Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles

Final Report

Phase II Final Deliverable to DOE

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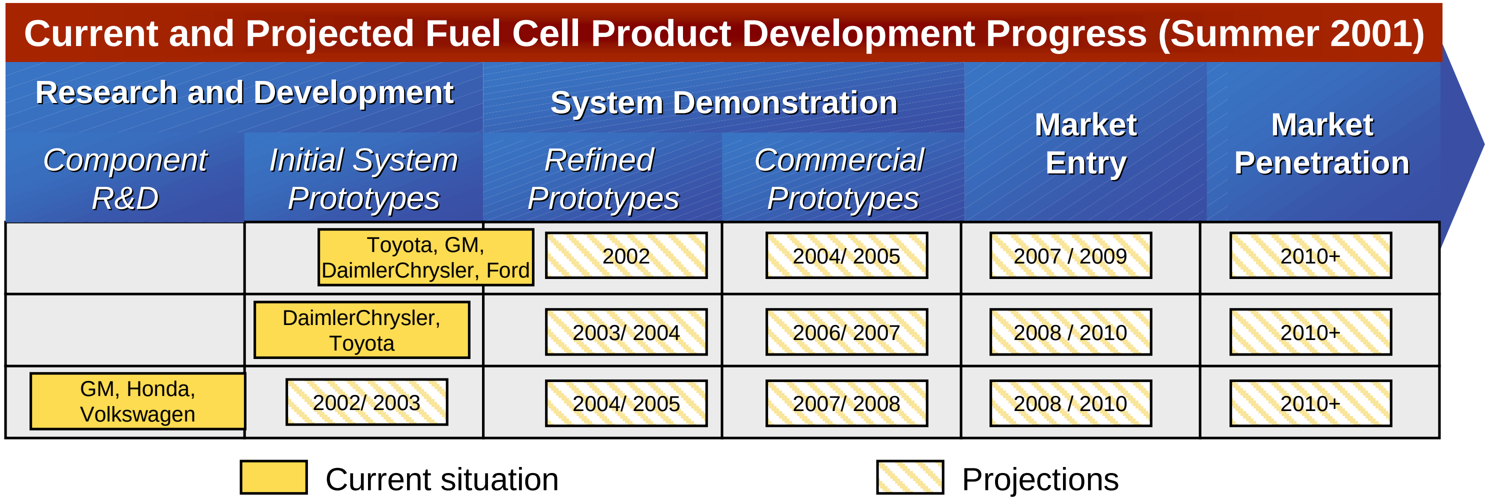
DOE has commissioned this study to support target setting and progress monitoring for its direct hydrogen fuel cell vehicle program.

- DOE Office of Transportation Technologies (OTT) supports proton exchange membrane fuel cells (PEMFCs) for transportation applications:
  - Focus since 1992 on on-board reforming of gasoline and other fuels
  - DOE/OTT is currently developing a direct hydrogen Fuel Cell Vehicle (FCV) program in coordination with DOE's Hydrogen Program
- DOE has commissioned this study to help set targets for its direct hydrogen program:
  - Targets are being set by comparison of direct hydrogen FCVs with alternative fuel and powertrain options
  - Consider energy efficiency, greenhouse gas emissions, cost, and safety
  - Include methanol, ethanol, diesel, and gasoline fuels but focus on hydrogen
  - Include internal combustion engine vehicles and battery electric vehicles for comparison

We focused our analysis on the timeframe around which fuel cells are now projected to become ready for mass-market introduction: 2010 and beyond.

- Current FCV technology is still in the initial prototype stage, so a projection of future FCV performance and cost had to be made
- Technology projections beyond 2010 would have little bearing on current experience and would be unacceptably speculative for this purpose of this project
- A scenario for the year 2010 was developed for comparison purposes
- Our 2010 projections are consistent with the goal setting objective of this project, but many different scenarios are possible in the future



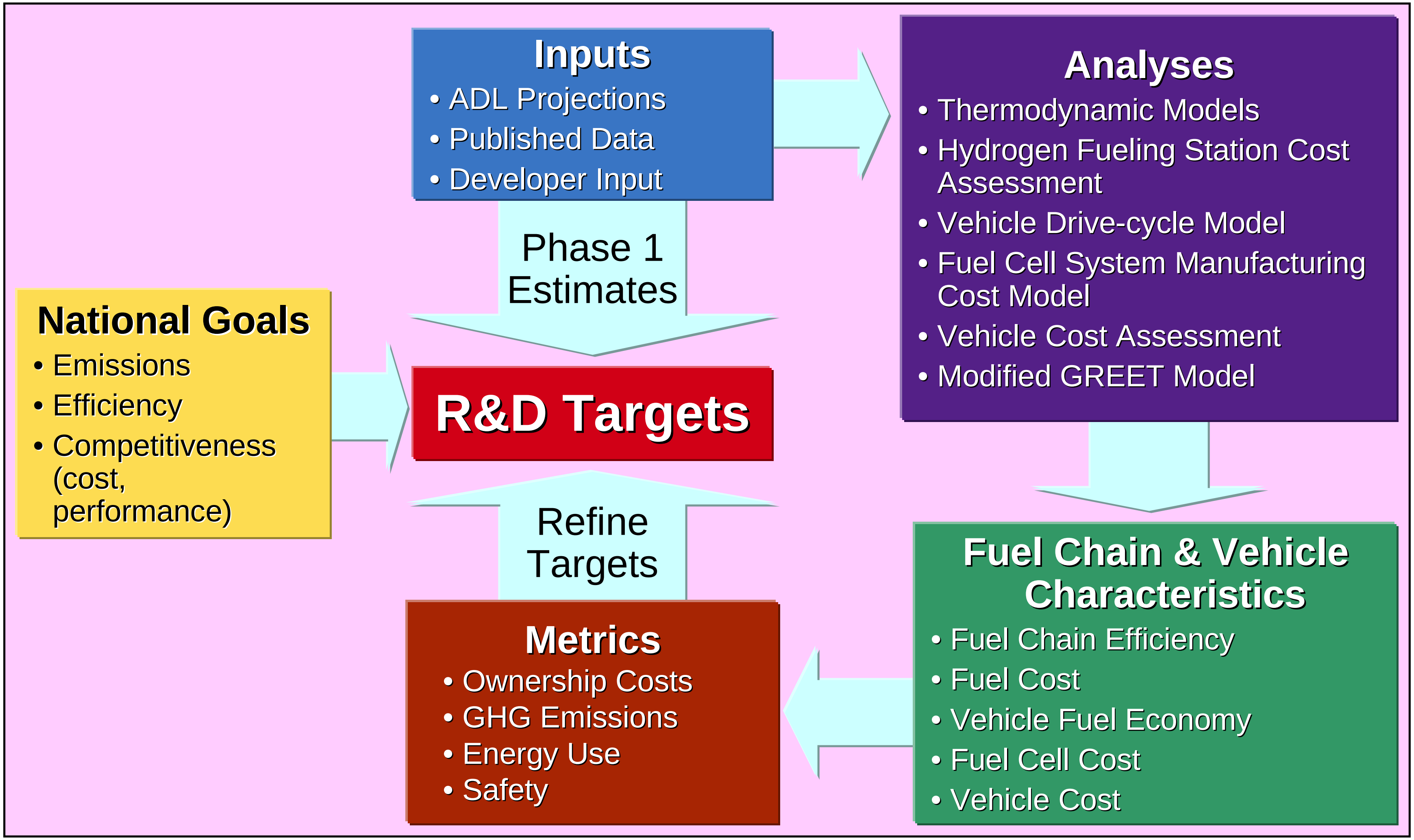
Current and Projected Fuel Cell Product Development Progress (Summer 2001)

	Research and Development		**System Demonstration**		**Market Entry**	**Market Penetration**
	Component R&D	*Initial System Prototypes*	*Refined Prototypes*	*Commercial Prototypes*		
Hydrogen		Toyota, GM, DaimlerChrysler, Ford	2002	2004/ 2005	2007 / 2009	2010+
Methanol		DaimlerChrysler, Toyota	2003/ 2004	2006/ 2007	2008 / 2010	2010+
Gasoline	GM, Honda, Volkswagen	2002/ 2003	2004/ 2005	2007/ 2008	2008 / 2010	2010+

🟨 Current situation ▨ Projections

* Based on public industry announcements and ADL projections, all projections are predicated on a reasonable measure or technical success.

Combining a variety of inputs through thorough analyses, we are able to develop meaningful and defensible guidelines for R&D targets.



Inputs
- ADL Projections
- Published Data
- Developer Input

Analyses
- Thermodynamic Models
- Hydrogen Fueling Station Cost Assessment
- Vehicle Drive-cycle Model
- Fuel Cell System Manufacturing Cost Model
- Vehicle Cost Assessment
- Modified GREET Model

Phase 1 Estimates

National Goals
- Emissions
- Efficiency
- Competitiveness (cost, performance)

R&D Targets

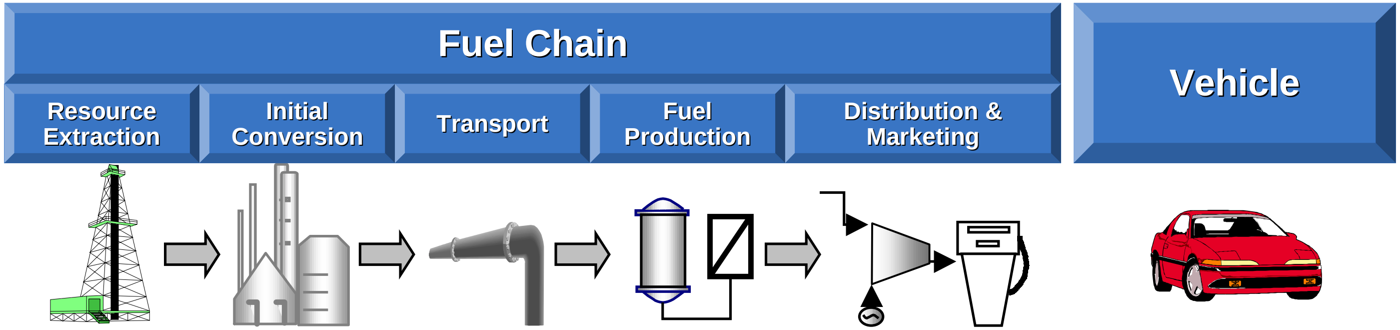
Refine Targets

Metrics
- Ownership Costs
- GHG Emissions
- Energy Use
- Safety

Fuel Chain & Vehicle Characteristics
- Fuel Chain Efficiency
- Fuel Cost
- Vehicle Fuel Economy
- Fuel Cell Cost
- Vehicle Cost

Approach Fuel Chain / Vehicle Separation

We separated the well-to-tank analysis from the tank-to-wheel analysis to allow for easy comparisons with conventional technology.



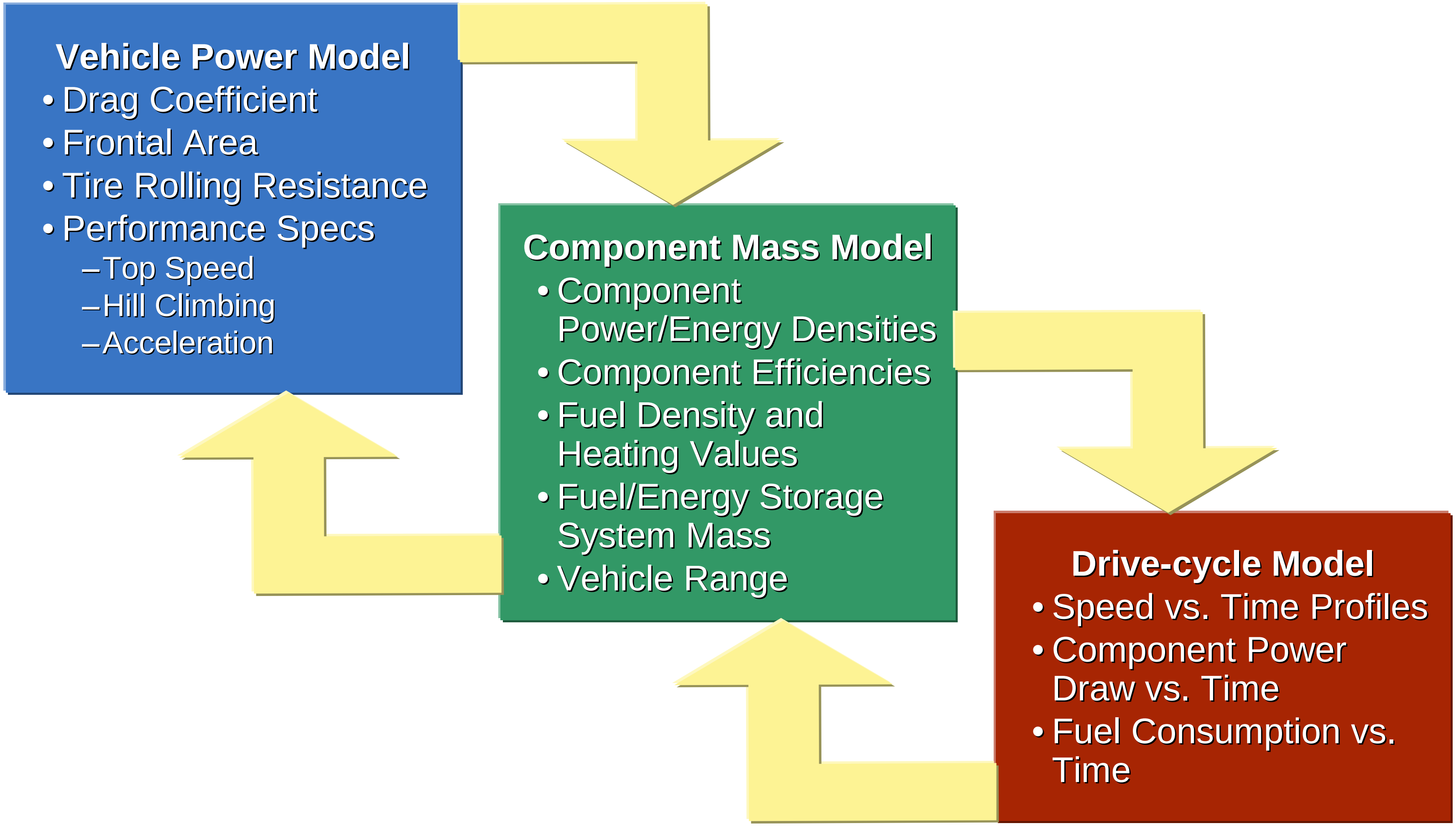
Energy Efficiency	% or MJ primary energy input / MJ fuel delivered	$\text{mpg}_{\text{gasoline equivalent}}$
	$\text{MJ}_{\text{primary energy input}}/\text{mile}_{\text{driven}}$	
Greenhouse Gas Emissions	$\text{g}_{\text{GHG fuel chain}}$ / GJ fuel delivered	$\text{g}_{\text{GHG tailpipe}}/\text{mile}_{\text{driven}}$
	$\text{g}_{\text{GHG total}}/\text{mile}_{\text{driven}}$	
Cost	$/GJ, or $/gallon gasoline equivalent	$/kW $/vehicle
	$/year	

The hydrogen fuel chain analysis builds on a recent project for DOE's Hydrogen Program, where we have analyzed the cost and performance of local hydrogen fueling stations in detail.

- We included the three most relevant on-site production methods from an on-going study for DOE's Hydrogen Program (DE-FC36-00GO10604):
    - Steam reforming natural gas, PSA purification, and compressed hydrogen storage[1]
    - Electrolysis with compressed hydrogen storage[1]
    - Central production & distribution options were added in addition
- Original analysis was needed to update the performance and cost estimates for hydrogen fuel chains
    - Detailed thermodynamic analysis of on-site hydrogen production
    - Detailed design considerations for hydrogen storage & dispensing
    - Cost analysis based on vendor quotes, publications, and bottom-up analysis
    - Consistent (but not necessarily identical) assumptions for central hydrogen production facilities and on-site production
    - Consistent transport and distribution assumptions for hydrogen and other fuels
- The cost estimates are based on high production volumes (100 units/yr) to meet the mature market demand of direct hydrogen FCVs

[1] High pressure on-site storage at 3600 psi with on-site boost compressors to achieve 5000 psi for cH_2 vehicles. Low pressure on-site storage at 100 psi for metal hydride vehicles.

We used a simple vehicle drive-cycle simulation model to estimate fuel economy and power requirements for each powertrain.



Vehicle Power Model
- Drag Coefficient
- Frontal Area
- Tire Rolling Resistance
- Performance Specs
  - Top Speed
  - Hill Climbing
  - Acceleration

Component Mass Model
- Component Power/Energy Densities
- Component Efficiencies
- Fuel Density and Heating Values
- Fuel/Energy Storage System Mass
- Vehicle Range

Drive-cycle Model
- Speed vs. Time Profiles
- Component Power Draw vs. Time
- Fuel Consumption vs. Time

Our FCV power unit analysis builds on ongoing ADL/DOE analysis of automotive fuel cell systems.

- In an ongoing program for DOE (DE-SCO2-98EE50526), ADL has developed a detailed cost and performance model for an on-board ATR FCV power unit
  - Model developed in conjunction with ANL, with feedback from OTT and PNGV
  - Assumes high production volumes but uses near-term performance inputs
- We have modified the model to estimate component costs and weights for scenarios of future performance
  - ADL, “Cost Analysis of Fuel Cell System for Transportation – Pathways to Low Cost”, 2001 Final Report, prepared for DOE, to be published in 2002
  - High temperature membranes, increased power density, and improvements in fuel processor catalysts and other materials
  - These assumptions reflect a best-case scenario of success in current R&D activities, but do not project future technology leaps
- We have also developed future performance scenarios for for methanol, ethanol, and direct hydrogen vehicles
  - Based on in-house kinetic and thermodynamic calculations
- The model cost estimates are based on high production volumes (500,000 units/yr) that will not likely be possible in the 2010 timeframe

The glider, powertrain, precious metals, maintenance and fuel costs were evaluated to determine the overall vehicle ownership costs.

Cost Categories		ICEV	HEV	FCV
Glider		Mid-sized and SUV	Mid-sized and SUV	Mid-sized and SUV
Powertrain	**Power Unit**	Engine Cooling System	Engine Cooling System	Fuel Cell Module Fuel Processor Cooling System
	Transmission/ Controls/ Accessories	Exhaust/Evap System Transmission Starter Motor, Alternator Accessories (power steering, AC, etc.)	Exhaust/Evap System Transmission Motor Power Electronics Electronics Radiator Accessories	Exhaust/Evap System Motor/Transmission Power Electronics Electronics Radiator Accessories
	Energy Storage	Fuel Fuel Tank Startup Battery	Fuel Fuel Tank Traction Battery Battery Radiator	Fuel Fuel Tank Traction Battery Battery Radiator
Precious Metals[1]		Catalytic Converter[2] (Pt/Pd)	Catalytic Converter (Pt/Pd)	Fuel Cell (Pt, Ru) Fuel Processor (Pt, Rh) Catalytic Converter[2] (Pt/Pd)
Maintenance		Brakes, Oil change, Inspections, Tires, etc.	Assumed same overall cost as ICEV[3]	Assumed same overall cost as ICEV[3]
Fuel		RFG, Diesel, cH_2	RFG, Diesel	RFG, MeOH, E100, cH_2

[1] Actually part of the powertrain (fuel cell module or exhaust), but broken out separately for illustrative purposes. Precious metals in FCVs contribute significantly to vehicle cost and will have different salvage value.

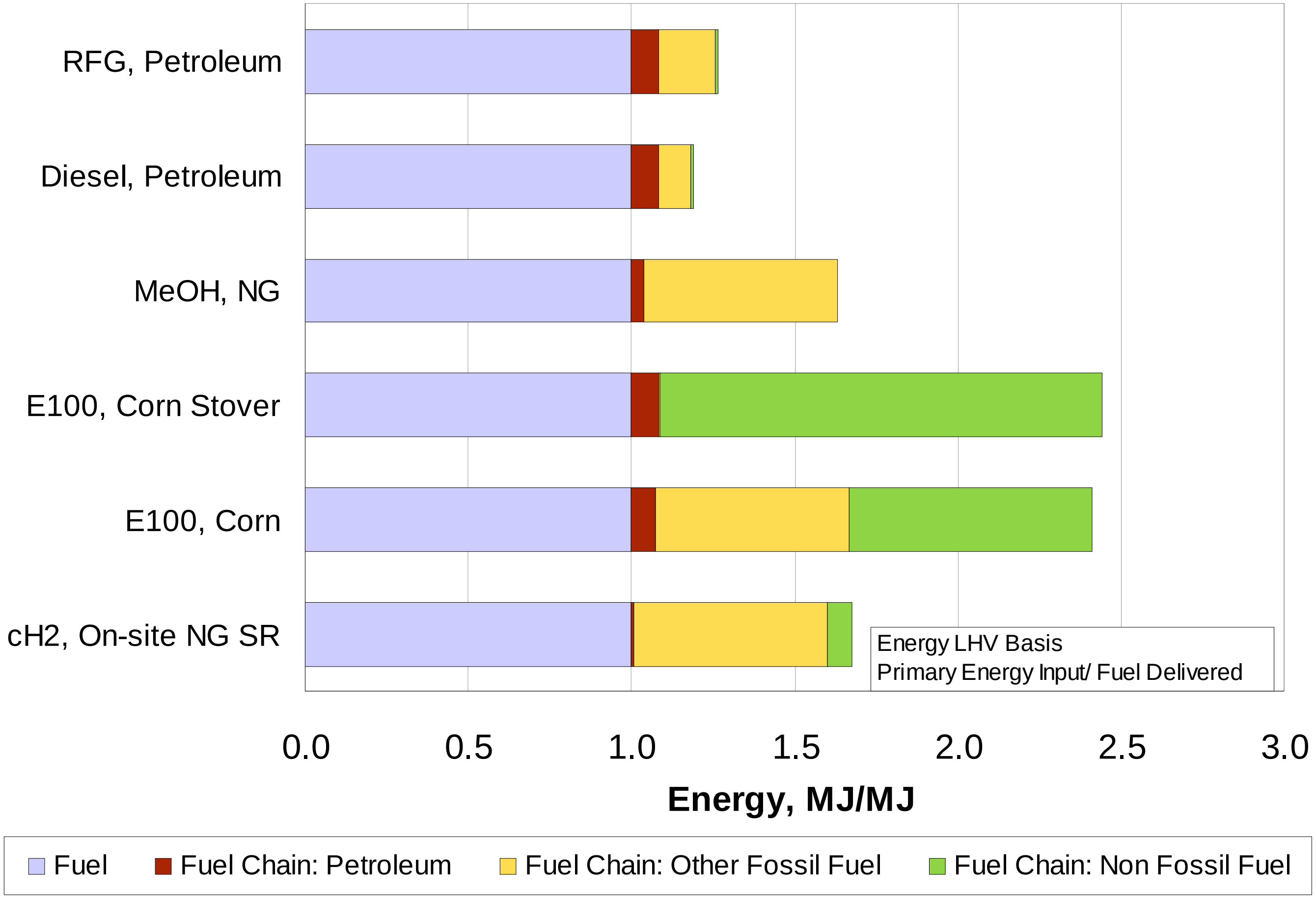
[2] We assume hydrogen vehicles do not require a catalytic converter.

[3] The underlying assumption is that for a mature market, the stack and fuel processor life will have been improved to last for the life of the vehicle.

None of the alternative fuels can be delivered with greater primary energy conversion efficiency than conventional fuels.

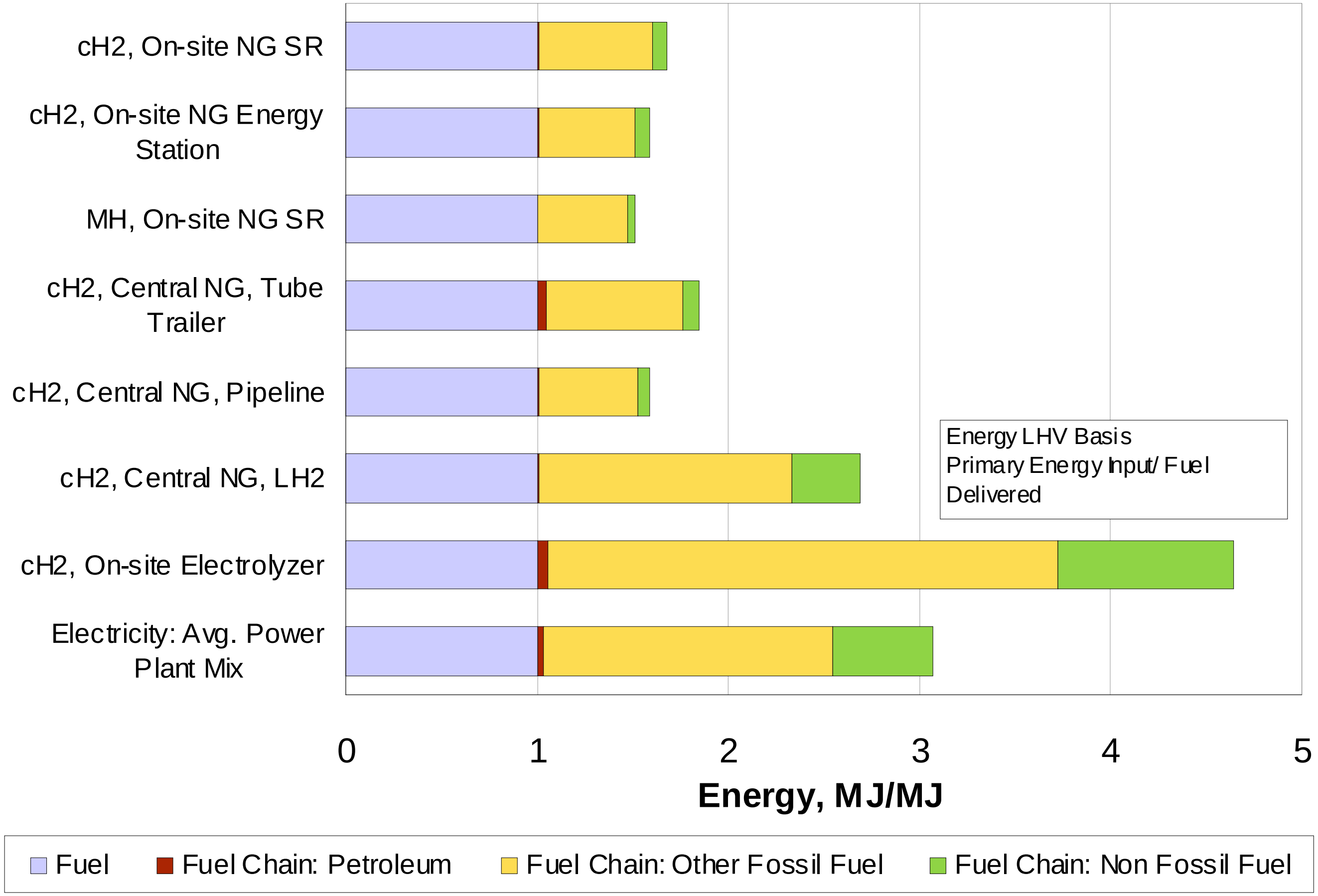
- ◆ The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel
  - ➤ Oil refineries provide unparalleled primary fuel conversion efficiencies of ~85%
  - ➤ Syngas production from natural gas (as needed in the production of hydrogen and methanol) imposes an additional penalty of roughly 15% on these fuel chains
  - ➤ Extensive use of electric power penalizes energy efficiency even more significantly, making electrolysis chains over 3 times more energy intensive than hydrogen from on-site NG reformers, and almost 4 times more than gasoline
- ◆ Biomass-based conversion chains (ethanol) have fuel chain efficiencies below 50%, though much of this primary energy may be renewable
- ◆ Due to their high energy density, the primary energy use for transport and distribution of conventional fuels is the lowest
  - ➤ Transport and distribution comprise less than 5% of energy use for petroleum fuels
  - ➤ Alcohol fuels have roughly half the energy density of hydrocarbon fuels, and hence transportation energy use is roughly double that of conventional fuels
  - ➤ Energy use for the compression, liquefaction, or hydrate formation associated with hydrogen transport & vehicle storage adds 10-30% to primary energy use

The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel



* Net E100 energy use include byproduct credits, as do petroleum products.

Steam reforming-based hydrogen production provides the most efficient options for hydrogen generation, especially in a co-generation context;...



* Electrolyzer energy consumption assumes a US average mix of grid power.

... liquid hydrogen and electrolysis options use far more energy.

Differences in primary energy efficiency explain the differences in greenhouse gas impact between most fuel chains.

- Natural-gas-based fuel chains benefit from low carbon content of natural gas, but not enough to outweigh lower efficiency
  - Natural gas has an energy-based carbon content around 20% lower than that of petroleum
  - However, energy conversion and fuel transport and distribution efficiency for natural gas-based fuels are more than 25% lower than those of petroleum fuels
- As expected, renewables-based fuel chains offer by far the lowest fuel chain-related greenhouse gas emissions
  - Biomass-based ethanol allows reduction of greenhouse gas impact by around 90%
  - Production of hydrogen via electrolysis from renewable or nuclear power virtually eliminates greenhouse gas emissions
    - However, additional hydro and nuclear power capacity would be required
    - "Green" power contracts would have to be made to assure only renewable or nuclear power was being used for hydrogen production
  - For all renewable chains, GHG emissions are low, despite low energy efficiency, because they use non-carbon or short-cycle carbon feedstocks

Note: Results not presented here (see Main Report).

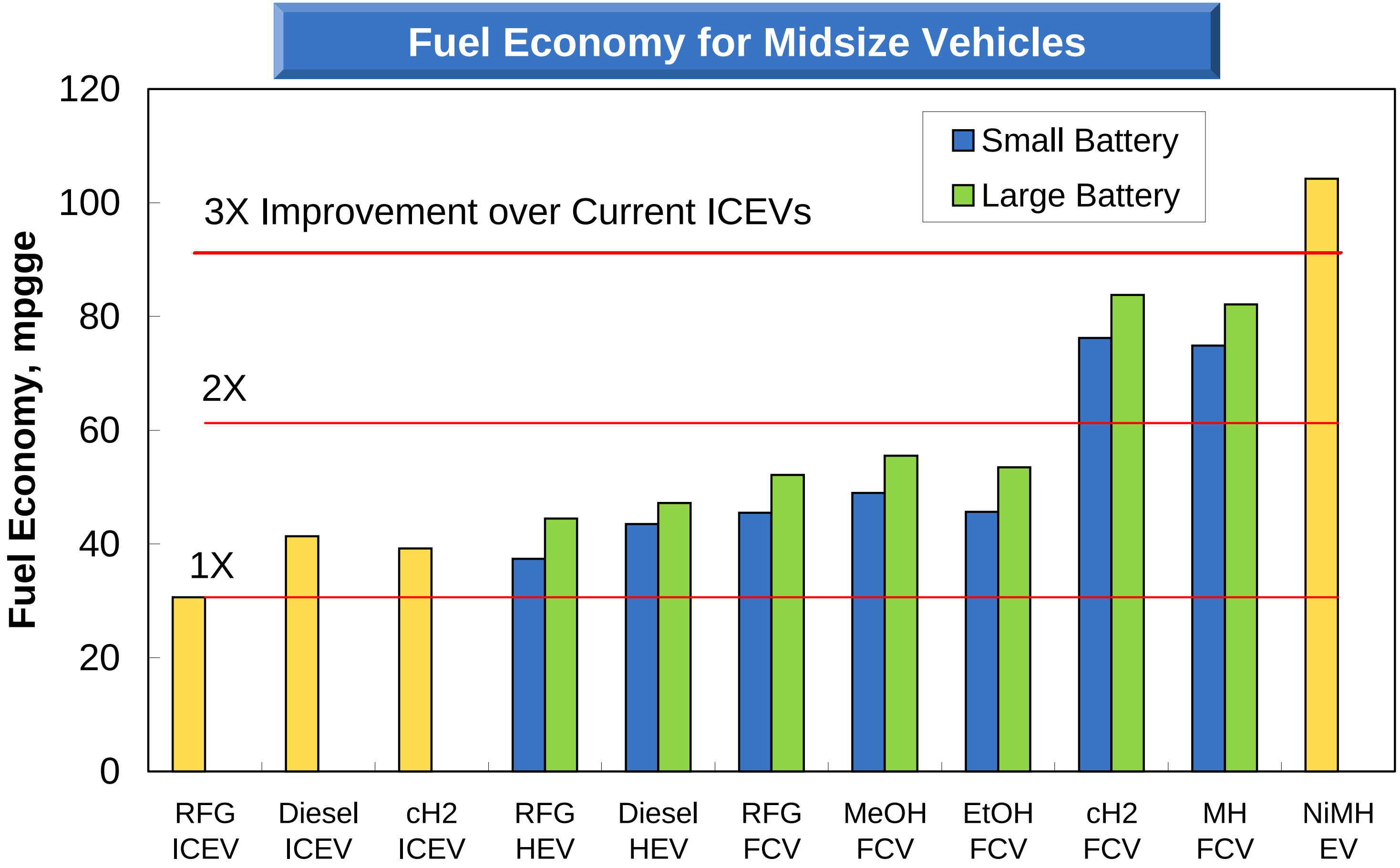
Projected future scenarios lead to direct hydrogen FCVs that are technically competitive with conventional and other advanced vehicles.

- High efficiency for direct hydrogen FCVs is due to high continuous power efficiency and excellent turn-down performance
  - Reformer based FCVs have much lower part load efficiencies, but still higher than ICEVs
- Direct hydrogen FCVs could provide performance benefits over other advanced vehicle options (ICE HEVs)
  - Lower weight
  - Good low-end torque performance (electric drive)
  - Almost three times better fuel economy
- Reformate-based FCVs are more compatible with conventional fuels and could provide performance benefits over conventional vehicles (ICEVs)
  - Good low-end torque performance (electric drive)
  - Efficiency on par with hybrid electric powertrains
  - Projected efficiency could be much higher if reformer start-up and turn-down issues were solved
- The future scenarios have aggressive performance assumptions requiring success in current fuel cell system R&D activities

Our analysis was based on future FCV scenarios in which fuel cell technology is improved consistently with success in current R&D activities.

- An ADL/DOE analysis of a near-term technology automotive fuel cell system was used as a baseline for the projected future scenarios
  - Detailed bottom-up cost and full-load performance estimates for fuel flexible ATR FCV power unit developed for DOE Costing Program (DE-SC02-98EE50526)
- Future scenarios assume current R&D efforts are successful:
  - High-temperature, humidity-independent membranes with nafion-like conductivity are developed and the system design takes full advantage of the benefits
  - Stack platinum loading is reduced to an optimum level with high current density
  - ATR space velocities are substantially increased, improving the power density of the fuel processor
  - Fuel cell engineering is optimized, and inefficiencies are reduced or eliminated
- Key performance improvements result, in addition to cost reductions described in the next chapter:
  - Reduced weight
  - Improved system efficiency
  - Faster start-up
- The direct hydrogen FCV powertrain was not re-optimized to achieve efficiency similar to the other vehicle options; this could further reduce its weight and cost

Under the future scenarios, the direct hydrogen FCV gives more than 2.5 times better fuel economy than the conventional gasoline ICE vehicle.

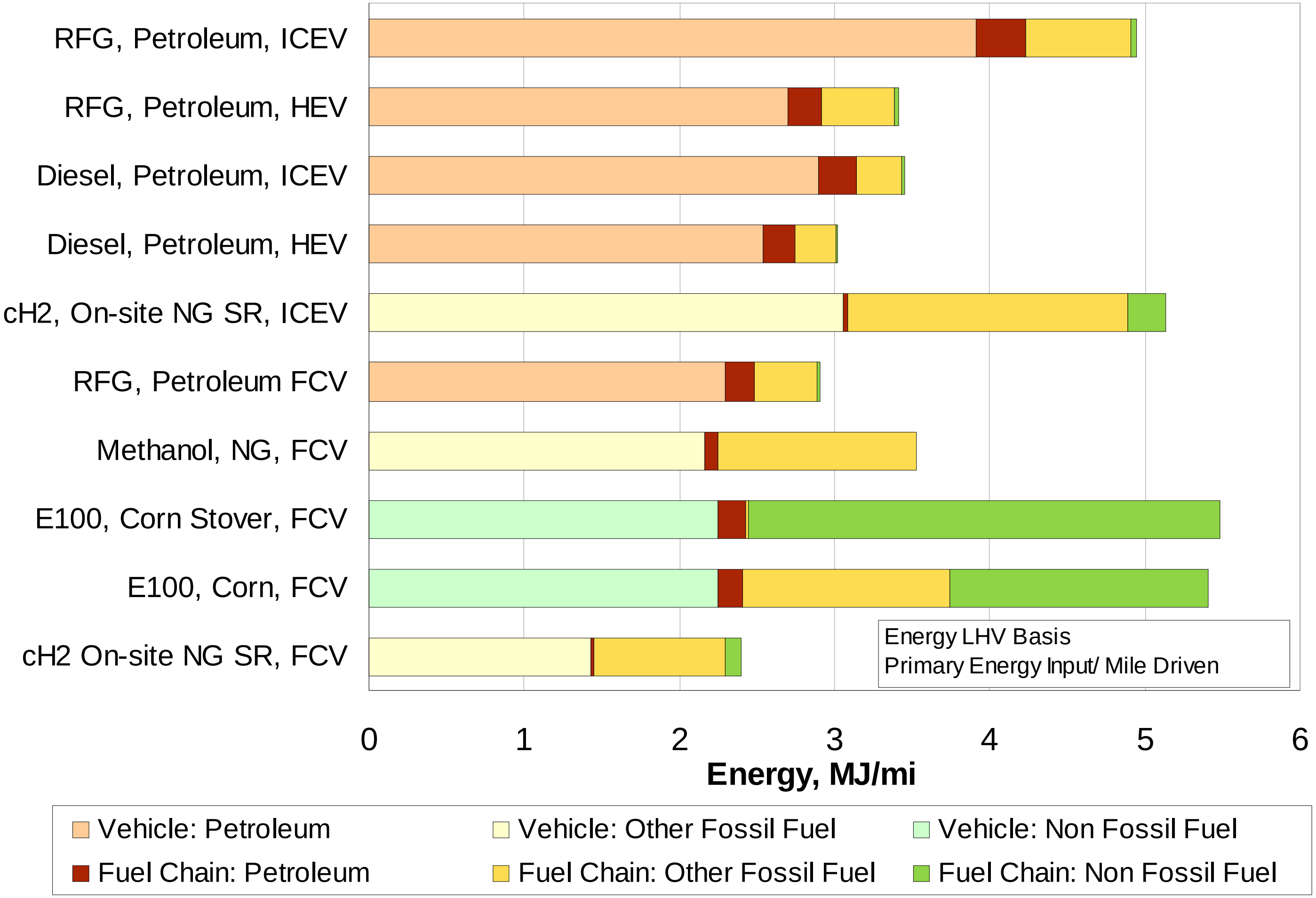


The large battery cases give better fuel economy, due to greater regenerative braking, so we used it for the subsequent well-to-wheel analysis.

Fuel cell powertrains can achieve substantially lower well-to-wheels energy consumption than ICE-based powertrains.

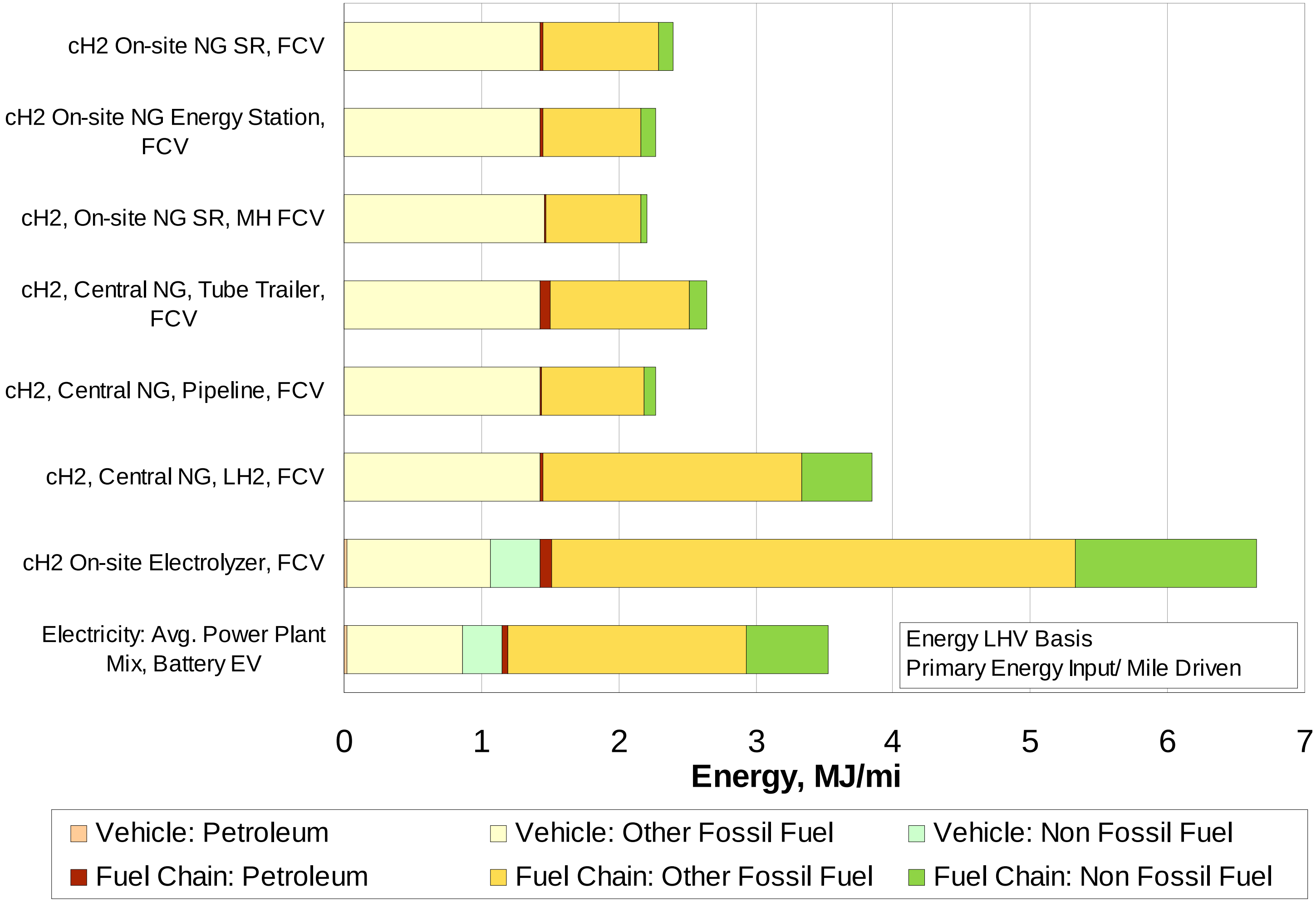
- Advanced CIDI engine vehicles using petroleum-based diesel fuel will likely be able to achieve similar energy efficiency to gasoline reformer-based FCVs
  - Methanol FCVs have higher well-to-wheels energy consumption, despite high vehicle efficiency, due to significant losses incurred in fuel production
- The inefficiency of ethanol production leads to well-to-wheel primary energy consumption for ethanol FCVs slightly above that of conventional vehicles
  - Primary fossil fuel consumption is of course strongly reduced
- Compressed hydrogen FCV options via centralized or decentralized production from natural gas can provide the most fuel efficient options:
  - Provided hydrogen production facilities are thermally well-integrated
  - Provided high vehicle fuel economy can be attained
  - If transportation distances from the central plant are modest (50 miles or less) using pipeline or tube trailers
- Hydrogen via electrolysis and battery EV options have high well-to-wheels energy consumption due to the relative inefficiency of power generation

On a well-to-wheels basis, direct hydrogen FCVs may reduce energy consumption by more than 50% over gasoline ICEVs...



... and gasoline reformer FCVs offer a 40% reduction.

Hydrogen via electrolysis and battery EV options have high energy consumption due to the relative inefficiency of power generation.

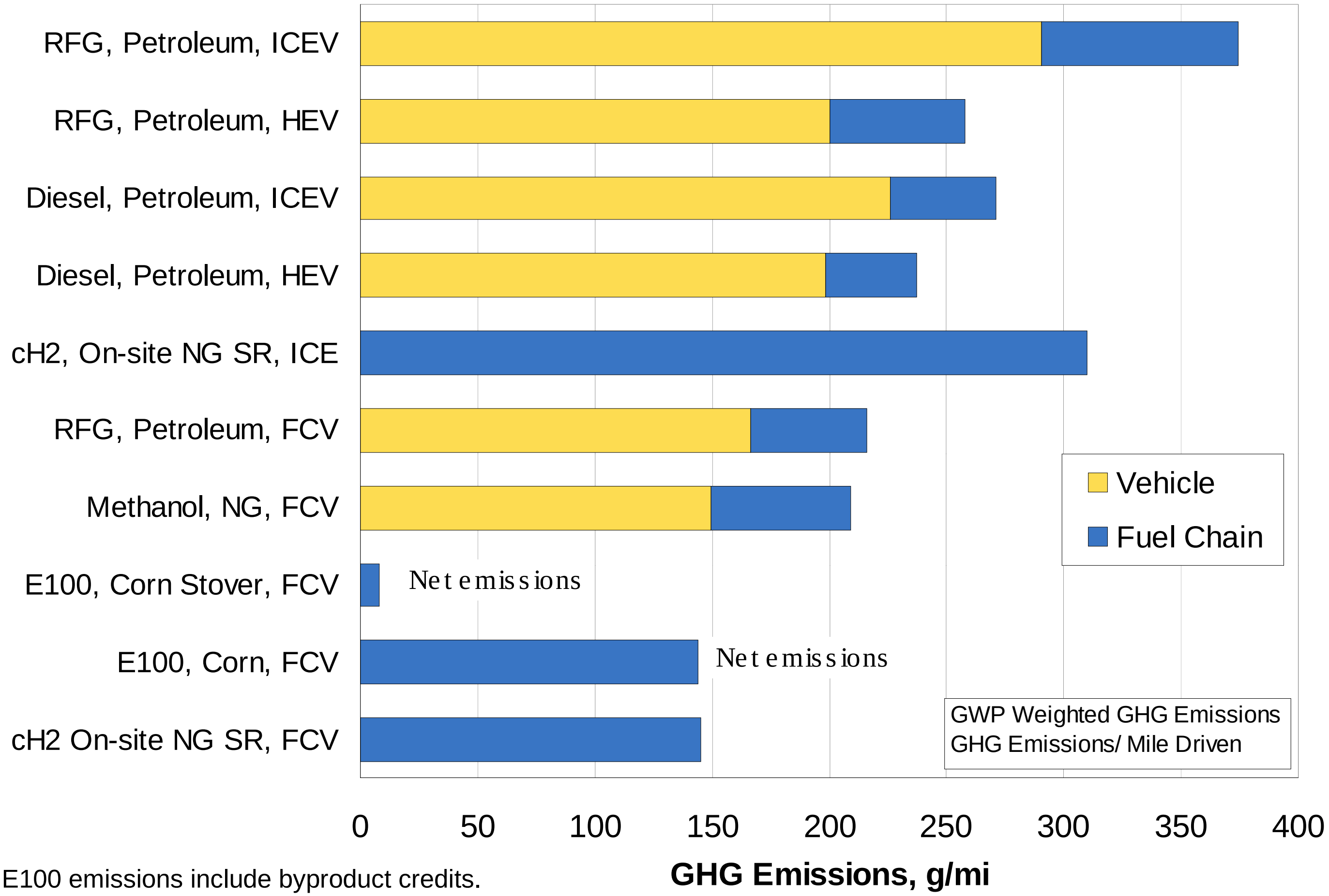


* Electrolyzer energy consumption assumes a US average mix of grid power.

Hydrogen-fueled FCVs are likely to provide the lowest greenhouse gas emissions of the non-renewable fuel chain options.

- Direct hydrogen FCVs can cut greenhouse gas emissions by 60% compared with conventional gasoline-fuel ICEVs
    - Integrated fuel production from natural gas (low-carbon fuel) leads to modest fuel production emissions
    - Vehicle greenhouse gas emissions are zero
    - Advanced diesel CIDI vehicles can achieve about half of this emissions reduction
- Gasoline and methanol FCVs have higher greenhouse gas emissions than most direct hydrogen fuel chains but lower than all ICE-based fuel chains
- In other studies, we found that greenhouse gas emissions could be reduced by over eighty percent if the right renewable energy sources are applied:
    - Hydrogen from electrolysis using wind, solar, or biomass power
    - Bio-ethanol from advanced cellulosic processes

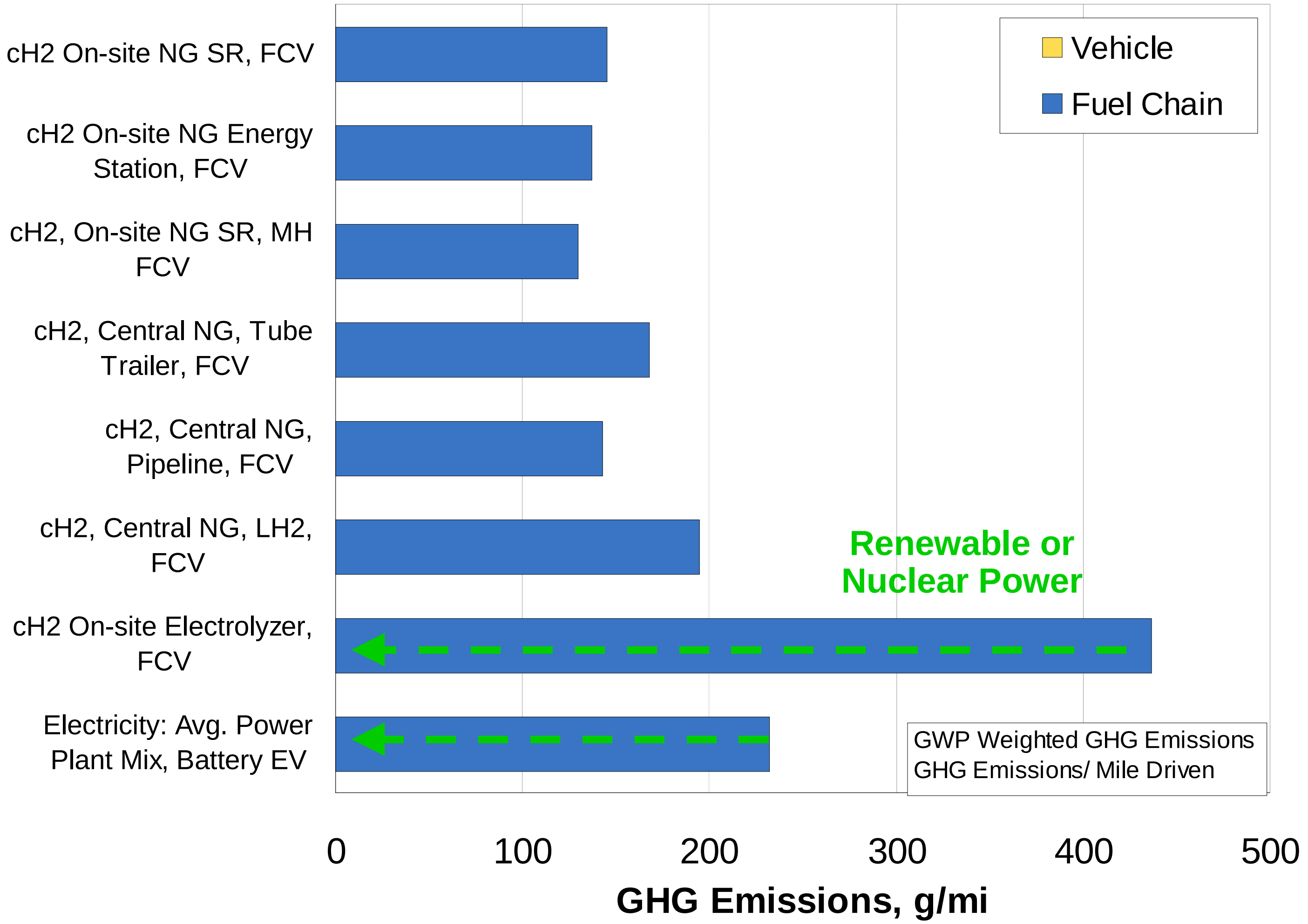
On a well-to-wheels basis, natural gas based direct hydrogen FCVs could reduce greenhouse gas emissions by 60% compared with gasoline ICEVs...



* Net E100 emissions include byproduct credits.

... comparable to current ethanol technology but still far higher than advanced (cellulosic) ethanol technology options.

The lowest GHG emissions can be achieved by direct hydrogen vehicles using hydrogen made from renewable or nuclear power...



… even considerably lower than renewable ethanol.

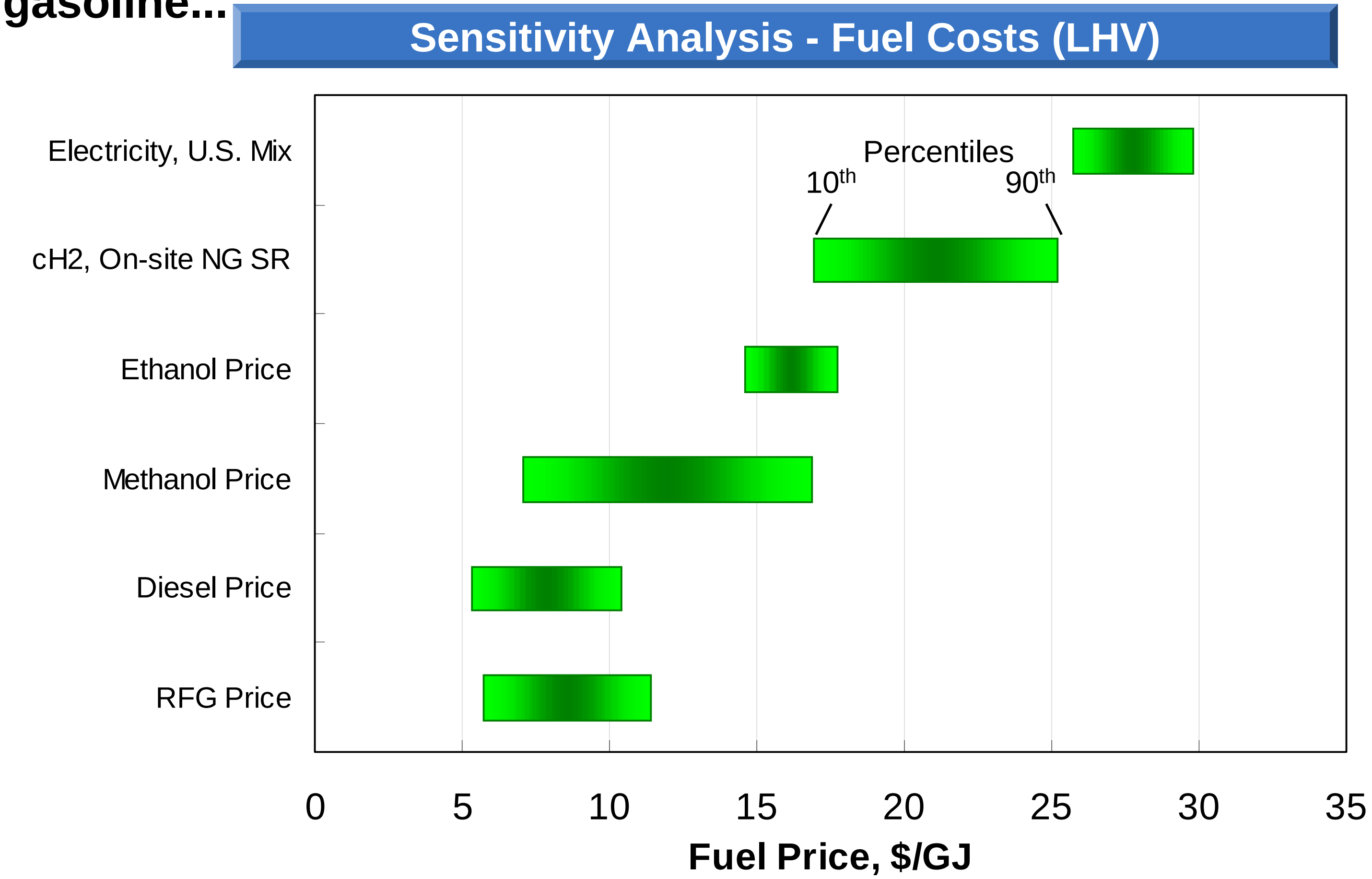
The most economical hydrogen fuel chains are expected to be over two times more expensive than gasoline, on a $/GJ basis.

- Capital costs are five to ten times more expensive than gasoline capital costs (including local and central plant capital)
  - Limitations in maximum train size (compared with refineries) and system complexity lead to high central plant capital cost
- Transportation and distribution costs (including compression and storage) are far higher than those for gasoline
- High feedstock cost dominates the high cost of locally produced hydrogen
- Electrolyzer-based production is costly with EIA energy price projections
  - Competitive with natural gas based reforming only if industrial electricity rates ($0.04/kWh) can be obtained at local fueling stations
  - When off-peak electric power is used, electrolysis equipment cost is higher because of low equipment utilization
- Alternative fuels, especially hydrogen, will require a significant upfront investment, representing a risk to both vehicle manufacture and fuel provider
  - Dealing with this risk represents a formidable barrier to the use of hydrogen for FCVs

Conventional fuels are expected to be by far the least expensive fuels on an energy content basis.

- EIA projections for conventional fuels do not show an appreciable upward trend by 2010
  - Eventually only expensive-to-produce oil resources will be left and conventional fuel prices will start to rise significantly, but this will be well after 2010
  - Development of other renewable fuels such as GTL will slow this rise
- Ethanol is expected to be around two times more expensive than gasoline when government subsidies are excluded
  - Assumes short transportation distances (50 miles)
  - Low conversion yield from biomass despite improvements with cellulosic biomass technology
  - Expensive processing
  - Further improvements beyond 2010 could eventually reduce cost to around 1.5 times conventional fuels
- Future wholesale methanol price projections are close to gasoline prices on a $/GJ basis
  - Assuming large-scale fuel-methanol plants will be built in regions with remote or stranded gas
  - Delivered fuel prices are slightly higher due to higher transport & distribution cost

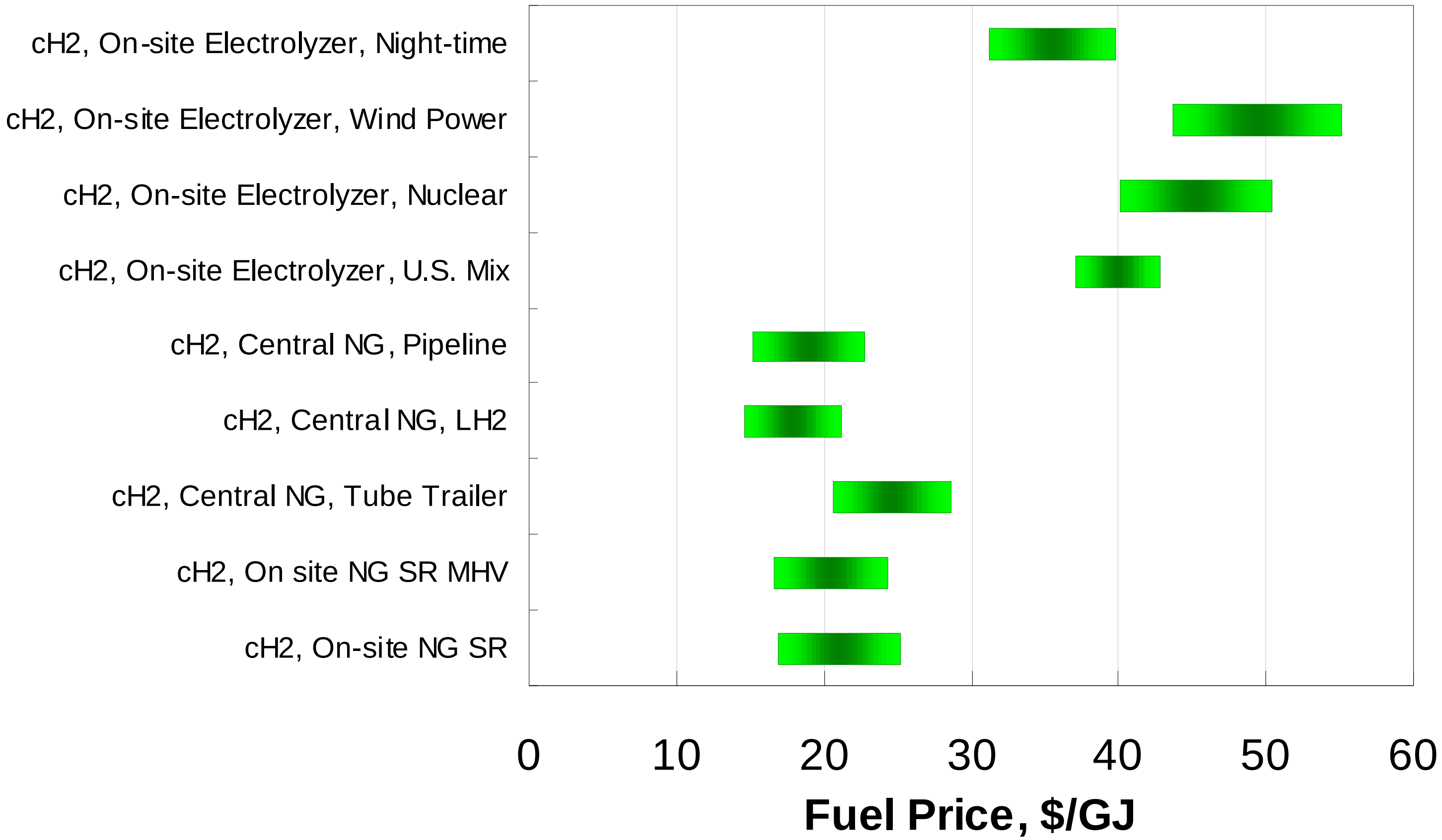
Even taking into account possible variations in fuel cost; electricity, hydrogen and ethanol are likely to be substantially more expensive than gasoline...



... while methanol may be competitive with gasoline and diesel in certain scenarios.

Uncertainty over electric power costs exacerbates the high cost of hydrogen from electrolyzers.

Sensitivity Analysis - Fuel Costs (LHV)



Substantial additional technology breakthroughs will be required to achieve FCV cost competitiveness with ICEVs.

- The cost difference between hydrogen-fueled FCVs and HEVs appears to be significant, around $4,000 per vehicle, given our assumptions
- Taking into account a wider range of assumptions, this difference may range from around $2,000 to around $10,000
  - Actual cost of HEVs and ICEVs varies and is not well-known (publicly):
    - No bottom-up cost-estimate for HEVs was performed
    - Some current manufacturers of HEVs indicate our HEV estimates are too low
    - ICE production costs vary widely and are not easy to obtain
  - FCV cost estimates are subject to several uncertainties which may increase or decrease the cost:
    - Vehicle cost and performance results in this study are based on aggressive technology scenarios for all FCV system components
    - FCV cost may be reduced by $1,000-1,500 more if the stack were designed for high peak power density rather than high efficiency
- However, FCVs costs, even reformer-based FCVs, would be lower than battery EVs costs while offering much higher range under these scenarios

The cost and performance of the fuel cell stack remains the key barrier in achieving cost parity with HEVs or conventional vehicles.

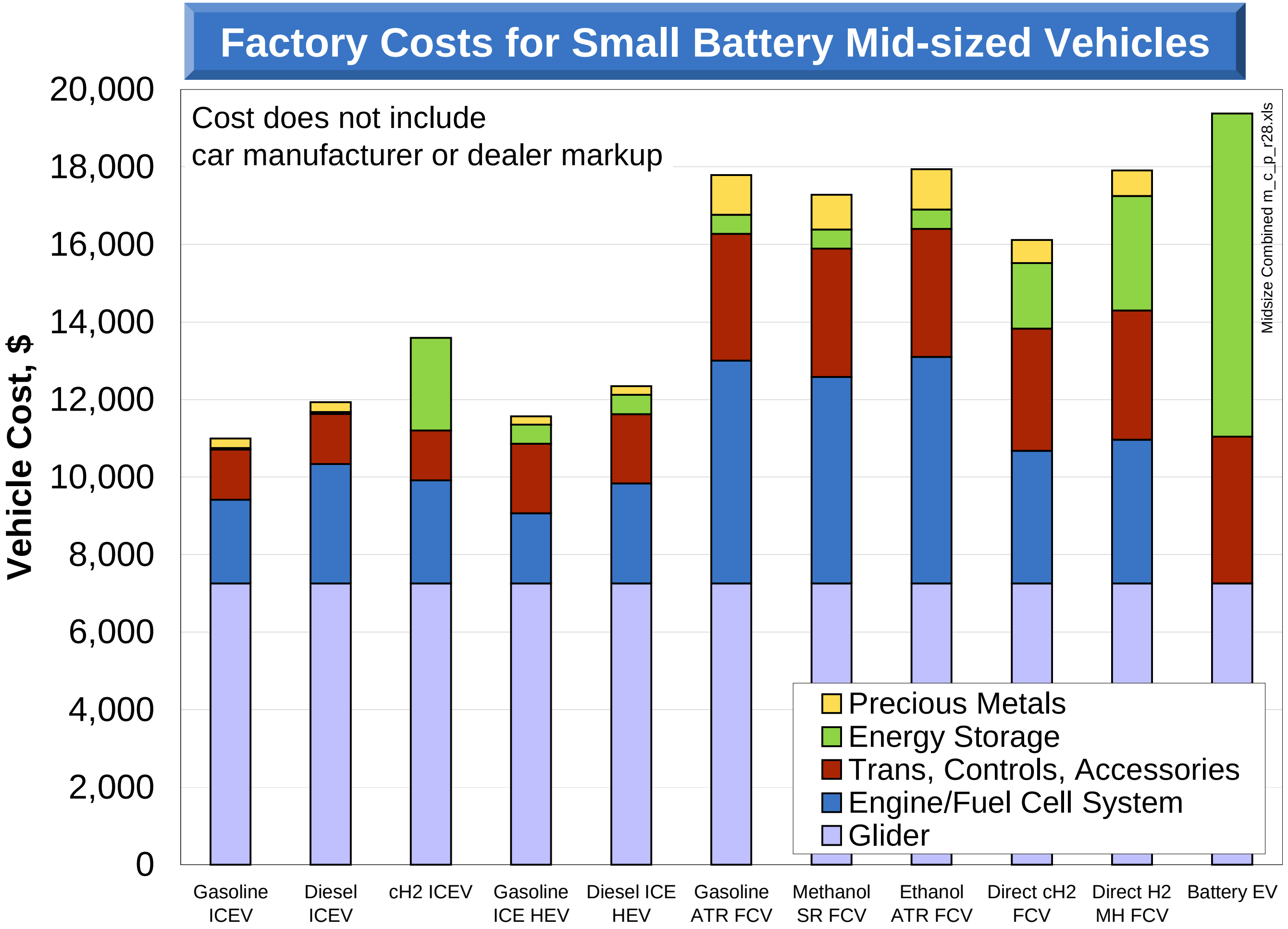
- The additional cost being projected for FCVs over conventional and HEV platforms is clearly significant
  - Current FCV power unit cost is 2-3 times the DOE/PNGV target of $45/kW
  - System components not counted in the $45/kW target further increase difference in cost with ICEVs
  - By using different assumptions, the gap could be reduced but would remain significant
- The differences in cost between various FCV fuel choices is significant, but does not appear deciding compared to the difference with ICEVs
- Stack remains key to further improving the cost of FCVs
  - Stack cost by itself remains the largest FCV power unit component
  - Power density, CO tolerance, and other performance limitations determine the need for other subsystems
- However, in order to further reduce FCV cost, the cost of other subsystems and components will also need to be addressed
  - Future scenarios for motor and power electronics costs are nearly as expensive as the fuel cell stack

Powertrain costs for compressed-hydrogen FCVs would be significantly lower than those of systems with on-board reformers in our scenarios.

- Fuel processor-based FCVs are projected to cost $1,000-$2,000 more than compressed cH_2 vehicles:
  - Fuel processors add cost directly
  - Fuel processors add weight, which increases power requirements to achieve desired performance, thus adding to entire power unit cost
  - Reformers impact the performance of the fuel cell stack, and cause its cost to increase:
    - Due to poorer fuel quality of reformate (compared with pure hydrogen), including dilution and poisoning effects (CO and S), reformer-based fuel cell stacks must be larger or have higher platinum loadings
    - The reformer losses significantly impact the well-to-wheel efficiency; if direct hydrogen FCVs were optimized to achieve the same efficiency, their cost could be reduced further (this was not done for this study)
- Fuel processor-based FCVs would cost roughly the same as metal hydride-based FCVs

Nevertheless, the difference in cost does not appear decisive by itself in light of the difference in cost between all FCVs and HEVS and ICEVs.

Based on our scenario analysis, factory costs of future FCVs would likely be 40-60% higher than conventional vehicles, but lower than battery EVs.



Factory Costs for Small Battery Mid-sized Vehicles

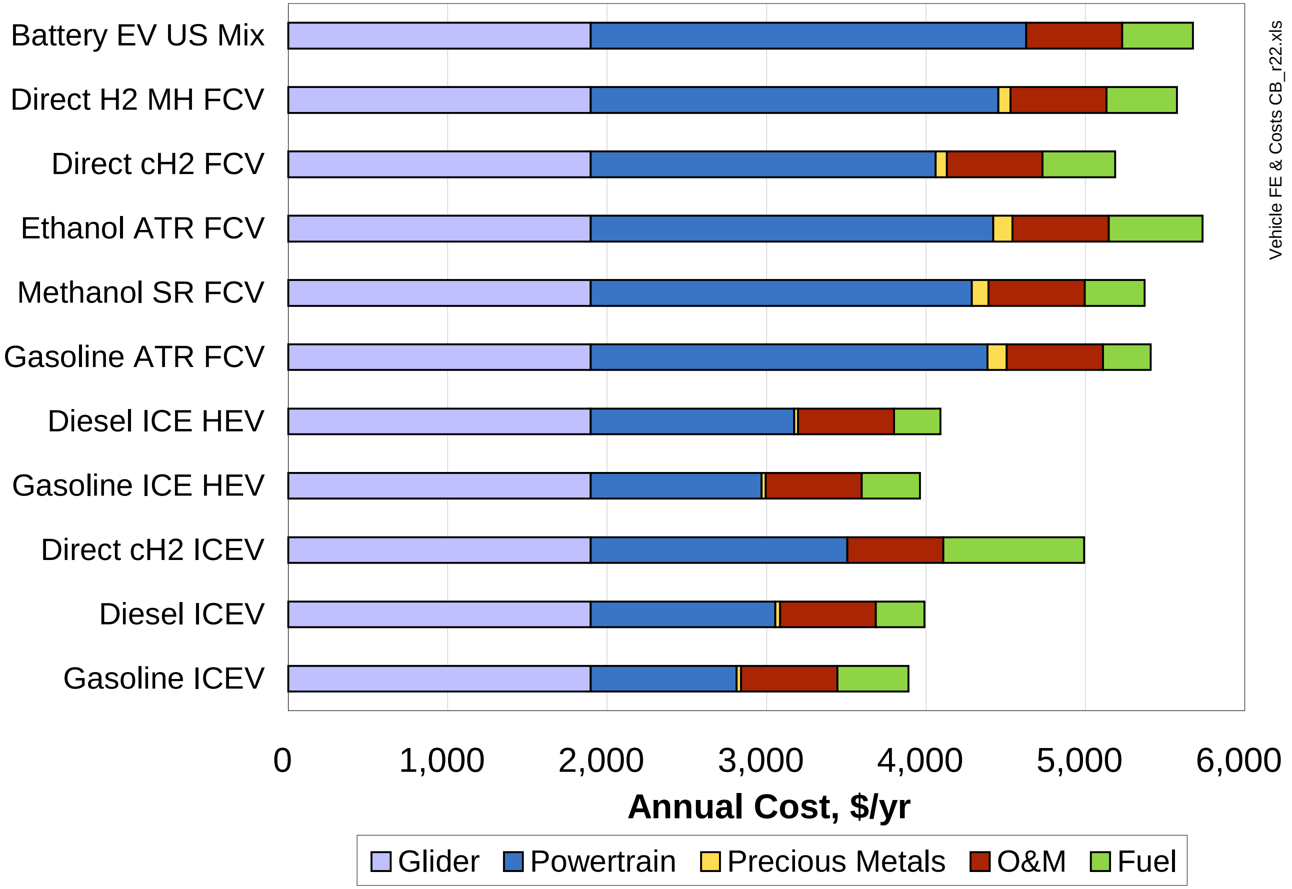
Note: All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

Typical FCV ownership cost would be $1,000-$2,000 per year higher than that of conventional ICEVs on account of the high initial vehicle cost.

