Technical Analysis of Hydrogen Production: Evaluation of H₂ Mini-Grids

Final Technical Report

Period covered: 7/17/2000-11/30/2003

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**Prepared for:
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In an earlier phase of work, we identified metal hydride (MH) slurries as having potential to provide benefits as a purification and storage media.

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

The purpose of this phase of work is to evaluate the attractiveness of using metal hydride slurries for purification, storage and delivery of hydrogen in a mini-grid concept.

- ◆ Evaluate mini-grid concepts including both vehicle refueling and building fuel cell power systems (FCPS) with potential for cogen heat
- ◆ Determine cost of hydrogen, cost of electricity, and capital costs
- ◆ Evaluate potential energy use and GHG emissions benefits
- ◆ Establish key barriers and possible development paths for metal hydride slurry distribution systems

Note: We had originally planned to assess the viability of using fluorinated metal hydrides for purification using molecular-level theoretical calculations. However, the contract was de-scoped in light of the Hydrogen Production/Delivery solicitation and the need to focus attention on evaluating other hydrogen concepts.

Distributed FCPS utilizing a H₂ mini-grid can provide all the benefits of a Hydrogen Energy Station and also provide cogen to buildings.

- ◆ Early market for hydrogen infrastructure
- ◆ Co-gen heating opportunities
- ◆ Reliability, efficiency, and cost improvements
- ◆ Reduced noise and on-site emissions

DOE R&D Plan

DG Technical Barrier F: Heat Utilization.

The low operating temperature of PEM fuel cell system technology limits the use of heat generated by the fuel cell, which represents approximately 50% of the energy supplied by the fuel. More efficient heat recovery systems and improved system designs and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) distributed generation power systems.

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 gaseous hydrogen (CH_2) options.

Potential Advantages:

- ◆ Perceived to be safer than CH_2 storage/delivery - reduced permitting and right-of-way costs
- ◆ Excellent efficiency if dehydrogenation heat can be supplied by waste heat (e.g. fuel cell)
- ◆ Protected (i.e. fluorinated) MH slurries can purify reformat streams at low cost
- ◆ Occupies less/comparable volume compared to low pressure CH_2 storage/delivery
- ◆ Convenient method for combined purification, storage/compression and delivery
- ◆ Reduced impact of metal alloy and liquid carrier cost due to closed-loop design

In a MH slurry mini-grid concept, waste heat from the reformer and fuel cell power system (FCPS) can be used to increase overall system efficiency.

Waste heat can be used for hydrogen desorption and thermal compression rather than burning natural gas or using electric power.

We have evaluated hydrogen mini-grid concepts and analyzed them in the context of supplying hydrogen to vehicles and stationary FCPS.

- ◆ We focused on two mini-grid pathways:
 - Baseline: Pressure Swing Adsorption (PSA) purification with compressed gaseous hydrogen (CH_2) storage and pipeline delivery
 - Metal hydride (MH) slurry purification and pipeline delivery: both CH_2 and MH slurry storage and compression options for vehicle fueling
- ◆ Detailed analysis includes:
 - Equipment conceptual designs and cost analysis at various production volumes
 - Process modeling and performance calculations
 - Building heat/power demand profiles for every hour of a typical mean year
 - Cost of utilities (natural gas, power) and estimated cost for hydrogen
 - Hydrogen delivery costs (e.g., right-of-way, materials, construction)

We have evaluated three hydrogen mini-grid configurations and compared them to a stand-alone system.

- ◆ *Stand-Alone: H₂ Station*
- ◆ *cH₂ Mini-Grid: PSA with high pressure cH₂ storage, mechanical compression, and low pressure cH₂ Mini-grid delivery*
- ◆ *MH Mini-Grid 1: FI MH slurry purification, storage, thermal compression, and MH Mini-grid delivery*
- ◆ *MH Mini-Grid 2: FI MH slurry purification and MH Mini-grid delivery, and high pressure cH₂ storage and mechanical compression*

We have built on the previous phase of work and other hydrogen analyses to evaluate the performance and economics of each system configuration.

- ◆ Conceptual designs and cost estimates were developed for the CH_2 and MH mini-grids
 - Based on discussions with industry experts for current natural gas, hydrogen, and slurry distribution practices
- ◆ FCPS Model calculates annual costs to building owners
 - Key Inputs: building hourly electric and heat load profiles for the entire year, thermodynamic model results (e.g. efficiencies, cogen potential), and cost assumptions (i.e., capital, hydrogen cost, utility rates, and maintenance costs)
 - Key Outputs: annual costs (fuel, utility, and capital cost charges), GHG emissions
- ◆ H2A Spreadsheets* calculate the required hydrogen selling price
 - Key Inputs: thermodynamic model results (e.g. NG and electricity requirements) and cost assumptions (i.e., capital, fuel, and O&M costs) updated from previous phase
 - Key Output: hydrogen selling price for a given internal rate of return (IRR)

* H2A is an ad-hoc group of analysts, national labs, and industry collaborators brought together by US DOE to bring consistency & transparency to hydrogen analysis (primarily cost assessments). H2A Spreadsheets are a work in progress.

MH slurry concepts are slightly more efficient than the CH_2 mini-grid when vehicle H_2 demand is small compared to FCPS power demand (i.e., small station case).

Note: Primary energy results assume fuel chain efficiencies of 36% for power and 94% for natural gas.

All mini-grid concepts are more efficient than the stand-alone option.

GHG emissions can actually increase over the stand-alone case if natural gas needs to be burned to supply heat for MH H₂ desorption and thermal compression.

Note: GHG emissions results assume fuel chain efficiencies of 36% for power and 94% for natural gas. GHG emissions factors are based on "H2A WTP GHG Calculations2.xls" generated for H2A activities by M. Wang of ANL and assuming 72.4 g GHG/MJ natural gas feedstock based on stoichiometry.

All mini-grid concepts result in about the same cost of hydrogen and are cheaper than the stand-alone option due to higher capacity factors.

Hydrogen Price – Large Station

Both MH mini-grid options are on par with the cost of the cH₂ mini-grid

Hydrogen Price – Small Station

All the mini-grid cases reduced the cost of hydrogen significantly over the small stand-alone hydrogen station due to economies of scale

Note: Metal hydride cases assume the metal hydride material will operate efficiently for the life of the station (assumed to be 20 years). Additional analysis is necessary to evaluate the likely material life.

H₂ from all mini-grid cases is half the cost of the stand-alone option when vehicle H₂ demand is small compared to FCPS demand (small station case).

The cost of electricity (COE) from the FCPS is much more expensive than the grid unless hydrogen can be purchased for <\$1.50/kg.

Note: Hydrogen sold to the building owner for just \$1.22/kg is equivalent to the cost of feedstock only. In a real situation, the hydrogen station owner would need to charge more to recover the significant capital investment.

At \$3/kg hydrogen, the FCPS fuel cost alone would equal the typical utility cost to the building owner.

Even factoring in natural gas savings from CHP does little to change the outlook.

Building owners will have to value other DG benefits (e.g., power quality, back-up power) in order to justify an investment in a FCPS.

MH slurry mini-grid concepts could provide relatively small reductions in overall energy use, cost, and GHG emissions compared to a CH_2 mini-grid.

- ◆ MH Mini-Grid 1 case can reduce energy requirements and GHG emissions compared to CH_2 provided reformer waste heat can be used effectively
 - Total hydrogen demand from the reformer should be >2X fueling demand
 - May require heat storage
- ◆ Most mini-grid options provided energy, GHG, and cost savings compared to stand-alone hydrogen stations
 - Hydrogen costs can be cut in half and primary energy use and GHG emissions can be reduced by 10-15% for the small station cases
- ◆ However, all mini-grid cases require the FCPS, or other H_2 end-use systems to achieve market success
 - FCPS operating on hydrogen from a mini-grid will not likely result in cheaper electricity than the grid
 - Cogen does not help much
 - Building owners will have to value other DG benefits (e.g., power quality, back-up power)
- ◆ In addition, all MH slurry concepts need further research, modeling, and experimental testing to advance them beyond the conceptual design stage

MH Slurries offer significant reductions in overall energy use compared to liquid (LH2) or chemical hydride (CH) delivery modes.

