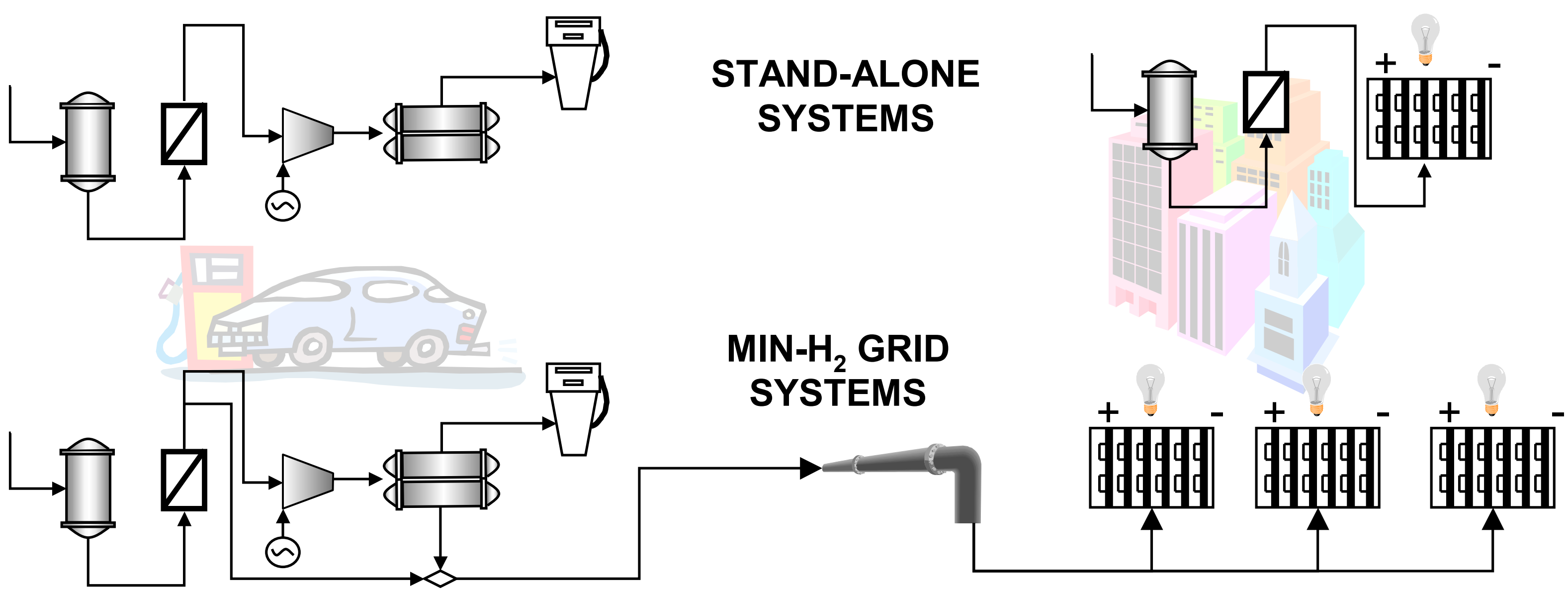
* GHG = green house gases (CO_2, CH_4, etc.)

We will investigate local hydrogen production for fueling direct-H_2 FCVs and distributed FCPS.

- <1,000 kg/day H_2 fueling capacity for compressed gas hydrogen (cH_2) FCVs
  - On-site hydrogen production via 10 atm steam reformer
    - Highest overall efficiency of the four reformer types investigated in Phase I
    - Renewables-based production is also a promising application for the H_2 Mini-Grid
  - On-site hydrogen storage via compressed gas or MH slurry
- <100 kWe PEM FCPS serving commercial and residential buildings
  - Various building load profiles - heat and power demands
  - Power and co-gen heating (conventional and high temperature PEM)
  - Grid connected for high utilization (note: load-following is possible for direct-H_2 FCPS)
  - Base-loaded during peak hours - reduces demand charges
  - Turned off when power demand drops below FCPS design power - simplest, doesn't cut into utilities' base-load and compete with cheap off-peak grid power
  - Hydrogen storage at fueling station also acts as a reliability enhancer for the FCPS

We will evaluate a number of H_2 Mini-Grid configurations and compare them to stand-alone FCPS.

