Low-Cost Hydrogen-from-Ethanol: A Distributed Production System

Presented at the
Bio-Derived Liquids to Hydrogen Distributed Reforming Working Group Meeting

Laurel, Maryland
Tuesday, November 6, 2007

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Topics

- H_2Gen Reformer System Innovation
- Natural Gas Reformer
  - Key performance metrics
  - Summary unique H2A inputs
- Ethanol Reformer
  - Key performance metrics
  - Summary unique H2A inputs

- Questions from 2007 Merit Review

H_2Gen Innovations' Commercial SMR

- Compact, low-cost 115 kg/day natural gas reformer proven in commercial practice [13 US Patents granted]
- Built-in, unique, low-cost PSA system
- Unique sulfur-tolerant catalyst developed with Süd Chemie

DOE Program Results

- Task 1- Natural Gas Reformer Scaling: Commercial HGM-2000 (115 kg/day) reformer successfully scaled up to 565 kg/day; field testing under way
- Task 2- Ethanol Experiments: Initial micro-reactor long-term testing of ethanol as feedstock for the H_2Gen reformer system on-going

Reformer Cost Reduction Methodology

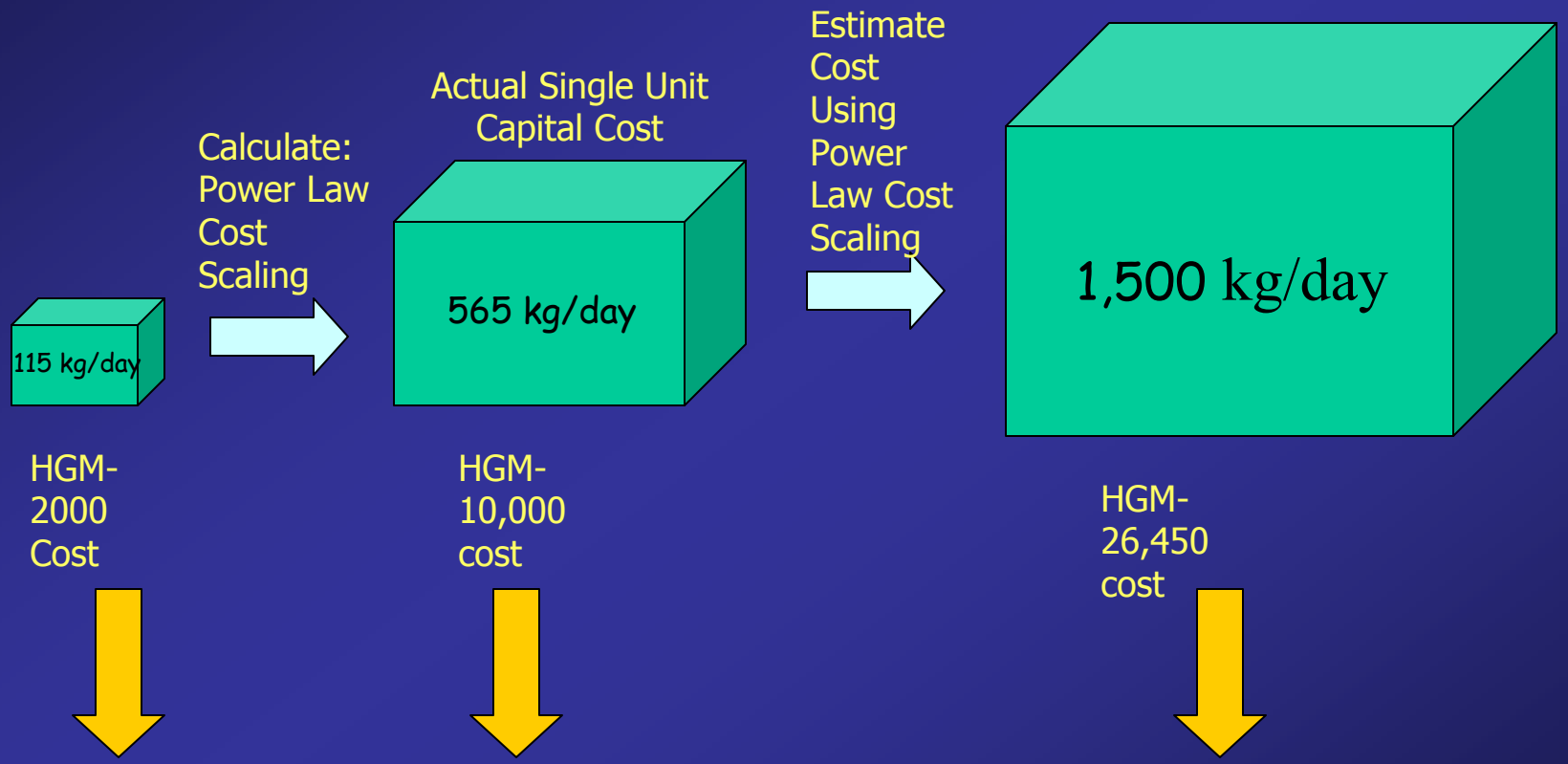
1. Optimize performance & cost using HGM-2000 platform (including extensive field testing)

2. Incorporate results and design, build and test HGM-10,000 to demonstrate pathway to DOE cost goals

3. Extrapolate to HGM-26,450 (1,500 kg/day)

Capital Cost Estimate Procedure

(500/year manufacturing rate)



