CHAPTER FOUR

PRIORITIES FOR TECHNOLOGY INVESTMENT

INTRODUCTION

Technology is one of the most important factors that can enable the introduction of new fuel-vehicle systems to improve transportation economics and energy security, and reduce greenhouse gas emissions. In recent years, new vehicle and fuel technologies have entered the market or have started to show potential for market introduction in the transportation sector. This chapter includes an analysis of such technologies for light-duty vehicles, heavy-duty vehicles, and alternative fuels (advanced biofuels, electricity, natural gas, and hydrogen) sectors.

Over 250 hurdles, both technical and nontechnical, were identified and evaluated, which represent barriers to the widespread commercialization of alternative fuel-vehicle systems or improvements to existing fuel-vehicle systems. This chapter focuses only on the technical hurdles. Overcoming these technology hurdles will require continued cooperation, investment, and support from government and industry.

The analysis identified twelve priority technology hurdles, which are the primary focus of this chapter. This chapter describes the priority technology hurdles, the challenges to overcoming each hurdle, and the opportunities enabled by overcoming the hurdles. Additionally, this chapter provides recommendations on the next steps for addressing the priority technology hurdles. The twelve priority technology hurdles identified in this study are shown in Table 4-1.

If there is sustained research and development (R&D) focused on resolving the priority technology hurdles, and transition hurdles are overcome, then there are circumstances when all of the fuel-vehicle systems can compete on total cost of driving basis. Figure 4-1 shows improvements in cost of driving between 2015 and 2050 for light-duty fuel-vehicle systems evaluated in this study through the resolution of priority technology hurdles.

Although not required for wide-scale commercialization, *disruptive innovations*[1] can provide an advantage to some relevant fuel-vehicle systems. Disruptive innovations have not been considered in the range of estimates for the cost of driving because they are early stage technologies with high uncertainty. It can take decades for a disruptive innovation to move through basic research, applied research, production engineering, and finally production. This chapter highlights a small sub-set of possible disruptive innovations.

This chapter focuses on describing the priority technology hurdles. Challenges associated with making fuels available to the transportation market are discussed in more detail in Chapter Five, "Infrastructure." The fuel-vehicle systems chapters describe the relevant hurdles to each system, both technology and nontechnology.

This chapter is structured as follows:

- Explanation of the technology analysis methodology
- Results of the analysis: the twelve priority technology hurdles followed by a detailed description and recommendations

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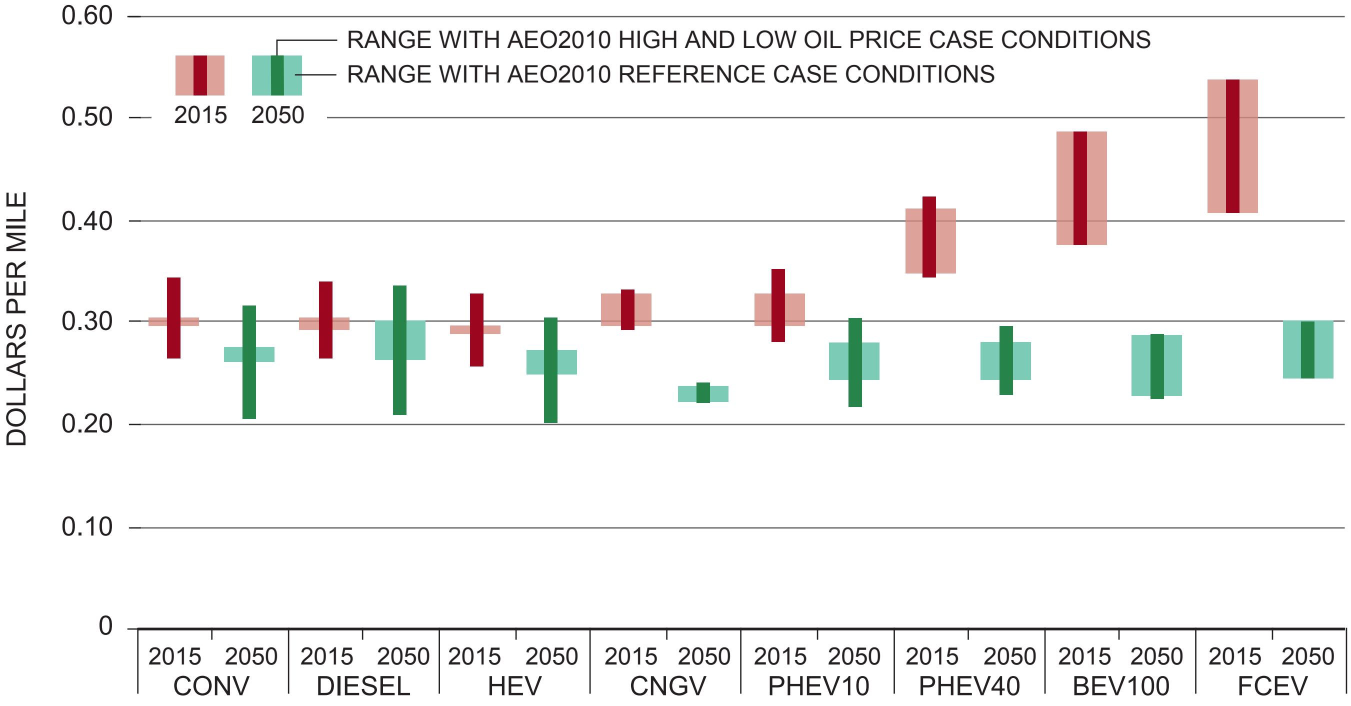
[1] Innovations that improve a product or service in ways that the market does not expect. Disruptive innovation is sometimes contrasted with the concept of continuous improvement, which focuses on achieving small, incremental changes in processes in order to improve efficiency and quality.

Light-Duty Engines and Vehicles	
Low-cost lightweighting (up to 30% mass replacement)	Low-cost lightweighting is the replacement of traditional steel in vehicles with much lighter materials in a way that is fully integrated into the original equipment manufacturers' operating models. Resolving this hurdle would mean wide-scale availability of vehicles that are 20–30% lighter than comparable vehicles today. Low-cost lightweighting can be leveraged by all vehicle types: internal combustion engines (ICEs), battery electric vehicles, plug-in hybrid electric vehicles, fuel cell electric vehicles, and compressed natural gas vehicles.
Biofuels	
Hydrolysis	Reduce the volume of enzymes required or advancement of chemical hydrolysis to break down pretreated lignocellulosic materials into component sugars.
Fermentation of C5 and C6 sugars	Develop microbes that can simultaneously ferment C5 and C6 sugars. Yeasts commonly used in corn ethanol production are able to ferment 6 carbon sugars, but fermenting 5 carbon sugars is critical to the economic viability of cellulosic ethanol.
Lignocellulose logistics/ densification	Improve economics of transportation and long-term storage of localized biomass to increase scale of biomass conversion plants
Production of higher-quality pyrolysis oil	Improve bio-oil quality and stability. Raw bio-oil contains potential impurities such as alkali metal, chlorine, nitrogen, and sulfur that could poison hydrotreating catalysts and limit long-term activity, stability, and lifetime of the catalyst.
Biotechnology to increase food and biomass	Continue to increase yield and productivity of land to enable both food and fuel needs to be met.
Light-Duty Compressed Natural Gas	
Leverage liquid ICE fuel economy technology	Incorporate gasoline powertrain and platform technology in compressed natural gas (CNG) light-duty vehicles for enhanced fuel economy. To date, no purpose built CNG vehicle has been developed. If this hurdle is overcome, the vehicle premium of CNG vehicles over ICE vehicles could be reduced through improved fuel economy and reduction in fuel storage requirements.
Light-Duty Electric	
Lithium-ion battery energy density	Increase the amount of stored energy per unit mass and/or volume. The energy density of lithium-ion chemistries (in today's newest mass-market models, they deliver a range of less than 100 miles) is still much lower than liquid fuels (which can travel more than 300 miles on a full tank for a similar type vehicle). Improvements in energy density could be used to reduce the cost of the vehicle and/or increase the driving range.
Lithium-ion battery degradation and longevity	Increase both the calendar life (life of the vehicle) and cycle life (how many times the battery can be charged and discharged). Resolving this technology hurdle means that the degradation that will occur in the battery will not impact the customer for the life of the vehicle, regardless of charging cycle.
Light-Duty Hydrogen	
Compression and storage for dispensing	Reduce land, maintenance, and capital requirements for compression and storage of hydrogen at a fueling station, so that dispensing capability can be added to existing fueling facilities. The land, maintenance, and capital required to compress hydrogen to 350 and 700 bar can be significant and operationally challenging. A typical hydrogen compression system for fueling requires ~100 square feet of land at a fueling station, and it should be located where sound is either not a concern or where it can be buffered. The cost of a compression system can range from 20% to 50% of the total cost of hydrogen fueling infrastructure at a fueling location. Traditional steel tube storage system with 300 kg storage capacity occupies ~450 square feet of land, not including setback requirements which vary based on site specifics (less than 5 feet to 30 feet for gaseous and 50 feet for liquid hydrogen). The cost of storage represents ~25% of the total capital required for a hydrogen fueling site.
Fuel cell degradation and durability	Improve fuel cell to last the life of the vehicle. Fuel cells need to last the life of the vehicle, without degradation impacting the customer.
Medium-/Heavy-Duty Engines and Vehicles	
Combustion optimization	Improve engine combustion efficiency addressing challenges in four key areas: in-cylinder pressure & fuel injection; gas exchange; emerging compression ignition technologies (e.g., low-temperature combustion technologies such as homogeneous charge compression ignition, premixed charge compression ignition, and reactivity controlled compression ignition); and friction reduction.

Table 4-1. *Twelve Priority Technology Hurdles*



Notes: Biofuels assumed to have the same cost of gasoline, so biofuel blend would be at the same price as the conventional gasoline.

Figure 4-1. *Cost of Driving Estimates for Small Cars, Assuming Technology Hurdles are Resolved*

- Benefits (in terms of cost of driving and greenhouse gas [GHG] reduction) of investing in the priority technology hurdles
- Short discussions on disruptive innovations that could impact the competitiveness of the relevant fuel-vehicle systems.

METHODOLOGY

The cornerstone of the technical analysis was the identification of current technology hurdles for each fuel-vehicle system. Technology hurdles are defined as challenges, requirements, or barriers that may prevent advances in fuels or vehicle systems from reaching wide-scale commercialization. They can be technical or non-technical.

A rigorous evaluation considered the functionality, cost, scalability, materiality, and acceleration of technology deployment of 250 technical and non-technical hurdles. Substantial effort was made to ensure consistency in the assessment of the levels of difficulty for overcoming each hurdle. Expert assessments were also conducted to review:

- Technology scope and team expertise
- Analysis of technology hurdles
- Prioritization of the technology hurdles.

The evaluation first considered degrees of difficulty in achieving wide-scale commercialization, prioritization, and critical path analysis of the hurdles within each fuel-vehicle system. This was followed by comparing only the technical hurdles across fuel-vehicle systems that are the focus of this chapter.

Expert Review Process and Study Briefings

To ensure that the technology analysis was comprehensive and robust, leading scientists and economists were recruited to be expert reviewers. This team of experts (shown in Table 4-2) evaluated the following:

- Breadth of the fuel-vehicle systems considered

Content Area	Name	Organization
Energy Security and Policy (Chair)	John Deutch	MIT
Agriculture — Biofuels	Robert Fraley	Monsanto
Applied Physics and Policy	Venkatesh Narayanamurti	Harvard University
Batteries/Electrochemistry	Yet-Ming Chiang	MIT
Biotechnology	Jay Keasling	UC Berkeley
Cryogenic Storage	Tom Drube	Chart Industries
Economics/Policy	Robert Topel	University of Chicago
Economics/Policy	Severin Borenstein	UC Berkeley
Energy Efficiency	Amory Lovins	Rocky Mountain Institute
Engines	John Heywood	MIT
Engines	Robert Dibble	UC Berkeley
Hydrogen/Fuel Cells	Henry White	University of Utah
Materials Science/Nanotechnology	George Whitesides	Harvard University
Solar Fuels	Daniel Nocera	MIT

Table 4-2. *Expert Review Panel*

- Aggressiveness of the accelerated case
- Quality of the data, assumptions, and analysis
- Normalization and assessment of the relative difficulty of overcoming the technology hurdles.

Three expert peer reviews were conducted, each of which had the following objectives:

Peer Review 1: Base data, team, and source review (December 3, 2010)

- Check the credibility and comprehensiveness of the data set used as a basis for the analysis
- Identify gaps, other sources, or other experts who should provide input into the subgroups
- Validate baseline data, technical assumptions, and evolution
- Confirm technical scope, simplifying assumptions, and exclusions.

Peer Review 2: Technology hurdles and chapter review (March 9, 2011)

- Highlight technology assumptions and highlight inconsistencies across subgroups
- Review the analysis of technology hurdles
- Evaluate methodology for normalization of hurdles across fuel-vehicle systems
- Provide initial feedback on the individual fuel-vehicle system chapters.

Peer Review 3: Review of priority technology hurdles (October 25, 2011)

- Review prioritization of technology hurdles
- Review specific technology priorities
- Verify that the right technology hurdles have been identified
- Discuss approach to integrated analysis.

In addition to the expert review process, study briefings on major studies and activities were organized for the study team. The study briefings are listed in Table 4-3.

Evaluation of Technology Hurdles

All technology hurdles were evaluated to determine which would have the greatest impact for wide-scale commercialization of the fuels and

Briefing Topic	Sponsoring Organization
Vehicle Technologies	
Plug-in Electric Vehicle Pilots	Accenture
Carbon Fiber for Vehicles	BMW/SGL Automotive Group
Vehicle Electrification	General Motors
Light-Duty Vehicle Technologies	National Academies
Medium- and Heavy-Duty Vehicles	SAE International
Fuel Technologies	
Biofuels/Artificial Photosynthesis	ANSER Solar Energy Research Center
Advanced Biofuels	Defense Advanced Research Projects Agency
Advanced Biofuels	Iowa State University
Future of Natural Gas	Massachusetts Institute of Technology
Alternative Liquid Transportation Fuels	National Academies
Hydrogen, Biofuels, Advanced ICEs/HEVs/PHEVs	National Academies
Coal and Fuels Program	National Energy Technology Laboratory
XTL Technologies (e.g., coal-to-liquid)	Noblis/Pennsylvania State University
Biomass	U.S. Department of Energy
Fuel and Lubricant Technologies	U.S. Department of Energy
Fuel Cell Technologies	U.S. Department of Energy
Renewable Natural Gas	U.S. Department of Energy
Environment and Efficiency	
Potential Transportation Energy Efficiency	Carnegie Mellon University
Light-Duty Vehicle GHG Technical Activities	Environmental Protection Agency
U.S. Drive (formerly FreedomCAR)	National Academies
Reducing GHG Emissions from U.S. Transportation	Pew Center on Global Climate Change
Transportation Options for Reducing GHG Emissions	Precourt Institute of Energy
Infrastructure and Investment	
Transportation Fuel Technology Investment	Advanced Research Projects Agency – Energy
Visualizing U.S. Urbanization and Transportation Trends	Toyota Research Institute
Clean Cities	U.S. Department of Energy
Electric Vehicle Infrastructure Initiatives	U.S. Department of Energy
Hybrid/Electric Systems R&D Investment	U.S. Department of Energy
Vehicle Miles Traveled Projections	U.S. Department of Transportation

Table 4-3. *Study Briefings*

vehicles systems reviewed in this study. There were four steps in the methodology used to finalize the priority technology hurdles (see Figure 4-2):

1. HURDLE IDENTIFICATION

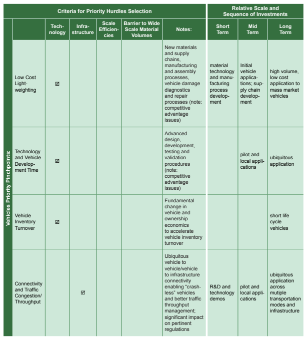
> 250
TECHNOLOGY AND NON-TECHNOLOGY HURDLES

2. DOWN SELECTION

~30
TECHNOLOGY PRIORITIES

- Technology improvement needed to realize performance
- Technology improvement required to attain acceptable cost
- Technology improvement that would accelerate deployment
- Fuel dispensing infrastructure, how the hurdle supports infrastructure development
- How the hurdle can enable scaling to material volumes

3. CRITICAL PATH



		Criteria for Priority Hurdles Selection					Relative Scale and Sequence of Investments		
		Tech-nology	Infra-structure	Scale Efficien-cies	Barrier to Wide Scale Material Volumes	Notes:	Short Term	Mid Term	Long Term
Vehicles Priority Pinchpoints:	Low Cost Light-weighting	☑				New materials and supply chains, manufacturing and assembly processes, vehicle damage diagnostics and repair processes (note: competitive advantage issues)	material technology and manufacturing process development	Initial vehicle applications; supply chain development	high volume, low cost application to mass market vehicles
	Technology and Vehicle Development Time	☑				Advanced design, development, testing and validation procedures (note: competitive advantage issues)		pilot and local applications	ubiquitous application
	Vehicle Inventory Turnover	☑				Fundamental change in vehicle and ownership economics to accelerate vehicle inventory turnover			short life cycle vehicles
	Connectivity and Traffic Congestion/ Throughput		☑			Ubiquitous vehicle to vehicle/vehicle to infrastructure connectivity enabling "crash-less" vehicles and better traffic throughput management; significant impact on pertinent regulations	R&D and technology demos	pilot and local applications	ubiquitous application across mutiple transportation modes and infrastructure

~20
TECHNOLOGY PRIORITIES

4A. LIGHT-DUTY GO/NO-GO ANALYSIS

11
TECHNOLOGY PRIORITIES

Can the technology achieve wide-scale material volumes if this technology hurdle is not resolved?

4B. MEDIUM-/HEAVY-DUTY COST/BENEFIT

1
TECHNOLOGY PRIORITY

Figure 4-2. *Technology Prioritization Methodology*

1. Hurdle Identification – review and assign a normalized difficulty rating to technical and non-technical hurdles for each fuel-vehicle system.
2. Down Selection – identify the most important technology hurdles for each fuel-vehicle system.
3. Critical Path – determine the critical path for technology hurdle resolution because some hurdles are contingent upon the resolution of others.

4a. Light-Duty Sector Go/No-Go Analysis – determine if a fuel-vehicle system is dependent on a single hurdle to achieve wide-scale commercialization.

4b. Medium- and Heavy-Duty Sector Cost/Benefit Analysis – determine which technology hurdles were the most important from a cost/benefit perspective.

Step 1: Hurdle Identification (250 Hurdles)

The 250 hurdles identified in the fuel-vehicle system chapters were reviewed and assigned a normalized rating that reflects the challenge or level of difficulty each presented. The difficulty assignment reflects the *current state of the hurdle* and is not an estimate of where a hurdle may be at some point in the future.

The study used difficulty rating definitions similar to the Department of Energy (DOE) Technology Readiness Levels based on the maturity of the technologies:

- **RED** ranges from Basic Research to Technology Demonstration. These hurdles require invention or have high uncertainty.
- **YELLOW** ranges from Technology Development to Technology Demonstration. For these hurdles, a pathway for success has been demonstrated and significantly tested, but sustained effort is required to achieve wide-scale commercialization.
- **BLUE** represents systems commissioning or operational. These hurdles have minimal or no barriers to wide-scale commercialization.

Step 2: Down Selection (30 Hurdles)

The prioritization of each technology hurdle is a reflection of its importance in enabling wide-scale commercialization of the corresponding technology. Technology hurdles were down selected for each fuel-vehicle system based on advances needed to:

- Realize performance
- Attain acceptable cost
- Accelerate deployment
- Scale to material volumes
- Facilitate fuel-dispensing infrastructure.

Step 3: Critical Path (20 Hurdles)

The critical path for the resolutions of the down selected hurdles was then mapped (i.e., gateways and deliverables, short term, medium term, and long term, were identified and sequenced). In some cases, if an earlier sequence technology hurdle could not be solved, then other technology hurdles that depend upon overcoming the first would not be pursued.

Step 4a: Light-Duty Sector Go/No-Go Analysis (11 Hurdles)

The final step for the light-duty vehicle hurdles was to ask the question, "If this technology hurdle is not resolved, would the fuel and vehicle system be able to reach wide commercialization another way?" If the answer was "NO," then not resolving this single technology hurdle could prevent wide-scale commercialization. For example, if hydrogen refueling compression and storage are not solved, then hydrogen will not achieve wide commercialization.

Step 4b: Medium- and Heavy-Duty Sector Cost/Benefit Analysis (1 Hurdle)

The final step in narrowing the technology priorities for medium-duty (Class 3-6) and heavy-duty (Class 7&8) fuel-vehicle systems was to prioritize the technology hurdles. The technology hurdles that were more attractive from a cost/benefit perspective were assigned higher priority than hurdles with lower cost/benefit attractiveness.

RESULTS AND DISCUSSION

Step 1: Hurdle Identification

Each fuel-vehicle system chapter provides a broad assessment of the technology and nontechnology hurdles across its supply chain, with the most important hurdles explained in detail. Although the assessment of very different technologies results in hurdles specific to a fuel-vehicle system, there are some hurdles that are common across natural gas, electricity, and hydrogen. The hurdle chart for electric vehicles is illustrated in Figure 4-3, and similar information for the other fuel-vehicle systems is in Appendix 4B, "Hurdle Charts."

Significant effort was made to normalize the assessment of >250 hurdles across the fuel-vehicle systems. The Technology Task Group, composed of the Assistant Chairs of all the technology groups, reviewed the rating of all of the hurdles as a group. The normalization activity is described in the detailed methodology document Appendix 4A, "Approach to Technology Analysis," at the end of this chapter.

Step 2: Down Selection

The 250 hurdles identified were down selected to ~30 technology hurdles, which are highlighted in figures in Appendix 4B as "Priority Focus Area."

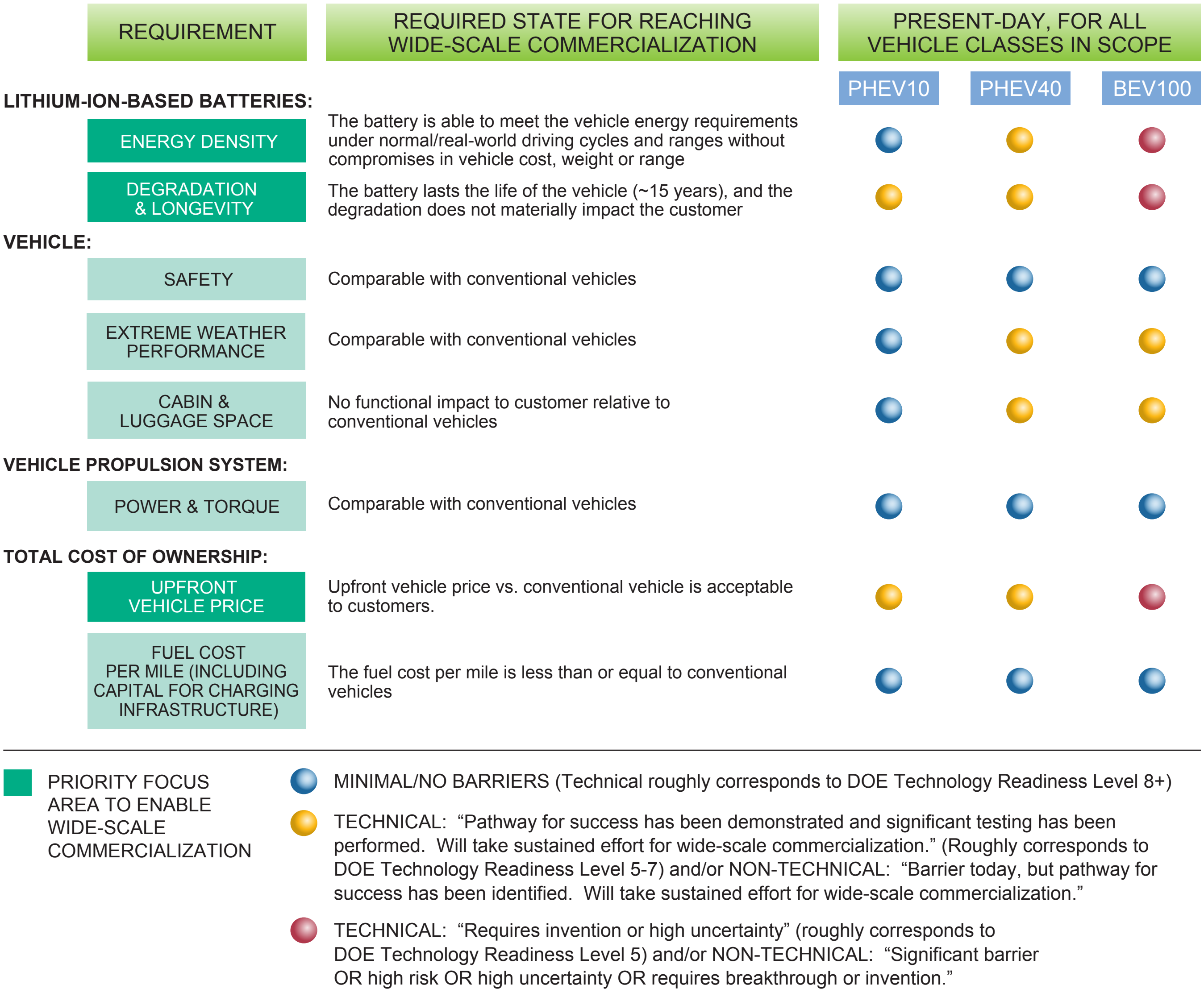
Step 3: Critical Path

The analysis further narrowed the number of technology hurdles from ~30 to 20 critical path hurdles. The critical path analysis identified the sequence in which down selected hurdles should be addressed (short term, medium term, and long term). The evaluation methodology for light-duty compressed natural gas (CNG) vehicles is illustrated in Table 4-4, and similar information for the other fuel-vehicle systems is in Appendix 4C.

A brief discussion of the critical path assessment for each fuel-vehicle system is provided below. Table 4-5 lists the 20 short-term critical path hurdles across all of the fuel-vehicle systems.