- PSA with high pressure cH_2 storage and low pressure cH_2 transmission
- FI MH slurry purification and transmission and high pressure cH_2 storage
- FI MH slurry purification, transmission, and storage
- Stand-alone: (1) Reformate-FCPS and (2) distributed reformate production with FI MH slurry purification/storage



In Task 2, we will perform a molecular-level theoretical evaluation of the long-term feasibility of fluorinated metal hydride purification.

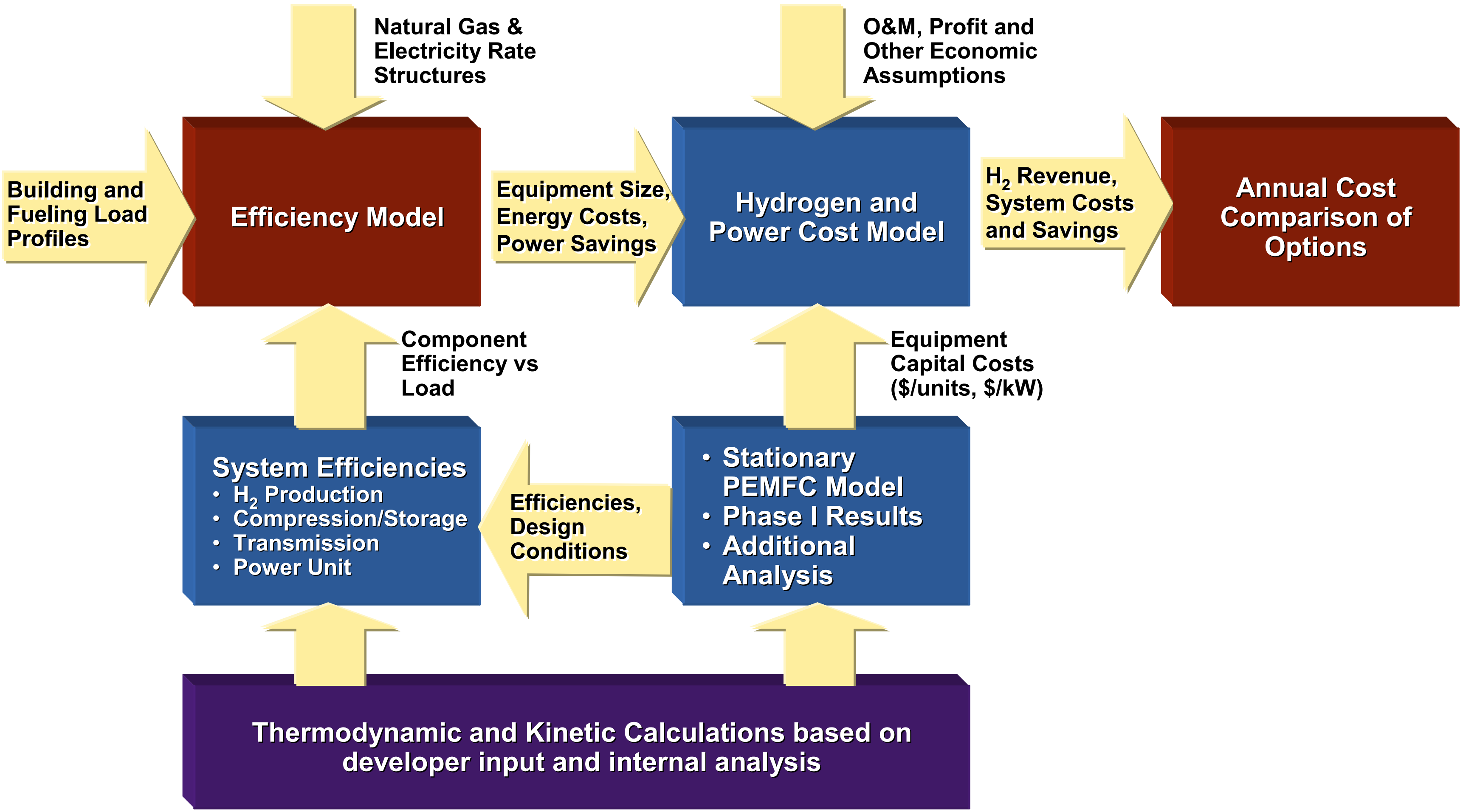
- Use first principles and quantum modeling to understand the underlying microscopic mechanism of a fluorinated metal alloy (e.g. La-Ni-Al)
- Test two main hypotheses:
  - Fluorination reduces the binding energy of undesired molecular species (e.g. O_2 and CO)
  - Diffusion barrier created by the fluorinated surface is much lower for hydrogen molecules than for undesired molecules
- Generate a general model for surface protection of metal hydrides
- Formulate general principles for protection techniques based on the general model
- Search for alternative protection methods or compounds that are even more effective in a practical application

We originally proposed to perform experimental tests to determine Fl MH properties and performance, but this contract did not support lab-based R&D.