- Shaded regions denote thermal energy (e.g. desorption heat), while solid regions denote electrical energy (e.g. liquefaction, compression, pumping)
- LH₂ and CH options do not include truck transportation (i.e., gasoline or diesel fuel for delivery truck) or dispensing energies, which would be small.
- MH Slurry option does not include energy required to dissipate absorption heat, which would be small. MH Slurry thermal energy is based on desorption and thermal compression energy for a typical AB-5 material (LaNi_{4.6}Mn_{0.4}).
- CH regeneration energy is based on electrolytic processes for sodium borohydride.
- The energy required to produce pure hydrogen is not included but would be the same for all options.

Given the inherent (and perceived) safety and reasonable cost/efficiency of the MH slurry systems, additional research and analysis is warranted.

- ◆ MH slurry transmission via a slurry pipeline could provide benefits for both short and longer distances
 - Safer due to low pressure operation and chemical bonding of the hydrogen atoms
 - Lower or comparable cost and energy requirements than CH_2 transport
 - Slurry settling, MH interactions, MH cycling performance/life, and safety benefits need to be studied in more detail
- ◆ In addition, MH slurry purification could result in an attractive low-pressure purification option
 - Permits the use of low-pressure (<10 atm) reformers
 - Excellent hydrogen recovery even for low-quality streams (e.g., biomass gasification)
 - Fluorinated or other coatings need to be modeled and tested
- ◆ Also, MH slurry thermal compression is an attractive alternative to mechanical CH_2 compression provided waste heat is available
 - Eliminates or reduces mechanical compressor costs and electric power requirements
 - Detailed conceptual designs are required to determine feasibility
 - Liquid (i.e., slurry medium) compatibility at high temperature needs to be evaluated

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The motivation of this study is to improve the commercialization potential for hydrogen and fuel cells by way of a MH slurry-based H₂ mini-grid.

◆ Why H₂ Mini-Grid?

- PEM fuel cell power systems (FCPS) could provide an early market fuel infrastructure for direct-hydrogen FCVs
- Reliability, efficiency, and cost of PEM FCPS is improved with centrally produced hydrogen
 - Reduced noise and on-site emissions compared to other DG technologies
- Mini-grids permit co-gen heating opportunities

◆ Why MH Slurries?

- Liquid and solid hydrogen delivery (i.e., MH slurries) are perceived to be safer than compressed gaseous delivery
 - Could improve acceptance and reduce right-of-way and permitting costs
- Overall, metal hydride purification, storage/compression and delivery systems could have higher efficiency and lower cost than PSA with CH₄
- MH slurries have excellent volumetric hydrogen density, and the impact of low gravimetric density is countered by using pipeline delivery

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However, before FI MH can be used for H₂ purification, further development is required to prove its feasibility and optimize its implementation.

- ◆ Current MH have low tolerance to impurities typically found in reformat streams, especially oxygen and carbon monoxide
- ◆ Protected metal hydrides should be able to demonstrate high tolerance to impurities
 - Researchers in Japan have shown a fluorinated surface layer will protect LaNi_{4.7}Al_{0.3} from multiple impurities:

Compound	Impurity Threshold, vol		Comment	Reference
	Untreated	Fluorinated		
Carbon Monoxide	<10 ppm	<100 ppm	Hydriding rates and initial activation time deteriorated for untreated MH	Japan Metals and Chemicals ^{1,3}
		<300 ppm	Was shown by applying a particular fluorination method	Kogakuin University ^{2,3}
Oxygen	<10 ppm	< 20%	During MH storage: no surface oxidation was found after 15 day exposure to air	X.-L. Wang, S. Suda ³
Carbon Dioxide	<100 ppm	< 20%	Physically adsorbs on the surface; may convert into inert methane ^{1,2}	Kogakuin University ² and Japan Metals and Chemicals ¹

¹ Personal communication with Mr. Tomioka and Mr. Kobayashi at Japan Metals and Chemicals Co., Ltd.

² Personal communication with Prof. S. Suda of Kogakuin University

³ Stability and Tolerance to Impurities of the Fluorinated Surface of Hydrogen-Absorbing Alloys, Journal of Alloys and Compounds 227 (1995) 58-62

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- ◆ Detailed analysis includes:
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 - Process modeling and performance calculations
 - Building heat/power demand profiles for every hour of a typical mean year
 - Cost of utilities (natural gas, power) and cost for hydrogen
 - Hydrogen delivery costs (e.g., right-of-way, materials, construction)

Detailed literature reviews, personal interviews, and system modeling were performed to accomplish this project's goals.

The overall concept consists of on-site H₂ production and dispensing at a fueling station with H₂ delivery via compressed gas or MH slurry to FCPSs.

- ◆ 69 and 690 kg/day H₂ fueling capacity for CH₂ vehicles
 - On-site H₂ production via 10 atm steam reformer was chosen because it showed the highest overall efficiency of the four reformer types investigated in Phase I
 - Compression and dispensing to vehicles at 6,250 psia
- ◆ 10 x 50 kWe PEM FCPS serving commercial and residential buildings
 - Grid connected for high utilization (note: load-following is possible for direct-H₂ FCPS)
 - Building heat and power demands met by a combination of the FCPS electrical output, cogen heat, grid electricity, and natural gas heating
 - FCPS is assumed to be base-loaded during peak hours - reduces demand charges
 - FCPS is assumed to be off when building power demand is below 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
- ◆ Our working assumption is that the mini-grid will be about 2 miles in length
 - This is much shorter than most existing hydrogen pipelines (10-100 miles)

We have evaluated three hydrogen mini-grid configurations and compared them to a stand-alone system.

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H₂ MINI-GRID SYSTEMS

Approach H₂ Mini-Grid Configurations

The three H₂ mini-grid configurations require various levels of system integration.

cH₂ Mini-Grid:

MH Mini-Grid 1:

MH Mini-Grid 2:

We have built on the previous phase of work and other hydrogen analyses to evaluate the performance and economics of each system configuration.

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 - Based on discussions with industry experts for current natural gas, hydrogen, and slurry distribution practices
- ◆ FCPS Model calculates annual costs to building owners
 - Key Inputs: building hourly electric and heat load profiles for the entire year, thermodynamic model results (e.g. efficiencies, cogen potential), and cost assumptions (i.e., capital, hydrogen cost, utility rates, and maintenance costs)
 - Key Outputs: annual costs (fuel, utility, and capital cost charges), GHG and other emissions
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A number of cost and performance inputs are required for the FCPS model.