Light-Duty Engines and Vehicles Critical Path

The engines and vehicles hurdle chart is split into powertrain, vehicle, fuel, industry model, and



REQUIREMENT	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	PRESENT-DAY, FOR ALL VEHICLE CLASSES IN SCOPE		
		PHEV10	PHEV40	BEV100
LITHIUM-ION-BASED BATTERIES:				
🟩 ENERGY DENSITY	The battery is able to meet the vehicle energy requirements under normal/real-world driving cycles and ranges without compromises in vehicle cost, weight or range	🔵	🟡	🔴
🟩 DEGRADATION & LONGEVITY	The battery lasts the life of the vehicle (~15 years), and the degradation does not materially impact the customer	🟡	🟡	🔴
VEHICLE:				
SAFETY	Comparable with conventional vehicles	🔵	🔵	🔵
EXTREME WEATHER PERFORMANCE	Comparable with conventional vehicles	🔵	🟡	🟡
CABIN & LUGGAGE SPACE	No functional impact to customer relative to conventional vehicles	🔵	🟡	🟡
VEHICLE PROPULSION SYSTEM:				
POWER & TORQUE	Comparable with conventional vehicles	🔵	🔵	🔵
TOTAL COST OF OWNERSHIP:				
🟩 UPFRONT VEHICLE PRICE	Upfront vehicle price vs. conventional vehicle is acceptable to customers.	🟡	🟡	🔴
FUEL COST PER MILE (INCLUDING CAPITAL FOR CHARGING INFRASTRUCTURE)	The fuel cost per mile is less than or equal to conventional vehicles	🔵	🔵	🔵

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS (Technical roughly corresponds to DOE Technology Readiness Level 8+)

🟡 TECHNICAL: "Pathway for success has been demonstrated and significant testing has been performed. Will take sustained effort for wide-scale commercialization." (Roughly corresponds to DOE Technology Readiness Level 5-7) and/or NON-TECHNICAL: "Barrier today, but pathway for success has been identified. Will take sustained effort for wide-scale commercialization."

🔴 TECHNICAL: "Requires invention or high uncertainty" (roughly corresponds to DOE Technology Readiness Level 5) and/or NON-TECHNICAL: "Significant barrier OR high risk OR high uncertainty OR requires breakthrough or invention."

Figure 4-3. *Vehicle Requirements for the Wide-Scale Adoption of Grid-Connected Vehicles*

mobility model hurdles. In these five categories, there are over 20 hurdles. Based on the down selection criteria described previously, four hurdles were identified: low-cost lightweighting, technology and vehicle development time, vehicle inventory turnover, and connectivity and traffic congestion/throughput. The critical path analysis of these hurdles narrows them to one technology hurdle, which is to focus on achieving low-cost lightweighting.

Biofuels Critical Path

Biofuels has the largest diversity of technology hurdles. The technical analysis reviewed feedstocks, biochemical processes, thermochemical processes, algae, and distribution. Of the over 150 hurdles identified, the down selection and critical path processes resulted in six technology hurdles. Three priority technology hurdles relate to using lignocellulose in a biochemical process: hydrolysis, fermentation of C5/C6 sugars, and densification. Two priority technology hurdles use lignocelluloses in a thermochemical process: pyrolysis and gasification. The final technology hurdle is related to the feedstock availability: biotechnology to increase food and biomass.

Natural Gas Critical Path

No substantive technology impediments for commercializing natural gas were identified.

Criteria for Priority Hurdle Selection							Critical Path / Timing		
		Technology That Reduces Cost	Ease Infrastructure Development	Drive-Scale Efficiencies	Wide-Scale Material Volumes	Notes:	Near Term	Medium Term	Long Term
Vehicles Priority Hurdles	**Full OEM Production**			☑		Plant investments to retool for natural gas engines and vehicles	Support for full OEM production of vehicles – move away from retrofit		
	Increased Engine & Vehicle Option Availability				☑	Broader range of engines required to fulfill market requirements and avoid perception that NG engines are low power/low torque	Engineering demonstration	Product line integration	Product line integration
	Advanced Fuel Economy Potential	☑			☑	R&D and demonstration of NG long-term technology compatibility with heavy truck fuel economy technology	Engineering demonstration	Product line integration	Product line integration
	Natural Gas Optimized Engine Designs	☑				Including combustion systems to avoid need for diesel particulate filters with Compression Ignition NG engines	Combustion optimization	Engineering demonstration	Product line integration
Fuels Priority Hurdles	**Fuel Station Availability**		☑			Limited infrastructure today. Growing but pace of acceleration is key to market growth	Investment in refueling to support major freight corridors	Infrastructure expansion to support broader markets	
	LNG Liquefaction Capacity Expansion				☑	Expanded availability of LNG required, primarily through new liquefaction plants	Investment to support fuel throughput		
	Small-Scale Liquefaction	☑				Cost reduction of small-scale liquefaction systems to support fuel availability	Engineering demonstration	Deployment scale up	

Table 4-4. *Critical Path Analysis for CNG Vehicles*

	Technology	Difficulty (Hurdle)
Light-Duty Vehicle Technology	Mass-market lightweighting	RED
Electric	Battery energy density	RED
	Battery degradation and longevity	RED
	Refuel time (time required to charge battery)	RED
Biofuels	Biotechnology to increase food and biomass	BLUE
	Biochemical hydrolysis	YELLOW
	Fermentation of C5 and C6 sugars	YELLOW
	Gasification clean up and conditioning	YELLOW
	Upgrading of pyrolysis oil	RED
	Lignocellulose logistics/densification	YELLOW
Natural Gas	Direct injection for light-duty CNG vehicles	RED
	Incorporating gasoline powertrain and platform technologies in CNG light-duty vehicles for enhanced fuel economy	YELLOW
	Incorporating gasoline powertrain and platform technologies in CNG heavy-duty vehicles for enhanced fuel economy	YELLOW
	Heavy-duty vehicle natural gas optimized engine design	YELLOW
	Small-scale liquefaction for heavy-duty LNG	YELLOW
Hydrogen/Fuel Cell	Hydrogen compression and storage technology	RED
	Fuel cell degradation and durability	YELLOW
Medium-/Heavy-Duty Vehicle Technology	Diesel combustion optimization for heavy-duty vehicles	YELLOW
	Hybrid battery costs for heavy-duty vehicles	RED
	Advanced gasoline engines for heavy-duty vehicles	YELLOW

🟥 RED hurdles range from basic research to technology demonstration. These hurdles require invention or have high uncertainty.

🟨 YELLOW hurdles range from technology development to demonstration. A pathway for success has been demonstrated and tested but sustained effort is required to achieve wide-scale material volumes.

🟦 BLUE hurdles range from systems commissioning to operational. These hurdles have minimal or no barriers to wide-scale material volumes.

Table 4-5. *Critical Path Technology Hurdles*

There are three hurdle charts for natural gas fuel-vehicle systems: natural gas supply and infrastructure, light-duty natural gas vehicles, and medium-/heavy-duty natural gas vehicles. Although across these charts there are over 60 hurdles, the majority of these are not technology related. However, there are opportunities to advance certain technology hurdles.

In the light-duty sector, the technology priorities on the critical path are incorporating new gasoline powertrain and platform technologies in CNG light-duty vehicles for enhanced fuel economy and CNG direct injection.

In the medium-/heavy-duty sector, the technology priorities on the short-term critical path are incorporating gasoline and diesel powertrain and platform technologies in vehicles for enhanced fuel economy, as well as natural gas optimized engine design (i.e., leveraging combustion optimization technologies in medium- and heavy-duty vehicle diesel), and small-scale liquefaction.

Electricity Critical Path

There are two hurdle charts for electric fuel-vehicle systems: vehicle and infrastructure. Across both charts, over 20 hurdles have been identified. Of those hurdles, three short-term hurdles were identified from the down selection and critical path processes: lithium-ion energy density, lithium-ion longevity, and refuel time.

Hydrogen Critical Path

There are two hurdle charts for hydrogen fuel-vehicle systems: fuel cell electric vehicle and hydrogen supply & infrastructure. Across both charts, over 25 hurdles have been identified. Of those hurdles, two short-term hurdles were identified from the down selection and critical path processes: fuel cell durability and compression & storage for fuel dispensing.

Heavy-Duty Critical Path

The heavy-duty hurdle chart is split into engines, vehicles, and fleet operations technology. In these three categories, there are over 15 hurdles. Based on the down selection and critical path processes described previously, three hurdles were identified: combustion optimization, batteries for hybrids, and advanced gasoline engines.

Step 4a: Light-Duty Go/No-Go Analysis

The go/no-go analysis reduced the light-duty priority hurdles from 14 to 11 as shown in Table 4-6. Resolution of these 11 technology hurdles is required for the fuel-vehicle systems under review to remain in the portfolio of future fueling options, or, as in the case of lightweighting, represents a key technology path for all systems.

If the hurdle is not resolved, there will be no pathway (Go/No-Go)	**Pathway could still succeed even if hurdle is not resolved (i.e., there may be other ways to work around this hurdle, commerciality still possible)**
• Battery energy density • Battery longevity • Incorporating gasoline powertrain and platform technologies in CNG light-duty vehicles for enhanced fuel economy • Hydrogen compression and storage technology • Fuel cell durability • Low-cost lightweighting* • Biotechnology to increase food and biomass • Biochemical hydrolysis[†] • Fermentation of C5 and C6 sugars[†] • Lignocellulose logistics/densification[†] • Upgrading of pyrolysis oil[†]	• Refuel time (time required to charge battery) • Gasification clean up and conditioning • Direct injection for light-duty CNG vehicles

Note: Chart excludes heavy-duty hurdles.

* Low-cost lightweighting is not Go/No-Go but benefits all pathways.

[†] For lignocellulosic, pathway depends on solving all three hurdles—biochemical hydrolysis, fermentation of C5 and C6 sugars, and densification OR upgrading of pyrolysis oil.

Table 4-6. *Go/No-Go Analysis*

Step 4b: Medium- and Heavy-Duty Cost/Benefit Analysis

The cost/benefit analysis reduced the medium- and heavy-duty sector hurdles from 3 to 1: combustion optimization.

This resulted in 12 priority technology hurdles for all of the fuel-vehicle systems considered in the study.

Twelve Priority Technology Hurdles

This section provides more information on the twelve priority technology hurdles identified in Table 4-1 and described in this section. Recommendations are provided for resolving the challenges for each priority technology hurdle.

The individual fuel-vehicle system chapters address these hurdles extensively. This section leverages the discussion in those chapters, focusing on hurdle analysis and recommendations.

Light-Duty Vehicles: Low-Cost Lightweighting

Current hurdle assessment (difficulty in resolving): RED

The technology analysis showed that lightweighting can improve the competitiveness of all vehicle technology platforms if available at the lower end of the range of estimated costs. However, lightweighting requires significant changes to original equipment manufacturers (OEM) supply chains and operating models, and lighter weight materials are still relatively expensive.

It is well demonstrated that vehicle mass has a major impact on fuel consumption, but mass reduction to reduce the weight of vehicles is a complex undertaking. Vehicle design factors that impact mass include structural stiffness (noise/vibration/harshness), safety, comfort (space), manufacturing investment and throughput, and material cost. Vehicle subsystems that comprise a majority of a vehicle's mass are body structure, body non-structural (interior seating, trim, and glass), closures, bumpers, powertrain, and chassis. Typical mass distribution of subsystems and material is shown in Figures 4-4 and 4-5. Materials that are major components of the mass include plastics and aluminum, but iron and steel (mild and high strength) comprise the majority of mass.

If components or subsystems can be lightweighted early in the vehicle design and development process, then other vehicle systems can be lightweighted as result of the primary mass reduction. This feedback/feedforward process is called mass decompounding and can result in vehicle performance and fuel economy improvement. Introduction of clean sheet vehicle designs are required to take full advantage of mass decompounding. An analysis based on the results of reports by Malen in 2007[2] and Vebrugge in 2009[3] and estimates that for every 1 kg of primary mass removed early in the vehicle design, an additional 1 kg of secondary mass can also be removed. The National Research Council estimated secondary benefits of up to 30% of primary mass reduction,[4] based on a 2008 report by IBIS Associates.[5]

Opportunities for mass reduction include changing vehicle design to use less material as well as substituting lighter materials for traditional materials. Mass reduction solutions can depend on whether the component has strength or stiffness as a design limitation. When strength is the design limit, steel components can be substituted with thinner components of high strength steel, reducing mass while maintaining strength. When stiffness is a design limitation, such as in structural components, technology employing layered material, with a lighter material sandwiched between outer layers of steel, can be used. This sandwich technology is expensive and difficult to join.

Most high-volume vehicles in production today are unibody designs. Aluminum can substitute for steel in a unibody design. Aluminum can also

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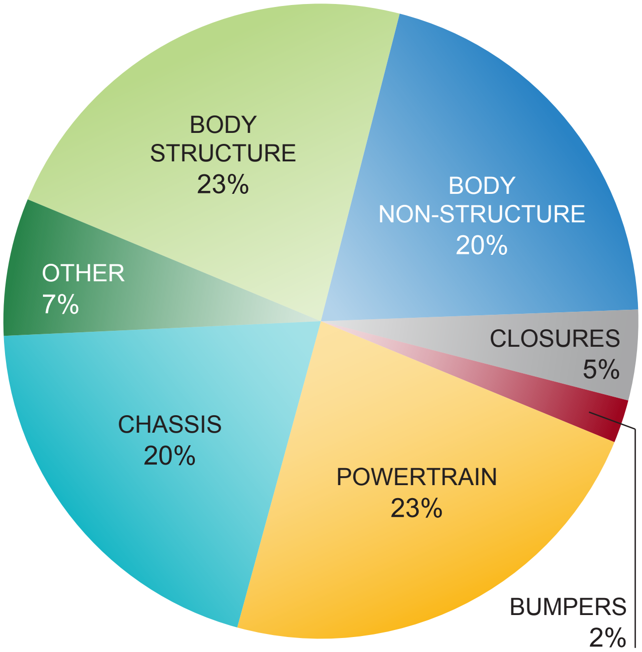
[2] D. E. Malen and K. Reddy, *Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients,* May 2007 (Revised June 26, 2007).

[3] M. Verbrugge, T. Lee, P. E. Krajewski, A. K. Sachdev, C. Bjelkengren, R. Roth, and R. Kirchain "Mass Decompounding and Vehicle Lightweighting," *Materials Science Forum* 618-619 (2009), pages 411-418.

[4] National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011.

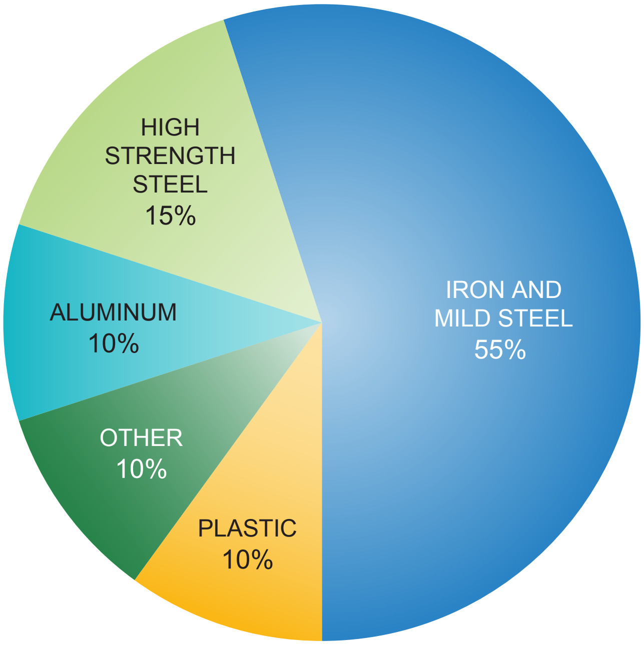
[5] IBIS Associates, Inc., *Benefit Analysis: Use of Aluminum Structures in Conjunction with Alternative Power Train Technologies in Automobiles*, 2008.



Note: Subsystem mass as a percentage of curb mass, average of selected 2002–2007 sedans.

Source: Mark Verbrugge et al., "Mass Decompounding and Vehicle Lightweighting," *Materials Science Forum* 618-619 (2009).

Figure 4-4. *Typical Mass Distribution by Vehicle Subsystem*



Note: Material shares in a typical 2009 midsize sedan, mass%.

Source: National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, June 2011.

Figure 4-5. *Typical Mass Distribution by Material*

substitute for steel in space frame designs, which have lower manufacturing investment costs but higher material costs, are economically suited to vehicle designs with low production volumes, and which tend to be premium applications with premium pricing. Magnesium is even lighter than aluminum. However, its properties such as brittleness may make it unsuitable for use in space frames or other structural materials. Work is underway to develop higher toughness magnesium alloys.

The Minerals, Metals, and Materials Society (TMS), in a recent publication,[6] identified lightweight materials, such as aluminum, magnesium, titanium, and polymer-based materials, as key to reducing weight in transportation body and structural applications. However, according to TMS, today's use of such materials is limited by high cost, corrosion issues, forming and assembly challenges, and end of life materials management challenges.

Polymer matrix composites (PMC), which are polymers reinforced with glass, natural, or carbon fibers, are having increasing application in vehicle production. According to TMS, the strength and stiffness of carbon fiber PMC exceeds that of steel and it is corrosion resistant. However, TMS highlights the need for research to overcome the following gaps and limitations:

- Processes to produce complex geometries are expensive and energy intensive.
- Manufacturing of layered/hybrid material systems for damage tolerance and corrosion resistance is only possible at high costs.
- Fiber-substrate adhesion limits the strength of composites.

A major European manufacturer has announced plans for producing two new models in 2013 that incorporate advanced lightweighting technologies. The smaller of the two vehicles is a battery electric urban vehicle in which the vehicle mass reduction offsets the mass increase of the batteries and results in a vehicle that is actually lighter than many internal combustion engine (ICE) vehicles in

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[6] The Minerals, Metals, and Materials Society, *Linking Transformational Materials and Processing for an Energy-Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization*, February 2011.

its vehicle class. The larger performance vehicle is a plug-in hybrid. With these vehicles, the manufacturer appears to be working with a "clean sheet" effort in which new materials, suppliers (including significant equity interest in the carbon fiber supplier), vehicle design and engineering, propulsion systems, manufacturing processes, and branding are all being attempted at the same time.

The cost/benefit estimates used in the technology analysis are largely based on two studies:

- The National Research Council[7] analyzed 5, 10, and 20% vehicle mass reduction, which included the impact of engine resizing,[8] but did not include the impact of decompounding on redesign of other vehicle components. Including the impact of powertrain resizing, fuel consumption is reduced by about 3, 7, and 12% relative to the three levels of mass reduction.
- The Environmental Protection Agency and the National Highway Traffic Safety Administration[9] analyzed pathways with 15, 20, and 30% vehicle mass reduction largely based on a study by Lotus Engineering.[10] At 30% mass reduction, the fuel consumption reduction is estimated at 16–22%.

The Rocky Mountain Institute[11] sees even greater opportunity for vehicle mass reduction. Their Revolution concept car emphasized a design based on achieving low mass. The structure was carbon fiber intensive. Mechanical vehicle dynamic components were replaced with electronics. The Revolution concept had an overall 50% mass reduction compared to a benchmark. Lightweighting in the 50–70% range is beyond what has been considered in the technology analysis and is discussed separately in the "Ultra-lightweighting" portion of the "Disruptive Innovations" section.

Recommendations and Next Steps. Lightweighting, implemented at the lower end of cost estimates, could improve the competitiveness of all of the alternative fuel-vehicle supply chains although the relative impact will differ by technology. However, significantly increasing the proportion of new lightweight materials will require new engineering and processes and significant changes to OEM operating models.

This study recommends that the government and business invest in driving down the cost of widescale implementation of lightweighting (e.g., the development of new materials, supply chains, and operating models).

Biofuels: Hydrolysis

Current hurdle assessment (difficulty in resolving): YELLOW

Hydrolysis is the process of using enzymes or chemical hydrolysis on pretreated lignocellulosic materials to breakdown cellulose, hemicellulose, and lignin into component sugars that can then be further processed. For example, the volume and type of enzymes used depends on the pre-treatment and the feedstock. The cost of cellulose converting enzymes is still ~10 times the cost of the enzymes used to convert starch in the corn ethanol process.

Cellulosic biofuels have the potential to significantly reduce carbon dioxide equivalent (CO_2e) per mile. However, to use lignocellulosic feedstock in a biochemical production process requires the resolution of technology hurdles that need to be overcome for the cost-effective use of cellulosic feedstock in the production of biofuels.

In its simplest embodiment, enzymatic hydrolysis takes place in a separate process step between pretreatment and fermentation, a configuration known as separate hydrolysis and fermentation. The major advantage of separating hydrolysis and fermentation is that each process can be run at its respective optimum conditions. The enzyme dose required to achieve a given cellulose conversion

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[7] National Research Council of the National Academies, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles,* June 2011.

[8] Ricardo Engineering, *Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures,* 2008.

[9] U.S. Environmental Protection Agency, National Highway Traffic Safety Administration, and California Air Resources Board, *Interim Joint Technical Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025,* September 2010.

[10] Lotus Engineering, *Vehicle Mass Reduction Opportunities,* May 2010.

[11] A. B. Lovins, E. K. Datta, J. G. Koomey, and N. J. Glasgow, *Winning the Oil Endgame: Innovation for Profits, Jobs and Security,* Rocky Mountain Institute, 2004.

level is of paramount importance in determining the overall cost of the enzymatic hydrolysis unit process, and in turn the minimum ethanol selling price. The main drawback of separate hydrolysis and fermentation is that the concentrations of cellobiose and glucose products build up during the course of the batch process and inhibit cellulases and thus limit yields.

In simultaneous saccharification and fermentation, enzymatic hydrolysis and fermentation is concurrent in a single vessel to which both enzymes and fermentation organisms have been added. With simultaneous saccharification and fermentation, cellobiose and glucose concentrations remain low because they are consumed by the fermentation organisms present in the fermenter and no longer inhibit cellulases. A second advantage is capital cost reduction since hydrolysis and fermentation occur in a single vessel. However, optimal temperatures for fermentation do not coincide with optimal temperatures for hydrolysis, at least for the fermentation of sugars to ethanol by *Saccharomyces cerevisiae*. Commercial preparations for biomass hydrolysis are most effective at 50°C, which is too high for most commercially relevant fermentation organisms.

Hybrid hydrolysis and fermentation represents a third approach in which hydrolysis is started under optimal conditions for hydrolysis. After a set time period, the temperature is lowered and fermentation organisms are added, but hydrolysis is allowed to continue under these non-optimal conditions.

High solids loading during enzymatic hydrolysis is important because the presence of water as a diluent increases processing costs. In particular, the energy needed to distill ethanol from the fermentation beer is a strong function of ethanol concentration, which in turn is directly related to the sugar concentration in the hydrolysate. However, conversion efficiency decreases nearly linearly with solids concentration.[12] Kristensen et al. conclude that the primary impact of solids loading on conversion results from the interference with enzyme adsorption to solid substrates by products.

Progress has been made in reducing the cost of enzymes used in biomass hydrolysis. DOE awarded two government contracts to develop more effective enzymes in the 2001–2005 time frame. In 2008, four more contracts were placed with leading enzyme companies to further develop cellulolytic enzymes for saccharification of biomass. These efforts are focused on increasing the specific activity of enzymes, leading to a reduction in the dose required to effect a given cellulose conversion level.

In addition, enzymatic hydrolysis performance is closely related to the type and severity of pretreatment. A tradeoff often exists between pretreatment cost and enzymatic hydrolysis cost. Pretreatments that are more effective in removing lignin and in opening the lignocellulosic structure typically use more chemicals, higher temperatures, and higher pressures, and are therefore more expensive. But as a result of improved pretreatment, lower enzyme doses can be used.

There are also chemical hydrolysis technologies. Acid hydrolysis for the production of fermentable sugars from biomass has matured in the past decade to enable higher yields of fermentable sugars. Three different avenues are being pursued to maximize this. The first is weak acid followed by enzymatic hydrolysis. This produces a soluble pentose stream and a more readily attacked cellulose substrate for subsequent enzymatic conversion. A second approach is two-stage acid hydrolysis. In this process, mild conditions are used to convert the hemicellulose to fermentable sugars followed by harsher conditions to hydrolyze the cellulose fraction. Finally, concentrated acid processes are being developed that can provide a relatively pure sugar stream under mild conditions. These latter processes require exotic materials of construction and efficient recovery and recycle of the acids. A variety of companies and research organizations are in different stages of development of these processes. As with enzymatic hydrolysis, getting to the demonstration scale to prove the economics is a key requirement.

Recommendations and Next Steps. Continued investment in R&D to reduce the cost of hydrolysis, including the trade-offs/optimization between the severity of pretreatments and enzyme dosage, is required to overcome the hurdle.

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[12] J. B. Kristensen, C. Felby, and H. Jørgensen, "Yield-determining Factors in High-solids Enzymatic Hydrolysis of Lignocelluloses," *Biotechnol Biofuels* 2, no. 11 (2009): pages 1-10.

Biofuels: Fermentation of C5 and C6 Sugars

Current hurdle assessment (difficulty in resolving): YELLOW

As of the date of this report, there is no organism that can ferment two different sugars (C5 and C6) as effectively as the yeasts used to ferment C6 during the corn ethanol fermentation process.

After the lignocellulose has been broken down into its component sugars using hydrolysis, these sugars need to be fermented.

Ethanol is the primary target for many of the companies proposing to produce cellulosic biofuels. *Saccharomyces cerevisiae* is a yeast used extensively in industrial fermentation processes, including the production of ethanol from corn. Relatively speaking, yeast are robust and can tolerate high titers of ethanol as well as other inhibitory substances present in the hydrolysate. Another advantage of yeast is that they have the ability to ferment at low pH values, which minimizes the possibility of infection by invading microorganisms. The familiarity with yeast in existing corn ethanol plants is another advantage in using this organism for cellulosic ethanol fermentations. The major drawback of *S. cerevisiae* is that it is not naturally capable of fermenting pentose (five carbon) sugars such as xylose and arabinose. Fermentation of pentose sugars to a fuel product (or other value-added product) is critical to the economic viability of a cellulosic biofuel plant.