- Vehicle ownership cost is dominated by vehicle depreciation, representing over 75% of annual cost for all vehicles
- Fuel cost typically amounts to less than $500 per year
  - High efficiency of direct hydrogen and methanol-based FCVs compensates for higher hydrogen and methanol cost bringing annual fuel cost on-par with ICEVs
  - Gasoline FCVs benefit from a 30% reduction in fuel cost compared with conventional vehicles, but this does not outweigh added depreciation cost
  - Fuel cost for hydrogen ICEVs roughly triples annual fuel cost compared with petroleum ICEVs
- Insufficient information was available to be able to differentiate FCV maintenance cost from that for conventional vehicles
- Sensitivity analysis shows that cost differences between FCVs and petroleum ICEVs are statistically significant
  - Differences amongst FCV options and between FCVs and hydrogen ICEVs are not statistically significant

Typical annual mid-size FCV costs are projected to be around $1,200 to $1,800 more than that of conventional vehicles.

Vehicle Ownership Costs for Small Battery Mid-sized Vehicles



* All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

Although no fundamental technical barriers exist, meeting safety standards may pose a challenge for the implementation of hydrogen fuel chains.

- Hydrogen transportation, fueling station, and on-board safety issues can likely be resolved without onerous cost-increases
  - Relatively low cost engineering solutions can probably be identified for all issues surrounding on-board storage and refueling facilities for cH_2 and MH
  - However, the current codes and standards for the safe handling of hydrogen may not be practical for consumer applications
  - Well-organized international code and standard setting and modification are currently under way
- Fuel cell vehicles will require modifications to garages, maintenance facilities, and on-road infrastructure that could be costly and difficult to implement
  - Fundamental safety-related properties of hydrogen are very different from gasoline
  - Implementation of critical safety measures for closed public structures may pose a serious hurdle to widespread use of cH_2, as responsibility for implementation does not easily align with interest in hydrogen as a fuel
  - This issue may necessitate alternative hydrogen storage methods (e.g. MH)
  - Insufficient attention is being paid to these issues by standard-setting efforts

A well-coordinated international effort is under way to tackle hydrogen safety issues, but it insufficiently addresses on-road issues.

There are some important areas that must be addressed before FCVs can be accepted as mass market vehicles.

- Key Uncertainties: home parking, maintenance facilities, and parking garages
  - Some studies and modeling has been conducted, but data gathering must be expanded
    - Ventilation and leak modeling at the University of Miami has been funded for several years
  - Elevated vents may be enough in most cases, but it must be done for all places the vehicle visits or there could be major consequences
    - Prohibiting FCVs in non-compliant areas may result in unreasonable inconvenience to FCV owner
    - FCV owners and manufacturers won't have a great deal of leverage to force these facilities to be hydrogen compliant
- Potential Show Stoppers: tunnels and other public road works
  - Safety equipment will have to be very cheap or the aggregate cost could be prohibitive
  - All roads must be compliant - keeping certain cars off a particular road would be extremely difficult and unacceptable to the FCV owner

Hydrogen FCVs should be able to significantly reduce energy use and greenhouse gas emissions over ICEVs, but at much higher cost.

- Based on our analysis, hydrogen FCVs could achieve 2.5 MJ/mi energy use and 150 g/mi greenhouse gas emissions on a well-to-wheels basis
  - 50-60% improvement over gasoline ICEVs
  - Requires compressed gas hydrogen production (central or local) from natural gas
  - Requires hydrogen FCVs to achieve 2.5x fuel economy improvement (80 mpgge) over gasoline ICEVs
- However, we estimate this hydrogen FCV to cost more than $5,000 per year for vehicle depreciation, fuel, and maintenance
  - Lowest among FCV options, but still $1,000/year more than HEVs and $1,500/year more than a gasoline ICEV
  - Hydrogen cost is not a major contributor, but this analysis indicates a target of $20/GJ should be achievable in the long-term
  - The estimated hydrogen FCV factory cost of $16,000 is $4,000 higher than HEVs and $5,000 higher than a gasoline ICEV due to higher FCV powertrain costs
- Our safety issues analysis indicates that more attention needs to be paid to covered public structure compatibility with hydrogen

FCVs offer many benefits including energy efficiency and emissions improvements over conventional ICEVs and HEVs...

- FCVs could provide significant reductions in primary energy consumption:
  - 50% for direct H_2 and 30-40% for gasoline and methanol FCVs over gasoline ICEVs
  - Direct H_2 FCVs could reduce consumption by 20% over HEVs, with gasoline and methanol FCVs matching HEV primary energy consumption
- FCVs offer the potential for significant greenhouse gas reductions, but change in fuel has more impact than improved energy efficiency
- Annual fuel cost for gasoline-based FCVs is expected to be up to 40% lower than that of direct H_2 FCVs and gasoline ICEVs
- FCVs are expected to have $4,000-$6,000 ($65-$100 per kW) higher factory cost than HEVs
- The safety risks of hydrogen, methanol and ethanol are technically manageable
  - However, implementation of safety standards for cH_2 and LH_2 for covered public structures may pose a serious hurdle to implementation of these fuel paths
- Technical and infrastructure risks for FCVs remain high

... but technical risk remains considerable and cost is expected to be significantly higher than for ICEVs and HEVs.

Although there are considerable differences in performance, risk, and cost of the FCV fueling options, no clear winner is identifiable.

- Compressed hydrogen FCVs could have significant benefits over reformer-based vehicles
  - 20-30% lower primary energy consumption than gasoline or methanol FCVs
  - $1,000-$2,000 ($15-$35 per kW) lower cost per vehicle; this could be increased to around around $3,500 ($60/kW) if some efficiency benefit is sacrificed
  - Significantly lower technical risk
- Reformer-based systems retain considerable benefits in terms of infrastructure risk
  - Delivered fuel costs are likely to be less than half that of hydrogen on a $/GJ basis
  - Even infrastructure investment for methanol is very modest compared to hydrogen
  - Safety issues for reformer fuels are comparatively simple to resolve, despite recent public perception of methanol’s toxicity risk
- Differences between FCVs and petroleum ICEVs overwhelm differences amongst FCV options
- Hydrogen ICEVs do not appear to offer significant benefits in typical ownership cost compared with direct hydrogen FCVs
  - cH_2 ICEV range is likely to be reduced due to the large volume of hydrogen required

The detailed analysis described in this study generally supports the targets defined in Phase I, ...

- Well-to-wheel energy efficiency projections based on our scenarios are generally consistent with the long-term (2008) targets suggested in Phase I
- Phase I hydrogen fuel cost targets appear difficult to achieve and the DOE should consider relaxing them
  - Given the modest impact of fuel cost on overall ownership cost
- None of the FCV future scenarios met DOE FCV cost targets of $45 per kW
- Given the performance benefits of FCVs, relaxing the target to match the cost of HEVs meeting the PZEV standard may be reasonable

... but indicates that hydrogen and FCV cost targets may be difficult to achieve without additional technology breakthroughs.

Table of Contents

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Outline

Main Report

- **Background, Objectives & Scope**
- Approach
- Energy Efficiency and Emissions
- Cost
- Safety
- Conclusion & DOE Target Setting

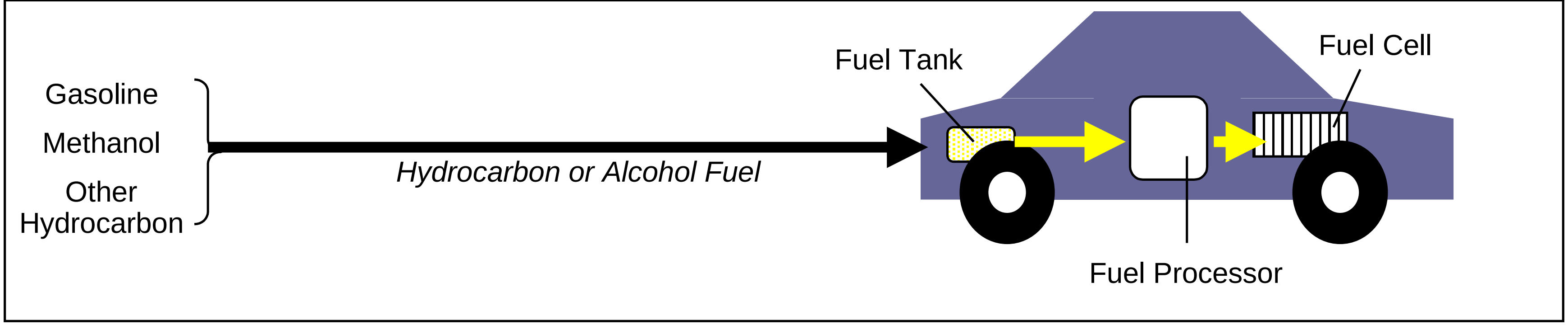
Details on pages: A18-20, 73-75, 166-118

DOE has commissioned this study to support target setting and progress monitoring for its direct hydrogen fuel cell vehicle program.

- DOE Office of Transportation Technologies (OTT) supports proton exchange membrane fuel cells (PEMFCs) for transportation applications:
  - Focus since 1992 on on-board reforming of gasoline and other fuels
  - DOE/OTT is currently developing a direct hydrogen Fuel Cell Vehicle (FCV) program in coordination with DOE's Hydrogen Program
- DOE has commissioned this study to help set targets for its direct hydrogen program:
  - Targets are being set by comparison of direct hydrogen FCVs with alternative fuel and powertrain options
  - In Phase I, Arthur D. Little provided initial targets for hydrogen FCVs based on quick estimates and readily available information

Fundamentally, two strategies may be followed for fueling PEM fuel cell vehicles (FCVs): on-board reforming and off-board hydrogen production.

On-Board Reforming (Reformer-Based Vehicle)



Gasoline

Methanol

Other Hydrocarbon

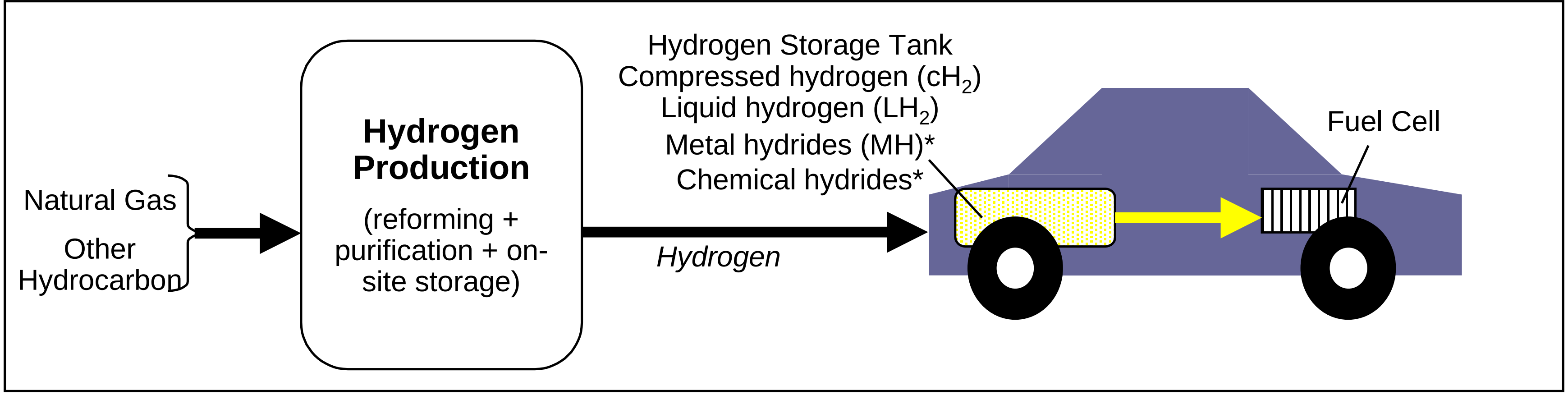
Hydrocarbon or Alcohol Fuel

Fuel Tank

Fuel Cell

Fuel Processor

Direct Hydrogen: (off-board hydrogen production)



Natural Gas

Other Hydrocarbon

Hydrogen Production

(reforming + purification + on-site storage)

Hydrogen Storage Tank
Compressed hydrogen (cH_2)
Liquid hydrogen (LH_2)
Metal hydrides (MH)*
Chemical hydrides*

Hydrogen

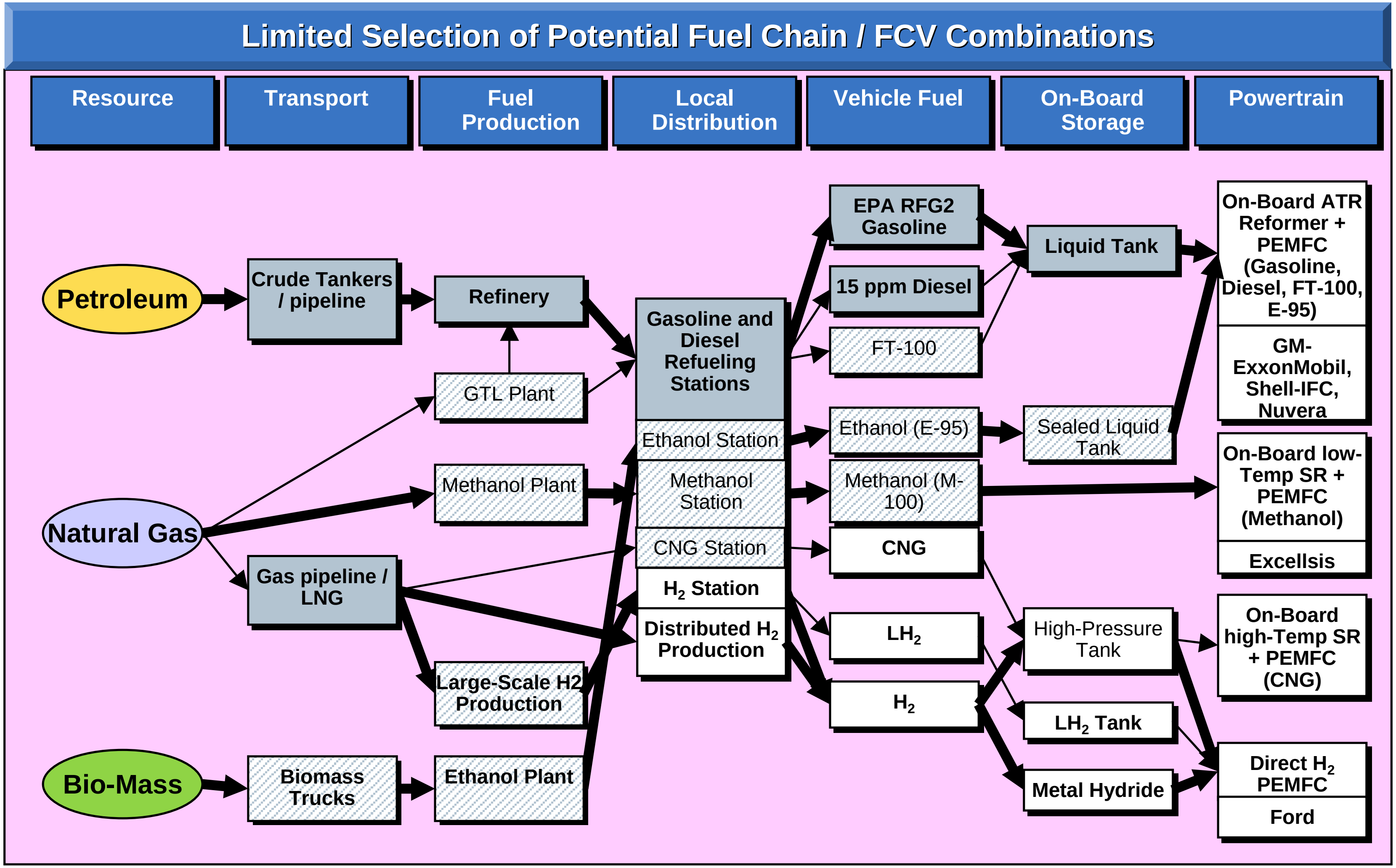
Fuel Cell

* Modest processing may be needed for these hydrogen storage options but the product is pure hydrogen.

As both direct-hydrogen and reformer-based fuel chains have advantages and carry considerable risks, a clear choice cannot be made now.

	On-Board Reformer	Direct Hydrogen
Fuel	***High efficiency:*** around 80% for gasoline	***Moderate efficiency:*** from 70% for central production to 60% for decentralized production with compression to 5,000 psia
	Infrastructure exists: for gasoline	***New infrastructure required***
	Low fuel cost: around $7/GJ for gasoline	***High fuel cost:*** more than $20/GJ for compressed hydrogen
Fuel Cell Power Unit	***Large stack***: reformate quality limits stack performance	***Compact stack***
	Complex: primarily because of fuel processing system	***Simple***: pressurized hydrogen ***Complex***: metal hydrides
	Heavy: due to larger stack and fuel processor	***Lighter:*** no fuel processor and compact light stack
	Good efficiency	***Excellent efficiency***
Vehicle	***Established safety standards***	***Safety standards yet to be completed***
	Compact, simple storage: high energy density	***Bulky, more complex storage:*** low energy density
	Requires ***sizable battery*** needed to bridge cold-start	Requires ***small battery*** for start-up & transients

A very large number of potential fuel chains and vehicle architectures can be and are being considered for fueling fuel cell vehicles.



DOE asked ADL to assess the implications of different fueling and powertrain options on vehicle efficiency, CO_2 emissions, cost, and safety.

- The overall goals (stated above) for all three Phases are the same
- The specific objectives for this Phase II are to refine DOE's R&D targets for its direct hydrogen FCV program by comparing them with a range of other powertrains:
  - Consider energy efficiency, greenhouse gas emissions, cost, and safety
  - Include methanol, ethanol, diesel, and gasoline fuels but focus on hydrogen
  - Include internal combustion engine vehicles and battery electric vehicles for comparison
- In Phase III the assessment will be refined in two important ways:
  - More detailed assessment of impacts on the existing fueling infrastructure will be made
  - Additional fuel chains will be considered if appropriate
  - The risk (including financial risk) of developing each of the pathways will be estimated (as opposed to assessing the "end-state" which was done in Phase II)

This phase has six specific objectives to help achieve the overall goal, each related to a comparison of hydrogen with other FCV fuel choices.

Task	Objective	Description
1	Refine well-to-tank fuel chain model	• Refine performance calculations for hydrogen and compare them with gasoline, diesel, CNG, ethanol, and methanol
2	Fuel cost assessment	• Determine fuel price projections for all fuels, focusing on hydrogen fuel chains
3	Develop tank-to-wheel vehicle model	• Develop detailed vehicle performance calculations for direct hydrogen and gasoline-fueled FCVs
4	Vehicle ownership cost assessment	• Compare direct hydrogen FCV ownership costs with other FCVs, electric vehicles, and conventional vehicles
5	Safety analysis	• Identify major safety concerns and perform a safety issues analysis on all fuel chains and vehicle options
6	Prepare final report	• Prepare final report summarizing our approach and final results to be reviewed by DOE and industry

Details on pages: M26, 42-46; A56-61

We focused our analysis on the timeframe around which fuel cells are now projected to become ready for mass-market introduction: 2010 and beyond.

- Current FCV technology is still in the initial prototype stage, so a projection of future FCV performance and cost had to be made
- Technology projections beyond 2010 would have little bearing on current experience and would be unacceptably speculative for this purpose of this project
- A scenario for the year 2010 was developed for comparison purposes
- Our 2010 projections are consistent with the goal setting objective of this project, but many different scenarios are possible in the future

Current and Projected Fuel Cell Product Development Progress (Summer 2001)

	Research and Development		**System Demonstration**		**Market Entry**	**Market Penetration**
	Component R&D	*Initial System Prototypes*	*Refined Prototypes*	*Commercial Prototypes*		
Hydrogen		Toyota, GM, DaimlerChrysler, Ford	2002	2004/ 2005	2007 / 2009	2010+
Methanol		DaimlerChrysler, Toyota	2003/ 2004	2006/ 2007	2008 / 2010	2010+
Gasoline	GM, Honda, Volkswagen	2002/ 2003	2004/ 2005	2007/ 2008	2008 / 2010	2010+

🟨 Current situation ▨ Projections

* Based on public industry announcements and ADL projections, all projections are predicated on a reasonable measure or technical success.

With input from DOE and industry, fifteen well-to-tank fuel chains were selected for detailed analysis.

Hydrogen Fuel Chains

- ***Compressed Hydrogen (cH_2)***
  - ***On-site SR from natural gas***
  - On-site Energy Station (SR with co-gen heat) from natural gas
  - On-site Electrolyzer
  - Central SR from natural gas with pipeline delivery
  - Central SR from natural gas with tube trailer delivery
  - Central SR from natural gas with liquid hydrogen delivery
- Metal Hydrides (MH)
  - On-site SR from natural gas with low pressure cH_2 to on-board MH storage

Other Fuel Chains

- ***Reformulated Gasoline (RFG)***
  - From petroleum
- **Diesel**
  - From petroleum
- **Electric Power**
  - **From US power plant mix**
  - From wind
  - From nuclear power
- Methanol (MeOH)
  - From remote natural gas
- Ethanol (EtOH)
  - From corn
  - From cellulose

Notes: Bold type are reference fuel chains, bold & italic options are primary objectives of the analysis, others are analyzed for comparison.

SR = Steam Reformer, assuming natural gas feedstock. Central production is assumed to be >10 MMscfd hydrogen with delivery to distributed fueling stations; on-site production is assumed to be < 1 MMscfd hydrogen at the fueling station. cH_2 = compressed hydrogen. RFG = reformulated gasoline. EtOH = ethanol

Based on DOE and industry inputs, eleven vehicle types were chosen for detailed tank-to-wheel analysis.

Fuel Cell Vehicles (FCV)

- **FCV with on-board reformer**
    - ***Reformulated Gasoline, ATR***
    - Methanol, SR
    - Ethanol, ATR
- **Direct Hydrogen FCV with storage**
    - ***cH_2 High Pressure storage***
    - Metal Hydride storage

Other Vehicles

- **Reformulated Gasoline ICE vehicle**
- Battery/Gasoline ICE Hybrid Electric vehicle
- Diesel CIDI vehicle
- Battery/Diesel CIDI Hybrid Electric vehicle
- Hydrogen ICE vehicle
- Battery Electric vehicle

Notes: Bold type are reference vehicles, bold & italic options are primary objectives of the analysis, others are analyzed for comparison
FCV = Fuel Cell Vehicle, assumed to be Polymer Electrolyte Membrane (PEM) type fuel cell
ATR = Autothermal Reformer used to convert gasoline or ethanol to reformate (~40% hydrogen)
SR = Steam Reformer used to convert methanol to reformate (~80% hydrogen)
ICE = Internal Combustion Engine
CIDI = Compression Ignition, Direct Injection, refers to advanced diesel engine
cH_2 = Compressed Hydrogen (study considered 5,000 psia, though pressures in the range from 3,600 to 10,000 psia are being considered

The fuel chains and vehicles chosen require a safety analysis of eight different fuels.

Fuel		On-board	Off-board	Comment
Hydrogen	Compressed Gas	✔	✔	On-board at 5000 psia, off-board at 150-3600 psia[1]
	Cryogenic Liquid		✔	Off-board transportation and storage at -260ºC
	Metal Hydride	✔		On-board at ~150 psia
Gasoline		✔	✔	Transported and stored as a liquid
Diesel		✔	✔	Transported and stored as a liquid
Methanol		✔	✔	Transported and stored as a liquid
Ethanol		✔	✔	Transported and stored as a liquid

[1] Off-board storage pressure depends on the fuel chain selection. Compressed hydrogen pipeline delivery and low pressure storage for use in MH FCVs will be around 150 psia. Compressed hydrogen tube trailer delivery and high pressure storage for use in cH_2 FCVs will be around 3600 psia.

Not all issues potentially facing FCVs and hydrogen infrastructure were addressed in this study.

- Given the early stage of development of FCVs and hydrogen infrastructure, certain issues have yet to be resolved
  - Some technical challenges facing fuel cell systems and vehicle integration:
    - ZnO bed replacement (for sulfur removal)
    - impurities effects on catalysts (e.g. salt, sulfur, smoke)
    - startup time
    - freezing conditions
    - necessary on-board safety
    - transient control issues
  - Certain hydrogen infrastructure issues:
    - footprint and space constraints for on-site production and storage
    - varying land rental, labor, and permitting costs
    - access for hydrogen delivery options (e.g. tube trailer street access, right of way for pipelines)
- Although we identified these issues, we did not incorporate their potential cost or efficiency implications

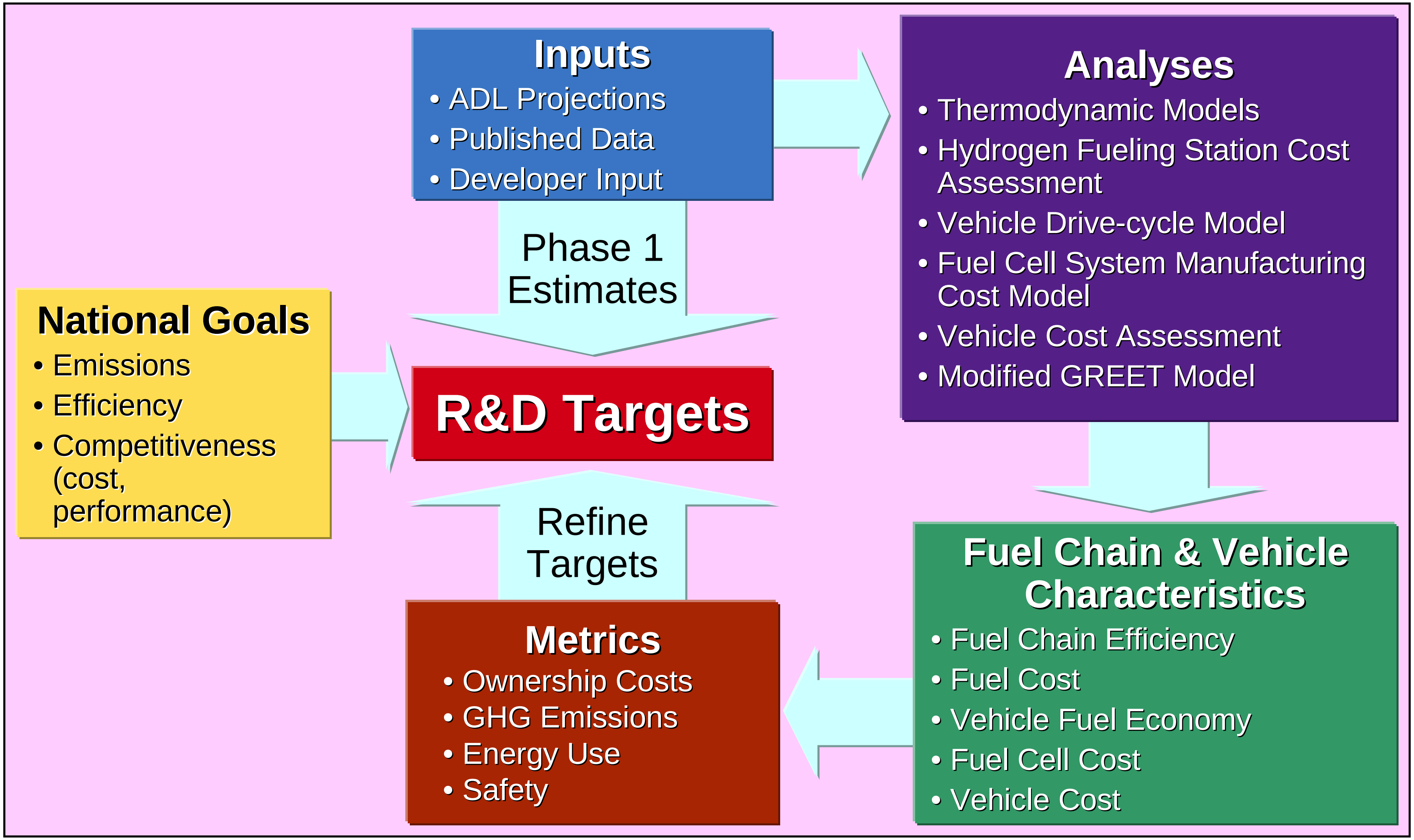
The analysis results should be considered in conjunction with all the assumptions presented in the main report and appendix.

Outline

Main Report

- Background, Objectives & Scope
- **Approach**
- Energy Efficiency and Emissions
- Cost
- Safety
- Conclusion & DOE Target Setting

Combining a variety of inputs through thorough analyses, we are able to develop meaningful and defensible guidelines for R&D targets.



Inputs
- ADL Projections
- Published Data
- Developer Input

Analyses
- Thermodynamic Models
- Hydrogen Fueling Station Cost Assessment
- Vehicle Drive-cycle Model
- Fuel Cell System Manufacturing Cost Model
- Vehicle Cost Assessment
- Modified GREET Model

Phase 1 Estimates

National Goals
- Emissions
- Efficiency
- Competitiveness (cost, performance)

R&D Targets

Refine Targets

Metrics
- Ownership Costs
- GHG Emissions
- Energy Use
- Safety

Fuel Chain & Vehicle Characteristics
- Fuel Chain Efficiency
- Fuel Cost
- Vehicle Fuel Economy
- Fuel Cell Cost
- Vehicle Cost

We used published and in-house data and information to develop a thorough analysis of FCV fuel options.

- Performed detailed well-to-wheel performance and cost calculations:
  - Built on existing models and analysis for energy efficiency and greenhouse gas emissions (specifically ADL in-house data and ANL's GREET model)
  - Added cost estimates for both fuel chain and vehicle consistent with on-going Arthur D. Little analyses for DOE
- Identified major potential safety issues with each fuel choice and characterized current industry efforts to address them
- Used the results to help DOE set targets that are aggressive but realistic
- The benefits of this analysis to DOE include:
  - Uses best available inputs for the fuel chain and vehicle analyses
  - Provides an independent analysis for DOE
  - Powertrain inputs to the vehicle analyses can be directly linked to our detailed cost and performance assessment of on-board reformer FCVs
  - Leverage DOE's investment in the GREET modeling spreadsheet and use its input assumptions where appropriate

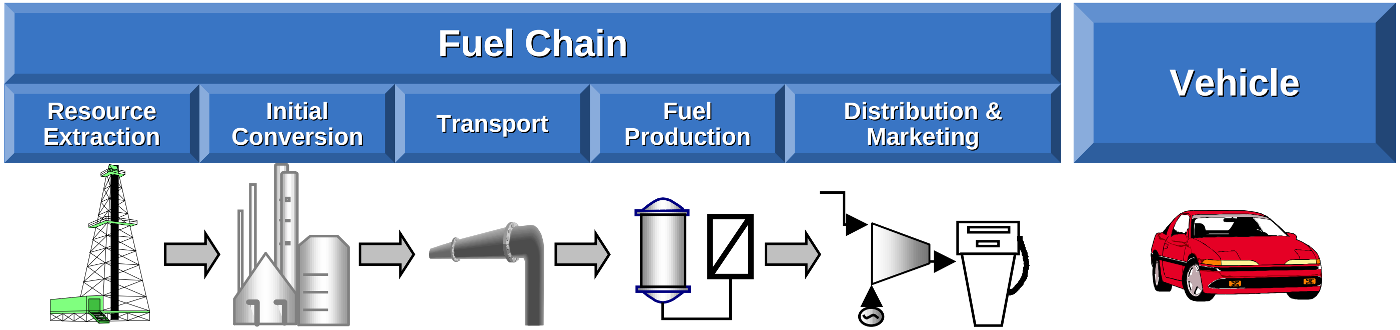
We used Argonne National Laboratory's GREET model as a starting point for our analysis, refined it and added a cost assessment.

- Separated the well-to-tank analysis from the tank-to-wheel analysis to allow for transparent comparisons with conventional technology
- Updated the fuel chain assumptions with in-house ADL information and original analysis where necessary:
  - Refined hydrogen production and refueling options based on in-house analysis
  - Improved analysis for ethanol and methanol
- Incorporated a more detailed and thorough analysis of FCV performance:
  - Vehicle drive-cycle analysis for two different vehicle types (5-passenger sedan and SUV)
  - Careful assessment of fuel cell system turn-down characteristics
- Added cost models:
  - Fuel chain cost based on EIA projections and bottom-up calculations
  - Fuel cell power unit costs based on our detailed bottom-up cost estimates developed under a separate DOE program

This section provides an overview of the methodologies used; more detailed analyses are shown in the subsequent chapters.

Details on pages:
A5, 8-9

We separated the well-to-tank analysis from the tank-to-wheel analysis to allow for easy comparisons with conventional technology.



Fuel Chain

Resource Extraction

Initial Conversion

Transport

Fuel Production

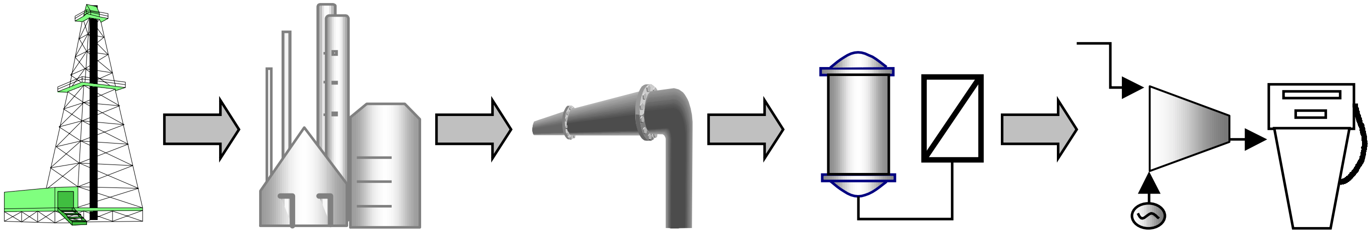
Distribution & Marketing

Vehicle

Energy Efficiency	% or MJ primary energy input / MJ fuel delivered	$mpg_{gasoline\ equivalent}$
	$MJ_{primary\ energy\ input}/mile_{driven}$	
Greenhouse Gas Emissions	$g_{GHG\ fuel\ chain}$ / GJ fuel delivered	$g_{GHG\ tailpipe}/mile_{driven}$
	$g_{GHG\ total}/mile_{driven}$	
Cost	$/GJ, or $/gallon gasoline equivalent	$/kW $/vehicle
	$/year	

Details on pages: A10-13; AS 7-25

To analyze well-to-tank impacts, we separated each fuel chain into five modules.



Energy Source	Step Energy Use (Input MJ/MJ Output), LHV basis				
	NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
Natural Gas	1.02	1.02	1.001	1.36	---
Petroleum	0.013	---	---	---	---
Gasoline	0.045	---	---	---	---
Diesel	0.013	---	---	---	---
Electricity[1]	0.013	0.02	0.001	0.016	0.078
Hydrogen	---	---	---	---	1.03

EXAMPLE

* Not complete without all performance inputs and assumptions for each fuel chain.

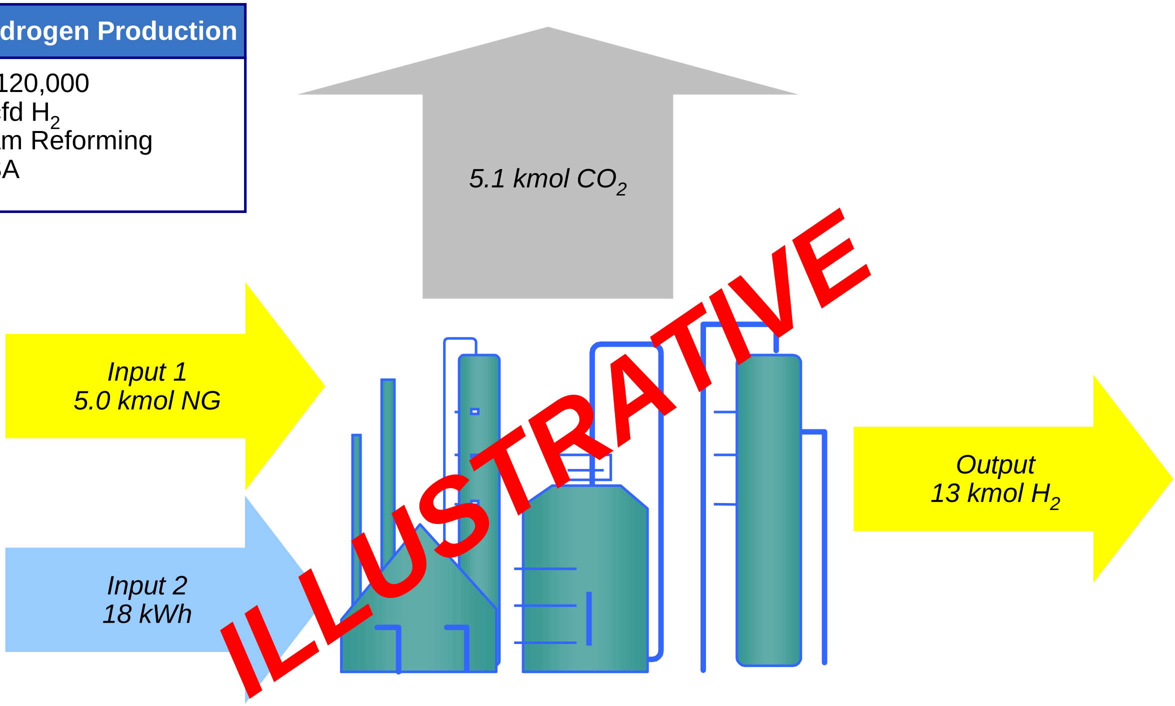
[1] Electricity is further broken down into primary fuel requirements based on the U.S. average power plant fuel mix.

We used GREET as a starting point, but performed separate analyses to refine performance and cost inputs when necessary.

For each module all energy, emissions, and cost parameters were developed...

Example: On-site Hydrogen Production

Equipment Cost: $1,120,000
Capacity: 275,000 scfd H_2
Reformer Type: Steam Reforming
Purification Type: PSA



5.1 kmol CO_2

Input 1
5.0 kmol NG

Input 2
18 kWh

Output
13 kmol H_2

ILLUSTRATIVE

Module Thermal Efficiency

$$\frac{\text{32 GJ Output}}{\text{44 GJ Total Input}} = 72\%\ \text{LHV}$$

…and by linking modules together, the overall environmental and economic impact of a given fuel chain was ascertained.

Details on pages:
M34-35, 67-72;
A16-17

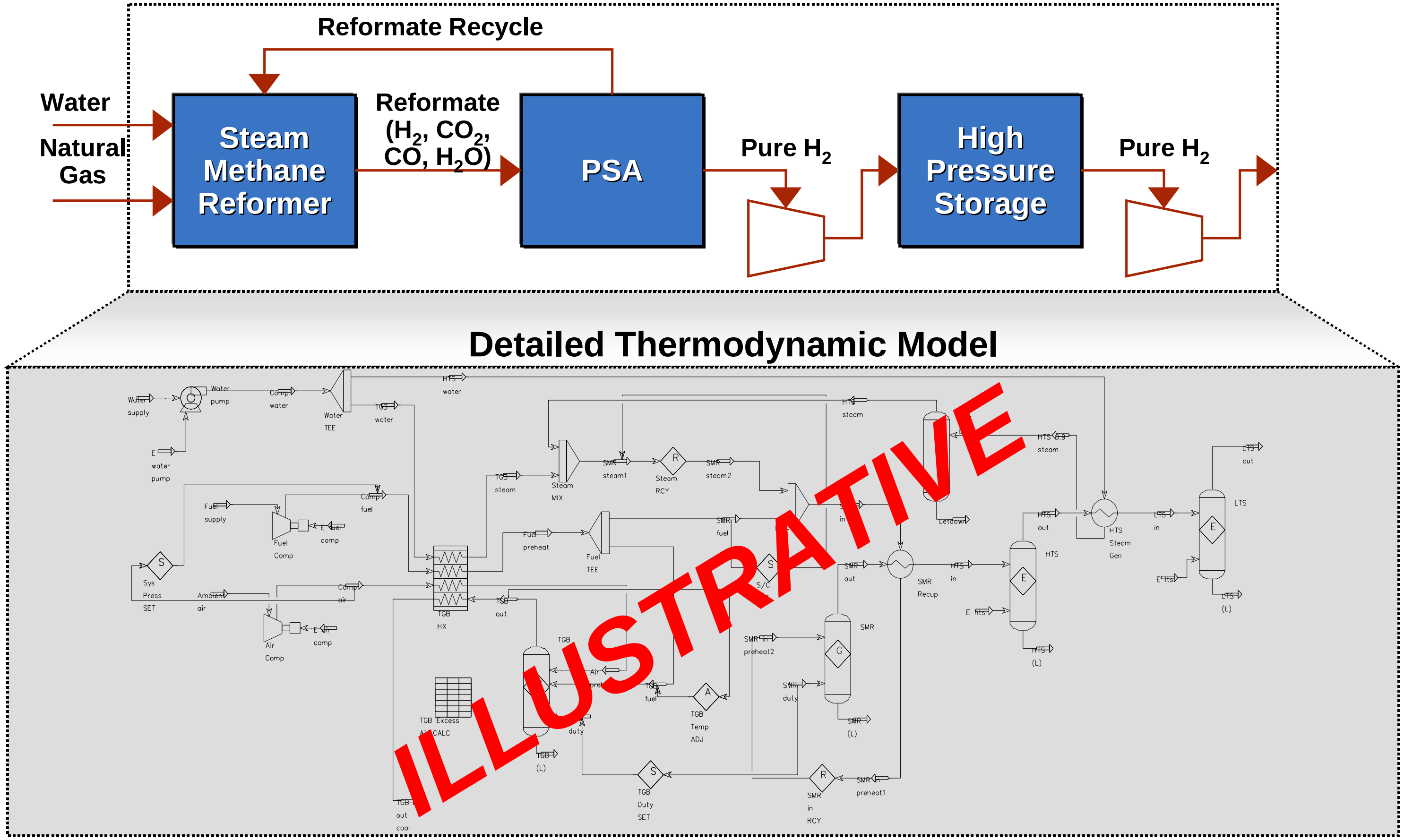
The hydrogen fuel chain analysis builds on a recent project for DOE's Hydrogen Program, where we have analyzed the cost and performance of local hydrogen fueling stations in detail.

- We included the three most relevant on-site production methods from an on-going study for DOE's Hydrogen Program (DE-FC36-00GO10604):
  - Steam reforming natural gas, PSA purification, and compressed hydrogen storage[1]
  - Electrolysis with compressed hydrogen storage[1]
  - Central production & distribution options were added in addition
- Original analysis was needed to update the performance and cost estimates for hydrogen fuel chains
  - Detailed thermodynamic analysis of on-site hydrogen production
  - Detailed design considerations for hydrogen storage & dispensing
  - Cost analysis based on vendor quotes, publications, and bottom-up analysis
  - Consistent (but not necessarily identical) assumptions for central hydrogen production facilities and on-site production
  - Consistent transport and distribution assumptions for hydrogen and other fuels
- The cost estimates are based on high production volumes (100 units/yr) to meet the mature market demand of direct hydrogen FCVs

---

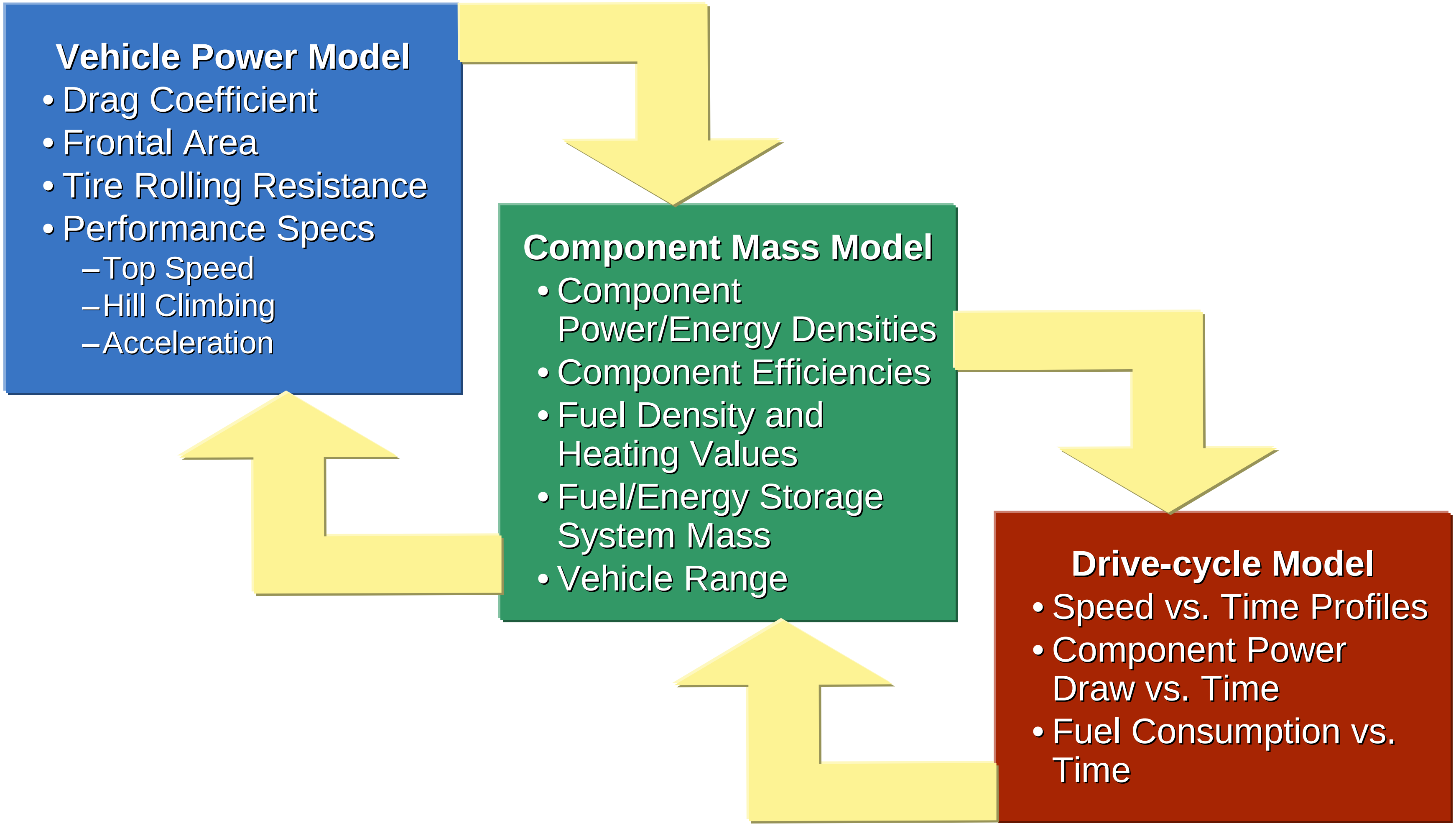
[1] High pressure on-site storage at 3600 psi with on-site boost compressors to achieve 5000 psi for cH_2 vehicles. Low pressure on-site storage at 100 psi for metal hydride vehicles.

Thermodynamic modeling was used to characterize the performance of the on-site hydrogen production, purification, and compression modules.



Material and energy streams were integrated, and overall system efficiencies were determined for each case.

We used a simple vehicle drive-cycle simulation model to estimate fuel economy and power requirements for each powertrain.



Vehicle Power Model
- Drag Coefficient
- Frontal Area
- Tire Rolling Resistance
- Performance Specs
  - Top Speed
  - Hill Climbing
  - Acceleration

Component Mass Model
- Component Power/Energy Densities
- Component Efficiencies
- Fuel Density and Heating Values
- Fuel/Energy Storage System Mass
- Vehicle Range

Drive-cycle Model
- Speed vs. Time Profiles
- Component Power Draw vs. Time
- Fuel Consumption vs. Time

Details on pages:
M91-93

The glider, powertrain, precious metals, maintenance and fuel costs were evaluated to determine the overall vehicle ownership costs.

Cost Categories		ICEV	HEV	FCV
Glider		Mid-sized and SUV	Mid-sized and SUV	Mid-sized and SUV
Powertrain	**Power Unit**	Engine Cooling System	Engine Cooling System	Fuel Cell Module Fuel Processor Cooling System
	Transmission/ Controls/ Accessories	Exhaust/Evap System Transmission Starter Motor, Alternator Accessories (power steering, AC, etc.)	Exhaust/Evap System Transmission Motor Power Electronics Electronics Radiator Accessories	Exhaust/Evap System Motor/Transmission Power Electronics Electronics Radiator Accessories
	Energy Storage	Fuel Fuel Tank Startup Battery	Fuel Fuel Tank Traction Battery Battery Radiator	Fuel Fuel Tank Traction Battery Battery Radiator
Precious Metals[1]		Catalytic Converter[2] (Pt/Pd)	Catalytic Converter (Pt/Pd)	Fuel Cell (Pt, Ru) Fuel Processor (Pt, Rh) Catalytic Converter[2] (Pt/Pd)
Maintenance		Brakes, Oil change, Inspections, Tires, etc.	Assumed same overall cost as ICEV[3]	Assumed same overall cost as ICEV[3]
Fuel		RFG, Diesel, cH_2	RFG, Diesel	RFG, MeOH, E100, cH_2

[1] Actually part of the powertrain (fuel cell module or exhaust), but broken out separately for illustrative purposes. Precious metals in FCVs contribute significantly to vehicle cost and will have different salvage value.

[2] We assume hydrogen vehicles do not require a catalytic converter.

[3] The underlying assumption is that for a mature market, the stack and fuel processor life will have been improved to last for the life of the vehicle.

Our FCV power unit analysis builds on ongoing ADL/DOE analysis of automotive fuel cell systems.

- In an ongoing program for DOE (DE-SCO2-98EE50526), ADL has developed a detailed cost and performance model for an on-board ATR FCV power unit
  - Model developed in conjunction with ANL, with feedback from OTT and PNGV
  - Assumes high production volumes but uses near-term performance inputs
- We have modified the model to estimate component costs and weights for scenarios of future performance
  - ADL, "Cost Analysis of Fuel Cell System for Transportation – Pathways to Low Cost", 2001 Final Report, prepared for DOE, to be published in 2002
  - High temperature membranes, increased power density, and improvements in fuel processor catalysts and other materials
  - These assumptions reflect a best-case scenario of success in current R&D activities, but do not project future technology leaps
- We have also developed future scenarios for for methanol, ethanol, and direct H_2 FCVs based on in-house kinetic and thermodynamic calculations
- The cost model estimates are based on high production volumes (500,000 units/yr) assuming mature manufacturing technology
  - These high volumes are not likely in the 2010 timeframe

Details on pages:
M44, 84; A48-53

A previous ADL/EPRI HEV study provided the backbone for the overall vehicle factory cost analysis.

- ADL/EPRI study provided cost and weight estimates for HEV components
  - EPRI, “Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options”, Palo Alto, June 2001
  - Reviewed component costs with ANL and GM
  - Glider, power unit, transmission/controls/accessories, and energy storage costs were determined for various vehicle requirements
- Fuel cell module, fuel processor, and precious metal estimates from the ADL/DOE study were combined with the EPRI study estimates to determine FCV cost and performance
  - We used the approach for determining hybrid vehicle costs and applied it to fuel cell powered vehicles
- We also made future assumptions for the hydrogen storage options considered in this analysis
  - High pressure compressed hydrogen storage in carbon fiber wrapped tanks
    - cost and performance based on claims by developers
  - Low pressure metal hydride storage
    - cost and performance based on internal analysis

Details on pages: M96-108; A112-114

A safety analysis was necessary to identify the major safety concerns of the alternative fuel choices.

Scope

- Identify major safety concerns of fuel choices
- Perform safety issues analysis & identify ongoing efforts to resolve issues

Approach

- Review latest information on codes and standards
- Identify properties of each fuel that affects safety
- Focus on local storage, transportation, and end use in vehicles
  - All fuels are already produced for industrial applications
  - Use in light duty vehicle setting is new for many fuels
  - Include impact on building safety
- Identify key safety barriers for each fuel

Details on pages: M99-101; A104-111

Six major safety variables were evaluated for each fuel based on it's properties.

Fuel Properties

- Minimum Ignition Energy
- Flammability Limit
- Diffusion Coefficient
- Odor, Color
- Flame Visibility
- Storage Condition
- Vapor Density
- Vapor Pressure
- Energy Content (weight and volume)

Safety Variables

- Flammability and Detonation
- Ignition Energy
- Gas and Flame Detection
- Toxicity
- High Pressure Storage
- Cryogenic Storage

Evaluation of hydrogen safety issues is presented in the main report, other fuels' safety issue evaluations are in the Appendix.

Outline

Main Report

- Background, Objectives & Scope
- Approach
- **Energy Efficiency and Emissions**
- Cost
- Safety
- Conclusion & DOE Target Setting

Outline

Main Report

- Background, Objectives & Scope
- Approach
- **Energy Efficiency and Emissions**
  - **Fuel Chain**
  - Vehicle
  - Well-to-Wheels
- C
- Safety
- Conclusion & DOE Target Setting

None of the alternative fuels can be delivered with greater primary energy conversion efficiency than conventional fuels.

- The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel
  - Oil refineries provide unparalleled primary fuel conversion efficiencies of ~85%
  - Syngas production from natural gas (as needed in the production of hydrogen and methanol) imposes an additional penalty of roughly 15% on these fuel chains
  - Extensive use of electric power penalizes energy efficiency even more significantly, making electrolysis chains over 3 times more energy intensive than hydrogen from on-site NG reformers, and almost 4 times more than gasoline
- Biomass-based conversion chains (ethanol) have fuel chain efficiencies below 50%, though much of this primary energy may be renewable
- Due to their high energy density, the primary energy use for transport and distribution of conventional fuels is the lowest
  - Transport and distribution comprise less than 5% of energy use for petroleum fuels
  - Alcohol fuels have roughly half the energy density of hydrocarbon fuels, and hence transportation energy use is roughly double that of conventional fuels
  - Energy use for the compression, liquefaction, or hydrate formation associated with hydrogen transport & vehicle storage adds 10-30% to primary energy use

Differences in primary energy efficiency explain the differences in greenhouse gas impact between most fuel chains.

- Natural-gas-based fuel chains benefit from low carbon content of natural gas, but not enough to outweigh lower efficiency
  - Natural gas has an energy-based carbon content around 20% lower than that of petroleum
  - However, energy conversion and fuel transport and distribution efficiency for natural gas-based fuels are more than 25% lower than those of petroleum fuels
- As expected, renewables-based fuel chains offer by far the lowest fuel chain-related greenhouse gas emissions
  - Biomass-based ethanol allows reduction of greenhouse gas impact by around 90%
  - Production of hydrogen via electrolysis from renewable or nuclear power virtually eliminates greenhouse gas emissions
    - However, additional hydro and nuclear power capacity would be required
    - “Green” power contracts would have to be made to assure only renewable or nuclear power was being used for hydrogen production
  - For all renewable chains, GHG emissions are low, despite low energy efficiency, because they use non-carbon or short-cycle carbon feedstocks

Energy consumption for on-site hydrogen production was estimated with the use of thermodynamic models and discussions with (future) vendors.

Local Hydrogen Fueling Station Energy Requirements (LHV) per kg Hydrogen

Hydrogen Option	**Natural Gas** MMBtu/kg	**Power** kWh/kg	**Total Primary Energy[4]** (GJ/kg)
High pressure gas dispensing from Tube Trailer delivery[1]	-	1.25	0.013
High pressure gas dispensing from Liquid Hydrogen delivery[1]	-	0.05	0.001
High pressure gas dispensing from Pipeline delivery[2]	-	3.04	0.031
On-site Electrolyzer with high pressure gas dispensing[1]	-	50.0	0.500
On-site SR with high pressure gas dispensing[1]	0.150	3.37	0.192
On-site SR with low pressure gas dispensing for MH FCV[3]	0.150	1.34	0.172

---

[1] Maximum 3,600 psia (240 atm) local on-site storage to 5,000 psia (340 atm) on-board storage for cH_2 vehicles.

[2] Compression from 100 psia (8 atm) delivery pressure to 5,000 psia (340 atm) on-board storage for cH_2 vehicles. Some pipeline pressures can be as high as 740 psia (50 atm), requiring less local fueling station compression power.

[3] Maximum 130 psia (9 atm) local on-site storage to 130 psia (9 atm) on-board metal hydride storage for MH vehicles. Note: on-site storage pressure is below 130 psia when tanks are not full.

[4] Primary energy delivered to the fuel production facility. 1.055 GJ/MMBtu natural gas, electric power is represented as 0.01 GJ/kWh, assuming a 36% power plant efficiency.

Details on pages:
A7; AS27-62

The central hydrogen plant energy requirements were taken from published values and additional Arthur D. Little analysis.

Central Plant Energy Requirements (LHV) per kg Hydrogen			
Central Plant Step	**Natural Gas** MMBtu/kg	**Power** kWh/kg	**Total Primary Energy**[4] (GJ/kg)
Central SR Hydrogen Production	0.147	0.022	0.155
Tube Trailer Compression[1,2]	0.011	1.174	0.023
Hydrogen Liquefaction[1]	0.036	4.264	0.081
Pipeline Compression[1,3]	0.001	0.059	0.001

---

[1] 50% electric and 50% natural gas IC engine power is assumed for for compression and liquefaction energy inputs; each of these options require hydrogen production (e.g. from NG) in addition.

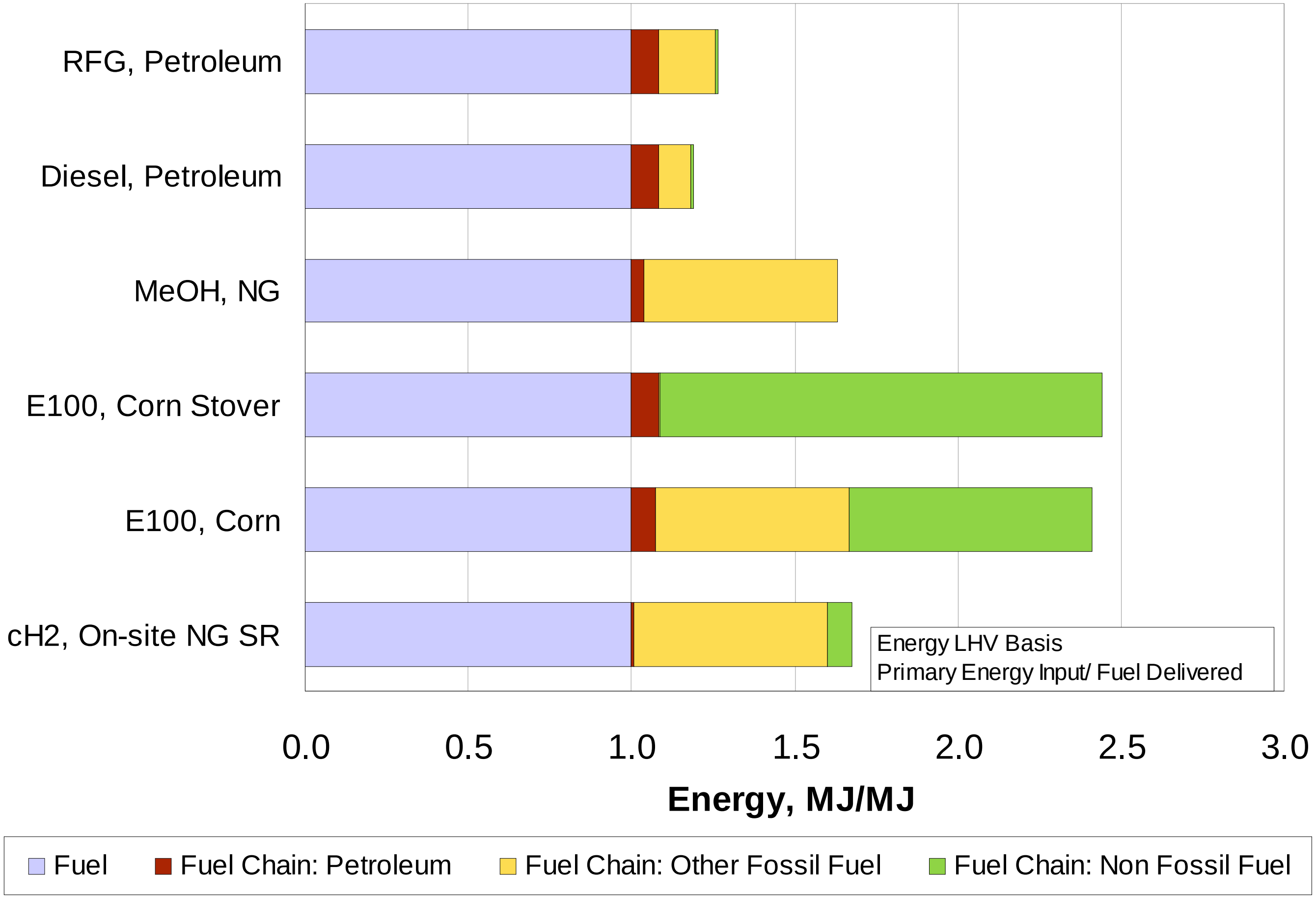
[2] Compression to 3600 psia (245 atm).

[3] Assuming 150 psia (10 atm) pressure. Some pipeline pressures can be as high as 740 psia (50 atm), requiring additional compression power.

[4] Primary energy delivered to the fuel production facility. 1.055 GJ/MMBtu natural gas, electric power is represented as 0.01 GJ/kWh (36% efficiency for generation).

Details on pages: M11, 18-21; A7, 19-20

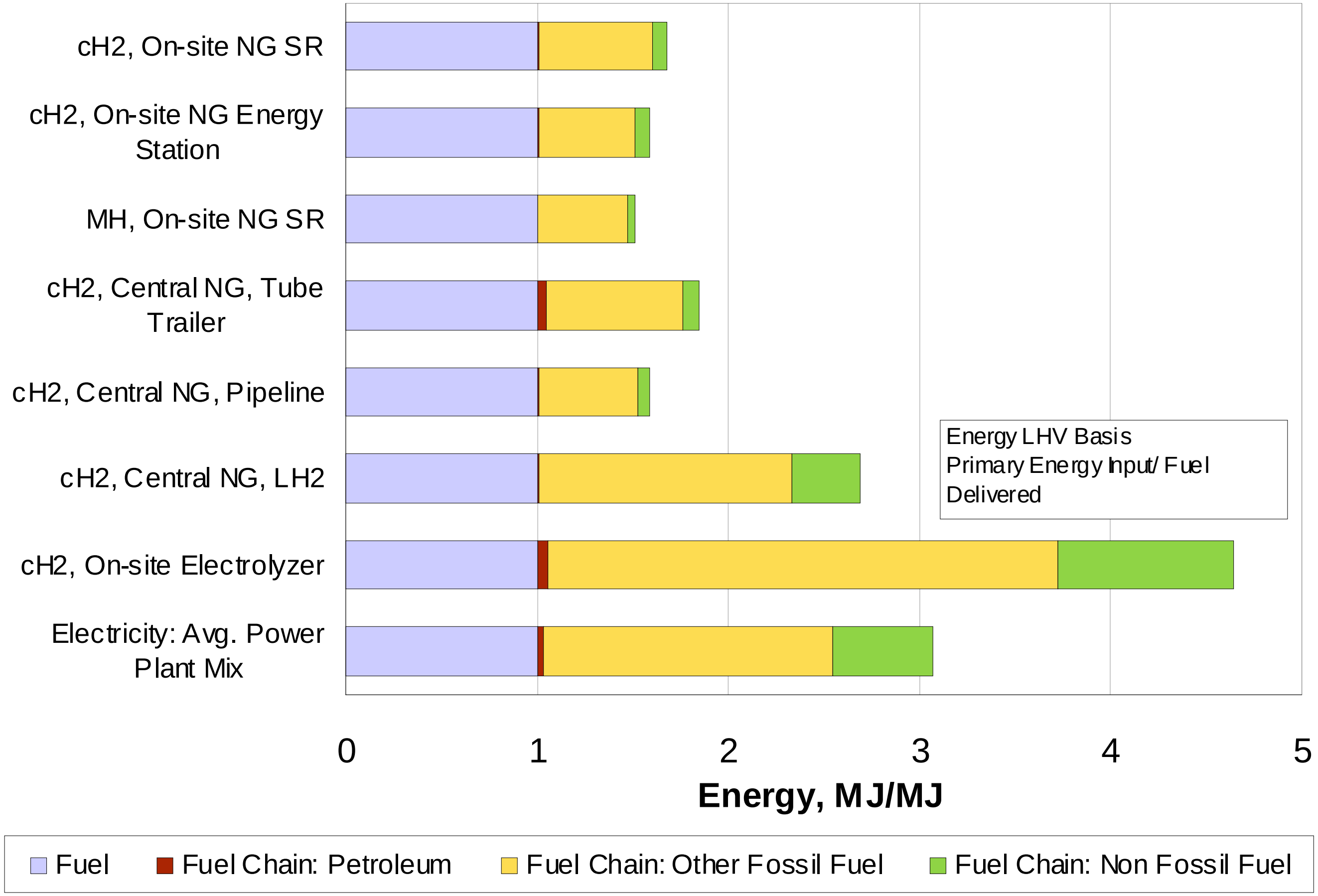
The hydrogen fuel chain requires 40% more primary-energy than petroleum-derived gasoline or diesel per unit of delivered fuel



* Net E100 energy use include byproduct credits, as do petroleum products.

Details on pages: M11, 18-21; A7, 19-20

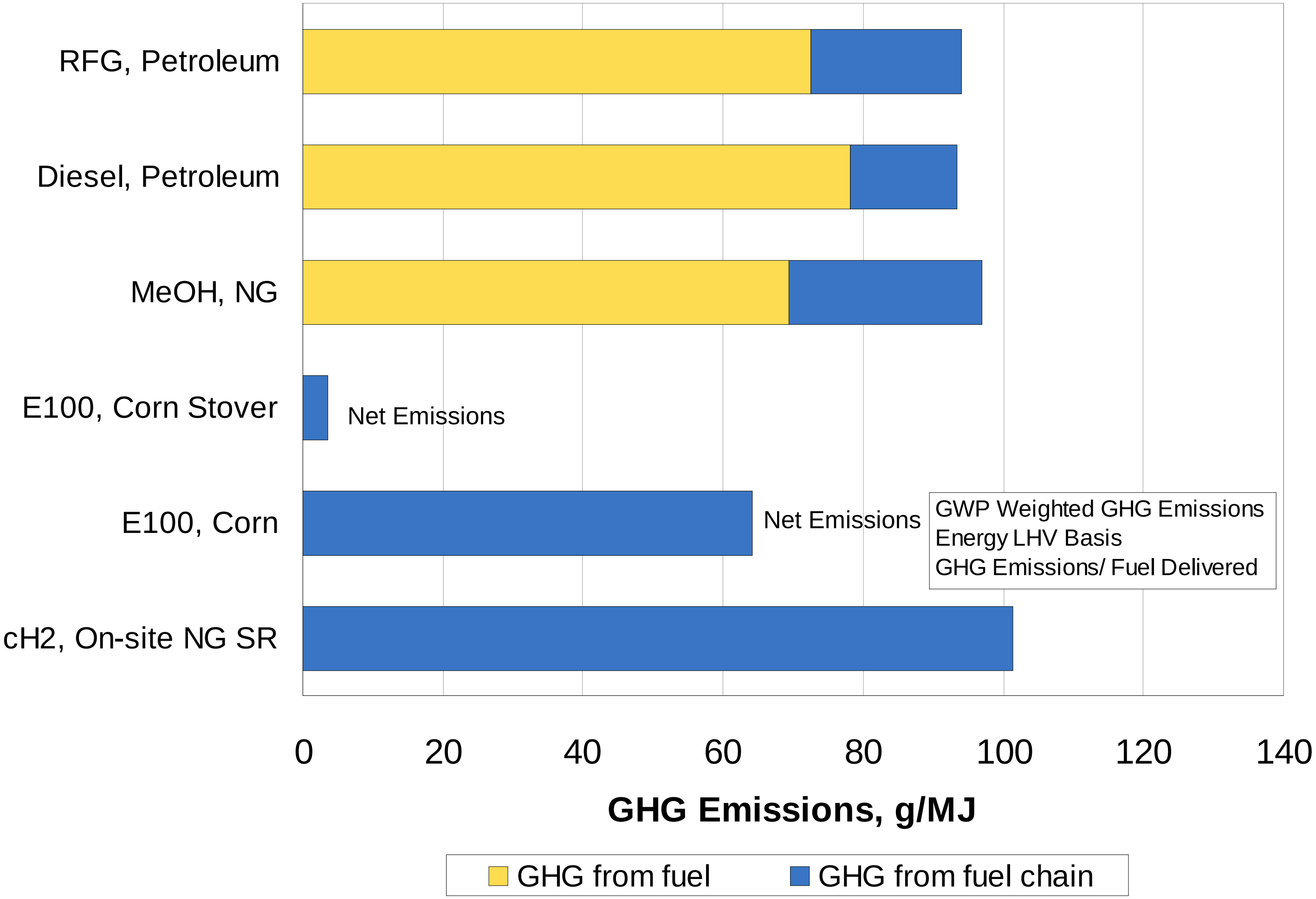
Steam reforming-based hydrogen production provides the most efficient options for hydrogen generation, especially in a co-generation context;...



* Electrolyzer energy consumption assumes a US average mix of grid power.

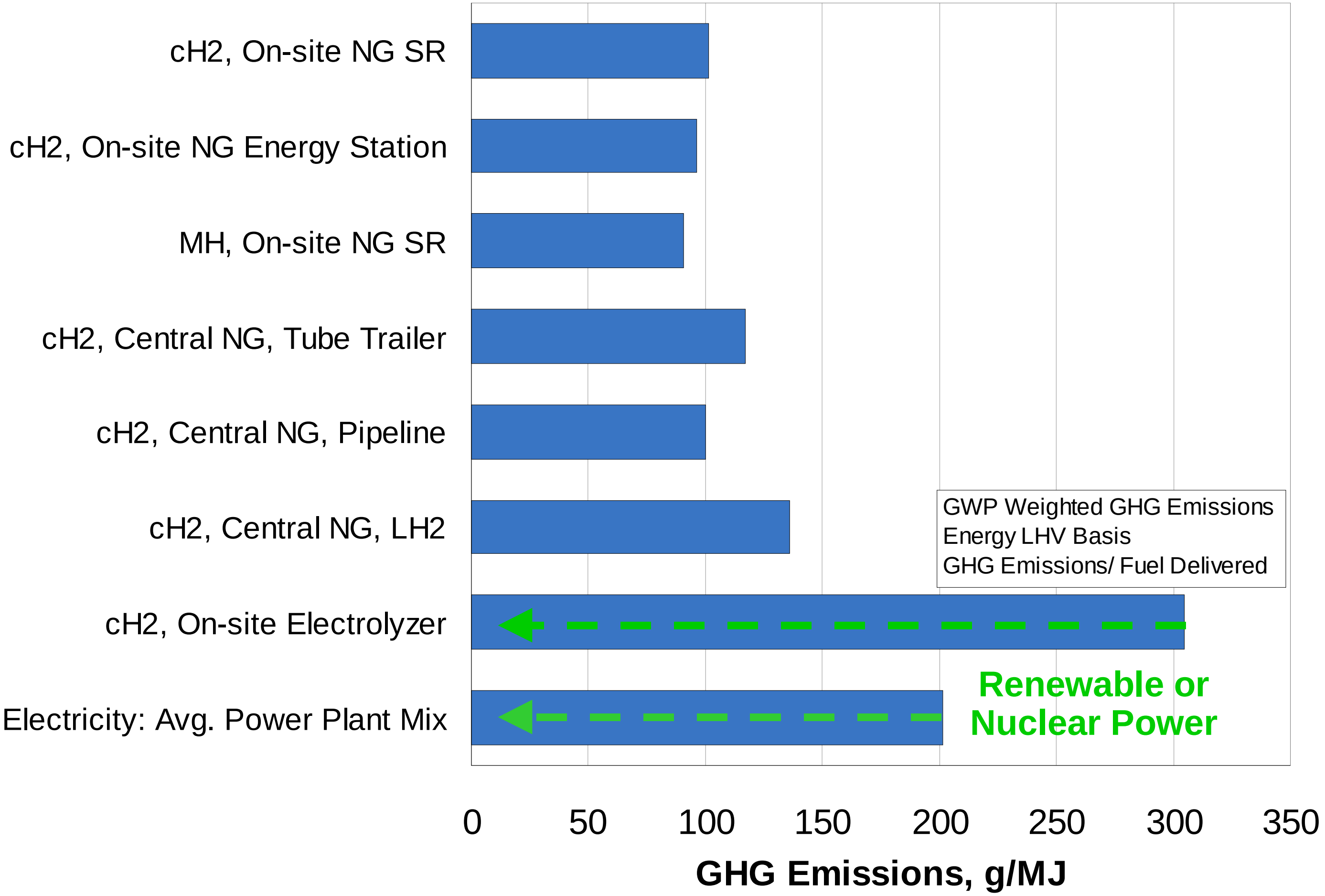
... liquid hydrogen and electrolysis options use far more energy.

GHG emissions for hydrogen from natural gas is on par with diesel and gasoline due to the lower carbon content of the feedstock.



* Net E100 emissions include byproduct credits.

Electrolysis-based hydrogen using renewable or nuclear power could virtually eliminate greenhouse gas emissions...



...but, special contractual arrangements would have to be made to assure only renewable or nuclear power was being used for hydrogen production.

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Projected future scenarios lead to direct hydrogen FCVs that are technically competitive with conventional and other advanced vehicles.