The H_2Gen HGM-2000

Natural Gas

Water

Hydrogen

53.6 Nm^3/h

2,000 scf/h

115 kg/day

- Low Cost
- Small Footprint
- Highly pure product

HGM-2000 Field Units

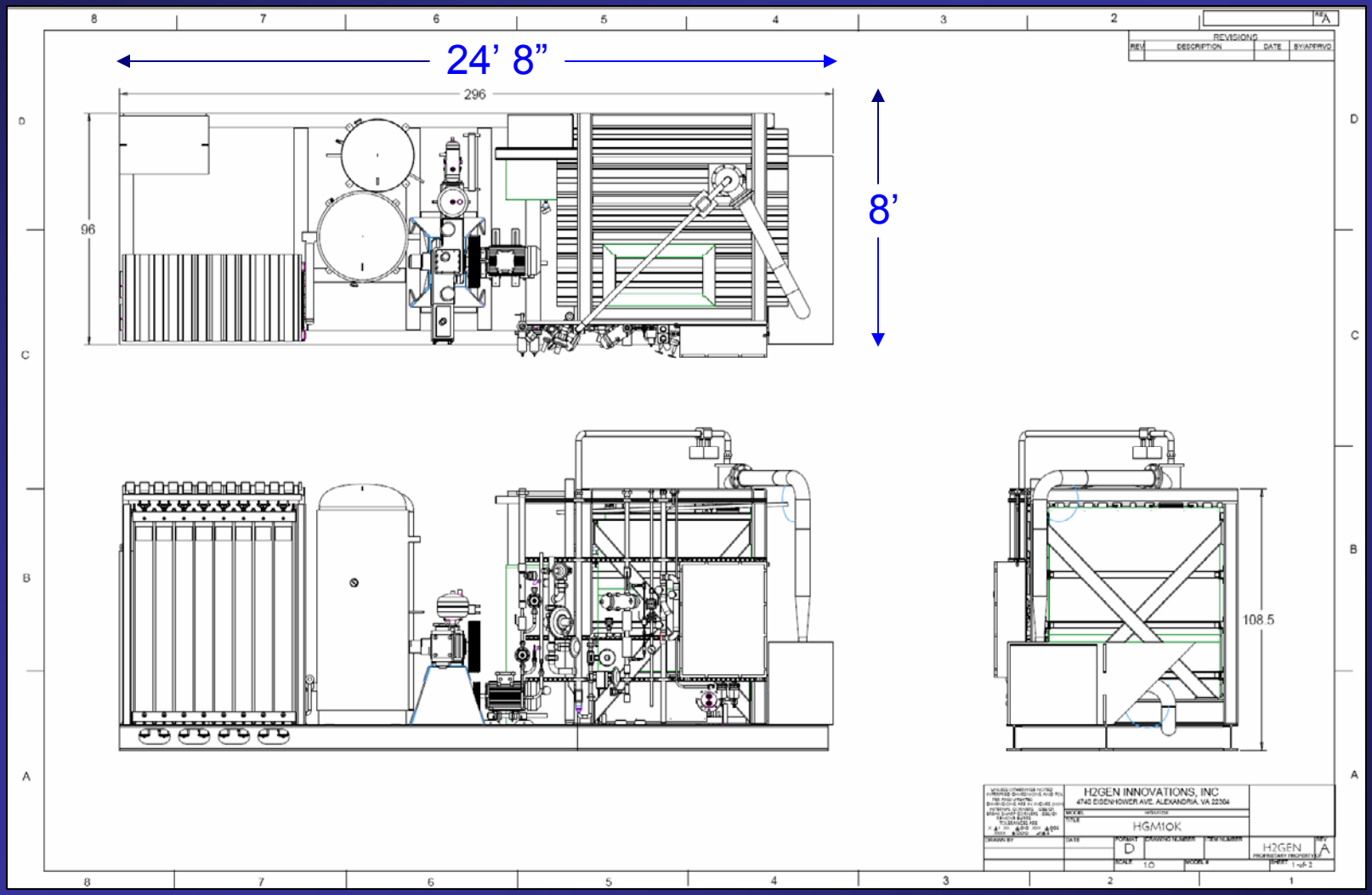
Plant Floor

DOE HGM-10,000 (565 kg/day)

Under construction

At field site

HGM 10,000 Layout drawings



Key Performance Metrics for H_2Gen Reformers

Fuel	NG	LPG	Ethanol
	Based on 565 kg/day SMR	Based on 80 kg/day SMR	Based on 80 kg/day SMR
Overall process	CH4+2H2O→ CO2+4H2	C3H8+6H2O→3CO2+10H2	C2H6O+3H2O→2CO2+6H2
Net pre-reforming	-	C3H8+2H2O→2CH4+CO2+2H2	C2H6O+H2O→1.5CH4+0.5CO2+H2
Fuel feed to SMR	100 nm3/hr	20 kg/hr	35 kg/hr
H2 yield	270 nm3/hr	70 nm3/hr	70 nm3/hr
S:C	4	4.2	2.5
Feed conversion	100%	100%	100%
LHV Efficiency	73%	68.9%	68.9%
Current status	HGM-2k in serial production HGM-10k unit started at customer's site	First unit under construction	Model data

Capital & Installation Cost H2A Variances for natural gas reformer

(based on 1,500 kg/day systems in 500 production quantities)

	H2A	H2Gen	Delta
SMR + PSA System FOB	**$1,172,478**	**$ 769,225**	**$ (403,253)**
Installation Costs			
State Sales tax (5%)	$ 58,624	$ 38,461	$ (20,163)
Unspecified (5%)	$ 58,624	$ -	$ (58,624)
Engineering Design	$ 30,000	$ -	$ (30,000)
Transportation & Insurance	$ -	$ 20,892	$ 20,892
On-Site Riggers	$ -	$ 16,200	$ 16,200
Site Preparation	$ 74,344	$ 81,993	$ 7,649
Utility Hook-ups	$ -	$ 26,714	$ 26,714
Permitting costs	$ 30,000	$ 30,000	$ -
Total Installation Costs	**$ 251,592**	**$ 214,260**	**$ (37,332)**
Total Capital Costs	**$ 1,424,070**	**$ 983,485**	**$ (440,585)**
Contingency %	*10%*	*2%*	
Contingency*	$ 201,270	$ 40,254	$ (161,016)
Total Costs with Contingency	**$ 1,625,340**	**$ 1,023,739**	**$ (601,601)**

*Contingency is also on compression, storage and dispensing at $1.52 million

H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'H2A Comparison';E21 - 11 / 2 / 2007