Several researchers have genetically transformed yeast to allow utilization of xylose (usually the dominant pentose sugar in lignocellulosic substrates).[13,14]

Yeast is not the only microorganism adept at producing ethanol. *Zymomonas mobilis* is an ethanol-producing gram-negative bacterium that has been genetically modified to allow it to utilize pentose sugars as well as hexose (six carbon) sugars.[15]

Recommendations and Next Steps. Continued investment is required in R&D to genetically modifying microorganisms (e.g., yeasts, bacteria) to allow them to ferment both five and six carbon sugars.

Biofuels: Lignocellulose Logistics/Densification

Current hurdle assessment (difficulty in resolving): YELLOW

Biomass is a relatively low-density, local product, and this is especially the case for crop residues and grasses. Feedstock logistics can be a significant portion of production cost and also limits the size of a centralized plant (and therefore available scale efficiencies).

High cost and inefficient delivery of the feedstock to centralized plants has placed severe limitations on the economies of scale of biomass conversion plants. Storage of biomass, until needed by a processing plant, is also a problem because of losses to the biomass of up to 15% over a season due to natural decomposition. Additionally, a very large footprint is required to store low-density biomass for delivery to a large central plant (e.g., baled corn stover requires 7 to 8 times the volume of storage as corn grain per unit mass).

Recommendations and Next Steps. While there are no major technical issues with developing the infrastructure for crop residues and energy crops, there is a significant capital requirement needed to build out this infrastructure. Local storage and conversion to a densified material are needed to minimize infrastructure needs, reduce energy required for transportation, and stabilize the biomass feedstock. As an example, pelletization and briquetting are two options but currently require considerable energy inputs.

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[13] M. Sedlak and N. Ho, "Production of Ethanol from Cellulosic Biomass Hydrolysates Using Genetically Engineered Saccharomyces Yeast Capable of Cofermenting Glucose and Xylose," *Applied Biochemistry and Biotechnology* 114, no. 1-3 (2004): pages 403-416.

[14] S. Watanabe, A. A. Saleh, S. P. Pack, N. Annaluru, T. Kodaki, and K. Makino, "Ethanol Production from Xylose by Recombinant Saccharomyces Cerevisiae Expressing Protein-Engineered NADH-Preferring Xylose Reductase from Pichia Stipitis," *Microbiology* 153, no. 9 (September 2007): pages 3044-3054.

[15] M. Zhang, C. Eddy, K. Deanda, M. Finkelstein, and S. Picatggio, "Metabolic Engineering of a Pentose Metabolism Pathway in Ethanologenic Zymomonas mobilis," *Science* 267, no. 5195 (January 1995): pages 240-243.

Biofuels: Higher Quality Pyrolysis Oil—An Alternative to Biochemical Production

Current hurdle assessment (difficulty in resolving): RED

Pyrolysis is a thermochemical processing option for producing liquid transportation fuels from biomass. Biomass pyrolysis technology is commercially available but has not been applied to commercial-scale fuel production. Bio-oil chemical composition is not suitable for direct biofuel production without further processing. It has high oxygen content, is corrosive (low pH), and thermally unstable (does not re-vaporize completely).

Pyrolysis is an alternative to resolving the three technology hurdles related to the biochemical production of cellulosic biofuels described previously. In pyrolysis, lignocellulosic feedstock is converted through a thermochemical process into a bio-oil that can then be transported and further processed in a refinery.

Pyrolysis in its simplest form consists of rapidly heating biomass to approximately 600°C and flashing off the volatiles, which are then condensed to produce bio-oil. Yields of up to 80% of feedstock are possible. Since biomass is made up of three major components (hemicellulose, cellulose, and lignin), each of which have their own optimal pyrolysis temperature, simple pyrolysis technology is a compromise in producing optimal bio-oil products from each of these fractions. Bio-oil produced in conventional pyrolysis is a mixture of low molecular weight acids, hydroxy acid and hydroxyl aldehydes as well as more upgradable components such as furans and phenolic compounds. This mixture poses problems for simple upgrading schemes. Current research to solve this issue is focusing on fractionation of simple pyrolysis products for more appropriate upgrading, or adopting catalytic pyrolysis methods to produce a larger fraction of components more amenable to upgrading.

Bio-oil can be upgraded either at the source prior to full production or after the formation of the liquid product. To date, the two most popular methods in post-production upgrading are adapted from traditional hydrocarbon processing.[16] These processes are bio-oil cracking over solid acid catalysts and hydrotreating in presence of a hydrodesulfurization catalyst and high-pressure hydrogen. Although both these processes have the potential to bring down the oxygen content to desirable level, both cracking and hydrotreating are accompanied by the loss of hydrogen (as H_2O) and carbon (as CO_2 or CO) from the bio-oil.

The impact of bio-oil quality and stability on hydroprocessing catalyst performance needs to be validated at the pilot- and commercial-scales. Raw bio-oil contains potential impurities such as alkali metal, chlorine, nitrogen, and sulfur that could poison hydrotreating catalysts and limit long-term activity, stability, and lifetime. Thermal stability of the bio-oil or bio-crude intermediate will have a major impact on coke formation during upgrading, and hence overall carbon efficiency. Catalytic pyrolysis processes under development may produce intermediates that have better thermal stability. Additionally, any oxygen removed before the upgrading step will lower the hydrogen demand of biofuel production and potentially improve process economics. Producing a finished fuel in a stand-alone biorefinery is not as cost effective as developing a biomass (catalytic) pyrolysis process that can be integrated within a petroleum refinery to utilize the existing capital assets and infrastructure.

The development and upgrading of higher quality pyrolysis oil is just getting to pilot demonstration scale. Hydrotreating raw bio-oil is technically feasible using existing refining technology (catalysts and process conditions). Processing includes a mild hydrotreating step followed by hydroprocessing to finished fuel. Yields are low, carbon efficiency is poor because of extensive coke formation, and hydrogen demand is high. All of this challenges the economics of pyrolysis oil to biofuels. Processing the hydrocarbon intermediates in an existing petroleum refinery improves process economics.

Recommendations and Next Steps. Progress has been made on some of the key challenges for pyrolysis, but continued R&D investment is required. Pyrolysis would address some of the

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[16] D. C. Elliott, "Historical Developments in Hydroprocessing Bio-Oils," *Energy & Fuels* 21, no. 3 (2007): pages 1792-1815.

feedstock logistics challenges and also support the integration into the existing refining infrastructure. Because pyrolysis can be done at a smaller scale than other biomass conversion processes, with the bio-oil more efficiently transported for further processing.

Biofuels: Biotechnology to Increase Food and Biomass

Current hurdle assessment (difficulty in resolving): BLUE

To date, yield and productivity gains in both the agricultural as well as ethanol industries have enabled both food and biofuel needs to be met. Both short- and long-term trends for crop yields indicate that agriculture productivity will be able to keep up with population growth and higher standards of living in the developing world. This would indicate that the technology is in place to achieve our long-term demands for both food and fuel. While encouraging, continued focus on maintaining the rate of yield improvement and enabling the third world to achieve the same levels of productivity will be needed to meet demands for food and biofuels.

Improvements in agricultural yield are due to several factors, including better agronomic practices and better seed genetics. In addition to better overall yields, the yields have become more consistent as improved technologies have minimized impacts of variations in weather conditions. Bringing the developing world to 70% of the current U.S. yields on carbohydrate-producing crops would double the total world supply of carbohydrates on existing acreage.

The linkage between energy and food prices is difficult to trace out and the subject of considerable debate. Modern agricultural practices are still energy intensive, ranging from fuel inputs for farm equipment to fertilizers such as ammonia. As with any enterprise, agriculture needs to pay for its inputs to stay in production. To grow or maintain current production will either require crop prices that pay for these inputs or increased government support of domestic agriculture. It is clear that there is a balance between energy prices and availability as well as food prices and availability. Impacts can be minimized when agricultural yield growth is balanced by demand growth across all sectors.

Recommendations and Next Steps. Biotechnology coupled with traditional breeding will be needed to maintain and increase the rate of improvement in food and energy crops. More efficient nutrient uptake, traits to increase the growing season, increased photosynthetic efficiency and tolerance to environmental factors such as salinity or drought are key targets to increase production and or make it more reliable from year to year. Continued investment by governments and industry in this area is a critical factor in ensuring the United States can meet the food and energy demands the future will put on agriculture and forestry.

CNG Vehicles: Leverage Liquid ICE Fuel Economy Technology

Current hurdle assessment (difficulty in resolving): YELLOW

CNG vehicles are still primarily adaptations or retrofits of gasoline vehicles. Gasoline engines and vehicles will continue to improve by incorporating technology improvements such as highly boosted downsized engines, direct injection, variable valve timing, and dual clutch transmissions to achieve fuel economy improvements. The integration of natural gas fuel variants with these advancements will require a degree of systems engineering, including design, software control, and calibrations to incorporate the additional base powertrain complexity and tailor them for optimal CNG operation. Currently, in the United States there are no recognized OEM offerings operating on CNG that comprehend these base powertrain advancements.

The transition to fully OEM developed and produced natural gas vehicles (NGVs) is critical in enabling wide-scale commercialization of NGVs in the marketplace. Current manufacturing models based on vehicle alterers or second stage manufacturers introduces substantive inefficiencies in the cost structure of NGVs.

In addition to the inefficiencies inherent in this production model, a range of technologies discussed within the Engines and Vehicles chapters exist for both powertrain and vehicle enhancements, which, if applied to CNG light-duty vehicles, would result in a significant improvement in overall NGV fuel economy. These technologies include chassis lightweighting, aerodynamics, and powertrain technologies such as highly boosted downsizing, direct injection, dual clutch transmissions, and variable valve timing. Table 4-7 summarizes the possible impact such technologies could have, highlighting the range of fuel economy considered for NGVs in each vehicle class being evaluated in this study. Naturally, adding such technology advancements comes at a cost, and therefore the trade-off between fuel economy, vehicle cost, and fuel price is critical in determining the cost effectiveness of any given solution set for NGVs.

	2010 Fuel Economy (laboratory)*	Maximum Fuel Economy Considered (laboratory)*
Small Car	34.5	69.0
Large Car	32.3	64.6
Pickup	23.9	47.8
Small SUV	27.3	54.6
Large SUV	24.4	48.8

* Fuel economy estimated in a laboratory in contrast to on the road. To convert to on-road use, a multiplier of 0.8 may be used.

Table 4-7. *Range of CNG Fuel Economy Considered in the Study (Miles per Gallon Gasoline Equivalent)*

While a number of studies are available examining the performance benefit and cost trade-off for new powertrain technologies for gasoline vehicles, few long-term performance studies have been conducted to quantify such metrics for CNG-fueled vehicles. The specific application, demonstration, and evaluation of gasoline technologies to CNG vehicles is required in order to identify optimum long-term technology configurations tailored specifically to CNG fuel. The following are areas of specific interest for research and engineering demonstration:

- High Compression Ratio – Compression ratio optimization to take advantage of the high octane rating of natural gas.

- High Boosting Levels (turbocharging and/or supercharging) – In light-duty applications based on gasoline engines, natural gas engines can have a lower power density, particularly on naturally aspirated (non-turbocharged) engines. The adoption of turbocharging for natural gas variants could be specified to address air charge displacement by gas.

- Downsizing – Turbocharged, downsized, high compression ratio engines, as witnessed in the latest European gasoline engines, offer a viable path for improved fuel efficiency of both gasoline and natural gas. The high octane rating of natural gas may even offer greater benefits than for gasoline, although gasoline injection has the advantage of charge cooling.

- Continuously Variable Valve Timing – Valve train optimization to the air and exhaust gas recirculation characteristics of natural gas engines.

- A move toward direct injection natural gas, similar to gasoline direct injection technologies, should also translate into improved combustion efficiency (refer to Chapter Fourteen, “Natural Gas,” regarding the challenges to direct injection CNG).

- Dual Clutch Transmissions – The same benefits as those achieved in gasoline engines are available to CNG vehicles.

- Friction Reduction – The same benefits as those achieved in gasoline engines are available to CNG vehicles.

- Hybridization – The same benefits as those achieved in gasoline engines are available to CNG vehicles. Packaging CNG storage and hybrid systems is a space and architecture challenge for the vehicle.

In addition to the tailoring of the engine technologies to CNG fuel, there are further opportunities to optimize light-duty CNG engine configuration, including:

- Improved piston chamber and intake port design to optimize air motion, turbulence, and fuel mixing for natural gas.

- Material optimization of intake/exhaust valves and valve seats required when combusting natural gas to reduce wear since natural gas is a low lubrication fuel.

- Improved exhaust aftertreatment systems to manage the methane emission requirements of natural gas engines to address higher light-off temperatures by considering a need for catalytic convertor precious metal loading, volume, and cell density.
- Improvements in conventional spark plugs and ignition systems to address potential increased wear due to the greater ignition requirement and the higher spark temperature in natural gas operation.
- Improved electronics and control systems that are fully integrated with vehicle systems including provisions for full On-Board Diagnostic 2 requirements (refer to Chapter Fourteen, "Natural Gas," regarding the challenges to conversion).
- Optimized trade-offs between fuel economy, driving range, and fuel storage costs.

Recommendations and Next Steps. CNG vehicles are available in many parts of the world. The view of the study is that if some initial production scale could be achieved, then the vehicle premium for CNG vehicles would be dramatically reduced. With the inclusion of CNG in long-term product planning, these vehicles could take advantage of the technology improvements available to gasoline engines, optimized for natural gas. Coupled with low natural gas prices, this could be a compelling value proposition for U.S. consumers. However, given the current production model, current production volumes and lack of refueling infrastructure, this may not happen "naturally." It is therefore recommended that the research and engineering demonstration activities outlined in this chapter are supported by government and industry as this could enable the development of ground up, CNG-fueled vehicles with technologies optimized specifically for this fuel.

Electricity: Lithium-Ion Battery Energy Density

Current hurdle assessment (difficulty in resolving):

- **RED for BEV100**
- **YELLOW for PHEV40**
- **BLUE for PHEV10**

The PHEV10 is rated BLUE because the shorter all-electric range, as well as the ability of the gasoline engine to propel and provide additional power when needed, requires a relatively small battery that causes minimal vehicle compromises. The PHEV40 is YELLOW because the battery is larger than that of the PHEV10, with attendant vehicle compromises. The large size of the battery, the limited vehicle range, and the cost of the vehicle all contribution to the RED rating for the BEV100.

The focus of the technology analysis on batteries has been lithium-ion. Lithium-ion batteries are discussed in detail in Chapter Thirteen, "Electric." The energy density of lithium-ion chemistries in today's battery electric vehicle (BEV) models deliver a range of less than 100 miles, which is much lower than equivalent liquid fueled vehicles traveling more than 300 miles on a full tank. Improvements in battery energy density could be used to reduce the cost of the vehicle, making it more competitive to its ICE equivalent, and/or increase the driving range.

There are two aspects of what is commonly referred to as "energy density":

- Specific energy density refers to the amount of "stored" energy per unit mass, typically watt-hours per kilogram.
- Volumetric energy density refers to the amount of "stored" energy per unit volume, typically watt-hours per liter.

This distinction is critical as either metric can be the key design driver, depending on the specific vehicle application.

Figure 4-6 illustrates conceptually the energy density challenges of batteries in automotive applications. For a pure BEV, mass increases significantly as range is extended by increasing the battery size, and even with advances in battery energy density, the curb weight for a small BEV300 would be substantially greater than that of a small gasoline ICE vehicle with a range of 300 miles.

Figure 4-7 provides a comparison of energy densities for common electrochemistries and highlights why lithium-ion has become the electrochemistry of choice for today's electric drive vehicles.

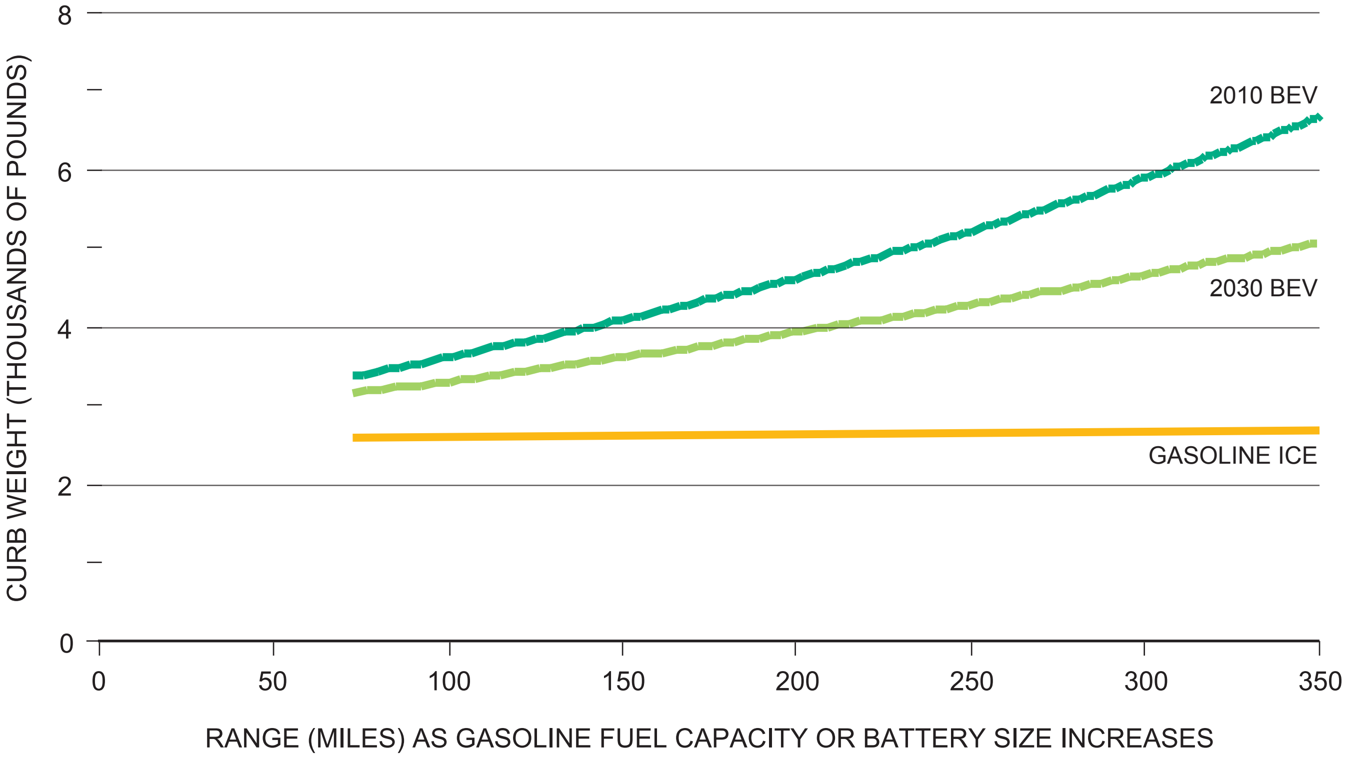
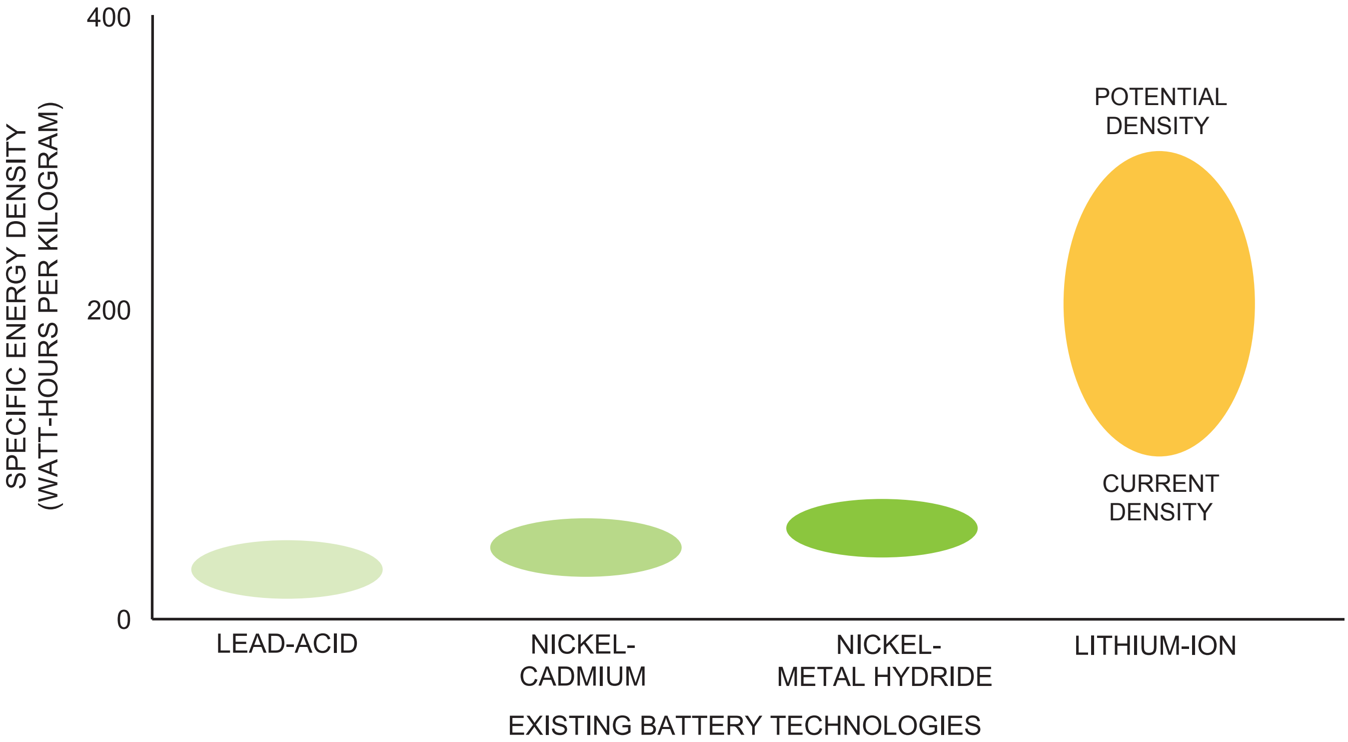


Figure 4-6. *Small Vehicle Curb Weight as a Function of Range*



Source: P. G. Bruce et al., "Li-O2 and Li-S Batteries with High Energy Storage," *Nature Materials* 11, January 2012.

Figure 4-7. *Energy Densities of Lithium-Ion Batteries*

The total amount of energy that a specific battery technology can deliver or accept is a function of the rate (power) requirement on discharge, recharge, or during energy recuperation (e.g., regenerative braking events). Therefore, the vehicle designer must also understand the functionality between power and energy for a particular battery type (chemistry).

To improve cell-level energy density, R&D is also needed on higher-capacity anode and cathode materials for lithium-ion batteries. Potential improvements include alternative anode materials with greater energy density, such as silicon and tin, or novel cathode materials such as lithium vanadium phosphate fluoride ($LiVPO_4F$) that operate at higher voltage, thus also increasing energy density. These higher-capacity materials, along with energy storage technologies that have potential for use in electric vehicle applications, are discussed in Topic Paper #17, "Advanced Batteries," found on the NPC website.

In addition to cell-level energy density, the battery system designer and powertrain engineer must consider the incremental mass and volume or burden of the non-cell battery system components. These other components include the battery protective casing, thermal management system, etc. Burden is typically defined as the ratio expressed in percent of the non-cell mass or volume to the cell mass or volume. For example, if a battery system has a cell mass of 40 kg and a non-cell mass of 40 kg, the mass burden is 100%. It is not unusual for a battery system volume burden to be well in excess of 100%.

Recommendations and Next Steps. Based on publicly available references, battery costs by 2020 are likely be in the range of $200 to $500 per kilowatt-hour (see Chapter Thirteen, "Electric"). Costs will drop further past 2020, but not at the pace of cost reduction between 2010 and 2020. This cost reduction in lithium-ion relies heavily on continued R&D. Going forward, optimal battery system design and supporting R&D will need to focus on both the cell and pack level technologies:

Cell Level

- Higher-capacity anode and cathode materials for lithium-ion batteries.

Pack Level

- The thermal characteristics of the cells and the corresponding size, mass, complexity, and cost of the requisite thermal management subsystem.
- Advanced thermal management technologies/devices to improve heat transfer rate, temperature uniformity, and volume/mass burden.
- Uniformity of performance from cell to cell (manufacturing quality), which to a large extent will determine the cost, complexity, mass, and volume of subsystems to monitor and control cell operation during discharge and recharge.
- Cell geometric format, module packing, and battery enclosure technology and design. There are many opportunities to improve battery system level performance, but these opportunities, to some extent, are tied to the choice of electrochemistry.
- Strategies for battery monitoring and control, including the hardware burden for sensors, signal wiring, and signal processing.

The R&D on cell-level lithium-ion improvements and on chemistries other than lithium-ion with higher theoretical energy densities are discussed in Topic Paper #17.

Electricity: Lithium-Ion Battery Degradation and Longevity

Current hurdle assessment (difficulty in resolving):

- **RED for BEV100**
- **YELLOW for PHEV40**
- **BLUE for PHEV10**

The longevity of lithium-ion batteries in automotive use is highly uncertain, as the vehicles have only recently been introduced, and as such there is a lack of historical data. In spite of this uncertainty, the PHEV10 and PHEV40 are both rated YELLOW because the decrease in all-electric range from natural battery degradation is compensated by the gasoline engine. The BEV100 is rated RED because the longevity is unknown and the battery degradation leads to a decrease in vehicle range that impacts the consumer.

All batteries experience power and capacity fade over time as functions of cycling and time/temperature. The mechanisms that degrade battery power and capacity vary with battery chemistry, the operating profile and ambient conditions. The main cause of the decrease in battery function in most commercial lithium-ion chemistries, however, is the undesirable side reactions between the electrolyte and active materials on the electrodes. These reactions consume lithium, thereby limiting the lithium available to participate in the desirable discharge/recharge reactions. These irreversible side reactions also result in the formation of films on the active materials that impede ionic and interfacial transfer. For lithium-ion batteries, this degradation increases with temperature and state-of-charge (SOC).