- High efficiency for direct hydrogen FCVs is due to high continuous power efficiency and excellent turn-down performance
  - Reformer based FCVs have much lower part load efficiencies, but still higher than ICEVs
- Direct hydrogen FCVs could provide performance benefits over other advanced vehicle options (ICE HEVs)
  - Lower weight
  - Good low-end torque performance (electric drive)
  - Almost three times better fuel economy
- Reformate-based FCVs are more compatible with conventional fuels and could provide performance benefits over conventional vehicles (ICEVs)
  - Good low-end torque performance (electric drive)
  - Efficiency on par with hybrid electric powertrains
  - Projected efficiency could be much higher if reformer start-up and turn-down issues were solved
- The future scenarios have aggressive performance assumptions requiring success in current fuel cell system R&D activities

Details on pages:
M10, 26; A56-61,
64-69

Our analysis was based on future FCV scenarios in which fuel cell technology is improved consistently with success in current R&D activities.

- An ADL/DOE analysis of a near-term technology automotive fuel cell system was used as a baseline for the projected future scenarios
  - Detailed bottom-up cost and full-load performance estimates for fuel flexible ATR FCV power unit developed for DOE Costing Program (DE-SC02-98EE50526)
- Future scenarios assume current R&D efforts are successful:
  - High-temperature, humidity-independent membranes with nafion-like conductivity are developed and the system design takes full advantage of the benefits
  - Stack platinum loading is reduced to an optimum level with high current density
  - ATR space velocities are substantially increased, improving the power density of the fuel processor
  - Fuel cell engineering is optimized, and inefficiencies are reduced or eliminated
- Key performance improvements result, in addition to cost reductions described in the next chapter:
  - Reduced weight
  - Improved system efficiency
  - Faster start-up
- The direct hydrogen FCV powertrain was not re-optimized to achieve efficiency similar to the other vehicle options; this could further reduce its weight and cost

Details on pages:
M10, 26; A56-61,
64-69

The future fuel cell system assumptions developed for the Costing program were used to estimate FCV power unit costs and performance.

Fuel Cell System Assumptions - Full Load	Units	Current Gasoline	Future Scenarios		
			Gasoline	MeOH	Hydrogen
Stack Temperature	°C	80	160	160	160
Stack Pressure	atm	3	3	3	3
Unit Cell Voltage	volts	0.8	0.8	0.8	0.8
Pt Loading (Cathode/Anode)	mg/cm^2	0.4/0.4	0.2/0.1	0.2/0.1	0.2/0.1
Pt Cost	$/g	15	15	15	15
Current Density	mA/cm^2	310	500	610	750
Fuel Utilization	%	85	85	85	95
Cathode Stoichiometry		2.0	2.0	2.0	2.0
Electrolyte Cost	$/m^2	100	50	50	50
CEM Efficiency	% (C/E)	70/80	75/90	75/90	75/90
Total Parasitic Power	kW	6.1	3	3	3

Used in this study

We also made future assumptions for the hydrogen storage options considered in this analysis.

Baseline Direct Hydrogen FCV and ICEV Cases: compressed hydrogen storage (cH_2)

- Storage pressure: 5,000 psi*
  - We estimate a 350 mile range requires160 liters of hydrogen for a FCV and 320 liters for an ICEV
  - Conventional vehicles require 45 liters of fuel for a 350 mile range
  - We did not accommodate additional volumetric capacity in vehicle design assumptions
- Projected future cost: $265/kg hydrogen
  - Based on discussions with Quantum (IMPCO)
  - A detailed bottom-up cost analysis has not been performed to date
- Weight density: 10%
  - Based on claims by Quantum (IMPCO)
  - Numbers should be verified later this year with independent bottom-up costing

Low Pressure Direct Hydrogen FCV Case: metal hydride storage (MH)

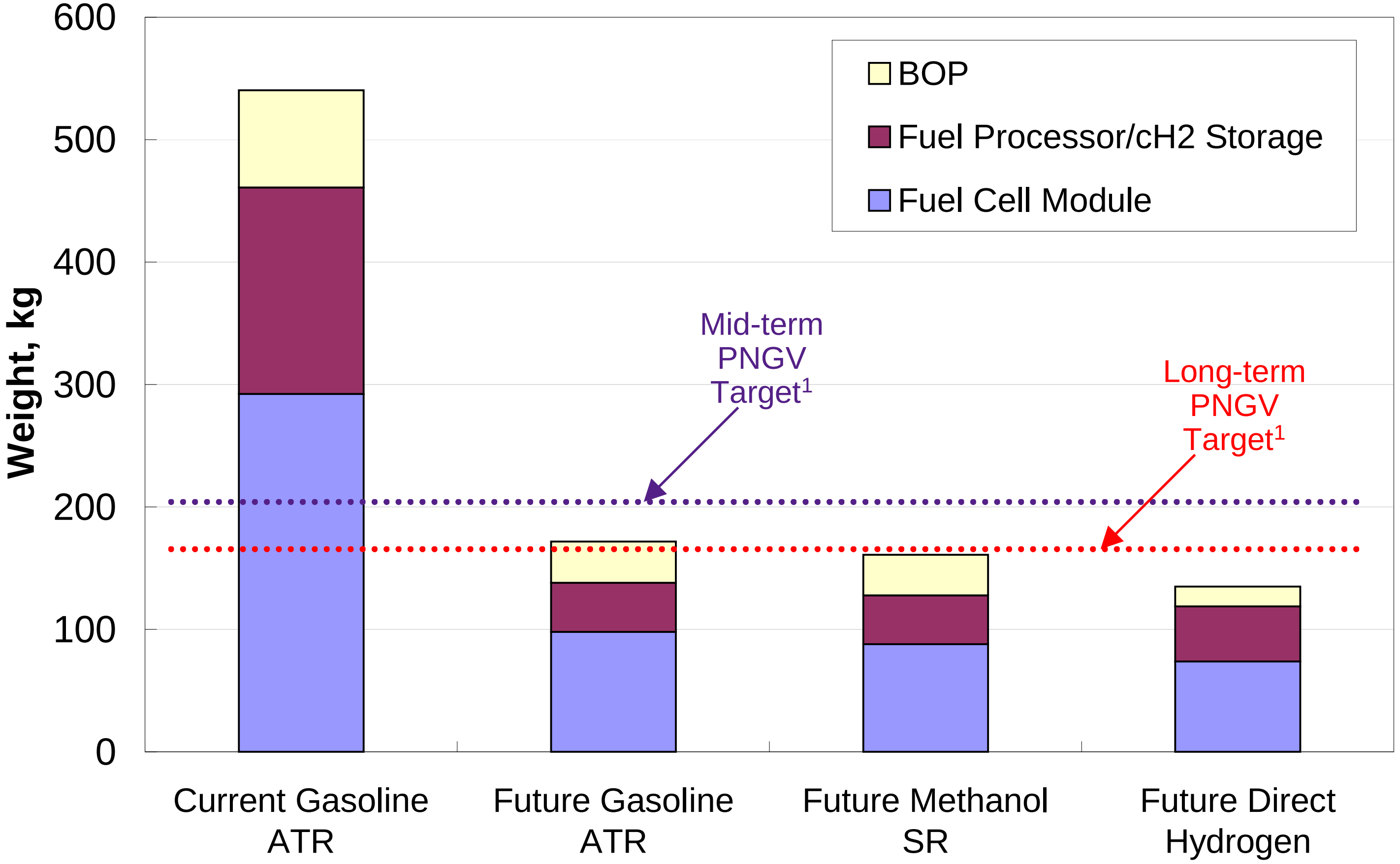
- Projected future cost: $535/kg hydrogen
  - Internal estimate assuming a typical AB5 material
  - Includes thermal management, tank, materials and processing costs
- Projected future weight density: 4.5%
  - Likely be for some chemical hydride material - cost basis will be similar to AB5
- A detailed bottom-up cost and performance analysis has not been performed to date

---

* Higher pressures (10,000 psi) are being developed, but will complicate refueling systems and add on-site compressor power.

The future scenarios' assumptions result in major weight reductions compared with the current technology baseline.

50 kW PEM Fuel Cell System Weights



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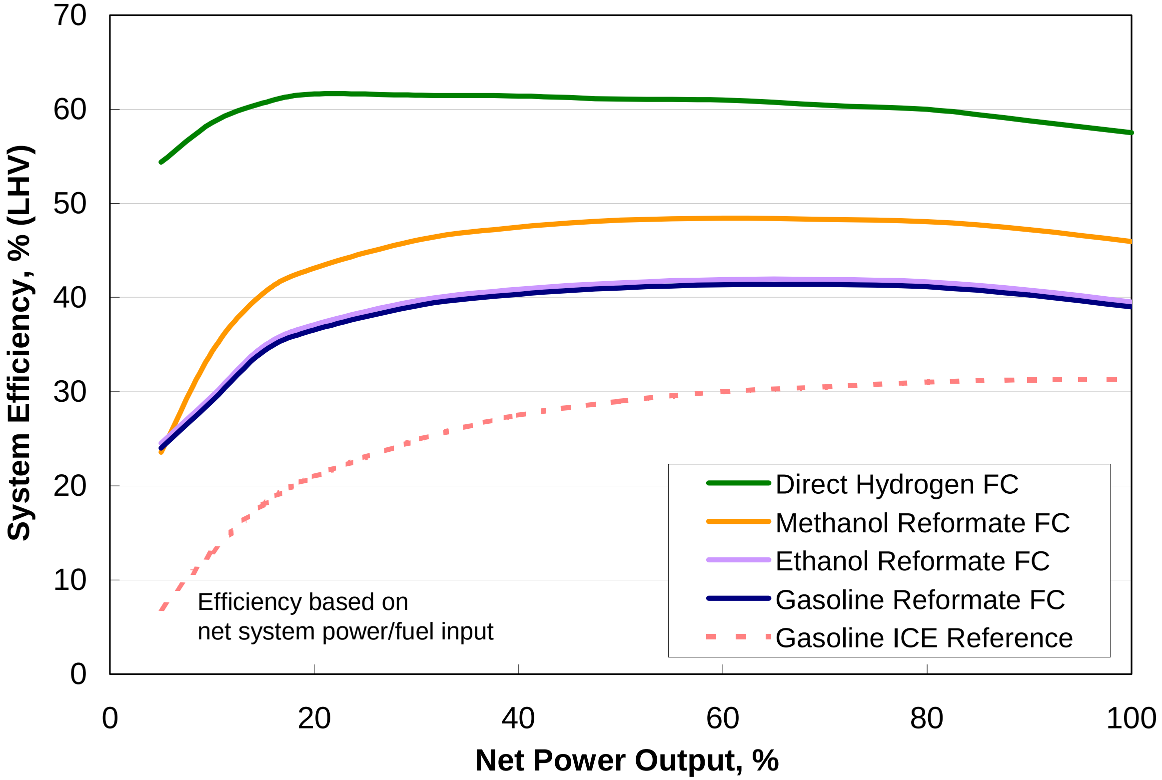
[1] Targets established for fuel cell system with on-board fuel flexible fuel processor and balance of plant.

Details on pages:
A40-46, 70-71, 76

Future projections for part load efficiencies were not available, so we constructed performance curves based on kinetic and thermodynamic analyses.

Power Unit Performance Curve Assumptions

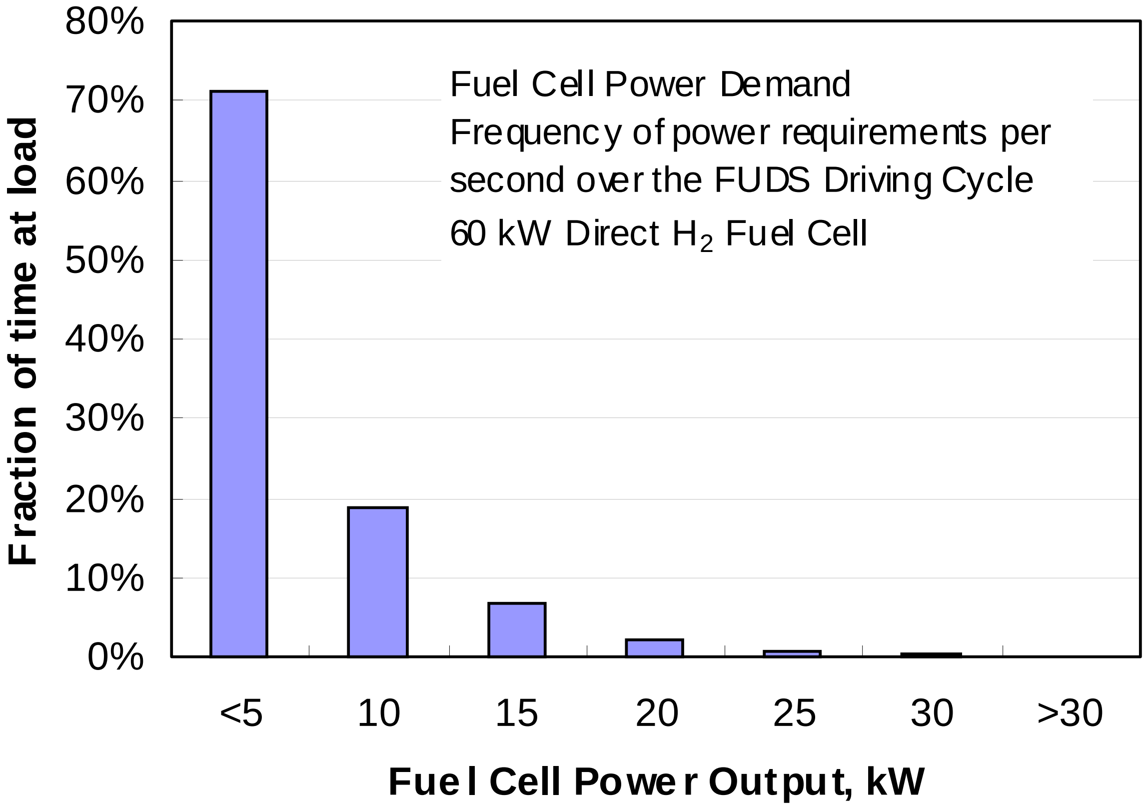


* Includes fuel cell, fuel processor (when present), and parasitic power losses. Motor and power electronic efficiencies are not included in this graph.

All FCVs have higher power unit efficiency than conventional vehicles, but high part-load efficiency sets direct hydrogen FCVs apart from all others.

Part load efficiency is important as city driving conditions require relatively low fuel cell power output.

FUDS Power Requirements for Hydrogen FCV



Our fuel economy results are based on a combination of city (FUDS) and highway (HFET) drive cycles.

Details on pages:
A27-29

Start-up energy demand represents a significant portion of the energy for FCVs with onboard reformers.

- ADL modeled energy inputs based on catalyst volume, heat capacity, system mass, and operating temperature
  - Start-up energy requirements are dictated by the energy input to the catalyst beds
  - Fuel cell generates power with hydrogen feed, even at low temperatures, so no start-up energy input is required
- Start-up energy inputs may need to occur twice a day for typical driving and represents about 10 percent of the typical drive-cycle energy
  - Start-up energy requirement is ATR: 2800 kJ, SR: 2260 kJ for 60 kW systems; and ATR: 1770 kJ, SR: 1430 kJ for 38 kW systems
  - Significant mass reductions in the fuel processor catalyst beds were projected
  - Short trips would have very low fuel economy unless a secondary power source (such as a hybrid battery) were used in place of the fuel cell system
- The best way to reduce start-up energy requirements is to ensure that useful power is produced sooner
  - Broaden the range of temperatures over which power is produced, e.g. by producing power while CO is still high
  - Partitioning the catalyst beds into multiple independent systems
  - Produce power in other ways while reformer is heating up

The difference in turn-down performance and weight necessitates considering different hybridization approaches for different FCVs.

- All FCVs are expected to be hybridized to some extent, even direct hydrogen FCVs
  - Simplifies start-up
  - Improves load-following characteristics
  - Improves fuel economy by storing regen braking energy
- Due to the difference in turndown characteristics and weight, the hybridization of direct hydrogen FCVs will likely be different that that of gasoline FCVs:
  - Shorter start-up time and better turndown characteristics will not require a large battery
  - However, increased regen capability resulting in potential for improved fuel economy, argues for a larger battery
- Vehicle characteristics and likely duty cycle also impact hybridization
- To explore the range of opportunities, we modeled a range of vehicle types and hybridization schemes:
  - Mid-size 5-passenger vehicle and Sport Utility vehicle (SUV)[1]
  - Small (9 kWe fixed) battery; and Large (~30 kWe variable) battery hybridization
  - For the large battery, the fuel cell power is fixed by the top speed or hill climb requirement and the battery makes up the balance required for acceleration

---

[1] SUV detailed results can be found in the appendix section “Additional Analysis Results”.

Details on pages: A37-39

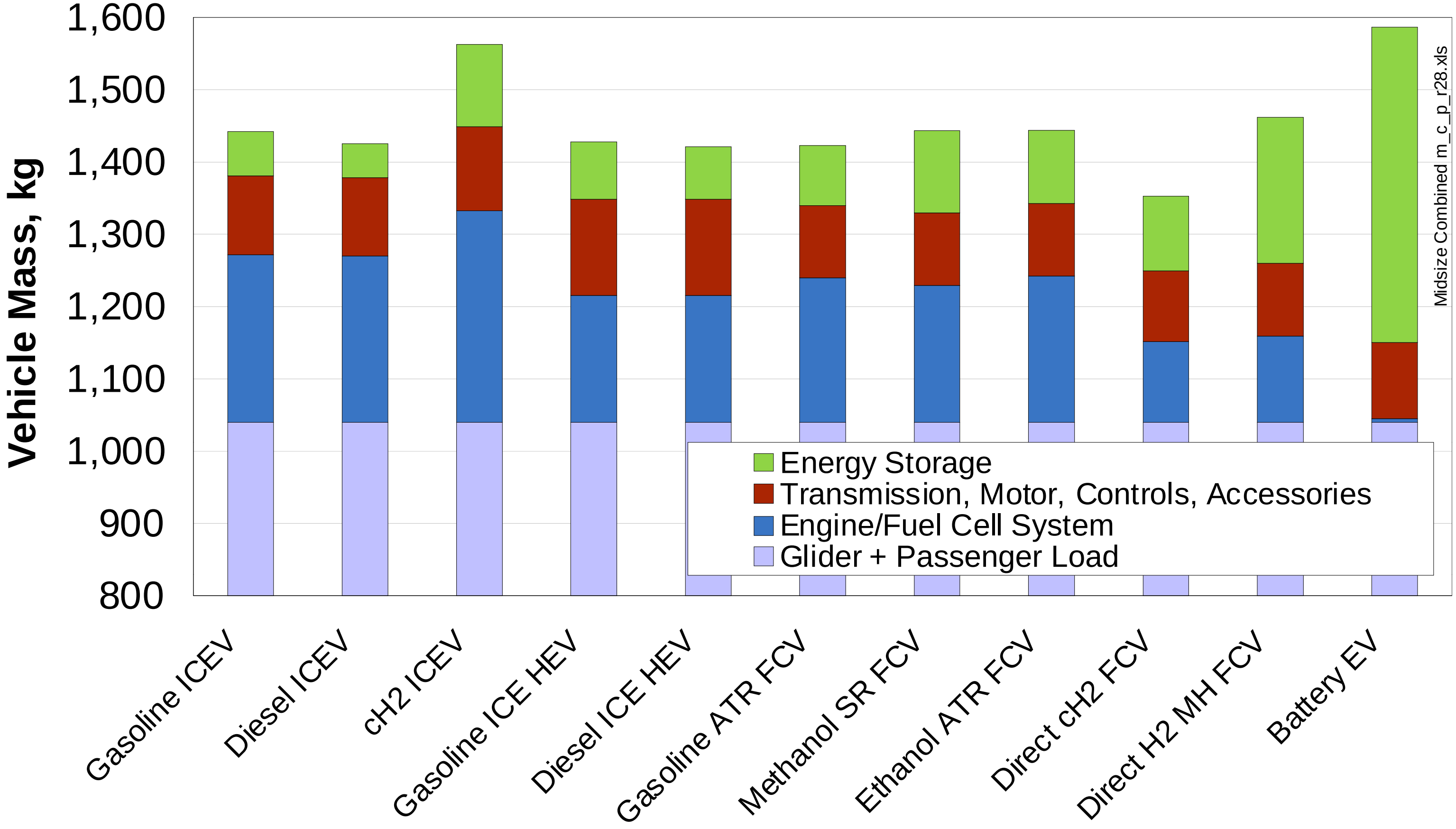
We have assumed advanced NiMH battery performance and cost for our hybrid electric and fuel cell vehicles.

- We assume NiMH hybrid battery design and duty cycle
  - Li ion batteries have not been modeled
    - potentially higher Wh/kg, higher power density, similar cost
- We assume future hybrid batteries will be $400/kWh, 750 W/kg, and 50 Wh/kg for the whole battery pack
  - Developers claim $1,000-1,500/kWh today (low production volumes)
  - Power and energy density assumptions are consistent with high end of current state-of-the art
  - PNGV HEV Specifications are 625 W/kg and 25-75 Wh/kg for PA/R batteries
- Charging and discharging efficiencies are assumed to be 85% each
  - Consistent with current hybrid battery operation

Cost optimization of the hybrid vehicle options strongly depends on the expected battery performance and cost.

With the aggressive future assumptions, reformer-based FCVs could weigh about the same as conventional vehicles...

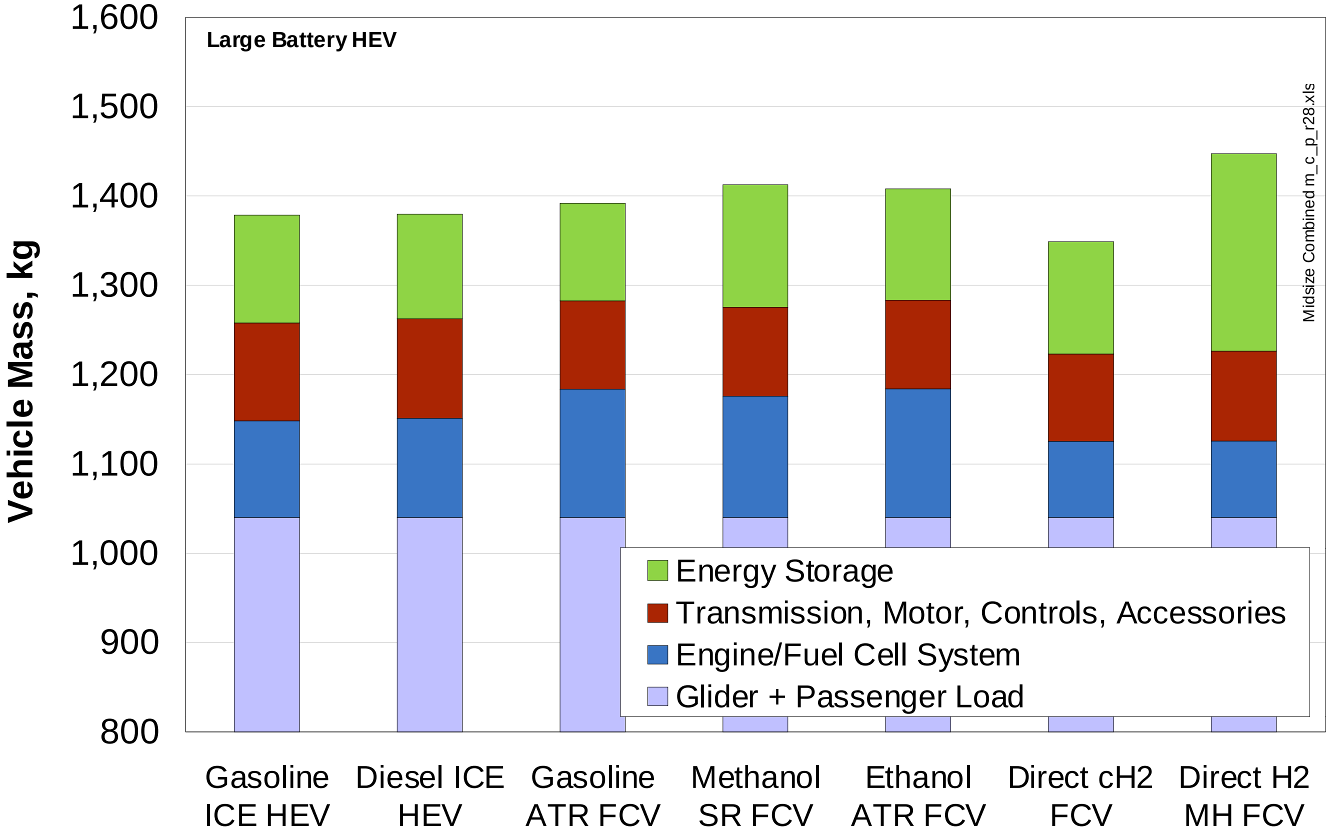
Vehicle Weights for Small Battery Mid-sized Vehicles



... but compressed-hydrogen FCVs could be lighter.

The large battery hybridization scheme reduces vehicle weights slightly due to drivetrain power density improvements[1].

Vehicle Weights for Large Battery Mid-sized Vehicles



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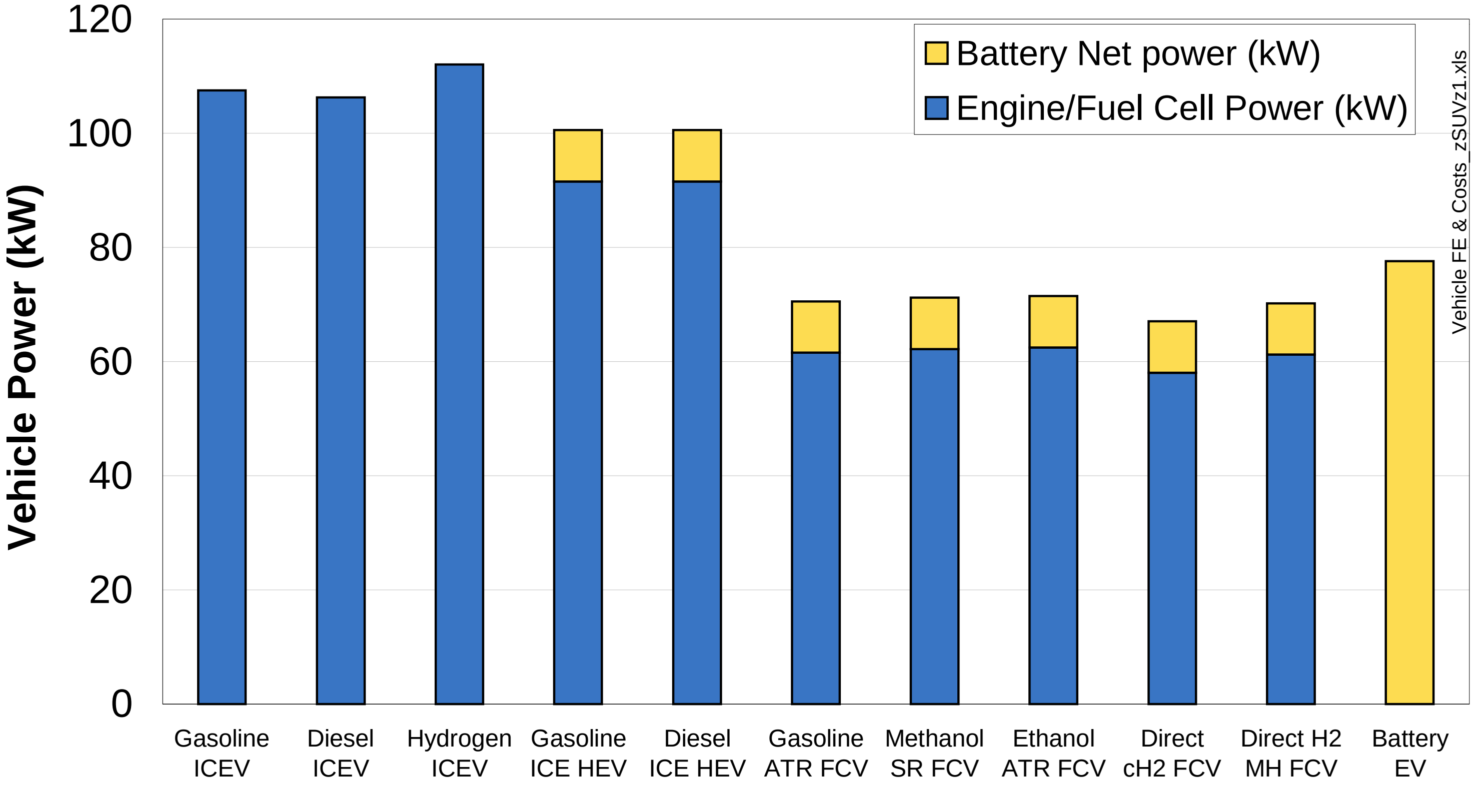
[1] In the case of the FCVs, the power density (kW/kg) is higher for the battery than the fuel cell plus reformer. For the ICE HEV, the power unit changes from a V6 to an L3. The change in engines combined with the change to a continuously variable transmission (CVT) results in a small mass reduction.

Details on pages:
M12; A34-36

Vehicle maximum power requirements vary considerably due to differences in powertrain characteristics, the mass of the powertrain and the fuel.

Power Requirements for Small Battery Midsize Vehicles



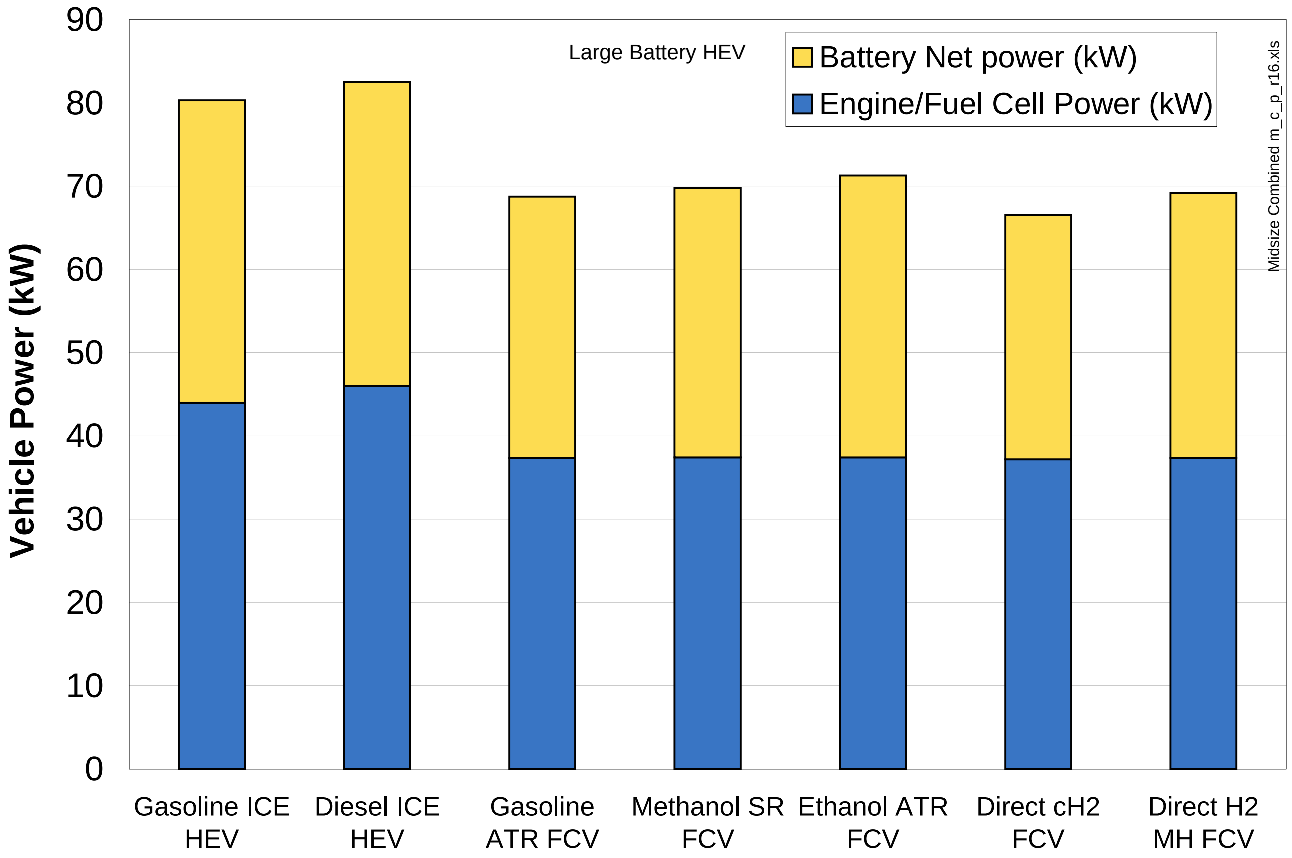
ICEVs require higher peak power in order to meet low speed acceleration requirements typical for US markets*.

* Other markets may have different requirements that would change this analysis substantively

Details on pages: M12; A34-36

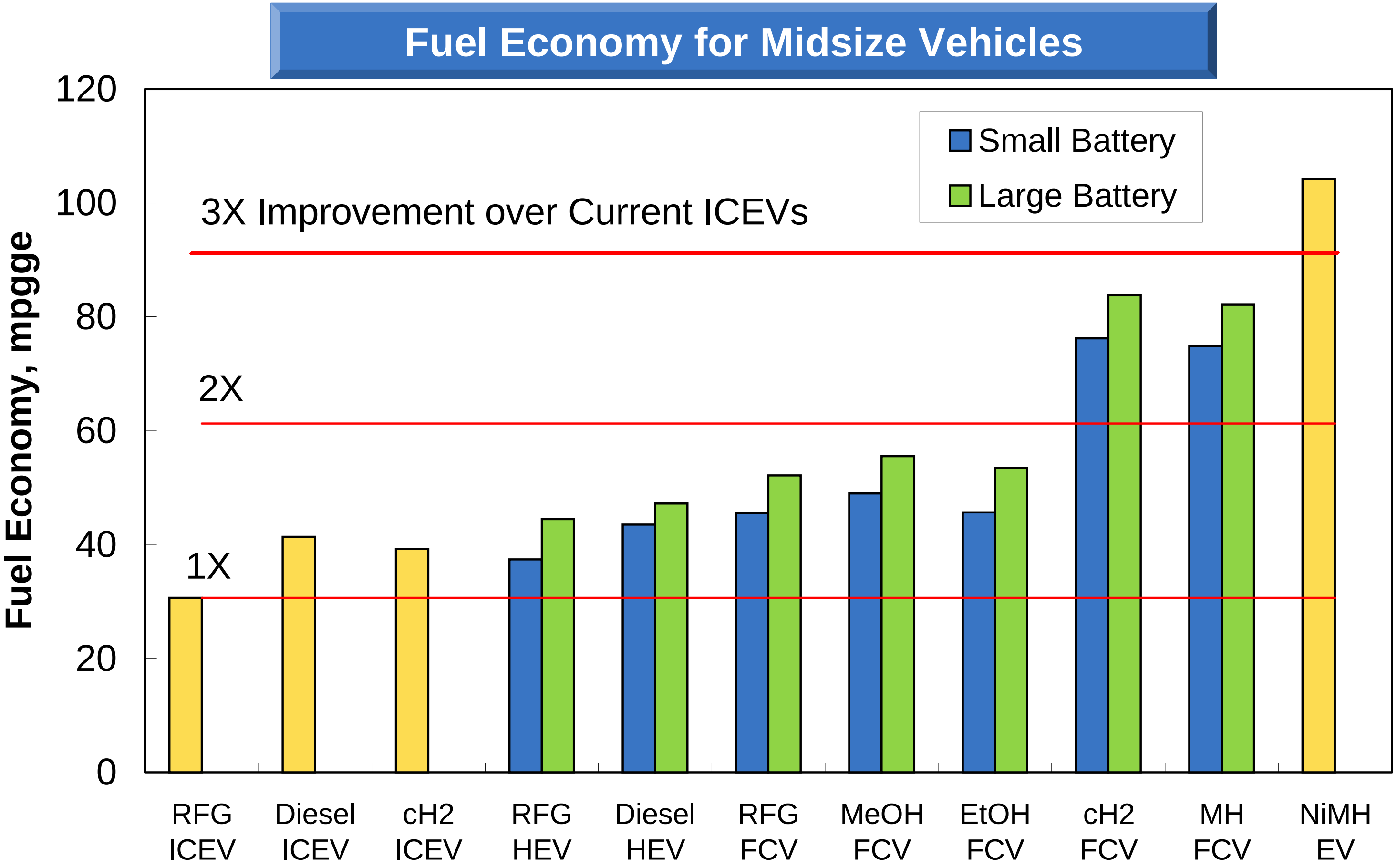
Choosing a larger battery of course considerably lowers the prime mover power requirements.

Power Requirements for Large Battery Midsize Vehicles



* Because ICE-HEVs are expected to be parallel hybrids, they still require a relatively large engine. If the hybrids were series, the overall power would be similar to the FCVs.

Under the future scenarios, the direct hydrogen FCV gives more than 2.5 times better fuel economy than the conventional gasoline ICE vehicle.



The large battery cases give better fuel economy, due to greater regenerative braking, so we used it for the subsequent well-to-wheel analysis.

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Fuel cell powertrains can achieve substantially lower well-to-wheels energy consumption than ICE-based powertrains.

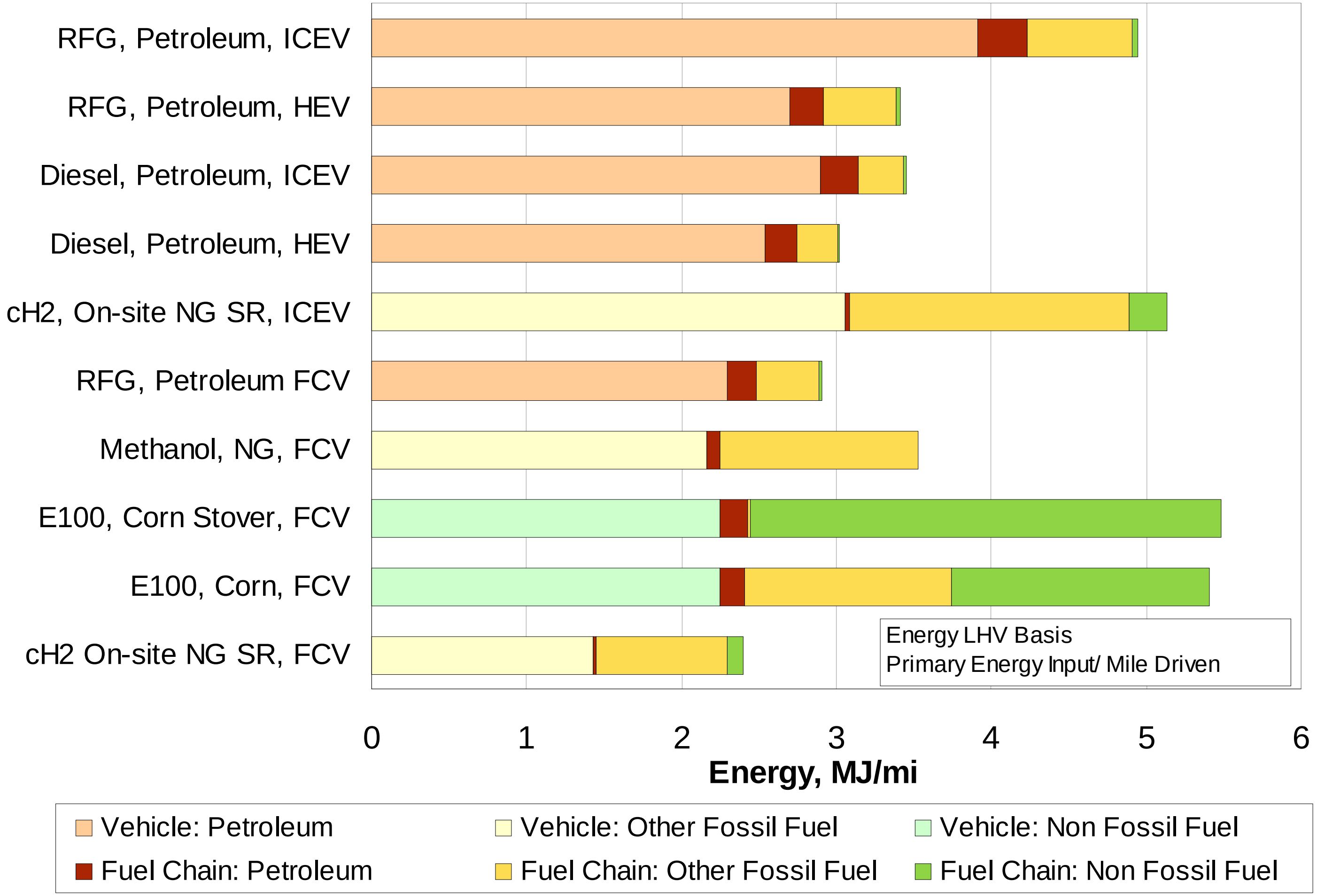
- Advanced CIDI engine vehicles using petroleum-based diesel fuel will likely be able to achieve similar energy efficiency to gasoline reformer-based FCVs
  - Methanol FCVs have higher well-to-wheels energy consumption, despite high vehicle efficiency, due to significant losses incurred in fuel production
- The inefficiency of ethanol production leads to well-to-wheel primary energy consumption for ethanol FCVs slightly above that of conventional vehicles
  - Primary fossil fuel consumption is of course strongly reduced
- Compressed hydrogen FCV options via centralized or decentralized production from natural gas can provide the most fuel efficient options:
  - Provided hydrogen production facilities are thermally well-integrated
  - Provided high vehicle fuel economy can be attained
  - If transportation distances from the central plant are modest (50 miles or less) using pipeline or tube trailers
- Hydrogen via electrolysis and battery EV options have high well-to-wheels energy consumption due to the relative inefficiency of power generation

Hydrogen-fueled FCVs are likely to provide the lowest greenhouse gas emissions of the non-renewable fuel chain options.

- Direct hydrogen FCVs can cut greenhouse gas emissions by 60% compared with conventional gasoline-fuel ICEVs
  - Integrated fuel production from natural gas (low-carbon fuel) leads to modest fuel production emissions
  - Vehicle greenhouse gas emissions are zero
  - Advanced diesel CIDI vehicles can achieve about half of this emissions reduction
- Gasoline and methanol FCVs have higher greenhouse gas emissions than most direct hydrogen fuel chains but lower than all ICE-based fuel chains
- In other studies, we found that greenhouse gas emissions could be reduced by over eighty percent if the right renewable energy sources are applied:
  - Hydrogen from electrolysis using wind, solar, or biomass power
  - Bio-ethanol from advanced cellulosic processes

Details on pages: M11-12

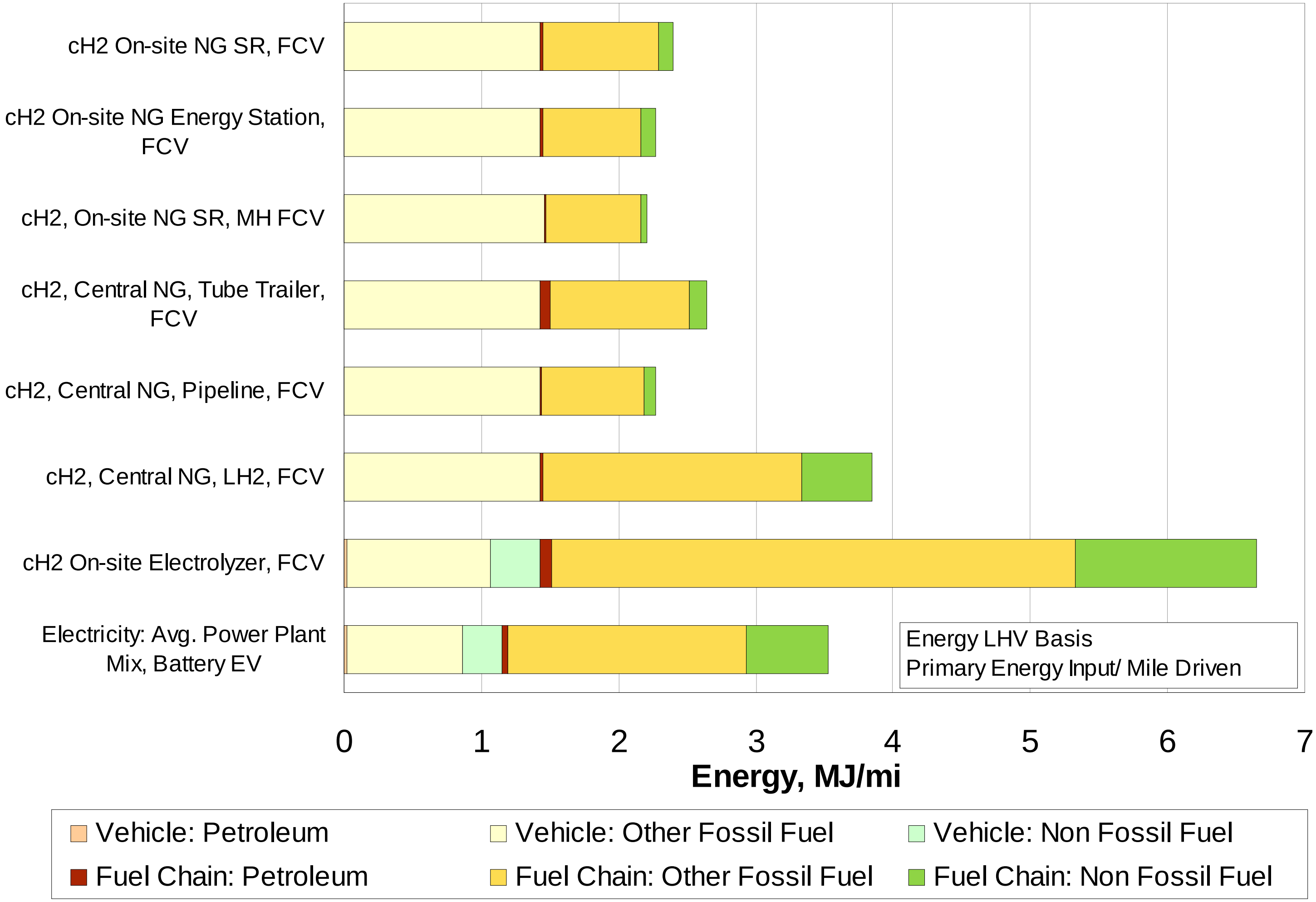
On a well-to-wheels basis, direct hydrogen FCVs may reduce energy consumption by more than 50% over gasoline ICEVs...



... and gasoline reformer FCVs offer a 40% reduction.

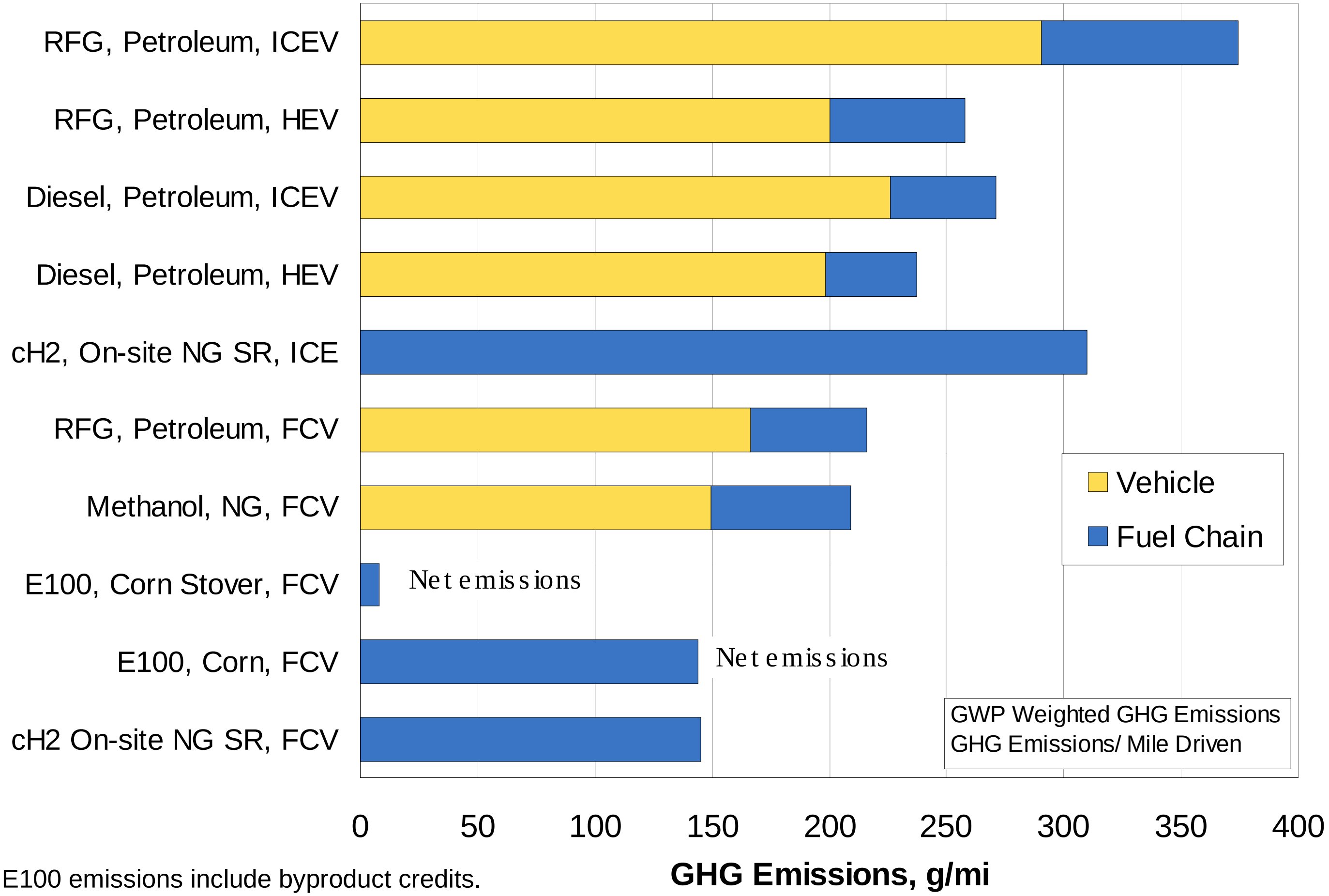
Details on pages: M11-12

Hydrogen via electrolysis and battery EV options have high energy consumption due to the relative inefficiency of power generation.



* Electrolyzer energy consumption assumes a US average mix of grid power.

On a well-to-wheels basis, natural gas based direct hydrogen FCVs could reduce greenhouse gas emissions by 60% compared with gasoline ICEVs...

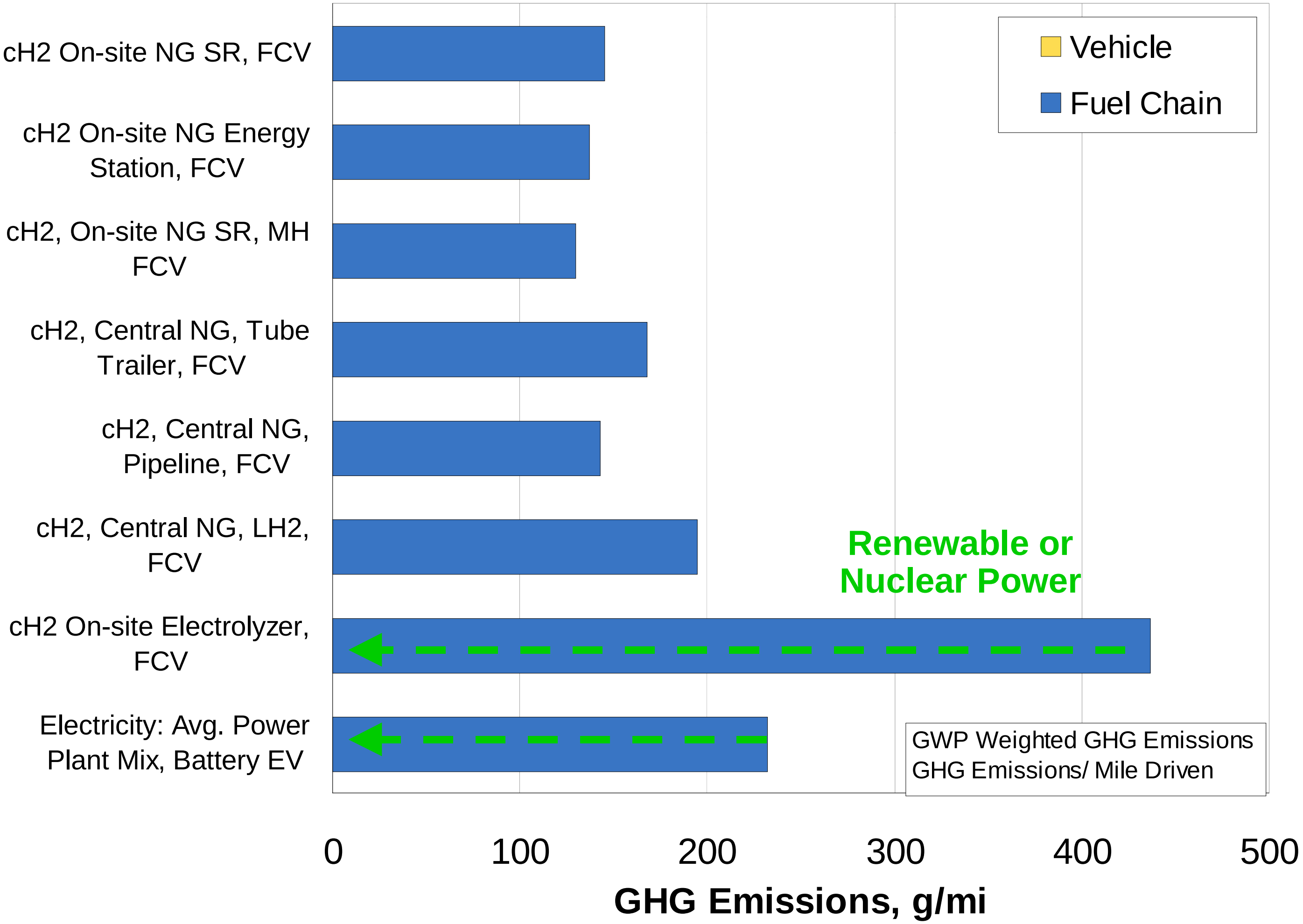


* Net E100 emissions include byproduct credits.

... comparable to current ethanol technology but still far higher than advanced (cellulosic) ethanol technology options.

Details on pages:
M11-12

The lowest GHG emissions can be achieved by direct hydrogen vehicles using hydrogen made from renewable or nuclear power...



… even considerably lower than renewable ethanol.

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The most economical hydrogen fuel chains are expected to be over two times more expensive than gasoline, on a $/GJ basis.

- Capital costs are five to ten times more expensive than gasoline capital costs (including local and central plant capital)
  - Limitations in maximum train size (compared with refineries) and system complexity lead to high central plant capital cost
- Transportation and distribution costs (including compression and storage) are far higher than those for gasoline
- High feedstock cost dominates the high cost of locally produced hydrogen
- Electrolyzer-based production is costly with EIA energy price projections
  - Competitive with natural gas based reforming only if industrial electricity rates ($0.04/kWh) can be obtained at local fueling stations
  - When off-peak electric power is used, electrolysis equipment cost is higher because of low equipment utilization
- Alternative fuels, especially hydrogen, will require a significant upfront investment, representing a risk to both vehicle manufacture and fuel provider
  - Dealing with this risk represents a formidable barrier to the use of hydrogen for FCVs

Conventional fuels are expected to be by far the least expensive fuels on an energy content basis.

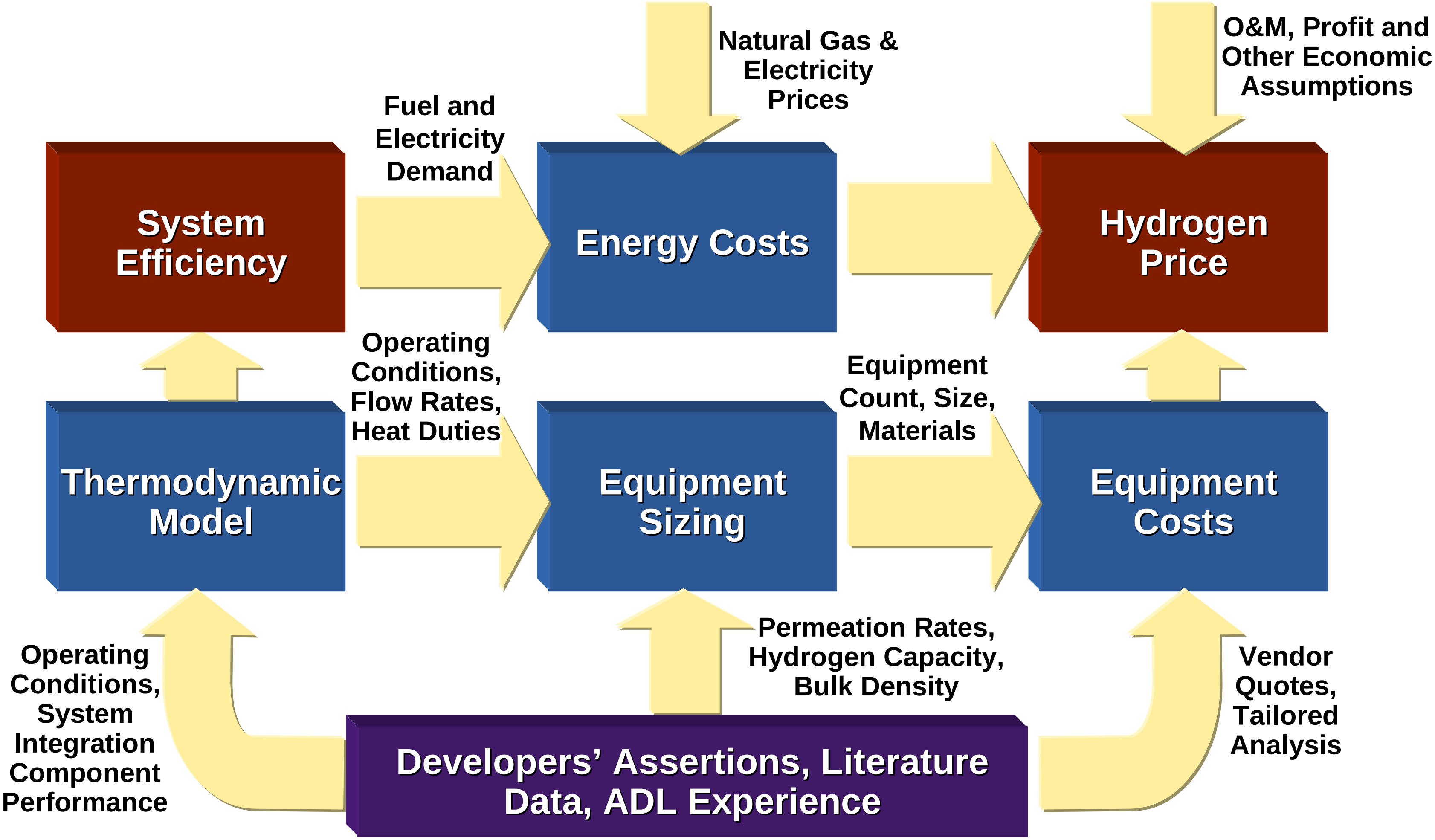
- EIA projections for conventional fuels do not show an appreciable upward trend by 2010
  - Eventually only expensive-to-produce oil resources will be left and conventional fuel prices will start to rise significantly, but this will be well after 2010
  - Development of other renewable fuels such as GTL will slow this rise
- Ethanol is expected to be around two times more expensive than gasoline when government subsidies are excluded
  - Assumes short transportation distances (50 miles)
  - Low conversion yield from biomass despite improvements with cellulosic biomass technology
  - Expensive processing
  - Further improvements beyond 2010 could eventually reduce cost to around 1.5 times conventional fuels
- Future wholesale methanol price projections are close to gasoline prices on a $/GJ basis
  - Assuming large-scale fuel-methanol plants will be built in regions with remote or stranded gas
  - Delivered fuel prices are slightly higher due to higher transport & distribution cost

Details on pages:
M22; A7, 14-17

Fuel costs are based on EIA price projections and on bottom-up estimates for hydrogen and other alternative fuels.

- Conventional fuel and electricity costs are based on EIA commodity price projections for 2010
  - Gasoline and diesel prices are based EIA projections for crude oil and historical price spreads between petroleum products and crude oil
- For non-hydrogen alternative fuels, bottom-up analyses from previous Arthur D. Little studies were used
  - Methanol costs relied on extensive GTL analyses performed for a range of studies vetted by several key methanol industry players
  - Ethanol costs are based on a previous ADL Biomass study and *The USDA 1998 US Ethanol Cost of Production Survey* (Shapouri, 1999)
- Costs of hydrogen are based on bottom-up cost analysis following the fuel chain analysis:
  - Fuel and electricity costs are estimated based on commodity price forecasts and fuel chain energy inputs
  - Local fueling station capital costs are based on modeling and vendor quotes adjusted for higher production volumes (100 units/yr) using progress ratios
  - Transportation and central plant capital costs are based on published data
  - Corporate expenses and other costs are consistent with industry practice
- Fuel sales and excise taxes are excluded

Thermodynamic modeling helped determine overall hydrogen costs by providing energy requirements and equipment sizing inputs.



Several key cost assumptions were made for the local hydrogen fueling stations.

Local Fueling Station			Notes
FCV capacity	300	vehicles/day	Design basis
Liquid fuel per fillup	8	eq. gal/fil	ADL data, experience
Hydrogen per fillup	2.3	kg/fill	Equivalent range
Capacity factor	90	%	Industry experience
Power price	0.07	$/kWh	EIA 2010 commercial rate
Natural gas price	5	$/MMBtu	EIA 2010 commercial rate
Labor requirement	18	hours/day	Field observation
Labor rate	10	$/hour	Field observation
Fuel/convenience store	50	% of overhead	Industry experience
Installation costs	33	% of TIC	ADL experience
Finance life	15	years	Industry experience
Salvage value	10	%	Engineering estimate
Discount rate	8	%	Industry experience
Operator margin	0.2	$/fill	EIA Petroleum Primer

* Financial assumptions reflect typical capital productivity expectations.

A different set of cost assumptions were made for the central hydrogen plant options.

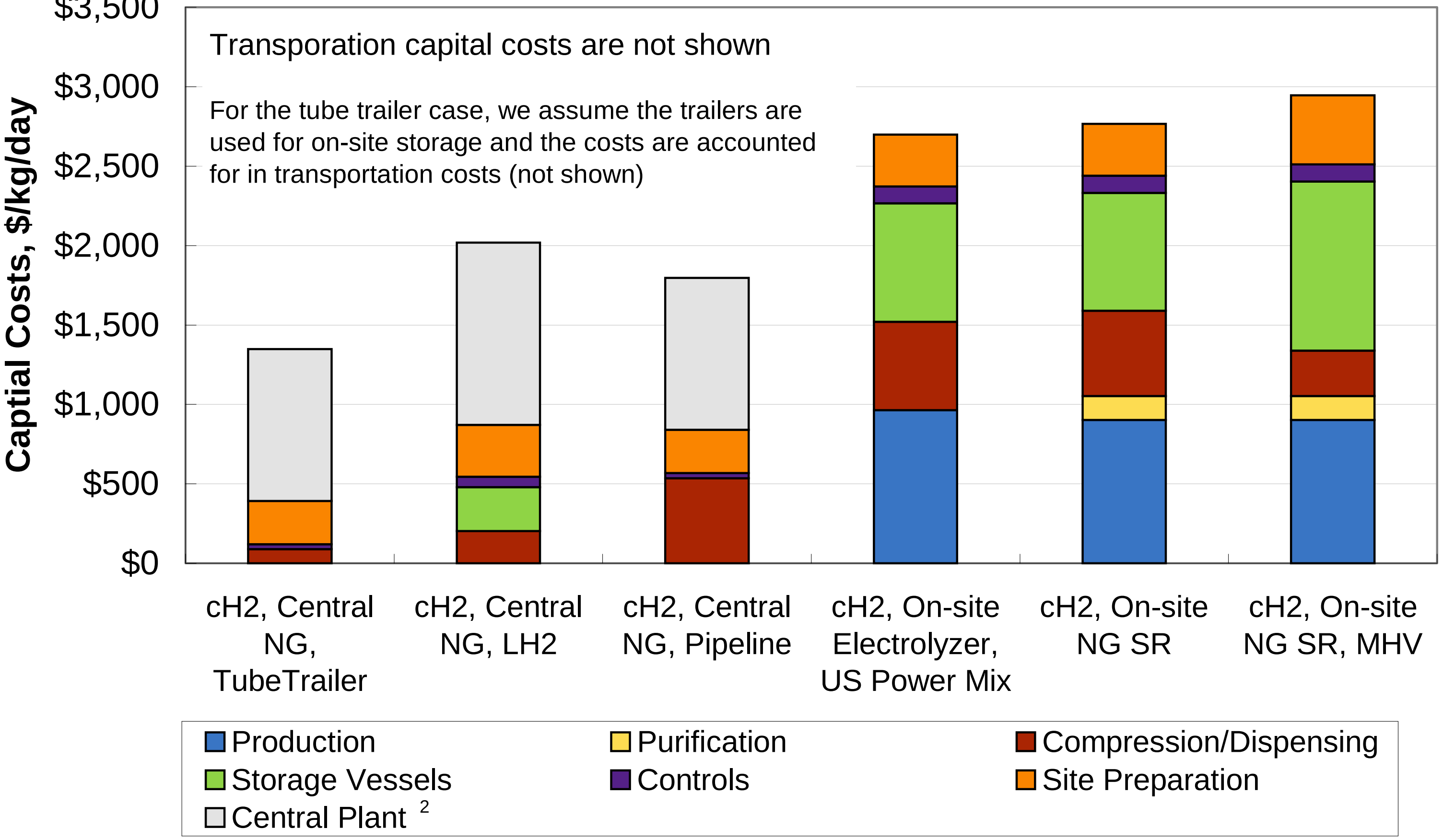
Central Hydrogen Plant			Notes
Daily Production	300	tonne H2/day	Design basis
Stream days	330		Industry experience
Power price	0.04	$/kWh	EIA 2010 industrial rate
Natural gas price	3	$/MMBtu	EIA 2010 industrial rate
Finance life	10	years	Industry experience
Salvage value	10	%	Engineering estimate
Discount rate	11	%	ADL experience
Operator profit	0.15	$/kg H2	Engineering estimate
Truck transport distance	50	miles	Assumed for urban area

* Financial assumptions reflect typical capital productivity expectations.

Details on pages: A14, 16

Local fueling station capital costs are significant, ranging from $300,000 to $2 million per station, far outstripping franchise owners' resources.

Hydrogen Fueling Station Capital Costs[1]



Transporation capital costs are not shown

For the tube trailer case, we assume the trailers are used for on-site storage and the costs are accounted for in transportation costs (not shown)

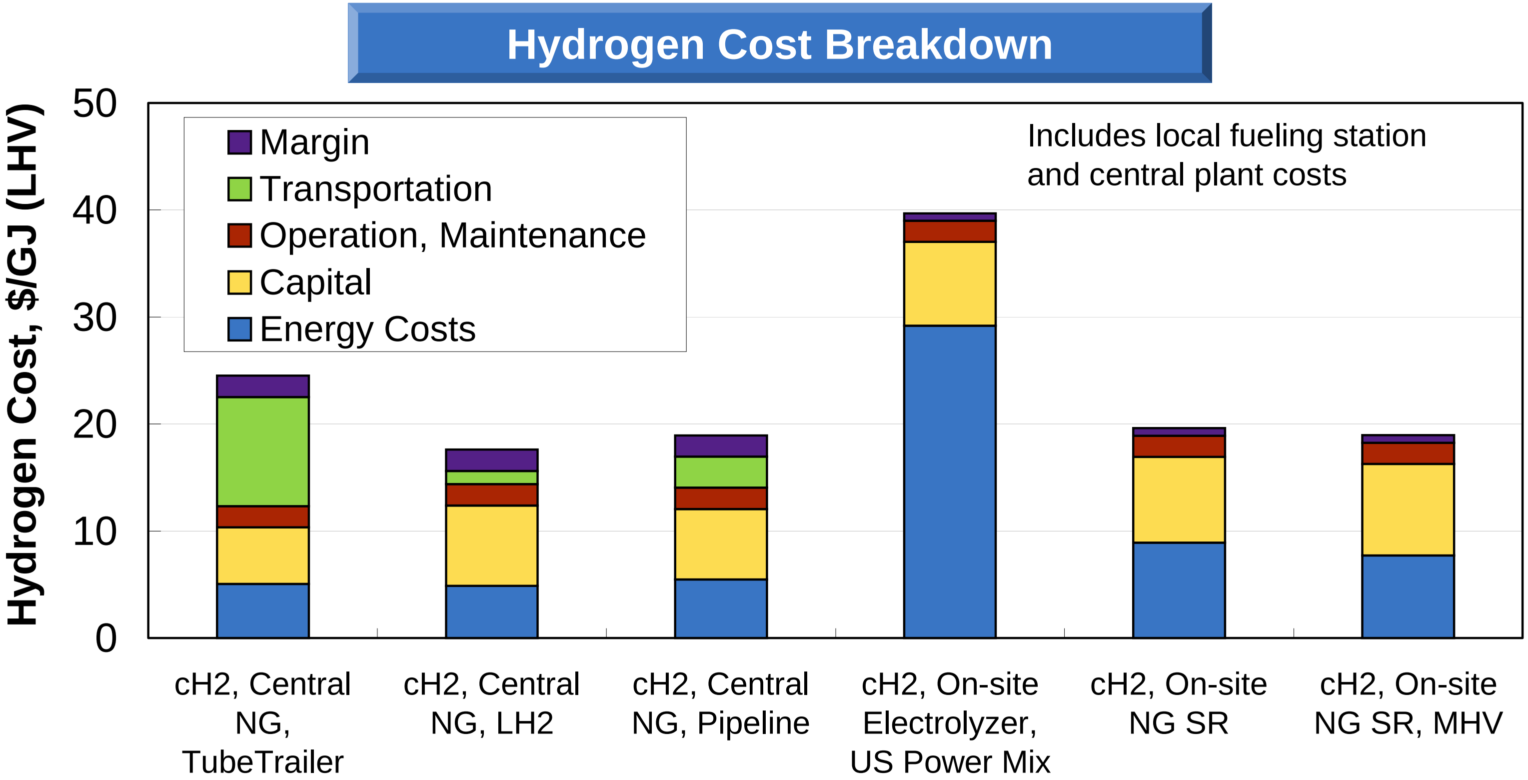
[1] Fueling station capacity is 690 kg hydrogen/day.

[2] Central plant capital costs are shown for comparison, but are not part of the fueling station cost

Hydrogen transport costs for the central plant options are in keeping with respective industry expectations.

Hydrogen Transportation			Notes
Liquid Hydrogen			
Average Distance	50	miles	Industry Experience
Cost	500	$/truck	Industry Data
Load	3350	kg/truck	Industry Data
Transportation Cost	0.15	$/kg	ADL Estimate
Pipeline			
Average distance	50	miles	Design Basis
Transmission rate	0.15	GW	Design Basis
Transportation Cost	0.35	$/kg	Industry Experience
Tube-Trailer			
Average distance	50	miles	Industry Experience
Load	520	kg/trailer	Industry Data
Transportation Cost	1.22	$/kg	ADL Data

Most hydrogen production options range in cost (before taxes) from about $15 to $25/GJ.