Reactor Replacement Costs

Year	H2A (Current)	H2Gen (Future-2012)	Delta
1			$ -
2			$ -
3			$ -
4			$ -
5			$ -
5-Year catalyst replacement (15% of SMR Capex) 6	$ 175,872		$ (175,872)
7			$ -
7-year replacement of hot module (12% of Capex) 8		$ 92,775	$ 92,775
9			$ -
10			$ -
SMR (H2A) & Dispenser replacements 11	$ 1,370,366	$80,640	$ (1,289,726)
12			$ -
13			$ -
14			$ -
15			$ -
16	$ 175,872	$ 92,775	$ (83,097)
17			$ -
18			$ -
19			$ -
20			$ -
Totals	**$ 1,722,110**	**$ 266,190**	**$ (1,455,920)**

H2A Model Input Changes for Natural Gas Reformers

(based on 1,500 kg/day systems in 500 production quantities)

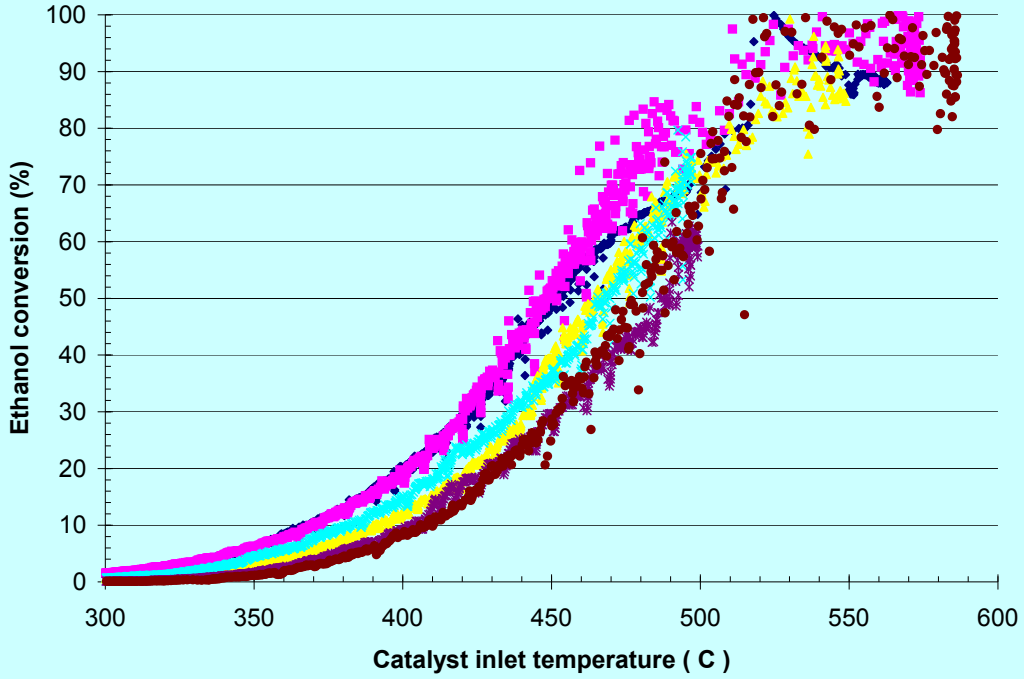
	H2A	H2Gen	Hydrogen Price
H2A with no changes	(current)	(future-2012)	$ 3.49 /kg
Reduced FOB SMR + PSA Cost	$1,172,478	$ 769,225	$ 3.16 /kg
Reduced Installation Costs	$ 251,592	$ 214,260	$ 3.15 /kg
Increased Efficiency	69.0%	73.0%	$ 3.09 /kg
Reduced Electricity consumption	1.50 kWh/kg	1.03 kWh/kg	$ 3.05 /kg
Reduced Annual Maintenance	$ 45,751	$ 36,452	$ 3.02 /kg
Reduced Reactor Replacement	$ 1,722,110	$ 266,190	$ 2.89 /kg
Reduced Start-up Time	1 year	1 month	$ 2.70 /kg
Reduced startup operating costs	100%	10%	$ 2.57 /kg
Reduced 2012 Compr. & storage	$ 1,520,085	$ 1,059,210	**$ 2.55 /kg**
Other costs			
Reduced Contingency	$ 201,270	$ 40,254	$ 2.47 /kg
Rent on 7,200 square feet	$ 43,194	$ -	$ 2.35 /kg
Dispensing labor (3/8 x 50%)	$ 18,478	$ -	$ 2.29 /kg

H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'H2A Comparison';E67 - 11 / 2 / 2007

Task 2: Ethanol Reforming

Change in approach from original program

- Pre-reforming to create CH_4 stream from ethanol fuel feed followed by an H_2Gen CH_4 reforming process
- Use H_2Gen pre-reforming process developed for commercial LPG reforming to handle heavy feed constituents (US Patent pending)



Pre-reforming of ethanol:

$C_2H_5OH + H_2O \rightarrow CH_4 + CO_2 + 2\ H_2$

Followed by reforming of methane :