Inputs	Value	Units	Comments
Fuel Cell Operation			
FC Size	50	kWe	Variable (0 for basecase)
Cell Voltage	0.7	V	Assumption, note that fuel cell cost should be increased if cell voltage is increased
Anode Utilization	95%		Typical for direct hydrogen PEM
Stack Efficiency	44.9%	HHV, kWe/kW fuel	LHV = 53%
Power Electronics Efficiency	95%		LHV = 95%
Parasitics w/o Cogen	0.0137	HHV, kWe/kW fuel	Hysys result designed for maximum efficiency
Parasitics w/ Max Cogen	0.0263	HHV, kWe/kW fuel	Hysys result designed for max cogen potential and high efficiency
Parasitics Used in Calculations	0.0263	HHV, kWe/kW fuel	LHV = 0.0311
Reformer Efficiency (on NG)	100%	HHV	LHV = 100%
Overall FC Efficiency	40.1%	HHV	LHV = 47.5%
Fuel Cell Hydrogen Demand	3.2	kg/hr at max load	H2 HHV (MJ/kg)= 142.1
Cogen Operation			
HTM Cogen	N	Y or N or 0	Y = HTM, N = LTM, 0 = no cogen
Cogen Efficiency	90%		FC waste heat to building heat (HX Effectiveness)
FC Cogen Potential	0.96	kWth/kWe	Hysys result designed for max cogen potential and high efficiency
FC Cogen Used in Calculations	0.96	kWth/kWe	
FC Cogen	0.1474	MMBtu/hr heat (HHV)	
Furnace Efficiency	83%	HHV	Natural gas to building heat
Fuel Chain			
Power Production Efficiency	34%	HHV	EIA database for 2003 US total of coal, petrol and NG net electricity production
Power T&D Efficiency	92%	HHV	Estimated average US T&D
NG PT&D Efficiency	95%	HHV	Estimated average US T&D
Power Production GHG Emissions	129.3	g/MJ Power	"H2A WTP GHG Calculations2.xls" generated for H2A activities by M. Wang of ANL using Electricity: NGCC - at wall outlet
NG Production GHG Emissions	9.4	g/MJ NG HHV	"H2A WTP GHG Calculations2.xls" generated for H2A activities by M. Wang of ANL using Natural gas: North American sources - at plant gate
Stand-alone H2 Production GHG Emissions	116.0	g/MJ H2 HHV	Calculated based on Stand-alone H2 Station energy use results and GHG emissions factors
Mini-Grid H2 Production GHG Emissions	104.0		Calculated based on MH Mini-grid 1 (small station) energy use results and GHG emissions factors
H2 Production GHG Emissions used in calculations	104	g/MJ H2 HHV	
Economics			
Power Cost	8.24	cents/kWh	So Cal Edison Industrial/Commercial Rate (GS-2), effective Jan 22, 2004
Power Demand Charge (Summer)	13.15	\$/kW/month	So Cal Edison Industrial/Commercial Rate (GS-2) for June-Sept, effective Jan 22, 2004
Power Demand Charge (Winter)	5.40	\$/kW/month	So Cal Edison Industrial/Commercial Rate (GS-2) for Oct-May, effective Jan 22, 2004
H2 Cost	22.28	\$/MMBtu	\$/kg = \$ 3.00
Local NG Cost	6.75	\$/MMBtu	Assumption
FCPS Production Volume	1000	100 or 1000	Variable
FCPS Installed Cost	31,700	\$	\$/kW (installed) = \$ 634
FCPS CRF	10%		Assumption
FCPS Labor	17.9	\$/mo	Based on TIAx study for SECA
FC Replacement Capital	12680	\$	Based on TIAx study for SECA
FC Parts Life	40,000	hrs life	Needed for commercialization
Cogen Cost	10,000	\$/MMBtu/hr heat (HHV)	Based on TIAx BPHP study for DOE
Cogen CRF	20%		Assumption

Hourly electric and heat load profiles for residential and commercial buildings for a typical meteorological year (TMY) are also model inputs.

- ◆ 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)

Jan 1 Profile for Restaurant in NYC

Jul 1 Profile for Restaurant in NYC

We constructed thermodynamic models to evaluate parameters that can affect 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

¹ Cogen is reduced by humidification requirements.

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

The FCPS model calculates grid power and natural gas and H₂ demands for each mini-H₂ grid system.

- ◆ Hourly electric load profiles are used to calculate fuel cell operating times
 - Profiles for multi-residential and small commercial buildings based on EnergyPlus software
 - Fuel cell turns on when the building demand exceeds fuel cell design power
- ◆ Conventional natural gas (for heat) and power demands are reduced according to the calculated fuel cell operating times
 - Fuel cell power reduces grid energy and demand charges
 - Fuel cell waste heat reduces natural gas demands for water and space heating
 - ➔ Waste heat is calculated using thermodynamic models

Greenhouse gas and other emissions can be calculated based on grid power and natural gas and H₂ requirements.

Cost inputs require the estimation of factory, installation, fuel, and maintenance costs.

We estimated FCPS factory costs at 100 and 1,000 units per year production volumes.

Industry experts, equipment manufacturers and construction contractors provided insight on the installed cost of cH₂ and MH slurry pipelines.

No.	Name	Organization	Profile	Designation
1	Dr. Nirmal Chatterjee	Air Products & Chemicals, Inc.	Industrial gases, chemicals, H ₂ pipelines, H ₂ safety, H ₂ storage, fuel cells	VP, Engineering
2	Dr. Venki Raman	Air Products & Chemicals, Inc.		Business Development Manager, Fuel Cells, H ₂
3	Dr. James Hansel	Air Products & Chemicals, Inc.		Sr. Engineering Associate, Global EH & S, Process Safety
4	Steve Dracos	Universal Ensco, Inc.	Right-of-way, permitting, land acquisition, material procurement, survey, construction, inspection	VP, Business Development
5	Aaron Duffy	Exelon Underground	Pipeline construction	
6	Tom Zondiros	Zondiros Corporation	Pipeline construction	Owner
7	Jay Parker	H. C. Peck & Associates	Right-of-way	Corporate Attorney
8	Bob	Coates Field Services, Inc.	Right-of-way	
9	Bill Sweeney	Global Right of Way Services	Right-of-way	
10	David Roberts	Boston Pipe & Fitting	Distributor for US Steel Corp.	
11	Steven Young	Pipeline Systems Inc.	Slurry pipeline design,	Manager, Business Development
12	Harold Roberts	International Uranium Corp.	Uranium tailings processing	VP, Corporate Development
13	Dan Harnett	Black Mesa Pipeline, Inc. (Northern Border Partners L.P)	Coal slurry pipeline operation	

MH slurry factory cost was estimated based on a MH manufacturer price quote and equipment cost estimates.

FI MH Slurry Storage System	Comment
MH Material	Based on communication with Ergenics and GfE; includes material processing, packaging and markup
Fluorination	Based on communication with Japan Metals and Chemicals
Thermal Management	Cost of heat exchangers, coolers and heaters were estimated using general chemical engineering considerations ¹
Mass Transfer Equipment	Absorber, stripping column, and desorber costs were estimated based on general chemical engineering considerations ¹
Containment Vessel	Assuming two 304 stainless steel vessels ¹
Process Equipment Manufacturing Volume	100 units/year
Controls	13% of the equipment cost excluding fluorinated MH cost
Miscellaneous Costs	5% of the equipment cost excluding fluorinated MH cost

¹ Reference: Peters, M.S. and K. D. Timmerhaus (1991) Plant Design and Economics for Chemical Engineers. New York, McGraw-Hill

H2A Spreadsheets and preliminary base cases were used to calculate hydrogen costs for mini-grid and standalone cases.

- ◆ H2A overall goal: Bring consistency and transparency to hydrogen analysis
 - Production and delivery analysis
 - Consistent cost methodology & critical cost analyses
- ◆ H2A approach: Cash flow analysis tool
 - Estimates levelized price of hydrogen for desired internal rate of return
 - Takes into account capital costs, construction time, taxes, depreciation, O&M, inflation, and projected feedstock prices
 - Data from published studies and industry design
 - Inputs, assumptions and results vetted by peer review and input from key industrial collaborators (KIC)
- ◆ Capital costs, energy use and other H2A inputs were modified to estimate and compare the cost of hydrogen for the TIAX mini-grid and standalone cases
 - Smaller capacity stations (i.e. 69/690 versus H2A base cases of 100/1500 kg/day)
 - Different storage/compression designs, efficiencies and costs

Capital costs, energy use and other H2A inputs were modified to estimate and compare the cost of hydrogen for the mini-grid and standalone cases.

- ◆ The TIAX Standalone H₂ Station assumes a smaller hydrogen vehicle fueling capacity than H2A
 - TIAX design going back to 2000 is based on 69 and 690 kg/day for 5,000 psi CH₂ vehicle fueling (versus 100/1,500 kg/day for H2A)
 - However, overall hydrogen design capacity for the Mini-grid cases is much larger = 637/1,258 kg/day to meet both vehicle fueling and FCPS hydrogen demands
- ◆ The Standalone H₂ Station also assumes different storage/compression designs
 - TIAX design assumes intermediate pressure (3,600 psi) storage with boost compression (via intensifiers) for vehicle fueling at 5,500 psi
 - H2A base case assumes high pressure (6,250 psi) storage
- ◆ Mini-grid cases result in higher capacity factor (CF) and reduced energy requirements, but additional capital costs compared to H2A
 - Improves station CF to 84% for the large station and 97% for the small station (versus 70% for the H2A and TIAX stand-alone cases)
 - Reduced natural gas and power consumption on a kWh/kg H₂ basis
 - Additional delivery system capital costs varied from about \$1-1.5 MM

The TIAx Standalone H₂ Station assumes a smaller hydrogen vehicle fueling capacity than H2A, but capital costs on a \$/kg/day basis are similar.