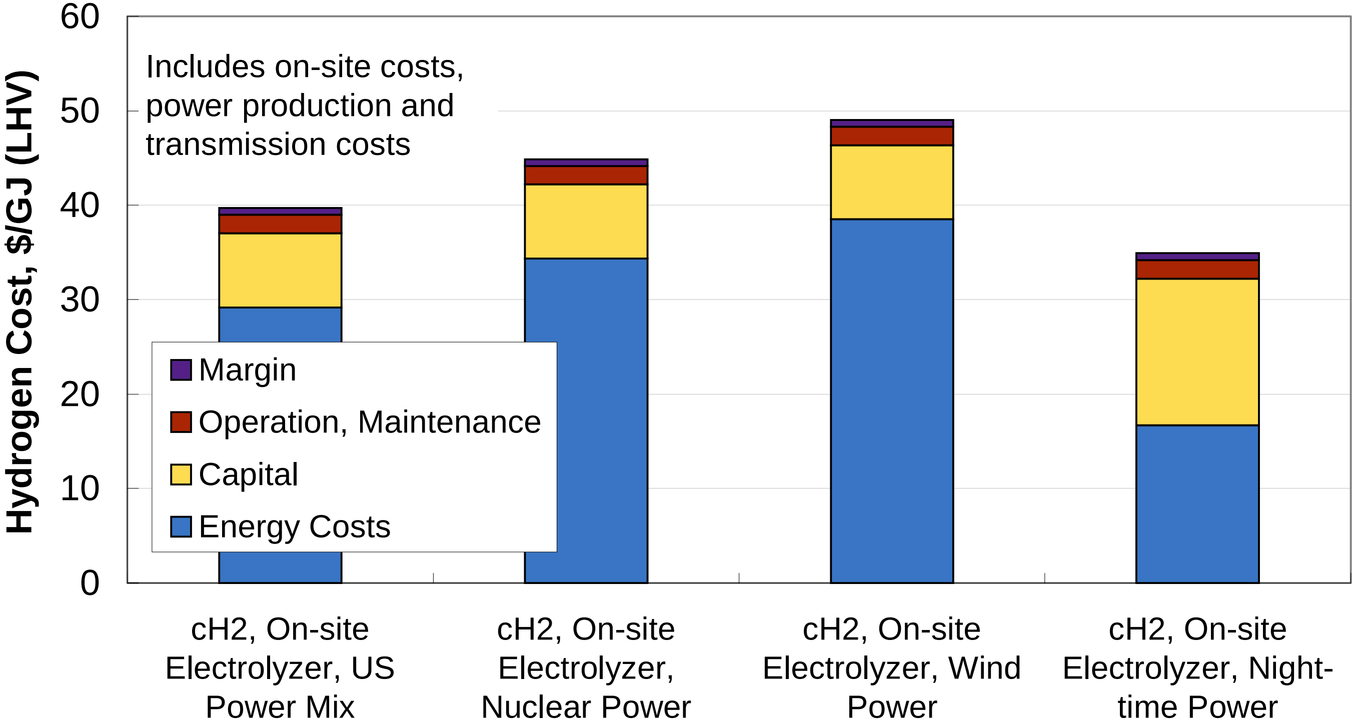


- Central plant costs were calculated based on internal and published values for energy demands and costs for capital, O&M, profit, and transportation
- Local fueling station operating costs and profit are consistent with current gasoline stations
- Local electricity and natural gas prices are assume to be 2010 EIA projected commercial rates of $0.07/kWh and $5/MMBtu, respectively

Details on pages: A14,16-17

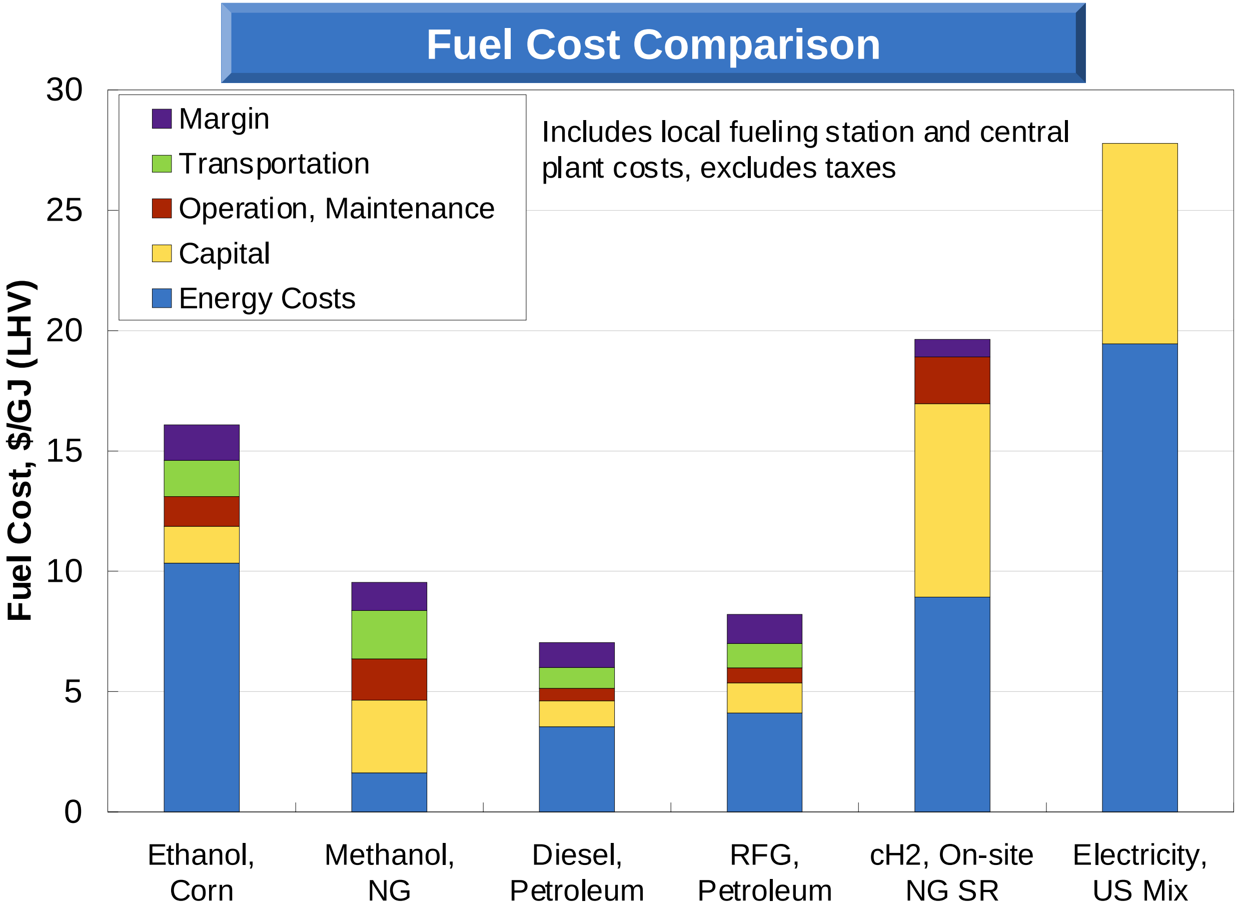
Even with optimistic assumptions on renewable and nuclear power cost, electrolysis-based hydrogen would be more expensive than natural gas based hydrogen.

On-site Electrolyzer Cost Breakdown



- US Power Mix, Nuclear, and Wind electricity prices are assumed to be 0.07, 0.08, and 0.09 $/kWh
- The night-time power case assumes the use of cheap off-peak renewable power for $0.04/kWh
  - Energy costs are much lower, but capital cost of this case is higher due to a reduced capacity factor

Hydrogen fuel from natural gas is about two and a half times more expensive than gasoline on a $/GJ basis.



* Local electricity and natural gas prices are assume to be 2010 EIA projected commercial rates of $0.07/kWh and $5/MMBtu, respectively. Central Plant rates are assumed to be projected industrial rates of $0.04/kWh and $3/MMBtu. Electricity case assume $0.03/kWh capital cost for the charging unit.

Details on pages:
A94-101

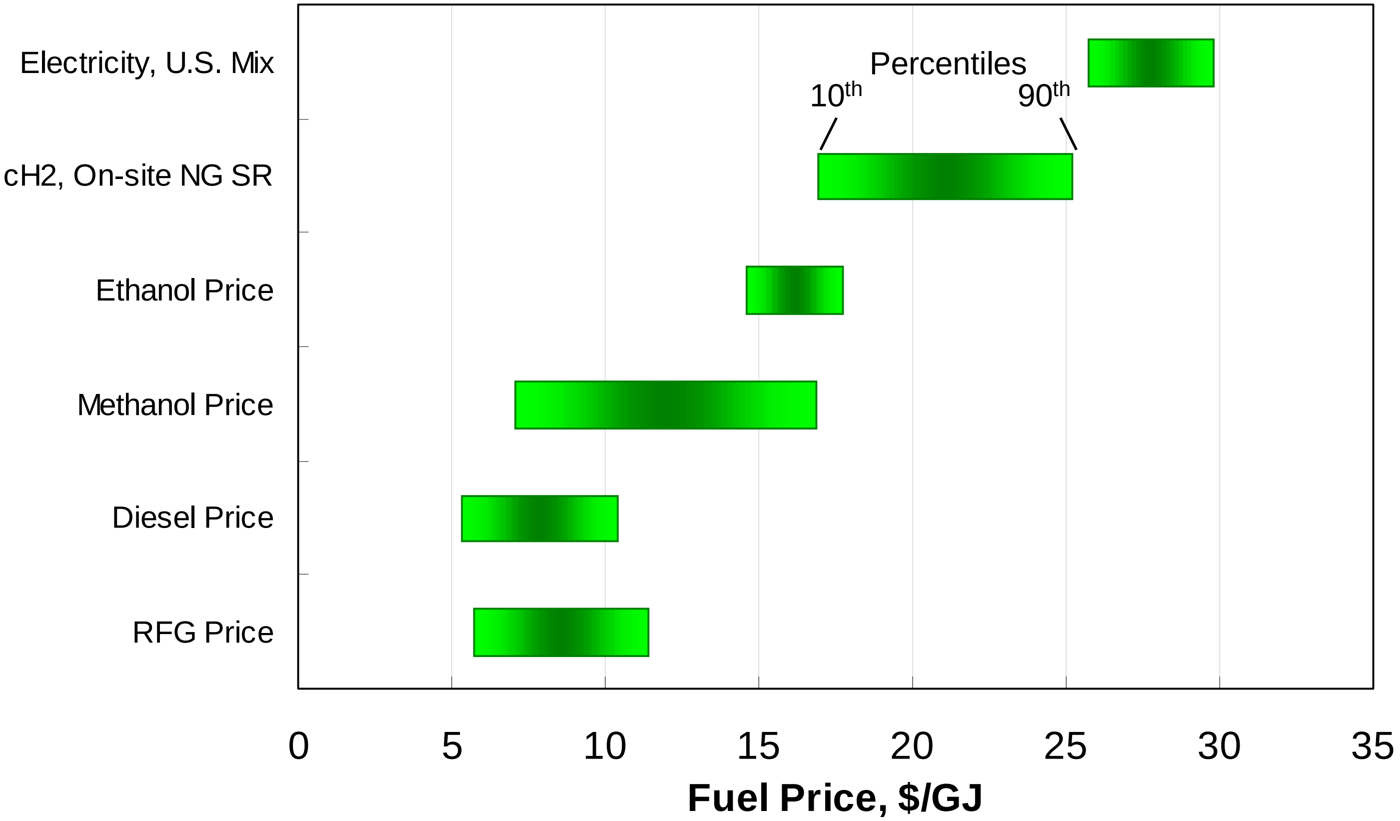
We analyzed the uncertainty in fuel costs with a Monte Carlo simulation of input variables.

Factor Influencing Cost	Basis for Uncertainty Estimate
Input Fuel Prices[1]	Lognormal distribution with standard deviations based on historical fuel prices (See Appendix)
Fueling Station Costs	Assumed +/- 15% uncertainty due to fuel transportation and fueling station costs (capital, operation, and maintenance)
Power Generation Capital Costs	Assumed +/- 15% uncertainty in wind and nuclear power capital costs for the on-site electrolzer scenarios

[1] The input fuel to the SR based hydrogen fueling stations or central production facilities is natural gas. Electricity is the input fuel for electrolyzers.

Even taking into account possible variations in fuel cost; electricity, hydrogen and ethanol are likely to be substantially more expensive than gasoline...

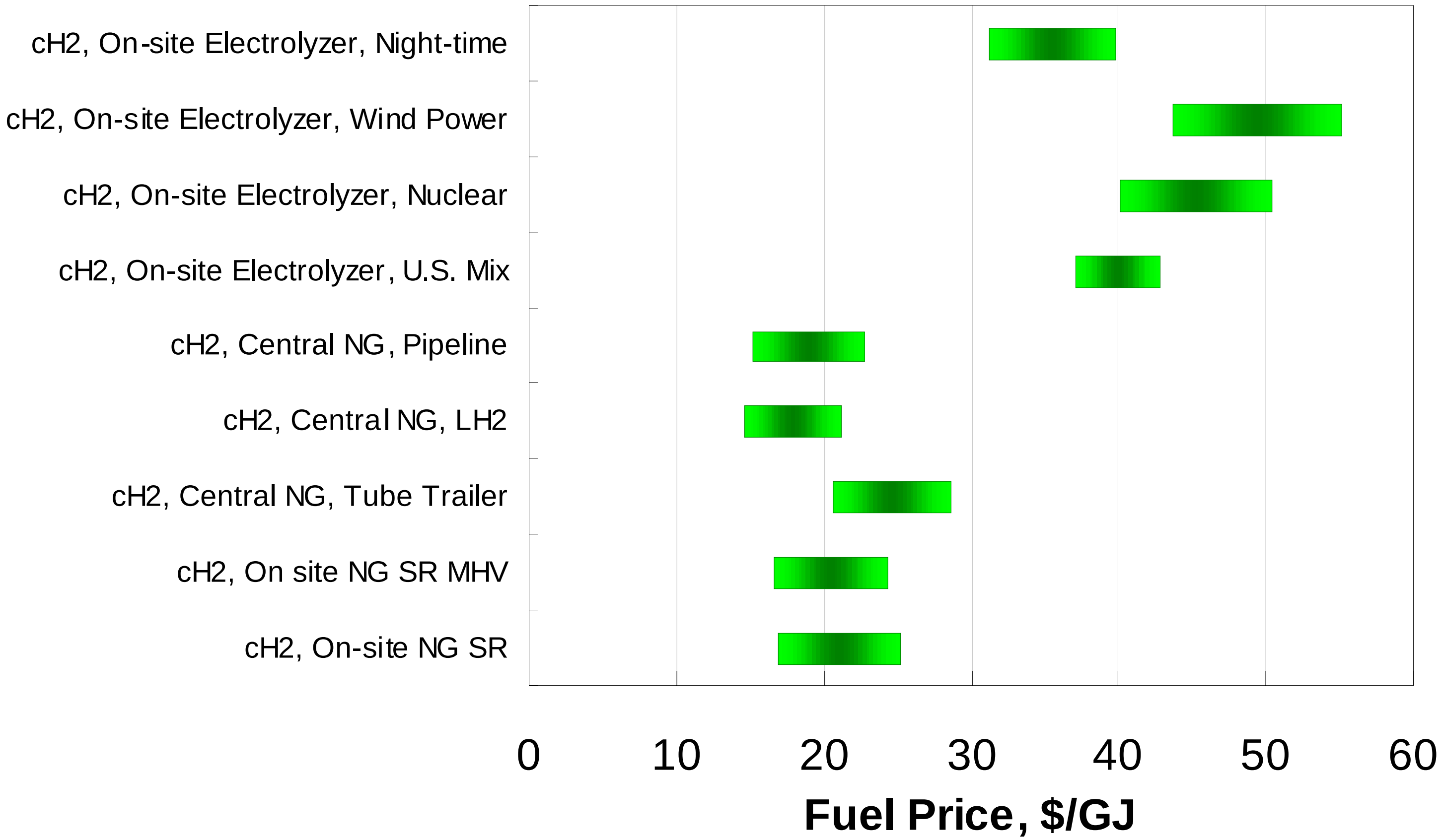
Sensitivity Analysis - Fuel Costs (LHV)



... while methanol may be competitive with gasoline and diesel in certain scenarios.

Uncertainty over electric power costs exacerbates the high cost of hydrogen from electrolyzers.

Sensitivity Analysis - Fuel Costs (LHV)



Outline

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- Background, Objectives & Scope
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- **Cost**
  - Fuel Chain
  - **Vehicle**
  - Well-to-Wheels
- Sa
- Concl

Substantial additional technology breakthroughs will be required to achieve FCV cost competitiveness with ICEVs.

- The cost difference between hydrogen-fueled FCVs and HEVs appears to be significant, around $4,000 per vehicle, given our assumptions
- Taking into account a wider range of assumptions, this difference may range from around $2,000 to around $10,000
  - Actual cost of HEVs and ICEVs varies and is not well-known (publicly):
    - No bottom-up cost-estimate for HEVs was performed
    - Some current manufacturers of HEVs indicate our HEV estimates are too low
    - ICE production costs vary widely and are not easy to obtain
  - FCV cost estimates are subject to several uncertainties which may increase or decrease the cost:
    - Vehicle cost and performance results in this study are based on aggressive technology scenarios for all FCV system components
    - FCV cost may be reduced by $1,000-1,500 more if the stack were designed for high peak power density rather than high efficiency
- However, FCVs costs, even reformer-based FCVs, would be lower than battery EVs costs while offering much higher range under these scenarios

The cost and performance of the fuel cell stack remains the key barrier in achieving cost parity with HEVs or conventional vehicles.

- The additional cost being projected for FCVs over conventional and HEV platforms is clearly significant
  - Current FCV power unit cost is 2-3 times the DOE/PNGV target of $45/kW
  - System components not counted in the $45/kW target further increase difference in cost with ICEVs
  - By using different assumptions, the gap could be reduced but would remain significant
- The differences in cost between various FCV fuel choices is significant, but does not appear deciding compared to the difference with ICEVs
- Stack remains key to further improving the cost of FCVs
  - Stack cost by itself remains the largest FCV power unit component
  - Power density, CO tolerance, and other performance limitations determine the need for other subsystems
- However, in order to further reduce FCV cost, the cost of other subsystems and components will also need to be addressed
  - Future scenarios for motor and power electronics costs are nearly as expensive as the fuel cell stack

Powertrain costs for compressed-hydrogen FCVs would be significantly lower than those of systems with on-board reformers in our scenarios.

- Fuel processor-based FCVs are projected to cost $1,000-$2,000 more than compressed cH_2 vehicles:
  - Fuel processors add cost directly
  - Fuel processors add weight, which increases power requirements to achieve desired performance, thus adding to entire power unit cost
  - Reformers impact the performance of the fuel cell stack, and cause its cost to increase:
    - Due to poorer fuel quality of reformate (compared with pure hydrogen), including dilution and poisoning effects (CO and S), reformer-based fuel cell stacks must be larger or have higher platinum loadings
    - The reformer losses significantly impact the well-to-wheel efficiency; if direct hydrogen FCVs were optimized to achieve the same efficiency, their cost could be reduced further (this was not done for this study)
- Fuel processor-based FCVs would cost roughly the same as metal hydride-based FCVs

Nevertheless, the difference in cost does not appear decisive by itself in light of the difference in cost between all FCVs and HEVS and ICEVs.

Cost of methanol steam reformer-based FCVs are somewhat lower than those of gasoline/ethanol ATR-based FCVs.

- Methanol steam reformer itself is somewhat less complex than gasoline or ethanol ATR:
  - Maximum operating temperature is much lower, simplifying heat integration
  - High temperature shift reactor (or equivalent) can be avoided
- Methanol steam reformer produces somewhat higher quality reformate:
  - No nitrogen diluent means the hydrogen partial pressure almost equals that of hydrogen systems (after anode humidification)
  - CO control (if needed, unlike with our HTM assumption) would be somewhat easier
- Methanol reformers carry lower technical risk and cost than gasoline reformers:
  - Multiple in-vehicle demonstrations of methanol technology under way
  - On-board reforming of gasoline or ethanol in vehicle demonstration has not been accomplished yet (GM plans for next year)

The differences between reformer-based options appear modest compared with implications of differences in infrastructure and technology risks.

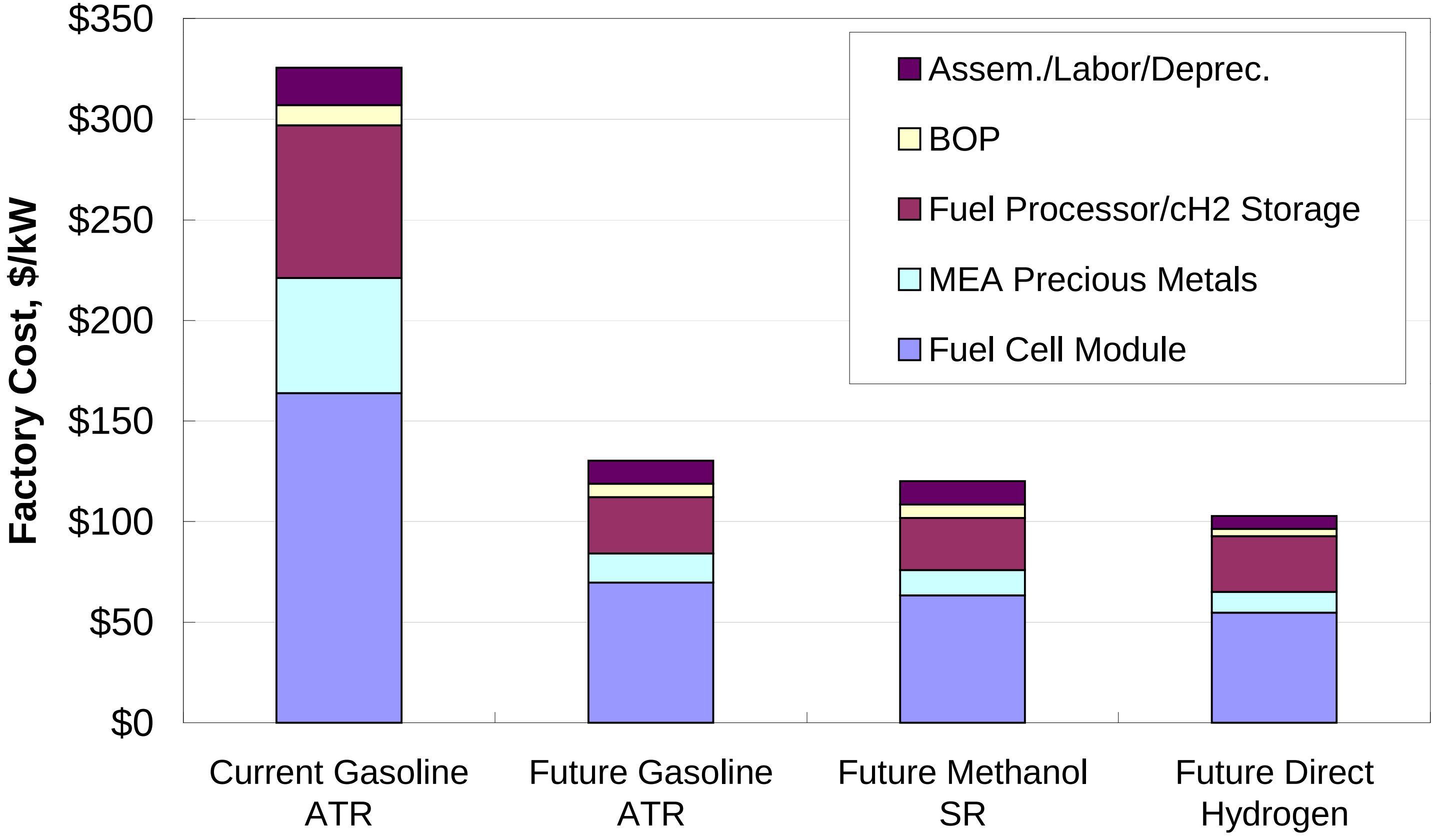
Our vehicle cost analyses build on ongoing ADL/DOE analysis of automotive fuel cell systems and ADL/EPRI analysis of hybrid vehicle cost.

- DOE study provided detailed bottom-up cost and weight estimates for fuel cell vehicle power units
  - Fuel cell, fuel processor, and BOP component costs were estimated for high production volumes (500,000 units/yr) assuming mature manufacturing technology
  - Includes performance inputs calculated in conjunction with ANL
- EPRI study provided detailed cost and weight estimates for HEV components
  - The EPRI study reviewed component costs with ANL and GM
  - Glider, power unit, transmission/controls/accessories, and energy storage costs were determined for various vehicle requirements
- To determine FCV cost and performance, the fuel cell module, fuel processor, and precious metals estimates from the DOE study were combined with the EPRI study estimates
  - DOE study hydrogen storage tank estimates were used for the direct hydrogen FCVs
  - DOE study BOP components were not used
    - EPRI traction battery replaced start-up battery
    - EPRI power electronics replaced control and electrical systems
  - We used the approach for determining hybrid vehicle costs and applied it to fuel cell powered vehicles

Details on pages: M26, 42-44; A56-61

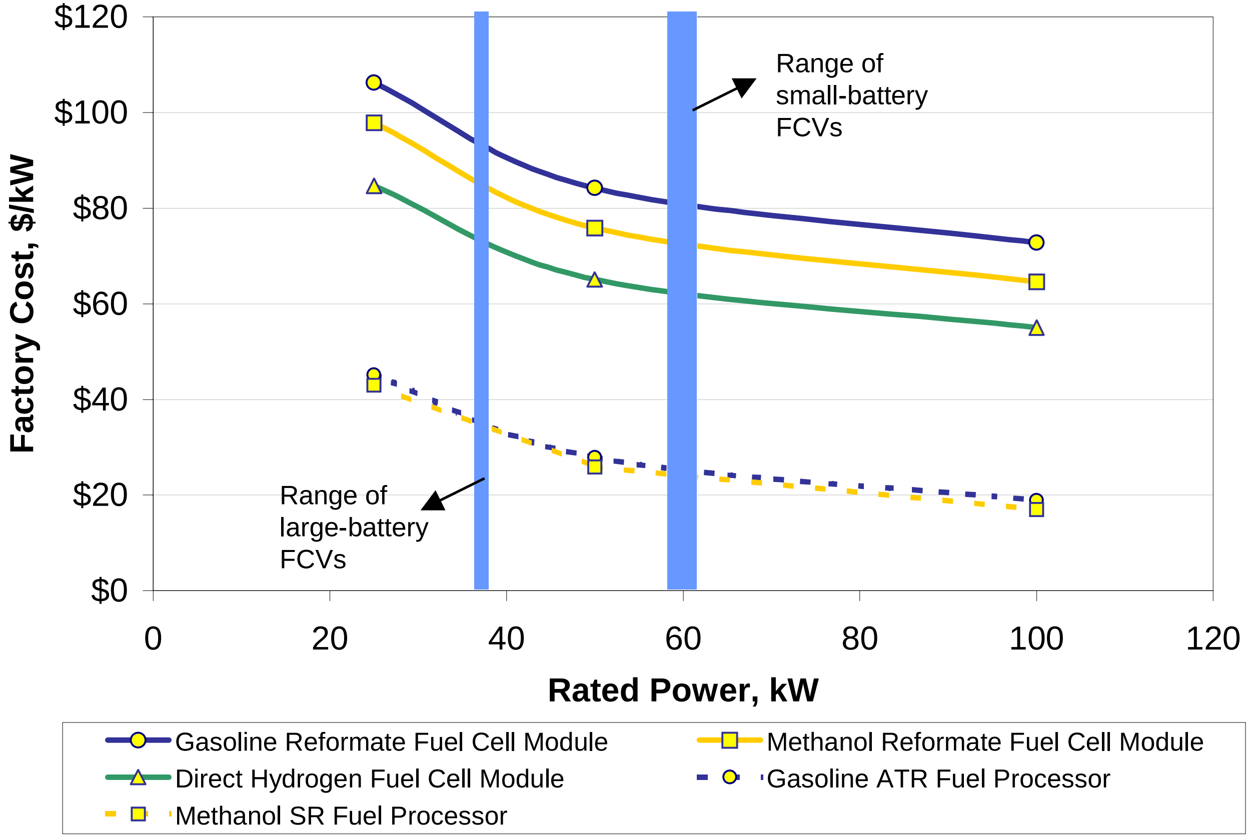
The future scenario assumptions used in this analysis have more than halved the fuel cell system costs projected for the current baseline system.

50 kW PEM Fuel Cell System Factory Costs



Significant changes in FC power unit costs on a $/kW basis over the actual system output were estimated and taken into account for this analysis.

Scaled PEM Fuel Cell and Fuel Processor Factory Costs

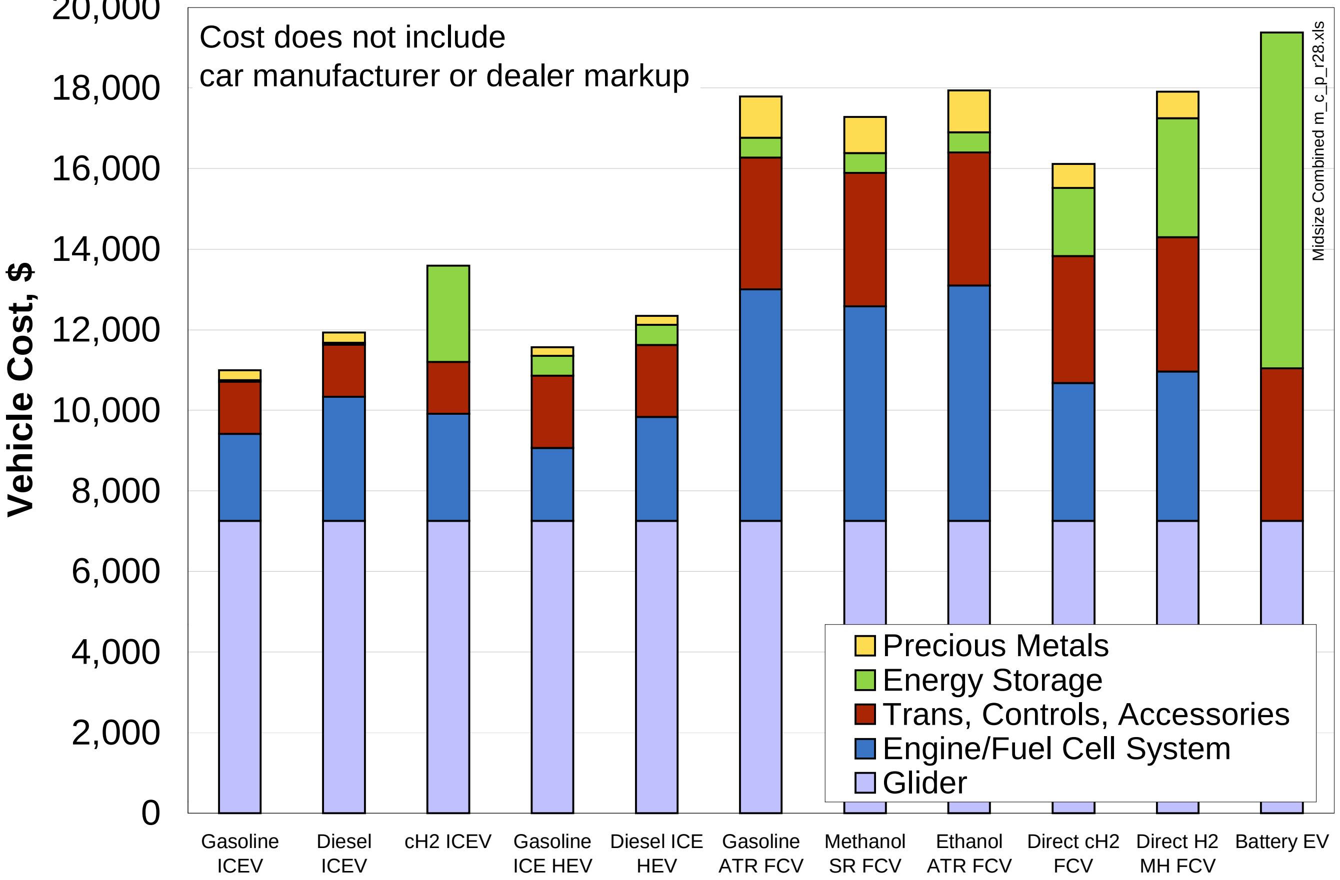


Small and large battery hybrid vehicle power unit costs are proportional to these curves.

Details on pages:
M12, 25; A49-52,
80-81

Based on our scenario analysis, factory costs of future FCVs would likely be 40-60% higher than conventional vehicles, but lower than battery EVs.

Factory Costs for Small Battery Mid-sized Vehicles


Cost does not include
car manufacturer or dealer markup

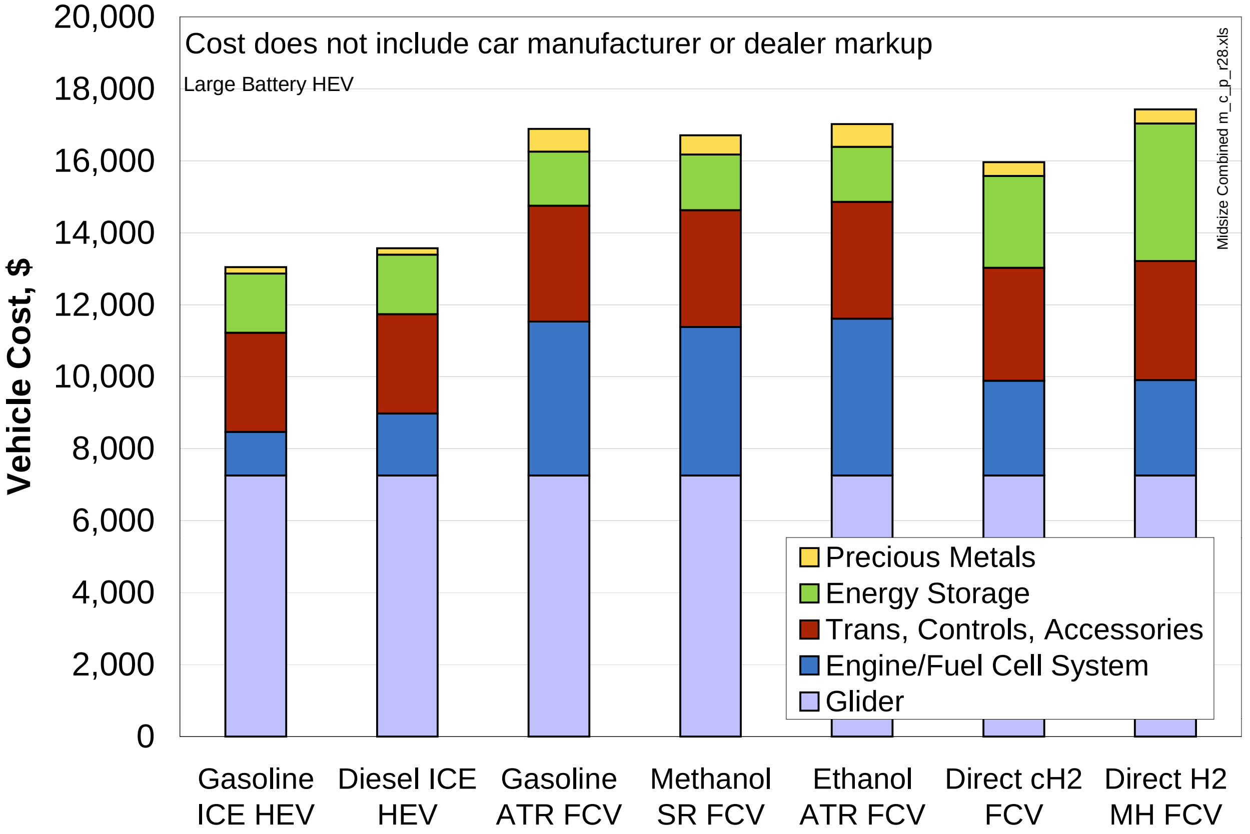
Midsize Combined m_c_p_r28.xls

Note: All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

Details on pages:
M12, 25; A49-52,
80-81

Given our battery cost assumptions, heavier hybridization would provide cost reduction, in addition to fuel economy benefits for FCVs...

Factory Costs for Large Battery Mid-sized Vehicles



* All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

... while it would increase ICE-based HEV cost.

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Typical FCV ownership cost would be $1,000-$2,000 per year higher than that of conventional ICEVs on account of the high initial vehicle cost.

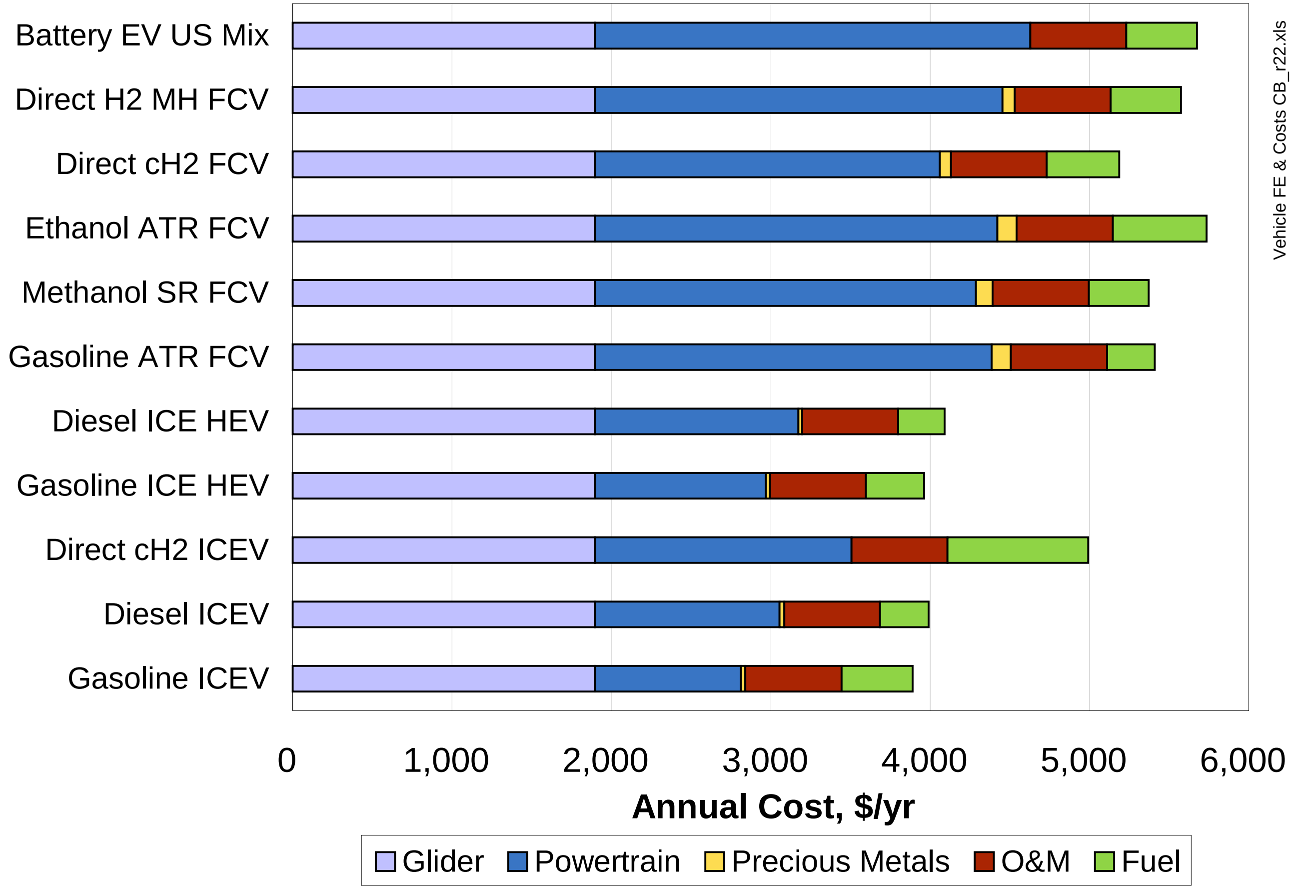
- Vehicle ownership cost is dominated by vehicle depreciation, representing over 75% of annual cost for all vehicles
- Fuel cost typically amounts to less than $500 per year
  - High efficiency of direct hydrogen and methanol-based FCVs compensates for higher hydrogen and methanol cost bringing annual fuel cost on-par with ICEVs
  - Gasoline FCVs benefit from a 30% reduction in fuel cost compared with conventional vehicles, but this does not outweigh added depreciation cost
  - Fuel cost for hydrogen ICEVs roughly triples annual fuel cost compared with petroleum ICEVs
- Insufficient information was available to be able to differentiate FCV maintenance cost from that for conventional vehicles
- Sensitivity analysis shows that cost differences between FCVs and petroleum ICEVs are statistically significant
  - Differences amongst FCV options and between FCVs and hydrogen ICEVs are not statistically significant

Vehicle, maintenance and fuel costs were combined to determine a typical ownership cost for each scenario.

- Vehicle costs are adjusted for resale value with monthly payments over 5 years at 4% finance rate
  - Resale value: assumed to be 39% for the vehicle minus the precious metals which are assumed to have 85% residual value
  - Insurance, tax and license costs are excluded
  - Glider cost is assumed to be the same for all vehicles in the same class
- Maintenance costs are based on an ADL/EPRI HEV study (EPRI, 2001)
  - Assume identical maintenance costs for all vehicles in the same class
    - Customer expectation is that maintenance will be at least as good as conventional vehicles
    - No real world data
    - Limited data from battery EVs suggests same cost, although warranty costs for first commercial vehicles are high for some EV manufacturers
- Fuel costs are based on 14,000 mi/yr driving, fuel economy analysis, and fuel cost analysis
  - Tax excluded

Typical annual mid-size FCV costs are projected to be around $1,200 to $1,800 more than that of conventional vehicles.

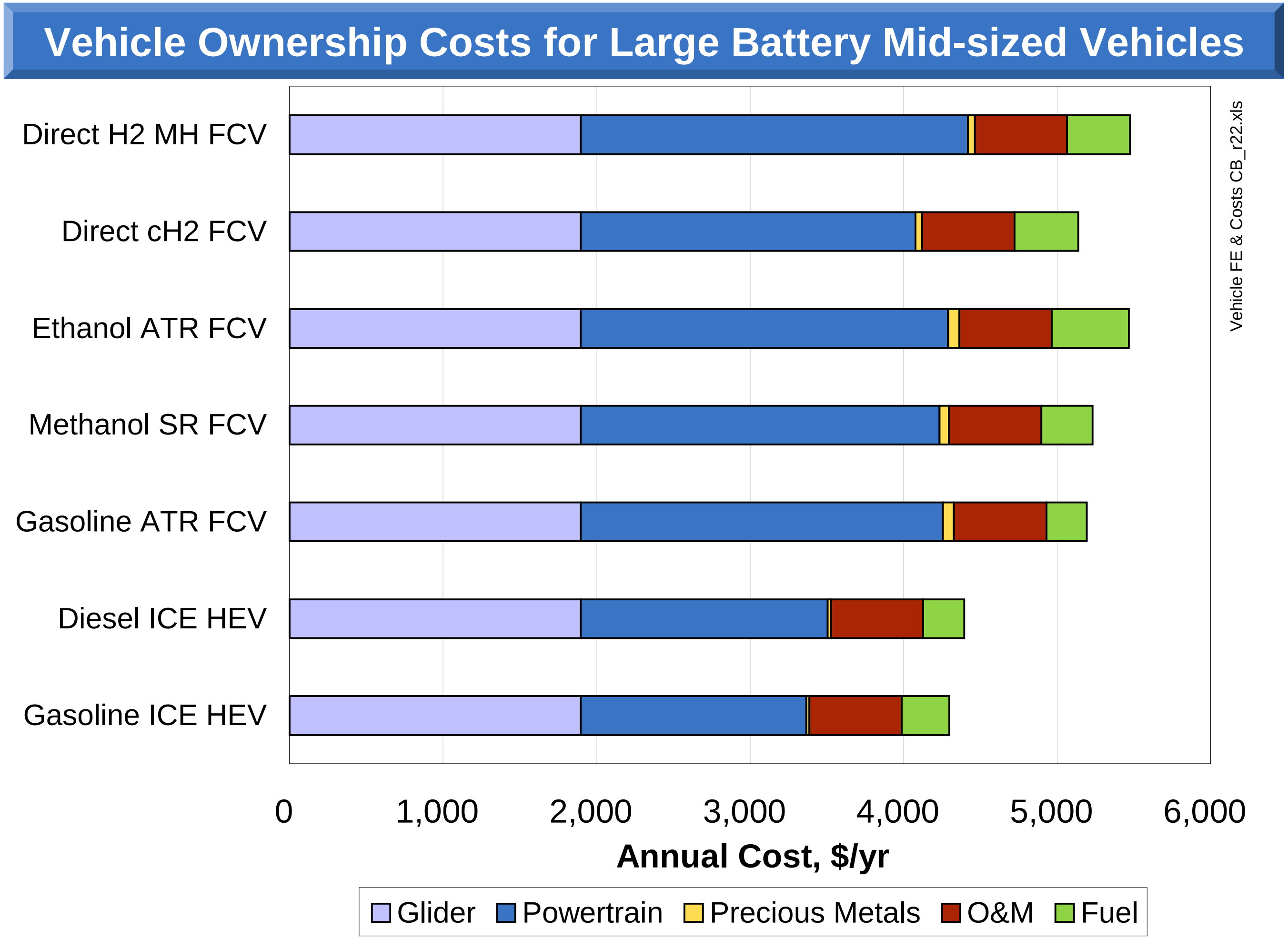
Vehicle Ownership Costs for Small Battery Mid-sized Vehicles



* All vehicles are based on the same midsized vehicle platform with 350 mile range except the Battery EV which has only a 120 mile range.

Details on pages:
M11-12; A82-84

A high degree of hybridization of FCVs could reduce FCV annual operating cost by several hundred dollars, while increasing HEV cost by the same.



* All vehicles are based on the same midsized vehicle platform with 350 mile range.

Details on pages:
A86-101

We analyzed the uncertainty in ownership costs with a Monte Carlo simulation of input variables.

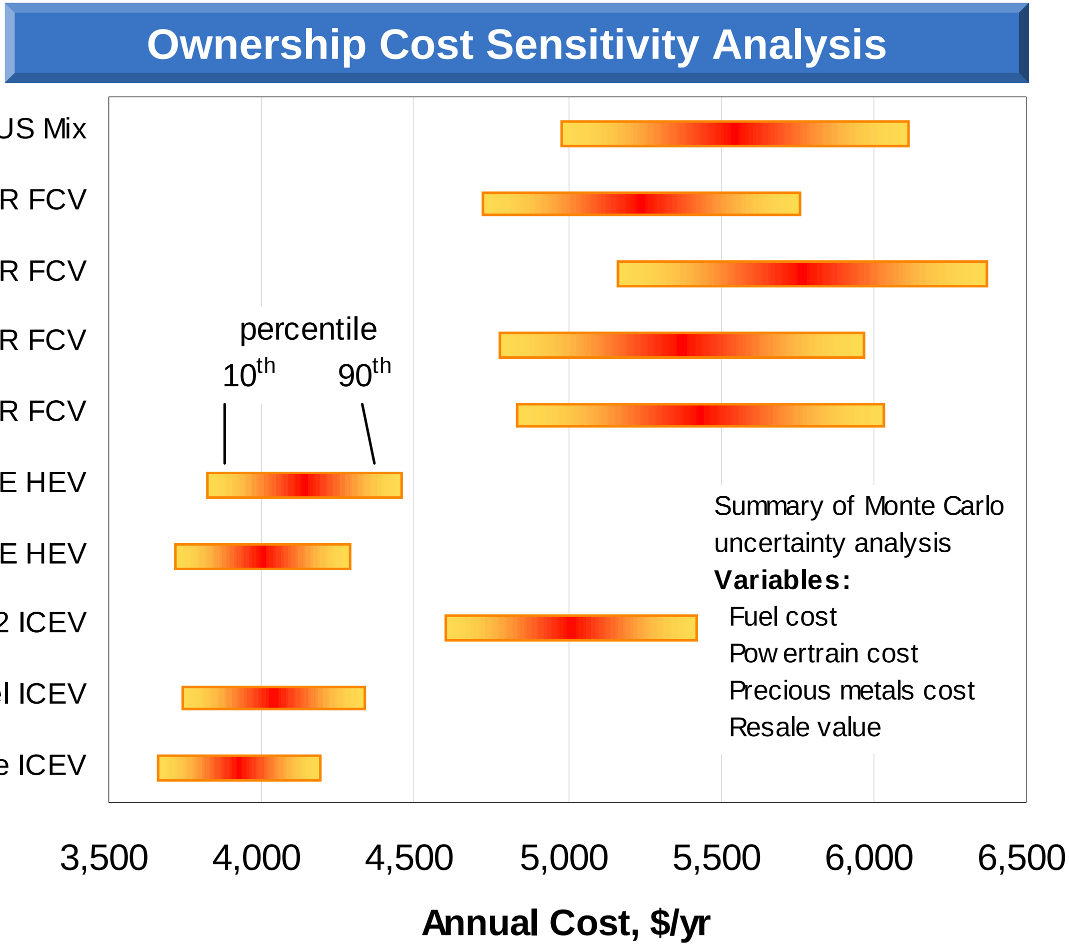
Factor Influencing Cost	Basis for Uncertainty Estimate
Input Fuel Prices[1]	Delivered fuel price assumptions were the same as those used in the well-to-tank analysis sensitivity analysis. Detailed assumptions can be found in the Appendix.
Fueling Station Costs	
Glider and Maintenance Cost, Interest Rates	Assumed to be the same and constant among vehicle options and held constant (i.e. not a sensitivity factor)
Powertrain Cost	Assumed uncertainty due to materials and labor costs at 10% -- normal distribution. Precious metals cost based on lognormal distribution of historical platinum prices
Resale Value	Varied from 30-53%, consistent with 5 year old vehicle sales
Fuel Economy	Performance attributes assumed constant for each technology (i.e. not a sensitivity factor)

[1] The input fuel to the SR based hydrogen fueling stations or central production facilities is natural gas. Electricity is the input fuel for electrolyzers.

We assumed vehicle and fuel production technologies can meet aggressive R&D goals, so costs related to technical performance were not analyzed.

Details on pages: A86-101

Our sensitivity analysis confirms that the difference in ownership cost between FCVs and petroleum ICEVs is statistically significant...



Summary of Monte Carlo uncertainty analysis

Variables:

- Fuel cost
- Powertrain cost
- Precious metals cost
- Resale value

... but that the difference amongst FCVs and hydrogen ICEVs is not.

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- Conclusion & DOE Target Setting

Although no fundamental technical barriers exist, meeting safety standards may pose a challenge for the implementation of hydrogen fuel chains.

- Hydrogen transportation, fueling station, and on-board safety issues can likely be resolved without onerous cost-increases
  - Relatively low cost engineering solutions can probably be identified for all issues surrounding on-board storage and refueling facilities for cH_2 and MH
  - However, the current codes and standards for the safe handling of hydrogen may not be practical for consumer applications
  - Well-organized international code and standard setting and modification are currently under way
- Fuel cell vehicles will require modifications to garages, maintenance facilities, and on-road infrastructure that could be costly and difficult to implement
  - Fundamental safety-related properties of hydrogen are very different from gasoline
  - Implementation of critical safety measures for closed public structures may pose a serious hurdle to widespread use of cH_2, as responsibility for implementation does not easily align with interest in hydrogen as a fuel
  - This issue may necessitate alternative hydrogen storage methods (e.g. MH)
  - Insufficient attention is being paid to these issues by standard-setting efforts

A well-coordinated international effort is under way to tackle hydrogen safety issues, but it insufficiently addresses on-road issues.

The major safety concerns for hydrogen result from its comparatively wide flammability range, low density, and low ignition energy.

Fuel Property	Hydrogen	Gasoline	Diesel	Methanol	Ethanol	Natural Gas
Min Ignition Energy, MJ	0.02	0.24	0.30	0.14	0.20	0.29
Flammability Limit in air, % vol	4.1-75	1.4-7.6	1.0-5.0	6.7-36	3.3-19	5.0-15
Diffusion Coeff. in air[1], cm^2/s	0.61	0.05	--	0.50	0.10	0.16
Odor, Color, or Taste	None	Yes	Yes	Yes	Yes	None
Flame Visibility in Sunlight	None	High	High	None	Low	None
Vapor Density, MW ratio to air	0.07	2-5	5-6	1.4	1.6	0.56
Vapor Pressure at 38 ^{o}C, kPa	NA	48-110	0.10-1.5	32	16	NA

[1] NTP air at 20 C and 1 atm.

In addition, the fact both hydrogen and methanol are odorless and have no visible flame in daylight raise further safety concerns.

Details on pages:
A104-111

The greatest combustion-related concern for hydrogen is a slow leak in a garage or enclosed area resulting in a fire or explosion.

Safety Variables of Concern	Negatives	Positives	Precautions
Flammability and Detonation	• Widest flammability range • Flammable at the high concentrations • More likely to detonate than other fuels	• Low volumetric energy density releases less energy during a leak, fire, or explosion • Flames are likely to be confined to a small area	• Ventilate enclosed areas or install miniature catalytic converters to eliminate hydrogen build-up • Prevent/detect leaks • Prevent entrance of air during fueling (collapsible storage vessels) • Install building and structural setbacks
Ignition Energy	• Very low ignition energy - common static (sliding over a car seat) is 10 times greater than minimum	• Ignition energy at the lower flammability limit is high (comparable to natural gas) • Conventional fuel cell temperatures (60-90º C) are too low for thermal ignition	• Use conductive fueling hoses • Wear NOMEX 11A static resistant protection while fueling • Use anti-static agents in fuel system components • Develop hydrogen compatible electrical products and use non-electrical devices when possible (e.g. hydraulic controls)

Details on pages:
A104-111

Potential leaks from high pressure storage systems have raised significant safety concerns.

Safety Variables of Concern	Negatives	Positives	Potential Actions
Gas and Flame Detection	• Asphyxiation from odorless and colorless gas • Burns from invisible flame	• Near-by people or object are less likely to get burned (low radiant heat transfer)	• Install UV/IR optical fire detection system • Develop fuel cell compatible odorant and flame visibility additive
Toxicity		• Hydrogen and its primary combustion product (water) are not toxic	• None required
High Pressure Storage	• High propensity to leak • Materials embrittlement • Rupture hazard • Damage from high pressure jet	• Unconfined leaks disperse quickly (high diffusion coefficient) • Current hydrogen designs project lifetimes of 15+ years at 3 cycles (refuelings) per day[1]	• Use 304 stainless to prevent embrittlement • Use X-ray welded seams to prevent leaks • Use break-away double shut-off fueling hoses • Install pressure relief and safety shut-off valves • Use ASME certified (or better), hydrostatically tested vessels • Thermal shock, corrosion, crash, high altitude, hot/cold weather tests

[1] Based on discussions with developers.

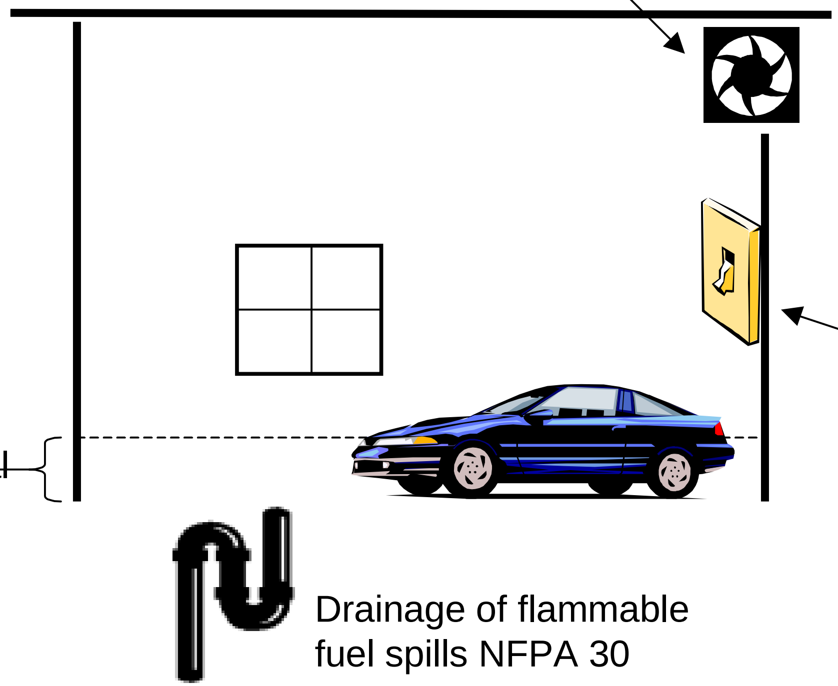
Details on pages:
A104-111

Cryogenic storage has most of the same safety concerns as compressed hydrogen, plus it can cause thermal damage.

Safety Variables of Concern	Negatives	Positives	Potential Actions
Cryogenic Storage	• Cold burns or frostbite from leaks/spills or un-insulated vessels or fuel lines • Combustion or asphyxiation from boil-off vapors/gases • Materials embrittlement • Rupture hazard	• Unconfined spills disperse quickly (high diffusion coefficient)	• Use 304 stainless to prevent embrittlement • Use break-away double shut-off transfer hoses • Install pressure relief and safety shut-off valves • Use ASME certified (or better), hydrostatically tested vessels • Thermal shock, corrosion, crash, high altitude, hot/cold weather tests • Rated insulation on all vessels, fuel lines, etc.

Metal hydrides are the safest storage option due to the high energy requirement for hydrogen release.

Even conventional and alternative liquid fueled vehicles require several facility safety design considerations.



Elimination of ignition sources - smoking,cutting, welding, static, hot surfaces NFPA 30, 70, 77, 78

Air Circulation
NFPA 30, 88A, 88B

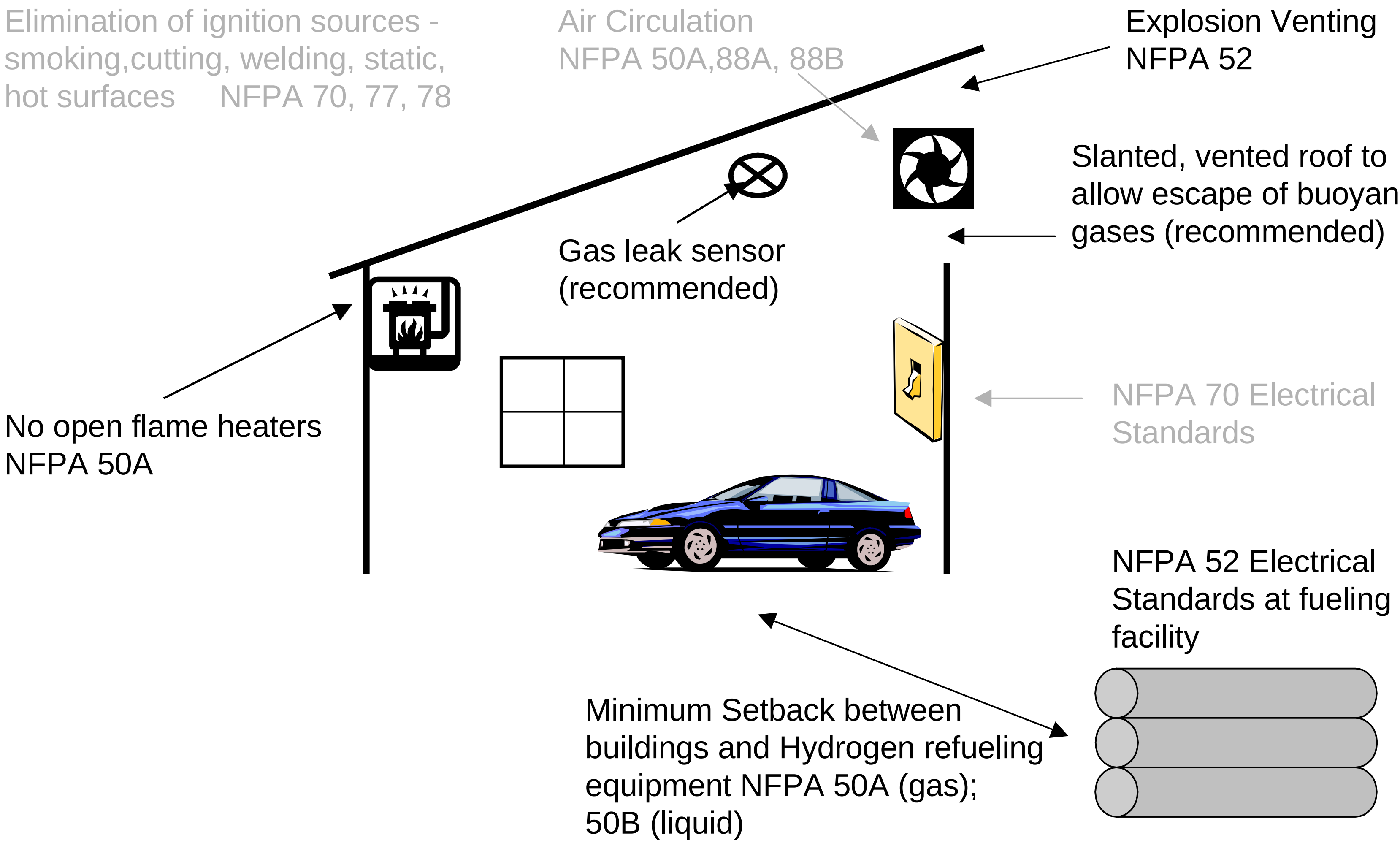
NFPA 70 Electrical Standards

Class 1, Div 2 only electrical equipment within 18 inches of floor NFPA70

Drainage of flammable fuel spills NFPA 30

Details on pages:
A113-114

Additional design considerations must be made for hydrogen vehicles, some of which could be very expensive in certain cases.



Elimination of ignition sources - smoking,cutting, welding, static, hot surfaces NFPA 70, 77, 78

Air Circulation
NFPA 50A,88A, 88B

Explosion Venting
NFPA 52

Slanted, vented roof to allow escape of buoyant gases (recommended)

Gas leak sensor (recommended)

No open flame heaters
NFPA 50A

NFPA 70 Electrical Standards

NFPA 52 Electrical Standards at fueling facility

Minimum Setback between buildings and Hydrogen refueling equipment NFPA 50A (gas); 50B (liquid)

Many organizations are responsible for or are working on hydrogen related safety standards.

- Guidelines for storage systems
  - National Fire Protection Association (NFPA)
- Regulations for hydrogen distribution over the roadways
  - Department of Transportation (DOT)
- Standards for hydrogen equipment
  - American National Standards Institute (ANSI)
  - American Society of Mechanical Engineers (ASME)
- Standards for gas production, handling, and use (including hydrogen)
  - Compressed Gas Association (CGA)
- Standards for fuel cell safety and interface
  - International Electrotechnical Commission (IEC)
- Standards for alternative automotive fuel systems
  - Society of Automotive Engineers (SAE)
- General Standards Organizations
  - American National Standards Institute (ANSI)
  - International Standards Organization (ISO)
  - International Codes Council (ICC)

Most of these categories overlap in one way or another.

The International Standard Organization is developing or has already adopted several hydrogen safety standards under ISO/TC-197.

- Published hydrogen related ISO standards:
  - ISO 13984: Liquid hydrogen - Land vehicle fuelling system interface
  - ISO 14687: Hydrogen fuel - Product specification
- Hydrogen related ISO standards under development:
  - ISO/CD 13985: Liquid hydrogen - Land vehicle fuel tanks
  - ISO/WD 13986: Tank containers for multimodal transportation of liquid hydrogen
  - ISO/WD 15594: Airport hydrogen fuelling facility
  - ISO/WD 15866: Gaseous hydrogen blends and hydrogen fuel - Service stations
  - ISO/WD 15869: Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks
  - ISO/WD 15916: Basic requirements for the safety of hydrogen systems
  - ISO/AWI 17268: Gaseous hydrogen - Land vehicle fuelling connectors

Source: Miller, K. (NHA), "Developing International Codes and Standards for the Safe Production, Storage, and Use of Hydrogen", presentation to SAE, March 2000

Despite the attention on hydrogen safety, it appears that the on-road safety of fuel cell vehicles is not being addressed.

Safety Standards	Organizations Pursuing	Comments
Transportation, Storage and Distribution of Hydrogen	NFPA, ANSI, ASME, ISO, CGA, DOT, SAE, CGA	Coordination and establishing reasonable (low cost) codes are required
Vehicle	Fuel Cell: IEC Fuel System: SAE, ISO, NHA	Preventing or handling small system leaks may be critical
Parking Garages	Preliminary: ICC, NFPA	They are just beginning to include hydrogen safety in National building codes. Studies and data gathering must be expanded
On-Road	??	Safety of tunnels, underpasses, and other public works is crucial, especially given the detonation potential of hydrogen

The hydrogen community is seriously looking at gaps in codes and standards.

The key danger of fuel cell vehicles is a slow or rapid leak leading to a conflagration or detonation.

- Hydrogen is buoyant which could result in accumulation in contained elevated areas (i.e. between ceiling beams), however:
  - It is difficult to contain hydrogen, due to its high diffusivity
  - Proper ventilation and/or mini catalytic converters can be used to eliminate hydrogen build-up
- High flame speed can result in detonation, however:
  - Explosive energy of hydrogen is 1/20 that of gasoline and 1/3 that of methane by volume
- Designing for a variety of fuels (gasoline, diesel, and hydrogen, maybe CNG, EtOH, or MeOH) complicates safety practices
  - Some fuels will rise, others pool
  - Ventilation alone won’t cover all vehicles

Both direct hydrogen and on-board reformer FCVs can leak from the fuel cell during operation or shutdown.

There are some important areas that must be addressed before FCVs can be accepted as mass market vehicles.

- Key Uncertainties: home parking, maintenance facilities, and parking garages
  - Some studies and modeling has been conducted, but data gathering must be expanded
    - Ventilation and leak modeling at the University of Miami has been funded for several years
  - Elevated vents may be enough in most cases, but it must be done for all places the vehicle visits or there could be major consequences
    - Prohibiting FCVs in non-compliant areas may result in unreasonable inconvenience to FCV owner
    - FCV owners and manufacturers won't have a great deal of leverage to force these facilities to be hydrogen compliant
- Potential Show Stoppers: tunnels and other public road works
  - Safety equipment will have to be very cheap or the aggregate cost could be prohibitive
  - All roads must be compliant - keeping certain cars off a particular road would be extremely difficult and unacceptable to the FCV owner

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Hydrogen FCVs should be able to significantly reduce energy use and greenhouse gas emissions, but at much higher cost.

- Based on our analysis, hydrogen FCVs could achieve 2.5 MJ/mi energy use and 150 g/mi greenhouse gas emissions on a well-to-wheels basis
  - 50-60% improvement over gasoline ICEVs
  - Requires compressed gas hydrogen production (central or local) from natural gas
  - Requires hydrogen FCVs to achieve 2.5x fuel economy improvement (80 mpgge) over gasoline ICEVs
- However, we estimate this hydrogen FCV to cost more than $5,000 per year for vehicle depreciation, fuel, and maintenance
  - Lowest among FCV options, but still $1,000/year more than HEVs and $1,500/year more than a gasoline ICEV
  - Hydrogen cost is not a major contributor, but this analysis indicates a target of $20/GJ should be achievable in the long-term
  - The estimated hydrogen FCV factory cost of $16,000 is $4,000 higher than HEVs and $5,000 higher than a gasoline ICEV due to higher FCV powertrain costs
- Our safety issues analysis indicates that more attention needs to be paid to covered public structure compatibility with hydrogen

FCVs offer many benefits including energy efficiency and emissions improvements over conventional ICEVs and HEVs...

- FCVs could provide significant reductions in primary energy consumption:
  - 50% for direct H_2 and 30-40% for gasoline and methanol FCVs over gasoline ICEVs
  - Direct H_2 FCVs could reduce consumption by 20% over HEVs, with gasoline and methanol FCVs matching HEV primary energy consumption
- FCVs offer the potential for significant greenhouse gas reductions, but change in fuel has more impact than improved energy efficiency
- Annual fuel cost for gasoline-based FCVs is expected to be up to 40% lower than that of direct H_2 FCVs and gasoline ICEVs
- FCVs are expected to have $4,000-$6,000 ($65-$100 per kW) higher factory cost than HEVs
- The safety risks of hydrogen, methanol and ethanol are technically manageable
  - However, implementation of safety standards for cH_2 and LH_2 for covered public structures may pose a serious hurdle to implementation of these fuel paths
- Technical and infrastructure risks for FCVs remain high

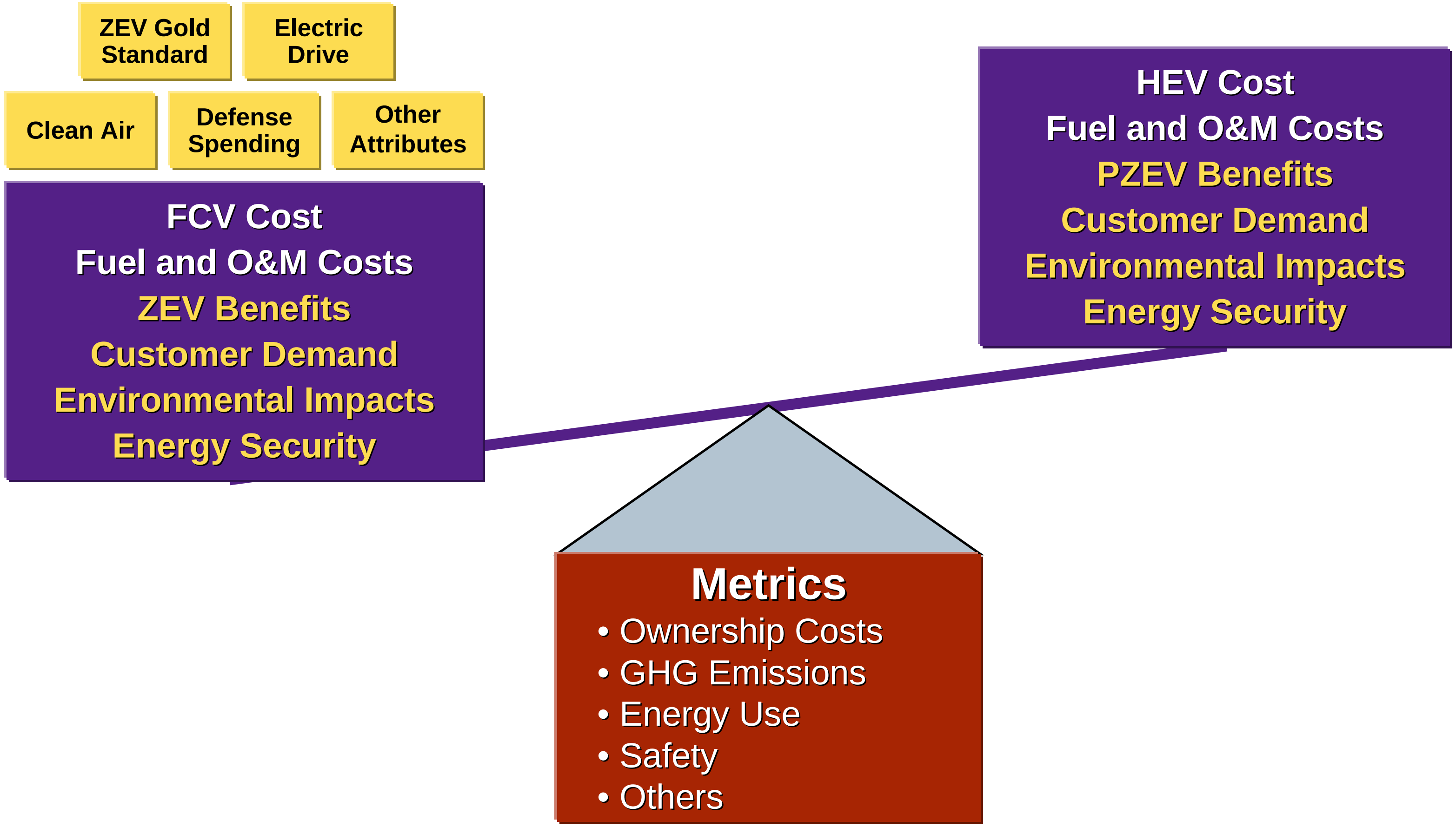
... but technical risk remains considerable and cost is expected to be significantly higher than for ICEVs and HEVs.

Although there are considerable differences in performance, risk, and cost of the FCV fueling options, no clear winner is identifiable.

- Compressed hydrogen FCVs could have significant benefits over reformer-based vehicles
  - 20-30% lower primary energy consumption than gasoline or methanol FCVs
  - $1,000-$2,000 ($15-$35 per kW) lower cost per vehicle; this could be increased to around around $3,500 ($60/kW) if some efficiency benefit is sacrificed
  - Significantly lower technical risk
- Reformer-based systems retain considerable benefits in terms of infrastructure risk
  - Delivered fuel costs are likely to be less than half that of hydrogen on a $/GJ basis
  - Even infrastructure investment for methanol is very modest compared to hydrogen
  - Safety issues for reformer fuels are comparatively simple to resolve, despite recent public perception of methanol's toxicity risk
- Differences between FCVs and petroleum ICEVs overwhelm differences amongst FCV options
- Hydrogen ICEVs do not appear to offer significant benefits in typical ownership cost compared with direct hydrogen FCVs
  - cH_2 ICEV range is likely to be reduced due to the large volume of hydrogen required

Details on pages:
A121-123

Our analysis shows that FCVs ownership costs will be high, but all attributes of vehicle operation are not taken into account.



ZEV Gold Standard

Electric Drive

Clean Air

Defense Spending

Other Attributes

FCV Cost
Fuel and O&M Costs
ZEV Benefits
Customer Demand
Environmental Impacts
Energy Security

HEV Cost
Fuel and O&M Costs
PZEV Benefits
Customer Demand
Environmental Impacts
Energy Security

Metrics
- Ownership Costs
- GHG Emissions
- Energy Use
- Safety
- Others

Details on pages:
A124-125

Minimum allowable cost for FCVs should be similar to advanced HEV powertrains with additional emissions control.

- Based on our “round-robin” analysis, HEV powertrain cost would be around $4,000 for gasoline HEVs and $5,000 for diesel HEVs
  - Compared with around $3,500 for a conventional powertrain
  - Gasoline HEVs would have higher well-to-wheels energy use than gasoline FCVs
  - Both would have higher emissions than gasoline FCVs
- ICE additional costs to meet PZEV emission regulations would increase gasoline HEV cost by another $500-$1,500
  - Based on “round-robin” analysis
  - Direct hydrogen FCVs provide emission reductions beyond PZEV
- Round-robin analysis may not accurately reflect projections of manufacturers:
  - Some current HEV manufacturers indicate that our HEV projections are not realistic
  - Round-robin assessment for FCVs would have likely led to lower cost estimate than projected here
  - However, HEVs are technically almost production-ready
- Not taking into account the accuracy of round-robin analyses, **minimum mid-sized vehicle powertrain targets should be around $5,000 per vehicle**
  - Our detailed analysis indicates a hydrogen FCV powertrain cost of $9,000

The detailed analysis described in this study generally supports the targets defined in Phase I, ...