$CH_4 + 2H_2O \rightarrow CO_2 + 4\ H_2$

Hydrogen from Ethanol Costs

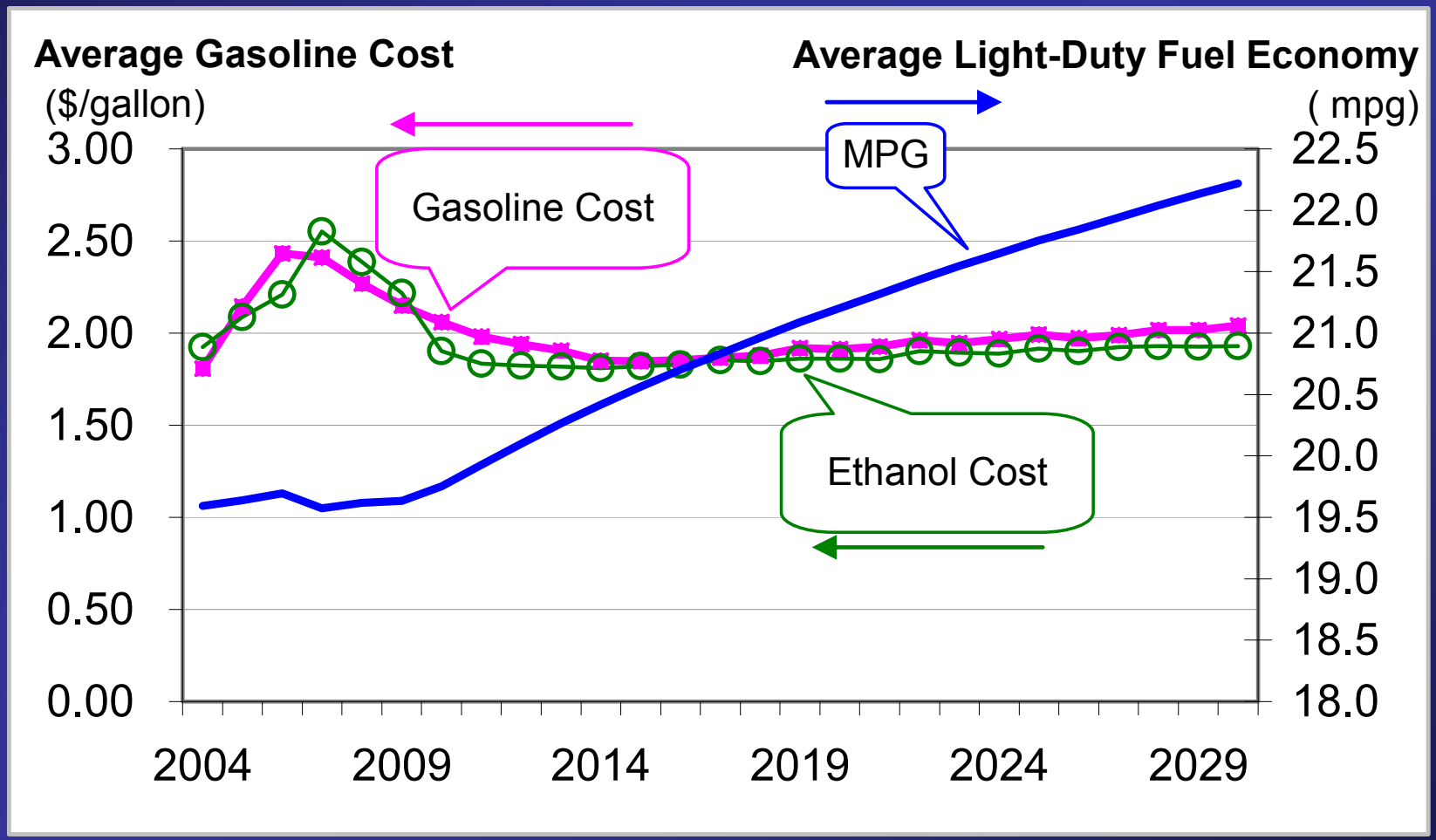
(based on 1,500 kg/day systems in 500 production quantities)

- Assumptions:
  - 68.9% LHV efficiency (vs. 73% for NG)
  - Same capital costs & other assumptions as for natural gas reformer
- Cost of Hydrogen from Ethanol*:
  - H2A model: $4.49/kg
  - H2A with H_2Gen data: $3.98/kg

*H2A assumes ethanol cost at $1.07/gallon

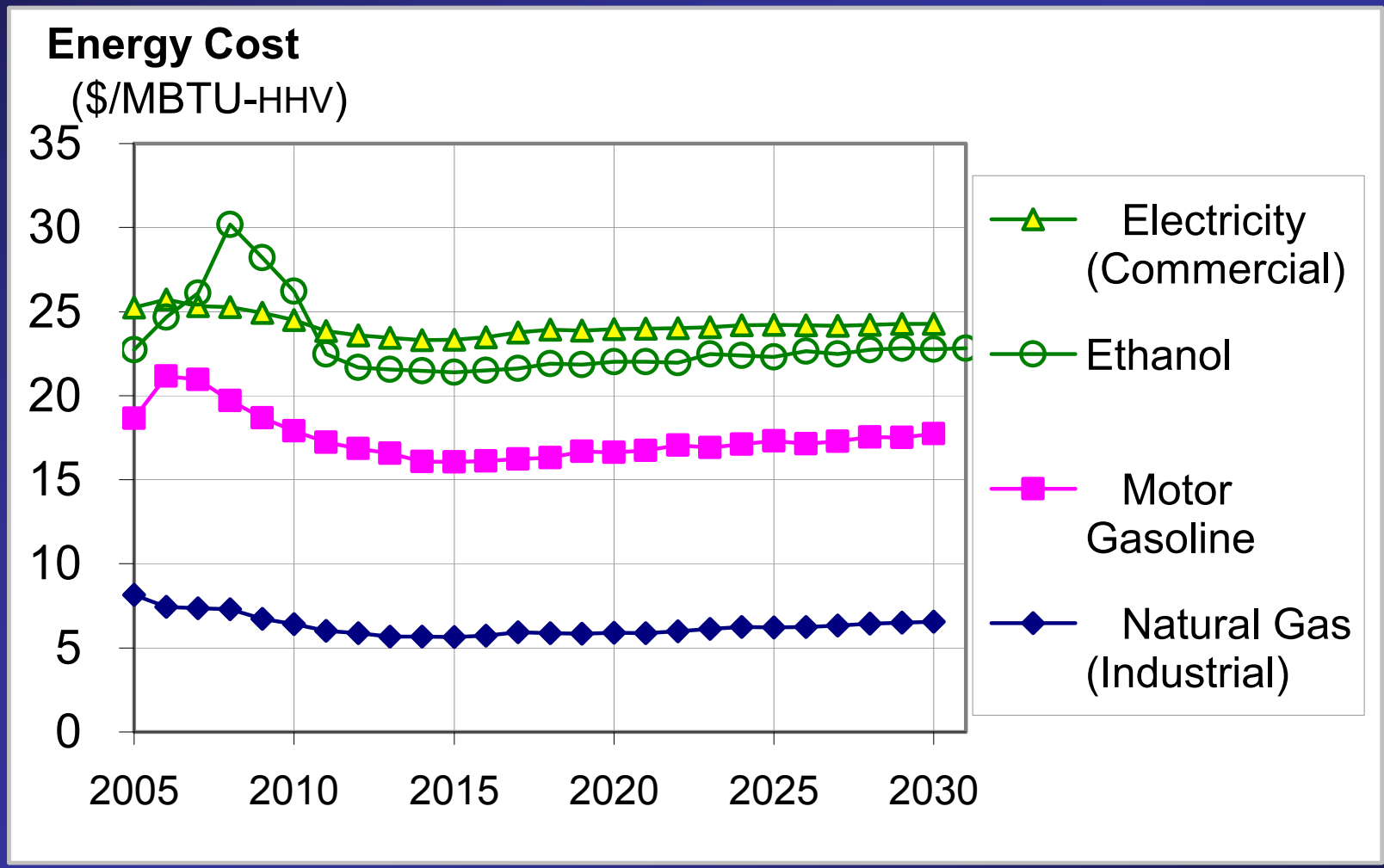
Future Implications of Energy Costs for Transportation