Equipment Costs	TIAx Large SMR Station - 690 kg/day			H2A Large SMR Station - 1500 kg/day		
	Uninstalled Costs	Installation Cost Factor	Calculated Installed Cost	Uninstalled Costs	Installation Cost Factor	Calculated Installed Cost
Production System	\$ 479,361	1.50	\$ 719,042	\$ 1,172,478	1.10	\$ 1,289,726
Purification System	\$ 84,762	1.50	\$ 127,143			\$ -
Compression System	\$ 124,250	1.50	\$ 186,375	\$ 286,250	1.20	\$ 343,500
Storage System	\$ 200,298	1.50	\$ 300,447	\$ 976,023	1.10	\$ 1,073,625
Dispenser System	\$ 67,200	1.20	\$ 80,640	\$ 67,200	1.20	\$ 80,640
Overall Control and Safety Equipment	\$ 18,600	1.20	\$ 22,320	\$ 18,600	1.20	\$ 22,320
Total Direct Capital Investment (Depreciable) (\$)			\$ 1,435,966			\$ 2,809,811
Engineering & design (\$)			Included in installed cost			\$ 30,000
Up-Front Permitting Costs (\$)			Included in installed cost			\$ 30,000
Capital Investment (\$)			\$ 1,435,966			\$ 2,869,811
Capital Investment (\$ per kg/day capacity)			\$ 2,081			\$ 1,913

Note: TIAx production system is assumed to last the life of the plant = 20 years with catalyst replacements every 5 years, while the H2A assumption is that the production must be completely replaced every 10 years.

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The safety advantage of metal hydride storage has driven significant development effort in stationary and automotive applications.

- ◆ Technology is based on selective absorption of hydrogen by hydriding alloys capable of reversible absorption and desorption of hydrogen
 - Charging or absorption: $M + x/2 H_2 \rightleftharpoons MH_x + \text{heat}$
 - Discharging or desorption: $MH_x + \text{heat} \rightleftharpoons M + x/2 H_2$
 - Heat required for the reactions is mainly a function of the hydriding material properties
 - The rate of these reactions increases with increased surface area, so powdered form is typically used
- ◆ Hydrogen can be stored in hydrides as a solid material at a relatively low pressure
- ◆ During absorption, hydrogen molecules are split and hydrogen atoms are inserted in the spaces inside the alloy lattice
 - Volumetric storage is comparable to liquid hydrogen but system weight can be four times higher (two times higher than high pressure storage)

A low temperature AB5 lanthanum-nickel based metal hydride material was selected for MH mini-grid options.

- ◆ $\text{LaNi}_{4.6}\text{Mn}_{0.4}$, a low temperature alloy, has superior performance and low cost compared to other low temperature alternatives
 - Low absorption/desorption temperatures
 - High intrinsic kinetics
 - Lanthanum-nickel based materials are well studied and have been used in multiple hydrogen storage projects such as the Savannah River Site for over 15 years (La-Ni-Al)
- ◆ We assumed a lanthanum rich mischmetal ($\text{LmNi}_{4.6}\text{Mn}_{0.4}$) whose properties were based on $\text{LaNi}_{4.6}\text{Mn}_{0.4}$ hydriding alloy
 - Assumed similar hydrogen capacity and P-T properties
 - Lanthanum rich mischmetal (Lm) was chosen for cost reduction

Metal hydride slurries offer significant system-level advantages over dry hydriding alloys.

- ◆ Protected metal hydride in slurry form can act simultaneously as a medium for hydrogen purification, storage and delivery
 - Once impurities are purged, the metal hydride can be used to store hydrogen
 - Metal hydride slurry is pumpable and can be transported via well-established slurry pipeline technology
- ◆ The use of a slurry instead of dry metal hydride allows for improved system performance characteristics
 - Heat transfer rate and, consequently, the rates of absorption and desorption are increased
 - ➔ Reduces amount of MH for purification only scenario
 - Pulverization caused by hydrogenation cycles does not create blockage problems as in dry MH systems
 - ➔ However, pulverization may still decrease the fluorinated coating effectiveness
 - Heat required for heating and cooling MH material can be reduced by using counter-flow heat exchange between absorbed and desorbed slurries
 - ➔ However, cooling and heating requirements can be higher due to the additional slurry medium

The limitation on metal hydride performance in slurry form is expected to be an overall weight and volume density decrease.

Slurry definition	Metal hydride slurry is a suspension of a metal hydride in an inert liquid, such as a light mineral oil or liquid alkane
Slurry impact on MH performance	The slurry has no impact on intrinsic hydrides performance in terms of hydrogen capacity, hydrogen uptake kinetics and thermodynamics
Slurry liquid phase properties	<ul style="list-style-type: none"> • In principle, any hydride can be used in a slurry form; in practice, it would be difficult to find a liquid compatible with high-temperature metal hydrides • Organic liquids should be stable against hydrogenation/dehydrogenation in presence of MHs, acting as catalysts at operating temperatures • This sets the real limit of about 150°C on the operating temperature for organic liquids slurries
Metal hydride concentration in a slurry	<ul style="list-style-type: none"> • 60% wt (14.6% vol) metal hydride in slurry is expected to be feasible in terms of slurry stability with the use of proper surfactants at 5 µm average solid particle size

Mischmetal based hydriding alloy properties for hydrogen storage were assumed based on the corresponding $\text{LaNi}_{4.6}\text{Mn}_{0.4}$ alloy properties.

Key MH H ₂ Storage Materials Properties Assumptions	Units	MH Slurry
MH alloy		$\text{LaNi}_{4.6}\text{Mn}_{0.4}$
Liquid phase		n-Decane
MH concentration in slurry ¹	% wt	60
Absolute MH H ₂ capacity	% wt	1.34
Reversible MH H ₂ capacity	% wt	1.21
Heat of MH Hydrogenation Reaction	kJ/mol	-39.4
Hysteresis	$\ln(P_a/P_d)$	0.05
MH heat capacity ²	J/mol K	27.7
Liquid phase heat capacity	J/mol K	1.97
MH slurry density ³	kg/l	1.9
Viscosity ⁴	cP	210

¹ Tested 15% wt; personal communication with Pr. G.W. Meindersma, former University of Twente

² Estimated based on material composition

³ Estimated based on % wt. of MH in slurry, MH density (7699 kg/m³) and liquid phase density (880 kg/m³)

⁴ Reference: R.W. Breault, et al., Hydrogen delivery/storage with a metal hydride/organic slurry, DOE Hydrogen Program Review Paper, Thermo Power Corporation. Independently verified using Gay et al correlation for Bingham plastic viscosity

Metal hydride alloys selectively and reversibly absorb hydrogen from gas mixtures thus providing hydrogen purification.

Absorption and Recovery Issues

- ◆ “Flow-through” reactor avoids accumulation of inert gases
 - Avoids surface blanketing and reduction of absorption dynamics
- ◆ Impurities are blown out of void spaces and particle pores/surfaces by pure H_2
 - H_2 loss depends on purity requirement, concentration and types of impurities
- ◆ In this study, H_2 loss is calculated using thermodynamic modeling software assuming 1 ppm CO

We assume the metal hydride is protected from typical reformat impurities, such as CO and water vapor, via fluorination or similar coating.

- ◆ Japanese researchers report that a 0.1-1 μm fluorinated surface layer can be formed on a hydriding alloy particle to protect it from multiple impurities
 - Coating is formed using a weak acidic F^- containing aqueous solution
 - Due to environmental and economic considerations, we assume large scale processing would use a gas phase fluorination process

Compound	Fluorinated Metal Hydride Impurity Tolerance ($\text{LaNi}_{4.7}\text{Al}_{0.3}$)		
	Vol. Fraction	Comment	Reference
Carbon Monoxide	<100 ppm	Hydriding rate and initial activation time deteriorated for untreated MH	Japan Metals and Chemicals ^{1,3}
	<300 ppm	Was shown by applying a particular fluorination method	Kogakuin University ^{2,3}
Carbon Dioxide	< 20%	Physically adsorbs on the surface - may convert into inert methane ¹	Kogakuin University ² and Japan Metals and Chemicals ¹
Methane	< 4000 ppm	Inert at the operating temperatures of 40-107°C	Kogakuin University ² and Japan Metals and Chemicals ¹
Oxygen	< 20%	During MH storage: No surface oxidation was found after 15 day exposure to air	X.-L. Wang, S. Suda ³
Water	-	During MH storage: No surface oxidation was found after up to 30 days exposure to liquid water	

¹ Personal communication with Mr. Tomioka and Mr. Kobayashi at Japan Metals and Chemicals Co., Ltd.