- Well-to-wheel energy efficiency projections based on our scenarios are generally consistent with the long-term (2008) targets suggested in Phase I
- Phase I hydrogen fuel cost targets appear difficult to achieve and the DOE should consider relaxing them
  - Given the modest impact of fuel cost on overall ownership cost
- None of the FCV future scenarios met DOE FCV cost targets of $45 per kW
- Given the performance benefits of FCVs, relaxing the target to match the cost of HEVs meeting the PZEV standard may be reasonable

... but indicates that hydrogen and FCV cost targets may be difficult to achieve without additional technology breakthroughs.

Table of Contents

Appendix Table of Contents

Outline

Appendix Glossary

ADL	Arthur D. Little, Inc.
ANL	Argonne National Lab
BOP	Balance of Plant
CEM	Compressor/Expander Module
cH_2	Compressed Hydrogen (gaseous)
CNG	Compressed Natural Gas
DOE	Department of Energy (United States)
E100	Ethanol (100%)
EV	Electric Vehicle
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas (CO_2, CH_4, etc.)
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (model developed by ANL)
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
LH_2	Liquid Hydrogen
Li Ion	Lithium Ion Battery
MeOH	Methanol
mpgge	Miles per Gallon Gasoline Equivalent
NG	Natural Gas
NHA	National Hydrogen Association
NiMH	Nickel Metal Hydride Battery
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
OTT	Office of Transportation Technologies
Pb Ac	Lead Acid Battery
PEMFC	Polymer Electrolyte Membrane Fuel Cell
R&D	Research and Development
RFG	Reformulated Gasoline
SAE	Society of Automotive Engineers
scfd	Standard Cubic Feet per Day
SR	Steam Reformer
V	Volts

Appendix Fuel Properties

Liquid and Gaseous Fuel Specifications

Fuel[1]	Formula/State	C	H	O	H/C	MW	Density[1] (kg/m³)	HHV (MJ/kg)	LHV (MJ/kg)
Diesel No. 2	$C_{12.4}H_{21.15}$ (l)	12.4	21.15	0	1.706	170.25	863	46.5	42.6
Gasoline	$C_{6.55}H_{13.26}$ (l)	6.55	13.26	0	2.024	92.03	719	48.4	44.7
RFG	$C_{6.69}H_{13.65}O_{0.121}$ (l)	6.69	13.65	0.12109	2.041	96.05	719	47.2	43.7
Natural Gas	$CH_{3.85}O_{0.019}N_{0.031}$ (g)	1	3.85	0.0192	3.85	16.63	0.81	52.34	47.22
CNG	(g) 245 bar						201.3		
Ethanol	C_2H_5OH (l)	2	6	1	3	46.07	785	29.8	27.0
Methanol	CH_3OH (l)	1	4.00	1	4	32.04	792	22.8	20.0
Hydrogen	H_2 (g)	0	2	0	--	2.02	0.098	142.1	119.9
cH2	(g) 340 bar						24.7		
LH2	(l) 1.58 bar, 22K						68.7		

Reference: Lindeburg '84, CRC Handbook of Chemistry and Physics '87, Gieck '89, Kanury & Unnasch, 1996, Heywood, 1988.

[1] Density for gaseous fuels are at 1 atm, 25 C.

Outline

Appendix

Glossary

Fuel Chain Analysis Assumptions

Vehicle Analysis Assumptions

Platinum Loading Modeling

Additional Analysis Results

Sensitivity Analysis Assumptions

Safety Analysis Addendum

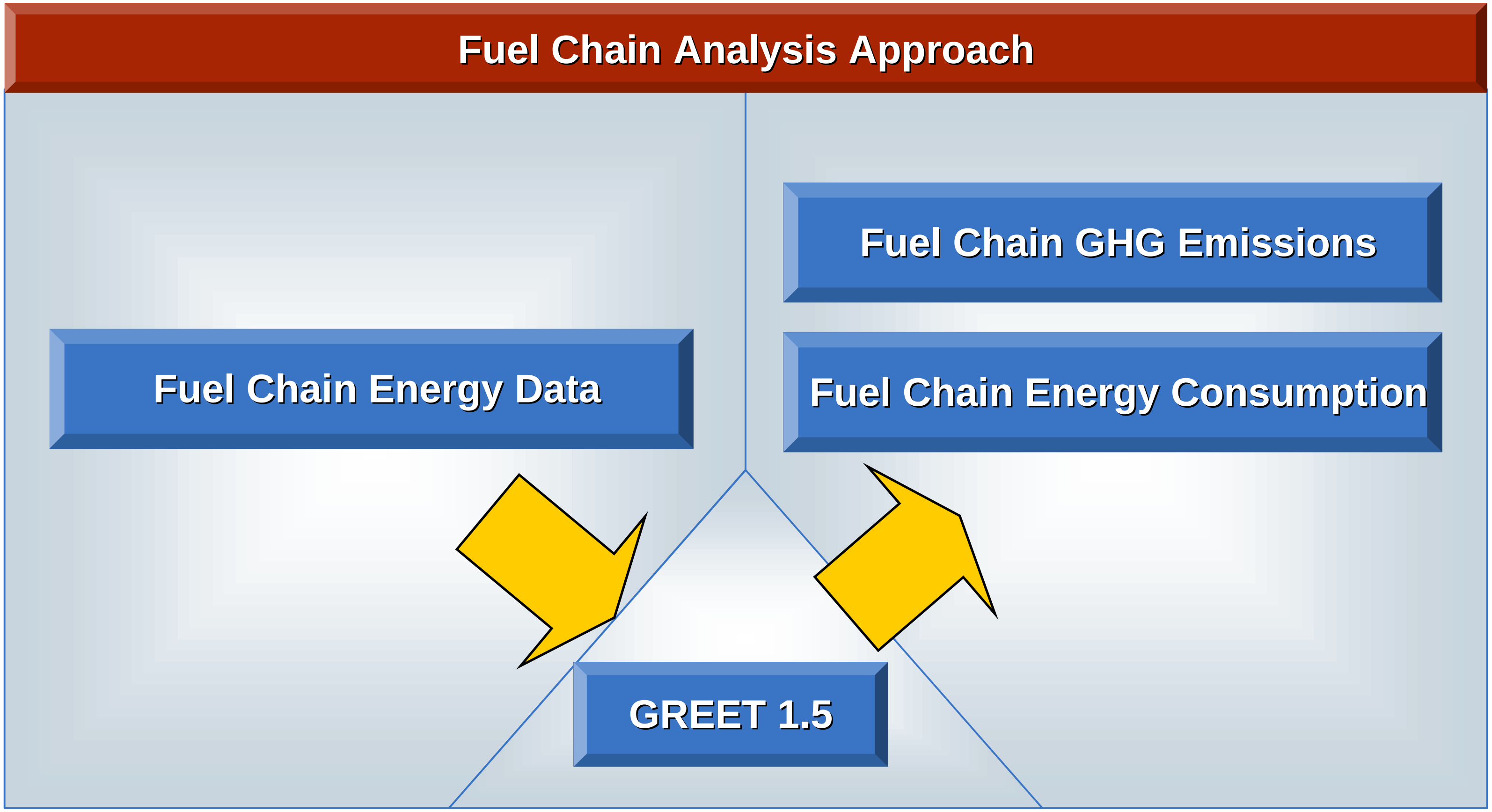
Target Setting

Bibliography

Energy efficiency inputs for the fuel chains were confirmed with process modeling and industry experience.

- Efficiency inputs for all fuel chain steps are documented
  - Data are represented in units that relate to referenced information
  - Values are converted to LHV efficiencies as input to GREET
- All compression associated with on-site hydrogen production is done with electric grid power assuming a U.S. average mix
- Liquification and compression associated with central hydrogen production is done with a 50/50 mix of electric grid and NG ICEs
- No credits for steam production for remote methanol plants
- Corn stover is feedstock for cellulosic biomass-to-ethanol facilities
- U.S. power generation mix is the baseline for EV power
  - Emissions & efficiency is weighted average of all sources

We updated Argonne National Lab's GREET Model with knowledge from our fuel chain database to provide a transparent and referable description of fuel chain options.



Fuel Chain Analysis Approach

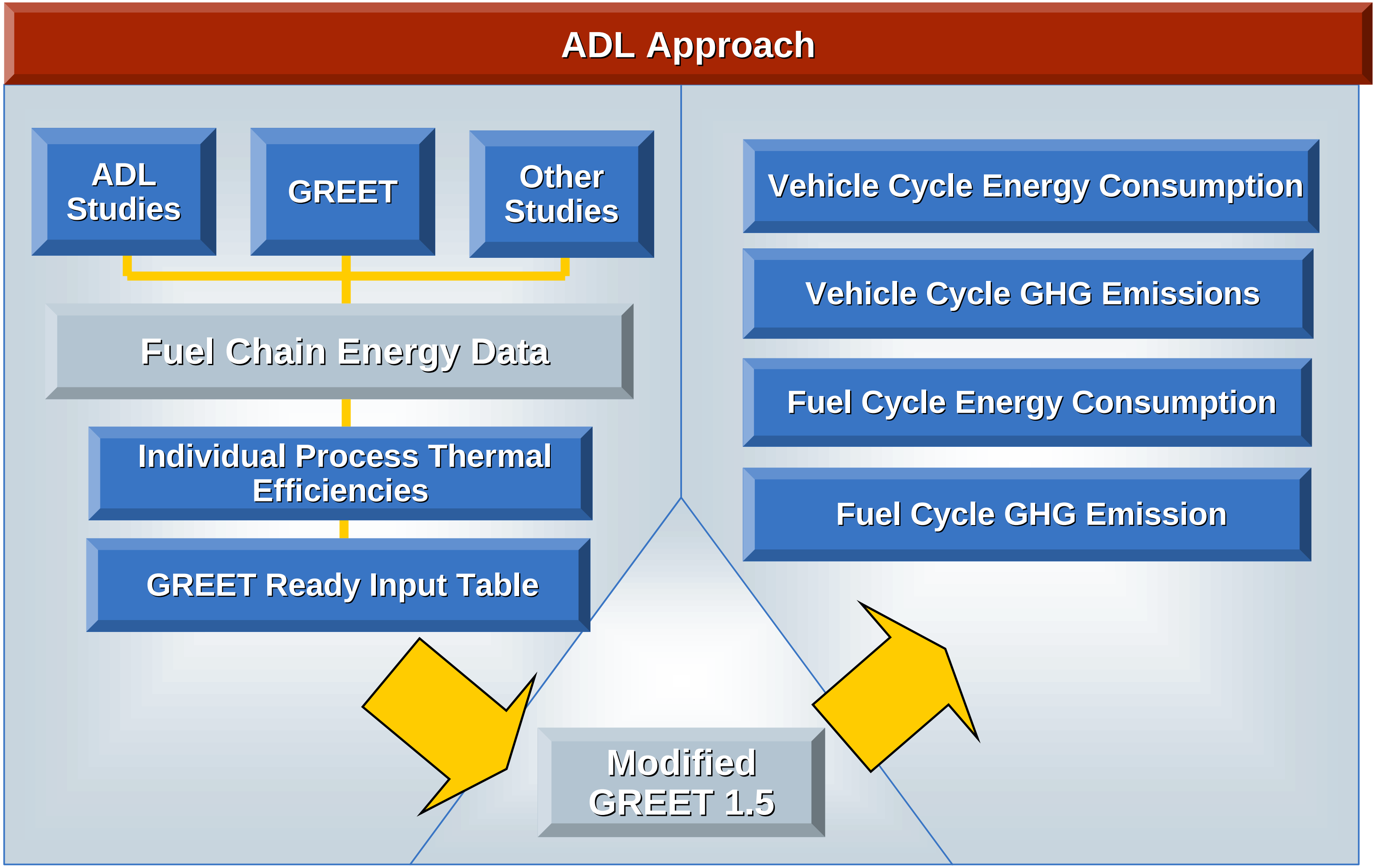
Fuel Chain Energy Data

Fuel Chain GHG Emissions

Fuel Chain Energy Consumption

GREET 1.5

ADL modified the typical GREET approach to accommodate new fuel-choice options and obtain sub-level information.



ADL Approach

ADL Studies

GREET

Other Studies

Fuel Chain Energy Data

Individual Process Thermal Efficiencies

GREET Ready Input Table

Modified GREET 1.5

Vehicle Cycle Energy Consumption

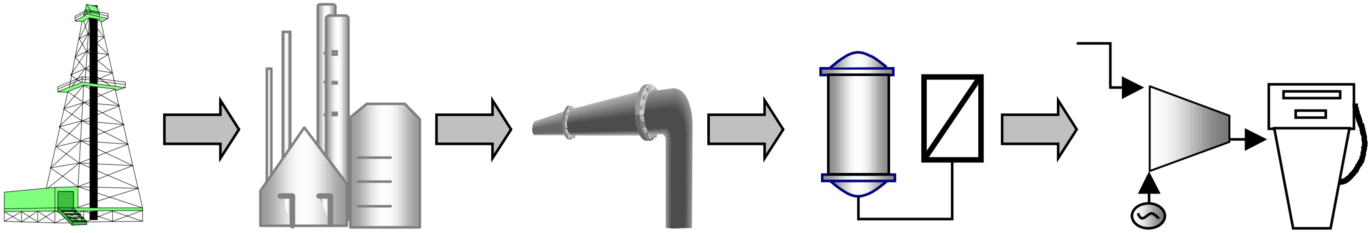
Vehicle Cycle GHG Emissions

Fuel Cycle Energy Consumption

Fuel Cycle GHG Emission

Each well-to-tank fuel chain calculation includes subsystem performance inputs. The key inputs to GREET are resource mix and energy efficiency.

Example: Compressed Hydrogen Production, On-site SR



Energy Source	Step Energy Use (Input MJ/MJ Output), LHV basis				
	NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
Natural Gas	1.02	1.02	1.001	1.36	---
Petroleum	0.013	---	---	---	---
Gasoline	0.045	---	---	---	---
Diesel	0.013	---	---	---	---
Electricity[1]	0.013	0.02	0.001	0.016	0.078
Hydrogen	---	---	---	---	1.03

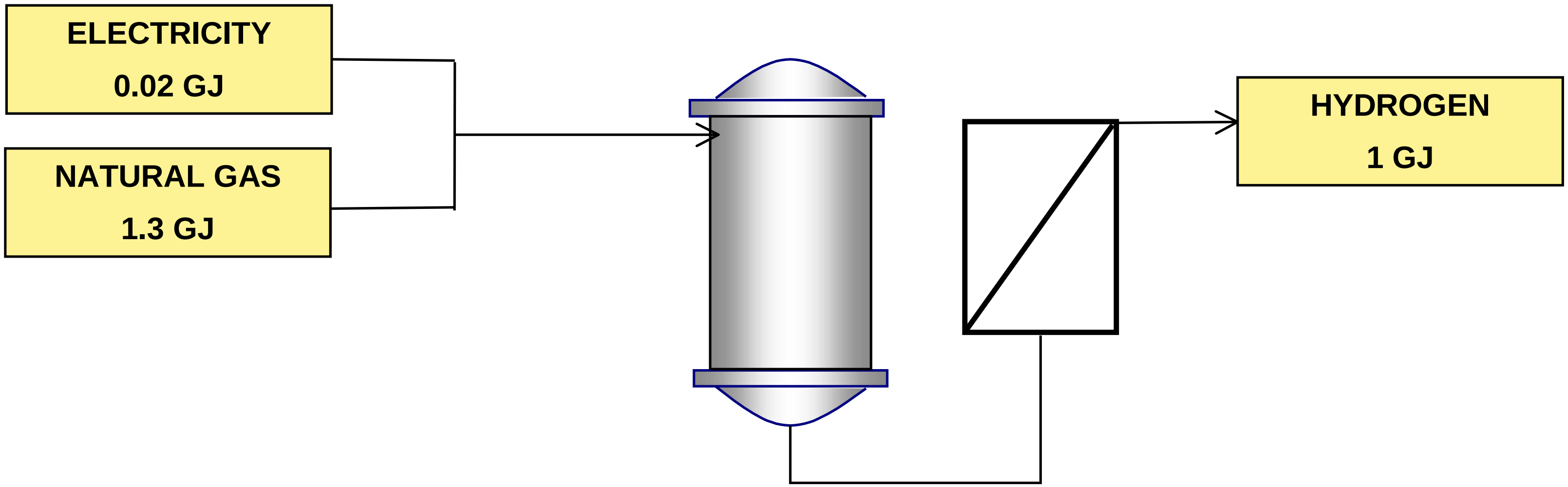
* Not complete without all performance inputs and assumptions for each fuel chain.

[1] Electricity is further broken down into primary fuel requirements based on the U.S. average power plant fuel mix.

When necessary, ADL has performed separate analyses to obtain accurate subsystem performance inputs.

We have defined the primary performance input for each module so that stage efficiency can be calculated on a LHV basis as an input to GREET.

Example: Compressed Hydrogen Production, On-site SR



Module Efficiency = Energy Output/ Energy Input

ME = 1/1.32 = 75.6%

We documented the calculations and data sources for each step in the fuel chain in production and transportation modules.

Production and Fuel Processing	
P1	Natural Gas Extraction
P2	Natural Gas Processing
P3	Hydrogen On-site Production & Compression
P4a	Hydrogen Central Production
P4b	Hydrogen On-site Compression, Tube-Trailer
P5	Hydrogen On-site Compression, Pipeline
P6	Hydrogen Central Liquefaction
P7	Hydrogen On-site Electrolysis
P8	Metal Hydride On-site Production & Compression
P9	Natural Gas Compression
P10	Petroleum Extraction
P11	Petroleum Refining to Gasoline
P12	Methanol from Natural Gas
P13	Corn Farming
P14	Ethanol from Corn
P15	Petroleum Refining to Diesel
P16	Biomass Chipping
P17	Biomass to Ethanol
P18	Corn Stover Collection
P19	Ethanol from Corn Stover
P20	Electricity Generation

Feedstock and Fuel Transport	
T1	Natural Gas Pipeline
T2	Hydrogen Pipeline
T3	Liquid Hydrogen Transport
T4	Hydrogen Tube Trailer
T5	Petroleum Transport
T6	Gasoline Truck
T7	Methanol Truck
T8	Methanol Marine Transport
T9	Corn Truck
T10	Ethanol Marine
T11	Ethanol Truck
T12	Ethanol Train
T13	Diesel Truck
T14	Biomass Truck
T15	Power Transmission

Note: Detailed fuel chain data and efficiency calculations are found in the Appendix Supplement

We assured that consistent assumptions were used for different fuels throughout the fuel chain.

Complete fuel chains are constructed from a combination of the modules.

Fuel Chain	Fuel Chain Module				
	Extraction	Processing	Transport	Production	T S & D
RFG, Petroleum	P10	--	T5	P11	T6
Diesel, Petroleum	P10	--	T5	P15	T13
Methanol, NG	P1	P2	T1	P12	T8, T7
Ethanol, Corn Stover	P18	T14	T10, T12	P19	T11
Ethanol, Corn	P13	T9	T10, T12	P14	T11
cH2, On-site NG SR	P1	P2	T1	P3	---
cH2, On-site NG SR, Energy Station	P1	P2	T1	P3	---
cH2, On-site NG SR, MH	P1	P2	T1	P3	P8
cH2, Central NG, Tube Trailer	P1	P2	T1	P4a,b	T4
cH2, Central NG, Pipeline	P1	P2	T1	P4a	T2,P5
cH2, Central NG, LH2	P1	P2	T1	P4a,P6	T3
cH2, On-site Electrolyzer	P20		T15	P7	--

Fuel cost assumptions were based on EIA energy projections, ADL experience with fuel production, and detailed modeling of local hydrogen fueling stations.

- Transportation and distribution costs are based on literature and ADL experience with fueling facility installations
- Gasoline and diesel wholesale prices are based EIA projections for crude oil and historical price spreads between petroleum products and crude oil
- Methanol and ethanol wholesale prices are based on ADL projections and cost analysis of production facilities
- Costs of hydrogen are based on bottom-up cost analysis
  - Local hydrogen fueling station capital costs are based on vendor quotes and central plant capital costs are based on published and internal data
  - All compression associated with on-site hydrogen production from natural gas is done with electric grid power at $0.07/kWh (EIA projected 2010 commercial rate)
  - On-site hydrogen production from electrolysis assumes 0.07, 0.08, 0.09 and 0.04 $/kWh for U.S. mix, nuclear, wind, and nighttime power, respectively
    - Nighttime power electrolysis option includes additional storage and hydrogen generation capacity to operate for only 12 hours a day

For non-hydrogen alternative fuels, bottom-up analyses from previous Arthur D. Little studies were used.

- Methanol wholesale costs relied on extensive GTL analyses performed for a range of studies vetted by several key methanol industry players
  - Whole sale price of $120/tonne including transportation to the local fueling station
    - Approximately the same price as RFG since refineries can use methanol as MTBE
- Ethanol costs are based on a previous ADL Biomass study (ADL, 2001) and *The USDA 1998 US Ethanol Cost of Production Survey* (Shapouri, 1999) for corn ethanol
  - This study assumed a future projected wholesale price of $1.10/gal
  - USDA Survey estimated $1.12/gal wholesale
    - Existing plants ranging from 1-50 million gal/year, both wet and dry mills
  - ADL Biomass study estimated $1.29 wholesale
    - Greenfield plant, dry mill
    - Assuming corn price of $2.90/dry bushel and DDS price of $0.151/kg based on 1996-1998 regional corn prices across the U.S.
- Transportation and local fueling station costs are consistent with gasoline, but higher on a $/MJ basis due to lower volumetric energy density

Local hydrogen fueling station capital costs are based on vendor quotes and central plant capital costs are based on published and internal data.

- Local capital costs are based on detailed thermodynamic modeling and vendor quotes for components
  - 300 hydrogen vehicle per day fueling stations
    - integrated into existing gasoline station serving 600 vehicles per day total
    - 90% capacity factor
  - 100 units per year production volume for all components
  - Appropriate scaling factors and progress ratios were applied
  - 11% Capital Recovery factor[1]
  - Maintenance cost 5% of capital
- Central plant capital costs are based on published and internal data
  - 300 ton per day plant
  - 17% Capital Recovery factor[1]

---

[1] Differences in financial assumptions reflect typical differences in capital productivity expectations in different parts of the value chain.

We estimated electricity costs from renewable and nuclear power for use in on-site electrolyzers.

- Cost assumptions for power generation are in keeping with respective industry expectations

Power Cost, $/kWh	CR Factor[1]	Capacity Factor[1]	Capital Costs	Operating Costs	T&D and Other Costs	Selling Price
Fossil Fuel CCGT for comparison	15%	65%	0.014	0.010	0.045	0.069
Solar (PV)	15%	21%	0.822	0.001	0.040	0.863
Wind (nighttime)	15%	33%	0.051	0.001	0.040	0.092(0.04)
Nuclear	9%	75%	0.027	0.010	0.045	0.082

  - Solar power is too expensive to be used for large scale hydrogen generation based on the capital cost assumptions used here
  - Nuclear and wind power could be 50% more expensive than grid power, but are essentially emission free
    - Contracts for nighttime purchases would be less costly
- While hydro-power is a relatively cheap and reliable source of renewable power, we did not include it in this analysis under the assumption that there would be no significant additional capacity in the U.S.

[1] CR = Capital Recovery Factor, Capacity Factor = hours/year

The detailed hydrogen cost analysis of on-site SR production performed in this Phase provided refinements to the cost estimates of Phase I.

- Phase I estimates used available performance and cost information
  - 15% Capital Recovery factor, maintenance cost 10% of capital
  - $0.05/kWh for power and $3/MMBtu (HHV) for natural gas
  - did not include site prep and controls
  - detailed analysis was not performed
- This analysis was based on detailed thermodynamic modeling and vendor quotes for components
  - 11% Capital Recovery factor, maintenance cost 5% or capital
  - $0.07/kWh for power and $5/MMBtu (HHV) for natural gas based on EIA projected 2010 commercial rates

Hydrogen processing and purification performance assumptions for Phase II were generally consistent with the ranges used in Phase I.

Local NG SR with PSA	Units	Phase I Analysis	Phase II Analysis
Processing scale	SCFD Hydrogen	<1 $x10^6$	275,000
SR pressure	atm	5-20	10
SR methane slip	%	5-6	9
Burner air compressor efficiency	%	NA	70
PSA inlet / outlet pressure	atm	10-55	10 / 9
PSA hydrogen recovery	%	75-90	76
Fan / pump efficiency	%	NA	55 / 80
Overall LHV efficiency (SMR+PSA)[1]	%	65-75	74

[1] Inefficiencies in the PSA (unburned hydrogen) are used in the SR to increase overall efficiency. Assumes 33% and 35% power plant efficiency penalty on power requirements for Phase I and Phase II, respectively.

Hydrogen compression, on-site storage, and dispensing performance assumptions for Phase II were also very similar to Phase I.

Local Compression, Storage & Dispensing	Units	Phase I Analysis	Phase II Analysis
Compressor adiabatic efficiency	%	65-75	70 and 90 [1]
Compressor parasitics[2]	%	15-25	18
Storage pressure[3]	atm	250-350	240
Storage efficiency	%	~100	100
Chiller COP[4]		NA	3.5

[1] 3-stage rotary compressor used to pressurize hydrogen from the PSA outlet to the on-site storage tanks (at 3500 psi) is assumed to be 70% efficient. The two accumulator type compressors used to fuel the vehicle are assumed to be 90% efficient.

[2] Percent of output hydrogen. Assumes 33% and 35% power plant efficiency penalty on power requirements for Phase I and Phase II, respectively.

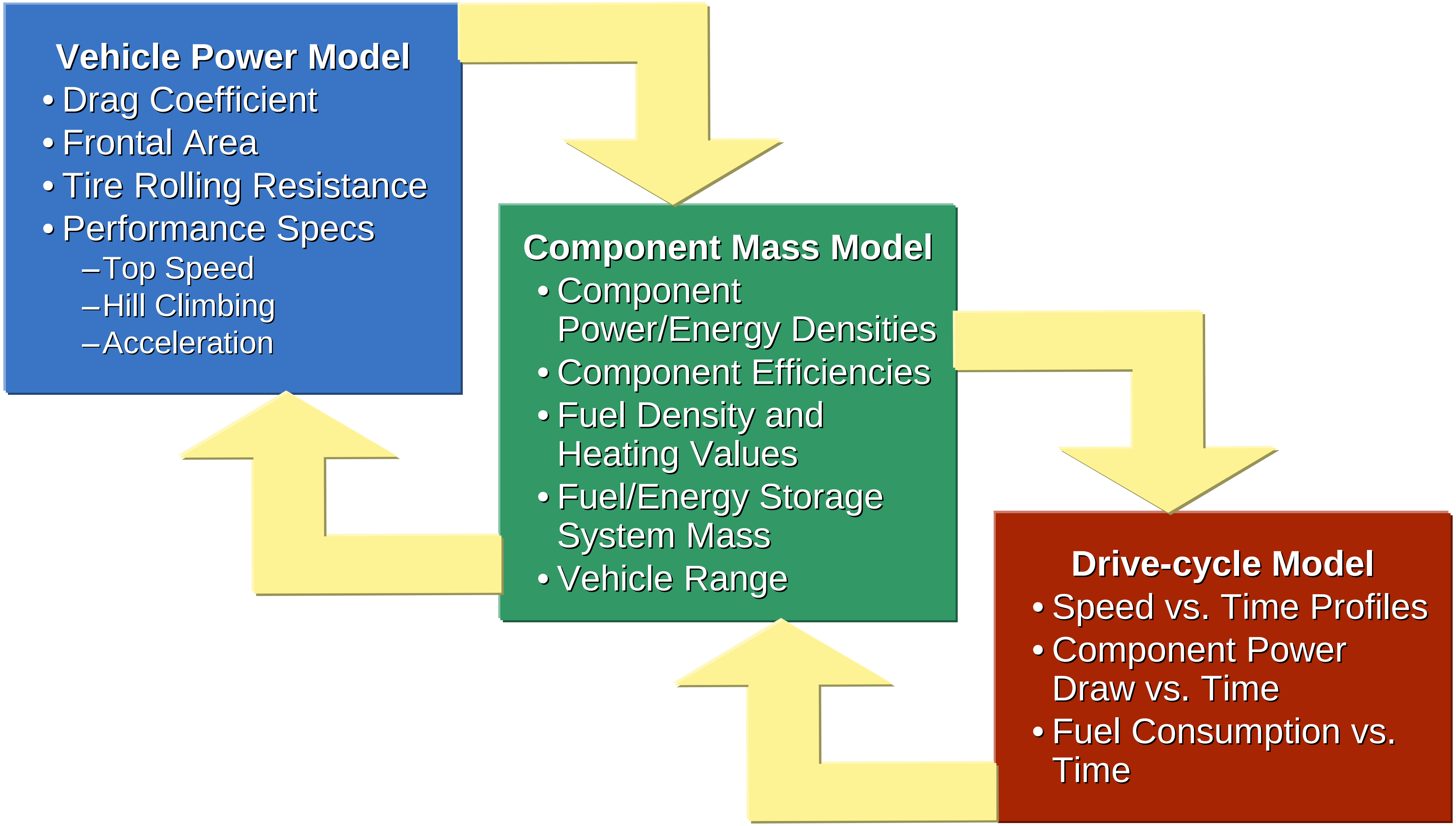
[3] For on-site pressurized tank storage from NG SR with PSA.

[4] We assume a chiller will be required to sub-cool the hydrogen entering the vehicle tank to prevent under-filling due to compression heating.

Outline

Appendix

We used a vehicle drive-cycle simulation model to estimate fuel economy and to estimate the power requirements for each powertrain.



Vehicle Power Model

- Drag Coefficient
- Frontal Area
- Tire Rolling Resistance
- Performance Specs
  - Top Speed
  - Hill Climbing
  - Acceleration

Component Mass Model

- Component Power/Energy Densities
- Component Efficiencies
- Fuel Density and Heating Values
- Fuel/Energy Storage System Mass
- Vehicle Range

Drive-cycle Model

- Speed vs. Time Profiles
- Component Power Draw vs. Time
- Fuel Consumption vs. Time

Key assumptions for vehicle performance and cost analysis:

- Vehicle mass and cost analysis based on previous and on-going ADL analyses
  - FCV power unit mass and cost based on on-going ADL/DOE analysis of automotive fuel cell systems (DE-SCO2-98EE50526)
  - Motor, transmission, battery, and other components based on ADL/EPRI HEV study (EPRI 2001)
  - Fuel cell and ICE engine costs are scaled with road power demand
  - Road power demand and vehicle mass are determined iteratively
- ICEV and HEV fuel economy based on industry comments and ADL analysis
  - Unnasch, S., “Fuel-Cycle Energy Impacts of Light-Duty Vehicles”, Prepared for California Energy Commission, June 2000
  - ADL, “U.S. Light-duty Dieselization Scenarios - Preliminary Study Final Report”, prepared for American Petroleum Institute, July 1999
- FCV fuel economy based on ADL analysis
  - FCV power unit performance curves based on ADL projections
    - kinetic and thermodynamic analyses using the full load assumptions from ADL/DOE analysis of automotive fuel cell systems
  - Motor and power electronic performance curves from Hauer, *Power Electronics*, SAE 2001-01-0543

The following assumptions were used in the vehicle model to determine overall performance and cost.

Vehicle Model Assumptions

- 2010 Model Year - modest weight reductions
- Vehicle Use: 14,000 miles per year
- Acceleration
  - Time to 60mph from stop <11.5s
  - Time to 60 mph from 40mph <5.0s
- Top Speed 105 mph
- Hill Climbing
  - 55 mph
  - 6.5% grade
- Ambient Air Density 1.18 kg/m^3
- Gasoline Energy Density: 119,200 MJ/gallon

<u>Mid-sized Vehicle</u>

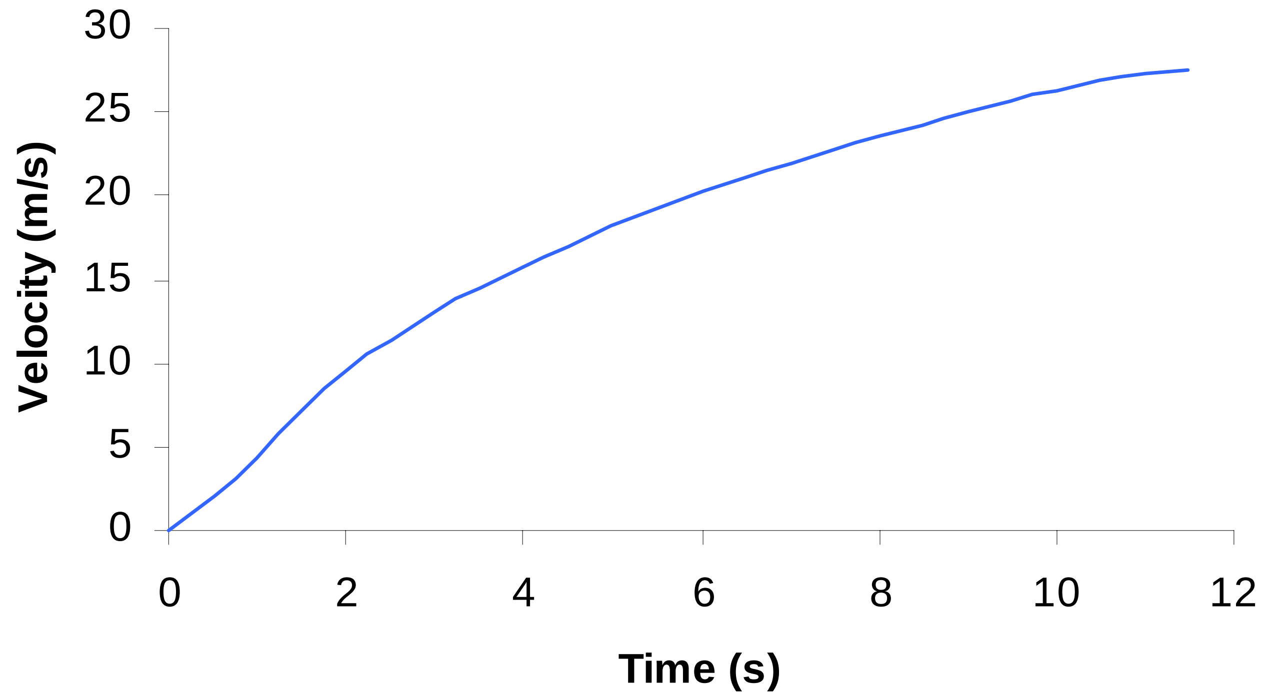
- Glider Weight 900 kg
- Drag Coefficient 0.28
- Vehicle Frontal Area 2.2 m^2
- Rolling Resistance Coefficients
  - Ad .008
  - Bd 1.42E-5

<u>Sport Utility Vehicle</u>

- Glider Weight 1050 kg
- Drag Coefficient 0.38
- Vehicle Frontal Area 2.6 m^2
- Rolling Resistance Coefficients
  - Ad .010
  - Bd 1.42E-5

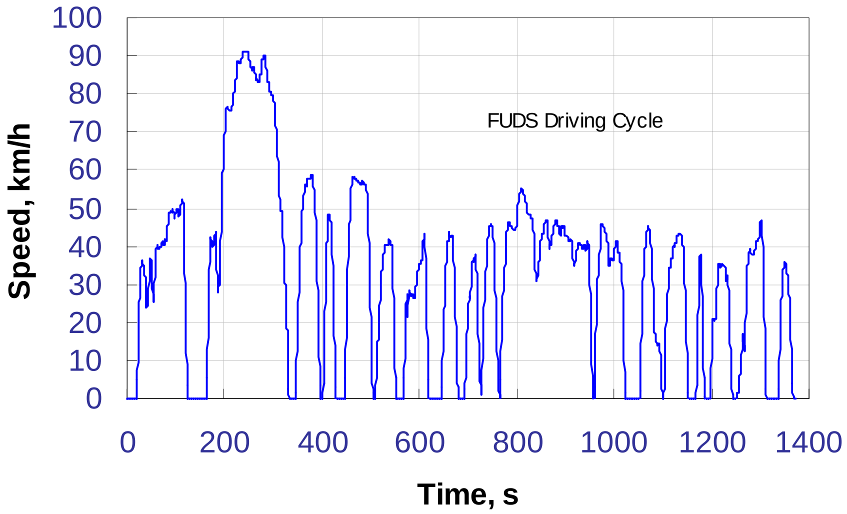
Powertrain sizing for all vehicles was based on meeting the same acceleration requirements.

Acceleration Profile

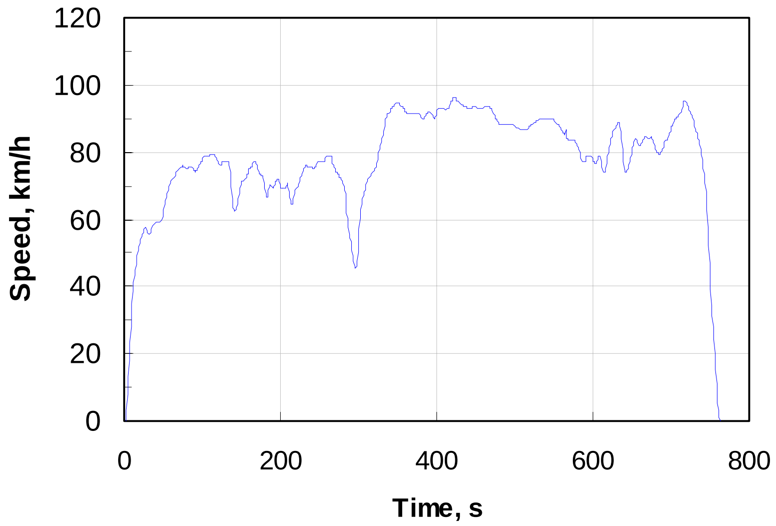


Fuel consumption was estimated for the EPA city and highway driving cycles.

City Driving Cycle (FUDS)



Highway Driving Cycle (HFET)



- Fuel consumption was calculated from the powertrain performance curves and drive cycle power requirements
- Our fuel economy results are based on CAFÉ fuel economy weightings:

Weighted fuel economy = 100/(55/City FE + 45/Highway FE)

Start-up energy demand represents a significant portion of the energy for FCVs with on-board reformers.

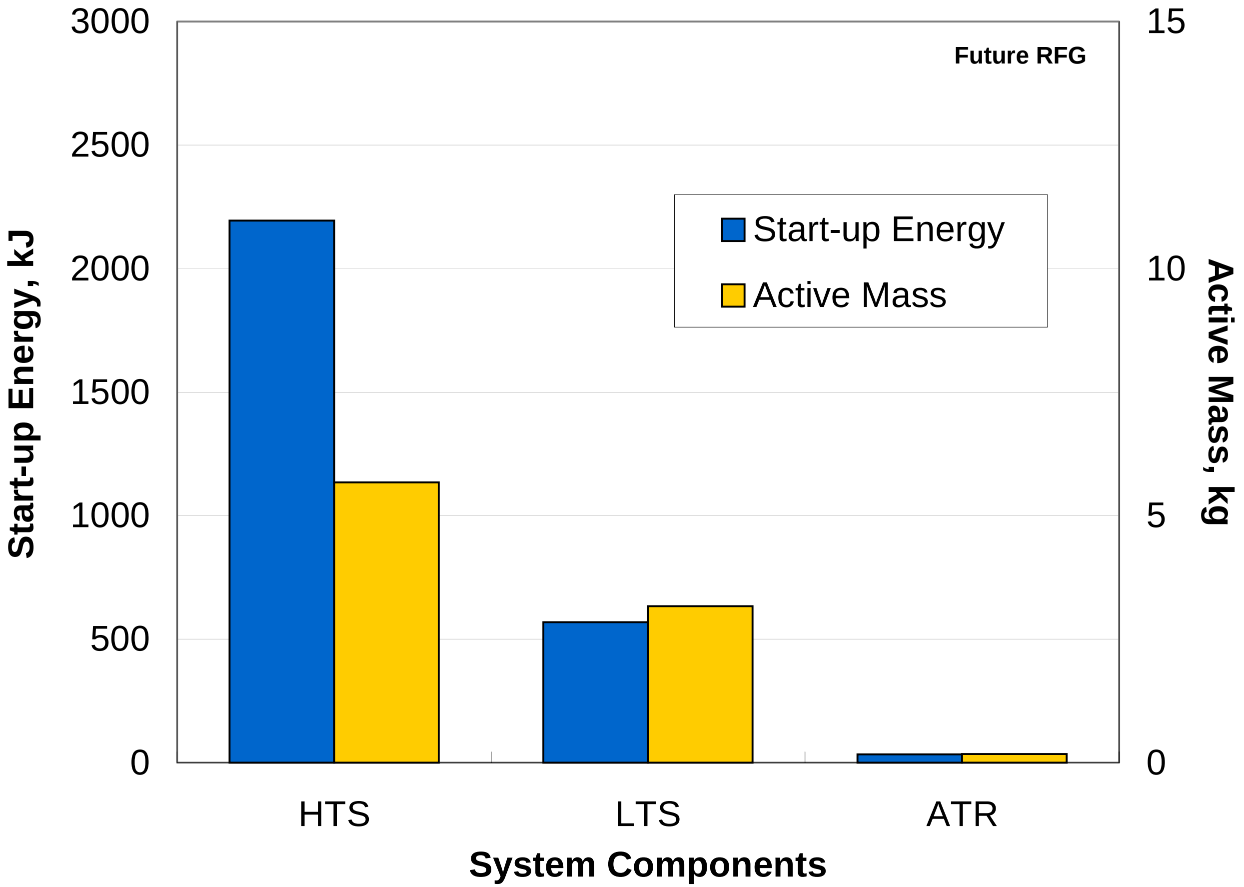
- ADL modeled energy inputs based on catalyst volume, heat capacity, system mass, and operating temperature
  - Start-up energy requirements are dictated by the energy input to the catalyst beds
  - Fuel cell generates power with hydrogen feed, even at low temperatures, so no start-up energy input is required
- Start-up energy inputs may need to occur twice a day for typical driving and represents up to 10 percent of the drive-cycle energy
  - Significant mass reductions in the fuel processor catalyst beds are projected

Energy requirements for future RFG ATR and Methanol SR FCVs

Fuel Processor, power unit size		Active Mass, kg	Start-up Energy, kJ	City Drive-cycle, kJ	Hywy Drive-cycle, kJ
RFG ATR	60 kW	9.0	2,800	17,700	21,900
	38 kW	5.7	1,770	15,600	20,600
Methanol SR	60 kW	8.8	2,260	17,700	21,900
	38 kW	5.6	1,430	15,600	20,600

The start-up energy requirement for system components decreases with active mass.

System component requirements for future 60 kW RFG FCVs



Starting the entire ATR represents a large fraction of the energy on a typical drive-cycle. Partial start-up of hybrids will reduce energy use.

- Partitioning the catalyst beds into 4 independent systems can improve turndown and cold start
  - Partial start-up on 25% of the HTS reduces start-up energy
  - Applicable to hybrid configurations where batteries can power the vehicle
- Waste heat from the ATR system and anode gas can be used to warm up the remainder of the HTS

Energy requirements for future RFG ATR FCVs					CAFÉ Fuel Economy mpg
Fuel Processor, start-up fraction		Start-up Energy, kJ	City Drive-cycle, kJ	Hywy Drive-cycle, kJ	
RFG ATR, 60 kW	100%	2,800	17,700	21,900	45.6
RFG ATR, 38 kW Large Battery Hybrid	100%	1,770	15,600	20,600	52.2
	25%	440	15,600	20,600	56.1
		Partitioned start-up saves fuel			

ANL has evaluated commercial and prototyped HEV fuel economy gains due to load reduction, engine downsizing, and hybridization[1].

- ANL compared the HEVs to their non-electric vehicle equivalent by evaluating gains due to:
  - Load reduction - weight, Cd, Cr, frontal area reductions
  - Engine downsizing - smaller engine
  - Hybridization - electrical components, drivetrains, and strategies
- Our HEVs assume the same glider and styling as the conventional vehicles, so we discounted the load reduction gains
  - ANL gives performance-equivalent CAFÉ mpg gains from engine downsizing and hybridization - “Adjusted EERs”
- We don’t expect our EERs to be exactly the same as ANL’s
  - ANL’s assumed vehicle mass, rolling resistance, and drag appear to be more aggressive than projections used in our model
  - The overall CAFÉ mpg estimates for our vehicles are much lower than the commercial and prototyped HEVs in ANL’s analysis
  - Even though ANL estimates provide EERs that account for improvements in vehicle components, these advances are not necessarily consistent with ADL projections

[1] Source: An, F. (ANL), “Evaluating Commercial and Prototyped HEVs”, presentation at FTT Conference 2000

Our projections for gasoline HEV performance are in line with ANL's adjusted EERs.

ANL Analysis of Gasoline HEVs[1]					
HEV Name	**Type**	**Status**	**Battery Power[2]**	**CAFÉ mpg**	**Adjusted EER**
Japan Prius	Gasoline Mid-sized	Commercial	41.0%	54	1.51
U.S. Prius	Gasoline Mid-sized	Commercial	38.7%	58	1.62
Nissan Tino	Gasoline Mid-sized	Commercial	18.6%	48	1.30
Honda Insight	Gasoline Small	Commercial	16.7%	76	1.36
ADL Projections					
Large Battery HEV	Gasoline Mid-sized	Projected 2010	45%	44	1.45
Small Battery HEV	Gasoline Mid-sized	Projected 2010	9%	37	1.22

[1] Source: An, F. (ANL), "Evaluating Commercial and Prototyped HEVs", presentation at FTT Conference 2000. Adjusted EER values represent improvement due to hybridization only.

[2] Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

Our projections for diesel HEVs are also in line with ANL's analysis, although all of these vehicles are prototypes.

HEV Name	Type	Status	Battery Power[2]	CAFÉ mpg	Adjusted EER
ANL Analysis of Diesel HEVs[1]					
GM Precept	Diesel Mid-sized	Concept Prototype	44.3%	80	1.64
DC ES X3	Diesel Mid-sized	Concept Prototype	31.2%	72	1.51
Ford Prodigy	Diesel Mid-sized	Concept Prototype	21.4%	70	1.46
ADL Projections					
Large Battery HEV	Diesel Mid-sized	Projected 2010	44%	47	1.54
Small Battery HEV	Diesel Mid-sized	Projected 2010	9%	44	1.42

[1] Source: An, F. (ANL), "Evaluating Commercial and Prototyped HEVs", presentation at FTT Conference 2000. Adjusted EER values represent improvement due to hybridization only.

[2] Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

Most of this analysis focuses on fuel cell vehicles, but hydrogen burned in ICEs could be an important transition technology.

- Hydrogen internal combustion engines (ICEs) have efficiency comparable to diesel ICEs and emissions comparable to fuel cells
  - 30% higher efficiency than gasoline ICEs resulting from higher compression and specific heat ratios
  - Order of magnitude lower NO_x emissions compared to gasoline ICEs and no other significant emissions besides water vapor
- Lower power density than gasoline ICEs due to hydrogen's very low energy content per unit volume
- While a hydrogen ICE will be more efficient, it comes with a significant fuel weight and volume penalty
  - 320 liters of fuel (assuming 5,000 psia storage pressure) and 100 kg of fuel and tank weight compared to 45 liters and 35 kg for gasoline ICEV
    - Assuming 350 mile range, 40 and 30 mpgge for hydrogen and gasoline ICEVs, respectively
  - We did not accommodate additional volumetric capacity in vehicle design assumptions

We assumed an EER of 1.28 due to the added fuel tank and engine weight.

Data from existing electric drive vehicles was collected so we could compare to ADL projections of electric versus ICE power requirements.

Electric Drive Powertrain Data

MY	Manufacturer	Country (prod)	Vehicle	Engine/FC	Battery	Baseline[1]
2001	Daimler-Chrysler	Germany	Necar 5	75	0	75
2001	Ford	US	Focus	80	0	82
2001	GM/OPEL	Germany	HydroGen1	80	0	75
2001	Hyundai	US	Santa Fe	75	0	84
2000	Honda	Japan	FCX-V3	62	0	86
2000	Ford	US	P2000 Contour	67	0	127
1998	Toyota	US	RAV4 EV	0	57	95
1999	Ford	US	Ranger EV	0	84	112
1998	Chevrolet	US	S-10 EV	0	99	134
2001	EPRI-Report	model study[2]	EPRI S0	89	0	127
2001	EPRI-Report	model study[2]	EPRI HEV0	44	19	127
2001	EPRI-Report	model study[2]	EPRI HEV0 LW	40	17	98
2004	GM	US	Paradigm SUV	164	24	202
1998	Audi[3]	Germany	Duo	38	29	84
2001	Toyota	US	Prius	52	33	80

[1] Baseline vehicle selection criteria:

a) Choose a production vehicle with similar market segment or platform as the advanced vehicle manufacturer.

b) For baseline vehicles with several powertrain options, the comparison is based on:

2 options: lower power rating

3 or more options: second lowest power rating

[2] Modeling studies, all with zero all electric range. S0 - series, HEV0 - parallel, HEV0 LW - parallel with lightweight glider. HEV0 configurations have additional peak acceleration capability from the battery.

[3] The Audi Duo has 67 kw of ICE power and 29 of motor power, but it cannot use both simultaneously. This calculation rates the abttery power as a fraction of peak power (67kW) and not the "total" power (67+29=96kW)

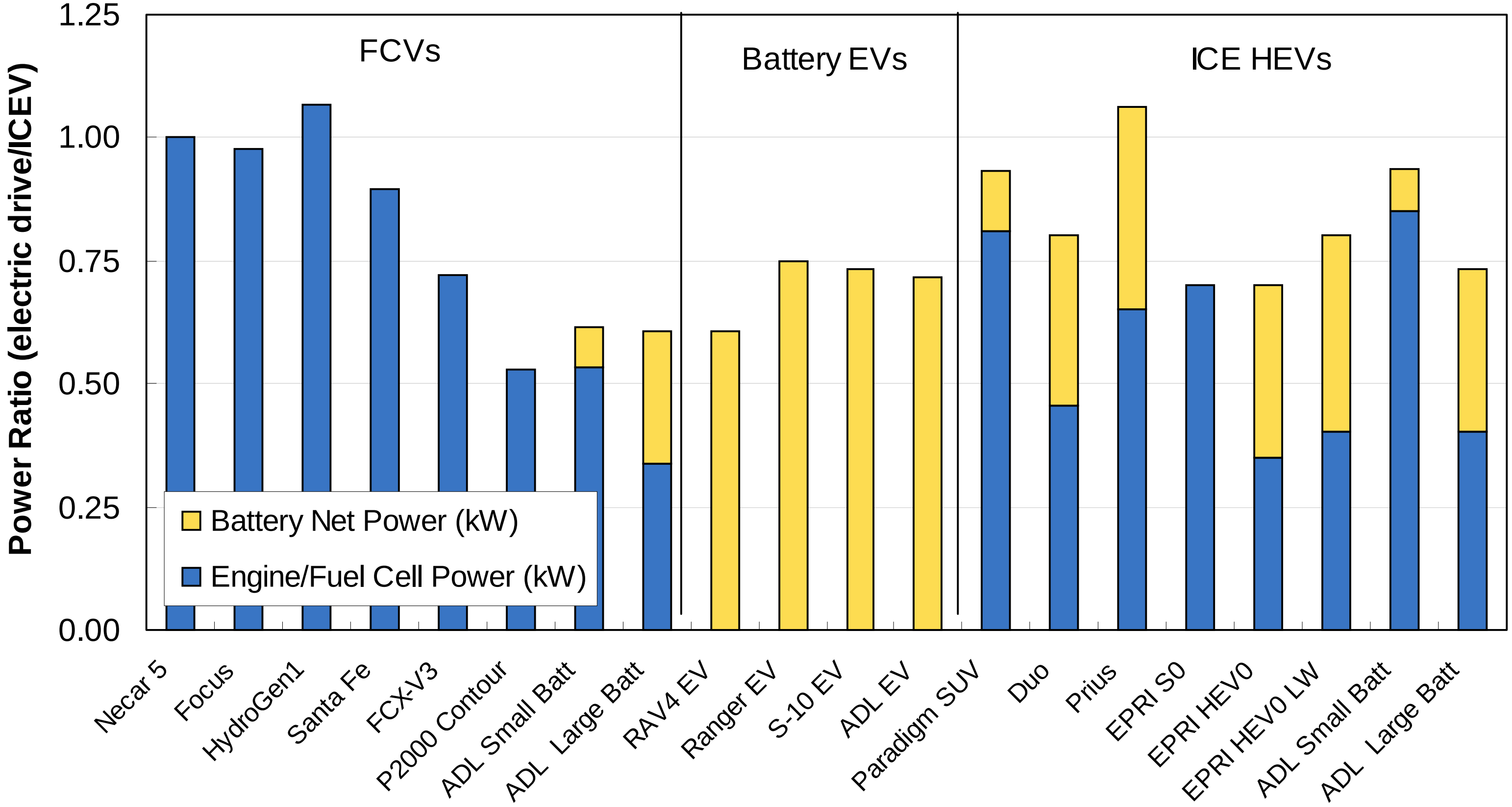
Powertrain power levels are based on values published by developers.

Electric Drive Powertrain Data Sources

Manufacturer	Vehicle	Information Sources EV_HEV_FCV Comparison.xls
Daimler-Chrysler	Necar 5	www.mercedesbenz.com/e/innovation/fmobil/fuelcell/necar5.html
Daimler-Chrysler	Sprinter Van	www.mercedesbenz.com/e/innovation/fmobil/fuelcell/sprinter
Toyota	Prius	www.toyota.com/details/specs.html
Honda	Insight	www.honda2001.com/models/insight/specs/specs0.html
Nissan	Altra EV Wagon	www.nissandriven.com/insideNissan/LookingAheadArticle/0,9401,535,00.html
Ford	Focus FCV	Automotive Engineering International, June 2001, pgs. 25-28
GM	Paradigm SUV	www.gm.com/company/gmability/environment/gm_and_the_env/releases/paradigm_hev_010401.html
GM/Opel	HydroGen1	www.gm.com/company/gmability/environment/products/fuel_cells/gapc_h1.html
Model Study	EPRI HEV0	Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options:, June 2001
Model Study	EPRI HEV0 LW	Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options:, June 2001
Model Study	EPRI S0	Electric Power Research Institute, "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options:, June 2001
Hyundai	Santa Fe	Hyundai promotional handout
Audi	Duo	www.caranddriver.com/xp/Caranddriver/roadtests/1997/July/199707_roadtest_audi_duo.xml?keywords=Audi%20Duo
Toyota	RAV4 EV	ev.inel.gov/fop/eva/toyrav98.html
Ford	Ranger EV	ev.inel.gov/fop/eva/ford99.html
Chevrolet	S-10 EV	ev.inel.gov/fop/eva/s10.html
Ford	P2000 Contour	www.thinkmobility.com/technologies/fordp2000.pdf
Honda	FCX-V3	www.honda2001.com/news/press.html?=2001&r=509, popularmechanics.com

In most cases, the electric drive power requirements were lower than their ICE counterparts, consistent with our projections.

Comparison of Electric Drive Powertrains



The comparisons are empirical and not always consistent.

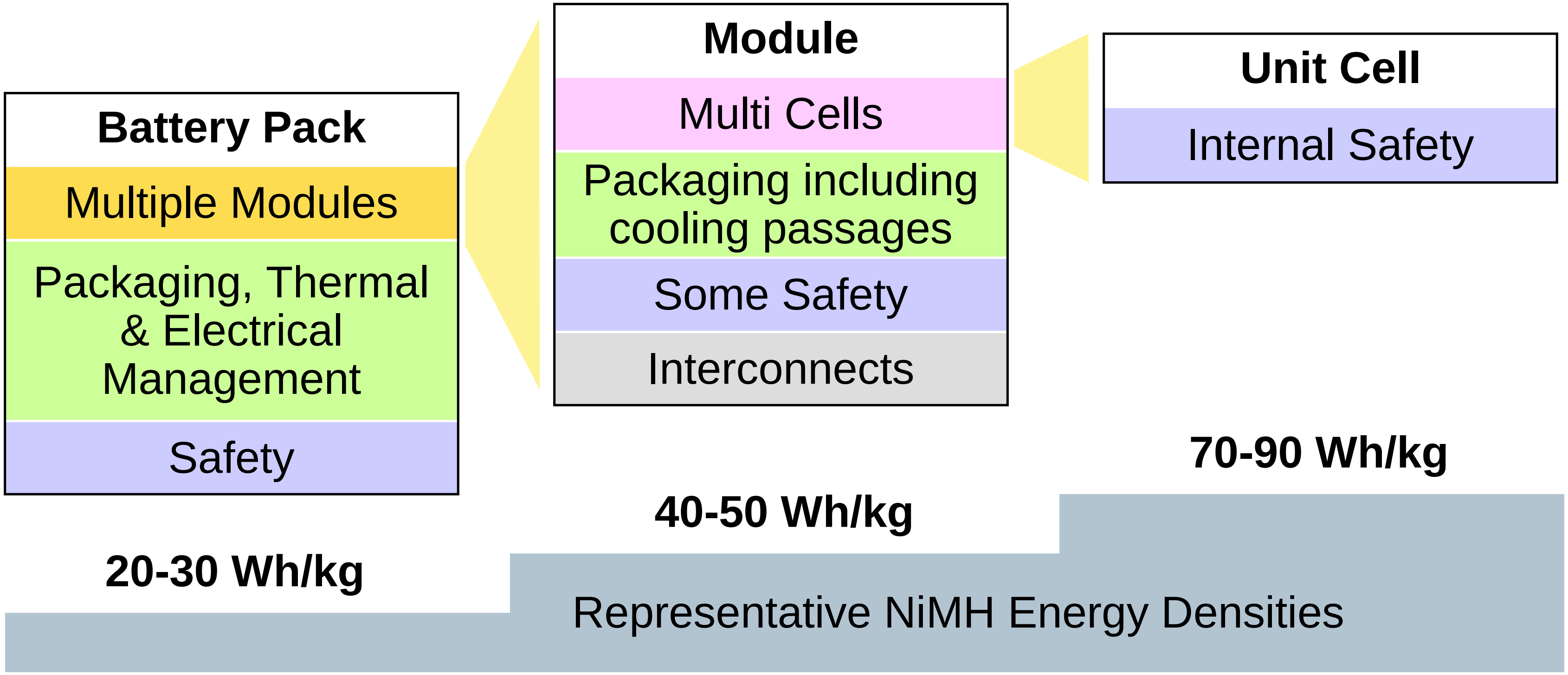
The range of power and energy specifications being pursued for HEVs reflects different vehicle requirements and design philosophies.

HEV Name	Status	Battery	Voltage	Energy (kWh)	Power (kW)	Battery Power[1]
Japan Prius	Commercial	NiMH	274	1.8	34	41.0%
Nissan Tino	Commercial	Li Ion	175	1.2	20	18.6%
Honda Insight	Commercial	NiMH	144	0.9	10	16.7%
GM Precept	Concept Prototype	NiMH or Li Polymer	350	3.0	25 peak 16 cont.	44.3%
DC ES X3	Concept Prototype	Li Ion	165		21	31.2%
Ford Prodigy	Concept Prototype	NiMH	288	1.1	35 peak 8 cont.	21.4%

* Values are estimated from literature data.

[1] Source: An, F. (ANL), “Evaluating Commercial and Prototyped HEVs”, presentation at FTT Conference 2000. Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

It is important to keep in mind the ancillary components, especially when quoting energy and power densities.



Battery Pack

Multiple Modules

Packaging, Thermal & Electrical Management

Safety

Module

Multi Cells

Packaging including cooling passages

Some Safety

Interconnects

Unit Cell

Internal Safety

20-30 Wh/kg

40-50 Wh/kg

70-90 Wh/kg

Representative NiMH Energy Densities

Lithium battery technology offers the highest performance in the long-term, as has been shown in portable electronics.

Battery Technology	Pb Ac (VRLA)	NiMH	Li Ion
Application	42 V Startup	Power Assist/Regen. (PA/R)	PA/R, Full HEV
Cell Energy Density, Wh/kg	35	45-60	100-120
Battery Energy Density, Wh/kg	35	20-50	50-100
Battery Power Density, W/kg		500-1,000	600-1,500
Cost[1] - current (projected), $/kWh	200-300 (100-150)	1,000-1,500 (400-500)	>1,500 (TBD)
Strengths	• Low Cost	• Most Demonstrated • High Power	• Highest Energy and Power Density
Issues	• Cycle Life • Energy & Power Density • Primarily 42 V Application	• Life • High Temp Charging • Low Temp Performance • Cost	• Life • Low Temp Performance • Cost • Safety

[1] Does not include thermal and electrical management of battery.

We assumed the DOE compressor/expander module (CEM) efficiency goals would be met by 2010 and used them to calculate CEM parasitic power.

Percent of Flow	DOE Goals			System P Drop[1], bar
	Inlet P, bar	Compress Efficiency	Expander Efficiency	
100%	3.2	75%	90%	0.40
80%	3.2	80%	90%	0.26
60%	2.7	75%	86%	0.09
40%	2.1	70%	82%	0.01
20%	1.6	65%	80%	0.00
10%	1.3	50%	75%	0.00

* These goals have been established for a CEM likely to operate on a 50 kWe net fuel cell system. Larger CEMs could have better efficiency.

[1] Estimated based on ANL and ADL analysis assumptions. A detailed analysis has not been performed.

Although simultaneously achieving cost and weight goals will be challenging.

Parasitic loads are calculated from the required flowrates and temperatures determined by thermodynamic modeling and other assumptions.

Parasitic Assumptions at 50 kW Rated Power	Units	Gasoline ATR	Methanol SR	Hydrogen
Compressor flowrate[1]	kg/s	0.065[2]	0.048	0.048
Expander flowrate[1]	kg/s	0.066[3]	0.053[3]	0.048[4]
Expander inlet temp	°C	255[3,5]	150[3,6]	230[4]
Other parasitics[7]	kW	0.5	0.5	0.5
Motor efficiency	%	95	95	95

* Based on thermodynamic analysis of 50 kW fuel cell systems. A detailed system analysis with complete heat integration has not been performed. Conditions are consistent with the future scenario assumptions (i.e. high temperature membrane, 100% excess air, etc.).

[1] Flowrates are determined by iteration with the gross power requirement.

[2] Additional air required for the ATR.

[3] Assumes 85% anode fuel utilization with a tailgas burner and water is removed from the fuel cell exhaust as needed for the reformer.

[4] Assumes 95% anode fuel utilization with a tailgas burner.

[5] The tailgas burner heat is used to vaporize the fuel prior to entering the expander.

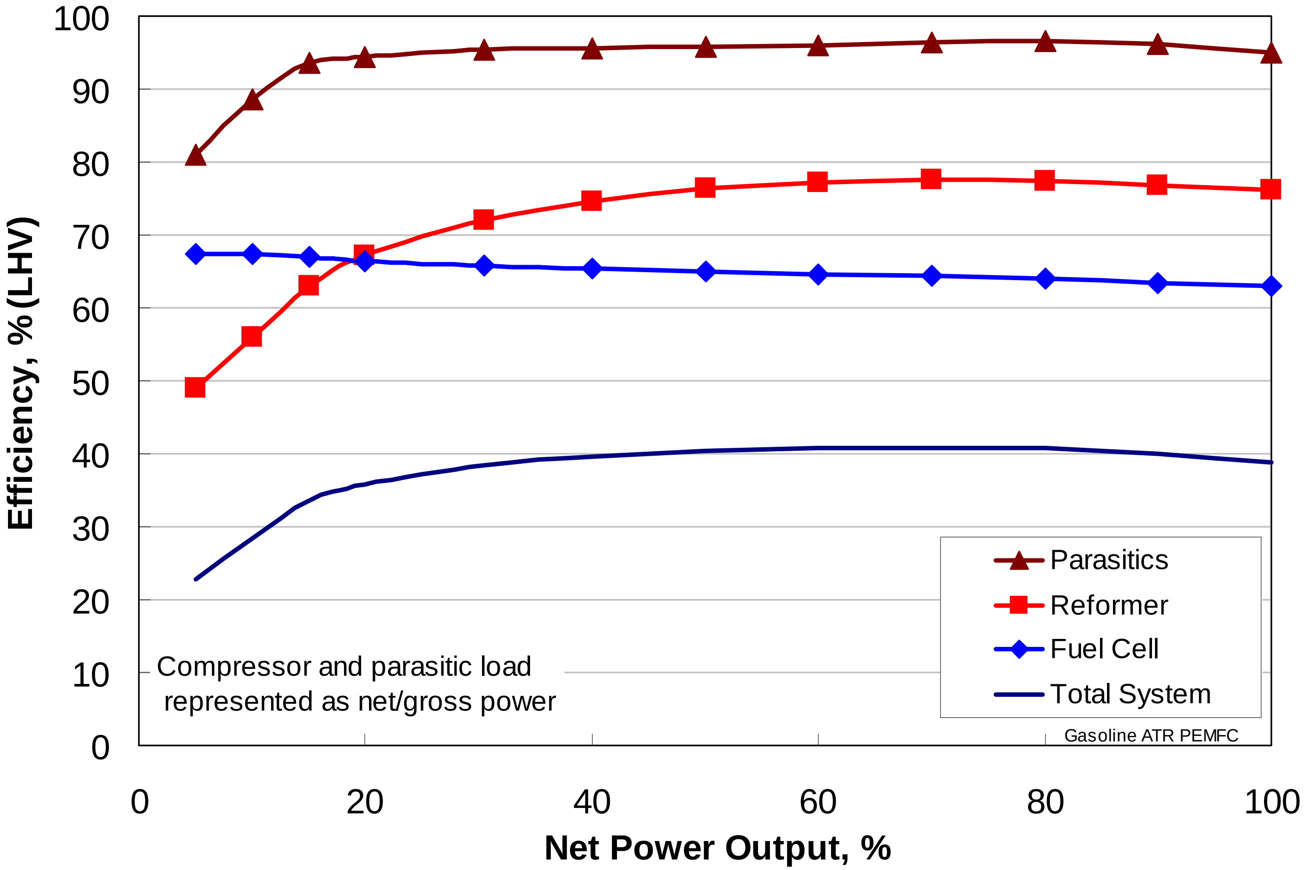
[6] The tailgas burner heat is used to drive the steam reforming reaction prior to entering the expander.

[7] Includes pumps and fans.

Part load inputs are estimated based on these full load assumptions.

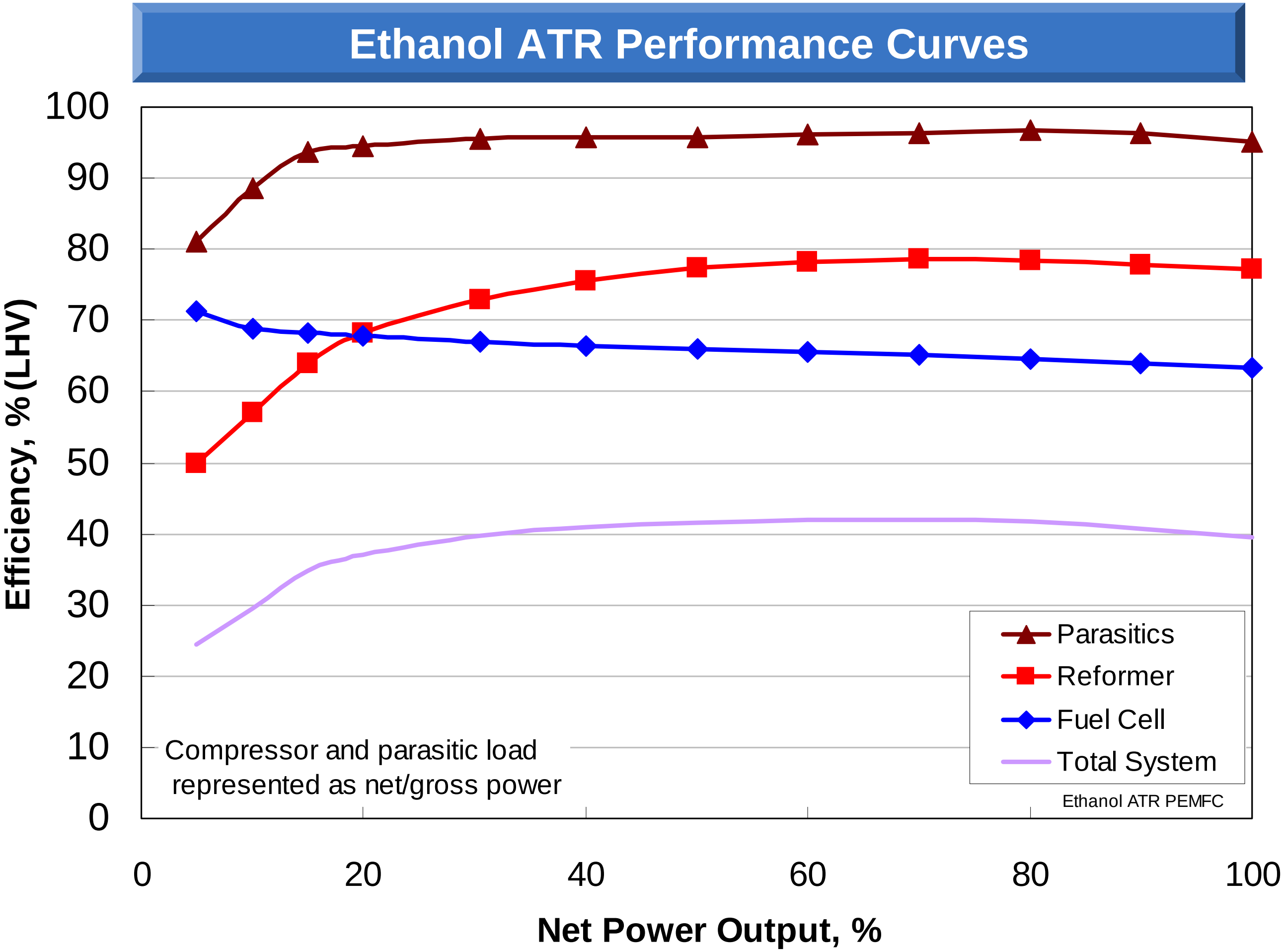
Voltage curves, parasitic loads, and reformer performance assumptions were used to generate performance curves for each system configuration.

Gasoline ATR Performance Curves



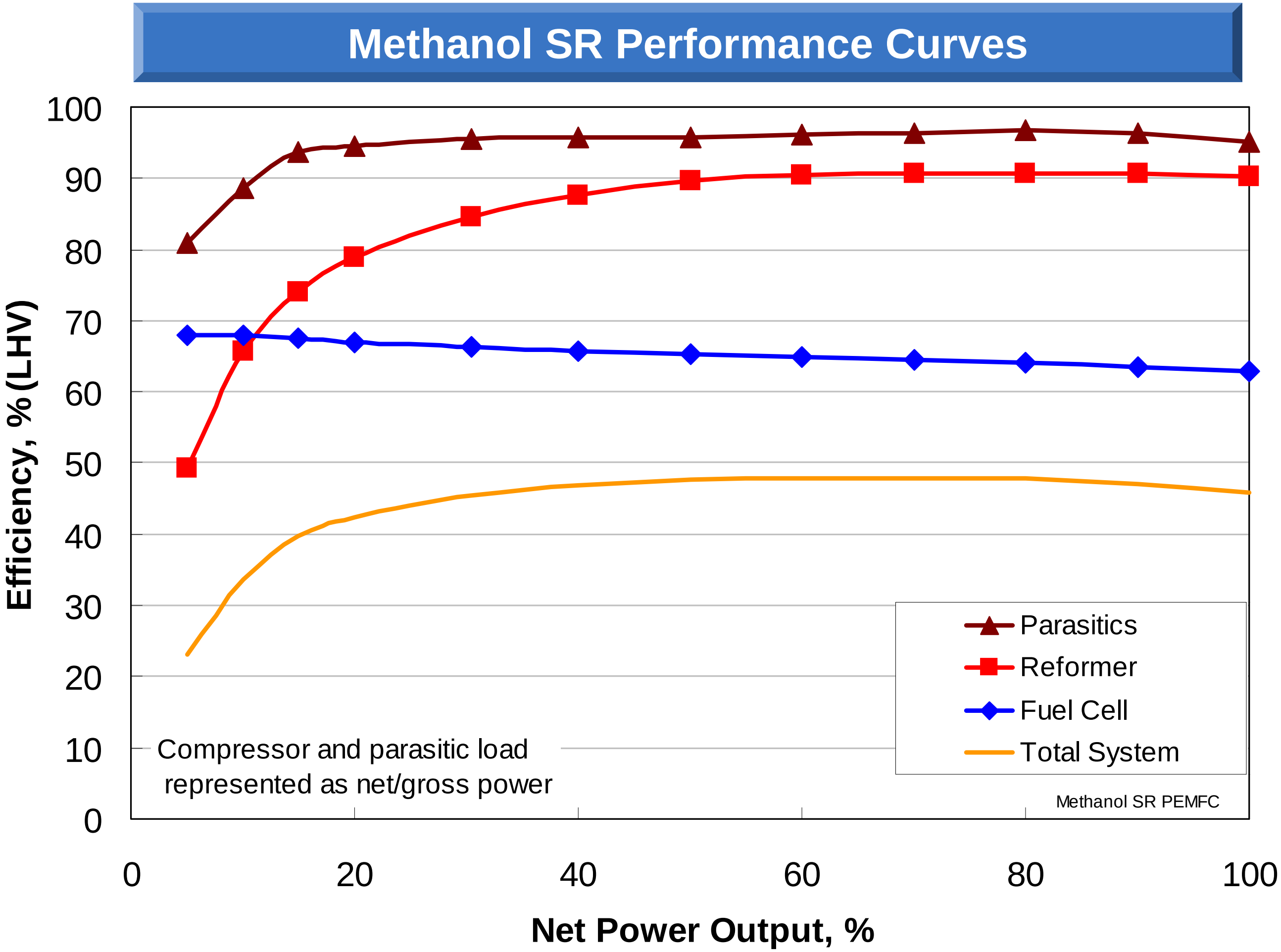
* Total system efficiency includes 85% anode utilization efficiency. Reformer performance curve is based on in-house kinetic and thermodynamic analysis.