(EIA 2007 Annual Energy Outlook Energy Projections)



H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'Fuel Costs';E106 - 10 / 23 / 2007

2007 AEO Projections in 2005$/MBTU



Reviewer's Comments

Weaknesses

- Requires integration into overall production, compression, and storage system to determine transients, turndown, etc.
  True, but turndown and transients have been measured independently

- Scale up from 113 to 567 was not clearly defined as to risk both on a market penetration basis and reliability of performance. Unclear whether the availability of components is within their current analysis or if a new evaluation will be undertaken since there is limited performance data available.
  Market risk: commercial demand has been identified and is very robust for 567 kg/day reformer
  Reliability of performance: not clear what this means….performance is being measured in the field.
  Availability of components has been demonstrated: first unit has been built and second is under construction.
- Catalyst development strategy does not fit with this project.
  Catalyst development with Süd Chemie is essential for both natural gas cost reduction and ethanol reforming.
- Unclear if it is necessary to pre-reform ethanol.
  Ethanol must be pre-reformed to utilize the existing low-cost SMR technology, and to pre-reform ethanol denaturants
- No safety and code analysis for the installation of the hydrogen generator at the field site.
  Every H_2Gen reformer system has undergone extensive HAZOP safety reviews by industrial gas companies and/or the site operator prior to installation.

Reviewer's Comments

Specific recommendations and additions or deletions to the work scope

- Continue to complete this project to benchmark progress to goals.
  Agreed.
- Add task to track hydrogen quality and its impact on cost of hydrogen.
  Good suggestion.
- Maybe they should focus on their primary objective which is the development of hydrogen generator for distributed production of hydrogen using natural gas as feedstock. Would like to see more of these hydrogen generators built instead of redirecting their effort on reforming ethanol.
  We agree that more hydrogen generators should be built, but DOE funding will not support additional units. Our commercial customers are providing the resources to continue reformer production and use in the industrial gas business.
  No other commercial organization will support the development of ethanol reforming, however. Since hydrogen made from ethanol is the least costly renewable hydrogen option, the DOE is the appropriate sponsor to capture the societal benefits of renewable hydrogen.
- It is a good idea for DOE to fund H2Gen for ethanol reforming.
  Agreed.

Thank You

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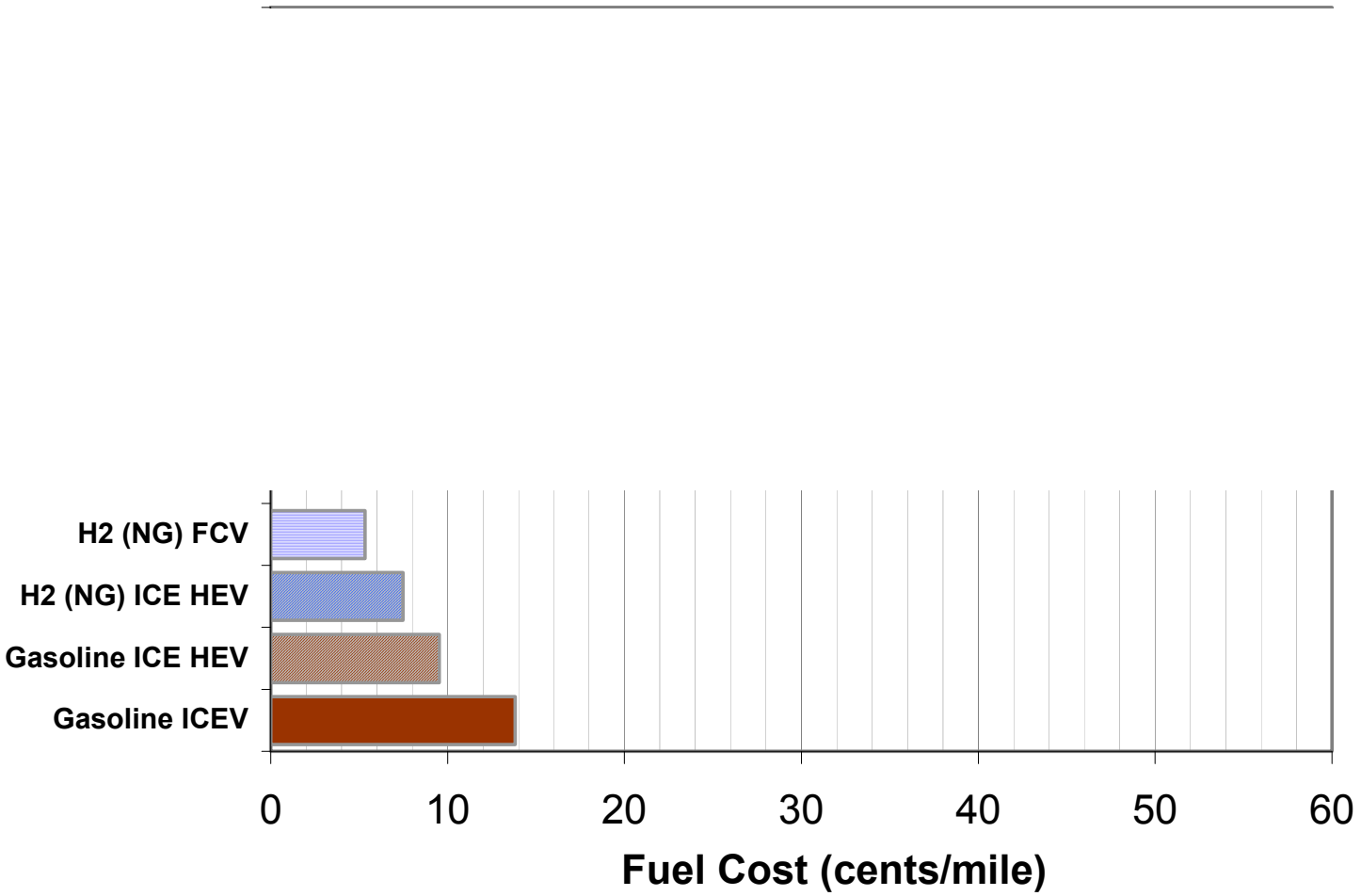
Back-up Slides