² Personal communication with Prof. S. Suda of Kogakuin University

³ Stability and Tolerance to Impurities of the Fluorinated Surface of Hydrogen-Absorbing Alloys, Journal of Alloys and Compounds 227 (1995) 58-62

A future scenario for fluorinated MH performance was assumed based on current results and developers projections.

- ◆ We assume the fluorinated coating will protect the MH material from all impurities present in the high temperature shift (HTS) reactor effluent (after water drop-out at 40 °C)
 - We assumed no significant deterioration of performance over time
 - ➔ Suda et al. measured less than 1% capacity loss and minimal hydriding reaction rate decrease after ten cycles in hydrogen containing 1,000 ppm CO at 50°C*
 - In practice, a low temperature shift (LTS) reactor and/or preferential oxidation (PrOx) reactor may be necessary to reduce CO further
- ◆ We assume the MH material and fluorinated coating will last the life of the fueling station
 - Regeneration and re-fluorination may be necessary on a periodic basis to maintain acceptable performance

* X.-L. Wang et al., Hydrogen purification using fluorinated LaNi_{4.7}Al_{0.3} alloy. *Journal of Alloys and Compounds*, 231, 1995

Waste heat from an oversized reformer at the fueling station can be used for simultaneous desorption and compression of H₂.

- ◆ Metal hydrides selectively absorb H₂ at a low pressure/temperature and upon the addition of heat, release H₂ at a higher pressure
 - E.g. 69 kg/day H₂ is absorbed into MH slurry at 40 °C and 10 atm total. Thermal energy needed for desorption at 425 atm is 45 kW_{th}
 - MH slurry thermal compression is an attractive alternative to mechanical compression of CH₂ provided waste heat is available

Utilizing the waste heat from the reformer and fuel cell power system (FCPS) can increase overall system efficiency significantly.

There has been limited research on metal hydride slurries applied to purification, hydrogen recovery and heat pumps, but not on H₂ delivery.

- ◆ DSM and the University of Twente, Netherlands have conducted demonstrations on hydrogen purification using metal hydride slurries
 - Several papers on kinetics of H₂ absorption/desorption in LaNi_{5-x}Al_x slurries and H₂ recovery from lean gas mixtures using MH suspended in slurry¹
- ◆ Researchers at Brookhaven National Lab have considered the behavior and properties of MH suspensions to facilitate their practical exploitation
 - Lectures on the isothermal kinetics of absorption/desorption of H₂ by LaNi₅H_x suspended in an inert hydrocarbon solvent like n-undecane or n-octane²
- ◆ A professor at the University of New Mexico has conducted research in thermal compression using MH slurries
 - MH and MH slurry heat pumps; absorption of H₂ in LaNi_{4.75}Al_{0.25} / n-octane slurries
- ◆ Although no MH slurry delivery research was identified, slurry pipeline transport is common in coal, metals and waste processing industries
 - e.g., Black Mesa pipeline, operational since 1970, carries a 50-50% coal-water slurry

¹ Ptasinski, van Swaaij, Holstvoogd, Versteeg et al 1980-1994

² J.J. Reilly and J.R. Johnson

³ Prof. Arsalan Razani of the Mechanical Engineering Department

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The cH_2 mini-grid concept incorporates PSA purification, mechanical compression, and compressed gas storage.

Note: Not all components are shown

The first metal hydride mini-grid concept replaces PSA and mechanical compression with slurry purification and thermal compression.

Note: Not all components are shown

The second metal hydride mini-grid concept incorporates slurry purification with mechanical compression and compressed gas storage.

MH slurry purification-only assumptions are within the range of conditions tested previously.

MH Slurry Purification Design Assumptions		Units	Value	Notes
Cooling Medium	Temperature	°C	30	Tested ¹ at 25 – 35 °C
	Approach Temp	°C	5	Approach to ambient air temperature
Cooling Fan Efficiency ²		%	55	
MH Absorption	Temperature	°C	40	Tested ¹ at 30 – 60 °C
	Total Pressure	atm	9	Tested ¹ at 5 – 21 atm
	H ₂ Partial Pressure	atm	7.4	Tested ¹ at 5 – 21 atm
	Superficial gas velocity	cm/s	5	Tested ¹ at 1 – 24 cm/s
Heating Medium	Temperature	°C	320	Tested ¹ at 120 – 130 °C
	Approach Temp	°C	10	Approach to TGB and auxiliary burner exhaust temperatures
MH Desorption	Temperature	°C	107	
	H ₂ Pressure	atm	5	

¹ Personal communication with Pr. G.W. Meindersma, former University of Twente.

² Includes adiabatic compression efficiency and motor efficiency.

For thermal compression, we assume a high desorption temperature can be achieved with the $\text{LaNi}_{4.6}\text{Mn}_{0.4}$ or similar metal hydride material.

MH Slurry Thermal Compression Assumptions		Units	Value	Notes
Heating Medium	Temperature	°C	320	Tested ¹ at 120 – 130 °C
	Approach Temp	°C	10	Approach to TGB and auxiliary burner exhaust temperatures
MH Desorption	Temperature	°C	318	Practical system would be re-configured for higher ΔT
	H ₂ Pressure	atm	425	Required for vehicle fueling

A liquid carrier would also have to be identified that could withstand high temperatures without significant reaction or degradation.

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The cH₂ mini-grid configuration delivers hydrogen to distributed fuel cell power systems (FCPS) via a compressed gas pipeline.

The cH₂ mini-grid design has been determined based on a combination of current natural gas and hydrogen distribution practices.

- ◆ cH₂ pipelines will be pressurized to about 9 atm
 - Equal to the reformer outlet pressure minus 1 atm pressure drop in PSA
 - Pressure drop through pipelines for up to 2 miles was determined to be minimal
 - Much higher than fuel cell operating pressure to prevent fluctuations in delivery pressure during peak demand
 - This is much lower pressure than most existing hydrogen pipelines (30-60 atm) but our system is low throughput
- ◆ Regular steel can be used as long as there are no sudden or large gradients in pipeline pressure which could result in hydrogen embrittlement¹
 - API 5L Grade X42 recommended below ground
 - Thick walled pipes are recommended to provide puncture resistance

¹ Based on discussions with Dr. James Hansel, Global EH & S, Air Products & Chemicals, Inc.

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

The MH mini-grid configuration delivers hydrogen via slurry pipelines to distributed FCPSs with integrated desorbers.

Industry experts, slurry pipeline owners and slurry consultants were contacted for design of the MH slurry pipeline.

- ◆ We selected the MH material based on it's unique properties for this application
 - H₂ storage capacity, H₂ desorption energy, pressure/temperature required
 - Additional experimental and modeling work is needed to optimize w.r.t particle size distribution, abrasiveness, weight percentage of solid in slurry, propensity to produce fines, resistance to impurities such as CO, H₂O
- ◆ We chose a generic liquid carrier medium for costing purposes - additional analysis is required to optimize w.r.t.:
 - Vapor pressure of liquid, slurry viscosity and density, stability against hydrogenation, settling properties, water/air reactivity of slurry
- ◆ We have used rules of thumb to design the MH slurry pipeline to withstand H₂ embrittlement, abrasion, and corrosion
 - The pipe inner wall may need to be treated by coatings, material alloying, heat treatment or extra allowance on wall thickness
- ◆ Pumping energy requirements were calculated assuming the slurry behaves as a non-Newtonian Bingham plastic
 - Solid particle loading, size and distribution affect slurry viscosity

Transport related issues were identified for design of slurry pipeline, but in-depth analysis and testing was not conducted in this phase of work.