To date, we have constructed efficiency and cost models for the overall analysis and are in the process of refining the model inputs.

- An efficiency model has been developed
  - Inputs: building hourly electric and heat load profiles for the entire year, thermodynamic model results (e.g. efficiencies, cogen potential) for the FCPS and H_2 station
  - Outputs: grid power, natural gas, and FCPS hydrogen demands; GHG and other emissions
- Detailed cost calculations are being determined
  - Inputs: efficiency model results, capital cost inputs, utility rates for grid power and natural gas
  - Outputs: annual costs (electric energy and demand, natural gas, and capital cost charges)
- Preliminary design of a cH_2 Mini-Grid has been determined
  - Based on a combination of current natural gas and hydrogen distribution practices

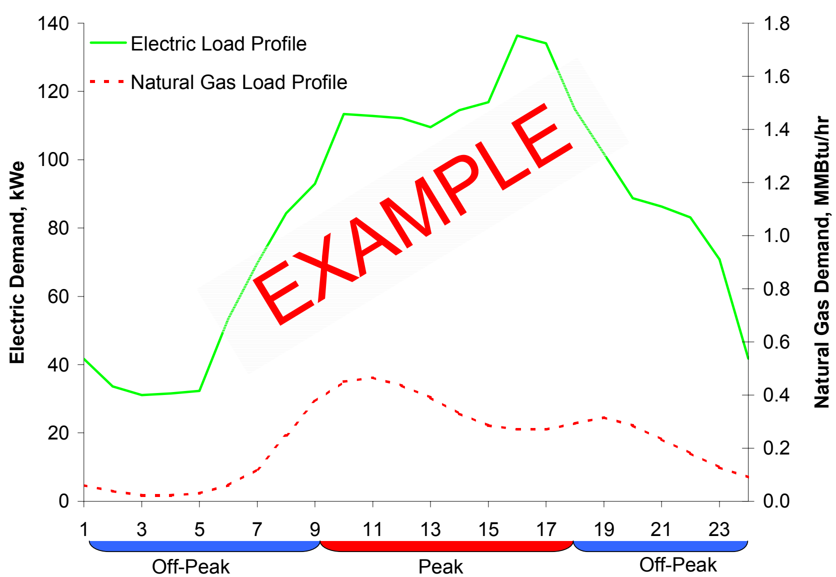
Efficiency and cost models are the backbone of the analysis to determine overall annual system costs and savings.



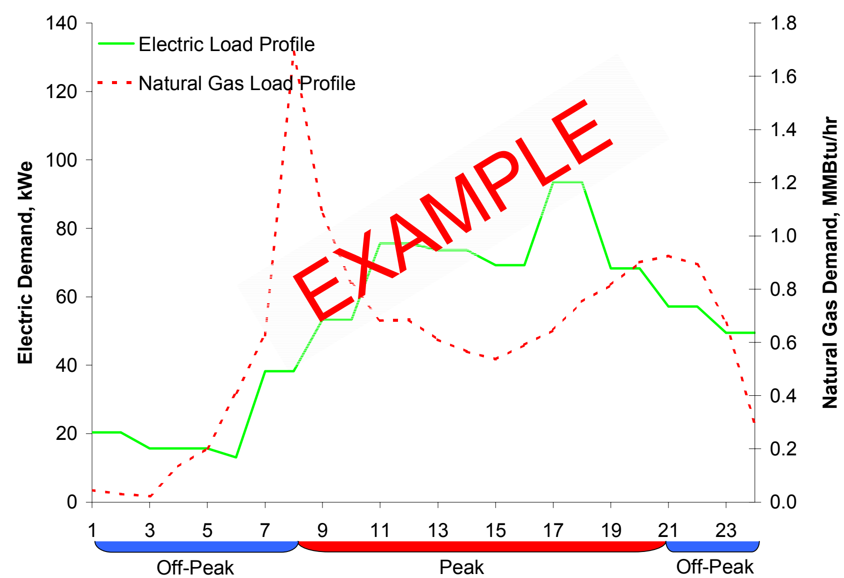
Hourly electric and heat load profiles for residential and commercial buildings have been generated for a typical meteorological year (TMY).