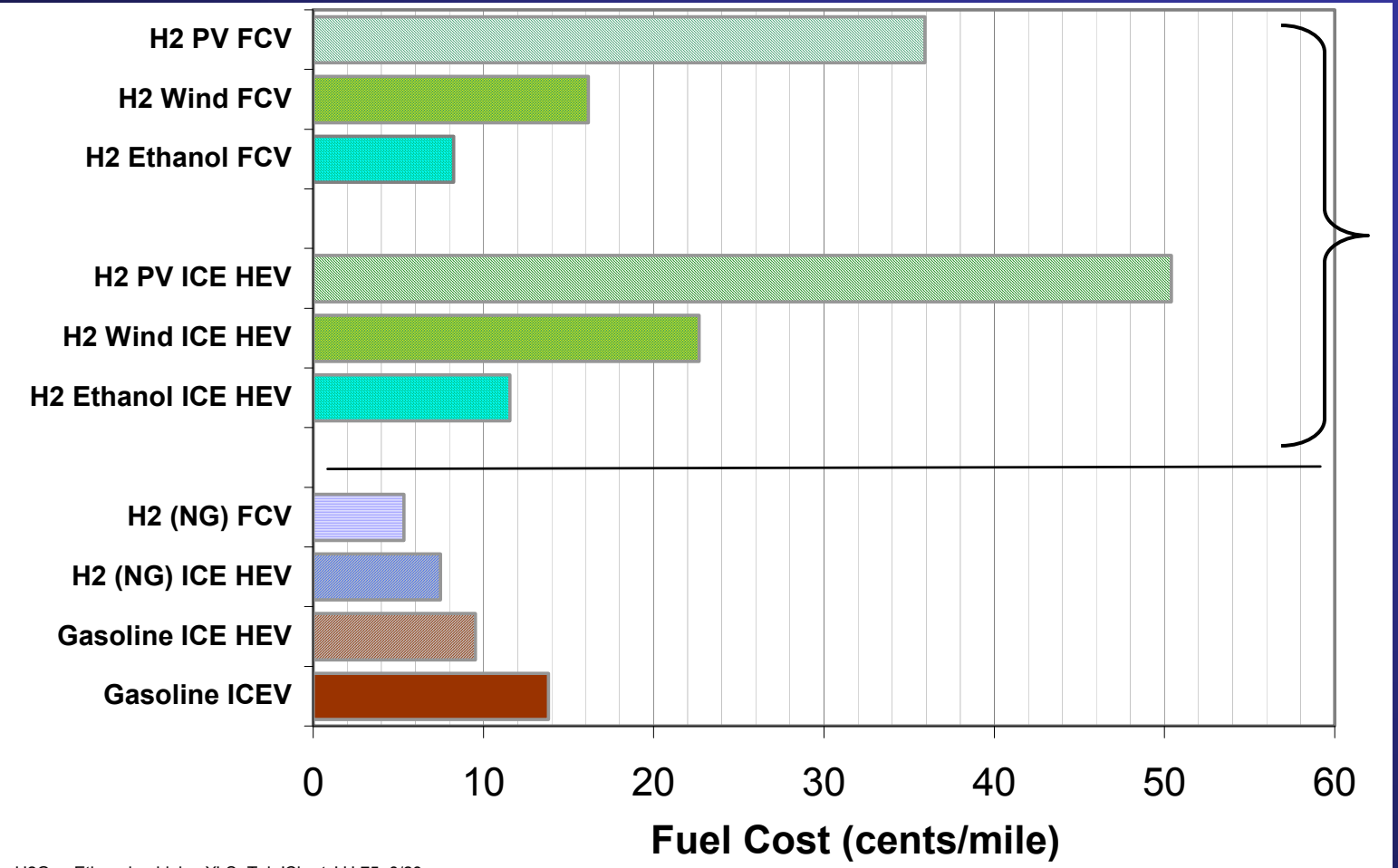
Fuel Costs per Mile



H2Gen:Ethanol vehicles.XLS; Tab 'Charts';H 75 8/28

Assumptions: Gasoline = $2.90/gallon; Ethanol = $1.50/gallon; PV = 20 cents/kWh for 7 hours/day; Wind = 5 cents/kWh for 12 hours/day; Gasoline-HEV fuel economy = 1.45 X ICEV; H2-HEV fuel economy = 1.71 x ICEV; FCV fuel economy = 2.38 X ICEV
[DOE cost parameters: 11% annual capital recovery, 90% capacity factor, NG = $3.97/MBTU (HHV), Electricity= 7 cents/kWh]