- ◆ We used simple rules of thumb to account for deposition velocity (V_d), which is the velocity below which bed deposits form in a slurry pipeline
 - If velocity is less than or equal to V_d for a given flow rate, then decrease pipe diameter until velocity is at least 1 ft/s above V_d . Note that average flow velocity should not exceed ~ 10 ft/s (industry experience)
 - Pipe diameter is critical in slurry pipelines and must be optimized to balance two competing factors:
 - Smaller pipe diameter $\Rightarrow$ Higher velocity $\Rightarrow$ Reduced deposition
 - Smaller pipe diameter $\Rightarrow$ Higher velocity $\Rightarrow$ Increased abrasive wear, frictional ΔP and pump energy requirement
- ◆ Considerations we have not accounted for in this analysis include
 - A dispersant (zeta-potential additive) may be required to maintain solids in suspension
 - Static mixers/turbulators in the pipeline or agitated slurry storage tanks should be considered to reduce possibility of settling
 - Design for location, isolation and elimination of plugs (deposited solid particles, impurities)
 - Design for re-initiation of slurry movement after an interruption in operations

Right-of-way consultants were interviewed to verify the mini-grid designs and estimate costs¹.

- ◆ Right-of-way (R-o-W) costs include:
 - Payments to private parties to cross and excavate on their land
 - Land acquisition costs
 - Obtaining right-of-eminent domain
 - Cost of restoration and business interruption costs
 - Permit or franchise agreement costs
- ◆ R-o-W costs are affected by a number of factors:
 - Location (rural, urban, big city) and the particular state involved (NH, NJ, ME are very expensive in terms of R-o-W acquisition)
 - Crossing of major highways/city roads, need to tear up sidewalks, need to re-route traffic, need to deploy police personnel
 - Safety of the specific material the pipeline will transport

¹ Based on discussions with Steve Dracos, VP Business Development, Universal Ensco, Inc.

The 50 kWe PEM FCPS was assumed to operate with a 40% HHV (47% LHV) efficiency for delivering electric power from hydrogen.

Inputs	Value	Units	Comments
Fuel Cell Operation			
FC Size	50	kWe	Variable (0 for basecase)
Cell Voltage	0.7	V	Assumption, note that fuel cell cost should be increased if cell voltage is increased
Anode Utilization	95%		Typical for direct hydrogen PEM
Stack Efficiency	44.9%	HHV, kWe/kW fuel	LHV = 53%
Power Electronics Efficiency	95%		LHV = 95%
Parasitics w/o Cogen	0.0137	HHV, kWe/kW fuel	Hysys result designed for maximum efficiency
Parasitics w/ Max Cogen	0.0263	HHV, kWe/kW fuel	Hysys result designed for max cogen potential and high efficiency
Parasitics Used in Calculations	0.0263	HHV, kWe/kW fuel	LHV = 0.0311
Reformer Efficiency (on NG)	100%	HHV	LHV = 100%
Overall FC Efficiency	40.1%	HHV	LHV = 47.5%
Fuel Cell Hydrogen Demand	3.2	kg/hr at max load	H2 HHV (MJ/kg)= 142.1
Cogen Operation			
HTM Cogen	N	Y or N or 0	Y = HTM, N = LTM, 0 = no cogen
Cogen Efficiency	90%		FC waste heat to building heat (HX Effectiveness)
FC Cogen Potential	0.96	kWth/kWe	Hysys result designed for max cogen potential and high efficiency
FC Cogen Used in Calculations	0.96	kWth/kWe	
FC Cogen	0.1474	MMBtu/hr heat (HHV)	
Furnace Efficiency	83%	HHV	Natural gas to building heat
Fuel Chain			
Power Production Efficiency	34%	HHV	EIA database for 2003 US total of coal, petrol and NG net electricity production
Power T&D Efficiency	92%	HHV	Estimated average US T&D
NG PT&D Efficiency	95%	HHV	Estimated average US T&D
Power Production GHG Emissions	129.3	g/MJ Power	"H2A WTP GHG Calculations2.xls" generated for H2A activities by M. Wang of ANL using Electricity: NGCC - at wall outlet
NG Production GHG Emissions	9.4	g/MJ NG HHV	"H2A WTP GHG Calculations2.xls" generated for H2A activities by M. Wang of ANL using Natural gas: North American sources - at plant gate
Stand-alone H2 Production GHG Emissions	116.0	g/MJ H2 HHV	Calculated based on Stand-alone H2 Station energy use results and GHG emissions factors
Mini-Grid H2 Production GHG Emissions	104.0		Calculated based on MH Mini-grid 1 (small station) energy use results and GHG emissions factors
H2 Production GHG Emissions used in calculations	104	g/MJ H2 HHV	

Note that the overall primary energy use efficiency is much lower than 40% due to the inefficiency of hydrogen generation from natural gas.

Both low (100 units/y) and high (1,000 units/y) production volume assumptions were used in the FCPS cost estimation.

Cost Estimate, \$/kWe	Low Vol	High Vol
Fuel Cell System	592	252
Power Electronics	50	50
Total Factory Cost	642	302
Total Installed Cost*	1,348	634
Replacement Cost	237	101

* Assumes typical mark-up of 2.1x for distributed power system installation.

Economics			
Power Cost	8.24	cents/kWh	So Cal Edison Industrial/Commercial Rate (GS-2), effective Jan 22, 2004
Power Demand Charge (Summer)	13.15	\$/kW/month	So Cal Edison Industrial/Commercial Rate (GS-2) for June-Sept, effective Jan 22, 2004
Power Demand Charge (Winter)	5.40	\$/kW/month	So Cal Edison Industrial/Commercial Rate (GS-2) for Oct-May, effective Jan 22, 2004
H2 Cost	22.28	\$/MMBtu	
Local NG Cost	6.75	\$/MMBtu	Assumption
FCPS Production Volume	1000	100 or 1000	Variable
FCPS Installed Cost	31,700	\$	
FCPS CRF	10%		Assumption
FCPS Labor	17.9	\$/mo	Based on TIAX study for SECA
FC Replacement Capital	12680	\$	Based on TIAX study for SECA
FC Parts Life	40,000	hrs life	Needed for commercialization
Cogen Cost	10,000	\$/MMBtu/hr heat (HHV)	Based on TIAX BCHP study for DOE
Cogen CRF	20%		Assumption

\$/kg = \$ 3.00

\$/kW (installed) = \$ 634

FCPS cost estimates are based on previous and on-going cost assessments by TIAX for PEMFC systems for stationary power.

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We have evaluated three hydrogen mini-grid configurations and compared them to a stand-alone system.

- ◆ *Stand-Alone: H₂ Station*
- ◆ *cH₂ Mini-Grid: PSA with high pressure cH₂ storage, mechanical compression, and low pressure cH₂ Mini-grid delivery*
- ◆ *MH Mini-Grid 1: FI MH slurry purification, storage, thermal compression, and MH Mini-grid delivery*
- ◆ *MH Mini-Grid 2: FI MH slurry purification and MH Mini-grid delivery, and high pressure cH₂ storage and mechanical compression*

In a MH slurry mini-grid concept, waste heat from the reformer and fuel cell power system (FCPS) can be used to increase overall system efficiency.

Waste heat can be used for hydrogen desorption and compression rather than burning natural gas or using electric power.

MH slurry concepts are slightly more efficient than the CH_2 mini-grid when vehicle H_2 demand is small compared to FCPS power demand (i.e., small station case).

Note: Primary energy results assume fuel chain efficiencies of 36% for power and 94% for natural gas.

All mini-grid concepts are more efficient than the stand-alone option.

For the large station, MH Mini-Grid 1 reduced power consumption significantly over all other options.

- ◆ Low-pressure requirement for the mini-grid reduces the overall power requirement per kg of H₂ compared to the stand-alone station
- ◆ Thermal compression for the MH Mini-Grid 1 case obviates the need for electrical compression power
- ◆ MH Mini-Grid 2 requires additional electrical power to pump the slurry through the grid
- ◆ Additional natural gas is required to provide heat for thermal compressor in MH Mini-Grid 1

For the small station, the CH_2 Mini-Grid used the least amount of electrical power.

- ◆ There is less opportunity to take advantage of power savings due to thermal compression in the small station case
 - Most of the H_2 goes to the Mini-Grid
- ◆ However, no additional NG needs to be burned for thermal compression in the MH Mini-Grid 1 case
 - Oversized reformer provided sufficient waste heat

GHG emissions can actually increase over the stand-alone case if natural gas needs to be burned to supply heat for MH H₂ desorption and thermal compression.

Note: GHG emissions results assume fuel chain efficiencies of 36% for power and 94% for natural gas. GHG emissions factors are based on "H2A WTP GHG Calculations2.xls" generated for H2A activities by M. Wang of ANL and assuming 72.4 g GHG/MJ natural gas feedstock based on stoichiometry.