The vehicle performance ramifications of year-to-year decreases in capacity and power are most significant for BEVs. As battery capacity decreases over time, the allowable SOC swing must increase in order for the battery to deliver the same number of all-electric miles. The expanded SOC swing can accelerate the degradation and decrease battery life. Further, at a low SOC, the battery may not be able to deliver sufficient power to the vehicle. For PHEVs, the ramification of reduced power from the electric motor is not as noticeable to the driver, because as the battery loses capacity and power, the gasoline engine takes on more of the power requirements. There are two ways of measuring battery life: cycle life and calendar life.

Cycle Life

The cycle life of a battery is measured by the number of times the battery can be charged and discharged. Some battery chemistries are more sensitive than others to the number of charge-discharge cycles incurred.

The cycle life of a battery is fundamentally determined by the reversibility of the electrochemical reaction(s) that are responsible for the energy storage. Cycle life degradation effects are more pronounced at elevated temperatures. The key factors responsible for the cycle life are:

- Mechanical/structural fatigue or failure of the active materials, especially at the microscopic level: materials deteriorate due to the stress, especially cyclic stress-induced fatigue upon charge-discharge cycling.
- Side reactions of positive and negative electrodes with the electrolyte results in the formation of highly resistive interfacial layers that impede the electrochemical reaction(s) and a loss of active materials (lithium, anode material, cathode material, and electrolyte), which lead to loss of capacity.

Calendar Life

The second measure of battery longevity, calendar life, is more straightforward, and is the age of the battery in years. The typical methods to increase the cell calendar life include electrode material structure and surface modification, electrolyte additives, and anode surface modification.

Temperature Effects

Battery life is extremely sensitive to the time–temperature characteristics of the vehicle environment, and not just during operation (i.e., storage temperature and key-off soak temperatures are important as well). As a practical matter, the "rule of thumb" employed by battery engineers is that for every 10°C increase in average temperature, battery life will be reduced by 50%. For example, a battery operated at an average temperature of 70°F (21°C) that demonstrates 15 years of calendar life, will, if operated at an average temperature of 106°F (41°C), yield at best 3.8 years of calendar life. It is important to note that thermal management for temperature control functions for both hot and cold environments. In cold operating environments, for example, it can make sense to "heat" the battery to ensure good power (acceleration/regeneration during braking) and range.

Temperature effects can be countered by:

- Thermal Management – Keep all cells within a pack at acceptable and similar temperatures.
- Limiting SOC Swing – Increasing the nominal (total) capacity of the battery and limiting the SOC swing.

The key for long cycle and calendar life is to reduce the mechanical fatigue, improve stability and reactivity between electrodes and electrolyte, and control the operating conditions of the battery (e.g., temperature, SOC swing, charge rate).

Recommendations and Next Steps. Although battery management systems, power controls, and thermal management techniques can extend the life of the battery, substantial investment in R&D is needed to alleviate the longevity barrier and to ensure that degradation does not impact the consumer.

Hydrogen: Compression and Storage Technology for Dispensing

Current hurdle assessment (difficulty in resolving): RED

Compression. The land, maintenance, and capital required to compress hydrogen to 350 and 700 bar can be significant as well as operationally challenging. A typical hydrogen compression system for fueling requires ~100 square feet of land at a fueling station and should be located where equipment noise is either not a concern or can be buffered.

Storage. Based on demonstration hydrogen stations built to date, a traditional steel tube storage system with 300 kg storage capacity occupies ~450 square feet of land, not including setback requirements which vary based on site specifics (less than 5 feet to 30 feet for gaseous and 50 feet for liquid hydrogen).

The compression and storage requirements represent significant footprint requirements at existing retail fueling locations where commercial land is leveraged for revenue generation through convenience stores, auto repair garages, car washes and other offerings. Storage and compression also account for 45–75% of the total cost of hydrogen.

Technology advances are required in both compression and storage to overcome the land requirements as well as bring down the investment cost for the refueling sites.

Compression for Dispensing

Current fuel cell electric vehicles (FCEVs) require 350 or 700 bar (5,000 or 10,000 psi) hydrogen. The cost of a compression system can range from 20 to 50% of the total cost of hydrogen fueling infrastructure at a fueling location,[17] as well as require about 100 square feet of additional land footprint. Additionally, based on operating data from demonstration fueling stations, the reliability of high-pressure hydrogen compressors at fueling locations has to date been inadequate for commercial applications as a result of a number of issues including metal fatigue, pressure too low or temperature too high, and hydrogen leaks.

But some advances have been made in compression technology. For example, one industrial gas provider has made advancements towards the commercial introduction of a high-pressure, high-throughput compressor that uses an ionic fluid and is expected to be more reliable and require less land than comparable traditional compressors. Although this advancement is promising, compression will still require significant land at the station.

Reducing or eliminating the need for on-site compression through high pressure delivery (>1,000 bar) can address the land, cost, and operating challenges associated with hydrogen compression at a fueling station. Two new on-road hydrogen distribution technologies (composite gaseous tube trailers and dual phase tankers) were introduced in 2010. These new technologies utilize composite gaseous storage tubes and have the capability to increase gaseous hydrogen distribution capacity for each delivery by increasing payload capacity and integrating technologies aboard delivery trucks (refer to Chapter Fifteen, "Hydrogen," for detail). If deliveries can be made at pressures at or above the pressure needed at the site, the need for on-site compression can be reduced and potentially eliminated.

Storage systems aboard FCEVs may also advance in the future such that high-pressure dispensing is no longer required. DOE has made significant investment in the development of advanced materials for onboard hydrogen storage. No material has yet been identified which has a high probability of achieving the necessary performance criteria; however, technology development work is continuing. If this or other efforts to reduce or eliminate the need for high-pressure dispensing are successful, they would offer greater flexibility in on-site storage systems development because compression

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[17] Based on industry analysis and interviews for Chapter Fifteen, "Hydrogen."

requirements can be based on the need for hydrogen storage capacity on site rather than dispensing pressure.

Recommendations and Next Steps. Even if the reliability of on-site compression were to improve, addressing all of the current issues required for commercial application, the land requirements will remain a significant challenge. Continued R&D should be invested in solutions to reduce or eliminate the compression requirements on site—e.g., high-pressure deliveries or low-pressure onboard FCEV storage.

Storage for Dispensing

At fueling locations, hydrogen is typically stored at ground level in liquid tanks and/or a cascade of steel tubes capable of holding high-pressure hydrogen, commonly >700 bar (10,000 psi). Hydrogen is not typically stored underground due to safety practices that require visual inspection of hydrogen storage vessels, or above ground due to structural requirements and cost.

Based on demonstration hydrogen stations built to date, a traditional steel tube storage system with 300 kg storage capacity occupies ~450 square feet of land, not including setback requirements, which vary based on site specifics (less than 5 to 30 feet for gaseous and 50 feet for liquid hydrogen). Of the total installed storage capacity of a system, approximately 70–80% is useable as dispensable fuel at service pressure. FCEVs are commonly filled by balancing the pressure within the vehicle's tank with a pressure in the storage system. Therefore, in order to achieve full fills, some hydrogen must remain in the station's storage system. Because greater storage capacity than that which is usable must be installed, land and capital requirements must be increased accordingly.

In the near future, the use of composite versus steel storage tubes, approved by the American Society of Mechanical Engineers in November 2010, is expected to reduce land requirements for a comparable system by ~75%, not including setback requirements. Given limited availability of land at existing fueling locations and the land requirements for contemporary hydrogen fueling equipment, technology advancements are needed for large volume hydrogen dispensing capabilities. However, the integration of low volumes of hydrogen into some existing conventional fueling locations for commercial introduction of FCEVs is feasible and being demonstrated today.

The cost of a storage system represents a significant portion (>25%) of the total capital required for the hydrogen fueling system. Reducing the cost of this system can materially impact total capital requirements and hydrogen fueling economics.

Advanced storage systems that require less land and capital are needed for the mass deployment of hydrogen fueling infrastructure. One opportunity is the development of advanced compression technologies that allow for greater utilization of the total installed storage system capacity by drawing low-pressure hydrogen from storage and boosting it to fueling pressures as the FCEV is being fueled.

On-site storage systems' costs can be reduced through the development of advanced materials for hydrogen storage, which are not more costly than current steel or composite systems and have greater storage density. Significant efforts have been made to advanced storage material for vehicle storage systems; however, government investments in on-site storage system solutions have been limited. Because on-site systems have different considerations than vehicle storage system, it should not be assumed that advancements in one area will transfer to the other. Therefore, targeted efforts towards on-site storage system advancements could be beneficial.

Another opportunity is to develop underground storage systems for hydrogen. This development would need to address the concerns and requirements that exist and are reflected in the codes and standards for current underground hydrogen storage systems. Successful development of underground hydrogen storage system would minimize the need for dedicated footprint at a fueling location, similar to conventional fuels today.

Recommendations and Next Steps. The use of composite vs. steel storage tubes is expected to reduce land requirements for a comparable system by 75% from historical levels. In addition, continued R&D is required on the opportunities described above to overcome this hurdle—e.g., compression technology (boosting), advanced materials, and/or the use of underground storage. Similar to compression technology, although there are options emerging that could resolve this hurdle, the specific path to resolution is not yet clear.

Hydrogen: Fuel Cell Degradation and Durability

Current hurdle assessment (difficulty in resolving): YELLOW

Today's conventional light-duty vehicles typically run for 5,000 hours and cover 150,000 miles. This same 5,000 hours of vehicle run time is the target for FCEVs for commercial introduction. Hydrogen storage systems are expected to prove capable of lasting over the lifetime of their vehicles. Achievement of durability targets for FCEVs therefore rests on a durable fuel cell stack.

In the laboratory, vehicle fuel cell systems have logged over 7,500 hours of operation, and the maximum projected durability for these laboratory systems exceeds 12,000 hours, further underscoring the potential of the next generation FCEVs to meet a 5,000 hour durability target.

The fuel cell degradation and durability hurdle does not require basic science advancements. This hurdle is expected to be overcome through incremental advancements and engineering.

Durability is a measure of whether the vehicle performs adequately over its expected lifetime of operation without material degradation in power output. Reliability, another measure that is related to durability, means that the vehicle does not fail suddenly and without warning. Achievement of durability targets for FCEVs rests on a durable fuel cell stack.

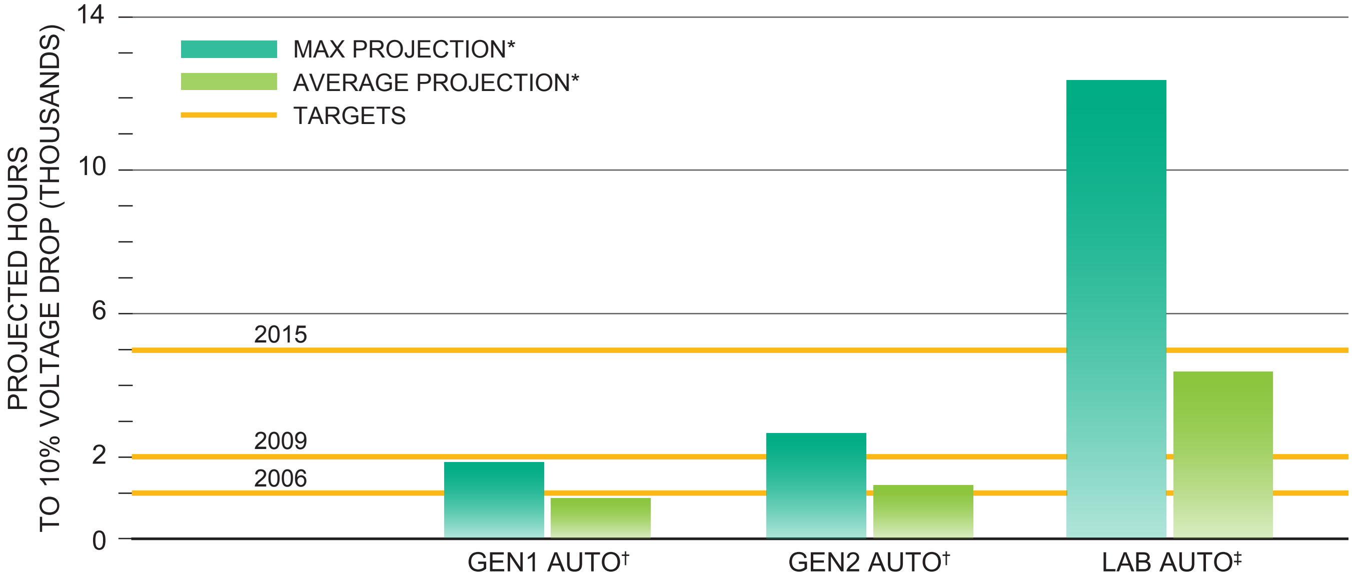
The fuel cell stack can fail in several ways. The electrolyte membrane can physically fail due to stress, chemical attack, or high-current hot spots. A rupture in the membrane, regardless of cause, means the end of stack operation. Membrane physical failure plagued early FCEVs, but improvements over the past few years are moving the industry beyond this failure mode. Durability work now focuses on minimizing stack degradation. When the stack degrades, it loses peak power capacity and it suffers efficiency losses at intermediate power levels. The fuel cell stack, like batteries and all other electrochemical systems, is subject to degradation over usage cycles and calendar life. The goal is not to eliminate this degradation, but rather to slow its rate such that power loss over 5,000 hours (150,000 miles of operation) does not impact the ability of the vehicle to meet its performance targets. This is consistent with the approach currently used to manage conventional vehicle performance degradation.

A common measurement point in discussing stack degradation is the number of hours until a loss of 10% of original power output. Using this definition, DOE measured stack operating life as shown in Figure 4-8 over the duration of its Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project. The maximum projections of stack durability based on on-road data have improved from 950 hours in 2006 to over 2,500 hours in 2009. Although the average durability projection for all fleets in the DOE demonstration is less than 1,100 hours, the maximum projection of 2,500 hours for the best performing second generation fleet well exceeded DOE's 2009 durability goal of 2,000 hours.

In the laboratory, vehicle fuel cell systems have logged over 7,500 hours of operation, and the maximum projected durability for these laboratory systems exceeds 12,000 hours, supporting the potential of the next generation FCEVs to meet a 5,000-hour durability target. The next step towards achieving fuel cell durability targets is to deploy next generation FCEVs in real world settings and confirm that on-road performance compares with laboratory projections.

A majority of the major automotive manufacturers (General Motors, Ford, Toyota, Honda, Nissan, Daimler, and Hyundai) are planning commercial introduction of FCEVs by 2015 in targeted geographies (e.g., United States, Germany, Japan, and South Korea).

Recommendations and Next Steps. No separate R&D is recommended beyond what the OEMs are doing to prepare for commercial introduction of FCEVs in 2015.



Notes: * The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.
† Gen1 and Gen2 Data from DOE's Learning Demonstration (2005–2010).
‡ Laboratory data providers may not be the same as participants in DOE's Learning Demonstration; 49% of data are full active area short stacks.

Source: National Renewable Energy Laboratory.

Figure 4-8. *Comparison of Fuel Cell Vehicle Field and Laboratory Durability Projections*

Medium-/Heavy-Duty Vehicles: Combustion Optimization

Current hurdle assessment (difficulty in resolving): YELLOW

Combustion optimization is not a single technology but a suite of technologies. Both in-cylinder pressure & fuel injection and gas exchange are YELLOW and friction reduction is BLUE. Although emerging compression ignition technologies is RED, many OEMs have demonstrated this technology. Overall, combustion optimization is YELLOW.

Combustion optimization has the largest potential benefit across all of the medium-/heavy-duty vehicle classes (up to 12% of fuel efficiency savings), including Class 7&8 Combination where most of the fuel is consumed, and is applicable to all classes in the medium-/heavy-duty sector for the lowest relative cost ($0–$7,000 per vehicle). Combustion optimization is also important for the advanced fuel economy potential for heavy-duty CNG/LNG vehicles. Achieving the potential benefits of diesel combustion optimization is dependent on resolving hurdles in four key areas: in-cylinder pressure & fuel injection; gas exchange; emerging compression ignition technologies—homogenous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), reactivity controlled compression ignition (RCCI); and friction reduction.

Optimizing the combustion event can drive significant improvement in fuel economy in many different ways. Currently, numerous technologies have been deployed that have already increased the efficiency of the combustion event; most future technology developments will consist of "pushing the envelope" on these existing technologies.

The National Academies has identified four major ways of optimizing the combustion event:

- Reduce heat transfer and exhaust losses. Such losses can be reduced through increasing fuel injection pressure and cylinder pressure. Industry norms for fuel injection pressure are currently 1,800–2,200 bar (26,000–32,000 psi) while cylinder peak pressures are typically in the 140–200 bar range. Increasing fuel injection pressure up to 4,000 bar (58,000 psi) along with improvements in number of injections per cycle and rate shaping can improve fuel consumption by 1–4%. Similar increases in cylinder pressure can also yield a 1–4% fuel consumption improvement. On-Board Diagnostics (OBD) with associated sensors and closed loop controls can complement these pressure increases yielding additional benefits. In tandem, these mechanisms can lead to a 4–6% improvement in fuel consumption at an incremental cost of $2,000 and $3,000 for 6–9 liter displacement engines and 9–11 liter displacement engines, respectively. It should be noted that, while OBD technology is scheduled to be mandated as of 2013, commercially available fuel systems peak at roughly 3,000 bar (44,000 psi) capability.

- Reduce gas exchange losses. Several evolving technologies can lead to reduced gas exchange losses and therefore to improved fuel economy. Variable valve actuation (VVA), advanced low-temperature exhaust gas recirculation, and improved efficiency in turbocharging (e.g., through supercharging) can lead to fuel economy improvements of 3–4% at an incremental cost of $2,000. These base technologies have all been developed but have seen limited commercial deployment.
- Reduce parasitic and accessory loads. Reducing the energy draw from accessory loads leads to improved fuel economy. Alternative power sources will be addressed in the chapters in Part 2 of this report. But incremental improvements on traditionally powered accessories (e.g., through variable displacement pumps) can yield fuel economy improvements as high as 2.5% for incremental costs of $700.
- Finally, continue to reduce friction through improvements in lubricants and bearings, which can yield fuel economy improvements of up to 2% at incremental costs of $500.

Combining this suite of technologies can yield fuel economy improvements of up to 12% across applications for combined incremental costs of $6,000 and $7,000 for medium- and heavy-duty applications, respectively. All of these improvements can be realized through continued, incremental improvements on existing technologies; increasing fuel injection pressure to 4,000 bar is the most significant technology hurdle.

Recommendations and Next Steps. Achieving the potential benefits of combustion optimization is dependent upon resolving hurdles in four key areas summarized in Table 4-8. If the hurdles are overcome, then combustion optimization could improve fuel efficiency from 4.5 to 12% at a cost of $0–$7,000.

The primary recommendation is continued RD&D from government and industry in the emerging compression ignition technologies. Refer to Topic Paper #6, "Low Temperature Combustion," on the NPC website for a further discussion of this topic.

Potential Benefits of Investing in Priority Technology Hurdles

The integrated modeling in this study provides an outlook of vehicle and fuel cost for each fuel-vehicle system. That analysis assumes all 12 priority technical hurdles are overcome. The modeled costs are at a fuel-vehicle system level (e.g., BEV100) vs. component technology or hurdle level (e.g., lithium-ion battery longevity), and are based on the technical analysis in the subgroup chapters.

Light-Duty Fuel-Vehicle Systems

If the eleven light-duty specific priority technology hurdles are resolved, then there could be significant cost reductions across all of the fuel-vehicle systems. Figure 4-9 shows the estimated 2015 and 2050 cost per mile of the different systems. The driving cost per mile is made up of vehicle plus fuel costs.

There is a significant variation in 2015 costs, with PHEV40s, BEVs, and FCEVs significantly more expensive than the ICE equivalents. If the light-duty vehicle hurdles are resolved, then all of the alternative fuel-vehicle systems could be competitive with a gasoline ICE in 2050. In Figure 4-9, each of the fuel-vehicle systems has an estimated cost of driving (vehicle and fuel cost) in 2050 based on the VISION 2050 Reference Case assumption.

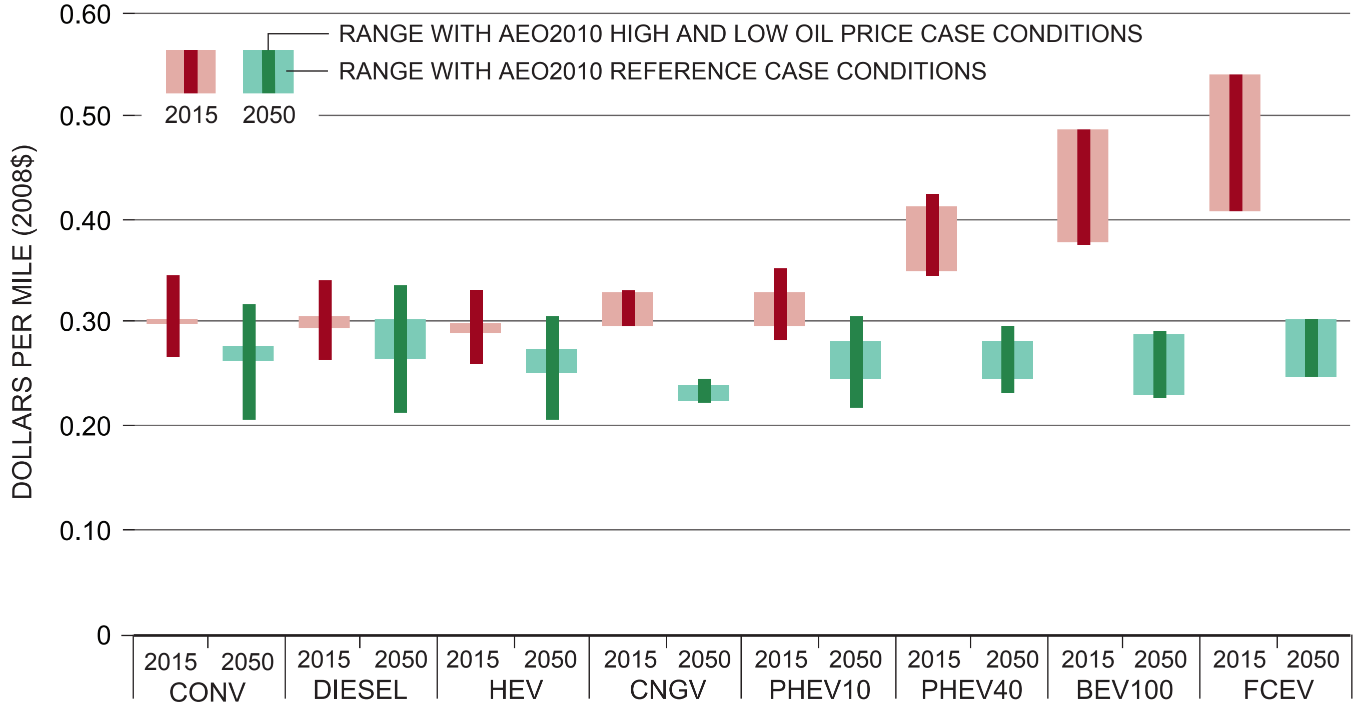
Hurdle	Rating	Conditions Required for Wide-Scale Material Volumes	Comments
In-Cylinder Pressure & Fuel Injection	🟨	Robust and reliable mass manufactured fuel systems	Optimized ultra-high pressure fuel systems are an enabling feature for highly optimized combustion
Gas Exchange	🟨	Cost-effective reliable variable valve actuation (VVA) and boosting systems	Multiple technologies are in development including VVA, multi-stage turbo, exhaust gas recirculation, supercharger, etc.
Emerging Compression Ignition Technologies (HCCI/PCCI/RCCI)	🟥	Life, torque, and transient operations of traditional diesel engines	Largely confined to laboratory studies due to controllability issues; may require specialty fuels/blends
Friction Reduction	🟦	Long-life lubricants, lead free bearings, and ring-packs	Low friction oils and bearings are available. Some barriers to adoption, including costs and tariffs.

🟥 RED hurdles range from basic research to technology demonstration. These hurdles require invention or have high uncertainty.

🟨 YELLOW hurdles range from technology development to demonstration. A pathway for success has been demonstrated and tested but sustained effort is required to achieve wide-scale material volumes.

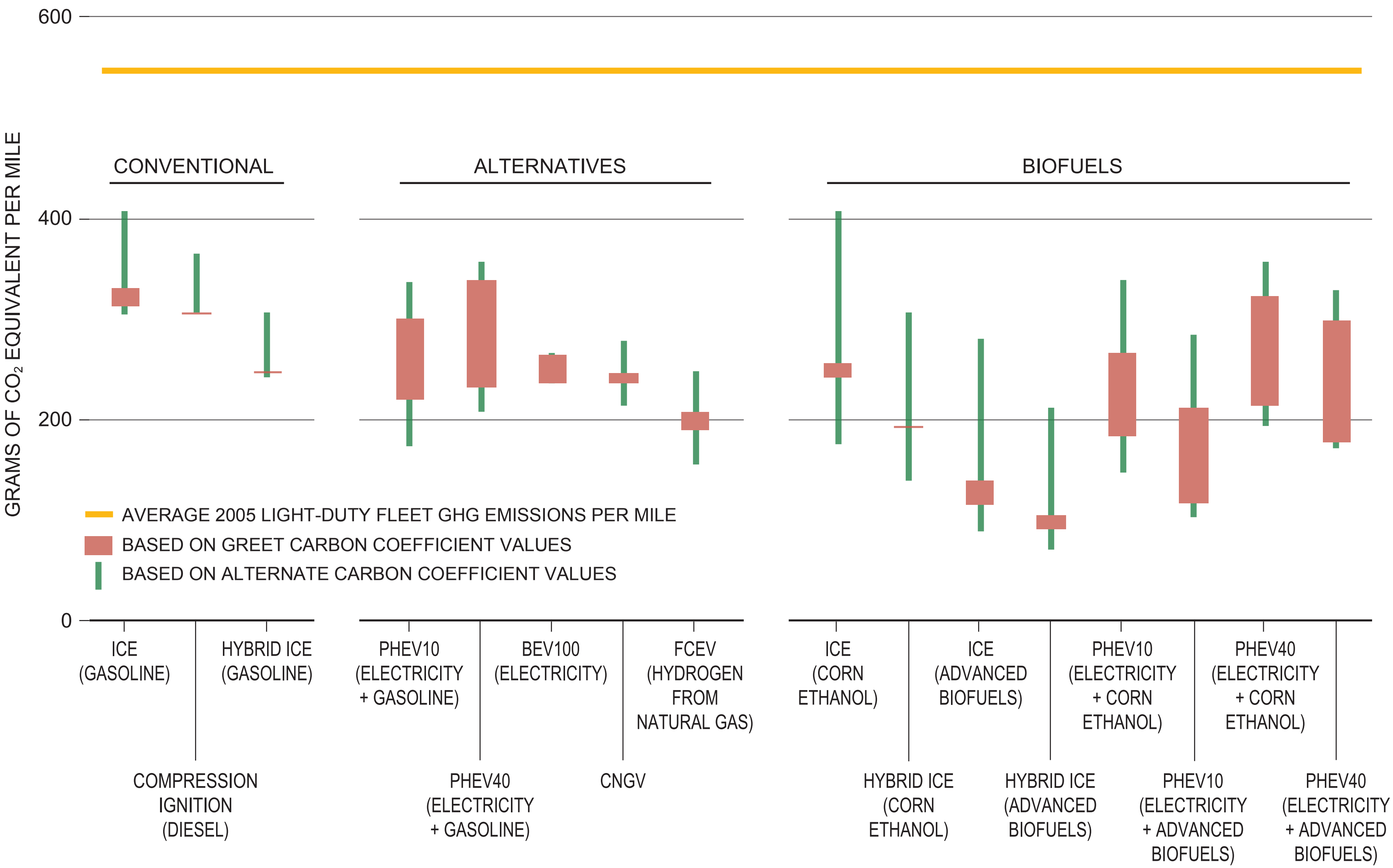
🟦 BLUE hurdles range from systems commissioning to operational. These hurdles have minimal or no barriers to wide-scale material volumes.