Fuel Costs per Mile



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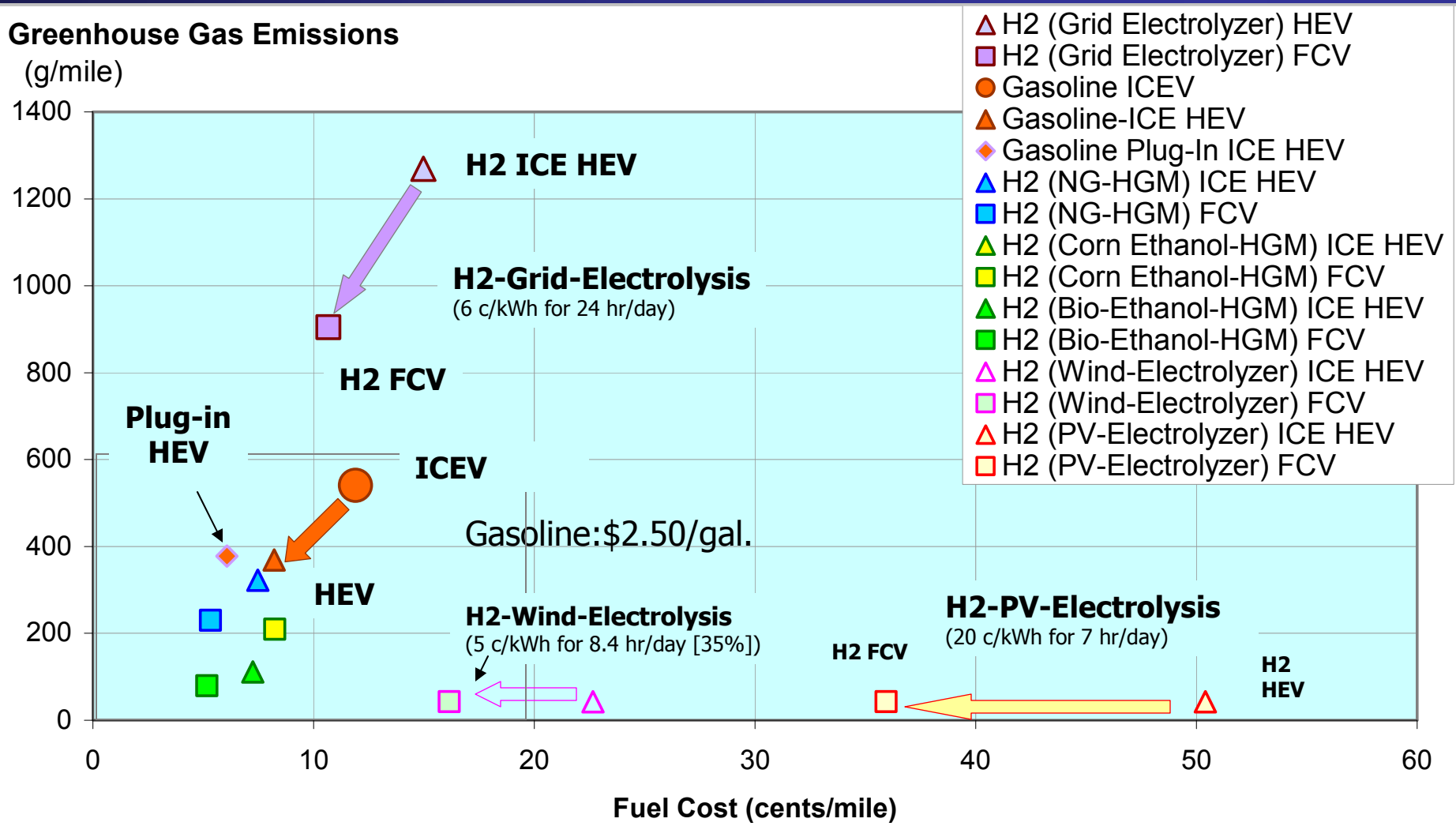
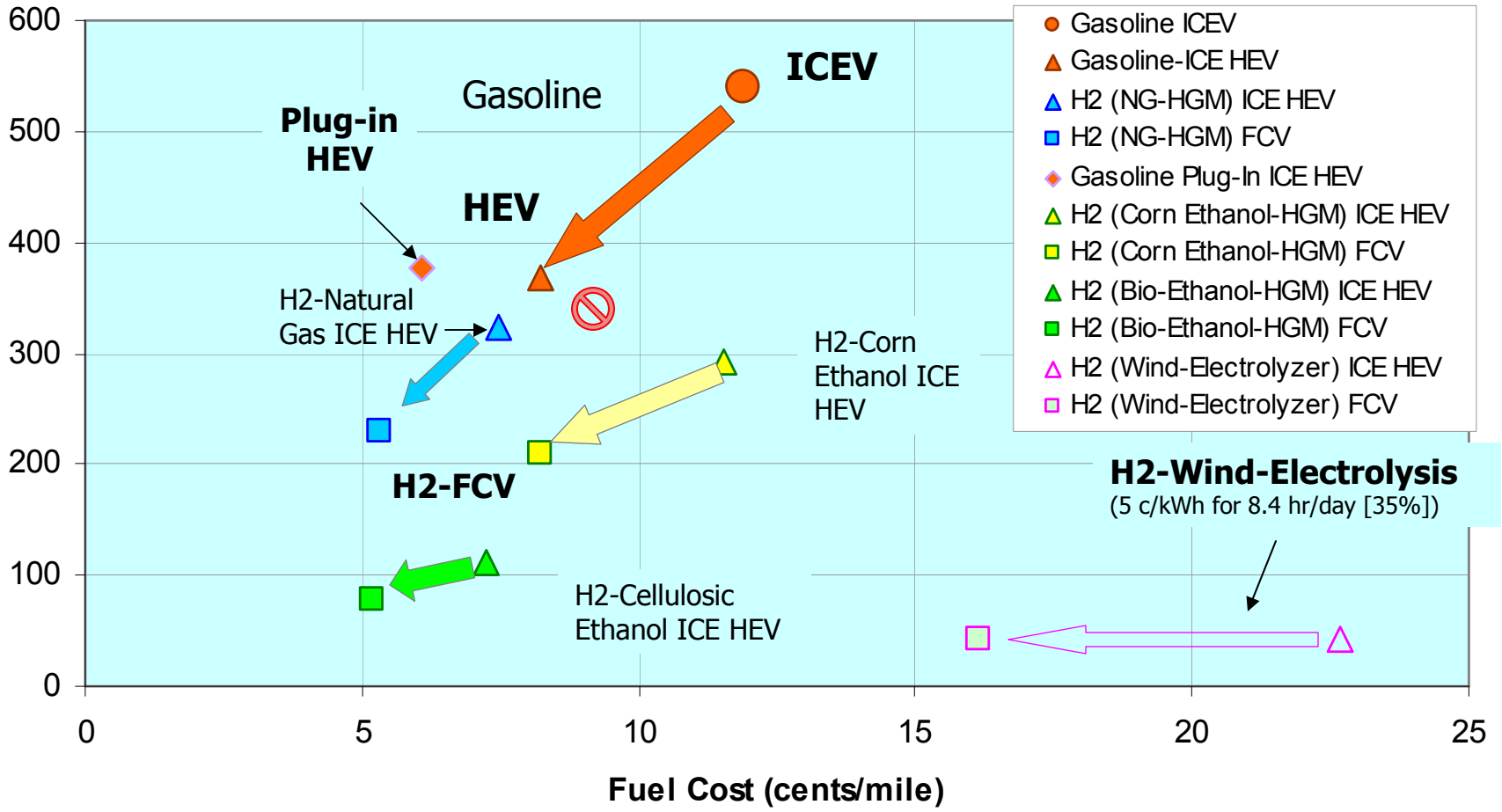
GHGs vs. Fuel Cost