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Assuming a MH slurry price of \$20/kg, purification and storage costs were estimated to be over \$50K for the small station MH mini-grid case 1.

MH Slurry System for Small Station ¹	Case 1: Purification and Storage	Case 2: Purification Only
Total MH Slurry Cost ²	\$41,400	\$520
Absorber	\$2,700	\$2,700
Stripping Column	\$600	\$600
Desorber	\$8,700	\$4,000
Storage Vessels Cost	\$2,500	\$0
Pump and Compressor	\$1,400	\$1,400
Total Uninstalled Cost	\$57,300	\$9,200

¹ See Appendix for large station case (300 cars/day or 690 kg H₂/day)

² Assumes solid MH costs = \$18/kg and liquid carrier cost = \$2/kg

MH slurry for purification only is much cheaper - less than \$10K for the small station.

An average between rural and urban pipeline construction costs were assumed for the hydrogen mini-grid cost estimates.

Hydrogen Mini-Grid Costs	<i>semi-rural KS</i>		<i>Downtown LA</i>		<i>Average</i>	
	cH2	MH slurry	cH2	MH slurry	cH2	MH slurry
Assumptions						
Daily H2 req. (kg/day)	568	568	568	568	568	568
Distance ¹ (mi.)	2	4	2	4	2	4
Pipe size NPS (")	4	2	4	2	4	2
Pipe schedule	80	80	80	80	80	80
Materials (\$/ft)	11	4	11	4	11	4
Construction (\$/ft)	10	10	30	30	20	20
Right-of-way (\$/ft)	25	20	65	55	45	37.5
Eminent Domain ² (\$/ft)	4	4	0	0	2	2
Costs						
Pipeline Installation ³ (\$)	527,000	446,000	1,118,000	984,000	822,000	715,000
City permit ⁴ (\$)	0	0	7,000	7,000	3,500	3,500
Valves (\$)	500	2,000	500	2,000	500	2,000
Pumps (\$)	2,500	3,000	2,500	3,000	2,500	3,000
Safety compliance ⁵ (%)	15%	10%	15%	10%	15%	10%
Total (\$)	609,500	496,100	1,297,200	1,095,600	952,775	795,850

¹ The MH slurry pipeline is twice the cH₂ pipeline length due to need for second pipe to return spent slurry to the absorber.

² Eminent domain is used in the context of rural areas to indicate that the construction is deemed to be for public good and an easement may be negotiated to cross a land-owner's property.

³ Material costs for MH slurry pipeline are for 4 mi. distance, but construction, right-of-way and eminent domain need only be calculated for a single 2 mi. pipeline. Return pipe can be installed within the same trench and same right-of-way.

⁴ City permit covers the review by the City engineering and legal staff.

⁵ The safety of the fluid being transported in the pipelines has an impact on the value of the easement paid to land-owner, as well as on cost needed to comply with H₂ safety regulations at building site.

All mini-grid concepts result in about the same cost of hydrogen and are cheaper than the stand-alone option due to higher capacity factors.

Note: Metal hydride cases assume the metal hydride material will operate efficiently for 20 years. Additional analysis is necessary to evaluate the likely material life.

All the mini-grid cases reduced the cost of hydrogen significantly over the small stand-alone hydrogen station due to economies of scale for H₂ production.

Note: Metal hydride cases assume the metal hydride material will operate efficiently for 20 years. Additional analysis is necessary to evaluate the likely material life.

The cost of electricity (COE) from the FCPS is much more expensive than the grid unless hydrogen can be purchased for <\$1.50/kg.

Note: Hydrogen sold to the building owner for just \$1.22/kg is equivalent to the cost of feedstock only. In a real situation, the hydrogen station owner would need to charge more to recover the significant capital investment.

At \$3/kg hydrogen, the FCPS fuel cost alone would equal the typical utility cost to the building owner.

Even factoring in natural gas savings from CHP does little to change the outlook.

Building owners will have to value other DG benefits (e.g., power quality, back-up power) in order to justify an investment in a FCPS.

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MH slurry mini-grid concepts could provide relatively small reductions in overall energy use, cost, and GHG emissions compared to a CH_2 mini-grid.

- ◆ MH Mini-Grid 1 case can reduce energy requirements and GHG emissions compared to CH_2 provided reformer waste heat can be used effectively
 - Total hydrogen demand from the reformer should be >2X fueling demand
 - May require heat storage
- ◆ Most mini-grid options provided energy, GHG, and cost savings compared to stand-alone hydrogen stations
 - Hydrogen costs can be cut in half and primary energy use and GHG emissions can be reduced by 10-15% for the small station cases
- ◆ However, all mini-grid cases require the FCPS, or other H_2 end-use systems to achieve market success
 - FCPS operating on hydrogen from a mini-grid will not likely result in cheaper electricity than the grid
 - Cogen does not help much
 - Building owners will have to value other DG benefits (e.g., power quality, back-up power)
- ◆ In addition, all MH slurry concepts need further research, modeling, and experimental testing to advance them beyond the conceptual design stage

MH Slurries offer significant reductions in overall energy use compared to liquid (LH2) or chemical hydride (CH) delivery modes.

- Shaded regions denote thermal energy (e.g. desorption heat), while solid regions denote electrical energy (e.g. liquefaction, compression, pumping)
- LH₂ and CH options do not include truck transportation (i.e., gasoline or diesel fuel for delivery truck) or dispensing energies, which would be small.
- MH Slurry option does not include energy required to dissipate absorption heat, which would be small. MH Slurry thermal energy is based on desorption and thermal compression energy for a typical AB-5 material (LaNi_{4.6}Mn_{0.4}).
- CH regeneration energy is based on electrolytic processes for sodium borohydride.
- The energy required to produce pure hydrogen is not included but would be the same for all options.

Given the inherent (and perceived) safety and reasonable cost/efficiency of the MH slurry systems, additional research and analysis is warranted.

- ◆ MH slurry transmission via a slurry pipeline could provide benefits for both short and longer distances
 - Safer due to low pressure operation and chemical bonding of the hydrogen atoms
 - Lower or comparable cost and energy requirements than CH_2 transport
 - Slurry settling, MH interactions, MH cycling performance/life, and safety benefits need to be studied in more detail
- ◆ In addition, MH slurry purification could result in an attractive low-pressure purification option
 - Permits the use of low-pressure (<10 atm) reformers
 - Excellent hydrogen recovery even for low-quality streams (e.g., biomass gasification)
 - Fluorinated or other coatings need to be modeled and tested
- ◆ Also, MH slurry thermal compression is an attractive alternative to mechanical CH_2 compression provided waste heat is available
 - Eliminates or reduces mechanical compressor costs and electric power requirements
 - Detailed conceptual designs are required to determine feasibility
 - Liquid (i.e., slurry medium) compatibility at high temperature needs to be evaluated

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API	American Petroleum Institute	HX	Heat Exchanger
ASME	American Society of Mechanical Engineers	IRR	Internal Rate of Return
CGA	Compressed Gas Association	LP	Low Pressure
CH ₂	Compressed Hydrogen (gaseous)	LTM	Low Temperature Membrane
CHP	Combined Heat & Power	LTS	Low Temperature Shift
COE	Cost of Electricity	MH	Metal Hydride
Cp	Specific Heat	NFPA	National Fire Protection Association
CRF		NG	Natural Gas
CSA	Canadian Standards Association	O&M	Operation & Maintenance
DG	Distributed Generation	OSHA	Occupational Safety & Health Administration
dH	Change in Enthalpy	P	Pressure
DOE	Department of Energy	PEM	Proton Exchange Membrane
DoT	Department of Transportation	PrOx	Preferential Oxidation
dT	Change in Temperature	PSA	Pressure Swing Adsorption
FCPS	Fuel Cell Power System	R-o-W	Right-of-Way
FCV	Fuel Cell Vehicle	RSPA	Research & Special Programs Administration
FI MH	Fluorinated Metal Hydride	SMR	Steam Methane Reformer
GHG	Greenhouse Gases	T	Temperature
HP	High Pressure	TGB	Tailgas burner
HTM	High Temperature Membrane	TMY	Typical Meteorological Year
HTS	High Temperature Shift	Vd	Deposition Velocity

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MH Slurry

Mini-Grid

MH slurry purification and storage system parameters for 30 cars/day or 69 kg/day station.