Table 4-8. *Diesel Combustion Optimization Hurdles*



Note: PHEV10 allows up to 10 miles of driving in all-electric mode, PHEV40 allows up to 40 miles of driving in all-electric mode, and BEV100 has up to 100 miles of driving range.

Figure 4-9. *Cost of Driving Estimates Assuming Technology Hurdles are Resolved*



Notes:
- Gasoline assumed to contain 10% corn ethanol.
- Based on NPC analysis new vehicle fuel economy in 2050 under AEO2010 Reference Case conditions and assumes technology hurdles are overcome.
- 2020 GREET fuel cycle carbon intensity used (GREET does not go beyond 2020).
- Advanced Biofuels carbon intensity based on 15% gasoline blended with 85% biofuels from forest residue or sugarcane feedstock.
- Biofuels uncertainty range values may include impact of indirect land use change (ILUC).
- Green vertical lines represent uncertainty based on alternate fuel cycle carbon intensity assumptions and may include impact of ILUC.

Figure 4-10. *Comparison of CO_2e Ranges in 2050 for Light-Duty Fuel-Vehicle Systems*

The length of the bar shows the potential range of costs and represents the band of uncertainty associated with implementing the technology for each system. BEVs and FCEVs have the largest uncertainty in estimating future cost per mile. For the BEVs, the key uncertainty is in estimating the future battery costs. For the FCEVs, there is uncertainty in both the fuel cell vehicle as well as in the refueling infrastructure costs (compression and storage).

In the case of biofuels, fuel costs are presumed to equal the cost of gasoline. Therefore, there is no difference in the cost of different blends or types of biofuels.

The impact of low-cost lightweighting is included in the cost reduction between 2015 and 2050. Each fuel-vehicle system balances vehicle cost and fuel efficiency, using the amount of lightweighting optimizes economics.

One outlier to highlight is the low cost per mile of CNG relative to the other fuel-vehicle systems. This is driven by the projection of natural gas costs relative to oil costs in the Energy Information Administration's (EIA) Annual Energy Outlook 2010 (AEO2010).

The impact on GHG is much more varied across the fuel-vehicle systems. Figure 4-10 shows the CO_2e/mile of the different systems in 2050. The CO_2e/mile is composed of fuel carbon intensity divided by vehicle fuel efficiency.

The comparison of CO_2e/mile characteristics shows that advance biofuels have lower CO_2e grams/mile than any of the other fuel-vehicle systems, if potential indirect land use change impacts are not considered. However, there is a supply constraint with advanced biofuel. FCEVs using hydrogen produced from natural gas steam methane reforming have the next lowest CO_2e/mile emissions. CNG and PHEV/BEV have similar CO_2e grams/mile. Important points to highlight are:

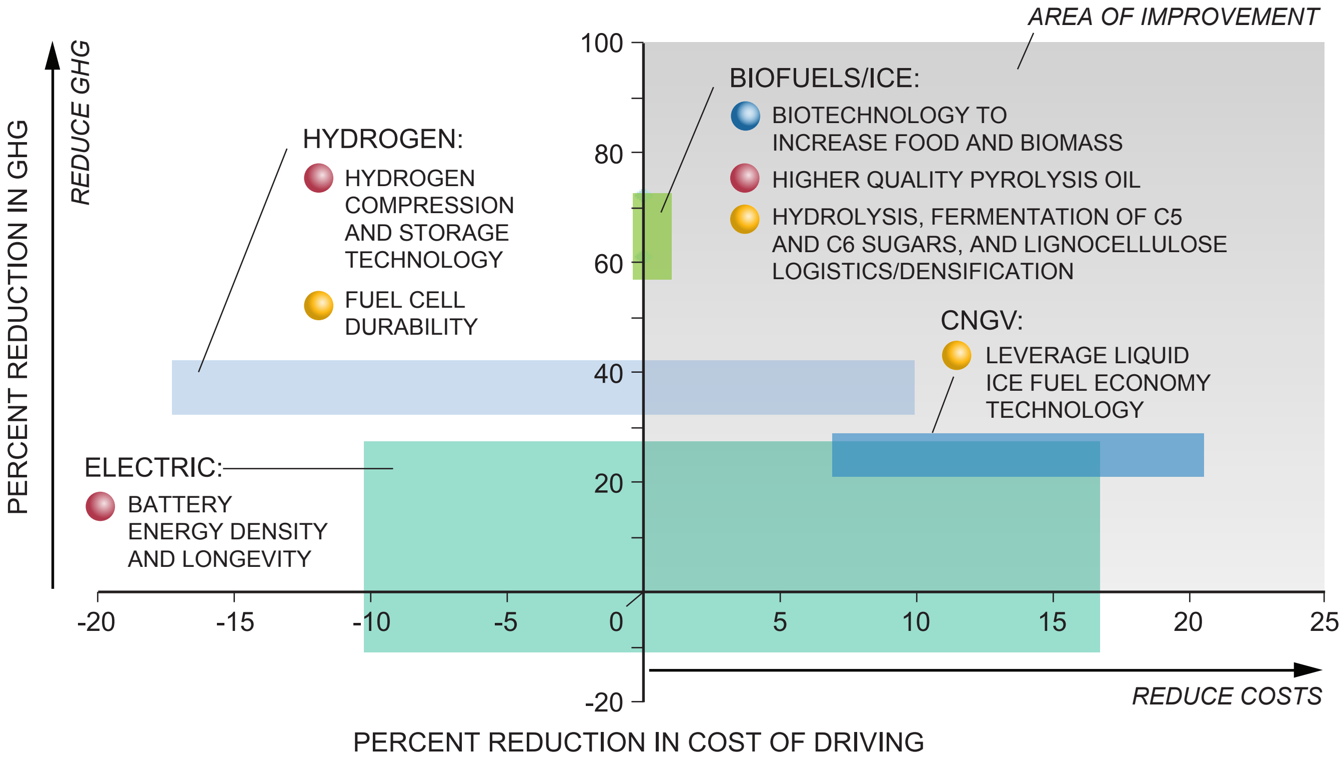
- PHEV/BEV assumes the electricity generation sources used in the AEO2010 Reference Case. A less carbon intensive grid—a "greener grid"—would have a significant impact on CO_2e grams/mile of PHEV/BEV but it may also come at a higher cost per mile. Modeling a greener grid was beyond the scope of this study.
- Biomass or landfill gas sources of CNG were also not included in this analysis, and hence their potential benefit in terms of CO_2e reduction is also not accounted for.
- Similarly, hydrogen from renewable sources, or from steam methane reforming combined with carbon capture and sequestration, was beyond the scope of this study, but would be expected to significantly reduce the GHG impact of FCEVs.

The potential reductions in \$/mile and CO_2e/mile is based on the cost and GHG data for each fuel-vehicle system. The potential reductions in \$/mile and CO_2e/mile and difficulty coding of the priority technology hurdles is illustrated in Figure 4-11.

The x-axis is the reduction in the cost of driving. This is defined as the difference between the minimum and maximum (min/max) of the gasoline ICE cost per mile and the min/max of each fuel-vehicle system cost per mile. The width of the rectangle represents the extreme points—i.e., the difference between lowest ICE cost (min) and the highest alternative fuel-vehicle system (max) and the difference between the highest ICE cost and the lowest alternative fuel-vehicle system. Similarly, the y-axis is the reduction in CO_2e/mile and represents the difference between the min/max of the gasoline ICE CO_2e/mile and the min/max of each vehicle/fuel technology CO_2e/mile. To the right is a reduction in cost of driving and upwards is a reduction in GHG. The shaded area represents improvement (i.e., the top right of the chart represents the highest reduction in cost and GHG). For example, if the light-duty CNG vehicle hurdle "Leverage Liquid ICE Fuel Economy Technology" is resolved, the potential reduction in driving cost compared to an ICE is approximately 20% and the reduction in GHG approximately 30%.

Light-Duty Fuel-Vehicle System Portfolios

To understand the relative impact of technology advancement for a single fuel-vehicle system on the cost of driving and GHG for the *overall fleet*, the light-duty integrated analysis portfolio calculations can be used—the methodology, tools, and results of which are described in Chapter Two, "Light-Duty Vehicles." Each fuel-vehicle system is compared to the gasoline ICE baseline. Figure 4-12 shows



Notes:
- The lack of range in the results for Cost of Driving for Advanced Biofuels is because biofuels are assumed to have the same price as gasoline
- PEV ranges include the lowest/highest cost and GHG across BEV, PHEV10, and PHEV40 (resulting in a large range, particularly for GHG)
- Chart uses the same data as Figure 4-9 and Figure 4-10.

● MINIMAL/NO BARRIERS

● WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

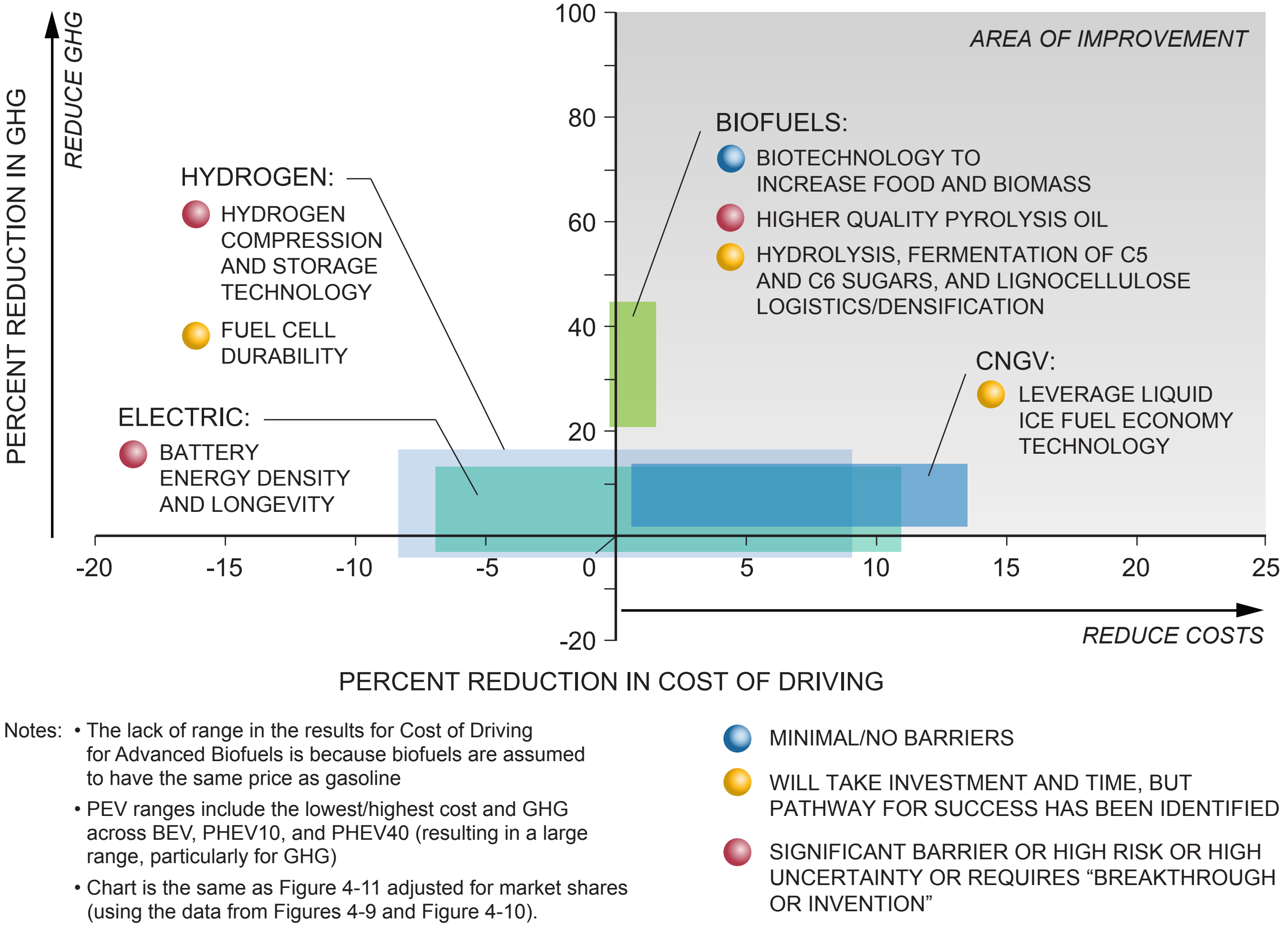
● SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES “BREAKTHROUGH OR INVENTION”

Figure 4-11. *Comparison of Inputs: Percent Reduction in GHG and Percent Reduction in Cost of Driving*

the potential cost per mile and GHG reduction that the individual technology can achieve compared to what can be achieved by the gasoline ICE. The difference in the overall fleet comparison is the consideration of the potential market shares that can be achieved by a fuel-vehicle system in the fleet. This analysis represents the greatest potential impact to \$/mile and CO_2e/mile in the overall fleet because the fuel-vehicle systems do not compete with each other (e.g., electricity is not compared to hydrogen). Important notes:

- The ICE only portfolio includes hybrid electric vehicles (HEVs). Although HEVs use a battery, the cut-off for electric was determined by the plug. It is acknowledged that HEVs do have a relationship with electric and could enable a transition to electric, particularly for PHEVs.
- Full availability of vehicles by 2020 is assumed for all fuel-vehicle systems.
- CNG uses the AEO industrial gas price relative to oil assumptions as the feedstock cost.
- Transition costs and barriers are not considered in this analysis (i.e., infrastructure development is funded and fully utilized from the beginning). This assumption is discussed in more detail in Chapter Five, “Infrastructure.”

Figure 4-12 is the same chart type as 4-11, but adjusted for the assumed market shares of the different fuel-vehicle systems. The consideration of market shares (and existing fleet characteristics) has reduced the potential impact of all of the individual systems.



Notes:
- The lack of range in the results for Cost of Driving for Advanced Biofuels is because biofuels are assumed to have the same price as gasoline
- PEV ranges include the lowest/highest cost and GHG across BEV, PHEV10, and PHEV40 (resulting in a large range, particularly for GHG)
- Chart is the same as Figure 4-11 adjusted for market shares (using the data from Figures 4-9 and Figure 4-10).

Figure 4-12. *Relative Impact of Technology on ICE Only Case (Reference Oil Price)*

- The largest potential CO_2e/mile reduction is achieved by overcoming the various hurdles associated with using lignocellulosic feedstock (reduction of 20–40%). Although those relating to biochemical production are YELLOW, there are still a significant number of hurdles to overcome.

- Of CNG, PEVs, and FCEVs, CNG has the lowest technical challenge (YELLOW hurdle) and has the potential to reduce cost of driving and GHG by over 10%. However, CNG has other nontechnical challenges that are discussed in Chapter Five, “Infrastructure,” as well as Chapter Fourteen, “Natural Gas.”

- FCEVs and PEVs have similar potential to reduce cost of driving by ~10% and GHG by ~10% with wide range of uncertainty and RED hurdles.

Low-Cost Lightweighting

Unlike the other priority hurdles that are specific to a fuel-vehicle system, low-cost lightweighting can impact multiple fuel-vehicle systems. Uncertainty in the cost of lightweighting accounts for most of the variation in the range of retail price equivalent for increased fuel economy of vehicles with liquid ICE propulsion (refer to Chapter Nine, “Light-Duty Engines and Vehicles”) and, at the lower end of cost estimates, lightweighting could have an impact on other fuel-vehicle systems. To estimate the benefits, the NPC considered the extent of lightweighting available to all fuel-vehicle systems at high cost vs. low cost. Using the integrated analysis portfolios, the study team compared the difference in the cost of driving in the portfolio with all the

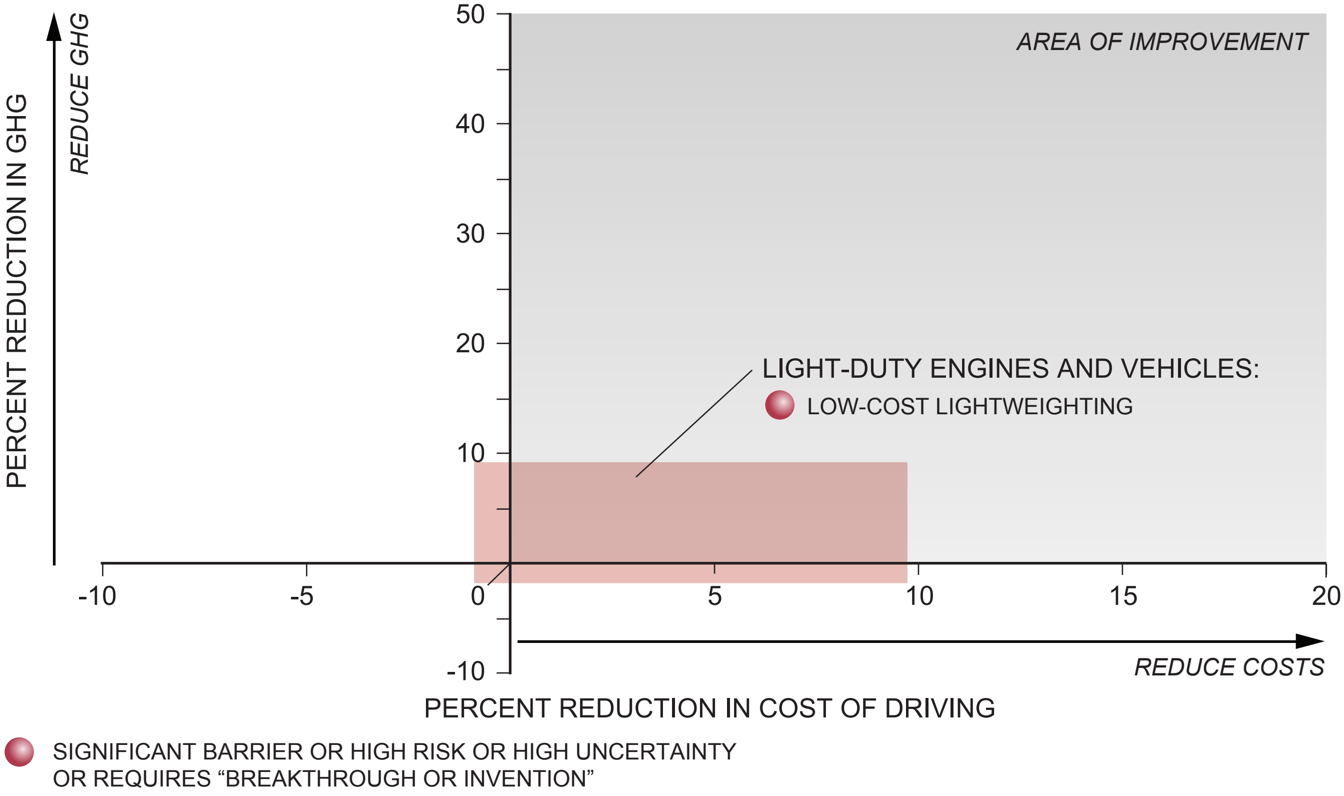


Figure 4-13. *Impact of Low-Cost Lightweighting (Compared to High-Cost Lightweighting)*

technologies, varying only the cost of lightweighting. This comparison (illustrated in Figure 4-13) is meant to illustrate the impact that low-cost lightweighing can have if it is available to all fuel-vehicle systems. One point to note is that the reduction in GHG does not include the manufacturing process of new lightweight materials.

Comparison of Difficulty in Overcoming Technology Hurdles

This section has so far focused on highlighting the potential benefits of the 11 light-duty priority technology hurdles. The level of difficulty has been noted by the color coding in the previous charts. Table 4-9 aims to present the data from the perspective of difficulty and underscores the point that significant effort by government and industry will be required to overcome the hurdles and provide access to the potential benefits.

Medium- and Heavy-Duty Vehicles

Medium- and heavy-duty vehicles do not have the large number of competing fuel-vehicle system that exist in the light-duty sector. The 12th priority technology hurdle, combustion optimization, has the largest potential impact on fuel consumption and GHG because of its potential fuel savings, wide applicability across all medium- and heavy-duty classes, and relevancy to natural gas vehicle platforms. Combustion optimization may also require relatively lower levels of investment than some of the other logistical and production intensive hurdles.

Achieving the potential benefits of combustion optimization is dependent on resolving technology hurdles in four key areas:

- In-cylinder pressure & fuel injection
- Gas exchange
- Emerging compression ignition technologies (HCCI/PCCI/RCCI)
- Friction reduction.

If the technology hurdles are overcome, then combustion optimization could improve fuel efficiency from 4.5 to 12% at a cost of $0 to $7,000.

Fuel-Vehicle System	Twelve Priority Technologies
Light-Duty Engines and Vehicles	Low-cost lightweighting (up to 30% mass replacement)
Biofuels	Hydrolysis
	Fermentation of C5 and C6 sugars
	Lignocellulose logistics/densification
	Production of higher-quality pyrolysis oil
	Biotechnology to increase food and biomass
Light-Duty Compressed Natural Gas	Leverage liquid ICE fuel economy technology
Light-Duty Electric	Lithium-ion battery energy density
	Lithium-ion battery degradation and longevity
Light-Duty Hydrogen	Compression and storage for dispensing
	Fuel cell degradation and durability
Medium-/Heavy-Duty Engines and Vehicles	Combustion optimization

🟥 RED hurdles range from basic research to technology demonstration. These hurdles require invention or have high uncertainty.

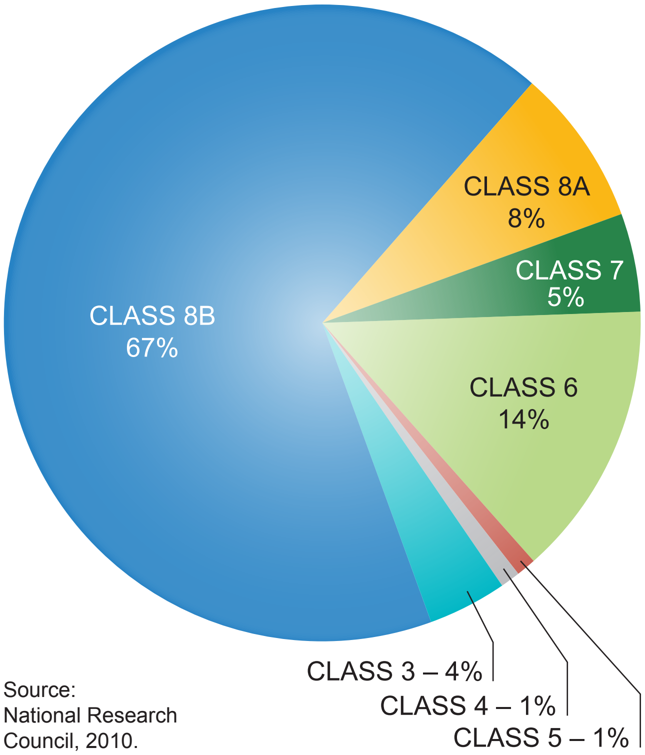
🟨 YELLOW hurdles range from technology development to demonstration. A pathway for success has been demonstrated and tested but sustained effort is required to achieve wide-scale material volumes.

🟦 BLUE hurdles range from systems commissioning to operational. These hurdles have minimal or no barriers to wide-scale material volumes.

Table 4-9. *Technology Hurdles*

It is important to note that the payback of combustion optimization depends on the medium-/heavy-duty vehicle class. For the percentages of medium-/heavy-duty vehicle fuel consumption shares, see Figure 4-14. It is estimated by the EIA that Class 3-6 trucks represent almost 4 million vehicles on the road today, and the Study Reference Case projects they will grow to over 11 million by 2050. Applications range from minibuses, step vans, and utility vans in Classes 2b and 3 to city delivery trucks and buses in Classes 4, 5, and 6. These vehicles consume from as little as 1,000 gallons per year for some Class 2b applications up to 7,000 gallons per year for some Class 6 applications.

Class 7&8 trucks account for over 4.5 million units and are expected to grow to over 7 million in 2050 in the Reference Case. Classes 7 and 8a trucks include buses, dump trucks, trash trucks, and other hauling trucks. These trucks represent heavy working trucks consuming typically 6,000–8,000 gallons of fuel per year for Class 7 and 10,000–13,000 gallons of fuel per year for Class 8a. Class 8b trucks are typically long-haul trucks weighing more than 33,000 pounds that have one or more trailers for



Source:
National Research
Council, 2010.