- Using EnergyPlus software
- Load profiles are used in the efficiency model to calculate:
  - FCPS operating times (turns on when the building demand exceeds design power)
  - Grid and FCPS monthly energy and peak power demands from the building
  - Cogen use (only when fuel cell is on and building heat is needed)

July 1 Profile for Multi-family residence in NYC



Jan 1 Profile for Multi-family residence in NYC



We constructed thermodynamic models to evaluate system parameters that can effect system efficiency and FCPS cogen capabilities.

- Using HYSYS process modeling software
- Thermodynamic results are used in the efficiency model to calculate:
  - Hydrogen (or natural gas) demand and cogen potential from the FCPS
  - Natural gas and power demand from the hydrogen station
- Models for both the FCPS and hydrogen station have been developed

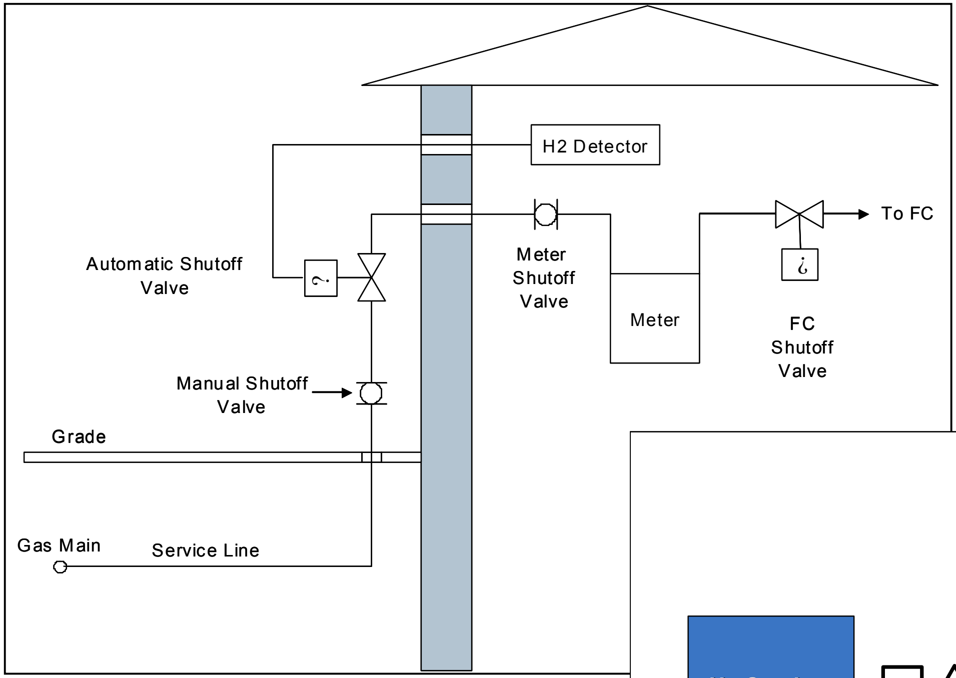
FCPS Parameters	Base Case	Low Temp.	Low Voltage	Low H_2 Util.	High Press.
Temperature, °C	80	70	80	80	80
Design Voltage, V	0.70	0.70	0.63	0.70	0.70
Hydrogen Utilization, %	95	95	95	88	95
Pressure, atm	1.2	1.2	1.2	1.2	1.5
Preliminary Results					
Cogen Capability[1], kWth/kWe	0.68	0.81	0.87	0.87	0.87
System Efficiency[2], % (LHV)	49	49	44	45	48

EXAMPLE

[1] Cogen is reduced by humidification requirements.