H2 = hydrogen; HEV = hybrid electric vehicle; FCV = fuel cell vehicle; ICEV = internal combustion engine vehicle; PV = photovoltaic (solar cells)
EPRI: Wind = 7.5 cents/kWh by 2010; Wind = 5.2 cents/kWh by 2020 with 29% average capacity factor

GHG vs. Fuel Cost (Scale change)



Electricity = 8 cents/kWh; PHEV electricity 40%

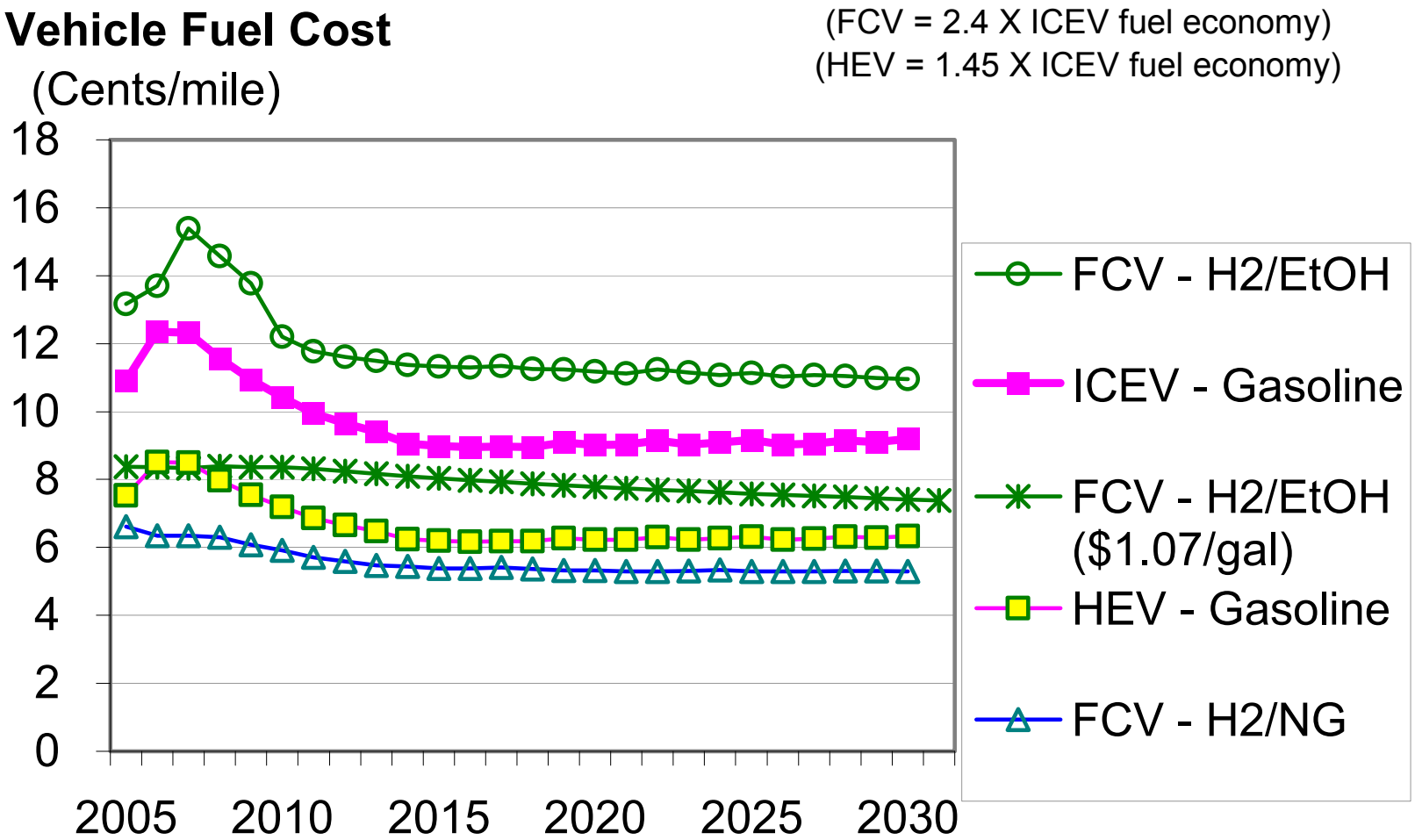
H2Gen:Ethanol vehicles.XLS; Tab 'GHG vs Fuel Cost';AC 51 2/19 /2007

Corn Ethanol = $1.5/gallon Cellulosic Ethanol = $0.75/gallon Natural Gas =$8.98/MBTU Gasoline =$2.5/gallon

Note: these charts are based on the NRC/NAS capital recovery assumptions (16% annual capital recovery & 90% capacity factor)

Vehicle Costs per Mile

(Constant 2005$)



H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'Fuel Costs';Q108 - 10 / 24 / 2007