Figure 4-14. *Medium- and Heavy-Duty Vehicle Fuel Consumption Shares* flatbed, van, refrigerated, and liquid bulk. These trucks typically consume 19,000–27,000 gallons of fuel per year and account for more than 50% of the total freight tonnage moved by trucks.

Therefore, although combustion optimization is applicable to all medium- and heavy-duty classes, because it impacts Class 7&8 Combination where most of the fuel in the medium-/heavy-duty sector is consumed, its impact on fuel consumption will be significant as illustrated in Figure 4-15.

The payback of an investment in combustion optimization varies depending on the average miles per year. Even at the highest estimated cost of $7,000 per vehicle, the payback period for combustion optimization in Class 7&8 would be two years or less. Figure 4-16 compares the fuel savings resulting from an investment in combustion optimization for each vehicle class.

Technology Transition Costs

One of the premises in the approach to analyzing the supply chain and technology hurdles was to push or accelerate each technology as far as feasible to understand what the technology could deliver in terms of $/mile and CO_2e/mile for light-duty vehicles and reduction in fuel use for medium-/heavy-duty vehicles if the technology hurdles were overcome. Significant effort was made to ensure that the assessment of the difficulty (i.e., the coding of RED, YELLOW, and BLUE) was consistently applied across the technology hurdles.

This approach, however, does not consider the full transition costs of the fuel-vehicle systems. Each fuel-vehicle system has a unique set of hurdles, and the optimal transition pathway for each technology will be different. Much of the discussion on what must be done to resolve the hurdles is contained in the individual chapters. Chapter Five, "Infrastructure," also has a significant discussion on the infrastructure development transition costs and why it has not been included in the analysis. It would not be possible, in the scope of this study, to quantify the transition costs (either R&D or infrastructure utilization) in a way that

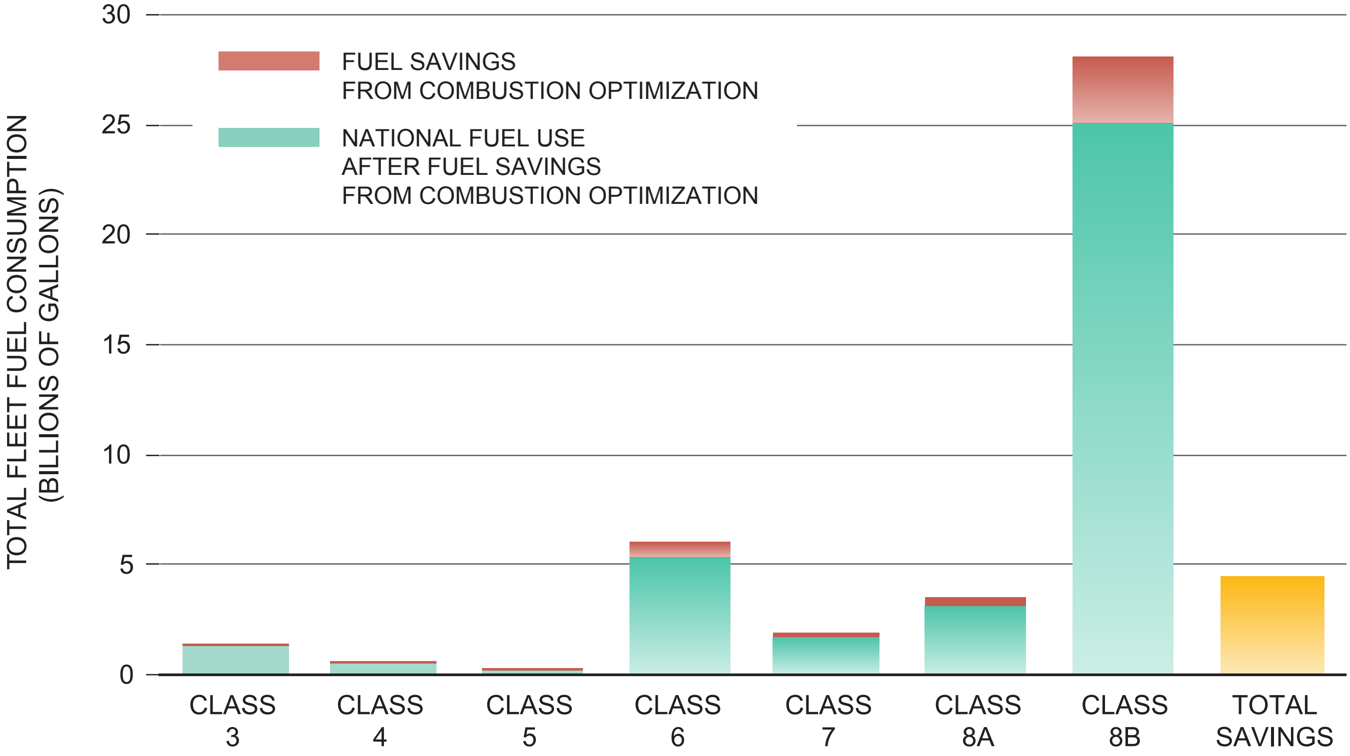


Figure 4-15. *Impact of Combustion Optimization on Total Fleet Fuel Consumption (Assuming 12% Fuel Efficiency Improvement)*

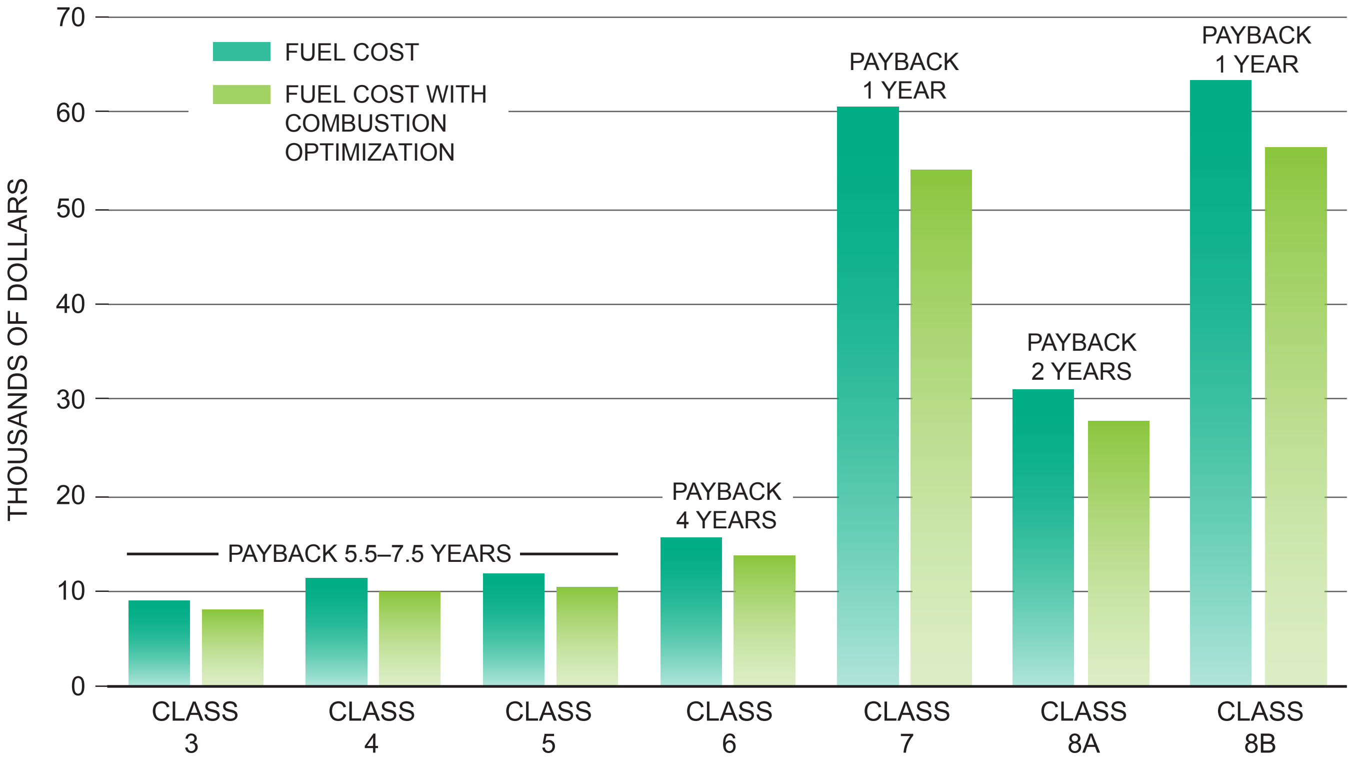


Figure 4-16. *Impact of Combustion Optimization on Annual Fuel Cost (Assuming 12% Fuel Efficiency, $7,000 Cost, AEO2010 Fuel Price)*

they are comparable or consistent. Therefore, any quantification has been excluded in the integrated analysis. However, it is recognized that to resolve all the priority technology hurdles and achieve the estimated 2050 costs, the effort and investment will be significant and should not be underestimated.

Disruptive Innovations

Research and development in disruptive innovations[18] is an area where the Department of Energy has historically played a significant role. Disruptive innovations are early in the development cycle and require invention. They are high risk in that only a small percentage is able to move from basic research to commercial production. In addition, the development path can take decades. Given the high risk, high uncertainty, and long-term commitment required, it is often difficult for industry, outside of a government-sponsored program, to fund development in these areas.

Some innovations still in R&D were considered by this study to be not yet mature enough to analyze in the fuel-vehicle systems under review. These innovations, however, could mature and be disruptive, either by advantaging a specific pathway or creating a completely new pathway. As a result, the study commissioned topic papers on some of these disruptive innovations and provides overview descriptions of six such disruptive innovations as examples. It is important to note that the list of disruptive innovations is not exhaustive, and to some extent, reflects what the study team were able to staff. There are many disruptive innovations not included below.

Table 4-10 lists some of the disruptive innovations for which topic papers were commissioned. The table is not an exhaustive list. The disruptive innovations listed in Table 4-10 are not required for wide-scale commercialization of the fuel-vehicle systems considered in this study. However, they do represent "disruptive" opportunities that would shift the cost curve of the relevant

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[18] Innovations that improve a product or service in ways that the market does not expect. Disruptive innovation is sometimes contrasted with the concept of continuous improvement, which focuses on achieving small, incremental changes in processes in order to improve efficiency and quality.

Disruptive Innovation Topic Paper	Description
Advanced Batteries: "Beyond Li-Ion"	Chemistries that will have higher energy densities than lithium-ion, capacitor technology, and new chemistries such as magnesium-ion, metal-air, aluminum-ion, and sodium-ion.
Advanced Storage Technologies for Hydrogen and Natural Gas	Technologies that would allow storage at higher densities and lower pressures, such as adsorbing onto the material surface, absorbing the material, or storing the fuel as a chemical compound.
Genetic Engineering to Add Traits Not Natural to the Feedstock	Traits that could deliver yield improvements to both conventional and non-conventional crops, such as frost tolerance and the ability to germinate at colder temperatures, drought and heat tolerances, water and nitrogen efficiency, saltwater tolerance, perenniality, photosynthetic efficiency, etc.
Development of Non-Precious Metal Catalyst for Oxygen Reduction in PEM Fuel Cells	Catalysts that fully meet the requirements of electrocatalysts for oxygen reduction in proton exchange membrane fuel cells but do not require high cost precious materials (e.g., platinum) like current catalysts.
Mass-Market Adoption of Ultralightweight Automobiles	Reductions of 50–70% of vehicle mass by eliminating components, using new materials, new processing and production methods.
The Connected Car: Smart Technologies to Reduce Congestion (Intelligent Transport Systems)	Application of "telematics," or the integration of telecommunication and informatics, has generated the possibility for the vehicle to communicate with the road infrastructure, vehicles to communicate with each other and to obtain this information about the traffic environment in which it is operating.
Vehicle to Grid (V2G)	Technologies that allow for two-way electrical service from a vehicle to the electric grid, under the control of a grid operator's signal. Vehicles would provide much needed service to the electric grid.
Artificial Photosynthesis	Technologies that directly convert solar energy into fuels through a fully integrated system, which apply the principles that govern natural photosynthesis to develop man-made solutions.
Microbial Fuel Cells	Fuel cells that are capable of converting chemical energy available in organic substrates into electrical energy using bacteria as a biocatalyst to oxidize the biodegradable substrates.
Fatty Acid Biosynthetic Pathway for the Production of Fuels in Genetically Engineered Bacteria	Technologies that use fatty acids as the basis for the production of new fuels such as short-chain alcohols (e.g., ethanol, butanol), branched-chain alcohols (e.g., isobutanol, isopentanol), and long-chain hydrocarbons.
Macroalgae (Seaweeds)	Growing, harvesting, and processing macroalgae for biofuels production at economically competitive costs and scale.

Table 4-10. *Disruptive Innovations*

fuel-vehicle system and create significant future advantage. They were not considered in the core technology analysis because they are highly uncertain and, unless there is a breakthrough, may not achieve wide-scale commercialization.

The following are six examples of disruptive innovations. They are also more fully developed in the topic papers for this study, listed in Appendix 4D at the end of this chapter and found on the NPC website.

Advanced Batteries – Beyond Lithium-Ion

This section provides an overview of current advanced battery research. Refer to Topic Paper #17, "Advanced Batteries," on the NPC website for a more detailed discussion.

Lithium-ion was the basis of the cost and performance estimates used in Chapter Thirteen, "Electric." Aggressive improvements have been assumed, bringing the low end of the range of estimates to just over $200 per kilowatt-hour at the pack level. This is in line with the most aggressive estimates of lithium-ion improvements. However, even at this level, there will be challenges on cost and range because of the inherent energy density of lithium-ion batteries.

Figure 4-17 illustrates the justified optimism and interest in exploring higher energy density electrochemistries beyond lithium-ion. As indicated, the theoretical specific energies of electrochemistries such as lithium-sulfur, lithium-air, zinc-air, etc., are well beyond that of lithium-ion. However, this optimism must be tempered with the reality that:

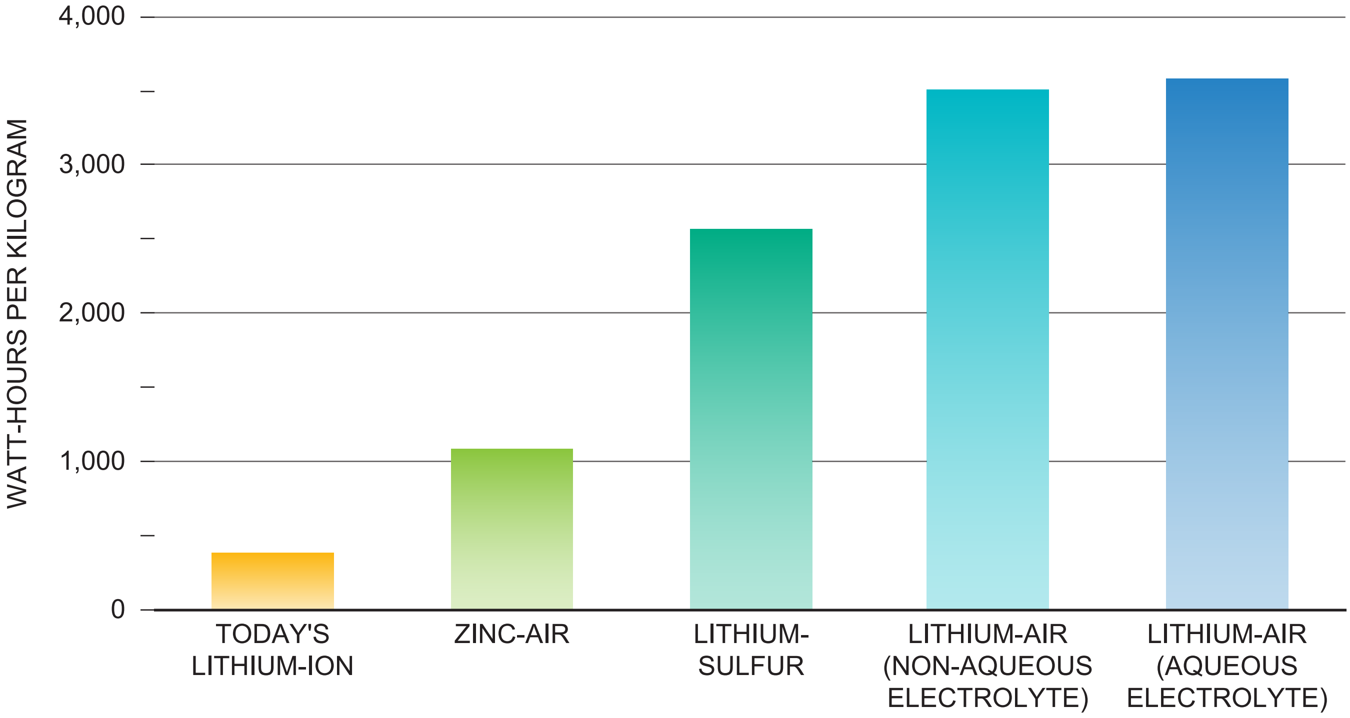
- Theoretical specific energy at a cell level is not achievable.
- System level burdens will further reduce these performance metrics.

In addition to new chemistries, there is significant research on anode and cathode technology to dramatically improve lithium-ion systems as well as the use of capacitors. Topic Paper #17, "Advanced Batteries," describes the technologies in R&D. (See Table 4-11 for a summary of the technologies reviewed in the topic paper.)

Impact on Relevant Fuel-Vehicle Systems. Breakthroughs in any of the battery technologies described in this section could have a significant impact on the competitiveness of electrification for transport due to improvements in energy density, battery life, and costs.

Advanced Storage Technologies for Natural Gas and Hydrogen

On-board fuel storage remains a key technical barrier to widespread commercialization of natural gas and hydrogen-fueled vehicles. Current storage applications for both fuels rely on compression or liquefaction, both of which have cost and performance barriers. This has led to dedicated



Source: P. G. Bruce et al., "Li-O_2 and Li-S Batteries with High Energy Storage," *Nature Materials* 11, January 2012.

Figure 4-17. *Comparison of Specific Energy for Various Battery Chemistries*

Materials for Next Generation Lithium-Ion Batteries
Advanced Cathode Materials
• Oxygen Release Cathode Materials
• Two-Lithium Cathode Materials
• High Voltage Spinels
Advanced Anode Materials
Electrochemical Energy Storage Beyond Lithium-Ion
Elemental Metallic Negative Electrodes
Metal-Air Batteries
• Lithium-Air
• Sodium-Air
• Aluminum-Air
• Zinc-Air
• Silicon-Air
Lithium-Sulfur
Displacement Reaction Cathodes
Alternative Working Ions
• Sodium
• Magnesium
• Aluminum
• Zinc

Table 4-11. *Summary of Technologies Reviewed in the "Advanced Batteries" Topic Paper*

research into alternative, low-pressure gas storage technologies that aim to meet performance and cost targets to support widespread hydrogen and natural gas vehicle deployment. This section provides a short overview of current research; refer to Topic Paper #24, "Advanced Storage Technologies for Hydrogen and Natural Gas," on the NPC website for a more detailed discussion.

Disruptive storage technologies seek to bypass the pressure and thermal challenges of traditional storage technologies by utilizing the chemical and physical properties of certain materials to store gas at low pressure and moderate temperatures. The common approach involves holding the hydrogen or methane atoms or molecules in storage materials that allow a greater density of fuel by adsorbing onto the material surface, absorbing into the material, or storing the fuel as a chemical compound. Using such technologies for hydrogen, it is possible to achieve volumetric and gravimetric storage densities rivaling liquid hydrogen because the H_2 molecule is dissociated into atomic hydrogen within the material, such as a metal hydride.

A range of materials is currently being assessed across these fuel-vehicle systems. This technology works by loading the gas into and forcing it out of the material by applying changes to pressure or temperature, or through a chemical reaction. Storage in materials offers great promise, but additional research is required to better understand the storage mechanism under practical operating conditions and to overcome critical challenges related to storage capacity, the uptake and release of the stored gas (i.e., kinetics), management of heat during refueling, system costs, and life-cycle impacts.

Impact on Relevant Fuel-Vehicle Systems. Breakthroughs in the storage technologies described could significantly improve the competitiveness of CNG vehicles and FCEVs. However, in assessing disruptive storage technologies, a systems approach must be taken, looking at all benefits and costs. In addition, if significant infrastructure is built for high-pressure or liquefied fuel supply chains, transformation costs and support for legacy systems must be considered.

Genetic Engineering to Add Traits that are Not Natural to the Feedstock

Agricultural practices that are both intensive and sustainable are needed to keep pace with humankind's demand for food and energy while maintaining critical environmental services. Agronomy cannot be viewed as a static field. Rapid and continual changes are needed to meet increasing production and environmental demand, while coping with changing climates and the age old problem of evolving insect, disease, and weed populations.

Research that promotes the dual goals of productivity gains and improved environmental stewardship will need to be supported at higher levels by government, industry, farmers, and the public. A key component of this research will include new traits, developed through selective breeding, genetic engineering, agronomic research or a combination of these technologies. Some of the traits relevant to yield and stewardship improvements of both conventional and non-conventional crops include:

- Frost tolerance and the ability to germinate at colder temperatures
- Drought and heat tolerances
- Nutrient use efficiency
- Cropping systems, such as the use of cover crops
- Saltwater tolerance
- Perenniality for crops such as corn and wheat
- Nitrogen fixation
- Plant-mediated and exogenous manipulation of rhizosphere microbial populations
- Increased photosynthetic efficiency
- Maintained photosynthetic efficiency during grain fill
- Controlled senescence of energy crop biomass, both annual and perennial
- Development of output traits that improve utility per unit dry matter.

While this list is not meant to be comprehensive, it illuminates the potential extent to which an increased understanding of how nature has been able to adapt plants to every environment will help our agricultural and forestry industries develop crops for increased yields with less intensive inputs. Most of the solutions that will be needed are already out there in the biosphere; the task is to recognize and deploy them to meet a growing global demand. More detail can be found in Topic Paper #11, "Genetic Engineering to Add Traits Not Natural to the Feedstock," on the NPC website.

Impact on Relevant Fuel-Vehicle Systems. Progress in this disruptive innovation will advantage biofuels, improving the yields and reducing the costs of using biomass to support the increased demand in for both food and fuel.

Non-Precious Metal Catalyst for Oxygen Reduction in PEM Fuel Cells

Due to the high cost of platinum, there has been considerable research on non-precious metal catalysts. However, none of the catalysts reported in the literature fully meet the requirements of electrocatalysts for oxygen reduction in proton exchange membrane (PEM) fuel cells due to:

- Low catalytic activity
- Poor stability
- Low selectivity toward four-electron reduction of oxygen to water (large amount of hydrogen peroxide >5%)
- High electronic resistance.

A new method is under development for the synthesis of nitrogen-modified carbon-based catalysts for oxygen reduction in PEM fuel cells. The synthesis process involves the modification of the carbon surface with nitrogen-containing organic precursors followed by heat-treatment at elevated temperatures. An optimized nitrogen-doped catalyst shows an onset potential for oxygen reduction as high as 0.9 V vs. Normal Hydrogen Electrode (NHE) in 0.5 moles/liter concentration sulfuric acid solution similar to that of platinum. More detail on this technology can be found in Topic Paper #23, "Development of Non-Precious Metal Catalyst for Oxygen Reduction in PEM Fuel Cells," on the NPC website.

Impact on Relevant Fuel-Vehicle Systems. Replacing platinum in fuel cells with non-precious metals would dramatically reduce costs and significantly increase the competitiveness of FCEVs.

Ultra-Lightweighting

The NPC study team analyzed low-cost lightweighting up to approximately 20–30%. The upper percentage was largely limited by the reference material that provided the cost and fuel efficiency information within this range. In the modeling of fleet characteristics, most fuel-vehicle systems found benefit from lightweighting at the lower end of the cost/benefit curve. Lightweighting in the 50–70% range was beyond the scope of the study and falls within research and design strategies often referred to as ultra-lightweighting.

The Rocky Mountain Institute (RMI) has long been a proponent of ultra-lightweighting. Within their work, 10 main barriers have been identified that need to be overcome to achieve 50–70%

lightweighting.[19] These are covered in greater detail in Topic Paper #7, "Mass-Market Adoption of Ultralightweight Automobiles," on the NPC website. Primary areas of focus from RMI's work are:

- "Clean sheet" design and engineering
- Integrated design process that supports optimization across the entire vehicle system vs. optimizing the design of specific parts
- Exploiting mass decompounding cycles through recursive design that shrinks and even eliminates components and subsystems
- Maximizing unique characteristics of carbon fiber, anisotropic structures with strength and stiffness in different directions
- Using modern, virtual tools for structural analysis and crash simulation
- Redefining and redesigning the parts supply chain
- Retraining engineers used to working with steel and changing the cultural biases towards specific materials and systems.

RMI applied these strategies in its Revolution concept car, which emphasized a design based on achieving low mass. The structure was carbon fiber intensive. Mechanical vehicle dynamic components were replaced with electronics. The Revolution concept had an overall 50% mass reduction compared to a gasoline ICE benchmark.

Impact on Relevant Fuel-Vehicle Systems. The examples of "ultra-lightweight" concept cars provide a glimpse of what is possible with a clean sheet. But before there can be wide-scale adoption of "ultra-lightweighting" in the percentages described by RMI, low-cost lightweighting as described in the twelve priority technology hurdles needs to be achieved. Wide-scale commercialization at these levels will pave the way for the operating model, design, engineering, and supply chain solutions that will make lightweighting at higher percentages possible.

Smart Vehicle and Infrastructure (to Reduce Congestion)

The five disruptive innovations above focus on individual components of overall vehicle and infrastructure systems that, if realized, could significantly change the prospects of one or a number of alternative fuel-vehicle systems. The final example of disruptive innovation, Smart Vehicle and Infrastructure, is different as it addresses the overall system, rather than an individual component.

There are three key categories where fuel economy can be improved and thus reduce greenhouse gases; the fuel-vehicle system, the driver's habits, and the transportation infrastructure. In addition to improvements to the internal combustion engine to improve fuel economy and reduce GHG emissions, there are information and communication technologies that can also be incorporated into the vehicle and the surrounding transportation infrastructure to further improve fuel efficiency and reduce GHG emissions. The application of "telematics," or the integration of telecommunication and informatics, has generated the possibility for the vehicle to communicate with the road infrastructure, for vehicles to communicate with each other, and for vehicles to obtain this information about the traffic environment in which it is operating. This section provides a short overview of smart vehicles and infrastructure activity and research. Refer to Topic Paper #5, "The Connected Car," on the NPC website for more details.