The assumed ethanol performance curve is very similar to the gasoline case.



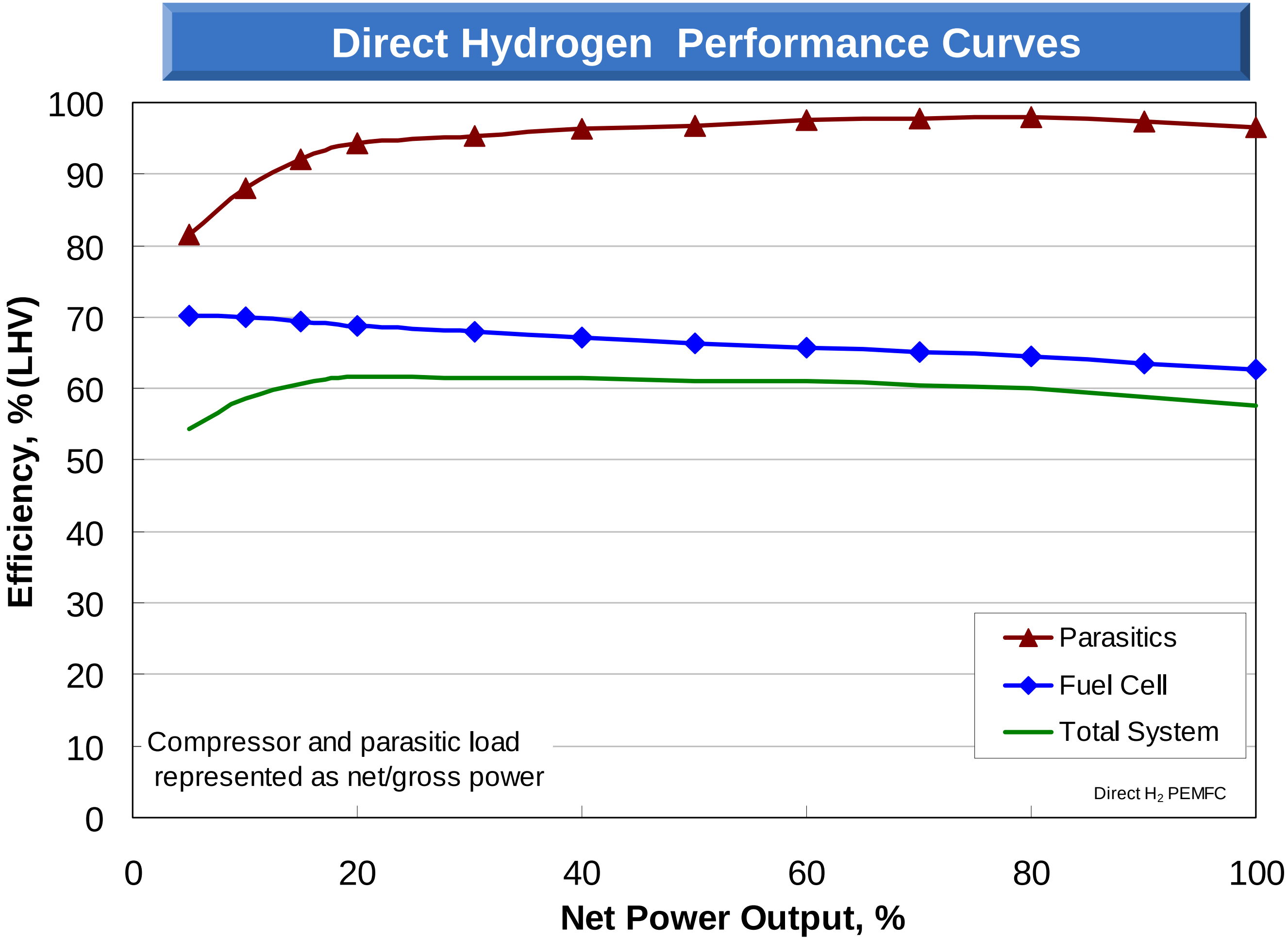
* Total system efficiency includes 85% anode utilization efficiency. Reformer performance curve is based on in-house kinetic and thermodynamic analysis.

The overall methanol efficiency is better than the gasoline and ethanol cases due to the higher efficiency of the steam reformer.



* Total system efficiency includes 85% anode utilization efficiency. Reformer performance curve is based on in-house kinetic and thermodynamic analysis. Note: Actual reformer efficiency remains near 91%. Anode utilization would be decreased to provide additional fuel for the reformer.

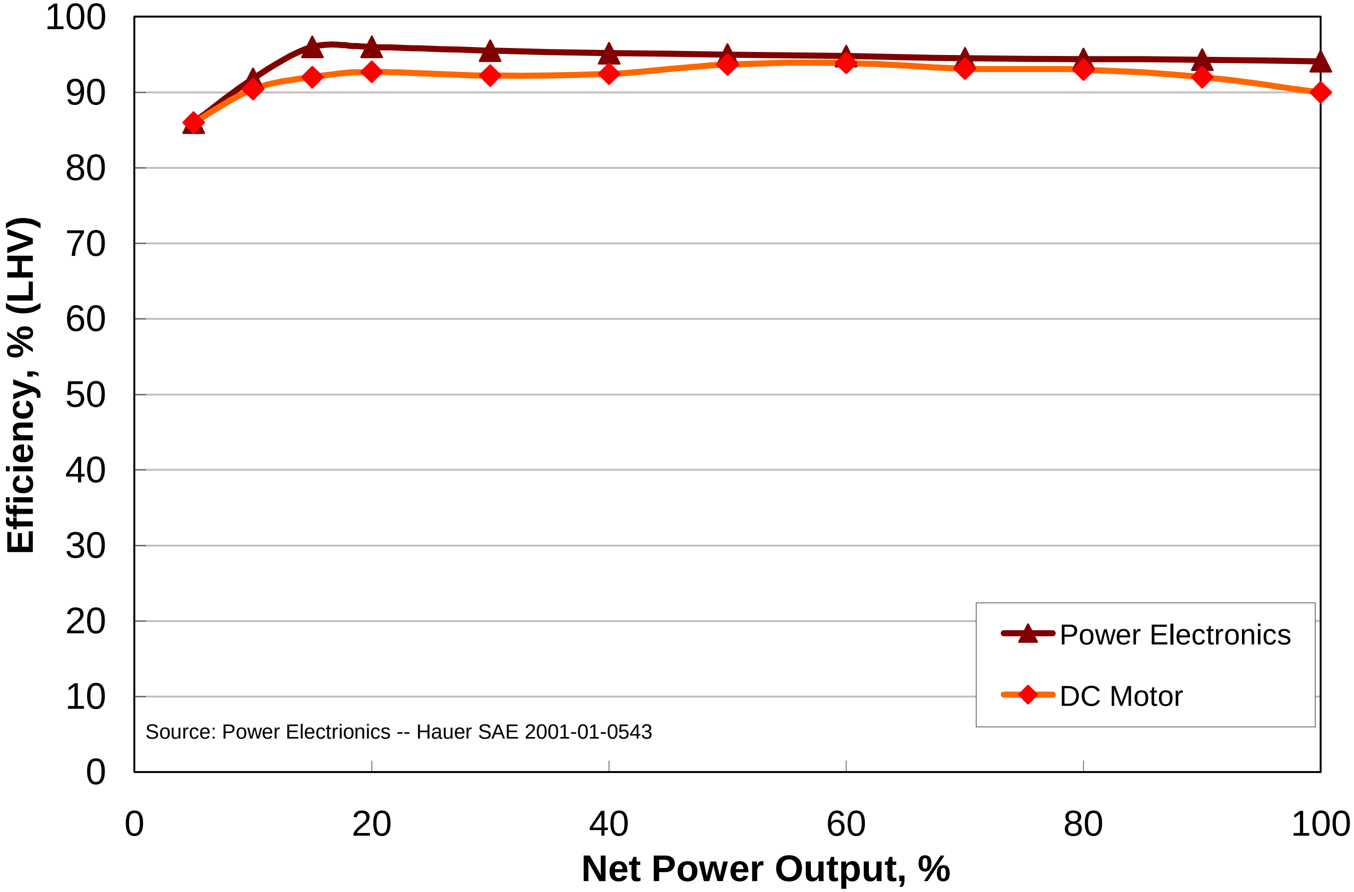
Lacking a reformer, the direct hydrogen system is much more efficient, especially at part load.



* Total system efficiency includes 95% anode utilization efficiency.

In addition to the power unit, motor and power electronic performance curves were applied to the overall powertrain performance.

Motor and Power Electronic Performance Curves



Source: Power Electrionics -- Hauer SAE 2001-01-0543

Key assumptions for vehicle ownership cost:

- Vehicle cost assumptions:
  - Monthly payments over 5 years
  - Adjusted for resale value: assumed to be 39% for the vehicle minus the precious metals which are assumed to have 85% residual value
  - 4% finance rate
  - Insurance, tax and license costs are excluded[1]
  - Glider cost is assumed to be the same for all vehicles in the same class[2]
- Maintenance cost assumptions:
  - Maintenance costs based on ADL/EPRI HEV study (EPRI 2001)
  - Assume identical maintenance costs for all vehicles in the same class
    - Customer expectation is that maintenance will be at least as good as conventional vehicles
    - No real world data
    - Limited data from battery EVs suggests same cost, although warranty costs for first commercial vehicles are high for some EV manufacturers
- Fuel cost assumptions:
  - Fuel costs are based on 14,000 mi/yr driving, fuel economy analysis, and fuel cost analysis
  - Tax excluded[3]

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[1] Would be higher for more costly vehicles under current practices.

[2] In practice, some changes to the glider would be required to accommodate differences in vehicle mass, brakes, and fuel storage.

[3] Would be lower for more fuel efficient gasoline and diesel vehicles. Road tax on hydrogen and electricity would be zero.

Consistent assumptions were used for the common powertrain weights for ICEVs, HEVs, FCVs, and Battery EVs.

Powertrain Parameters

Component	Value	Unit
Mass estimates, light-weight vehicles		
Mid-size glider mass	900	kg
SUV glider mass	1050	kg
Engine, Misc.		
Engine Misc, V6, ICEV	38.7	kg
Engine Misc, parallel HEV	10	kg
Engine Mounts	5	kg
FC mounts	5	kg
Electrical, Misc.		
Battery Pack, Tray Hardware 9kW	15	kg
Battery Pack, Tray Hardware 50kW	25.5	kg
Motor/electronics Thermal	16.6	kg
Battery Thermal	14.6	kg
Power Transmission		
HEV Transmission	50	kg
V6 Transmission/ICE Weight	1.30	kW/kg
Power Controls (HEV inverter)	5	kg
Power Controls (EV inverter)	7	kg
Midsized Fixed Battery Power	9	kW
Midsized Fixed Fuel Cell Power	Varies with vehicle weight	

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* , Palo Alto, June 2001.

Internal Combustion Engine costs depend upon fuel type and power rating. Smaller engines could be used in full parallel HEVs.

IC Engine Parameters

Engine Type	Intercept ($ @ 0 power)	Cost ($/kW)	Power Density (kW/kg)
RFG L4 ICE	$424	12	0.73
Diesel I4 ICE	$636	18	0.73
RFG V6 ICE	$693	10.9	0.78
Diesel V6 ICE	$1,040	16.4	0.78
Hydrogen ICE Cost Premium	$400	--	0.59

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* , June 2001.

Arthur D. Little*, U.S. Light-duty Dieselization Scenarios - Preliminary Study Final Report,*

prepared for American Petroleum Institute, July 1999.

We used ADL cost model projections for fuel cell and fuel processor costs.

Fuel Cell and Fuel Processor Parameters

Vehicle Component	ADL Projection	Unit	ADL Projection	Unit
Fuel Cell Type				
ATR FC (62 kW)	62.3	$/kW	0.596	kW/kg
MeOH FC (62 kW)	56.1	$/kW	0.676	kW/kg
EtOH ATR FC (62 kW)	62.3	$/kW	0.596	kW/kg
cH2 FC (59 kW)	50.5	$/kW	0.786	kW/kg
MH FC (59 kW)	50.5	$/kW	0.786	kW/kg
ATR FC (39 kW)	72.9	$/kW	0.544	kW/kg
MeOH FC (39 kW)	66.6	$/kW	0.613	kW/kg
cH2 FC (39 kW)	59.5	$/kW	0.720	kW/kg

Vehicle Component	ADL Projection	Unit
Precious Metals		
V6 Catalyst Precious Metals	250	$/unit
L4 Catalyst Precious Metals	180	$/unit
Assume same cost for diesel cat		
RFG FC and ATR	16.9	$/kW
Direct H_2 Fuel Cell	14.4	$/kW
MeOH FC and SR	10.3	$/kW

Vehicle Component	ADL Projection	Unit	ADL Projection	Unit
Fuel Processor				
ATR FP (62 kW)	23.4	$/kW	1.41	kW/kg
MeOH SR FP (62 kW)	21.4	$/kW	1.43	kW/kg
ATR FP (39 kW)	32.6	$/kW	1.13	kW/kg
MeOH SR FP (39 kW)	30.5	$/kW	1.13	kW/kg

Source: ADL analysis, fuel cell cost model

Consistent assumptions were used for the common HEV, FCV, and Battery EV powertrain costs.

Powertrain Parameters

Vehicle Component	Value	Unit
Radiator		
ICE (127 kW)	0.236	$/kW
Fuel Cell System (62 kW)	4.48	$/kW
Transmission		
ICE (127 kW)	1045	$/vehicle
HEV, parallel	625	$/vehicle
Motor intercept	190	$/unit
Motor slope	13.7	$/kW
Power Controls intercept	411	$/unit
Power Controls slope	18.9	$/kW
Exhaust/Evaporative	250	$/vehicle
Accessories	250	$/vehicle

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* , Palo Alto, June 2001.

Fuel storage and battery costs are significant for direct hydrogen vehicles as well as battery EVs and HEVs.

Fuel Storage and Fuel Costs

Vehicle Component	ADL Projection	Unit
Fuel Tank		
Liquid fuel	9.75	\$/vehicle
cH2, 350 bar, carbon fiber	265	\$/kg H_2
Metal Hydride	535	\$/kg H_2
NiMH Battery	23.9	\$/kW

Source: ADL analysis

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* , Palo Alto, June 2001.

Type	ADL Projection	Unit
Gasoline	1.20	\$/gal
Diesel	1.10	\$/gal
Methanol	0.72	\$/gal
Ethanol	1.30	\$/gal
Hydrogen	2.20	\$/kg

Since cars are sold with a full tank of fuel, this cost was also included in the analysis.

Vehicle costs are marked up to a retail price equivalent for the ownership cost analysis.

Price and Cost Parameters

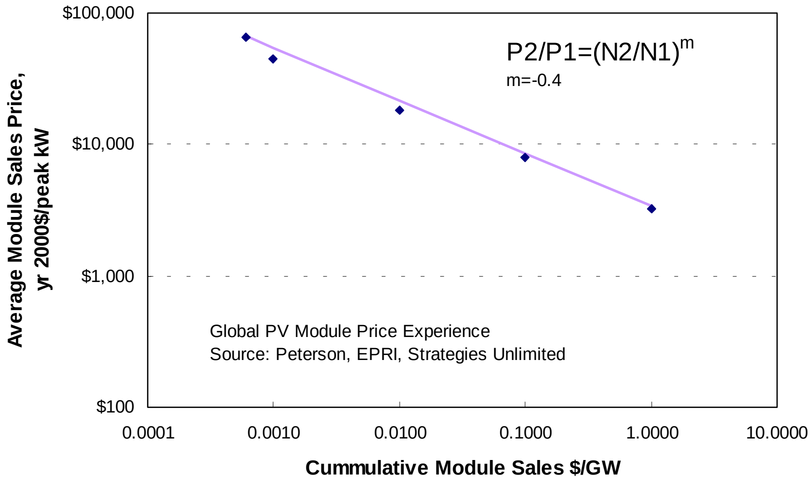
Item	Value	Unit
Glider	7255	$/vehicle
Manufacturer Markup	1.50	$/$cost
Dealer Markup (Post-manuf)	1.163	$/(cost+mrk up)
Combined Markup	1.745	$/$cost
Max. Markup for Engine/Fuel Cell	2500	$/vehicle
Max. Markup for Traction Battery	1000	$/vehicle

EPRI, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options* , Palo Alto, June 2001.

Component and manufacturing costs can drop with increased production volume above 500,000 units per year.

- Economies of scale have been documented for several industries
- Manufacture FC power plant in high volume and sell to several FCVs product lines
    - FCVs could be sold in a more premium vehicle market and compete with more costly ICEVs
    - However, expecting a price premium from a high volume product line may be unrealistic
- "Chunk Engineering" or modular manufacturing advances could also reduce materials and manufacturing costs

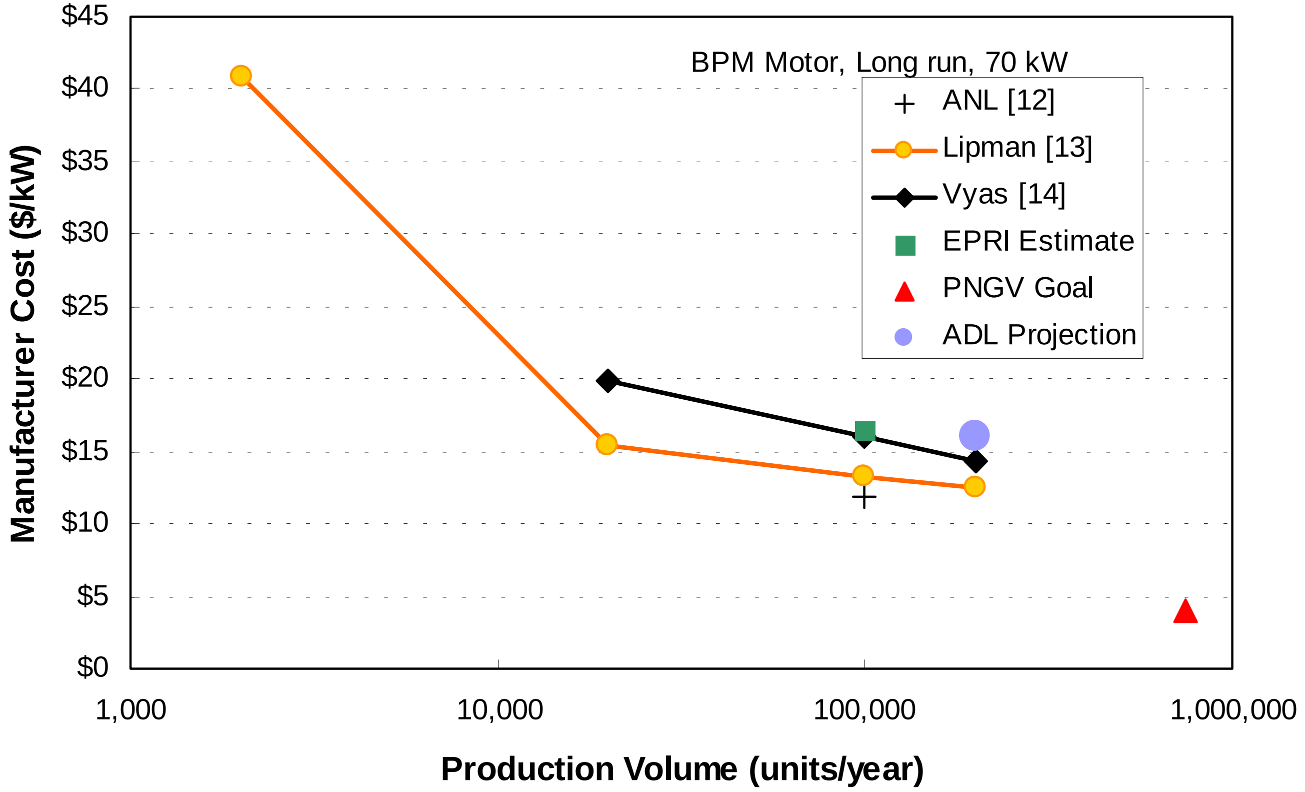
Historical PV Module Prices



On the other hand significantly higher costs could apply to FCV power units if high manufacturing volumes (per manufacturer) are not reached.

ADL projections for EV components are within range of other studies but are more conservative than the PNGV goals.

Estimates for Electric Motor Costs



Using DOE's aggressive goals for EV components would reduce FCV costs in comparison to ICEVs and even HEVs.

FCV power unit costs and performance built on ADL/DOE's current fuel cell system assumptions with the following changes to the stack.

Model Changes	Comments
Increased Membrane Operating Temperature from 80°C to 160°C	◆ Increases CO tolerance - eliminates PrOX and related equipment ◆ Assume reduced humidity requirements - eliminates cathode humidifying equipment eliminates low temperature water economizer and reformate cooler ◆ Assume reduced stack cooling requirements - fewer coolant plates per cell ◆ Increases radiator LMTD - reduces radiator size
Increased Current Density[1] from 310 to 500 mA/cm^2 at 0.8 V on gasoline reformate	◆ Based on expected improvements in CO tolerance, catalyst utilization and catalytic activity
Decreased Pt loading from 0.4/0.4 mg/cm^2 to 0.2/0.1 mg/cm^2 (Cathode/Anode sides)	◆ Based on modeling of polarization curve as a function of catalyst loading and ohmic resistances
Decreased Electrolyte Cost from 100 to 50 \$/m^2	◆ Basic materials are not intrinsically expensive ◆ Assumes high temperature membranes will not be significantly different in cost and will have equivalent performance
Decreased Platinum Processing Mark-up from 20% to 10%	◆ Assumes cost reductions at high volumes with future development

[1] Current density at 0.8 V, 0.2/0.1 mg/cm^2 (Cathode/Anode sides) Pt loading for the future case, 85% fuel utilization, 100% excess air, 3 atm operating pressure, and reformate with 1,000 ppm CO.

We made additional changes in the gasoline fuel processor and BOP to obtain a lowest cost system.

Model Changes	Comments
Improved ATR GHSV from 80,000 to 1,000,000	◆ Assumes short contact time reactor using 2% wt Rhodium ◆ Decreases fuel processor weight and cost despite high cost of Rhodium
Improved Shift Bed GHSVs significantly	◆ Assumes precious metal catalysts and higher allowable exit CO concentration in the LTS, and future improvements in catalyst performance in the HTS
No sulfur in fuel	◆ Assumes Energy Companies will remove sulfur at the refinery ◆ Eliminates sulfur removal bed
Reduced start-up time from 10 to 5 min	◆ Assumes shorter start-up times based on smaller fuel processor - less thermal mass to heat up ◆ Reducing start-up times further will require system modification (e.g. hybrids) ◆ Reduces size of the start-up battery
Decreased net parasitic power from 6.1 to 3 kW	◆ Assumes future improvements in CEM efficiency equivalent to DOE goals, and reduced fan parasitics (high temperature membrane) ◆ It may be difficult to simultaneously achieve CEM efficiency, cost and weight goals
Reduced CEM weight and cost from $630 to $500	◆ Assumes future improvements in CEM designs ◆ Reducing cost further will require significant development - the much simpler turbo chargers produced at high production volumes today are about $200/ea
Reduced sensor costs	◆ Reduced high temperature sensor cost from $25 to $10/ea ◆ Reduced general sensor cost from $70 to $25/ea ◆ Assumes future cost reductions

We made additional assumptions that primarily affected overall system weight.

Model Changes	Comments
Decreased Bipolar Plate Material Density from 2.25 to 1.12 g/cm^3	◆ Based on lighter weight material densities (such as GRAFOIL)
Decreased Width of Border around Fuel Cell Active Area from 1.5 to 1 inches[1]	◆ Increases cell active area significantly for high power density design points - reduces overall fuel cell stack size
Decreased Weight of Low Temperature Packaging Materials	◆ Assumes high density plastic materials instead of stainless steel for vessels less than 100°C
Included RAM Air in Radiator Analysis	◆ Based heat exchange coefficient on GM analysis of an automotive radiator for a fuel cell systems that takes RAM air effects into account ◆ Reduces radiator size significantly

[1] Border required for gasket and flow passages.

For the direct hydrogen FCV scenario, we increase the power density and replaced the fuel processor with compressed hydrogen storage.

Model Changes	Comments
Increased Current Density[1] to 750 mA/cm^2 at 0.8 V	◆ Based on experimental data that shows 1.5 times improvement for hydrogen versus gasoline reformate fuel cells, and kinetic verification (see Platinum Loading Modeling section for details)
Eliminated Ruthenium (Ru) from the MEA	◆ Assumed there is no CO or CO_2 in the hydrogen
Decreased Start-up Time from 5 to 1 min	◆ No warm-up time associated with the fuel processor
Added Compressed Hydrogen Storage System at $1200 and 45 kg[2]	◆ Assuming carbon fiber-wrapped tank rated for 5,000 psi working pressure ◆ Based on discussions with component developers - assuming high production volumes, future technology, including the whole storage system (tank, fuel injector, controls, safety) ◆ A detailed analysis has not been performed to date
Eliminated Fuel Processor Components	◆ Fuel supply, reformate generator, reformate conditioner, fuel processor water supply
Eliminated Fuel Processor Start-up Components in the Tailgas Burner	◆ Fuel vaporizer, warm-up steam generator

[1] Current density at 0.8 V, 0.2/0.1 mg/cm^2 (Cathode/Anode sides) Pt loading for the future case, 95% anode utilization, 100% excess air, 3 atm operating pressure, and 100% hydrogen.

[2] Assumes 350 mile range, 80 mpgge fuel economy, and 10% storage wt percent based on current claims by developers.

The following performance and component cost variables were assumed in the fuel cell stack and balance of plant for each scenario.

Cost Model Inputs 50 kW PEMFC System		**Current (1)** **Gasoline FCV**	**Future Scenarios**		
			Gasoline FCV	**Methanol FCV**	**Hydrogen FCV**
Fuel Cell	**Units**				
Cathode Platinum loading	mg/cm^2	0.4	0.2	0.2	0.2
Anode Platinum loading	mg/cm^2	0.4	0.1	0.1	0.1
Anode Ruthenium loading	% Pt	50	50	50	0
Current Density at 0.8 V	mA/cm^2	310	500	610	750
Electrolyte Cost	\$/m^2	100	50	50	50
Pt Processing Cost Mark-up	%	20	10	10	10
Cells per Coolant Plate		2	4	4	4
Bipolar Plate Material Density	g/cm^3	2.25	1.12	1.12	1.12
Gasket Perimeter	cm	3.8	2.5	2.5	2.5
BOP	**Units**				
Total Parasitic Power	kW	6.1	3	3	3
Start up time	min	10	5	5	1
CEM Weight	kg	8.2	5	5	5
CEM Cost	$	630	500	500	500
Low Temp. Packaging Materials		SS304	PTFEPE	PTFEPE	PTFEPE
Radiator Weight	kg	82	4.1	4.1	4.1
General Sensor Cost	$/ea	70	25	25	25
High Temperature Sensor Cost	$/ea	25	10	10	10

[1] ADL's 2001 OTT / PNGV Costing Program inputs.

We projected the future scenarios for current densities based on kinetic analysis (see Platinum Loading Modeling section for details).

Fuel processor performance and component costs were also varied for each scenario.

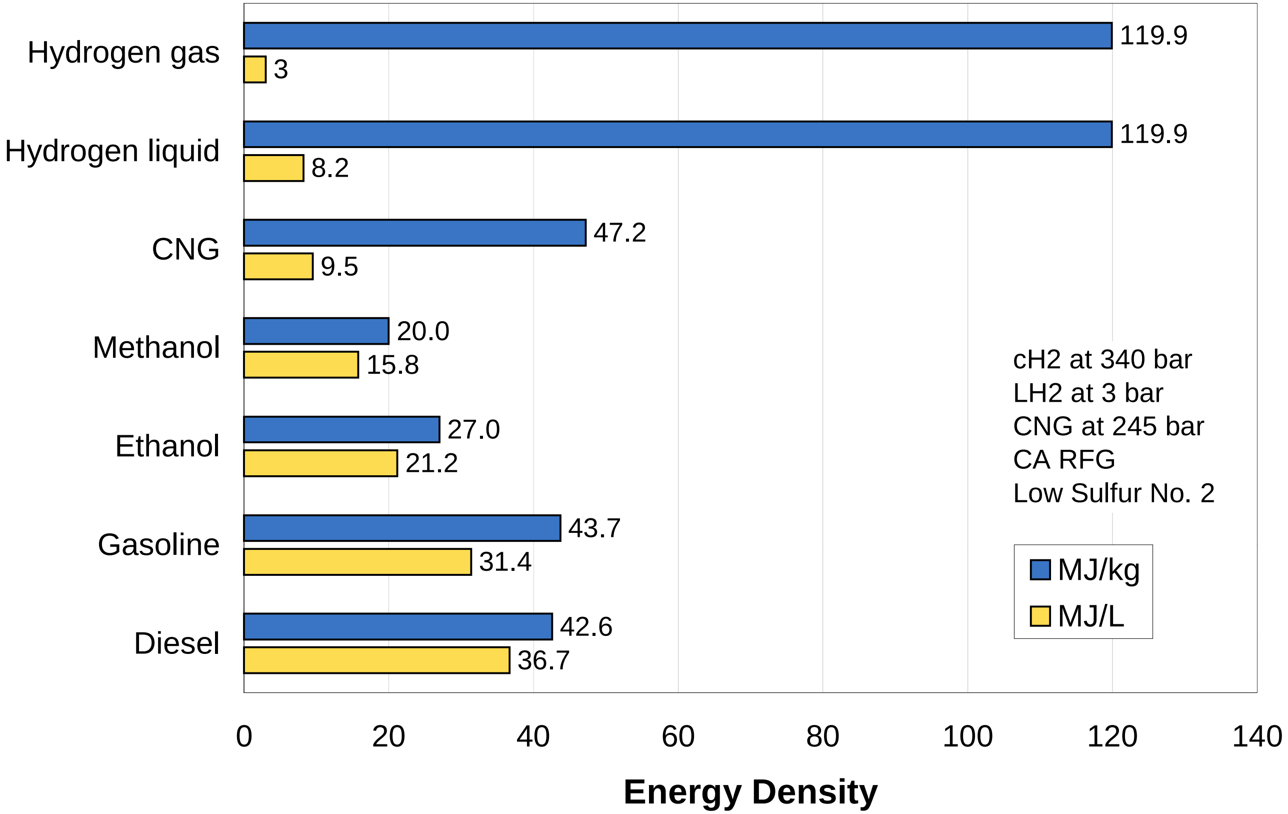
Cost Model Inputs 50 kW PEMFC System		**Current (1)** **Gasoline FCV**	**Future Scenarios**		
			Gasoline FCV	**Methanol FCV**	**Hydrogen FCV**
Fuel Processor	**Units**				
NH3 Bed		yes	yes	removed	NA
Space Velocities					
ATR1 (Precious metal)	hr^{-1}	80,000	1 MM	removed	NA
ATR2 (Ni)	hr^{-1}	15,000	removed	removed	NA
ZnO bed	hr^{-1}	45,000	removed	removed	NA
HTS	hr^{-1}	10,000	40,000	40,000	NA
LTS	hr^{-1}	5,000	80,000	80,000	NA
PrOX	hr^{-1}	10,000	removed	removed	NA
ATR1 Catalyst Cost	$/kg	81 (2)	630 (3)	removed	NA
ATR2 Catalyst Cost	$/kg	15 (4)	removed	removed	NA
LTS Catalyst Cost	$/kg	14 (5)	82 (2)	82 (2)	NA
cH_2 Storage	**Units**				
Hydrogen Storage Cost	$	NA	NA	NA	1200
Hydrogen Storage Weight	kg	NA	NA	NA	45

[1] ADL's 2001 OTT / PNGV Costing Program inputs.
[2] Less than 0.5% Platinum ($15/g).
[3] 2% Rhodium ($30/g).
[4] Ni+K based catalyst.
[5] Cu+Zn+Al based catalyst.

We assumed the methanol steam reformer costs would be similar to the water gas shift beds of the autothermal reformer.

Even at 5,000 psia, hydrogen's volumetric energy density is an order of magnitude lower than gasoline and diesel.

Fuel Energy Content by Weight and Volume

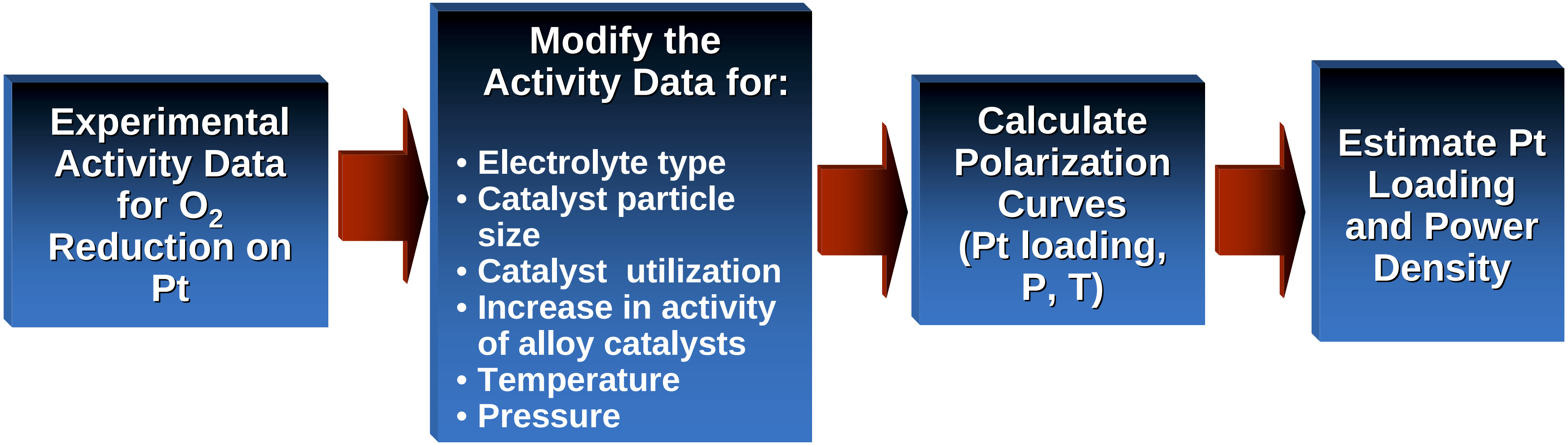


Compressed hydrogen storage at 10,000 psi or metal hydrides may be necessary to meet consumers' demands for trunk and passenger space.

Outline

Appendix

Optimistic but physically attainable power densities for each fuel cell system were calculated based on kinetic analysis.



Experimental Activity Data for O_2 Reduction on Pt

Modify the Activity Data for:

- **Electrolyte type**
- **Catalyst particle size**
- **Catalyst utilization**
- **Increase in activity of alloy catalysts**
- **Temperature**
- **Pressure**

Calculate Polarization Curves (Pt loading, P, T)

Estimate Pt Loading and Power Density

For the projection of future scenarios, we assume the availability of high temperature electrolyte technology with performance similar to current electrolytes.

We assume operation at a high cell voltage based on the ADL/DOE analysis of reformate systems.

- System efficiency goals dictate operation at high cell voltages
    - 0.8 V at rated power
    - Cathode kinetics dominates stack polarization at these voltages
    - Mass transfer effects in the catalyst layer (electrode) and the gas diffusion layer assumed to be negligible
- Other parameters accounted for in the analysis include:
    - Inherent catalyst activity
        - Function of catalyst material
    - Reaction rate
        - Function of operating conditions (P, T, reactant concentrations)
    - Catalyst utilization
        - Function of catalyst particle size, catalyst support, electrolyte type, and electrode structure

Lower cell voltage operation could simplify turndown performance and reduce powertrain cost, especially for direct hydrogen systems.

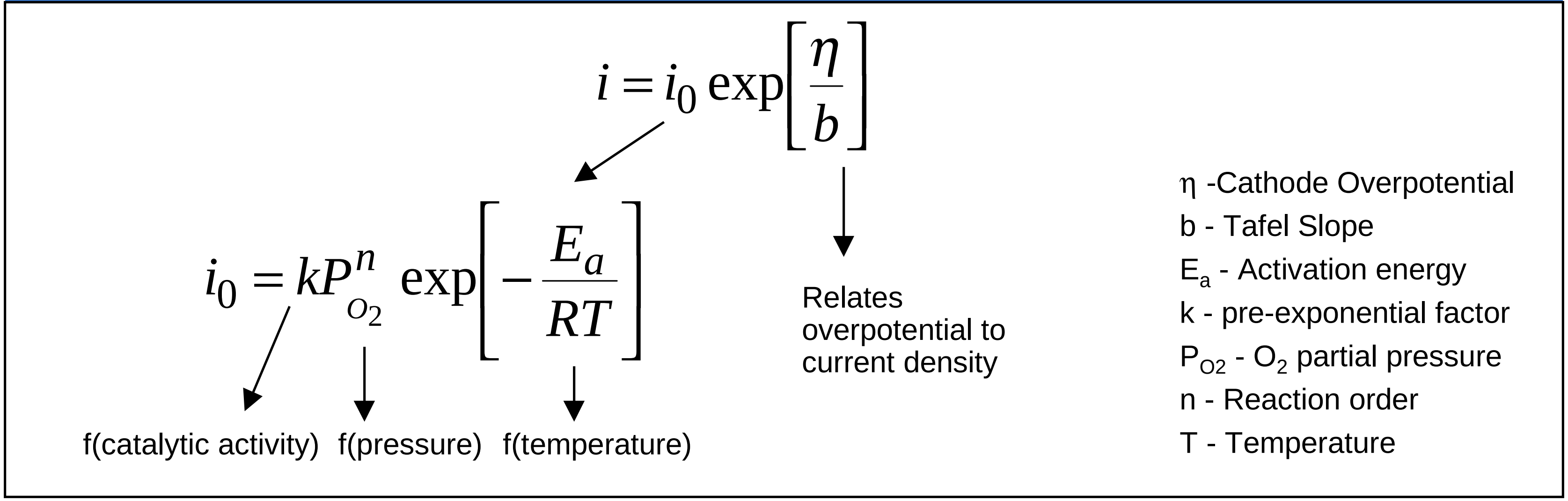
Catalysis loading, power density, and ohmic resistance are critical parameters that influence the active and inactive materials stack costs.

- Active Materials
  - Electrode material cost dominated by the catalyst material(s)
  - Catalyst loading determines the kinetics of the MEA
    - Anode catalyst loading assumed to equal 50% of the cathode loading
    - Assume 15% utilization (3.5 nm particle [30%], 50% available area)
    - Assume alloy catalyst with twice the activity of Pt
  - Electrode area for specified power and operating voltage determined by polarization curve
- Inactive Materials
  - Electrode area determines inactive material cost
  - Ohmic resistance of inactive materials influences polarization curve

Tafel kinetics is used to model the cathode current density versus overpotential for different catalyst activity and loading, pressure, and temperature.

- Assumptions:
  - Activity is defined as Amperes per unit Platinum surface area
  - Tafel kinetics
  - The Tafel slope is assumed constant for the temperature range considered

Tafel Kinetics



$$i = i_0 \exp\left[\frac{\eta}{b}\right]$$

$$i_0 = kP_{O_2}^{n} \exp\left[-\frac{E_a}{RT}\right]$$

η -Cathode Overpotential
b - Tafel Slope
E_a - Activation energy
k - pre-exponential factor
P_{O2} - O_2 partial pressure
n - Reaction order
T - Temperature

For the future scenarios, we chose a cathode catalyst loading of 0.2 mg/cm² because of stack power density targets.

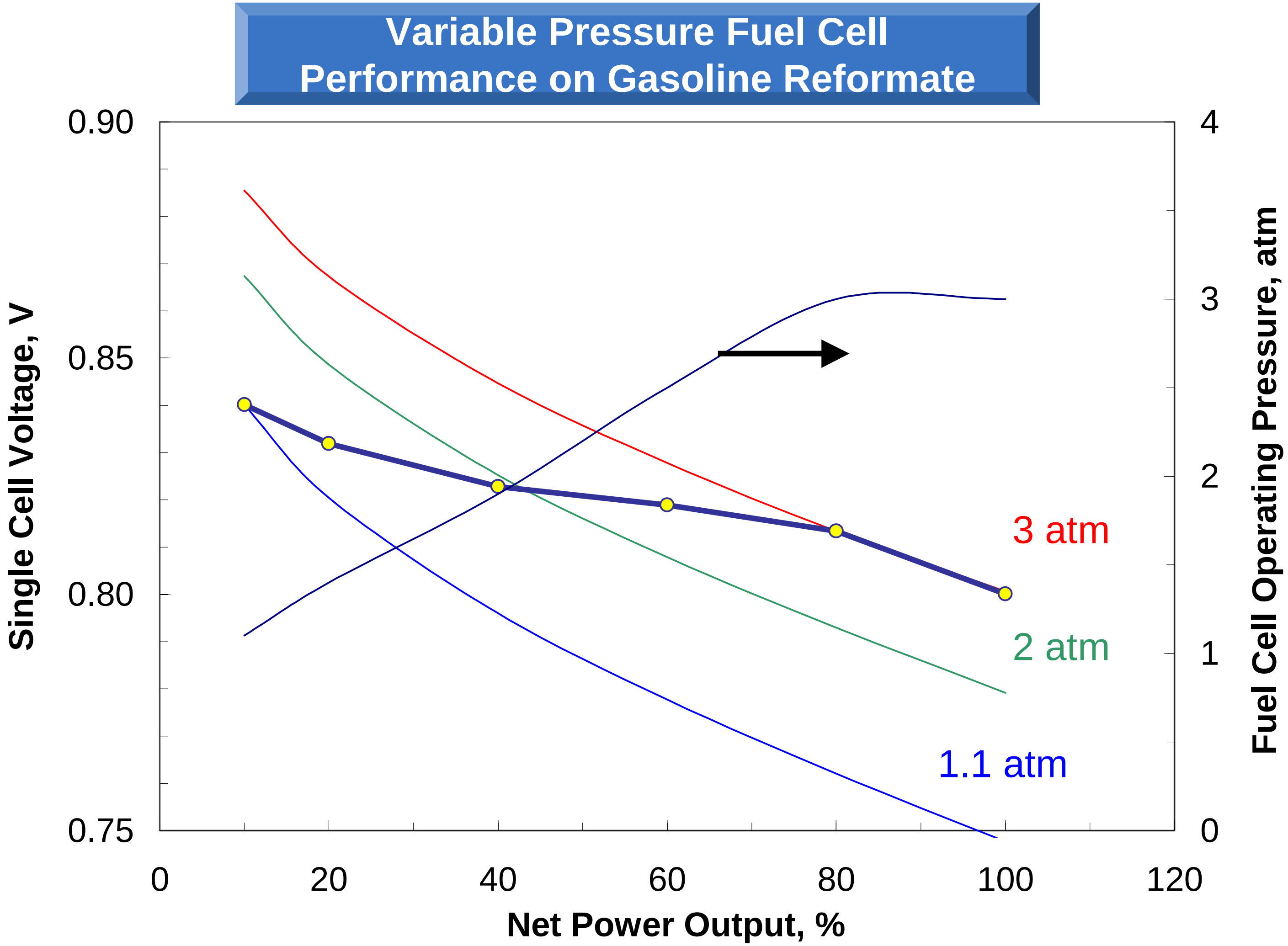
Assumptions	**Hydrogen**	**MeOH Reformate**	**Gasoline Reformate**
Cathode Pt Loading (mg/cm²)	0.2	0.2	0.2
Anode Pt Loading (mg/cm²)	0.1	0.1	0.1
Anode overpotential (mV)	0	18	30
Membrane Resistance (mΩ cm²)	50	50	50
Electronic Resistance (mΩ cm²)	20	20	20
Current Density (mA/cm²)	750	610	500

Operating Conditions:
0.8 V, 3 atm, 160 C, 3.5 nm Particles, 2x Pt activity

The specific currents estimated in this analysis correspond to a 'best case scenario' for platinum; lower currents would result at 0.8 V if:

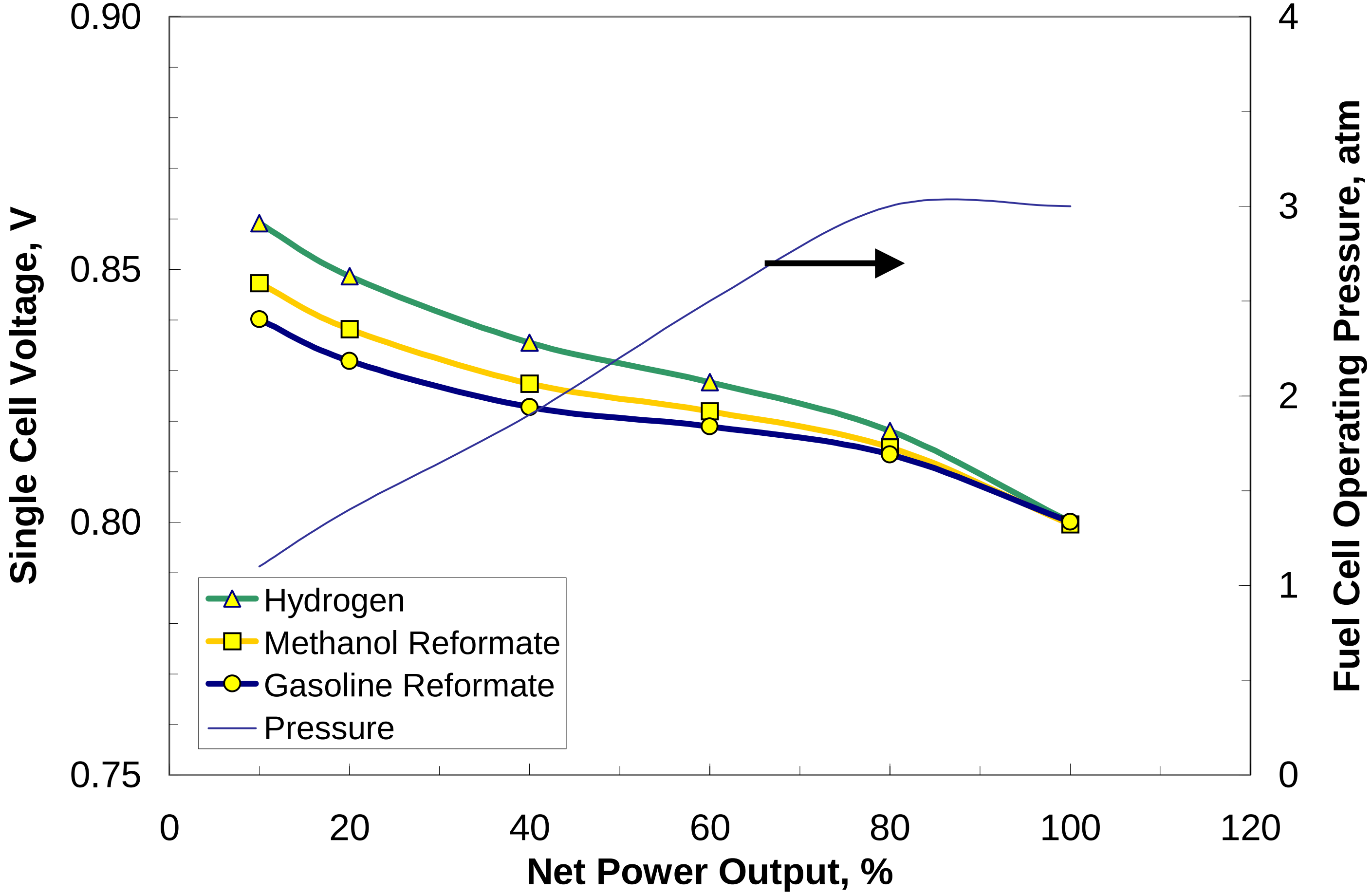
- The catalyst area utilization is less than 50%
- Either ionic or molecular diffusion resistances in the catalyst layer become significant
  - Literature data indicates that current densities on the order of 2 A cm^{-2} are not diffusion limited for cells with supersaturated feed streams
  - However, the ionic resistance in the catalyst layer can become limiting for saturated or partially saturated feed streams
- The electrolyte resistance is greater than 0.05 Ω cm^{-2}
- If the solubility of oxygen in the high temperature electrolyte is lower than the solubility of oxygen in Nafion at room temperature
- Anode overpotentials are significantly greater than those assumed

Stack voltage curves were constructed based on kinetic analysis assuming lower pressure at part load.



The direct hydrogen case allows for higher cell voltage operation (better efficiency) at part load.

Variable Pressure Fuel Cell Performance on Reformate and Hydrogen



Outline

Appendix

In Phase I of this project, we performed quick estimates of well-to-wheel efficiency based on available information.

	Phase I Fuel Efficiency Estimates (HHV)						
Well-to-Wheel Step	Current Gas ICEV	Gas HEV	Diesel HEV	Gas FCV	Battery EV	Current cH$_2$ FCV	Target cH$_2$ FCV
Resource Extraction	93 - 97 %	93 - 97 %	93 - 97 %	93 - 97 %	95 %	~ 95 %	N/A
Transportation	98-100 %	98-100 %	98 -100 %	98-100 %	~100 %	~ 100 %	
Fuel Production	85 - 90 %[1]	85 - 90 %[1]	90 - 97 %[1]	85 - 90 %[1]	30 - 50 %[2]	56 - 72 %	76 %
Distribution & Marketing	~100 %	~100 %	~100 %	~100 %	93 %	80 - 90 %	85 - 93 %
Powertrain	14 - 18 %[3]	21 - 27 %[4]	24 - 32 %[5]	22 - 35 %	65 - 80 %	35 - 45 %	40 45 %
Overall	11 - 16 %	16 - 26 %	20 - 30 %	17 - 31 %	18 - 34 %	15 - 26 %	28 %

[1] Assuming modern refinery with emissions controls and meeting California product specs

[2] Range of power generation efficiencies

[4] Gasoline HEVs appear to have the potential to be about 50% more efficient than conventional gasoline ICEVs

[5] Industry consensus from a previous study is that CIDI HEVs could be up to 75% more efficient than conventional gasoline ICEVs, however, it is uncertain whether they will be able to meet environmental standards

We estimated CO_2 emissions from the efficiency estimates.

	Phase I CO_2 Emissions Estimates (g/km)						
Well-to-Wheel Step	Current Gas ICEV	Gas HEV	Diesel HEV	Gas FCV	Battery EV	Current cH_2 FCV	Target cH_2 FCV
Resource Extraction	9.	6	5	5	4	5	N/A
Transportation	2	1	1	1	<1	1	
Fuel Production	24	16	3	13	104	108	91
Distribution & Marketing	<1	<1	<1	<1	0	10	7
Power train	193	129	113	107	0	0	0
Overall	228	152	122	127	108	123	98

Quick estimates of overall ownership cost were also developed in Phase I.

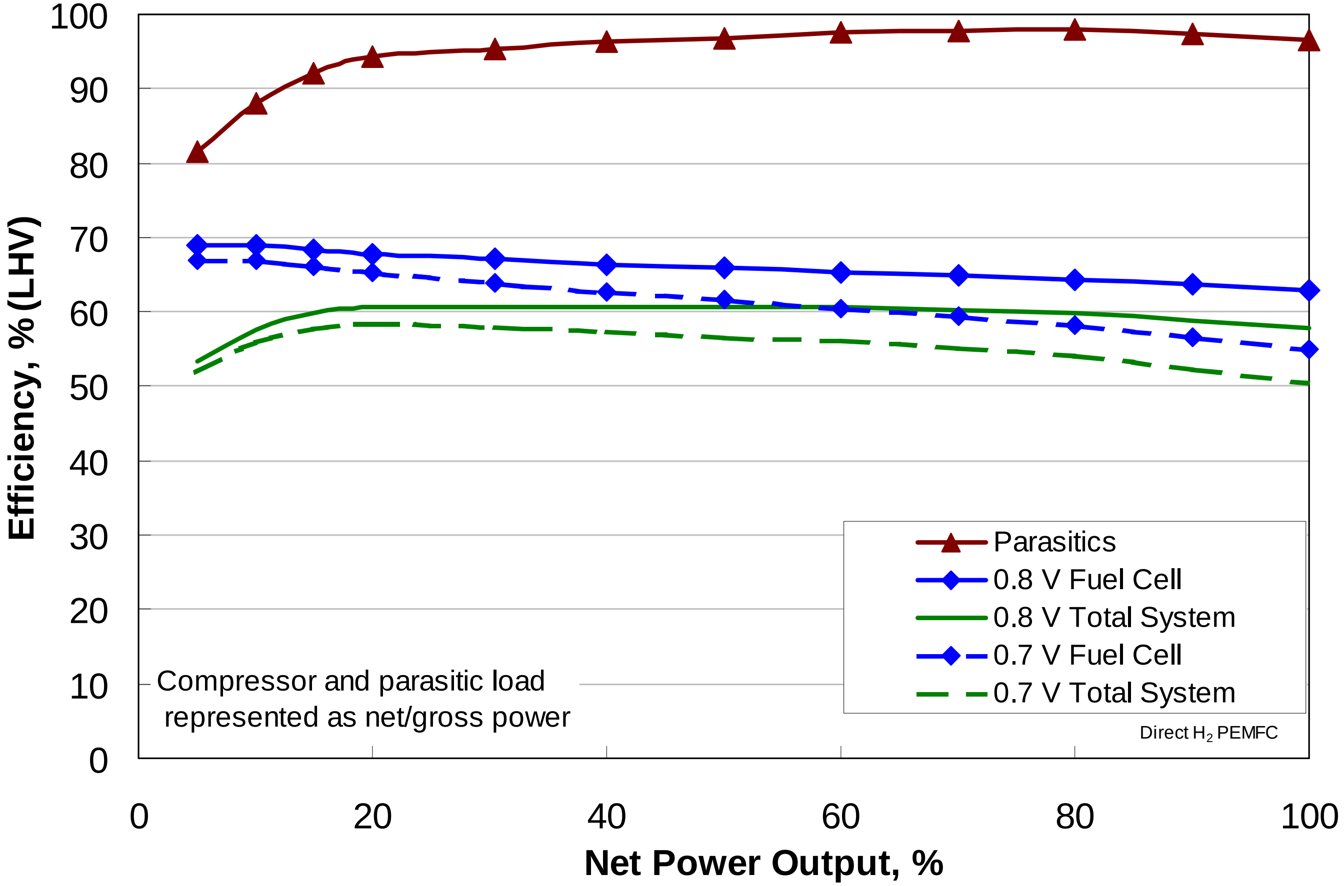
	Phase I Cost Estimates						
Ownership Cost Category	Current Gas ICEV	Gas HEV	Diesel HEV	Gas FCV	Battery EV	Current cH_2 FCV	Target cH_2 FCV
Fuel Cost ($/GJ)	7.86[1]	7.86[1]	7.86[1]	7.86[1]	13.89[2]	13.37	11
Fuel cost (ct/km)	2.2	1.5	1.3	1.3	0.7	1.5	1
Power train ($)	4,000	6,000 - 10,000	8,000 - 12,000	15,000 - 40,000	15,000 - 40,000	10,000 - 30,000	12,000
Power Train ($/kW)	40	60 - 100	80 - 120	150 - 400	150 - 400	100 - 300	120
Power Train (ct/km)	2.0	3 - 5	4 - 12	7.5 - 20	7.5 - 20	5 -15	6
Maintenance (ct/km)	2	2	2	5	6	4	3
Total (ct/km)	6	6 - 9	7 - 14	14 - 26	14 - 27	11 - 20	10

[1] Based on $1.00 /Gal price at the pump on a pre-tax basis

[2] Based on $0.05 per kWh power prices

Assuming there are no mass transport limitations, operating at 0.7 V rated power will result in only a 3-4%efficiency reduction at less than 20% load where a vehicle will spend most of its time.

Future Direct Hydrogen Scenario Performance Curves



* Total system efficiency includes 95% anode utilization efficiency.

Assuming only the power density changes by operating at 0.7 V (from 750 to 1,900 mA/cm^2), the fuel cell subsystem cost decreases 30%.

Characteristic	Units	Mid- term PNGV Target	Long-term PNGV Target	Current Hydrogen	Future Hydrogen	
					0.8 V	0.7 V (4)
Overall System Cost[1]	$/kW	125	45	196	103	83
Overall System Specific Power[1]	W/kg	250	325	165	365	450
Fuel Cell Subsystem Cost[2]	$/kW	100	35	157	65	45
Fuel Cell Subsystem Specific Power[2]	W/kg	400	550	213	658	1,000
Fuel Processor Cost[3]	$/kW	25	10	NA	NA	NA
Fuel Processor Specific Power[3]	W/kg	700	800	NA	NA	NA

* Targets are based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057.

[1] Includes fuel processor or hydrogen storage, stack, auxiliaries and startup devices; excludes gasoline tank and vehicle traction electronics.

[2] Includes tailgas burner and fuel cell ancillaries: heat, water, air management systems; excludes fuel processing/delivery system.

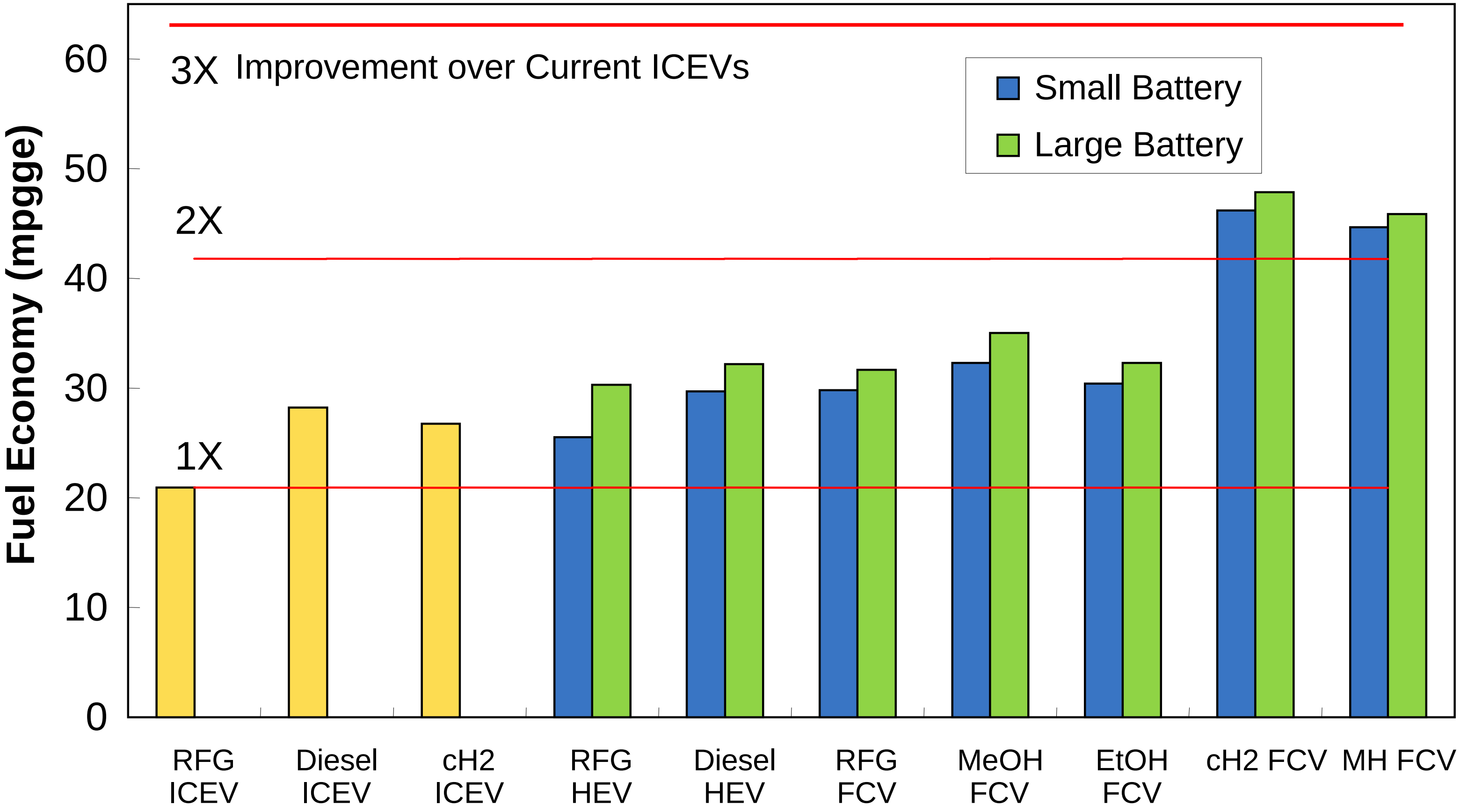
[3] Includes controls, shift reactors, CO cleanup, and heat exchanges; excludes fuel storage.

[4] Cost and specific power results for the 0.7 V case are very optimistic because only the current density was changed from 750 to 1,900 mA/cm^2. Heat exchanges, pumps, compressors, and the hydrogen storage unit cost and weight were not increased for the less efficient fuel cell operation.

Heat exchangers, pumps, compressors, and the hydrogen storage unit have not been scaled for the less efficiency 0.7 V fuel cell operation.

Fuel consumption for SUVs is higher than mid-sized vehicles, but the relative differences between options remains nearly the same.

Fuel Economy for SUVs



* The large battery cases give better fuel economy due to their great regenerative braking capacity.

Our projections for gasoline SUV HEV performance are in line with ANL's adjusted EERs.

ANL Analysis of Sport Utility Gasoline HEVs[1]					
HEV Name	**Type**	**Status**	**Battery Power[2]**	**CAFÉ mpg**	**Adjusted EER**
Escape HEV	Gasoline Small SUV	Planned	35.0%	40	1.58
Durango HEV	Gasoline Full SUV	Production Prototype	33.7%	19	1.20
ADL Projections					
Large Battery HEV	Gasoline Full SUV	Projected 2010	28.7%	30.3	1.45
Small Battery HEV	Gasoline Full SUV	Projected 2010	7.1%	25.5	1.22

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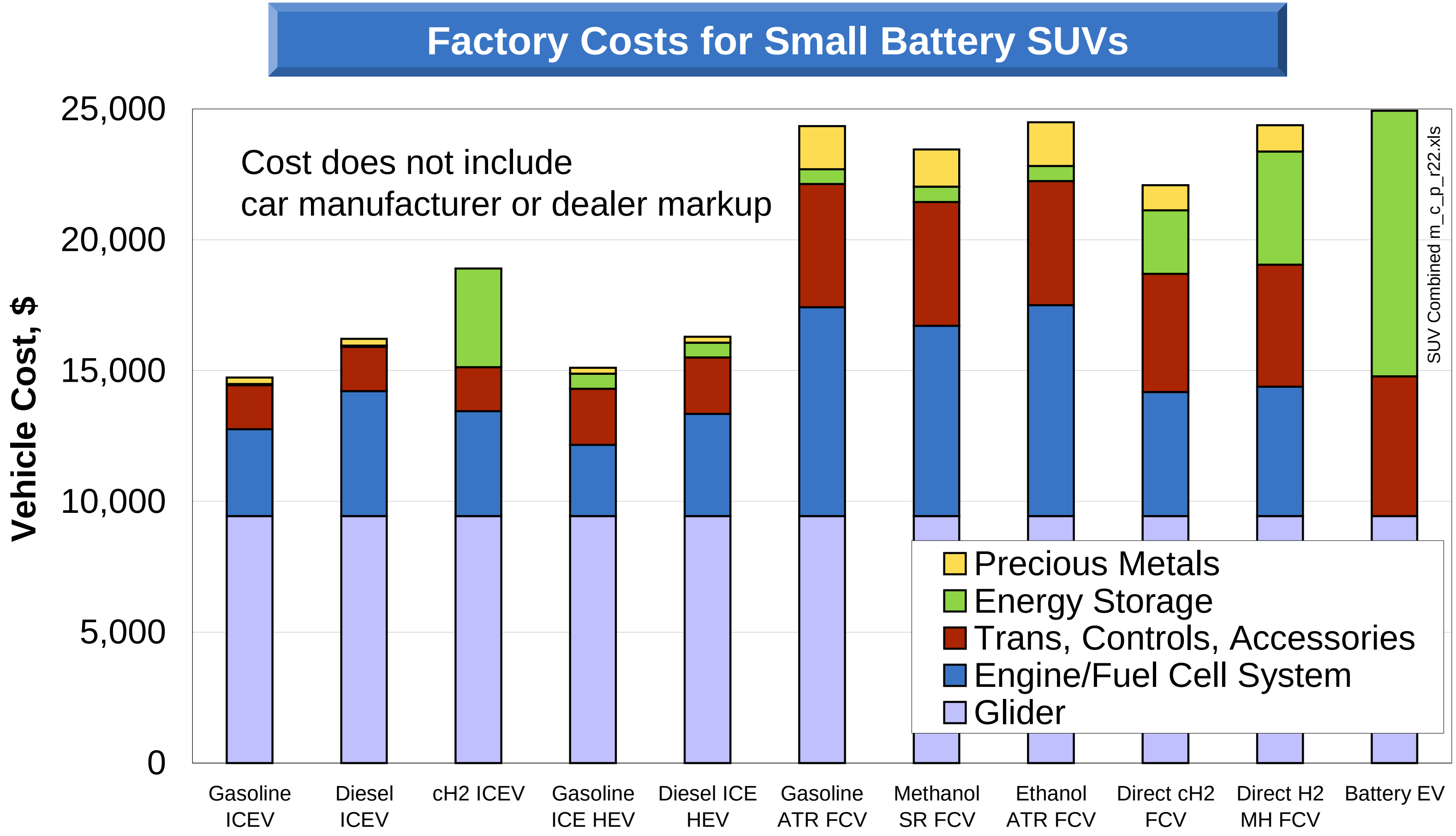
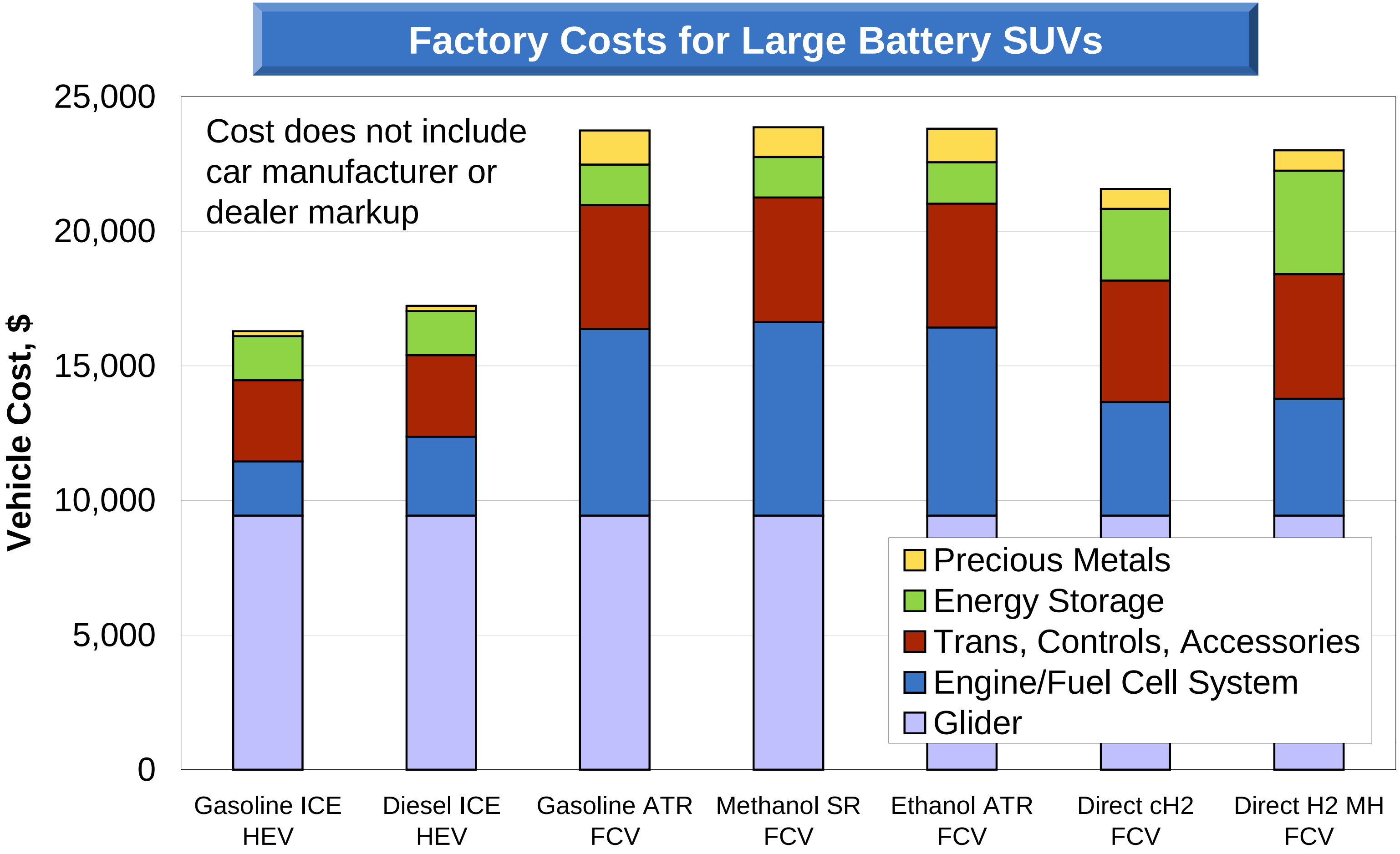
[1] Source: An, F. (ANL), "Evaluating Commercial and Prototyped HEVs", presentation at 2000 FTT Conference. Adjusted EER values represent improvement due to hybridization only.

[2] Fraction of rated power. HEV battery power equals motor power (parallel drivetrain).

Factory costs for small battery SUVs are around 40-70% more expensive than conventional SUVs.

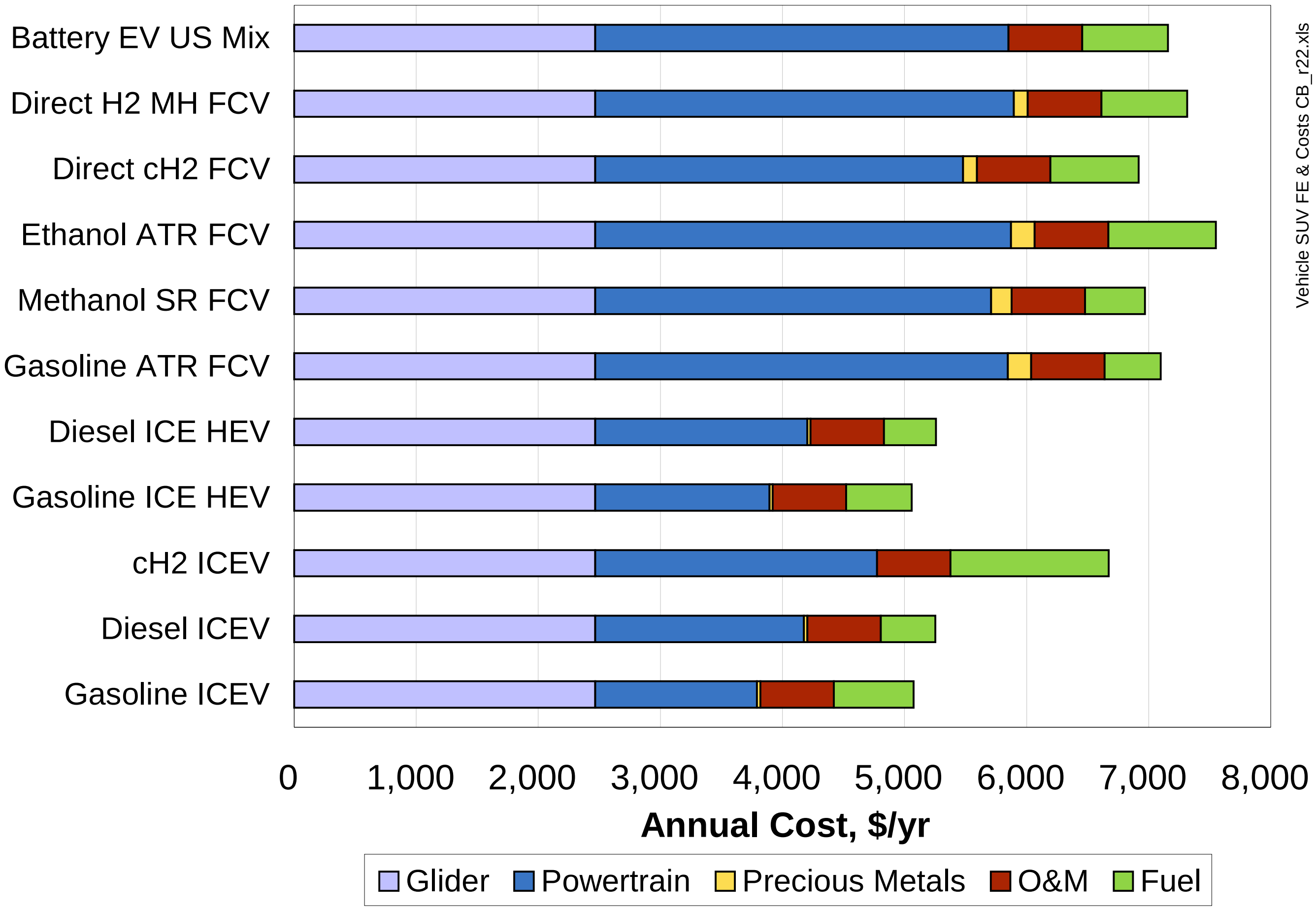


Reducing fuel cell size by increasing battery size reduces overall SU-FCV factory cost slightly.