MH Slurry System for Small Station		Units	Purification and Storage	Purification Only
SMR Operating Pressure		atm	10	10
MH Total Weight		kg	2,040	26
MH Slurry Total Weight		kg	3,400	42
MH Slurry Total Volume		m ³	1.8	0.02
Absorber	Type		P	P
	Number of Stages		3.6	3.6
	Diameter	cm	20	20
	Height	m	1.1	1.1
Stripping Column	Type		P	P
	Number of Stages		8.1	8.1
	Diameter	cm	4	4
	Height	m	2.5	2.5
Desorber	Type		T	P
	Number of Stages		4	3.8
	Diameter	cm	59	4
	Height	m	1.4	2.0
Storage Vessels Total Volume		m ³	2	0

P – packed column; T – tray column

MH slurry purification and storage system parameters for 300 cars/day or 690 kg/day station.

MH Slurry System for Large Station		Units	Purification and Storage	Purification Only
SMR Operating Pressure		atm	10	10
MH Total Weight		kg	20,400	260
MH Slurry Total Weight		kg	34,000	425
MH Slurry Total Volume		m ³	18	0.2
Absorber	Type		T	T
	Number of Stages		4	4
	Diameter	cm	62	62
	Height	m	1.4	1.4
Stripping Column	Type		P	P
	Number of Stages		8.1	8.1
	Diameter	cm	14	14
	Height	m	2.5	2.5
Desorber	Type		T	T
	Number of Stages		4	4
	Diameter	cm	102	66
	Height	m	1.4	1.4
Storage Vessels Total Volume		m ³	18	0

P – packed column; T – tray column

Assuming a MH slurry price of \$20/kg, purification and storage costs were estimated to be over \$400K for the large station MH mini-grid case 1.

MH Slurry System for Large Station ¹	Units	Purification and Storage	Purification Only
Total MH Slurry Cost ²	\$	\$413,900	\$5,200
Absorber	\$	\$8,400	\$8,400
Stripping Column	\$	\$2,800	\$2,800
Desorber	\$	\$12,600	\$8,100
Storage Vessels Cost	\$	\$5,100	\$0
Pump and Compressor	\$	\$1,800	\$1,800
Total Uninstalled Cost	\$	\$444,600	\$26,300

MH slurry for purification only is much cheaper at less than \$30K for the large station

¹ See System Cost for small station case (30 cars/day or 69 kg H₂/day)

² Assumes solid MH costs = \$18/kg and liquid carrier cost = \$2/kg

Integration of the MH slurry system with an oversized reformer, allows waste heat to be used for desorption / thermal compression of H₂ at the station.

Desorption Requirements	H2 demand (kg/day)	Desorption P (atm)	Desorption T (C)	Cp dT (kWth)	MH dH (kWth)	Total heat req. (kWth)
MH compressor, ave. (30 veh/day)	69	425	318	29	16	45
MH compressor, peak (30 veh/day)	9.2	425	318	94	50	145
MH purification, ave. (30 veh/day)	69	5	107	7	16	23
MH purification, peak (30 veh/day)	9.2	5	107	22	50	72
FCPS, ave.	57	1.3	70	3	13	16
FCPS, peak	3.2	1.3	70	3	17	21

Desorption Vs. Waste Heat Availability	Desorption T (C)	Waste heat T (C)	Small Station		Large Station	
			Total heat req. (kWth)	Waste heat avail. (kWth)	Total heat req. (kWth)	Waste heat avail. (kWth)
MH compressor, ave.	318	327	45	48	452	94
MH compressor, peak			145		1447	
MH purification, ave.	107	130	23	93	225	183
MH purification, peak			72		722	
FCPS, ave.	70	75	16	34	NA	
FCPS, peak			21			

Utilizing the waste heat from the reformer and FCPS increases the overall system efficiency significantly.

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Mini-Grid

The MH slurry options provided some energy efficiency benefits and, in one case, a reduction in hydrogen storage.

Summary of Hydrogen Station Design parameters	Stand-Alone FCPS		cH ₂ Mini-Grid		MH Mini-Grid 1		MH Mini-Grid 2	
Vehicle demand per day	300	30	300	30	300	30	300	30
Peak vehicle H ₂ demand, kg/hr	40	4	40	4	40	4	40	4
Vehicle H ₂ demand, kg/day	690	69	690	69	690	69	690	69
Peak mini-grid H ₂ demand, kg/hr	-	-	32	32	32	32	32	32
Max. mini-grid H ₂ demand, kg/day	-	-	568	568	568	568	568	568
Max. H ₂ station H ₂ demand, kg/day	690	69	1258	637	1258	637	1258	637
cH ₂ (actual) storage reqd. , kg H ₂	456	46	456	46	-	-	456	46
MH slurry storage reqd., kg H ₂	-	-	-	-	355	157	142	142
Total storage reqd., kg H ₂	456	46	456	46	355	157	598	188
Total NG demand, MMBtu/kg	0.176	0.176	0.176	0.176	0.195	0.166	0.170	0.166
Total power demand, kWh/kg	2.80	2.80	1.80	0.83	0.71	0.87	2.03	1.13

1. Metal hydride cases assume effective heat storage (5% heat loss) and no buffer storage is required for the mini-grid.
2. No additional storage is required for the cH₂ mini-grid case; it can store 649 kg H₂ for a fluctuation between 8-9 atm in a 2 mi. long, 4" Φ pipeline.

A parametric analysis was performed to evaluate the effect of metal hydride H₂ capacity and pipeline length on H₂ production/delivery parameters.

◆ **Mini-grid scenario (2 - 10 miles) :**

- Higher H₂ capacity does not significantly reduce total energy required for delivery of MH slurry as compared to cH₂.
- MH slurry pipeline diameter is half that of the cH₂ pipeline for the same delivered H₂ energy.
- Therefore, the lower temperature, lower capacity hydride LmNi_{4.6}Mn_{0.4} seems appropriate for this scenario.

◆ **Long-distance delivery (100 - 200 miles) :**

- Higher H₂ capacity does significantly reduce total energy required for delivery of MH slurry as compared to cH₂.
- MH slurry pipeline diameter is slightly more than half that of the cH₂ pipeline for the same delivered H₂ power.
- If lower H₂ capacity is used, then pipeline diameter for MH slurry and cH₂ is identical.

◆ **In either case, total energy (delivery + compression/desorption/storage) is comparable for MH slurry pipeline and cH₂ pipeline of same length and delivering the same total H₂ energy.**

The following key assumptions were made for total energy calculations for short and long distance H₂ delivery:

◆ **Mini-grid scenario**

- 2 miles long, H₂ throughput 1.5 TPD (2.08 MW),
- cH₂ pipeline pressure 10 atm (150 psia)

◆ **Long-distance delivery**

- 100 miles long, H₂ throughput 1,066 TPD (1,475 MW),
- cH₂ pressure pipeline 68 atm (1,015 psia)

◆ **Weight percent of MH in slurry is assumed to be 60%**

◆ **Total energy = (Reformer + Purification energy) + (Delivery energy) + (Storage energy) + (Dispensing energy) requirements**

- Delivery energy requirement is the power used in pumping the slurry to overcome frictional losses
- cH₂ energy requirement assumes compression up to pipeline pressure using four stage compression with intercooling
- LH₂ liquefaction energy requirement assumes 6-35 TPD liquefaction plant referenced from R. Drnevich, Praxair (May 2003) data

Total energy is comparable for MH slurry pipeline and cH_2 pipeline of same length and delivering the same total H_2 energy.

- Shaded regions denote thermal energy (e.g. desorption heat), while solid regions denote electrical energy (e.g. liquefaction, compression, pumping)
- LH2 does not include truck transportation (i.e., gasoline or diesel fuel for delivery truck) or dispensing energies, which would be small.
- MH Slurry option does not include energy required to dissipate absorption heat, which would be small. MH Slurry thermal energy is based on desorption and thermal compression energy for a typical AB-5 material ($\text{LaNi}_{4.6}\text{Mn}_{0.4}$).
- The energy required to produce pure hydrogen is not included but would be the same for all options.