The push behind "connected vehicles" is to ensure that cars are driving smoothly, safely, and efficiently by reducing congestion and fuel consumption. Integrated information and communication technologies make up what is known as an "Intelligent Transportation System." Real-time traffic data can be transmitted from field sensors, RFID readers, or cameras, and integrated into the traffic management software and traffic control center. This integrated view can allow control centers to facilitate availability of information back to vehicles directly in on board units or internet-enabled phones to allow travel choices and can intelligently and adaptively manage traffic flow through traffic signal changes to optimize road networks and reduce congestion.

A connected vehicle can be equipped with GPS, maps, cameras, radar, lasers, and sensors that figure out where the vehicle is and convey information about the surrounding traffic and how to get to its destination. In addition, a more advanced "autonomous" self-driving vehicle may

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[19] A. B. Lovins, E. K. Datta, J. G. Koomey, and N. J. Glasgow, *Winning the Oil Endgame: Innovation for Profits, Jobs and Security*, Rocky Mountain Institute, 2004.

be equipped with additional advanced decision-making software. The information received and conveyed from the multiple "connected" cars on the highway allows for the car to follow traffic speeds and signals, sense other vehicles, make room for merging vehicles, pass other vehicles, adjust a vehicle's velocity, and choose alternate routes.

In addition to the communication infrastructure to transmit data, sensors and monitoring devices must be deployed throughout travel routes to gather data from passing vehicles and an integrated transportation center must be created to analyze the data and provide "best options" to drivers. Several such monitoring devices and control networks are already available. For example, infrared emitting and receiving units that collect and provide information and traffic monitoring at signal junctions and motorways.

Beyond providing information between vehicles and infrastructure to improve safety and reduce congestion, the Intelligent Transportation System could also one day function as an automated highway system to significantly increase highway throughput (vehicles per lane per hour moving along the highway).

Impact on Relevant Fuel-Vehicle Systems. The increased use of Smart vehicles and infrastructure could increase the safety of vehicles and reduce fuel consumption. This will have an impact on the type of vehicles that are built (e.g., mass requirements may be different if cars are safer), on the emissions legislation in these areas (reduced congestion results in less pollution and fuel consumption), and on demand.

Supplemental Topics

The following potential innovations and areas of research could materially impact development and progression of the fuel-vehicle systems under review for this study. Topic papers have been provided on supplemental topics that the study subgroups found to offer important potential. These topic papers can be found on the NPC website and a complete list can be found in Appendix 4D at the end of this chapter. Topic paper abstracts can be found in Appendix C at the back of Part 2 of this report.

The list in Table 4-12 has been provided because these topics may be of interest to readers. This list also provides insights into the depth and range of technologies consider in this study.

FINDINGS

Twelve Priority Technology hurdles were identified that must be overcome for wide-scale commercialization of advanced fuel-vehicle systems by 2050.

- There are circumstances when all vehicle technology systems can achieve wide commercialization if there is sustained R&D investment to resolve the technology hurdles and if transition hurdles are overcome.
- The largest potential CO_2e/mile reduction is achieved by overcoming the various technology hurdles associated with using lignocellulosic feedstock.
  - Biochemical hyrolysis is the process of using enzymes on pretreated lignocellulosic materials to break down complex cellulose into component sugars. Currently, the volume of enzymes required to break down cellulose is significantly higher than is used in corn ethanol production.
  - Fermentation of C5 and C6 sugars simultaneously is still a challenge. Fermentation of pentose (five carbon) sugars to a fuel product (or other value-added product) is critical to the economic viability of a cellulosic biofuel plant.
  - Lignocellulose logistics/densification, including long-term storage and transportation to conversion facilities is a problem that has not yet been solved. Biomass is a relatively localized product and this is especially the case for crop residues and grasses. The cost and inefficient delivery of the feedstocks to centralized plants has placed severe limitations on the economies of scale of biomass conversion plants.
  - Pyrolysis is a thermochemical alternative to the biochemical conversion processes. Pyrolysis produces a bio-oil that can then be transported and further processed in a refinery. Pyrolysis

Paper	Subgroup
Alcohol Boosted Turbo Gasoline Engines (Paper #4)	Engines & Vehicles (LD and HD)
Low Temperature Combustion (Paper #6)	Engines & Vehicles (LD and HD)
Production of Alternative Liquid Hydrocarbon Transportation Fuels from Natural Gas, Coal, and Coal and Biomass (XTL) (Paper #8)	Hydrocarbon Liquids
Are We Going to be Able to Meet World Food and Biofuel Demands in 2050? (Paper #10)	Biofuels
Separations Landscape for the Production of Biofuels (Paper #14)	Biofuels
U.S. Woody Biomass Yields at the State and Regional Level (Paper #15)	Biofuels
Yield Projections for Major U.S. Field Crops and Potential Biomass Crops (Paper #16)	Biofuels
Emerging Electric Vehicle Business Models (Paper #18)	Electric
The Interaction Between Plug-in Electric Vehicles, Distributed Generation, and Renewable Power (Paper #19)	Electric
Safety Considerations for LNG Use in Transportation (Paper #21)	Natural Gas
Renewable Natural Gas for Transportation (Paper #22)	Natural Gas
Hydrogen-Compressed Natural Gas (HCNG) Transport Fuel (Paper #25)	Hydrogen
Carbon Capture & Storage (CCS) (Paper #27)	GHG Emissions
Greenhouse Gas Life Cycle Assessment/Analysis (Paper #29)	GHG Emissions

Table 4-12. *Examples of Subgroup Topic Papers*

can be done on a smaller scale, and so does not rely on densification.

- Low-cost lightweighting has the potential to reduce GHG and cost of driving and is relevant to all fuel-vehicle systems, but overcoming challenges will require progress in many areas of development.
- CNG has the lowest technical challenge. The Leverage Liquid ICE Fuel Economy Technology hurdle relates to CNG adopting and continuing to leverage the relevant ICE fuel efficiency improvements. If CNG is able to optimize around the ICE fuel efficiency technologies, the vehicle premium of CNG vehicles over ICE vehicles could be reduced through improved fuel economy and reduction in fuel storage. CNG has non-technical hurdles primarily related to infrastructure. The transition to fully OEM-developed and produced NGVs is critical in enabling wide-scale adoption of NGVs in the marketplace.
- Among PEVs, priority hurdles exist within the battery, which represents both the technology hurdles (lithium-ion energy density and longevity). The Advanced Battery emphasis in disruptive innovations may also provide solutions to these hurdles.
- The FCEV is unique among the fuel-vehicle systems and has technical hurdles in both the vehicle, to extend fuel cell durability and life, and more significantly in compression and storage infrastructure. Advanced storage systems that require less land and capital are needed for the mass deployment of hydrogen fueling infrastructure.
- Medium- and heavy-duty vehicles face hurdles in Combustion Optimization, which includes a suite of technologies that can be combined for improved fuel economy. Combustion Optimization is also

important for achieving the Advanced Fuel Economy Potential for heavy-duty CNG/LNG vehicles.

A broad portfolio of technology options provides the opportunity to benefit from potential Disruptive Innovations.

- Disruptive innovations have not been considered in the range of cost estimates for 2050 because they are early stage technologies with high uncertainty. It could be decades for a disruptive innovation to move through basic research, applied research, production engineering, and finally production.

APPENDIX 4A:

APPROACH TO TECHNOLOGY ANALYSIS

This study is unique in that it compares and evaluates very different technologies. This appendix supplements the Methodology section in the chapter and focuses on:

- Explaining the team structure and how technology expertise was structurally built into the teams at all levels
- Describing the approach to ensure the consistency in the assessment of the levels of difficulty in overcoming each hurdle
- Highlighting the common hurdles across the fuel-vehicle systems.

TECHNOLOGY TEAM STRUCTURE

From the beginning, the technology approach sought to ensure that the evaluation of technologies was a rigorous as possible and involved the leading scientists in all areas. The Methodology section of this chapter described the expert review panel. In addition to the expert review panel, the other components of the technology team structure included:

- Core team of the Assistant Chairs of all the technology groups. This group, referred to as the Technology Task Group, ensured comparability of the analysis.
- Experts in the technology teams. In addition to the expert review panel, each technology had their own experts as part of their core team.
- Experts who contributed topic papers. In each area, e.g., low-temperature combustion, advanced batteries, etc., the NPC sought leading industry experts to write the papers. Refer to Appendix 4D for the authors of the topic papers.

APPROACH TO ENSURING CONSISTENCY IN DIFFICULTY CODING

As described in the Methodology section of this chapter, the color coding denotes the current level of difficulty. No RED or no YELLOW hurdles means that no further significant investment or effort is required. As pointed out by the expert review panel, you cannot ask for significant R&D support for a technology and have no RED hurdles—this would be contradictory. It is expected that RED hurdles will take more effort and investment than YELLOW. An all-BLUE chart would indicate that no significant government or private actions are needed to achieve wide-scale commercialization.

Subgroup Evaluation

Each subgroup assessed each hurdle using the definitions provided for technology and nontechnology hurdles, based on literature and/or the collective view of each subgroup. The evidence for this assessment is provided in the chapter. In particular, there is a fairly robust discussion in the chapter on any RED hurdles and all priority hurdles.

Comparison of Treatment of RED Technology Hurdles in Subgroup Chapters

Additional emphasis was placed on comparing the RED technology hurdles in the subgroup chapters. Key areas of comparison were:

- Importance of technology breakthroughs for wide-scale commercialization of the fuel-vehicle system
- Level of technical detail in the description of key technical areas
- Assumptions on technology evolution.

Peer Review, All Subgroup Assistant Chairs, Box-by-Box Comparison of Level of Detail and Optimism

Significant effort was spent by all of the Subgroup Assistant Chairs on this activity. Together with the Technology Task Group Chair and Assistant Chair, every hurdle was reviewed by the group

Hurdle	Common Definition of Required State for Reaching Wide-Scale Commercialization
Production capacity	Sufficient, cost-effective production capacity exists to support wide-scale vehicle adoption
Distribution capacity	Sufficient, cost-effective distribution capacity exists to support wide-scale vehicle adoption
Fueling availability	Equally available to gasoline
Ease and speed of refueling	Does not result in greater inconvenience for customers relative to conventional vehicles
Safety	Comparable with conventional vehicle
Extreme weather performance	Comparable with conventional vehicle
Power and torque	Comparable with conventional vehicle
Cabin & luggage space	No functional impact relative to conventional vehicle
Vehicle premium	Cannot be beyond purchase ability even if it pays off in fuel savings
Fuel cost (incl. capital for infrastructure)	Fuel cost per mile less than or equal to conventional vehicle

Table 4A-1. *Common Hurdles*

representing all content areas, comparing across the charts to ensure that the hurdles:

- Were consistent in level of detail
- Had consistent evidence for RED, YELLOW, BLUE coding.

In addition, key differences in coding were discussed, so that there was a common basis of understanding. For example, why compression is YELLOW for natural gas, but RED for hydrogen.

Expert Reviews

The expert review panel reviewed the coding of the subgroup hurdles in the first, second, and third expert reviews.

COMMON HURDLES FOR NATURAL GAS, ELECTRICITY, AND HYDROGEN

The hurdles highlight the areas that will impact wide-scale commercialization of these technologies. Many hurdles are unique to the vehicle-fuel pathway, but there are some that are common for natural gas, electricity, and hydrogen. These common hurdles are listed in Table 4A-1. In the hurdle charts for these three technologies, there is the same generic definition, but in some cases this definition has been translated to a lower level of detail into something more meaningful and specific for the vehicle/fuel pathway.

APPENDIX 4B:
HURDLE CHARTS

Engines & Vehicles

Biofuels

Electric

Natural Gas

Hydrogen

Medium- and Heavy-Duty Vehicles

HURDLE		REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
VEHICLE:				
MASS	🟩 LIGHT-WEIGHTING	Low cost structural applications of aluminum, carbon fiber or other advanced materials for mass market vehicles	🔴	New materials involve new supply chains, manufacturing processes and service processes
ACTIVE SAFETY	🟩 CONNECTIVITY	Ubiquitous “smart” vehicles and “smart” infrastructure	🔴	“Crashless” vehicles enable significant light-weighting (e.g., removal of structure, airbags)
AERODYNAMICS	DESIGN	Low drag designs compliant with other design criteria	🟡	Matters more at high speeds; can be at odds with other design and regulatory criteria (pedestrian protection)
ROLLING RESISTANCE	TIRES	Low cost application of low rolling resistance tires	🔵	Rolling resistance / traction trade-offs are being overcome
POWERTRAIN:				
INTERNAL COMBUSTION ENGINE	STRATIFIED CHARGE/ LEAN BURN	Cost competitive, robust lean aftertreatment	🟡	Incremental benefit relative to existing technology
	HOMOGENEOUS COMPRESSED CHARGE IGNITION	Cost competitive robust control system	🟡	Incremental benefit relative to existing technology
	CLEAN DIESEL	Cost competitive robust aftertreatment	🟡	Fuel + Vehicle must cost less than gasoline hybrid to be competitive
	EXHAUST HEAT RECOVERY	Cost competitive fuel economy improvement	🔴	Thermoelectric and rankine cycle approaches being developed
	FUEL FLEXIBILITY	Cost competitive ultra-low emissions	🟡	High cost exhaust and evaporative emissions control with LEVIII standards
HYBRID POWER BATTERIES	COST	HEV fuel savings offset incremental vehicle price	🟡	Hybrid system cost is primary barrier
	RECYCLING	Zero or positive value at vehicle disposal	🟡	Significant disposal cost with today’s technology; second use applications under study
	MATERIALS	Multiple geographic sources for key raw materials	🟡	Some materials used in batteries and motors are sourced primarily in one country and have dramatically risen in price
HYBRID SYSTEMS	MOTORS	Lower cost, mass and alternative (non-rare earth) materials	🔵	Hybrid system cost is primary barrier
	CONTROLLERS / POWER ELECTRONICS	Lower cost, simpler systems with better thermal management characteristics	🟡	Hybrid system cost is primary barrier
	REGENERATIVE BRAKING	HEV fuel savings offset incremental vehicle price	🟡	Hybrid system cost is primary barrier
FUEL:				
CARBON FOOTPRINT	AVAILABLE VOLUMES	Widespread, cost competitive low carbon fuels (cellulosic ethanol)	🟡	Scaling to high volume has been slower than anticipated
OCTANE	ENGINE EFFICIENCY	Minimum U.S. RON increases from 90 to 95 (Europe minimum)	🟡	Alcohols more effective than hydrocarbons at same RON
INDUSTRY MODEL:				
TECHNOLOGY & VEHICLE DEVELOPMENT	🟩 LONG LEAD-TIMES	Economically viable faster development and deployment	🔴	Need advanced math-based design, development, testing, and validation tools
VEHICLE LONGEVITY	🟩 SLOW STOCK TURN-OVER	Economically viable faster turnover of vehicle stock	🔴	Requires massive reduction in vehicle cost
MOBILITY MODEL:				
VEHICLE UTILIZATION	VEHICLE OWNERSHIP	Improved utilization of vehicle stock for personal mobility	🔴	Car-sharing programs emerging
TRAFFIC MANAGEMENT	CONGESTION/ POOR THROUGHPUT	Integration of “smart” vehicles and roads	🔴	Improve traffic throughput efficiency to reduce wasted time and energy

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES “BREAKTHROUGH OR INVENTION”

Figure 4B-1. *Hurdles for Light-Duty Engines and Vehicles*

BIOFUELS FOR TRANSPORTATION:

HURDLE			RATING	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION
BIOCHEMICAL	PRETREAT	INHIBITORY SUBSTANCES	🔵	Pretreat is usually an energy intensive process. Research to minimize energy and chemical inputs is needed.
		CAPITAL COST/ CHEMICAL USE	🟡	
	🟩 HYDROLYSIS		🟡	Because cellulose is a complex structural material developing simple processes for either enzymatic or chemical systems has been difficult. Cheaper enzymes and chemistries which minimize the crystallinity of cellulose need to be developed.
	🟩 ETHANOL FERMENTATION		🟡	Ethanol fermentation: development of efficient micro-organisms that will ferment a variety of sugars to 7+% ethanol in less than 30 hours and that are either tolerant to contamination or run under conditions where contamination is minimized still needs to be developed.
	NON-ETHANOL FERMENTATION	PRODUCT TOLERANCE/ TOXICITY & AERATION	🔴	There is a real requirement for these to anaerobic or require minimal oxygen to minimize energy inputs. Ability to produce wanted product at concentrations that can be recovered energy efficiently is also important.
		FUEL/ORGANISM	🟡	
THERMOCHEMICAL	FEEDSTOCK PREPARATION		🔵	For biological processes minimizing water usage and have sugars produced be concentrated enough to minimize energy required is important as well as minimizing inhibitors. For thermochemical processes size reduction and drying methods that minimize energy inputs are required.
	🟩 GASIFICATION		🟡	Tar removal and quality of syn gas produced need to fit conversion process. Oxygen blown systems are problematic from a logistical and scale issue.
	🟩 PYROLYSIS	STABILIZATION	🔴	Production of pryrolysis oils that are readily converted to a high yield of liquid transportation fuel is problematic. Upgrading processes for the wide variety of chemicals present in pyrolysis oil are still in development. Stable storage of pyrolysis oils are also problematic.
		SOLID/VAPOR SEPARATION	🟡	
	RENEWABLE DIESEL	FEEDSTOCK	🟡	Technologies are available. Fischer Tropsch processes have a low energy yield relative to other processes and require scales not suitable for biomass at present.
		CATALYST/ INTEGRATION	🔵	
	HYDROTHERMAL LIQUEFACTION	FEEDSTOCK	🔵	Rapid heat transfer needed for this process is imperative. Biomass is relatively difficult to get into a form that can be pumped into the high pressure, temperature zones needed for this at reasonable concentrations.
		CATALYST	🔴	
	SUGAR TO HYDROCARBONS	PRETREATMENT & SEPARATION	🟡	Sugar to hydrocarbon process needs to produce a clean sugar stream without contaminants, contaminants will poison a precious metal catalyst. It is difficult to achieve these purities with lignocellulosic streams. Development of separation technologies specific for sugar will greatly advance this area.
		CATALYST	🔴	
	HYBRID TECHNOLOGIES		🔴	Hybrid technologies are not yet developed to an extent that they are deployable.
ALGAE	CULTIVATION/ HARVESTING		🔴	Expensive, huge water evaporation losses, controlling contamination problematic, energy efficient CO_2, dilute cell growth and disconnect between rapid cell growth and energy product production.
	CO-PRODUCTS		🟡	Major challenge is development of markets for the non-oil fraction of algae for food or feed fuel.
	BIO-OIL RECOVERY		🔴	Algal growth is relatively dilute, energy efficient cell mass recovery, development of low energy oil separation processes needed for success.
	CONVERSION		🔴	Conversion technology must be tailored to the specific product slate, but it is likely that existing processes can be tailored to process microalgae effectively.

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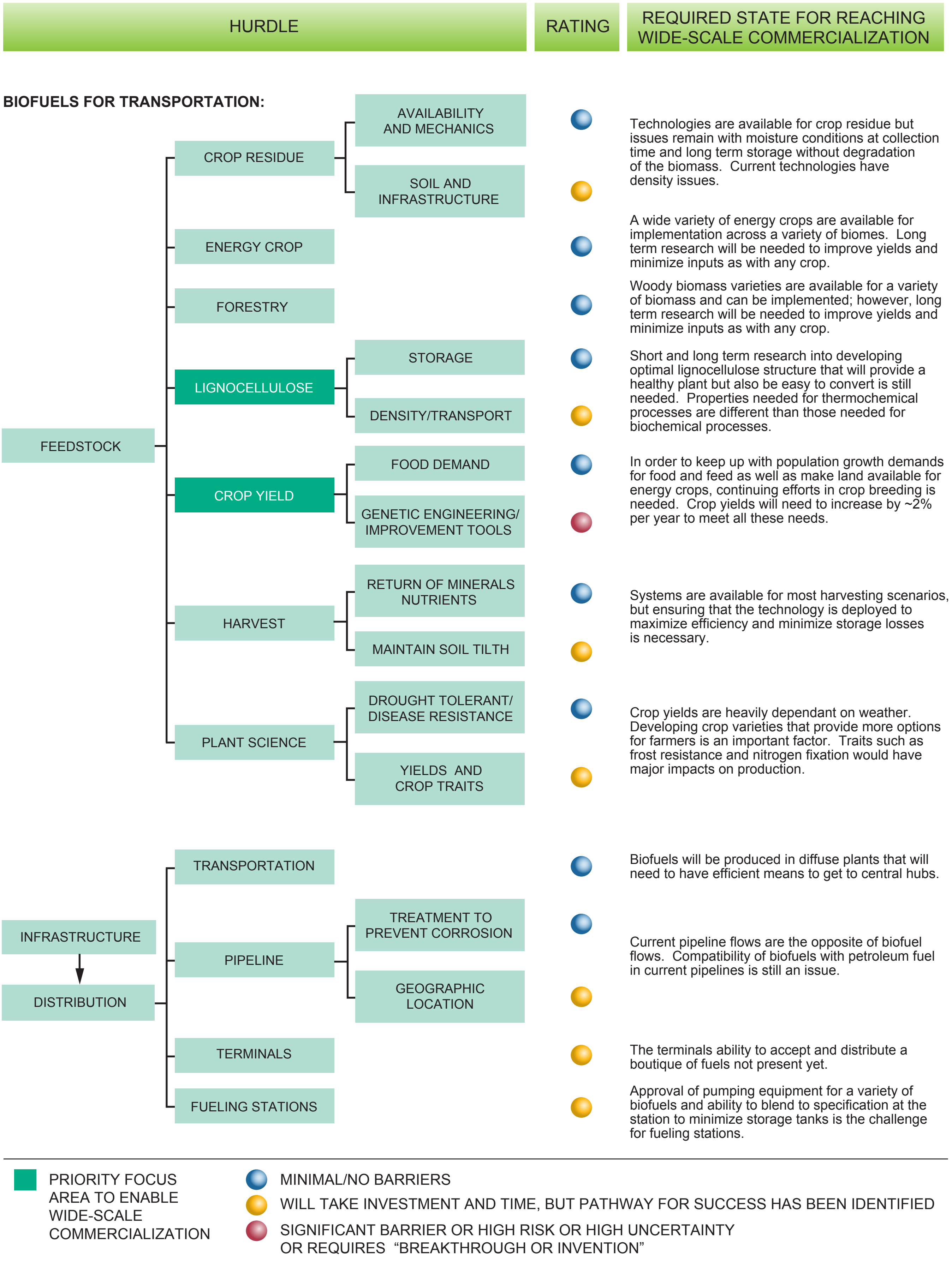
Figure 4B-2. *Hurdles for Biofuels*



Technologies are available for crop residue but issues remain with moisture conditions at collection time and long term storage without degradation of the biomass. Current technologies have density issues.

A wide variety of energy crops are available for implementation across a variety of biomes. Long term research will be needed to improve yields and minimize inputs as with any crop.

Woody biomass varieties are available for a variety of biomass and can be implemented; however, long term research will be needed to improve yields and minimize inputs as with any crop.

Short and long term research into developing optimal lignocellulose structure that will provide a healthy plant but also be easy to convert is still needed. Properties needed for thermochemical processes are different than those needed for biochemical processes.

In order to keep up with population growth demands for food and feed as well as make land available for energy crops, continuing efforts in crop breeding is needed. Crop yields will need to increase by ~2% per year to meet all these needs.

Systems are available for most harvesting scenarios, but ensuring that the technology is deployed to maximize efficiency and minimize storage losses is necessary.

Crop yields are heavily dependant on weather. Developing crop varieties that provide more options for farmers is an important factor. Traits such as frost resistance and nitrogen fixation would have major impacts on production.

Biofuels will be produced in diffuse plants that will need to have efficient means to get to central hubs.

Current pipeline flows are the opposite of biofuel flows. Compatibility of biofuels with petroleum fuel in current pipelines is still an issue.

The terminals ability to accept and distribute a boutique of fuels not present yet.

Approval of pumping equipment for a variety of biofuels and ability to blend to specification at the station to minimize storage tanks is the challenge for fueling stations.