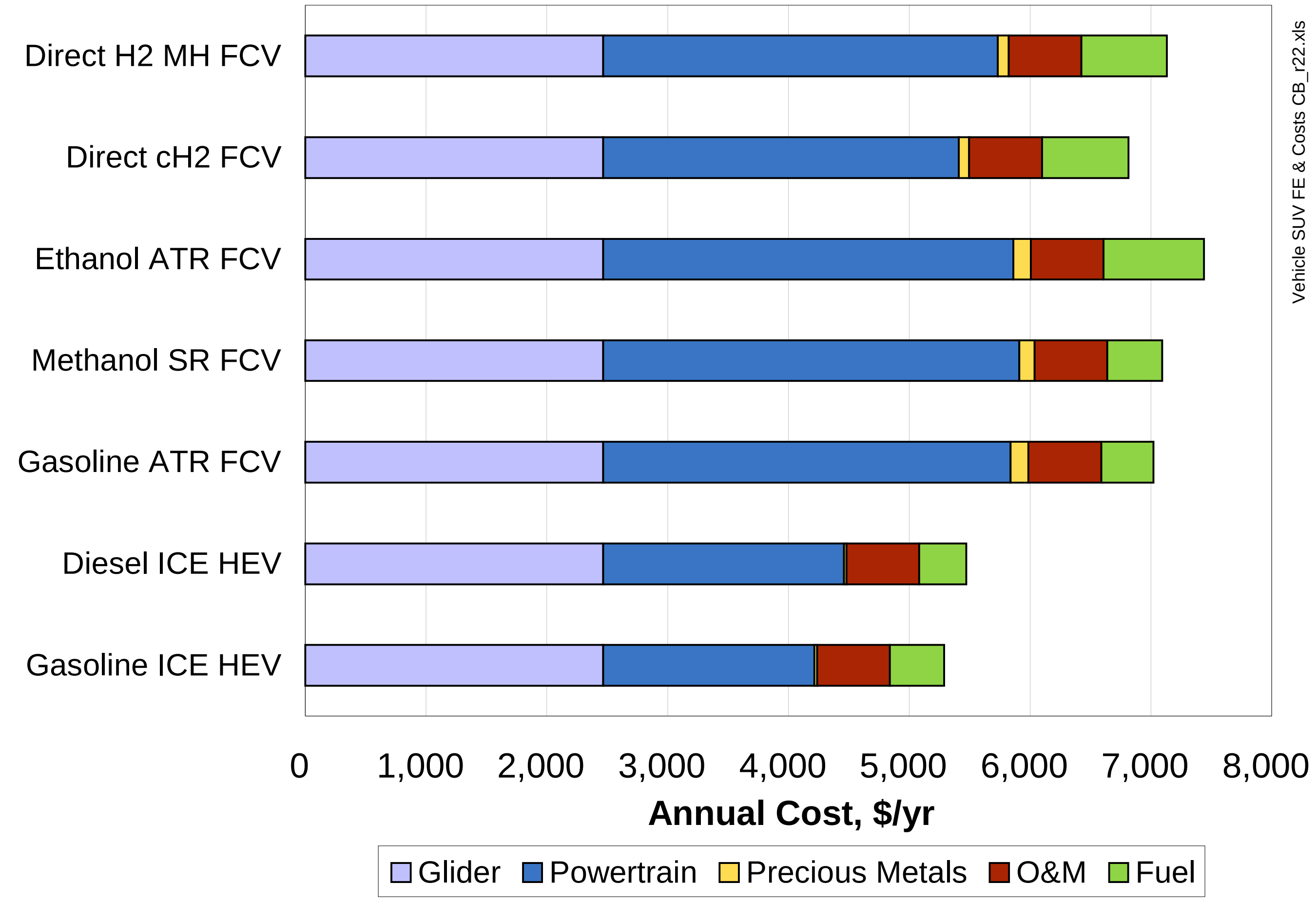
Annual sport utility FCV cost is around $2,000 to $3,000 more than that of conventional vehicles.

Vehicle Ownership Costs for Small Battery SUVs



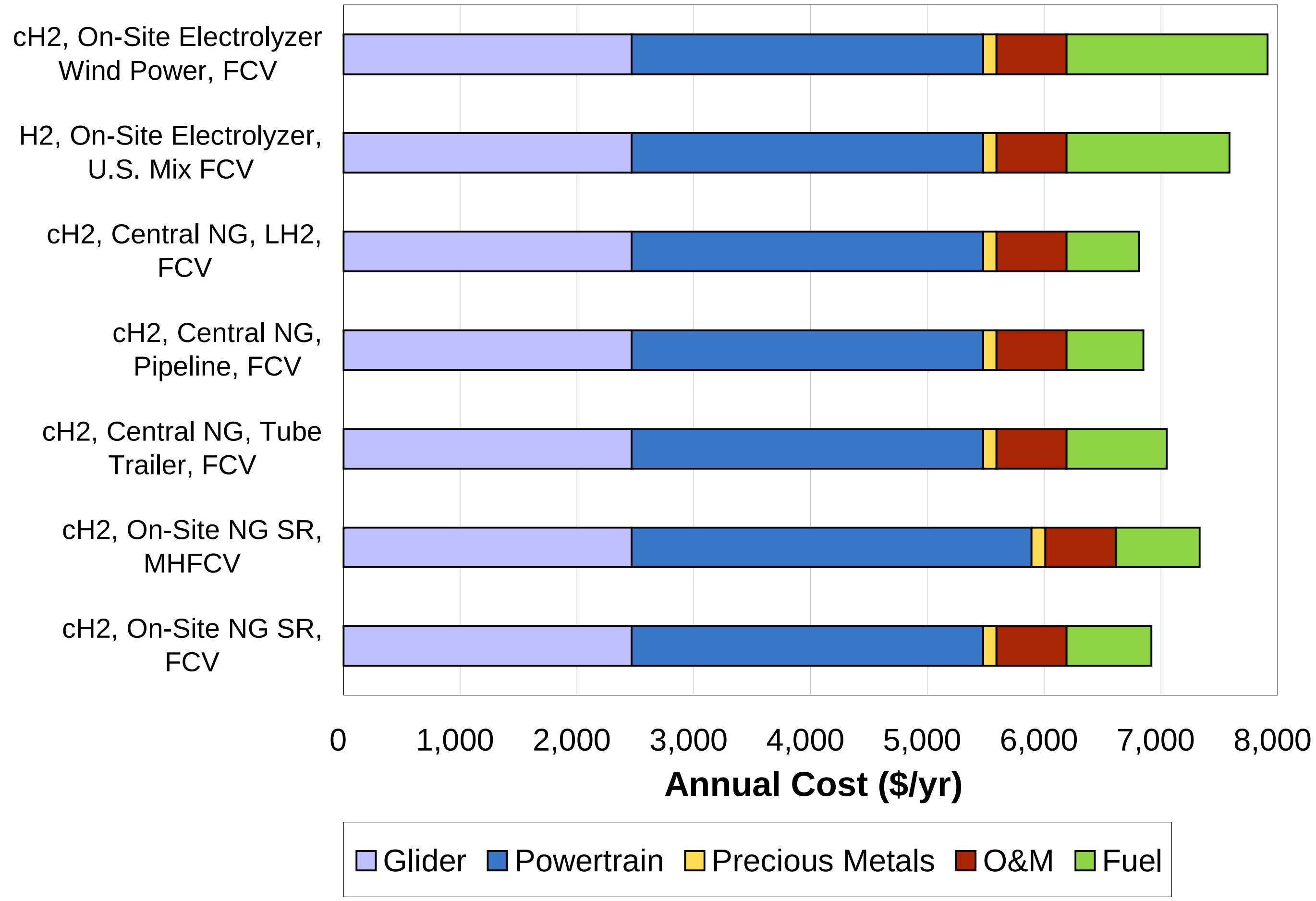
Highly hybridized SU-FCVs are only slightly less expensive under the assumptions used in this analysis.

Vehicle Ownership Costs for Large Battery SUVs



Costs for different hydrogen pathways can vary direct hydrogen FCV ownership cost by several hundred dollars per year.

Vehicle Ownership Costs for Small Battery Mid-sized Vehicles



Outline

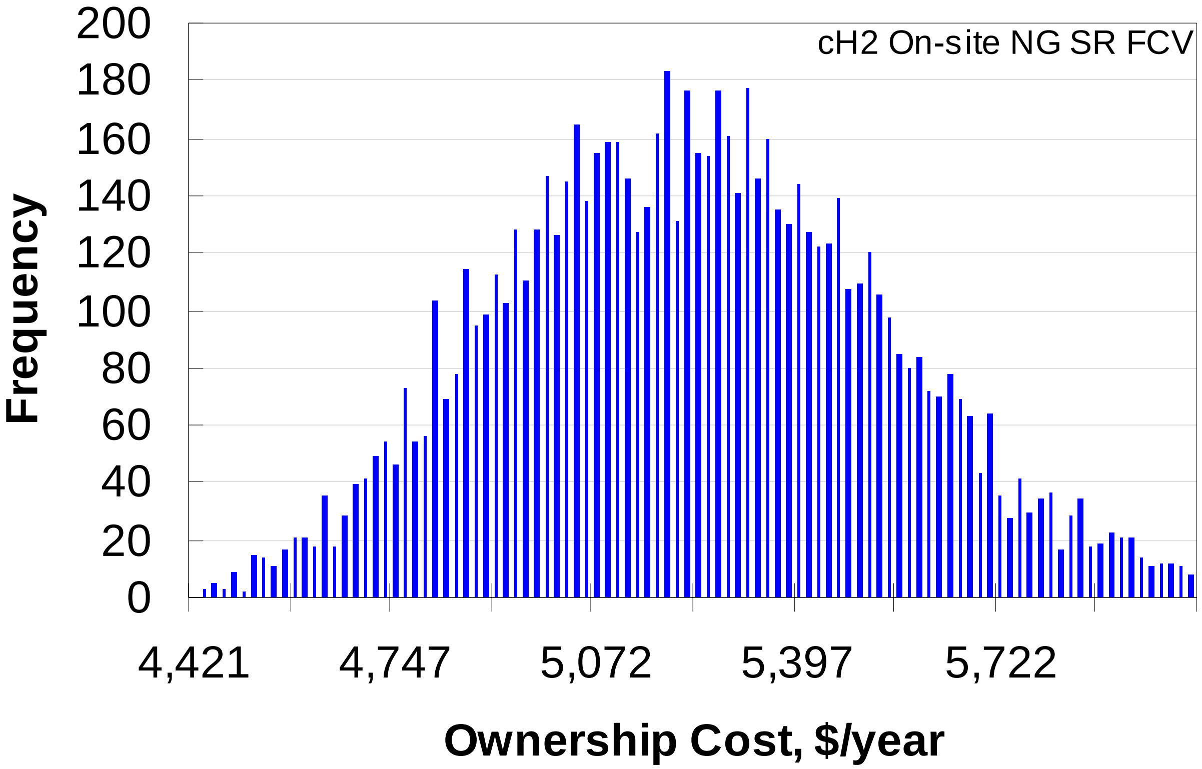
Appendix

Key assumptions for ownership cost sensitivity analysis:

- A Monte Carlo simulation was used to assess the uncertainty in the ownership costs for all vehicles and fuel options
  - Using Crystal Ball software, the effect of uncertainties in the ownership cost assumptions were independently varied to forecast the likely range of costs
  - Uncertainty assumptions are defined as a distribution
- Input variables for fuel price
  - Fuel cost
    - Based on historical volatility of oil and gas prices
  - Transportation and fueling station capital and operating costs
- Input variables for vehicle operation
  - Precious metals
  - Power train cost
  - Dealer markup applied to powertrain
  - Manufacturer markup applied to fuel cell, batteries, and powertrain

Ownership costs for direct hydrogen fuel cell vehicles (small battery mid-sized) are expected to be between $4,500 and $5,800 per year.

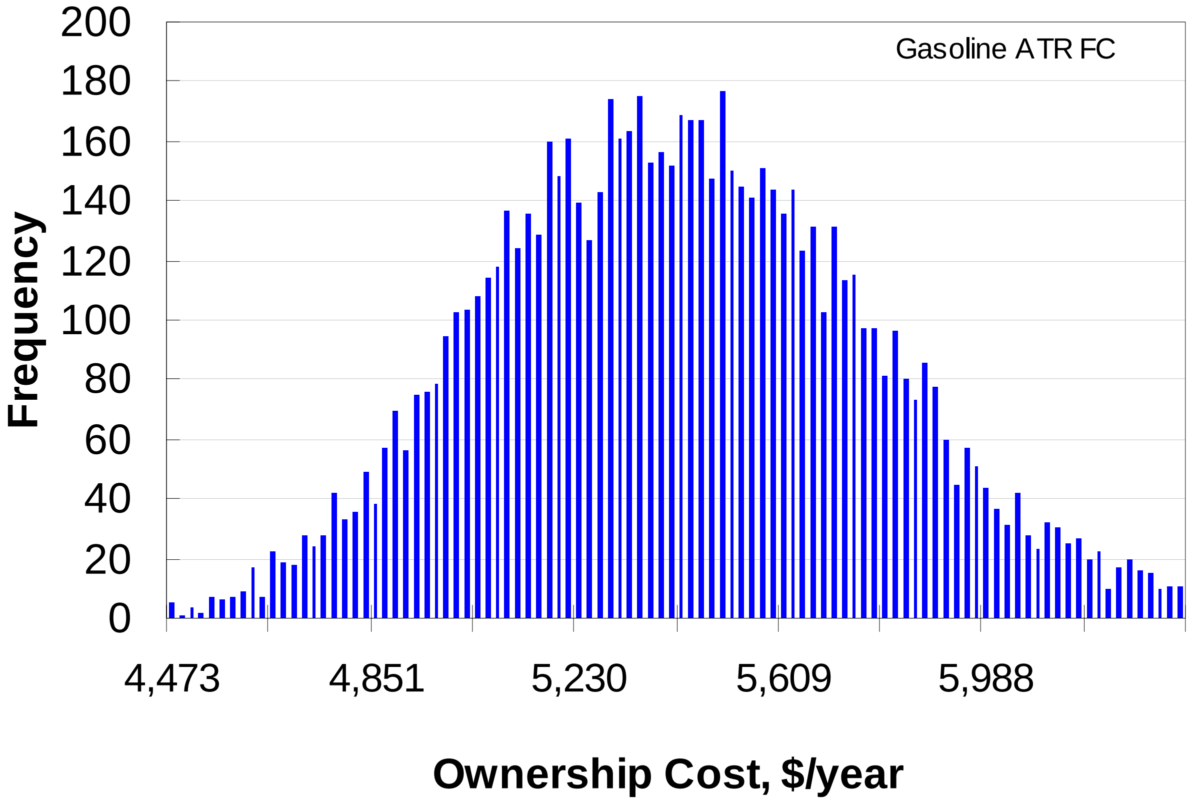
Ownership Cost Sensitivity - cH_2 FCV



Monte Carlo analysis results are presented as histograms of the forecasted outcomes of the analysis.

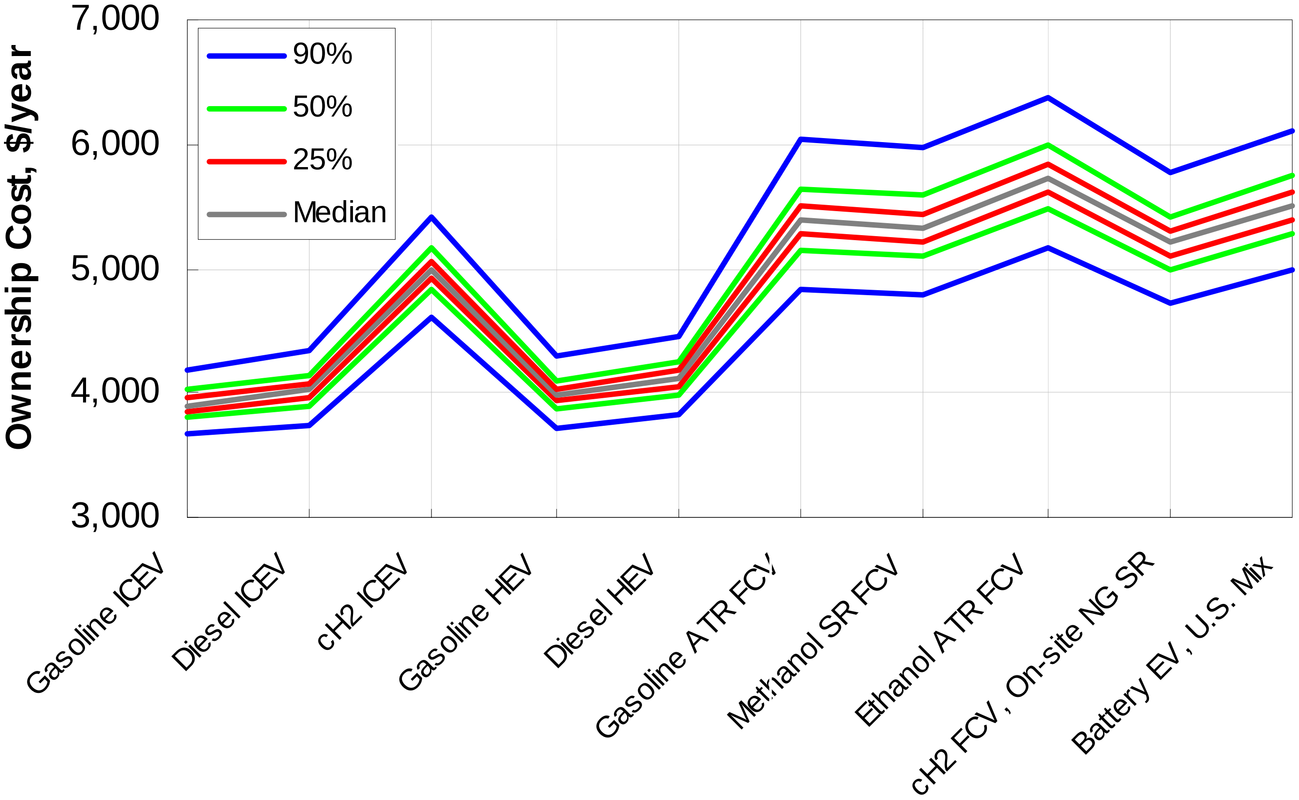
Ownership costs for gasoline ATR fuel cell vehicles (small battery mid-sized) are expected to be slightly higher, between $4,500 and $6,200 per year.

Ownership Cost Sensitivity - Gasoline ATR FCV



Overall, FCVs are expected to cost around $5,000-6,000 per year versus $3,500-4,500 per year for conventional and HEVs.

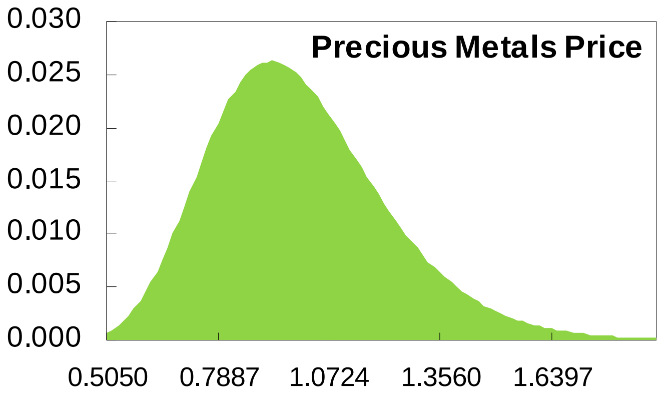
Sensitivity Analysis - Percentiles



Input assumptions are represented as probability distributions.

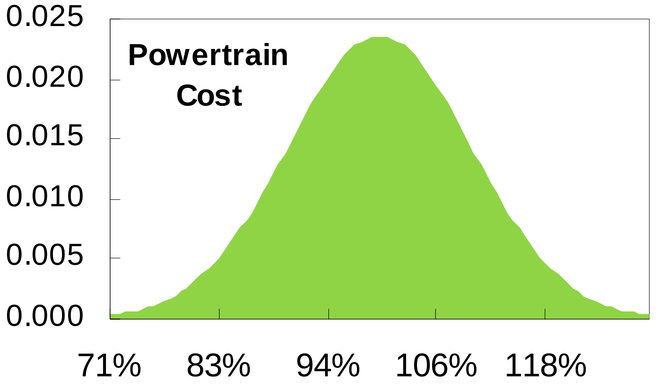
- Input assumptions for precious metals are based on the historical volatility of platinum prices

Price Range



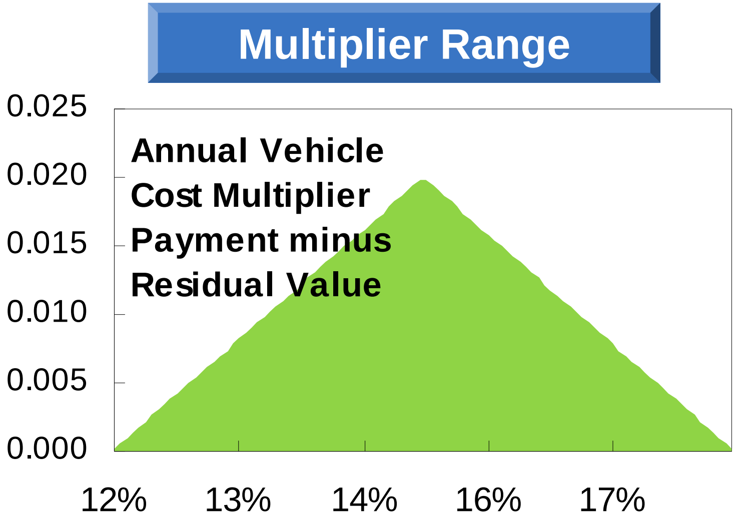
- Vehicle powertrain costs were estimated to have a 10 percent standard deviation in cost

Cost Range



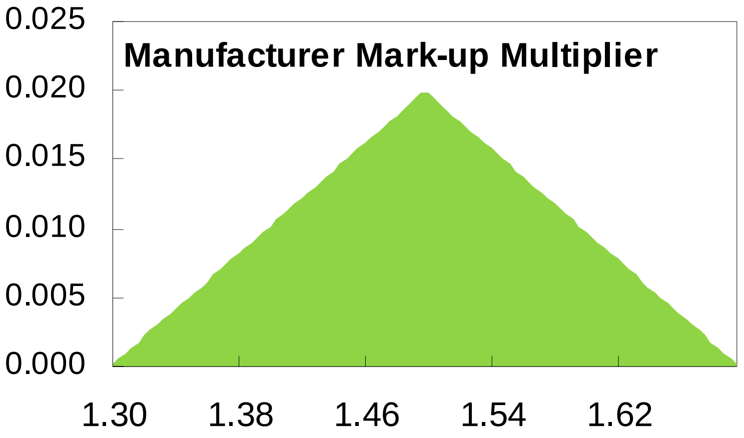
Annual vehicle costs are based on the payments over 5 years adjusted for resale value.

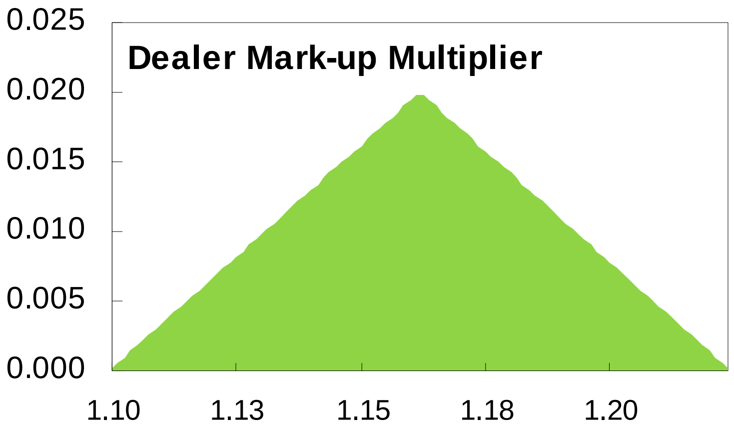
- We determined the distribution in resale values and calculated the monthly car payments, adjusted for future resale values
- The annual cost multiplier is shown here

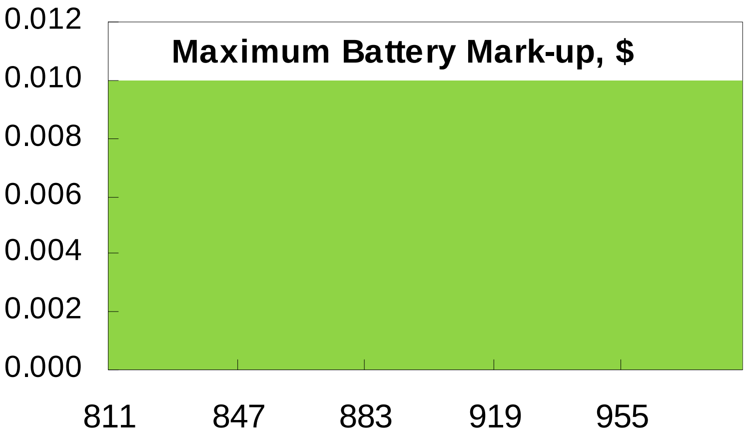


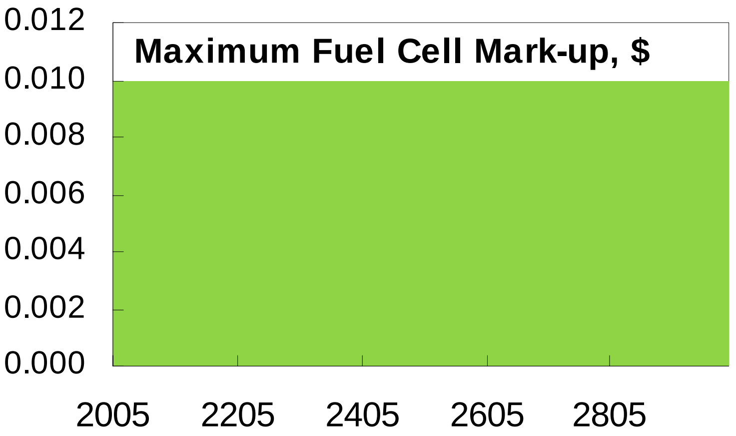
Source: Kelly Blue Book, 5 year 70,000 mile resale values for 12 most popular mid-size cars.

The effect of mark-up on powertrain components was included in the sensitivity analysis.



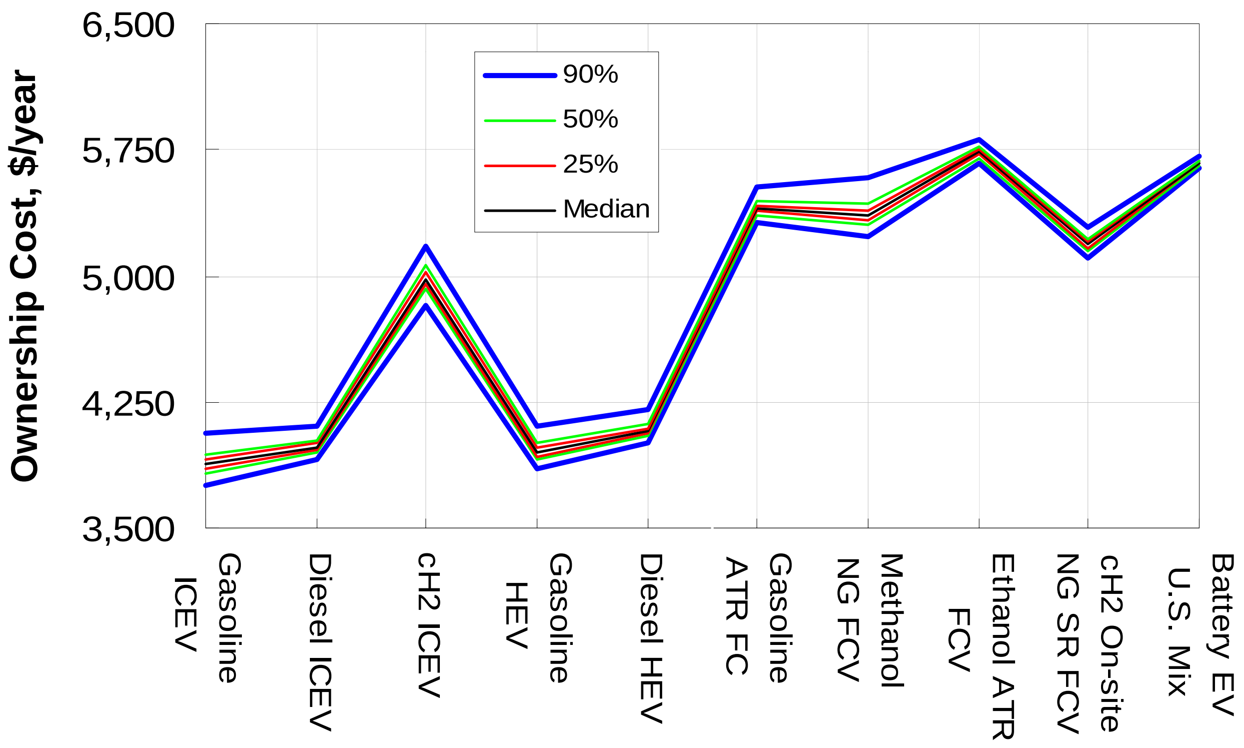






Fuel cost represents a relatively small uncertainty in ownership costs….

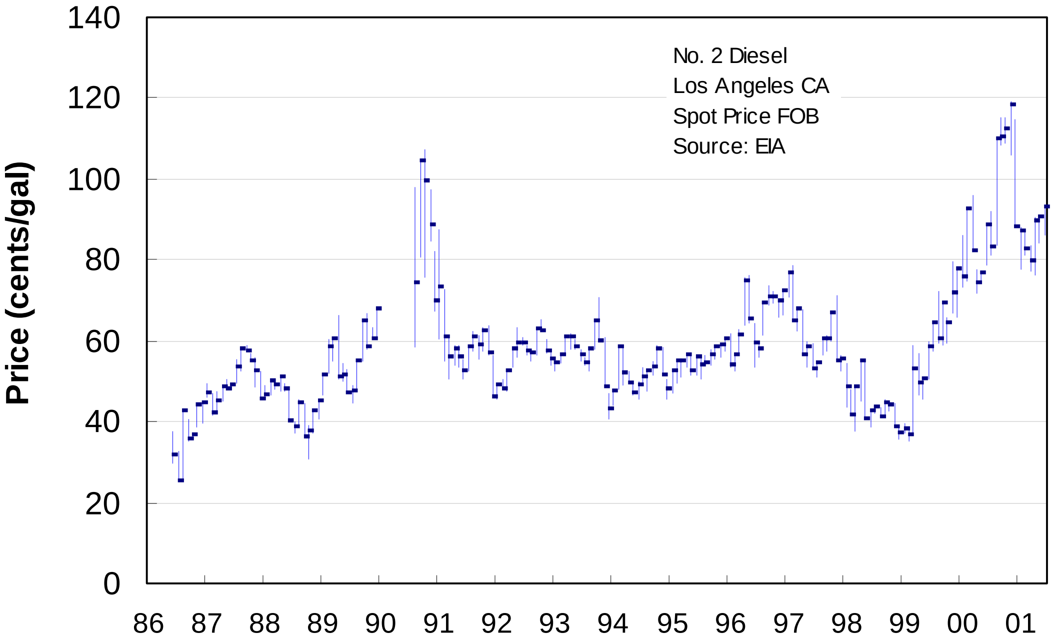
Sensitivity Analysis - Percentiles - Only Fuel Costs Varied



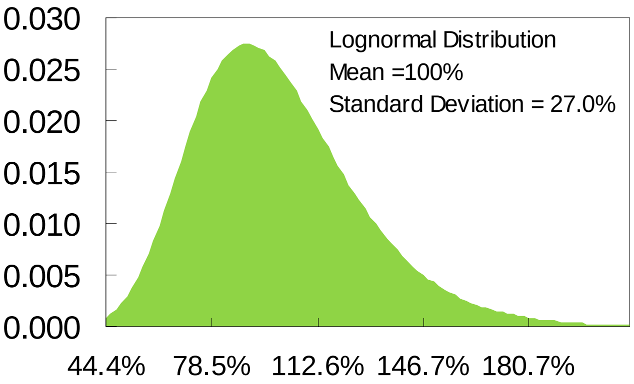
…however, the customers does not see it that way, once the vehicle purchase has been made.

The standard deviation of monthly closing prices was selected as the metric for fuel price uncertainty.

Diesel Prices, Monthly Data

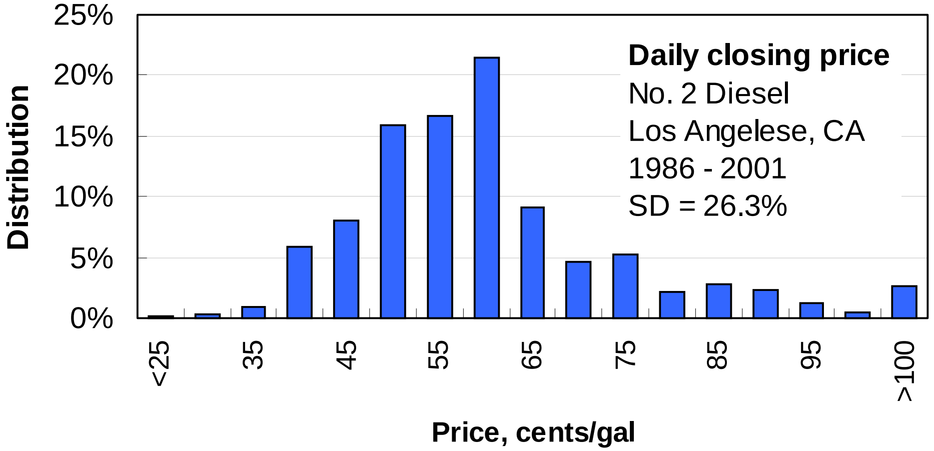


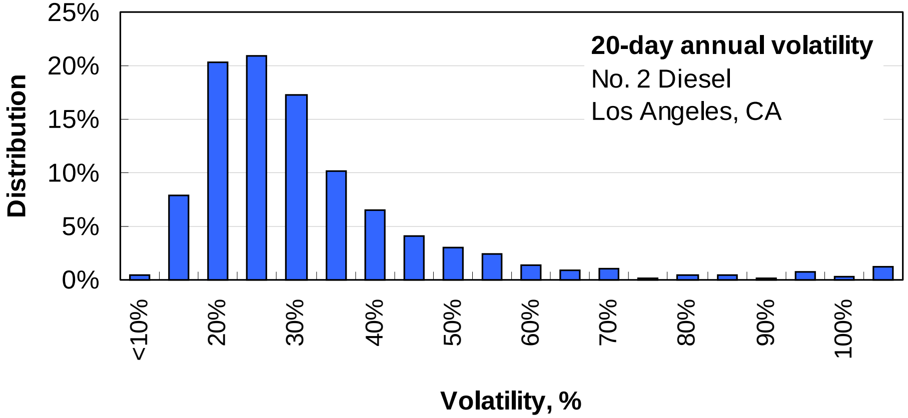
Fuel Price Range



Historical volatility determines the standard deviation used in the sensitivity analysis.

Diesel Price and Volatility





- Volatility was used to characterize fluctuations in prices
  - ➤ $(\text{Volatility})^2 = \Sigma\ (ln(P_t/P_{t-1}))^2 \times D/N$
    where:
    P = daily price,
    D = trading periods per year (12)
    N=1 month
- Price data was available for more financial instruments on a monthly basis so monthly values were used to represent fuel price uncertainty
- Monthly values were similar to 20-day volatility values which are more typically used for commodity volatility analysis
- Volatility is used as the SD for a lognormal price distribution for the uncertainty analysis

Sources: Natenberg, S., “Option Pricing and Volatility”, Probus, 1994; and Etzkorn, M., “Know Thy Volatility,” Futures Inside Option Trading, 1996

Monthly closing prices were collected from a variety of EIA and other publications.

Product	Data Source	Data Set
Natural Gas (Commercial)	EIA[1]	Commercial CA Sales, 1989-2001
Natural Gas (Industrial)	EIA[1]	Industrial CA Sales, 1989-2001[2]
Electricity (Comm. & Ind.)	EIA[1]	U.S. Average from all sectors, 1990-2001
Gasoline & Diesel[3]	EIA[1]	Los Angeles, CA Crude Oil Spot Prices, 1986-2001
Methanol	PCI[4]	Gulf Coast Barge Spot Prices, 1994-2001
Ethanol	Hart[5]	Midwest Spot Prices, 1992-1997

[1] Energy Information Agency, “Annual Electric Utility Report”, EIA-861, http://www.eia.doe.gov

[2] Data set includes 10% of customers.

[3] Gasoline and Diesel prices are based on EIA data for crude oil and historical price spreads between petroleum products and crude oil.

[4] Petrochemical Consulting International

[5] Hart Publications, Alcohol Week

Historical price data was used to determine fuel price uncertainty, while 2010 prices were based on EIA and ADL projections.

Product	Units	2010 Projection[1]	Historical Data		
			Average Price	Price Range	Volatility[2]
Natural Gas (Commercial)	$/MMBtu (HHV)	5.0	6.8	3.9-14.2	22.5%
Natural Gas (Industrial)	$/MMBtu (HHV)	3.0	4.0	2.0-11.4	30.8%
Electricity[3] (Comm. & Ind.)	c/kWh	7.0 comm. 4.0 ind.	6.7	6.2-7.4	4.2%
Gasoline[4]	$/gal	0.82	0.62	0.28-1.28	27.0%
Diesel[4]	$/gal	0.82	0.59	0.23-1.19	27.0%
Methanol	$/gal	0.41	0.56	0.25-1.55	40.5%
Ethanol	$/gal	1.15	1.20	1.01-1.54	9.1%

[1] Projected plant gate price plus delivery to fuel station. Natural gas and electricity are inputs for hydrogen production.

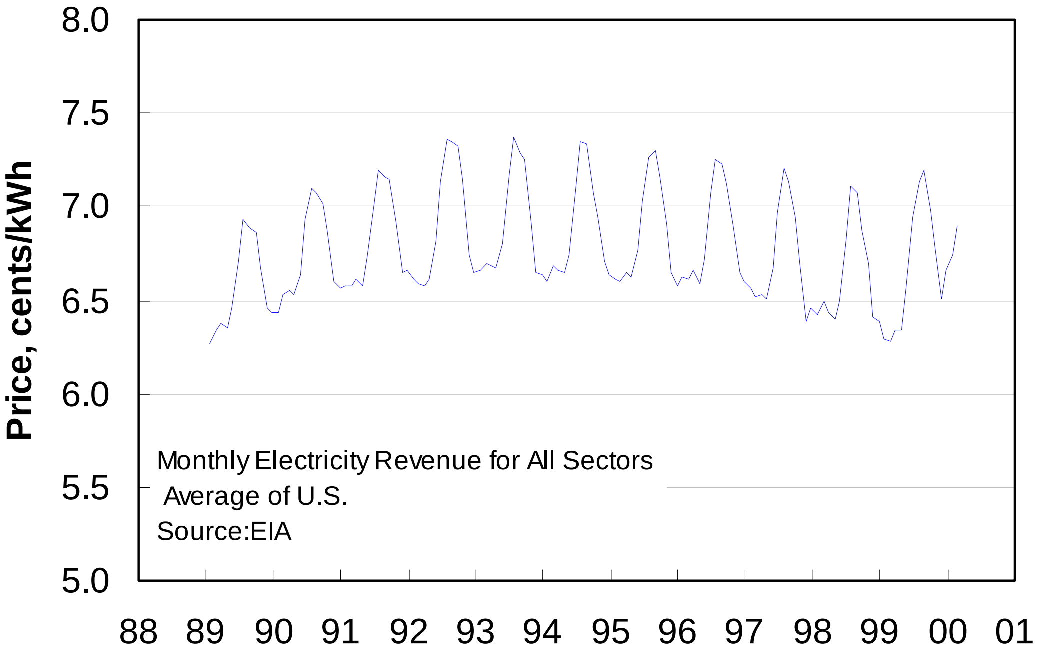
[2] Volatility based on historical monthly data. Volatility is used as the SD for a lognormal price distribution for uncertainty analysis.

[3] EIA historical data is electricity prices from all sectors (residential, commercial, and industrial).

[4] Projected prices are based on EIA data for crude oil and historical price spreads between petroleum products and crude oil.

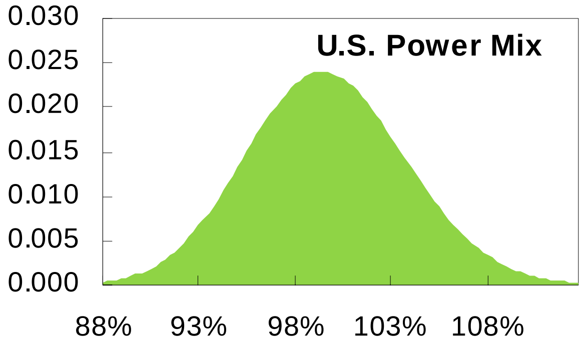
Historical power prices have fluctuated little; however, this may change with deregulation.

Electricity Prices, Monthly Data



Monthly Electricity Revenue for All Sectors
Average of U.S.
Source:EIA

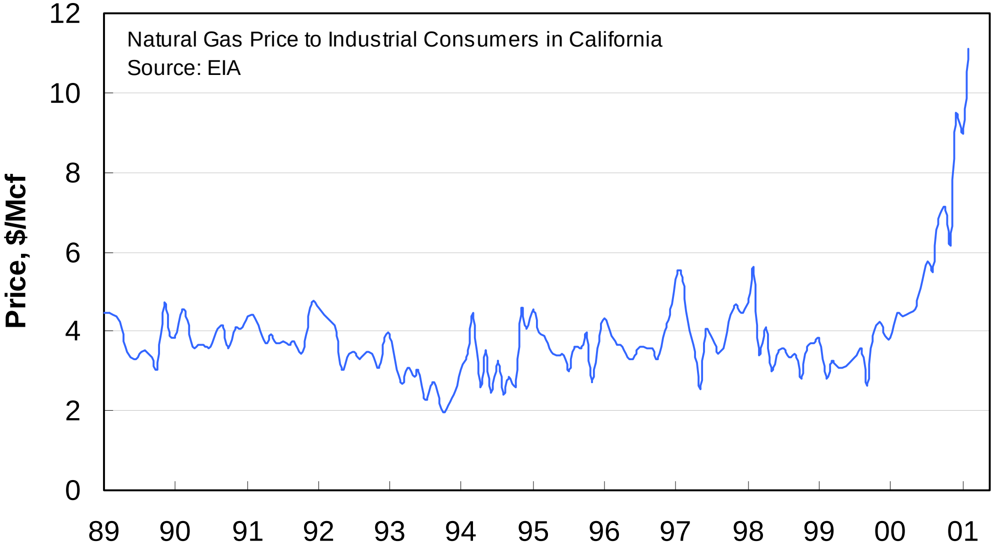
Price Range



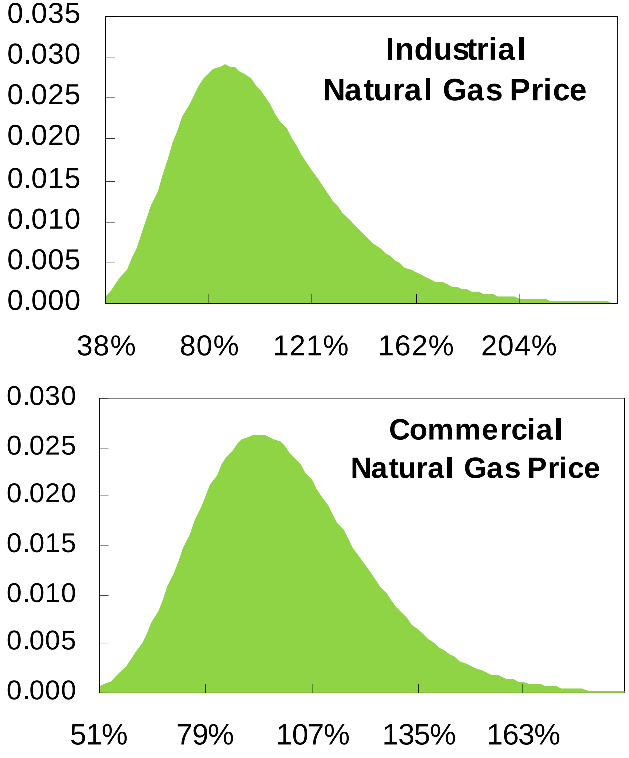
The data set does not cover all of the recent CA power crisis. However, it is clear that natural gas prices have a significant impact on power prices.

Even before the recent rise in natural gas prices, the range in prices has been high. Prices outside California show similar volatility.

Natural Gas Prices, Monthly Data



Price Range

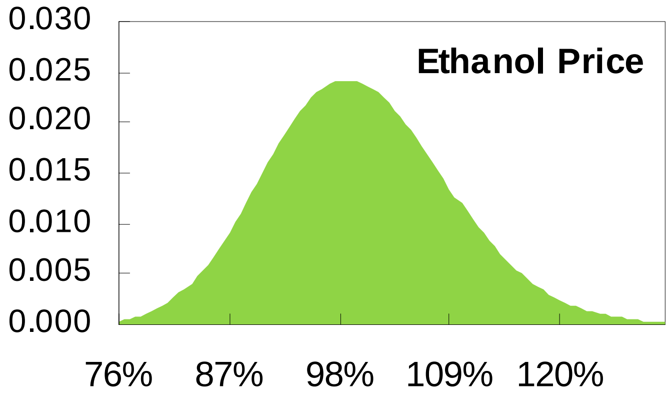


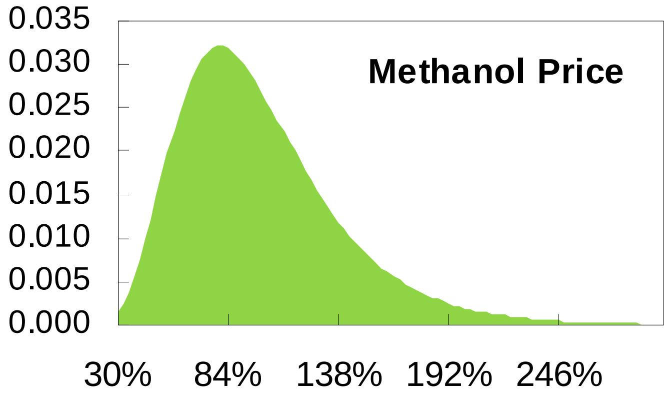
The cost of natural gas represents a significant part of the cost of hydrogen production.

Variations in ethanol and methanol prices were also based on historical price data.

- The high volatility of methanol prices occurred because of varying degrees of production capacity in the industry over time as well as changes in the MTBE market
- It appears that ethanol will be used more prominently as an oxygenate in the future
- During the transition to greater ethanol use, the price may become more volatile

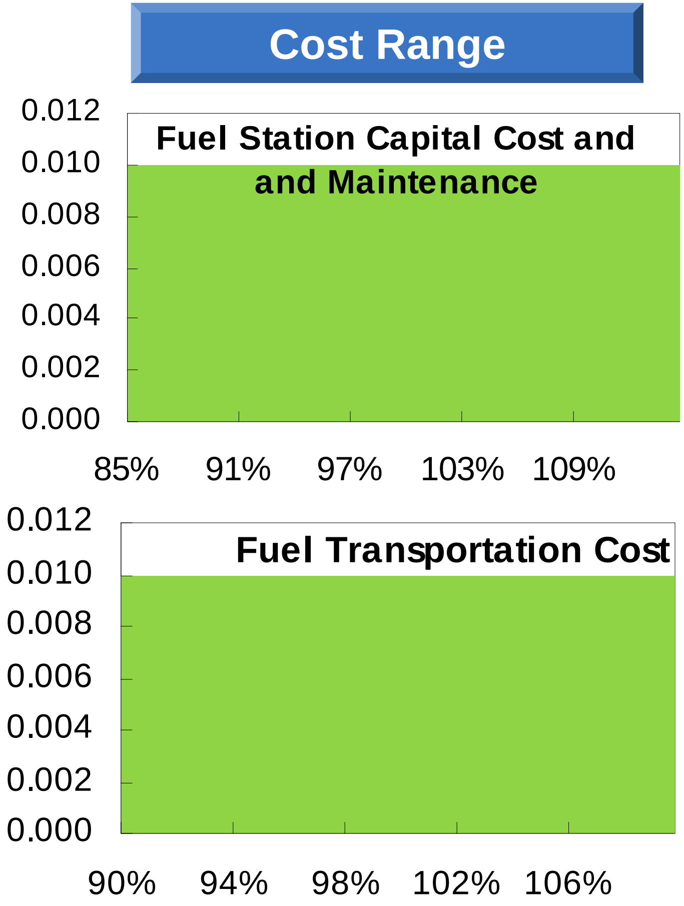
Price Range





Uncertainty in local fueling station costs and transportation costs from the central plant are also included in the sensitivity analysis.

- Fueling station costs represent a much higher share of the total cost for hydrogen, compared with other fuels



Outline

The safety risks of hydrogen, methanol and ethanol are not necessarily more dangerous than today's liquid hydrocarbon fuels...

- All fuels present safety issues, including the conventional liquid fuels used in today's vehicles
- Providing safe fuel transportation, fueling station, and vehicles are possible
  - Additional infrastructure is required for methanol, ethanol and fuel cell compatible gasoline, but the fueling equipment is similar to today's gasoline
  - Hydrogen equipment will be much different than today's gasoline but similar to CNG
- Fuel cell vehicles will require modifications to garages, maintenance facilities, and the on-road infrastructure that could be costly
  - Dealing with infrastructure issues related to the behavior of hydrogen in closed spaces may be a serious hurdle to its widespread use
- The public's safety concerns with alternative fuels will need to be addressed with reliable, convenient, safe products and pubic education
  - Consumers are presently accustomed to the safety issues with most liquid fuels, but do not have experience with compressed gas fuels in vehicle applications

… but making design changes and installing safety equipment on the large scale could be prohibitively expensive.

Combustion-related safety variables include flammability and detonation, ignition energy, and gas and flame detection.

- Flammability and Detonation - fuels can only ignite when they constitute a certain range of concentrations in air
  - hydrogen has a wide flammability range
  - diesel and gasoline are flammable at low concentrations
  - hydrogen is flammable at high concentrations
- Ignition Energy - fuels require a minimum amount of energy (flame, spark, static charge) to start ignition or combustion
  - hydrogen's ignition energy is an order of magnitude lower than gasoline
- Gas and Flame Detection - fuels and their flames can pose safety risks if they are difficult to detect by sight or smell
  - undetected gas leaks of hydrogen or natural gas can cause asphyxiation if there is insufficient ventilation
  - undetected flames from hydrogen, methanol, or ethanol can cause burns and other fire hazards

National Fire Protection Association Codes (NFPA) determines electrical equipment, ventilation, equipment off-set distances, drainage, and other fire safety building requirements.

Additional safety variables, such as toxicity and storage requirements, are important to specific fuels.

- Toxicity - gasoline, diesel, and methanol contain compounds that are toxic to humans if inhaled, ingested, or absorbed through the skin
- High Pressure Storage - high pressure storage of the gaseous hydrogen and natural gas pose risk of leaks and ruptures of the vessels
  - Hydrogen poses additional risks due to its high propensity to leak and its ability to deteriorate the strength and integrity of some storage materials
- Cryogenic Storage - liquid hydrogen spills can cause cold burns if contacted with skin and boil-off poses a leak risk if not properly contained

Flammability and Detonation Safety Variables

Potential Hazards

- Combustion of liquid fuel vapors in closed spaces
- Combustion of gaseous fuel leaks from vehicle or fueling station

Applicable Codes and Standards

- NFPA 70 (National Electrical Code)
- NFPA 88A (Parking Structures), NFPA 88B (Repair Garages)
- NFPA 50A (Gaseous Hydrogen Systems at Consumer Sites)
- NFPA 52 (CNG Vehicular Fuel Systems)
- ISO/TC 197 is developing new codes, standards, and guidelines for design and operation of hydrogen fueling stations and fuel cell systems for automobiles

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

Ignition Energy Safety Variables

Potential Hazards

- Combustion of gas leaks from heat or static charges
    - Operation of electronic devices (cell phones) can cause ignition
    - Common static (sliding over a car seat) is about ten times what is needed to ignite hydrogen
    - Static charges can develop during refueling of liquid fuels into ungrounded fuel containers

Applicable Codes and Standards

- NFPA 70

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

Gas and Flame Detection Safety Variables

Potential Hazards

- Asphyxiation from odorless and colorless hydrogen gas leaks
- Burns from invisible hydrogen, methanol, or ethanol flames

Applicable Codes and Standards

- 49 CFR Sec. 192.625 - requires odorants in gaseous fuel pipelines to permit smell detection at concentrations of 1/5 of the lower flammability limit

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

Toxicity Safety Variables

Potential Hazards

- Inhalation of toxic vapors (methanol, gasoline, diesel)
  - carcinogenic
- Ingestion of toxic liquids
  - methanol: small quantities can cause blindness/death
  - ethanol: alcohol poisoning from excessive consumption
  - all liquid fuels: leaks can contaminate water supply
- Absorption of toxic liquids (methanol, gasoline, diesel)
  - through skin contact

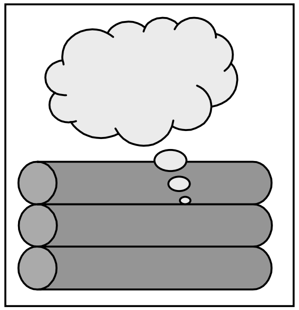
Applicable Codes and Standards

- NFPA 88A, 88B - ventilation of enclosed areas

Affected Aspects

- Fueling Stations
- Fire Fighting
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation

High Pressure Storage Safety Variables



Potential Hazards

- Storage vessel leak or rupture
- Hydrogen’s high propensity to leak and cause embrittlement

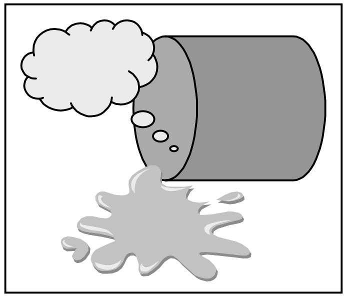
Applicable Codes and Standards

- NFPA 50A for hydrogen - building and structural setbacks
- NGV2, DOT-3A/3AA - mobile tanks testing at 5/3 service pressure, hydrostatic testing, bonfire, gunfire, drag testing
- NFPA 50A
- NFPA 52

Affected Aspects

- Fueling Stations
- Fuel Transportation
- Vehicle Configuration

Cryogenic Storage Safety Variables



Potential Hazards

- Combustion or asphyxiation from boil-off vapors/gases
- Cold burns from leaks/spills

Applicable Codes and Standards

- NFPA 50B for liquid hydrogen - building and structural setbacks
- NFPA 70

Affected Aspects

- Fueling Stations
- Enclosed Spaces (Garages/Tunnels, Maintenance Facilities)
- Fuel Transportation
- Vehicle Configuration

The National Hydrogen Association is coordinating hydrogen safety codes and standards development in the U.S. and internationally.

- NHA has formed a number of working groups on hydrogen safety
  - WG 1: Connectors - being conducted through ISO
  - WG 2: Containers - high pressure containers are being advanced by ISO/TC-197 based on CNGV standard; NHA will continue work on hydrides
  - WG 3: Refueling stations - being advanced by ISO/TC-197
- NHA has proposed new work items
  - WG 4: Electrolyzers
  - WG 5: Self-service refueling - plans to coordinate with NFPA, ISO, DOT and SAE
  - WG 6: Hydrogen vehicle fuel system certification - actively working with SAE
  - WG 7: Maritime applications - plans to coordinate with MHTDG, led by DCH Technologies

Source: Miller, K. (NHA), "Developing International Codes and Standards for the Safe Production, Storage, and Use of Hydrogen", presentation to SAE, March 2000

Details on hydrogen and other alternative fuels safety issues can be found in the following sources (page 1 of 2):

- Acurex Environmental Corporation, “Development of a Universal Methanol Fuel Formulation for use in both light and heavy-duty Vehicles, Phase I – Risk Assessment”, prepared for National Renewable Energy Laboratory, November 1996A
- Acurex Environmental Corporation, “Evaluation of Fuel-Cycle Emissions on Reactivity Basis”, prepared for California Air Resources Board, September 19, 1996B
- Acurex Environmental Corporation, “Maintenance Facility Modifications to Accommodate Methanol Fuel Buses”, prepared with Stone & Webster Engineering for Los Angeles County Metropolitan Transportation Authority, 1993
- DeLucci, M., “Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts and Cost”, International Journal of Hydrogen Energy, Vol. 14, P. 81-130, 1989
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- Krupka, M.C., Peaslee, A.T., Laquer, H. H., “Gaseous Fuel Safety Assessment for Light-Duty Automotive Vehicles”, Los Alamos National Laboratory, 1983
- Machiele, P.A., “Methanol Fuel Safety: A Comparative Study of M100, M85, Gasoline, and Diesel Fuel as Motor Vehicle Fuels”, Office of Mobile Sources, U.S. Environmental Protection Agency, 1990

Details on hydrogen and other alternative fuel safety issues can be found in the following sources (page 2 of 2):

- Moy, R., F. Jen, “Regulatory and Code Considerations for Climate Change Fuel Alternatives”, presentation to the SAE, Government/Industry Meeting, June 2000
- Murphy, M., “Properties of Alternative Fuels”, FTA report FTA-08-06-0060-94-1, March 1994
- Office of Transportation Assessment, “Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles”, September 1990
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- Stone & Webster Engineering Corporation, “Maintenance Facility Modifications to Accommodate CNG Buses”, Final Report prepared for the Los Angeles County Metropolitan Transportation Authority, 1994
- Swain, M., “Safety Analysis of High Pressure Gaseous Fuel Container Punctures”, University of Miami, FL, 1995
- Swain, M., B. Sievert, “Hydrogen Safety Analysis”, University of Miami, FL, 1996
- Swain, M., E.Grillio, “Risks Incurred by Hydrogen Escaping from Containers and Conduits”, University of Miami, FL, 1997
- Thomas, C.E., “Hydrogen Vehicle Safety Report”, prepared for DOE by the Ford Motor Company, May 1997
- Wilkman Productions, “Safety First with CNG”, video produced for DOE, NREL & RTD, 1992

Outline

Appendix

Due to the coupled nature of the subsystem efficiencies, targets should be formulated so that the total efficiency targets are met.

Fueling Station Efficiencies, %LHV	Phase II Detailed Analysis	Phase I Analysis and Targets		
		Analysis	2004	2008
Reforming	80 [1]	70-75	75-77	80
Purification	75 [1]	75-90	82-90	90
Compression	82 [2,3]	75-85	77-87	80-88
Storage & Dispensing	100 [3]	100	100	100
Total	62	NA	50-60	60-65

* Assumes power plant efficiency penalty on power requirements.

[1] Assuming the purification off-gas is used to drive the steam reforming reaction, the combined Reforming and Purification efficiency is 74%.

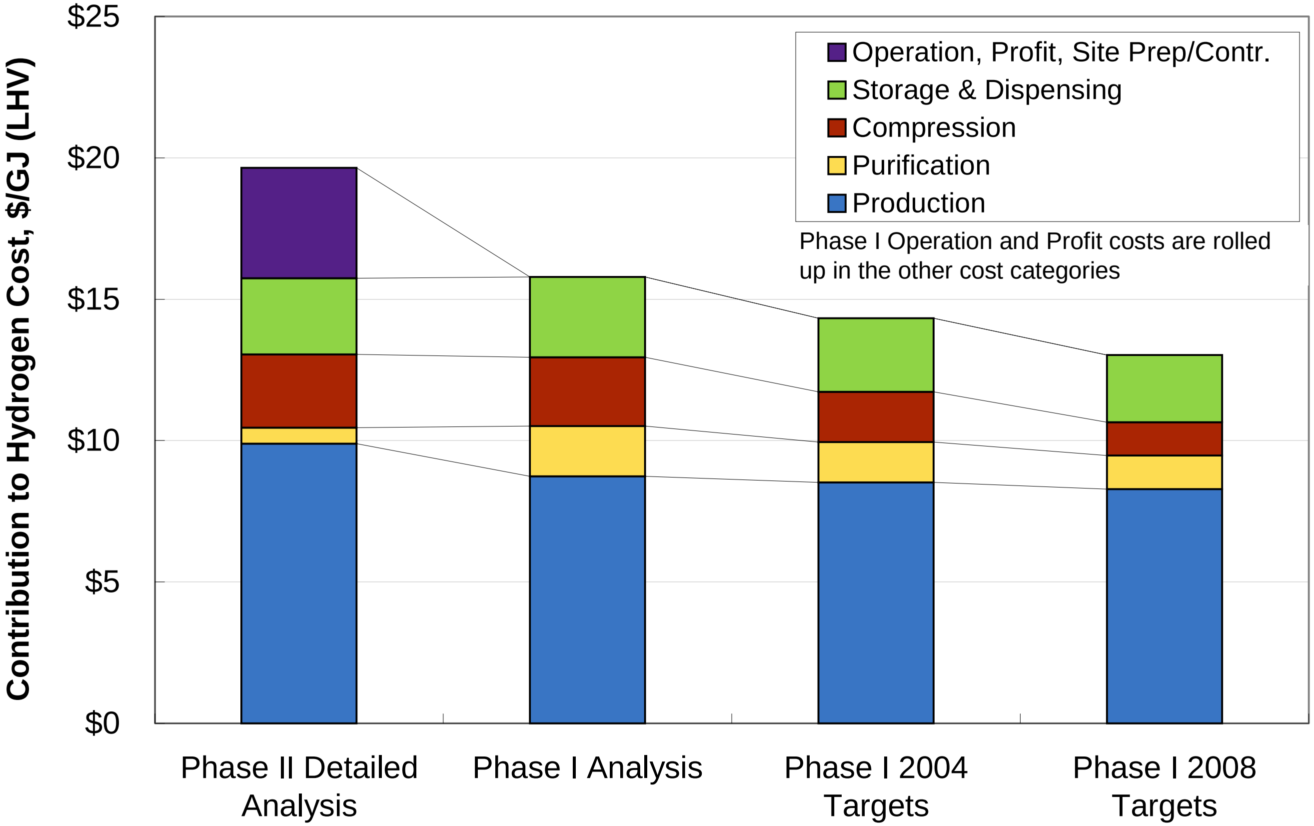
[2] Includes 3% hydrogen loss in the compressors that is recycled to the reformer burner.

[3] Based on 10 atm SR system with PSA operating at reformer outlet pressure, and 3500 psi storage to 5000 psi storage on-board the vehicle.

The efficiency targets set in Phase I still look reasonable. Given the high well-to-wheel efficiency projected for direct hydrogen FCVs, more aggressive targets aren't necessary.

Our Phase II hydrogen fuel chain cost projections significantly exceed Phase I estimates and targets primarily due to higher feedstock costs.

Comparison of On-site SR Fueling Station Costs



Phase I Operation and Profit costs are rolled up in the other cost categories

Annual fuel cost for direct hydrogen FCVs are on par with conventional vehicles: we refocus hydrogen production targets on risk reduction.

Assuming direct hydrogen FCVs can achieve 2.5 better fuel economy than conventional ICEVs, hydrogen cost target should be around $20/GJ, which coincides with our Phase II Results.

Hydrogen Cost, $/GJ (LHV)	Production	Purification	Compression	Storage & Dispensing	Operation, Profit, Site Prep/Contr.	Total
Phase II Analysis						
Energy Costs	$ 7.26	$ 0.12	$ 1.55	$ -		
Capital Recovery	$ 2.58	$ 0.43	$ 1.03	$ 2.64		
Maintenance Costs	$ 0.05	$ 0.01	$ 0.02	$ 0.05		
Subtotal	$ 9.89	$ 0.56	$ 2.59	$ 2.69	$ 3.91	$ 19.65
Previous Estimates						
Phase I Analysis	$ 8.73	$ 1.78	$ 2.44	$ 2.84		$ 15.79
Phase I 2004 Target	$ 8.52	$ 1.42	$ 1.78	$ 2.60		$ 14.32
Phase I 2008 Target	$ 8.28	$ 1.18	$ 1.18	$ 2.37		$ 13.02
Gasoline (Reference)						$ 8.21
Gasoline x 2.5 Fuel Economy						$ 20.52

* Based on the lower heating value of hydrogen or gasoline. There are 3600 kJ in one kWh.

We recommend delivered fuel costs targets be raised to $15-20/GJ ($0.05-0.07/kWh).

We investigated the impact of the DOE fuel cell system goals on our projected future scenarios of fuel cell system cost.

- Future gasoline and hydrogen baseline scenarios
  - ADL projected future (2010 timeframe) performance assumptions for fuel cell, balance of plant, and fuel flexible (gasoline) fuel processor or hydrogen storage
  - Based on in-house kinetic, thermodynamic, and other calculations
- DOE Goals gasoline and hydrogen scenarios
  - Assumptions changed to reflect the DOE goals published in the Annual Review and latest RFP[1]
    - current density and Pt loading
    - balance of plant component costs
    - fuel processor space velocities
  - **Other assumptions, not addressed by the RFP, were kept the same as the future baseline scenario**
  - Most DOE goals, particularly MEA Pt loading, are more aggressive than the future baseline scenario assumptions

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[1] Based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057, and DOE's 2000 Annual Progress Report (Oct. 2000).

None of the scenarios were able to meet the long-term DOE cost targets outlined in the recent RFP.

Characteristic	Units	DOE Target		Future Scenarios		With DOE Goals	
		Near-term	Long-term	Gasoline	Hydrogen	Gasoline	Hydrogen
Overall System Cost[1]	$/kW	125	45	130	103	122	104
Overall System Specific Power[1]	W/kg	250	325	291	365	266	314
Fuel Cell Subsystem Cost[2]	$/kW	100	35	84	65	79	66
Fuel Cell Subsystem Specific Power[2]	W/kg	400	550	510	658	440	520
Fuel Processor Cost[3]	$/kW	25	10	28	NA	25	NA
Fuel Processor Specific Power[3]	W/kg	700	800	1,240	NA	993	NA

* Targets are based on DOE's Nov. 21, 2000 SFAA No. DE-RP04-01AL67057.

[1] Includes fuel processor or hydrogen storage, stack, auxiliaries and startup devices; excludes gasoline tank and vehicle traction electronics.

[2] Includes tailgas burner and fuel cell ancillaries: heat, water, air management systems; excludes fuel processing/delivery system.

[3] Includes controls, shift reactors, CO cleanup, and heat exchanges; excludes fuel storage.

Comparing FCVs to ICEVs requires a comparison among dimensions that do not lend themselves to an "apples to apples" comparison.

	Attribute	Comments	Included in Target Setting
System Cost	***Lower Peak Power***	*FCVs will need less peak power than typical ICEVs and even HEVs*	*Yes*
	Fuel Cost	*Hydrogen FCVs and ICEVs will be equivalent, but gasoline FCVs will likely be lower than ICEVs*	*No - small affect on ownership cost*
	Maintenance	*Largely unknown for FCVs, but customers will demand same as ICEVs*	*No - not well known*
Energy and Emissions Impact	***PZEV Status***	*Additional costs will be required for ICEVs and HEVs*	*Yes*
	ZEV or Near ZEV Status	*Government incentives, credits, avoided cost of "smog check" programs for hydrogen FCVs*	*No*
	Lower GHG Emissions	*Potential government incentives for FCVs and HEVs*	*No*
	Crude Oil Independence	*Significant impact on economy (increased GDP, less defense spending) for alternative fueled vehicles*	*No*
Customer Preference	***Quiet, "Green" Vehicle***	*Pro environment, mobile office, etc. for FCVs*	*No*
	Features of Electric Drivetrains	*Genset and other capabilities for FCVs and HEVs*	*No*
	Fueling Convenience	*Convenient, quick, and fewer trips to the fueling station*	*No*

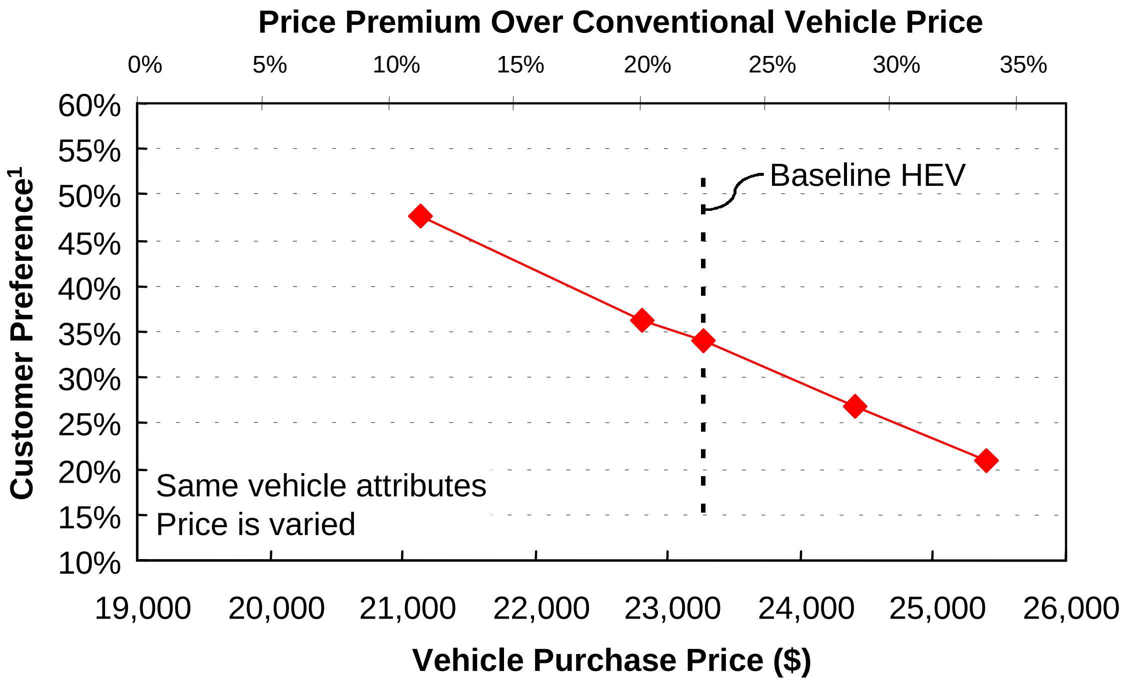
Because most energy, emissions and customer preference benefits of FCVs are difficult to monetize: we propose not to attribute a quantitative value to them in the cost target setting.

For perspective, Arthur D. Little worked previously with EPRI and Applied Decision Analysis to analyze the possible customer valuations of added HEV attributes (EPRI, 2001).

- For several HEV vehicle platforms, Applied Decision Analysis tested consumer responses
  - Survey included brief education on HEVs
  - HEV attributes are similar to FCV attributes
- Attributes include:
  - Fuel savings/fuel economy versus conventional vehicle
  - Mileage range/number of trips to the gas station versus conventional vehicle
  - Maintenance savings over conventional vehicle
  - Added HEV functionality like 110/120 volt plug in capability, heating/cooling with engine off
  - Environmental benefits versus conventional vehicle
- A model was developed to predict market share for a combination of vehicle attributes at a given vehicle price
  - We believe the indicated customer preferences represent an upper bound of the value of HEV benefits to consumers

The model predicted a 35% customer preference for HEVs over ICEVs with a $4,000 HEV price premium.

Market Preference for HEV vs ICEV



[1] Estimated market (customer) preference based on multi attribute survey of 100 recent purchasers of mid size cars. The model estimates "stated preference". Actual preference may be lower.

HEV Attributes

- Price for a conventional vehicle (27 mpg) = $19,000
- Price premium for Baseline HEV = $4,000
- Attributes of Baseline HEV:
  - 35 mpg
  - 33% CO_2 reduction
  - 30% Smog reduction
  - $66/year maintenance savings
  - No battery replacement over lifetime

The study indicates that a sizable HEV or FCV cost premium would significantly reduce their market potential over conventional ICEVs.

We propose that powertrain cost targets for FCVs should reflect some of the emissions, efficiency, and powertrain benefits FCVs are expected to offer.