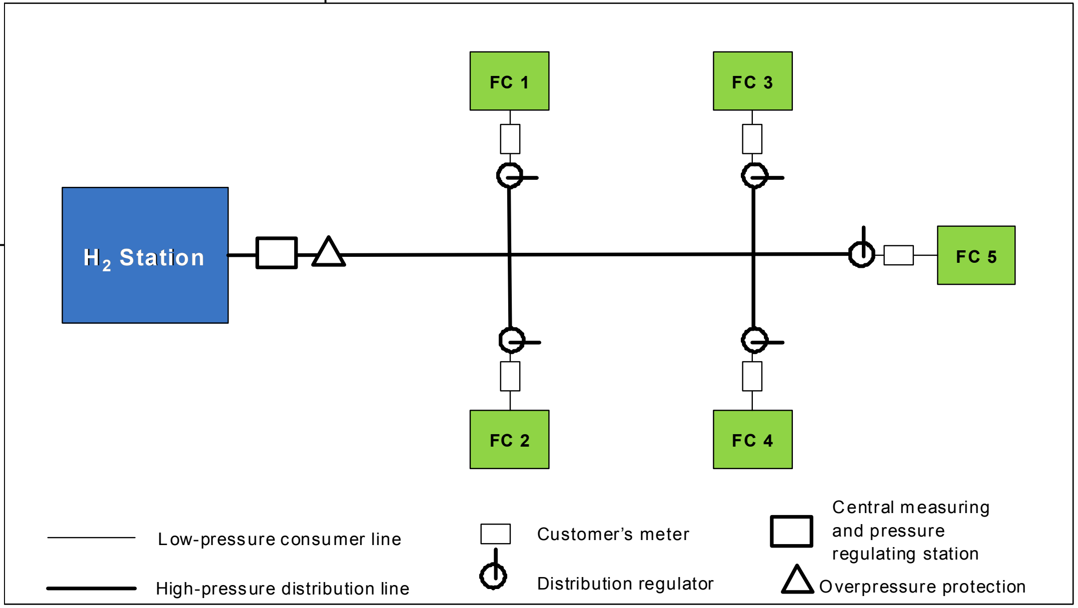
[2] Includes 95% power electronics (i.e. inverter) efficiency, 95% hydrogen utilization, and parasitic loads.

U.S. Gas Pipeline Code, NFPA, and industry experts were consulted for the design of hydrogen gas delivery systems to consumer sites.



Codes and standards incorporated in conceptual design

ASME B31.3	Pipeline design code
CGA G-5.4	H2 piping systems at consumer locations
OSHA 29 CFR 1910.103	H2
NFPA 50A	CGH2 at consumer sites
NFPA 54	Fuel gas piping systems, accessories
CSA B51	Canadian code for pressure piping containing H2
DOT RSPA 49 CFR 192	Valve spacing on gas pipelines

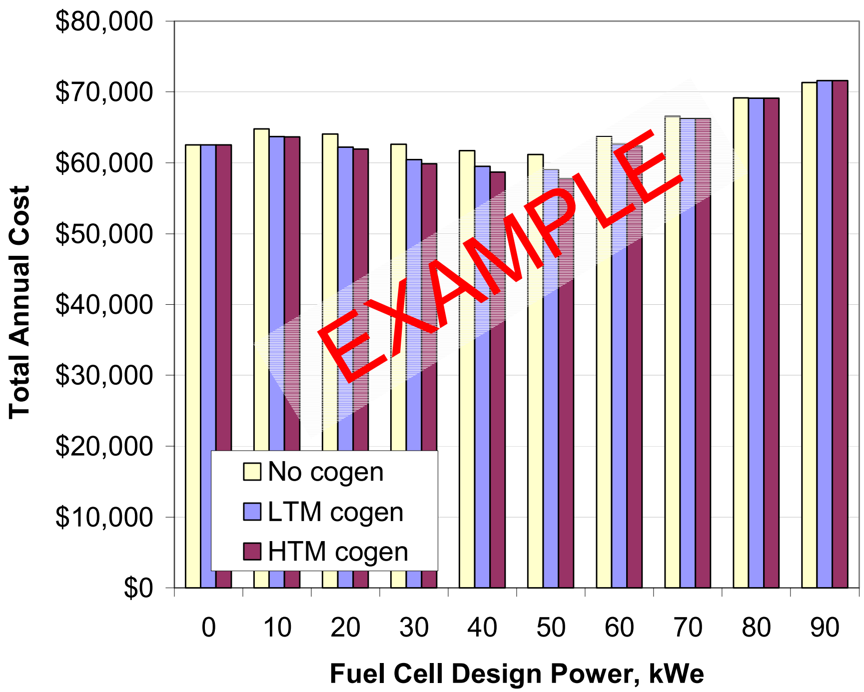


Annual costs will be determined once capital costs have been estimated (work in progress).