- Cost targets should be set in terms of total powertrain cost for a “standard” vehicle, rather than on a $/kW basis
  - FCVs require lower peak power than ICEVs and even HEVs
- Cost targets can be bounded by extreme cases
  - Allowable cost should be much lower than the expected cost of battery EVs
- Allowable factory cost should not be expected to be less than the cost of an advanced diesel HEV or a gasoline HEV that meet PZEV standards
  - An advanced gasoline mid-sized HEV powertrain will likely cost around $4,000 plus $1,000 for components necessary to meet PZEV
  - As a minimum, mid-sized FCV powertrain cost targets should be around $5,000
- Fuel costs end up being a small contributor to ownership cost and can be ignored for powertrain cost target setting
  - Fuel is a $90/year cost adder for hydrogen FCVs versus gasoline HEVs, while the powertain (plus precious metals) is a $1,200/year cost adder

In this analysis, both gasoline and direct hydrogen vehicles are about twice the $5,000 powertrain cost target.

Powertrain Factory Costs for Selected Small Battery Mid-sized Vehicles

	Units	Gas HEV	Delta	Target	Gas FCV	cH2 FCV
Power Unit		$ 2,024	$ 500	$ 2,500	$ 6,781	$ 4,277
Trans, Controls, Accessories		$ 1,793	$ 500	$ 2,300	$ 3,268	$ 3,167
Energy Storage		$ 495	$ -	$ 500	$ 493	$ 1,691
Total		$ 4,311	$ 1,000	$ 5,300	$ 10,542	$ 9,135
Total Powertrain Size	kW	101.9		67.1	70.0	67.1
Power Unit + Energy Storage	$/kW	$ 25		$ 45	$ 104	$ 89
Trans, Controls, Accessories	$/kW	$ 18		$ 34	$ 47	$ 47
Total	$/kW	$ 42		$ 79	$ 151	$ 136
Power Unit Size	kW	92.9		58.1	61.0	58.1
Power Unit	$/kW	$ 22		$ 43	$ 111	$ 74

* Energy storage includes traction batteries and fuel tank. The hydrogen storage tank is a significant fraction of the overall cH2 FCV cost.

Designing for maximum power could reduce the direct hydrogen powertrain cost by $1,000-$1,500.

FCV market share would be enhanced with incentives and credits that value energy and emission reductions, however, such incentives are not available...

- Without incentives and credits, our ownership cost analysis results in FCVs that cost 30-50% more than gasoline ICEVs or HEVs
  - Includes vehicle, fuel, and O&M costs
- Direct hydrogen FCVs could appear attractive if all attributes are valued and incentivized
  - Effect of new fueling infrastructure on customer preference is not taken into account
  - Incentives may not be available
- Vehicles with higher cost can still achieve some market share
  - Need to assess potential market share as a function of vehicle price, fuel price, and other attributes

...limited state and local programs offer significant incentives, although the life of these programs may be limited.

Outline

Appendix

Appendix Bibliography

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Note: Additional references can be found in the Safety Analysis Addendum section of the Appendix and the Module Calculations section of the Appendix Supplement.

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Appendix Supplement Table of Contents

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Outline

Appendix Supplement

Fuel Chain Analysis Approach

Fuel Chain Performance Parameters

Module Calculations

We documented the calculations and data sources for each step in the fuel chain. The analysis is sorted according to the fuel chain type.

Production and Fuel Processing	
P1	Natural Gas Extraction
P2	Natural Gas Processing
P3	Hydrogen Production
P4	Hydrogen Purification
P5	Hydrogen Compression
P6	Hydrogen Liquefaction
P7	Hydrogen Electrolysis
P8	Metal Hydride Compression
P9	Natural Gas Compression
P10	Petroleum Extraction
P11	Petroleum Refining to Gasoline
P12	Methanol from Natural Gas
P13	Corn Farming
P14	Ethanol from Corn
P15	Petroleum Refining to Diesel
P16	Biomass Chipping
P17	Biomass to Ethanol
P18	Corn Stover Collection
P19	Ethanol from Corn Stover
P20	Electricity Mix

Feedstock and Fuel Transport	
T1	Natural Gas Pipeline
T2	Hydrogen Pipeline
T3	Liquid Hydrogen Transport
T4	Hydrogen Tube Trailer
T5	Petroleum Transport
T6	Gasoline Truck
T7	Methanol Truck
T8	Methanol Marine Transport
T9	Corn Truck
T10	Ethanol Marine
T11	Ethanol Truck
T12	Ethanol Train
T13	Diesel Truck
T14	Biomass Truck

Note: Detailed fuel chain data and efficiency calculations are found in *FuelChainModules.pdf*

We assured that consistent assumptions were used for different fuels throughout the fuel chain.

Complete fuel chains are constructed from a combination of modules.

Fuel Chain	Fuel Chain Module				
	Extraction	Processing	Transport	Production	T S & D
RFG, Petroleum	P10	--	T5	P11	T6
Diesel, Petroleum	P10	--	T5	P15	T13
Methanol, NG	P1	P2	T1	P12	T8, T7
Ethanol, Corn Stover	P18	T14	T10, T12	P19	T11
Ethanol, Corn	P13	T9	T10, T12	P14	T11
cH2, On-site NG SR	P1	P2	T1	P3	P5
cH2, On-site NG SR, Energy Station	P1	P2	T1	P3	P5
cH2, On-site NG SR, MH	P1	P2	T1	P3	P8
cH2, Central NG, Tube Trailer	P1	P2	T1	P4	P5, T4
cH2, Central NG, Pipeline	P1	P2	T1	P4	T2, P5, T4
cH2, Central NG, LH2	P1	P2	T1	P4	P6
cH2, On-site Electrolyzer	P20		T1	P7	--

Outline

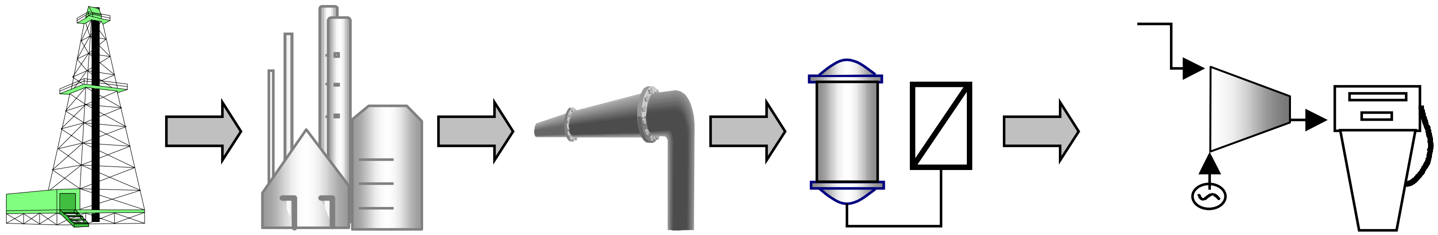
Appendix Supplement

Fuel Chain Analysis Approach

Fuel Chain Performance Parameters

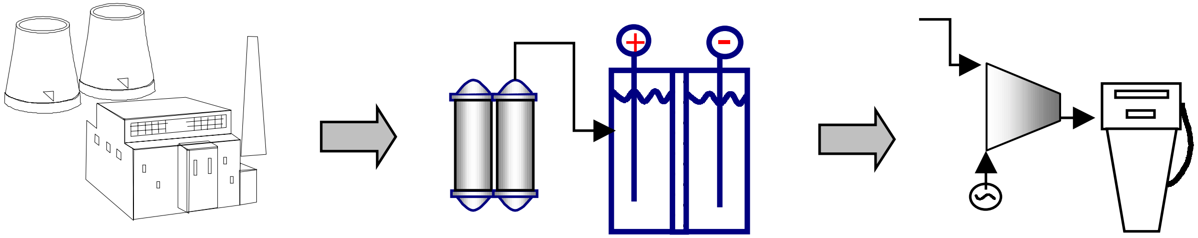
Module Calculations

Compressed H_2 from natural gas, on-site steam reformer:



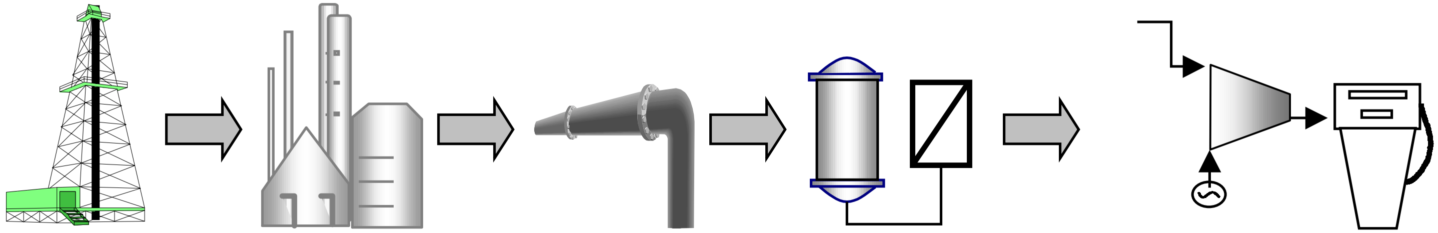
NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P5	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors 50/50 mix of NG/electric power	◆ 300 vehicle per day station capacity ◆ SMR production at 10 atm	◆ H_2 compression and storage at 3600 psia ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 76%	◆ MTE = 93%

Compressed H_2 from on-site electrolyzer:



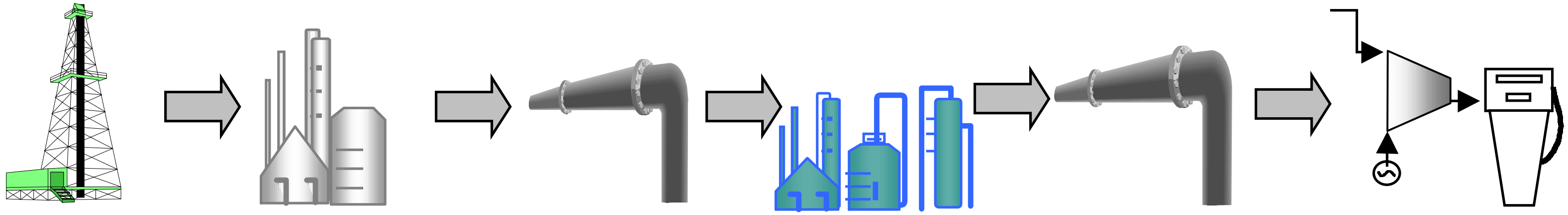
Electricity Generation	On-site H_2 Electrolyzer	T S & D
◆ Module P20	◆ Module P7	◆ Module P5
◆ Average US electricity mix. Based on GREET assumptions	◆ Average US power generation mix used for electricity supply	◆ H_2 compression and storage at 3600 psia ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters		
◆ Generation Mix = 39%	◆ MTE = 71%	◆ MTE = 93%

Metal Hydride (dry) from natural gas, on-site steam reformer with low pressure on-site storage:



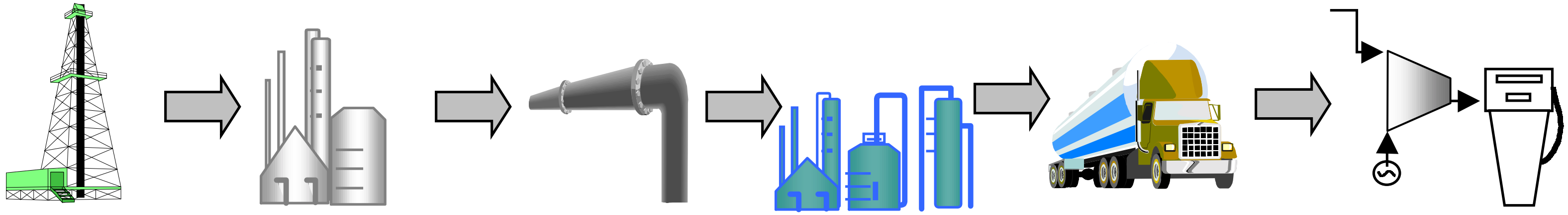
NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P5	◆ Module P8
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ 300 vehicle per day station capacity ◆ SMR production at 10 atm	◆ Low pressure H_2 on-site storage (~10atm)
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 76%	◆ MTE = 98%

Compressed H_2 from natural gas, central steam reformer with pipeline delivery:



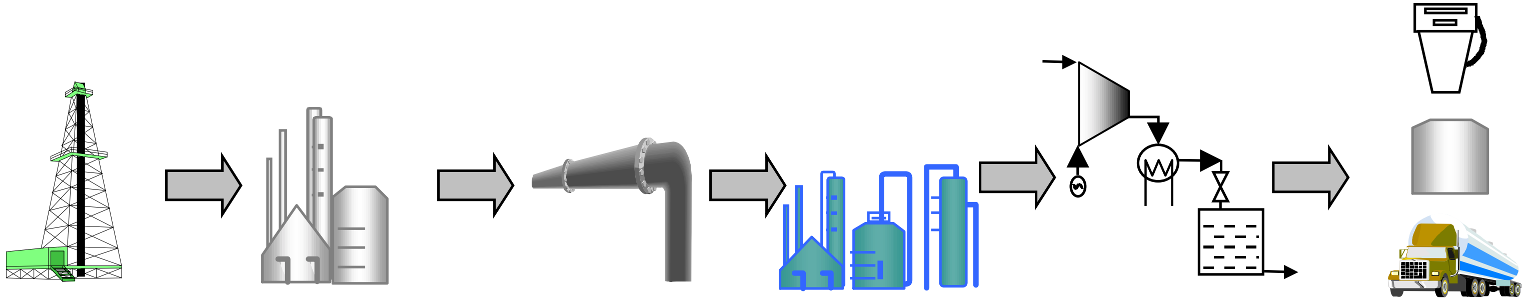
NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Pipeline Length = 50 miles ◆ In-line hydrogen compressors ◆ Pipeline pressure = 40 atm	◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 99+%	◆ MTE = 93%

Compressed H_2 from natural gas, central steam reformer with tube-trailer delivery:



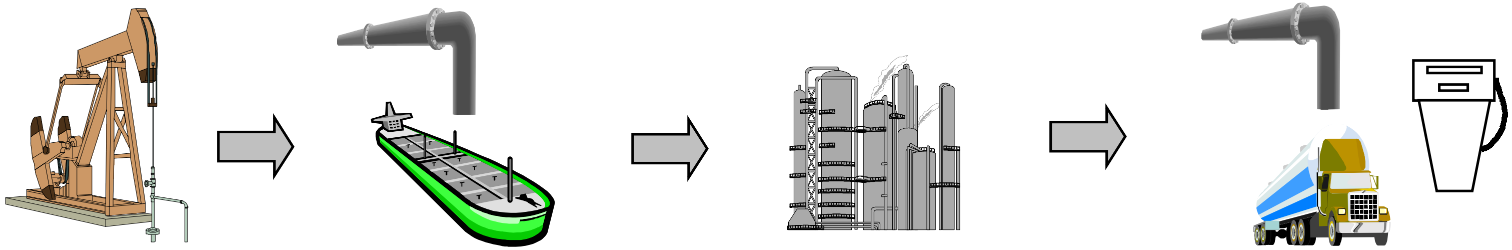
NG Extraction	NG Processing	NG Transport	Central H_2 Production	Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Assumed 50 miles one-way ◆ Tube-trailer H_2 pressure = 3600 psia	◆ Tube trailer storage ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 99%	◆ MTE = 99+%

Liquid H_2 from natural gas, central steam reformer with truck delivery:



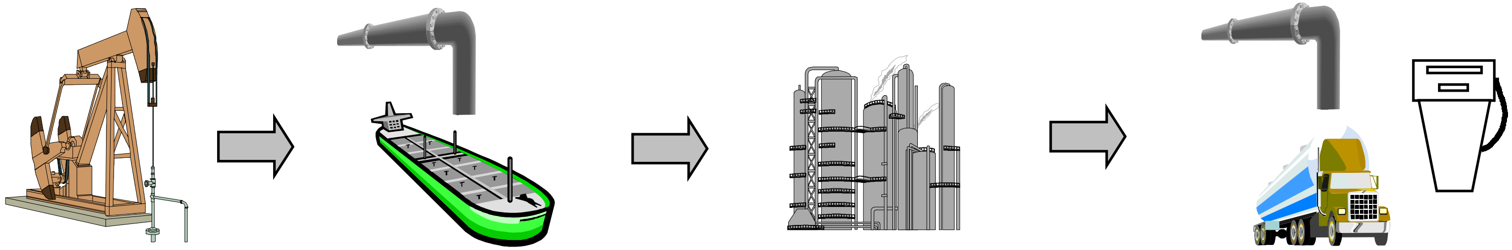
NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Liquefaction	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module P6	
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Assumed standard Linde process	◆ Truck distance = 50 mi one-way ◆ Truck capacity = 7800 gallons
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 70%	◆ MTE = 99%

Gasoline (RFG2) from petroleum:



Petroleum Extraction	Transport	Refining	TS & D
◆ Module P10	◆ Module T5	◆ Module P11	◆ Module T6
◆ Fuel shares mainly natural gas, electricity	◆ EIA data on percentage of domestic versus imported petroleum ◆ Average shipping distance = 5,000 miles ◆ Average pipeline length = 1,000 miles	◆ Fuel shares estimate based on MathPro report to CEC, 2000	◆ Average pipeline distance = 50 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 97%	◆ MTE = 99+%	◆ MTE = 84%	◆ MTE = 99%

Diesel (RFD) from petroleum:

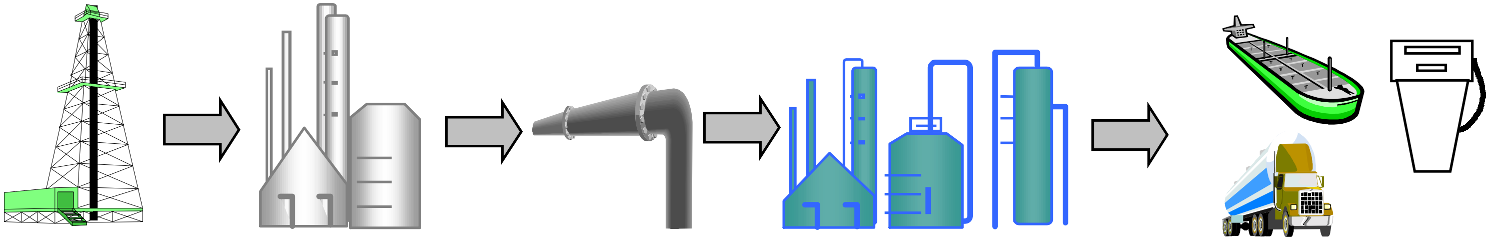


Petroleum Extraction	Transport	Refining	TS & D
◆ Module P10	◆ Module T5	◆ Module P15	◆ Module T13
◆ Fuel shares mainly natural gas, electricity	◆ EIA data on percentage of domestic versus imported petroleum ◆ Average shipping distance = 5000 miles ◆ Average pipeline distance = 1000 miles	◆ GREET estimates of process fuel shares and energy consumption for the production of RFD	◆ Average pipeline length = 50 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 97%	◆ MTE = 99+%	◆ MTE = 89%	◆ MTE = 99%

* Under evaluation.

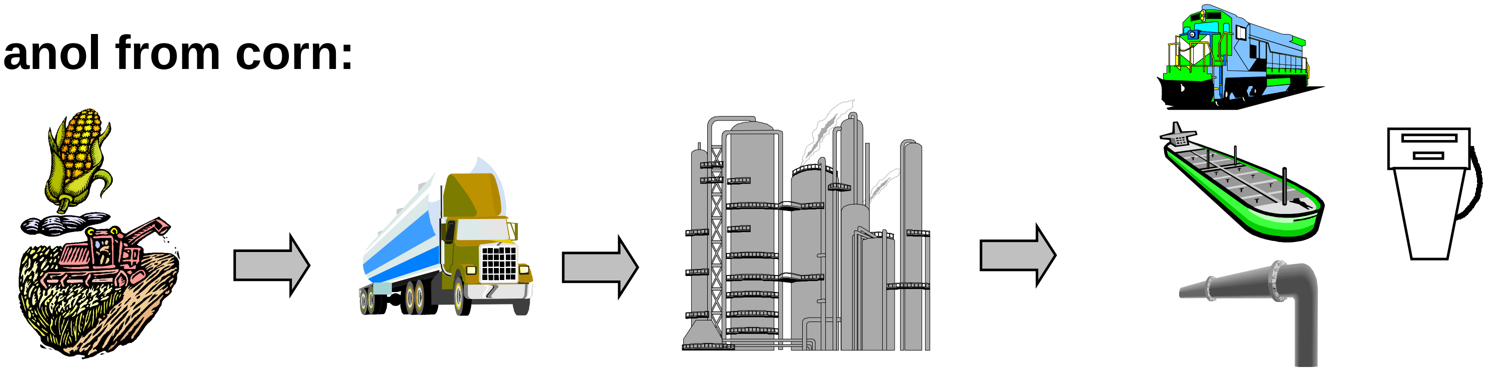
^{A} Based on ADL estimate unless stated otherwise.

Methanol from remote natural gas, central production:



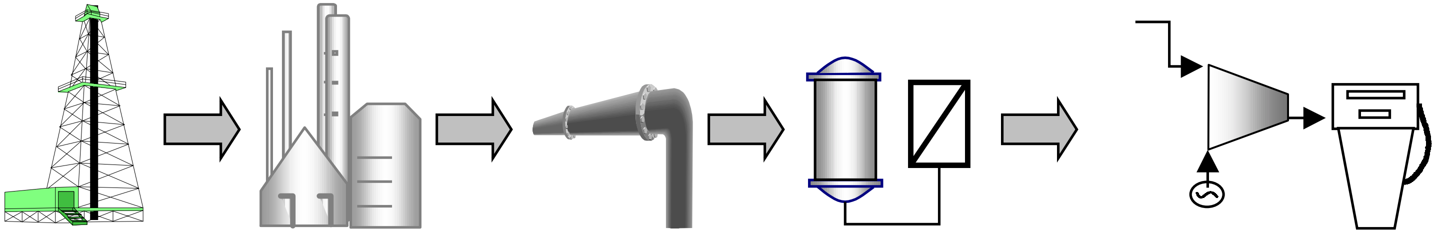
NG Extraction	NG Processing	NG Transport	Methanol Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P12	◆ Module T8, T7
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 25 miles ◆ In-line compressors 100% NG	◆ In-line compressors 50/50 NG/electric	◆ Average shipping distance = 7,500 miles ◆ Average truck distance = 50 miles
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 66%	◆ MTE = 97%

Ethanol from corn:



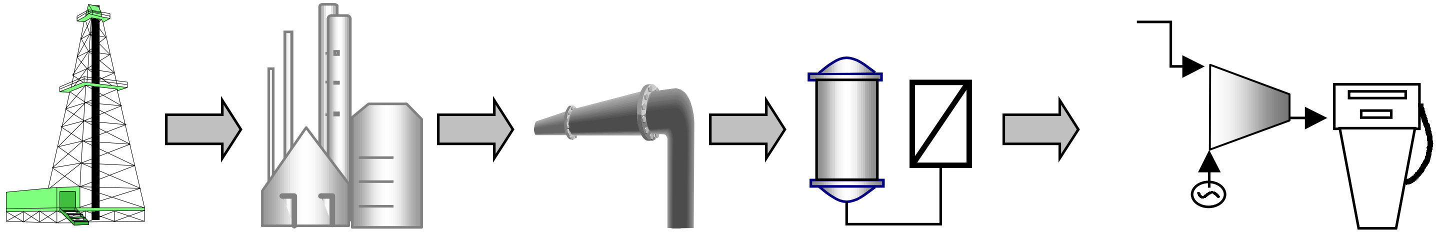
Corn Farming	Transport	Ethanol Production	T S & D
◆ Module P13, T9	◆ Module T10, T12	◆ Module P14	◆ Module T11
◆ GREET estimate of process fuel shares ◆ 17,091 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ GREET estimate of process fuel shares ◆ 4,407 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ Dry mill corn ◆ Ethanol yield = 2.65 gal/bushel ◆ 44,278 Btu/Bushel	◆ Average shipping distance = 3,500 miles ◆ Average railcar distance = 500 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 96%	◆ MTE = 98%	◆ MTE = 46%	◆ MTE = 97%

Compressed H_2 from natural gas, on-site steam reformer:



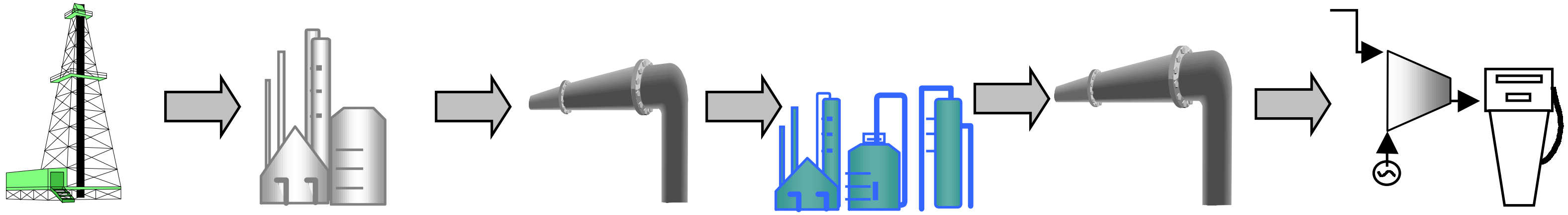
NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P5	◆ Module P5
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors 50/50 mix of NG/electric power	◆ 300 vehicle per day station capacity ◆ SMR production at 10 atm	◆ H_2 compression and storage at 3600 psia ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 76%	◆ MTE = 93%

Metal Hydride (dry) from natural gas, on-site steam reformer with low pressure on-site storage:



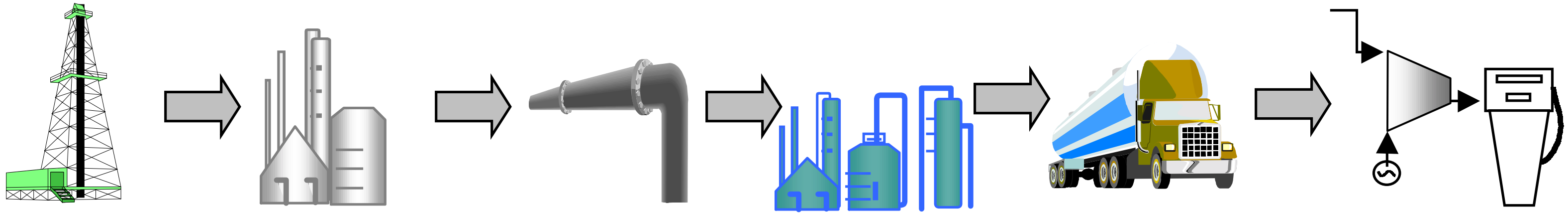
NG Extraction	NG Processing	NG Transport	On-site H_2 Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P5	◆ Module P8
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ 300 vehicle per day station capacity ◆ SMR production at 10 atm	◆ Low pressure H_2 on-site storage (~10atm)
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 76%	◆ MTE = 98%

Compressed H_2 from natural gas, central steam reformer with pipeline delivery:



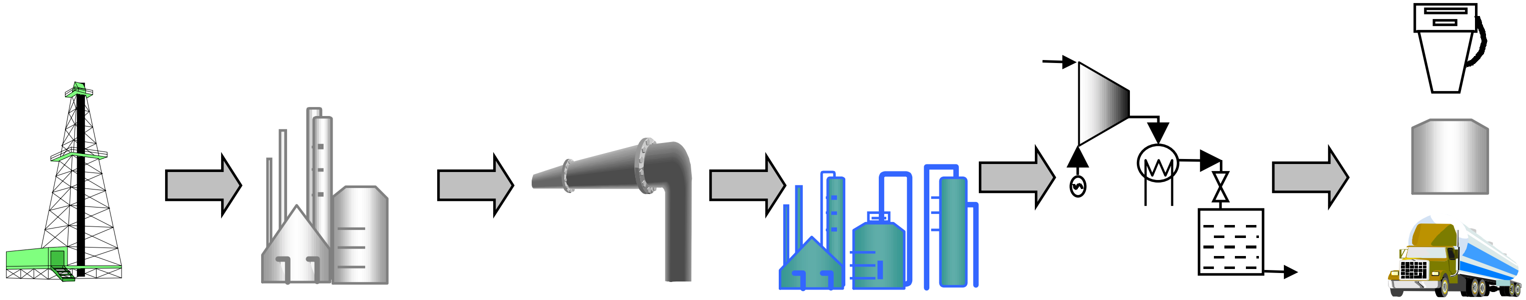
NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5(b)
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Pipeline Length = 50 miles ◆ In-line hydrogen compressors ◆ Pipeline pressure = 40 atm	◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 99+%	◆ MTE = 93%

Compressed H_2 from natural gas, central steam reformer with tube-trailer delivery:



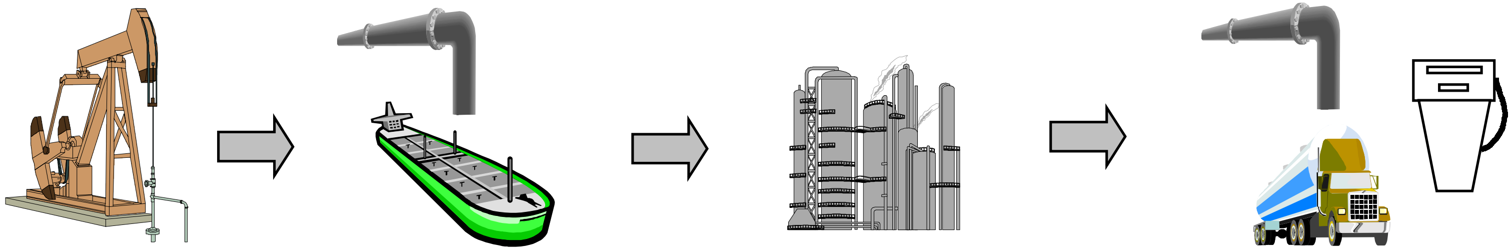
NG Extraction	NG Processing	NG Transport	Central H_2 Production	Transport	S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module T2	◆ Module P5(b)
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Assumed 50 miles one-way ◆ Tube-trailer H_2 pressure = 3600 psia	◆ Tube trailer storage ◆ H_2 compression and dispensing on-board the vehicle at 5500 psia
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 99%	◆ MTE = 99+%

Liquid H_2 from natural gas, central steam reformer with truck delivery:



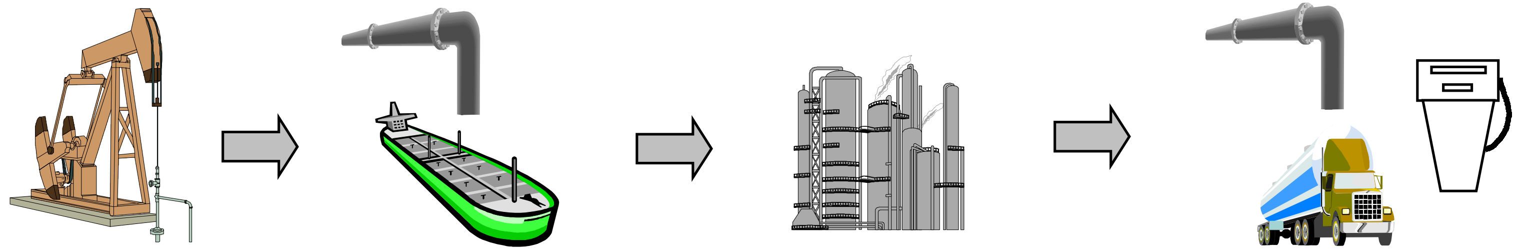
NG Extraction	NG Processing	NG Transport	Central H_2 Production	H_2 Liquefaction	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P4	◆ Module P6	
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 1,000 miles ◆ In-line compressors mix of 50/50 NG/electric	◆ No steam or electricity export assumed	◆ Assumed standard Linde process	◆ Truck distance = 50 mi one-way ◆ Truck capacity = 7800 gallons
Performance Parameters					
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 79%	◆ MTE = 70%	◆ MTE = 99%

Gasoline (RFG2) from petroleum:



Petroleum Extraction	Transport	Refining	TS & D
◆ Module P10	◆ Module T5	◆ Module P11	◆ Module T6
◆ Fuel shares mainly natural gas, electricity	◆ EIA data on percentage of domestic versus imported petroleum ◆ Average shipping distance = 5,000 miles ◆ Average pipeline length = 1,000 miles	◆ MathPro	◆ Average pipeline distance = 50 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 97%	◆ MTE = 99+%	◆ MTE = 84%	◆ MTE = 99%

Diesel (RFD) from petroleum:

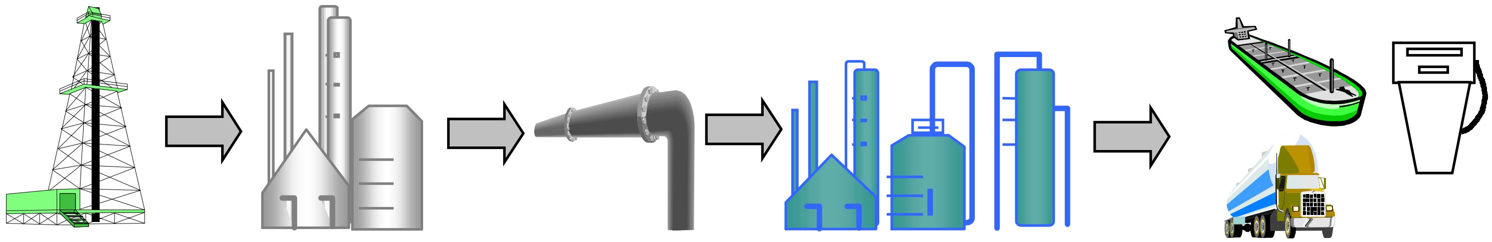


Petroleum Extraction	Transport	Refining	TS & D
◆ Module P10	◆ Module T5	◆ Module P15	◆ Module T13
◆ Fuel shares mainly natural gas, electricity	◆ EIA data on percentage of domestic versus imported petroleum ◆ Average shipping distance = 5000 miles ◆ Average pipeline distance = 1000 miles	◆ GREET estimates of process fuel shares and energy consumption for the production of RFD	◆ Average pipeline length = 50 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 97%	◆ MTE = 99+%	◆ MTE = 89%	◆ MTE = 99%

* Under evaluation.

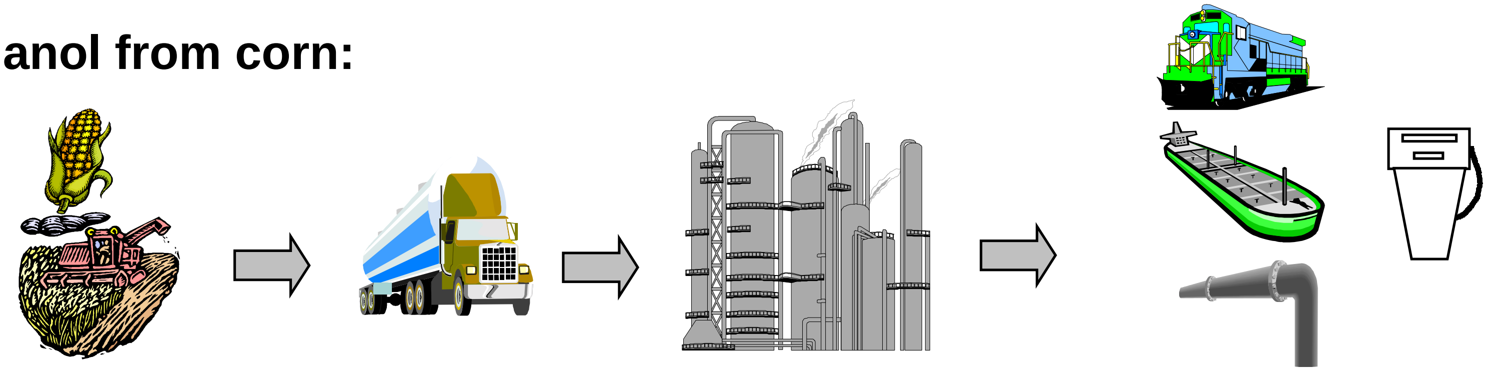
^{A} Based on ADL estimate unless stated otherwise.

Methanol from remote natural gas, central production:



NG Extraction	NG Processing	NG Transport	Methanol Production	T S & D
◆ Module P1	◆ Module P2	◆ Module T1	◆ Module P12	◆ Module T8, T7
◆ NG is the primary process fuel	◆ NG is the primary process fuel	◆ Pipeline Length = 25 miles ◆ In-line compressors 100% NG	◆ In-line compressors 50/50 NG/electric	◆ Average shipping distance = 7,500 miles ◆ Average truck distance = 50 miles
Performance Parameters				
◆ MTE = 97%	◆ MTE = 98%	◆ MTE = 99+%	◆ MTE = 66%	◆ MTE = 97%

Ethanol from corn:



Corn Farming	Transport	Ethanol Production	T S & D
◆ Module P13, T9	◆ Module T10, T12	◆ Module P14	◆ Module T11
◆ GREET estimate of process fuel shares ◆ 17,091 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ GREET estimate of process fuel shares ◆ 4,407 Btu/Bushel ◆ MTE based on corn-ethanol yield of 2.65 gal/bushel	◆ Dry mill corn ◆ Ethanol yield = 2.65 gal/bushel ◆ 44,278 Btu/Bushel	◆ Average shipping distance = 3,500 miles ◆ Average railcar distance = 500 miles ◆ Average truck distance = 50 miles
Performance Parameters			
◆ MTE = 96%	◆ MTE = 98%	◆ MTE = 46%	◆ MTE = 97%

Outline

Appendix Supplement

Fuel Chain Analysis Approach

Fuel Chain Performance Parameters

Module Calculations

APPENDIX Module P1 Natural Gas Extraction

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Natural Gas	37.79	GJ, HHV	34.01	1.000	97.42%
Process Fuels					
Natural Gas	848	scf	0.830	0.02	2.38%
Petroleum	0.08	gal	0.011	0.000	0.03%
Diesel	0.29	gal	0.039	0.001	0.11%
Electricity	3.13	kWh	0.011	0.000	0.03%
Gasoline	0.09	gal	0.011	0.000	0.03%
TOTAL INPUT				1.027	100%

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	37.79	GJ, HHV	34.01	1.000
Secondary Products				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				97.4%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
Gasoline	115,500	Btu/gal
Natural Gas	1.111	HHV/LHV
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

APPENDIX Module P2 Natural Gas Processing

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Natural Gas	42.07	GJ, HHV	37.87	1.000	97.80%
Process Fuels					
Natural Gas	848	scf	0.830	0.02	2.14%
Electricity	5.56	kWh	0.020	0.001	0.05%
Gasoline	0.004	gal	0.000	0.000	0.00%
TOTAL INPUT			0.850	1.022	100.00%

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	42.07	GJ, HHV	37.87	1.000
Secondary Products				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				97.8%

Input Parameters		LHV
Natural Gas	928	btu/scf
Natural Gas	1.111	HHV/LHV
Gasoline	115,500	Btu/gal
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

APPENDIX Module P4a SMR Hydrogen Production, Central

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	71.700	scf	0.070	1.26
Process Fuels				
Electricity	0.0100	kWh	3.60E-05	0.001
TOTAL INPUTS				1.261

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	1.000	lb	0.056	1.00
Secondary Products				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				79.3%

Input Parameters		LHV
Natural Gas	928	Btu/scf
	47	MJ/kg
Hydrogen	52802	Btu/lb
	119.9	MJ/kg
Conversion	0.0036	GJ/kWh
Additional Conversions		
NG	MMBtu/kg-H2	0.147
electricity	kWh/kg-H2	0.022

References

1. ADL analysis

2. "Hydrogen production Plants: Emissions and Thermal Efficiency Analysis," Contadini, J.F., Diniz, C. V., Sperling, D. and Moore, R. M., Institute of Transportation Studies, Univ. of California, Davis, 2000

APPENDIX Module P3, P4, P5 & P8 Hydrogen Production and Storage (On-Site, HYSIS Modeling)

Module Nos.		P3	P4b	P5	P8
Feedstock		**Natural Gas**	**Natural Gas**	**Natural Gas**	**Natural Gas**
Production		**Local SMR**	**Central SMR****	**Central SMR****	**Local SMR**
Purification		**PSA**			**PSA**
Transportation/On-site Storage		**3600 psi**	**Tube Trailer**	**Pipeline**	**100 psi**
On-board Storage		**cH2**	**cH2**	**cH2**	**MH**
On-site Energy Requirements from HYSYS					
Fuel in, kmol/hr		0.505			0.535
Fuel MW, g/mol		16.27			16.27
Fuel LHV, MJ/kg		48.83			48.83
Hydrogen out, kmol/hr		1.258	1.373	1.373	1.333
Production, kW		1.330			1.411
Purificaiton, kW		0.551			0.584
Storage, kW		6.692	3.462	8.435	1.610
Natural Gas Input	kg/hr	8.210			8.707
	MMBtu/hr, HHV	0.421			0.447
	GJ/hr, HHV	0.444			0.471
	MMBtu/hr, LHV	0.380			0.403
	GJ/hr, LHV	0.401			0.425
Power Input	kW	1.881			1.995
	GJ/hr	0.007			0.007
Hydrogen	kg/hr	2.541	2.773	2.773	2.692
	GJ/hr, HHV	0.361	0.394	0.394	0.383
	GJ/hr, LHV	0.305	0.332	0.332	0.323
Module Thermal Efficiency (Production)	**%**	**74.7%**	**See P4a****	**See P4a****	**74.7%**
Compression (Storage)	kW	6.692	3.462	8.435	1.610
	GJ/hr	0.02409	0.01246	0.03037	0.00580
Process Fuel Shares					
Natural Gas	%	93.5%	0.0%	0.0%	97.0%
Electricity	%	6.5%	100.0%	100.0%	3.0%
Module Thermal Efficiency (Compression)*	%	**92.7%**	**96.4%**	**91.6%**	**98.2%**

* - Central compression power is accounted for in the transportation modules

** - See Module P4a for Central SMR H2 Production

APPENDIX Module P6 Hydrogen Liquefaction

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Hydrogen	300.00	tons	33,429	1.00
Process Fuels				
Power Requirements* (see liquefaction tal	4,477.20	MWh	16,118	0.482
TOTAL INPUTS				1.482

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	300.00	tons	33,429	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Thermal Efficiency, GJ-output/GJ-input				67.5%

Input Parameters		LHV
Hydrogen	0.056	GJ/lb
Hydrogen-gas	lb/scf	#REF!
Conversion	GJ/kWh	0.0036

References	
1. ADL internal estimate based on " Study of Large H2 Liquefaction Proces," Matsuda and Nagami, Nippon Sanso Corp, (see Liquefaction Reference)	
Other Studies, MTE	
GREET, LHV	70%
ADL FORD Report, HHV	NA
NOVEM Report, HHV	81%

APPENDIX Calculation Hydrogen Liquefaction

Hydrogen Claude Cycle

General Process Description

1. Compressed to 5 MPa
2. Cooled to 80 K
3. Ortho-Para Converter - converted to 47% para hydrogen
4. Further cooling
5. Liquefied at 0.1 MPa, 20.4K, by expansion (J-T) valve

Plant Basis	300	tons/day	12500	kg/hr
Total Power Required	106.6	MW	2558	MWh
NG Compressor Efficiency	40.00%			
Assume Power Mix				
Natural Gas	50%			
Electricity	50%			
Actual Natural Gas Input to Plant	133.3	MW	0.036	MMBtu/kg
(prior to efficiency losses)				
Electricity Input	53.3	MW	4.26	kWh/kg
Total Actual Power Input	4477	MWh/day		
	14.9	MWh/ton		
	7.5	kWh/lb		

Reference: Matsuda and Nagami, Nippon Sanso Corporation, 1997, (www. enaa.or.jp/WE-NET/ronbun/1997/e5/sanso1997.html)

APPENDIX Module P7 Hydrogen from Electrolyzer

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Process Fuels				
Electricity	4.270	kWh	0.015	1.388
TOTAL INPUTS				1.388

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	0.1988	lb	0.011	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency				72.1%

Input Parameters		LHV
Hydrogen	Btu/scf	274
Hydrogen	Btu/lb	52802
Electrolysis power	kWh/Nm3	5.6
Conversion	kWh/GJ	0.0036

References

1, Personal Communications with Stuart Energy, August 2001

2. Teledyne Energy Systems, Specification Sheet ES-678, April 2000

Other Studies, MTE	
ADL FORD Report, HHV	89%
NOVEM Report, HHV	80%

kWh/kg		**kWh/kg**
Electricity	Compressor	Total
47.35	2.634	50.0

APPENDIX Module P9 Natural Gas Compression

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	100.00	scf	0.098	1.00
Process Fuels				
Natural Gas	6.50	scf	0.0064	0.065
Electricity	0.75	kWh	0.0027	0.028
TOTAL INPUTS				1.093

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	100.00	scf	0.098	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				91.53%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Electricity	0.015	kWh/scf
Conversion	0.0036	GJ/kWh

References

1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains, " ADL Report, November 1999.
2. ADL Internal Estimations

NG ICE efficiency	40%
Other Studies, MTE	
GREET, LHV	97%
ADL FORD Report, HHV	94%
NOVEM Report, HHV	NA

APPENDIX Module P10 Petroleum Extraction

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Petroleum	6.19	bbl	35.680	1.00	96.95%
Process Fuels					
Petroleum	9.1E-01	gal	1.2E-01	3.5E-03	0.34%
Diesel	0.70	gal	0.095	2.6E-03	0.26%
Heavy Fuel Oil	0.05	gal	0.007	2.0E-04	0.02%
Natural Gas	695.0	scf	0.680	1.9E-02	1.85%
Electricity	49.60	kWh	0.179	5.0E-03	0.49%
Gasoline	0.31	gal	0.038	1.1E-03	0.10%
TOTAL INPUTS			1.1E+00	1.032	100.00%

OUTPUTS FROM MODULE				
Primary Products:				
Petroleum	6	bbl	35.680	1
Secondary Products				
TOTAL INPUTS				1.000
Module Efficiency, GJ-output/GJ-input				96.9%

Input Parameters		LHV
Natural Gas	928	btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
Gasoline	115,500	Btu/gal
Conversion	42.000	gal/barrel
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References	
1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains," ADL Report, November 1999.	
Other Studies, MTE	
GREET, LHV	98%
ADL FORD Report, HHV	96%
NOVEM Report, HHV	96%

APPENDIX Module P11 Petroleum Refining to Gasoline

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Petroleum	0.15	bbl	0.870	1.03	87.3%
Process Fuel					
Petroleum Coke	8.6E-04	tons	1.9E-02	0.02	1.9%
Diesel	0.010	gal	0.001	0.00	0.1%
Heavy Fuel Oil	0.0685	gal	0.010	0.01	1.0%
LPG	0.0157	gal	0.001	0.00	0.1%
Natural Gas	62.5	scf	0.061	0.07	6.1%
Ethanol	0.000	gal	0.000	0.00	0.0%
Electricity	1.09	kWh	0.004	0.005	0.4%
Refinery Gas	31.00	scf	0.030	0.04	3.0%
TOTAL INPUT			1.3E-01	1.185	100.0%

OUTPUTS FROM MODULE				
Primary Products:				
FRFG2	7.11	gal	0.842	1.00
Secondary Products				
None				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				84.4%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Refinery Gas	928	Btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
LPG	84,000	Btu/gal
FRFG	112,265	Btu/gal
Petroleum Coke	20,532,600	Btu/Ton
Ethanol	76,000	Btu/gal
Conversion	42.000	gal/barrel
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References

1. ADL internal estimate based on the MathPro report - " Analysis of the refining economics of California Phase 3 RFG ," Jan 5, 2000, submitted to CEC.
2. Assume ethanol to be the long-term oxygenate

Other Studies, MTE		
GREET, LHV	86%	
ADL FORD Report, HHV	87%	RFG
NOVEM Report, HHV	88%	conventional gasoline

APPENDIX Module P12 Methanol from Natural Gas

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	93	scf	0.091	1.514
Process Fuels				
TOTAL INPUTS				1.514

OUTPUTS FROM MODULE				
Primary Products:				
Methanol	1	gal	0.060	1.00
Secondary Products				
Steam	0	Btu	0.000	0.00
TOTAL OUTPUTS			0.060	1.000
Module Thermal Efficiency, GJ-output/GJ-input				66.05%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Methanol	57,000	Btu/gal
Steam Export	110,000	Btu/MMBtu
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References	
ADL/JT data - 68% efficiency, HHV basis	
Other Studies, MTE -- no steam credit	
ADL/JT New high cost ethanol pla	72%
ADL/JT New low cost ethanol plar	68%
GREET, LHV	70%
ADL FORD Report, HHV	62%

APPENDIX Module P13 Corn Farming

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Corn	1.00	Bushel	0.354	1.00
Process Fuels				
Energy Use (process fuels+fertilizers)	17,091	Btu	0.018	0.051
TOTAL INPUTS				1.051

OUTPUTS FROM MODULE				
Primary Products:				
Corn	1.00	Bushel	0.354	1.00
Secondary Products				
TOTAL OUTPUTS			0.354	1.000
Module Efficiency, GJ-output/GJ-input				95.2%

Input Parameters		LHV
Ethanol yield	2.65	gal/bushel
Ethanol	76,000	Btu/gal
Corn Weight	56	lb/bushel
Corn Heat Value	6,000.00	Btu/lb
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

REFERENCES

1. Greet 1.5 - Transportation Fuel-Cycle Module, Vol. 1, Aug, 1999
ANL Transportation TEchnology R&D CEnter, ANL/ESD-39
2. ADI estimates

Other Studies, MTE		
GREET, LHV	17,091	Btu/Bushel
ADL FORD Report, HHV	87%	
NOVEM Report, HHV	87%	

APPENDIX Module P14 Ethanol from Corn

		Units	LHV Btu	LHV, kJ
INPUTS TO MODULE				
Input Fuel				
Corn	2.65	gal/bushel		
Other Inputs				
Natural Gas	17,414	mmBtu/gal	12,689	16,733
Coal	17,414		12,689	16,733
Electricity	2.10	kWh/gal	7,165	7,559
Total			32,543	41,026
OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	1	gal		76,000
Secondary Products				
DDGS, 21% protein				
Total				

INPUT PARAMETERS

Corn	Btu/lb LHV	6000
Ethanol	Btu/gal LHV	76,000
	lb/gal	6.60
	kg/gal	2.996
Natural Gas	Btu/scfLHV	970
	lb/100scf	4.52
	kg/100scf	2.05
Steam Boiler Efficiency	Btu/Btu	80%
Electricity Conversion	Btu elec/kWh	3412
Power Plant Efficiency		38%
Energy Conversion	kJ/Btu	1.055
Portion of energy from electricity production available as steam	%	50%

References
1. 2.65 gal/bushel refers to yield in ProForma Cost Summary Report for Dry-Mill corn ethanol plant
2. 34,828 Btu at 80% boiler efficiency to produce 27,862 Btu of needed steam (carbonbalance.xls)
3. 2.1 kWh/gal is electricity input required in ProForma Cost Summary Report (carbonbalance.xls)

4. NREL, 1999. Environmental Life Cycle Implications of Fuel Oxygenate Production from California Biomass

Notes
1. Natural Gas is energy required for steam production. Cogen assumes that steam is also obtained from waste heat in electricity production
2. Other fuels could be used to provide steam energy. Assumption is that boiler efficiency is constant at 80%. Assumption also used in NREL, 1999 (see below).
3. Allocation of input energy to co-product not accounted for here
4. Cogen operation assumes that 50% of electricity-produced steam is used in production and therefore avoids additional natural gas
5. A good figure of merit for energy consumption is an on-site energy consumption value for steam production and a value for electricity consumption. Some other studies and the GREET model, however, use a combined figure of merit. As a result, we converted our electricity consumption into a Btu elec/gal value so the total could be input into GREET. In order to compare with other studies, this number must be converted to Btu thermal/gal. This conversion results in a value of 54,000 Btu/gal not including cogen, which is within the range of the other studies that also neglected cogen: approximately 48,000 Btu/gal to 63,000 Btu/gal.
Table of other studies' results is in CornModule.xls

APPENDIX Module P15 Petroleum Refining to RFD

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Petroleum	0.16	bbl	0.922	1.050	93.55%
Process Fuel					
Petroleum Coke	1.9E-04	tons	4.0E-03	0.005	0.41%
Heavy Fuel Oil	0.0198	gal	0.003	0.003	0.30%
LPG	0.0047	gal	0.000	0.000	0.04%
Natural Gas	25.2	scf	0.025	0.028	2.50%
Electricity	0.31	kWh	0.001	0.001	0.11%
Refinery Gas	31.00	scf	0.030	0.035	3.08%
TOTAL INPUTS			6.3E-02	1.122	100.00%

OUTPUTS FROM MODULE				
Primary Products:				
Diesel	6.50	gal	0.878	1
Secondary Products				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				89.1%

Input Parameters		LHV
Natural Gas	928	Btu/scf
Refinery Gas	928	btu/scf
Petroleum	130,000	Btu/gal
Diesel	128,000	Btu/gal
Fuel Oil	140,000	Btu/gal
LPG	84,000	Btu/gal
Gasoline	115,500	Btu/gal
Petroleum Coke	20,532,600	Btu/Ton
Conversion	42	gal/barrel
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References

1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains," ADL Report, November 1999.

Comments		
Other Studies, MTE		
GREET, LHV	87%	
ADL FORD Report, HHV	97%	conventional diesel
NOVEM Report, HHV	95%	

APPENDIX Module P16 Biomass Chipping

		Units	LHV, Btu	LHV, kJ	J/MJprimary product delivered
INPUTS TO MODULE					
Input Fuel					
Forest Material	1	BDT	17,000,000	17,935,000	1,000,000
Other Inputs					
Diesel	2.20	gal/BDT	281,600	297,088	16,565
Total			17,281,600		1,016,565
OUTPUTS FROM MODULE					
Primary Products:					
Forest Material	1	BDT	17,000,000	17,935,000	1,000,000
Secondary Products					
None					
Total					1,000,000
Module Efficiency, GJ-output/GJ-input					98.4%

INPUT PARAMETERS		
Forest Material	Btu/dry-lb	8500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Chipping fuel requirement within range of various studies
2. QLG Feasibility Study suggests a cost of $30-40/BDT for this processing

COMMENTS

1. Assume heat rate of biomass is 8500 Btu/dry lb

Other Studies, MTE		
GREET, LHV	234,770	gal diesel/BDT
ADL FORD Report, HHV		
NOVEM Report, HHV		

A

APPENDIX Module P17 Ethanol from Biomass

		Units	LHV Btu	LHV, kJ
INPUTS TO MODULE				
Input Fuel				
Forest Material	77.70	gal/BDT		
Other Inputs				
Natural Gas	0	mmBtu/gal	0	0
Electricity	0.00	kWh/gal	0	0
Diesel	1.45	gal/1000 gal	186	176
Total				
OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	1	gal	76,000	72,038
Secondary Products				
Electricity	2.066	kWh thermal/gal	18,594	17,625
Total				

INPUT PARAMETERS		
Biomass	Btu/dry-lb	8500
Ethanol	Btu/gal LHV	76,000
	lb/gal	6.60
	kg/gal	2.996
Diesel	Btu/gal LHV	128000
Electricity Conversion	Btu/kWh	9000
Energy Conversion	kJ/Btu	1.055

References

1. ProForma Cost Summary Report (calculations in carbonbalance.xls)
2. Scenario is midterm ethanol plant using lignin to provide energy inputs (Case 34)

Notes

1. Lignin by-product is combusted to produce steam and excess electricity

2 No marketable co-products are accounted for

APPENDIX Module P18 Corn Stover Collection

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Corn Stover	1.00	BDT	15.071	1.00
Process Fuels				
Diesel	181,665	Btu/BDT	0.192	0.013
TOTAL INPUTS				1.013

OUTPUTS FROM MODULE				
Primary Products:				
Corn Stover	1.00	BDT	15.071	1.00
Secondary Products				
None				
TOTAL OUTPUTS			15.071	1.000
Module Thermal Efficiency, GJ-output/GJ-input				98.7%

Input Parameters		LHV
Ethanol yield	95.00	gal/bdt
Ethanol	76,000	Btu/gal
Corn Weight	56	wet lb/bushel
Corn Stover/Corn ratio	1	lb/lb
Corn Stover Heat Value	7,143	Btu/dry-lb
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

REFERENCES

1. Greet 1.5 - Transportation Fuel-Cycle Module, Vol. 1, Aug, 1999
ANL Transportation TEchnology R&D CEnter, ANL/ESD-39
2. Corn Stover Collection Project, DOE, 1998.
3. Estimate that diesel required for collecting stover is equal to one quarter of diesel
used in corn farming (17091Btu/Bushel)

Other Studies, MTE		
GREET, LHV	17,091	Btu/Bushel
ADL FORD Report, HHV	87%	
NOVEM Report, HHV	87%	

APPENDIX Module P19 Ethanol from Corn Stover

		Units	LHV Btu	LHV, kJ
INPUTS TO MODULE				
Input Fuel				
Corn Stover	95.00	gal/BDT		
Other Inputs				
Natural Gas	0	mmBtu/gal	0	0
Electricity	0.00	kWh/gal	0	0
Diesel	1.45	gal/1000 gal	186	176
Total				
OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	1	gal	76,000	72,038
Secondary Products				
Electricity	2.066	kWh thermal/gal	18,594	17,625
Total				

INPUT PARAMETERS		
Ethanol	Btu/gal LHV	76,000
	lb/gal	6.60
	kg/gal	2.996
Diesel	Btu/gal LHV	128000
Electricity Conversion	Btu/kWh	9000
Energy Conversion	kJ/Btu	1.055

References

1. Energy inputs based on ethanol from woody material in ProForma Cost Summary Report (calculations in carbonbalance.xls)
2. Scenario is midterm ethanol plant using lignin to provide energy inputs (Case 34)
3. Yield of 95 gal/ton based on 80gal/wet ton estimated as initial corn stover yields in DOE Corn Stover Collection Project, 1998. With mature conversion technology, up to 130 gal/ton

Notes

4. Lignin by-product is combusted to produce steam and excess electricity

APPENDIX Module P20 Electricity Generation

		Units	LHV, GJ	GJ/GJ primary product	Process Fuel Shares
INPUTS TO MODULE					
Throughput Fuel/Feedstock					
Coal	5,341	Btu	5.6E-03	1.57	54.0%
Oil	79	Btu	8.3E-05	0.02	0.8%
Natural Gas	1,309	Btu	1.4E-03	0.38	21.1%
Nuclear	1,244	Btu	1.3E-03	0.36	12.4%
Other (Renewables)	998	Btu	1.1E-03	0.29	11.7%
TOTAL INPUT	8,971	Btu	9.5E-03	2.6E+00	

OUTPUTS FROM MODULE				
Primary Products:				
Electricity	1.00	kWh	0.004	1.00
Secondary Products				
None				
TOTAL OUTPUT				1.000
Module Efficiency, GJ-output/GJ-input				38.03%

Input Parameters		LHV
Conversion	3,412	Btu/kWh
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ
U.S. AVERAGE ELECTRICITY GENERATION MIX		
REF: GREET		
	%	Efficiency, %
COAL	54.0%	34.5%
OIL	0.8%	34.5%
NG*	21.1%	55.0%
NUCLEAR	12.4%	34.0%
OTHER**	11.7%	40.0%

* -- Combined Cycle
** -- Industry Experience

APPENDIX Module T1 Natural Gas Transport, Pipeline

		Units	LHV, GJ	GJ/GJ primary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Natural Gas	1,000,000	scf	9.79E+02	1.000
Process Fuel				
Electric + NG Power	1,575	hp-hr/MMscf	4.23E+00	0.004
TOTAL INPUTS				1.004

OUTPUTS FROM MODULE				
Primary Products:				
Natural Gas	1,000,000	scf	9.79E+02	1.000
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				99.57%

INPUT PARAMETERS		
Natural Gas		
Heating Value, LHV	Btu/scf	928
Pipeline Length	mi	1000
NG Compressor ICE efficiency factor		0.4
Use Factor	hp-hr/MMscf/mi	1.575
Conversion Factor	kJ/hp-hr	2684.52

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environmental

Other Studies, MTE	
GREET, LHV	97.0%
ADL FORD Report, HHV	97.4%
NOVEM Report, HHV	99.9%

APPENDIX Module T2 Hydrogen Transport, Pipeline

		Units	LHV, GJ	GJ/GJ primary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Hydrogen	1,000,000	scf	2.89E+02	1
Process Fuel				
NG + Electricity	1.75	GJ	1.75E+00	0.01
TOTAL INPUTS				1.01
OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	1,000,000	scf	2.89E+02	1.00
Secondary Products				
None				
TOTAL OUTPUTS				1.00
Module Efficiency, GJ-output/GJ-input				99.40%

INPUT PARAMETERS		
Hydrogen		
Heating Value, LHV	Btu/scf	274
	Btu/lb	52802
	lb/MMscf	5189.20
	kg/MMscf	2353.38
NG, LHV	Btu/scf	928
Process Fuel Power	GJ/MMscf	1
Natural Gas ICE Efficiency Factor		0.4
NG Process Fuel Share		50%
Electricity Process Fuel Share		50%
Conversion	GJ/MMBtu	1.055
Conversion	GJ/kWh	0.0036
Additional Conversions		
NG Process Fuel Share	MMBtu/kg	0.0005
Electricity Process Fuel Share	kWh/kg	0.0591

REFERENCES

1. "Analysis and Integral Evaluation of Potential CO2-Neutral Fuel Chains, NOVEM, November 1999.

COMMENTS

1. Assumes a 50-mile long pipeline

Other Studies, MTE		
GREET, LHV	97.0%	
ADL FORD Report, HHV	99.2%	100-mile pipeline
NOVEM Report, HHV	99.6%	50-mile pipeline

APPENDIX Module T3 Liquid HydrogenTransport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
LH2	3,370	kg/truck	407	1.00
Process Fuels				
Diesel	18.18	gal (round trip)	2.5	0.01
TOTAL INPUTS				1.01

OUTPUTS FROM MODULE				
Primary Products:				
LH2	7,800	gal	407	1.00
Secondary Products				
None				
Total				1
Module Efficiency, GJ-output/GJ-input				99.4%

INPUT PARAMETERS		
Average Truck	mi/gal	5.5
Average One-way Trip Distance	mi	50
LH2	Btu/gal LHV	30100
	lb/gal	0.580
	kg/gal	0.263
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

References

1. Refinement of Selected Fuel-Cycle Emissions Analyses, Vol. 1 Final Report, Dec 2000 Prepared for CARB and SCAQMD, FR-00-101 by Arthur D. Little
2. Hydrogen - The Coming Fuel, Linde Presentation, INTERTECH, Nice, France, May 2001

Other Studies, MTE

GREET, LHV	95.0%
NOVEM Report, HHV	99.9%

APPENDIX Module T4 Hydrogen Transport, Tube Trailer

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Hydrogen	530	kg	68.01	1.000
Process Fuel				
NG + Electricity (Ref:2)	#REF!	kWh	#REF!	#REF!
Diesel	20.00	gal (round trip)	2.7	0.040
TOTAL INPUTS				#REF!

OUTPUTS FROM MODULE				
Primary Products:				
Hydrogen	530	kg	68.01	1.000
Secondary Products				
None				
TOTAL OUTPUTS				1.000
Module Efficiency, GJ-output/GJ-input				#REF!

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Compression Power	kWh/GJ	#REF!
Hydrogen	kg/kmol	2.016
	Btu/lb, LHV	52802
	Btu/kg, LHV	116428
	Btu/kmol, LHV	245198
	GJ/kmol, LHV	0.2587
	Btu/scf, LHV	274
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24
conversion	kWh/GJ	278

References

1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environmental
2. ADL see tab "H2 Compression"

Other Studies, MTE	
GREET, LHV	97.0%

APPENDIX Calculation Hydrogen Tube Trailer Compression

Central SMR, Hydrogen Compression for Tube Trailer				
Hydrogen	1.373	kmol/hr	0.337	GJ/hr
Required Power	6.84	kW_e	0.025	GJ/hr
Power Shares				
Natural Gas	50%			
Electric Motor Efficiencv	95%			
IC Engine Efficiency	40%	LHV		
Actual Input Compressor	8.6	kW_{th}	0.011	MMBtu/kg
Electricity	50%			
	3.25	kW	1.174	kWh/kg
Input				
Compressor	11.8	kW	0.042	GJ/hr
	35.061	kWh/GJ		
Output				
Hydrogen	1.26	kmol/hr	0.337	GJ/hr
Module Thermal Efficiency			88.8%	

APPENDIX Module T5 Petroleum Transport, Pipeline&Marine

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Petroleum	142,500	DWT	6.11E+06	1.000
Other Inputs				
Bunker Fuel	513,000	kg (round trip)	2.18E+04	0.004
Diesel	2,243	gal	3.03E+02	0.000
Total				1.004

OUTPUTS FROM MODULE				
Primary Products:				
Petroleum	142,500	DWT	6.11E+06	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.64%

INPUT PARAMETERS		
Petroleum		
Density	kg/gal	3.2
Energy Content	Btu/gal, LHV	130000
	Btu/kg	40625
Bunker Fuel		
Tanker Fuel Consumption	kg/ton-mi	0.0018
Average One-way Trip Distance	mi	1000
Bunker Fuel	Btu/kg	40350
Tanker Load Efficiency		0.95
Diesel		
In-port use factor	kg/DWT	0.051
Energy Content	Btu/gal, LHV	128000
Diesel Density	kg/gal	3.24

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	99.5%

APPENDIX Module T6 Gasoline Transport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Gasoline	7,800	gal	950	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.003
Total				1.003

OUTPUTS FROM MODULE				
Primary Products:				
Gasoline	7,800	gal	950	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.7%

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Gasoline	Btu/gal LHV	115500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	98.5%

APPENDIX Module T7 Methanol Transport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Methanol	7,800	gal	469	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.006
Total				1.006

OUTPUTS FROM MODULE				
Primary Products:				
Methanol	7,800	gal	469	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.4%

INPUT PARAMETERS		
Average Truck	mi/gal	5
Average One-way Trip Distance	mi	50
Methanol	Btu/gal LHV	57000
	lb/gal	6.60
	kg/gal	2.996
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

References

1. Refinement of Selected Fuel-Cycle Emissions Analyses, Vol. 1 Final Report, Dec 2000
Prepared for CARB and SCAQMD, FR-00-101 by Arthur D. Little

APPENDIX Module T8 Methanol Transport, Marine

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Methanol	142,500	DWT	6.07E+06	1.0000
Other Inputs				
Bunker Fuel	3,847,500	kg (round trip)	1.64E+05	0.0270
Diesel	2,243	gal (In-port)	3.03E+02	0.0000
Total				1.0270

OUTPUTS FROM MODULE				
Primary Products:				
Methanol	142,500	DWT	6.07E+06	1.0000
Secondary Products				
None				
Total				1.0000
Module Efficiency, GJ-output/GJ-input				97.37%

INPUT PARAMETERS		
Bunker Fuel		
Tanker Fuel Consumption	kg/ton-mi	0.0018
Average One-way Trip Distance	mi	7500
Bunker Fuel	Btu/kg	40350
Tanker Load Efficiency		0.95
Diesel		
In-port use factor	kg/DWT	0.051
Energy Content	Btu/gal, LHV	128000
Diesel Density	kg/gal	3.24
Methanol		
	Btu/gal LHV	57000
	lb/gal	6.60
	kg/gal	2.996

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environemntal

APPENDIX Module T9 Corn Transport, Truck

		Units	LHV, GJ	GJ/GJ primary product
INPUTS TO MODULE				
Input Fuel				
Corn-ethanol	1.00	Bushel	0.414	1.00
Other Inputs				
Energy Use forTransportation	4,897	Btu	0.005	0.012
Total				1.012

OUTPUTS FROM MODULE				
Primary Products:				
Corn-ethanol	1.00	Bushel	0.414	1.00
Secondary Products				
None				
Total			0.414	1.000
Module Efficiency, GJ-output/GJ-input				98.8%

Input Parameters		LHV
Ethanol yield	2.65	gal/bushel
Ethanol	76,000	Btu/gal
Corn	7,000	Btu/lb
	56	lb/Bushel
Corn Stover	95	gal/BDT
Conversion	947817	Btu/GJ
Conversion	278	kWh/GJ

References

1. Greet 1.5 - Transportation Fuel-Cycle Module, Vol. 1, Aug, 1999
ANL Transportation TEchnology R&D CEnter, ANL/ESD-39
2. ADL industry experience

APPENDIX Module T10 Ethanol Transport, Marine

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Ethanol	142,500	DWT	3.61E+06	1.000
Other Inputs				
Bunker Fuel	1,795,500	kg (round trip)	7.64E+04	0.021
Diesel	2,243	gal (In-port)	3.03E+02	0.000
Total				1.021

OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	142,500	DWT	3.61E+06	1.000
Secondary Products				
None				
Total				1.000
Module Efficiency, GJ-output/GJ-input				97.92%

INPUT PARAMETERS		
Bunker Fuel		
Tanker Fuel Consumption	kg/ton-mi	0.0018
Average One-way Trip Distance	mi	3500
Bunker Fuel	Btu/kg	40350
Tanker Load Efficiency		0.95
Diesel		
In-port use factor	kg/DWT	0.051
Energy Content	Btu/gal, LHV	128000
Diesel Density	kg/gal	3.24
Ethanol		
Heat Content	Btu/gal LHV	76000
Density	kg/gal	2.996
Density	lb/gal	6.60

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environemntal

APPENDIX Module T11 Ethanol Transport, Truck

		Units	LHV, GJ	J/MJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Ethanol	7,800	gal	625	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.004
Total				1.004

OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	7,800	gal	625	1.000
Secondary Products				
Total				1.000
Module Thermal Efficiency				99.6%

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Ethanol	Btu/gal, LHV	76000
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996 Prepared for CARB by Acurex Environmental

APPENDIX Module T12 Ethanol Transport, Train

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Throughput Fuel/Feedstock				
Ethanol	30,000	gal	2,405	1.000
Process Fuels				
Diesel	53.57	gal (round trip)	7	0.003
Total				1.003

OUTPUTS FROM MODULE				
Primary Products:				
Ethanol	30,000	gal	2,405	1.000
Secondary Products				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.7%

INPUT PARAMETERS		
Average Train Fuel Usage	gal/1000-ton mi	87.2
Average One-way Trip Distance	mi	500
Ethanol Transport Factor		0.25
Ethanol	Btu/gal, LHV	76000
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Evaluation of Fuel-Cycle Emissions on a REactivity Basis, Vol. 1, Main Report, Sep 1996
Prepared for CARB by Acurex Environmental

APPENDIX Module T13 Diesel Transport, Truck

		Units	LHV, GJ	GJ/GJprimary product delivered
INPUTS TO MODULE				
Input Fuel				
Diesel	7,800	gal	1,053	1.000
Other Inputs				
Diesel	20.00	gal (round trip)	3	0.003
Total				1.003

OUTPUTS FROM MODULE				
Primary Products:				
Diesel	7,800	gal	1,053	1.000
Secondary Products				
None				
Total				1.000
Module Efficiency, GJ-output/GJ-input				99.7%

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	5
Average One-way Trip Distance	mi	50
Gasoline	Btu/gal LHV	115500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES	
1. Evaluation of Fuel-Cycle Emissions on a Reactivity Basis, Vol. 1, Main Report, Sep 1996	
Prepared for CARB by Acurex Environmental	
Other Studies, MTE	
GREET, LHV	98.6%

APPENDIX Module T14 Biomass Transport, Truck

		Units	LHV, Btu	LHV, kJ	J/MJprimary product delivered
INPUTS TO MODULE					
Input Fuel					
Forest Material (chipped)	1	BDT	8,500	8,968	1,000,000
Other Inputs					
Diesel	1.57	gal/BDT (round trip)	201,143	212,206	23,663,866
Total			209,643		24,663,866
OUTPUTS FROM MODULE					
Primary Products:					
Ethanol	1	BDT	8,500	8,968	1,000,000
Secondary Products					
None					
Total					1,000,000

INPUT PARAMETERS		
Average Truck Fuel Usage	mi/gal	4
One way distance for 40 mill gal plant	mi/trip	44
Mass	BDT/truck	14
Forest Material (chipped)	Btu/BDT, LHV	8500
Diesel	Btu/gal LHV	128000
	lb/gal	7.14
	kg/gal	3.24

REFERENCES

1. Costs and Benefits of Biomass-to-Ethanol Production Industry in California, ADL report to the California Energy Commission, March 2001

COMMENTS

1. One way distance is the average travel for a plant with biomass available within a 50 mile radius Reference 1 estimated costs at $9-19/BDT ($50-55 per hour of travel)

Other Studies, MTE		
GREET, LHV	308,400	gal diesel/BDT

APPENDIX Module T19 Power Transmission

		Units	LHV, GJ	GJ/GJ, primary fuel
INPUTS TO MODULE				
Input Fuel				
Electriciy	1.0000	kWh	0.004	1.053
Other Inputs				
Total				
OUTPUTS FROM MODULE				
Primary Products:				
Electricity	0.9500	kWh	0.003	1.000
Secondary Products				
None				
Total				
Module Thermal Efficiency				95.00%

INPUT PARAMETERS		
Conversion	GJ/kWh	0.0036