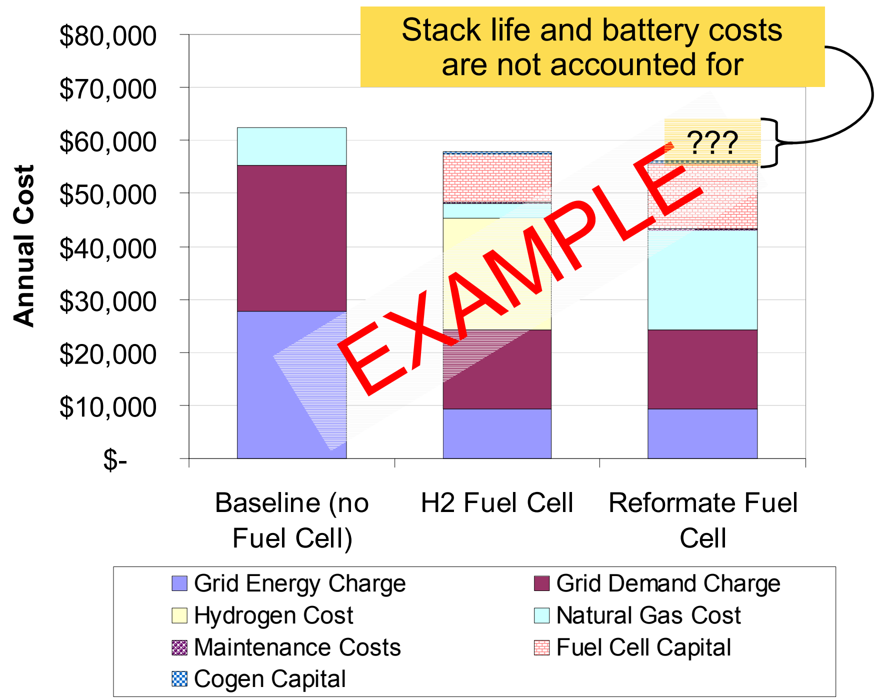
- Capital costs for the hydrogen station (production, compression, and storage equipment)
  - We are updating capital costs, scaling factors, and progress ratios
  - Based on detailed vendor quotes and internal analyses from Phase I
    - Phase I analysis assumed 100s units per year production volumes
- Hydrogen transmission cost
  - System designs have been conceptualized
  - We are estimating capital costs based on vendor quotes and additional cost assessments
  - “Right-of-way” costs dominate in most cases
- Capital costs for distributed FCPS
  - We are constructing a cost model that will automatically scale costs according to the user supplied production volume and rated power assumptions
  - Based on previous stationary PEMFC cost model

For this presentation, examples of annual costs have been generated based on assumptions for hydrogen and capital costs.

Direct-H_2 FCPS Ownership Cost



FCPS Ownership Cost Comparison



Key Assumptions:
50 kW FCPS with high temperature membrane (HTM); capital costs = \$916/kW Direct H_2 and \$1,253/kW Reformate-FCPS; H_2 = \$1.00/kg

Using the cost model, design power and various other model inputs can be optimized to reduce total annual cost or GHG emissions.

At the end of Task 1, we will be able to assess the attractiveness and viability of using fluorinated metal hydride slurries in a H_2 Mini-Grid.

- Investigate performance of MH slurries and H_2 Mini-Grid systems:
  - Cost: hydrogen, power/heating, annual
  - Environment: energy use, GHG and other emissions
  - Other benefits: technical risk, reliability enhancement, and others
- Comparison to baseline and other systems:
  - Integrated hydrogen station concept Vs. stand-alone hydrogen station
  - MH slurry Vs. cH_2 transmission
  - FCPS (with and without cogen) Vs. conventional grid power and natural gas heating
  - FCPS utilizing a H_2 Mini-Grid Vs. stand-alone FCPS (hydrogen and reformate-based)

At the end of Task 2, we will be able to assess the long-term viability of using fluorinated (or otherwise treated) MHs for hydrogen purification.

- Establish selectivity of CO/H_2 separation based on energy surface calculation for transport through the layer
- Determine viability of fluorinated hydrides
- Develop and test hypothesis for optimization of barrier layer
- Establish R&D objectives for MH slurries based on Task 1 and 2 results
  - Identify key barriers and possible development paths
  - Contingent on a positive outcome from above