Figure 4B-2. *Hurdles for Biofuels (Continued)*

REQUIREMENT			REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	PRESENT DAY, FOR ALL VEHICLE CLASSES IN SCOPE		
				PHEV10	PHEV40	BEV100
ELECTRICITY GENERATION & TRANSMISSION:						
		CAPACITY	Sufficient, cost-effective fuel production capacity exists to support wide-scale vehicle adoption, or can be added within existing business practices	🔵	🔵	🔵
ELECTRICITY DISTRIBUTION:						
		CAPACITY	Sufficient, cost-effective fuel distribution capacity exists to support wide-scale vehicle adoption, or can be added within existing business practices	🔵	🔵	🟡
CHARGING:						
	RESIDENTIAL (SINGLE UNIT)	🟩 EVSE INSTALLATION PROCESS	The installation process for the electric vehicle supply equipment (EVSE) is quick and easy and is not a deterrent to vehicle purchase	🔵	🔵	🟡
		EVSE INSTALLED COST	The cost of the EVSE plus installation is not a deterrent to vehicle purchase	🔵	🔵	🟡
	RESIDENTIAL (MULTI-UNIT)	EVSE INSTALLED COST	The cost of the EVSE plus installation is not a deterrent to placement of EVSEs	🔴	🔴	🔴
		🟩 BUSINESS MODEL	Business models, regulations, codes and standards are aligned to allow 3rd-party providers to install and charge for public charging	🟡	🟡	🟡
	COMMERCIAL/ PUBLIC	UNIVERSAL ACCESS	All chargers are useable by all customers	🟡	🟡	🟡
		CHARGING AVAILABILITY	Sufficient charging locations exist to support all trips	n/a	n/a	🔴 *
		ELECTRICAL STANDARDS (DC)	Standards developed and implemented for high-voltage DC charging ("Level 3")	n/a	n/a	🟡
		SYSTEM DIAGNOSTICS & REPAIR	If vehicle charging fails and the vehicle cannot operate, a seamless system exists to diagnose and repair the problem	🔵	🔵	🟡
		🟩 TIME REQUIRED TO CHARGE BATTERY	Does not result in greater inconvenience for consumers relative to conventional vehicles	🔵	🔵	🔴 *
GRID INTEGRATION:						
		MANAGED CHARGING TO MINIMIZE NEGATIVE IMPACT TO GRID	Communication and/or Management systems are standardized and capable of controlling charging to minimize negative impacts to the grid	🟡	🟡	🟡
		REGULATORY CERTAINTY	A sufficient level of regulation exists in jurisdictions across the country to allow EVSE installation/operation (including revenue generation) to support wide-scale PEV adoption	🟡	🟡	🟡
FUEL ECONOMICS:						
		CAPITAL REQUIRED FOR CHARGING INFRASTRUCTURE	Capital required for dispensing infrastructure to support all trips can be accommodated within existing business practices	n/a	n/a	🔴 *
		DISPENSED FUEL COST	Fuel cost per mile is less than or equal to conventional vehicles	🔵	🔵	🔵

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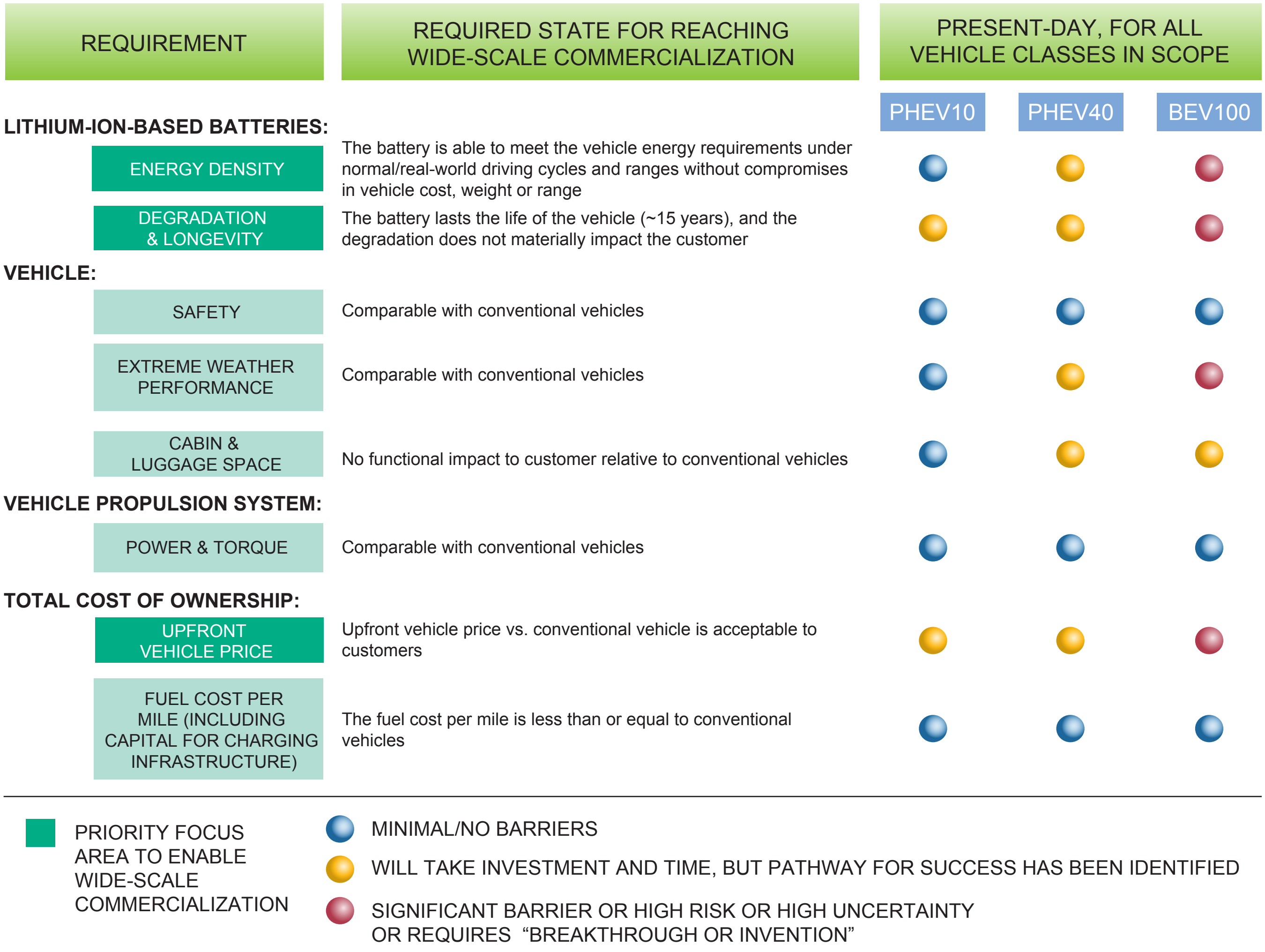
* There is a minority view within the Electricity Subgroup that BEVs do not need to be one-to-one substitutions for conventional vehicles. The argument is that if households adjust their driving behavior, such as using the BEV only for trips where the limited range is not an issue, then (1) battery charging time is not an issue, and (2) away-from-home charging infrastructure is not needed, thus, the capital required to enable such infrastructure is not an issue. Additionally, as described in this chapter, there are potentially non-economic factors included in the purchase decision that could outweigh any perceived vehicle limitations.

Figure 4B-3. *Infrastructure Requirements for Grid-Connected Vehicles*



REQUIREMENT	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	PRESENT-DAY, FOR ALL VEHICLE CLASSES IN SCOPE		
		PHEV10	PHEV40	BEV100
LITHIUM-ION-BASED BATTERIES:				
ENERGY DENSITY	The battery is able to meet the vehicle energy requirements under normal/real-world driving cycles and ranges without compromises in vehicle cost, weight or range	🔵	🟡	🔴
DEGRADATION & LONGEVITY	The battery lasts the life of the vehicle (~15 years), and the degradation does not materially impact the customer	🟡	🟡	🔴
VEHICLE:				
SAFETY	Comparable with conventional vehicles	🔵	🔵	🔵
EXTREME WEATHER PERFORMANCE	Comparable with conventional vehicles	🔵	🟡	🔴
CABIN & LUGGAGE SPACE	No functional impact to customer relative to conventional vehicles	🔵	🟡	🟡
VEHICLE PROPULSION SYSTEM:				
POWER & TORQUE	Comparable with conventional vehicles	🔵	🔵	🔵
TOTAL COST OF OWNERSHIP:				
UPFRONT VEHICLE PRICE	Upfront vehicle price vs. conventional vehicle is acceptable to customers	🟡	🟡	🔴
FUEL COST PER MILE (INCLUDING CAPITAL FOR CHARGING INFRASTRUCTURE)	The fuel cost per mile is less than or equal to conventional vehicles	🔵	🔵	🔵

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Figure 4B-4. *Vehicle Requirements for Grid-Connected Vehicles*

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
FUEL PRODUCTION:			
GAS RESOURCE AVAILABILITY	Sufficient resource to support large scale vehicle deployment and use	🔵	Sufficient reserves to supply in excess of 8 tcf added demand from North American sources
CENTRALIZED LIQUEFACTION	Large scale liquefaction capable of cost effectively supplying large vehicle fleets	🟡	Mature technology, but significant investment required to build scale capacity dedicated to vehicle fuel
DISTRIBUTED LIQUEFACTION	Localized, small scale liquefaction (<50,000 gal/day) providing LNG at fleet depots	🟡	Small scale liquefaction improves smaller fleet penetration. Solutions required to be cost effective at low output
RNG (BIO/GAS) FUEL	Efficient RNG feedstock collection systems for widescale, scalable production	🟡	Feasible for localized fleets. Approx 4.5 tcf supply potential but significant logistics to aggregate feedstocks. Thermal gasification required to maximize feedstock compatibility
FUEL QUALITY & COMPOSITION	No vehicle performance derate due to geographic or seasonal fuel quality variation	🔵	Need harmonized codes & standards for CH_4 content, impurities, etc., to ensure emissions, driveability and vehicle quality, reliability, and durability
FUEL DISTRIBUTION:			
PIPELINE CNG-FOSSIL	Uniform pipeline gas standards and incremental expansion to serve all markets	🔵	Existing pipe network enables access to most, but not all geographic markets. Expansion for use of NG in other industries should include provision for Transport demand
PIPELINE CNG-RNG	RNG must be fully fungible with pipeline gas system for mass market uptake	🟡	Need harmonized, consistent and achievable utility gas specifications for RNG injection to pipelines
LNG VIA TRUCK	Must add no insurmountable cost to dispensed fuel	🔵	Dedicated trailers required for cryogenic storage. Lower delivered energy per trailer load increases number of deliveries but cost can be accommodated in fuel price
LNG VIA RAIL	Broad availability of dedicated rail car use available for transportation and storage	🟡	Few dedicated rail cars. Could supplement truck transport but not market critical
FUEL STORAGE:			
STATION CNG STORAGE	*Not applicable*		*Not applicable*
CENTRALIZED LNG STORAGE	Sufficient centralized storage available to fulfill demand during production disruptions	🔵	Peak shavers could be used for reserve storage. They also provide a bridge to support vehicle deployments while dedicated liquefaction capacity is built
STATION LNG STORAGE	On-site fuel storage can accommodate dispensing capacity without fugitive emissions release	🟡	Fuel storage achievable within land requirements. Fuel venting can be an issue if throughput is not predictable. LCNG stations can use boil off fuel, or pipeline reinjection
LIGHT-DUTY CNG DISPENSING:			
FUEL STATION AVAILABILITY	Fleet solutions, plus geographic availability and dispensing capacity to replicate 30% of current gasoline network	🔴	Limited availability today, approx. $50 billion to build new dedicated CNG stations, plus up to $30 billion if land purchases required rather than upgrade existing gasoline stations
STATION-BASED COMPRESSION	Low cost highly reliable compression to accept a wide range of input pressures	🔵	Can generally use low pressure pipeline for feed, or use variable first stage compression if needed
EASE & SPEED OF REFUELING	Does not result in greater inconvenience for customers relative to conventional vehicles	🔵	Advances in compression reduce station O&M costs. Some increase in refuel duration. Need to implement widespread use of temperature compensated fill algorithms or pre-chilled fuel to guarantee complete tank fill
HOME REFUELING	Any CNG LD vehicle can be cost effectively refilled at home overnight or in a few hours	🔴	Not specifically required for market penetration, but would add to customer appeal. High cost technology and potential reliability and safety concerns
HEAVY-DUTY CNG/LNG DISPENSING:			
FUEL STATION AVAILABILITY	Fleet solutions, plus geographic availability and dispensing capacity to match 30% of current diesel truck stops	🟡	Limited availability today. Initial expansion via fleet centric stations. LCNG stations will make both LNG and CNG available for multiple vehicle types
LNG/LCNG STATION DESIGNS	Low cost, highly reliable and standardized systems to streamline robust network build out	🔵	Mature technologies, can be modularized for scale. LCNG can serve multiple vehicle types, and provide CNG to areas where pipeline network is not available
EASE & SPEED OF REFUELING	Does not result in greater inconvenience for customers	🔵	Some increase in refueling duration but manageable within operations. Training required for LNG dispensing – handling cryogenics, dedicated staff under truck stop model
FUEL ECONOMICS:			
DISPENSING CAPITAL INVESTMENT	Manageable total investment with minimal impact on dispensed fuel costs	🔴	Multi-billion dollar investment to provide ubiquitous supply, replicating 30% of gasoline or diesel dispensing capacity
DISPENSED FUEL COST	Sustainably lower than diesel or gasoline fuel	🔵	Even with land, liquefaction, & dispensing capital, Natural Gas can be materially lower price than equivalent hydrocarbon fuels. RNG competitive with gasoline and diesel

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Figure 4B-5. *Hurdles for Natural Gas Supply and Fueling Infrastructure*

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
ENGINE:			
POWER & TORQUE	Match equivalent gasoline engine ratings	🔵	When properly optimized for CNG, no impact on power or torque, particularly in dedicated configuration
FUEL ECONOMY	Minimal or no penalty relative to gasoline	🔵	Dedicated CNG engines can exceed gasoline efficiency via higher compression ratio
HOT/COLD WEATHER PERFORMANCE	Comparable performance to ICEs	🔵	Utilize similar engine control strategies to gasoline
ADVANCED FUEL ECONOMY POTENTIAL	Long term viable roadmap for continued improvement	🟡	Compatible with boosting, downsizing, hybridization, lightweighting, etc.
DIRECT INJECTION	Technical pathway for Direct Injection CNG	🔴	Non-critical as market can persist as PFI, but value in R&D needed to identify solution for dedicated CNG DI. Reliance on PFI only may incur fuel economy limit
EMISSIONS COMPLIANCE	Emissions compliance with no incremental aftertreatment over gasoline	🔵	May require custom catalyst formulations to meet future CH_4 standards
OBD COMPLIANCE	Fully compliant with all OBD requirements	🔵	Requires tailored Electronics and Software architecture to capture full range of CNG system states
NG OPTIMIZED DESIGNS	Engine systems designed specifically for NG operation	🔵	Piston, valvetrain, air handling optimization. Can be justified when sufficient market volume is achieved
DURABILITY	No penalty relative to gasoline	🔵	No impact with shared architecture, ratings and OEM support
OEM PRODUCTION	Factory built, first fit engines to provide build capacity and diversity of product options	🟡	Limited range of engine options available. Some plant investment required to adapt assembly lines
ONBOARD FUEL STORAGE:			
CNG STORAGE CAPACITY	No impact on required vehicle operating range compared to gasoline	🟡	Increased tank volume (and weight) due to low energy density of CNG. Sufficient fuel can be stored for 300 mile range. Near term cost issues
INCREASED ENERGY DENSITY	Not specifically required but would be beneficial	🔴	Not market critical, but R&D into nano-structure or adsorbent materials could provide step change in fuel energy storage, range extension or reduced packaging
FUEL VENTING	No unintentional venting of fuel	🔵	No issue for CNG systems
VEHICLE:			
VEHICLE OPTON AVAILABILITY	Broad range of OEM vehicles tailored for different segments and vocations	🟡	Majority of options available only as aftermarket today. More OEM produced “CNG ready platforms” being offered. Not a barrier if market pull is sufficient
OEM INTEGRATION	Optimized vehicle integration into vehicle platform and factory build	🔵	OEM involvement is obsoleting requirement for retrofit natural gas conversions
OPERATING RANGE	Minimum 250 to 300 mile range capability	🔵	Fuel storage can be integrated for 300 mile range. Improved fuel economy or fuel storage will further improve range.
CABIN & LUGGAGE SPACE	No functional impact relative to conventional gasoline & diesel vehicle	🟡	Requires OEM consideration for CNG within model architecture definition. Trending to no impact in Europe, with fuel tank/chassis/body integration
WEIGHT	Weight increase manageable without operating impact	🔵	Manageable. Type 1 CNG tanks can result in a weight increase, offsetting fuel economy. Type 4 carbon tanks significantly lighter, but more costly
SAFETY	No unmanageable safety risks from vehicle operation & maintanance	🔵	Appropriate use of design, codes & standards, education, and training
VEHICLE ECONOMICS:			
VEHICLE PRICE PREMIUM	Premium relative to conventional vehicles is manageable within equivalent purchase constraints	🔴	Current high price premium only recovered over very high mileage use, e.g., fleet operations. Viable pathway to competitive price via OEM integration & scale
FUEL COST PER MILE	Equal or less than comparable ICE vehicle	🔵	Low cost per mile due to comparable vehicle efficiency and low cost fuel
TOTAL COST OF OWNERSHIP	Equal or less than comparable ICE vehicle	🟡	Long-term economics are much more favorable with scaled production and lower price premiums

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Figure 4B-6. *Hurdles for Light-Duty Natural Gas Vehicles*

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
ENGINE:			
POWER & TORQUE	NG ratings should be equal to Diesel for target HD applications	🔵	Able to match majority of ratings by engines size as diesel
EFFICIENCY	Within 10% of diesel to preserve fuel economy, GHG, with long term pathway for improvement	🔵	Compression Ignition engines meet diesel efficiency. Spark Ignition within 10% in some applications
HOT/COLD WEATHER PERFORMANCE	Equal cold performance to ICEs	🔵	Utilize similar strategies to gasoline or diesel
EMISSIONS COMPLIANCE	Emissions compliance with no incremental aftertreatment over diesel	🔵	Able to comply with use of DPF and/or SCR. Spark Ignition complies with three-way catalyst
FUEL SUBSTITUTION	Maximize diesel displacement for optimum fuel efficiency and cost trade-off	🔵	100% diesel substitution by Spark Ignition. Up to 95% with Compression Ignition
FUEL QUALITY ROBUSTNESS	Tolerant to expected range of NG composition without excessive de-rate	🟡	Able to operate down to 75 MN (methane number) without damage. Benefit from fuel quality sensing to adjust power under extreme fuels
DURABILITY	Engine durability equal to Diesel	🔵	With shared architecture, ratings and OEM support. May require dedicated NG maintenance
OEM PRODUCTION	Factory built, first fit engines to provide build capacity and diversity of product options	🟡	Limited range of engine options available today but OEM engagement increasing. Minimal plant investment required
NG OPTIMIZED DESIGNS	Engine systems designed specifically for NG operation	🟡	Current HD NG engines use diesel architecture. Custom designs not required for acceptable performance, but could offer improvements
ONBOARD FUEL STORAGE:			
CNG STORAGE CAPACITY	No impact on required vehicle operating range compared to diesel	🟡	Acceptable for municipal, transit, refuse and urban delivery. Unsuitable for long haul. Benefit from R&D in high density storage – adsorbent nano-structures
LNG STORAGE CAPACITY	No impact on required vehicle operating range compared to diesel	🔵	400 to 600 mile range is possible with dual LNG tank systems, but high cost premium in low volume
FUEL VENTING	No unintentional venting of fuel	🟡	LNG must be used within timeframe. OK for high use fleets. Benefit from dev't of vapor recovery & reinjection systems
CRYOGENIC SYSTEM DURABILITY	No impact on vehicle robustness or failure rate	🟡	High Pressure LNG pumps needed for some Compression Ignition systems. Durability needs continued improvement. Fuel level sensing robustness
VEHICLE:			
VEHICLE OPTON AVAILABILITY	Broad range of OEM vehicles tailored for different segments and vocations	🔵	Increasing diversity of vehicle options available today. Will grow as market expands
OEM INTEGRATION	Optimized vehicle integration into vehicle platform and factory build	🔵	OEM involvement is obsoleting requirement for retrofit NG conversions
OPERATING RANGE	Fit for purpose by segment, vocation, without excessive refueling	🟡	Some current limitation. Leverage fuel economy technology to reduce fuel storage required and increase range
TELEMATICS	Compatible with IT based scheduling, monitoring & optimization systems	🔵	No restriction, investment in product options required and system tailoring for NG needed
WEIGHT & CARGO LOAD	Weight increase manageable without operating impact	🟡	NG fuel storage increases vehicle weight (and may displace cargo in some applications). Benefit from lightweighting and fuel economy improvement
SAFETY	No unmanageable saftey risks from vehicle operation & maintanenance	🔵	Appropriate use of design, codes & standards, education and training
VEHICLE ECONOMICS:			
VEHICLE PRICE PREMIUM	Competitive with comparable ICE vehicle	🔴	Significant premium today, requiring extended capital or incentives. Can be reduced with volume & OEM engagement
FUEL COST PER MILE	Equal or less than comparable ICE vehicle	🔵	Combined fuel efficiency and lower fuel price creates operating cost advantage
PAYBACK PERIOD	Within 3 years to offset capital expense	🟡	Can be achieved with low fuel cost, and sufficient mileage. Assisted by price premium reductions
TOTAL COST OF OWNERSHIP	Competitive with, or lower than, diesel	🔵	Fuel cost savings dominate over longer periods. Secondary market required to protect residual value to first owner

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

Figure 4B-7. *Hurdles for Medium- and Heavy-Duty Natural Gas Vehicles*

HURDLE	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
VEHICLE:			
VEHICLE PLATFORM	Capable of applying non-propulsion system improvement made on conventional gasoline vehicles	🔵	See Vehicles & Engines chapter for details
CABIN & CARGO SPACE	No functional impact to customer relative to conventional vehicles	🔵	No functional impact to customers due to packaging improvement in current generation vehicles
ON-BOARD STORAGE SYSTEM	Vehicle range between fueling is acceptable (>=300 miles)	🟡	Some FCEVs have demonstrated range of 300 miles or greater; however, not across all vehicle classes
SAFETY	Comparable with conventional vehicles	🔵	FCEVs have been designed to the same safety standard as conventional vehicles
FUEL CELL:			
🟩 DURABILITY & DEGRADATION	Last life of vehicle (150,000 miles) and degradation does not materially impact customer	🟡	>150,000 mile life has been demonstrated in the lab and must be proven in field trials
EXTREME WEATHER PERFORMANCE	Comparable with conventional vehicles	🟡	Rapid startup in cold weather and sustained high power performance in hot weather do not yet match conventional vehicles
PRECIOUS METAL REQUIREMENTS	Vehicle life is comparable to conventional vehicles and fuel cell system costs are not prohibitive	🟡	Platinum requirements have dropped significantly and are not expected to be a technical or economic limitation
ELECTRIC MOTOR:			
POWER & TORQUE	Comparable with conventional vehicles	🔵	Electric drive results in no comprises in power and torque
FCEV ECONOMICS:			
🟩 UPFRONT PRICE PREMIUM	Vehicle price results in acceptable economics for consumers	🔴	Current costs for fuel cell and storage system are high; lower costs can be achieved with scale production and lower platinum requirements
FUEL COST PER MILE	Fuel cost per mile is less than or equal to conventional vehicles	🔴	Fuel costs are expected to be higher in the near term; larger fueling capacity stations and high utilization improve economics, however – this has significant uncertainty

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

Figure 4B-8. *Fuel Cell Electric Vehicle Hurdles – 2012 Status*

HURDLES	REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
CENTRALIZED PRODUCTION & DISTRIBUTION:			
EMISSIONS COMPLIANCE	Fully compliant with regulations	🔵	Shifts emissions from tailpipe to fuel production; overall ~50% reduction in emissions on a well-to-wheels basis
EXISTING PRODUCTION CAPACITY	Sufficient, cost effective, production capacity exists to support wide-scale vehicle adoption	🟡	Large scale production exists and some merchant capacity exists; however, addtional capacity will be needed
EXISTING DISTRIBUTION CAPACITY	Sufficient, distribution capacity exist to support wide-scale vehicle adoption	🟡	Investments needed to expand existing capacity
DISTRIBUTION ECHNOLOGY	Payload capacity can meet demand requirements without materially impacting existing fueling station business operations	🟡	On-road truck deliveries, which are likely in the near and long term, require incremental increases in payload capacity
TRADITIONAL PRODUCTION TECHNOLOGY	Production can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand	🔵	Technology is mature and efficient and has been used at large scale for decades
NON-TRADITIONAL PRODUCTION	Production can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand	🔴	Steam methane reforming (SMR) with biomethane, water electrolysis and carbon capture & sequestration are options; however, installed capacity is limited
DISTRIBUTED PRODUCTION:			
EMISSIONS COMPLIANCE	Fully compliant with regulations	🔵	~20% increase in emissions over gasoline on an energy basis; however, ~50% reduction in emissions on a well-to-wheels basis
EXISTING CAPACITY	Sufficient, cost effective, production capacity exists to support wide-scale vehicle adoption	🔴	Localized production stations have been demonstrated but a material number of stations do not currently exist
TRADITIONAL PRODUCTION TECHNOLOGY	Production efficiencies can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand	🟡	SMR production efficiency is acceptable; however, scaling and incremental improvements for low maintenance operation needed
NON-TRADITIONAL PRODUCTION TECHNOLOGY	Production efficiencies can achieve acceptable economics, equipment requires low maintenance and capacity can be scaled to meet demand	🔴	SMR with biomethane, wind-based electrolysis, biomass pyrolysis, and biological water-splitting are options, but economics are challenging
DISPENSING:			
LAND REQUIREMENTS AT NEW STATIONS	Equipment can scale up while providing efficient economic returns given land utilized	🟡	Fuel retailers can purchase land lot large enough to accommodate hydrogen fueling equipment when justified by fuel economics
LAND REQUIREMENTS AT EXISTING STATIONS	Equipment can scale up while providing efficient economic returns given land utilized	🔴 *	Some stations have land for fueling equipment; however, uncertainty if land for compression/storage is available at a sufficient number of stations
EASE AND SPEED OF REFUELING	Does not result in greater inconvenience for consumers relative to conventional vehicles	🔵	Vehicle refuel time is comparable to conventional vehicle and refueling can be performed by consumers
FUELING AVAILABILITY	Access to fueling comparable to existing stations (fueling locations equal to 15% to 30% of existing locations within a geography)	🔴	Insufficient fueling locations for material consumer adoptions and lack of compelling economics for early infrastructure deployment
FUEL ECONOMICS:			
CAPITAL INVESTMENT FOR STATIONS	Capital required for dispensing infrastructure to achieve wide scale fuel availability can be accommodated within existing practices	🔴	Significant capital required for wide-scale dispensing capacity with limited first mover benefits
DISPENSED FUEL COST	Fuel cost per mile is less than or equal to conventional vehicles	🔴 *	Fuel costs are expected to be higher in the near term; larger fueling capacity stations and high utilization improve economics; however – this has significant uncertainty

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🟨 OPTIONAL PATHWAYS

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

🔴 SIGNIFICANT BARRIER OR HIGH RISK OR HIGH UNCERTAINTY OR REQUIRES "BREAKTHROUGH OR INVENTION"

* Some authors assert that existing stations have the land required in the near term, and future stations can accommodate hydrogen fueling equipment in their designs, thereby changing these color codes from red to yellow. Under this scenario, current technology can meet near-term performance requirements, and as fuel demand develops and capacity utilization increases, fuel costs will be lower.

Figure 4B-9. *Hydrogen Fuel Hurdles – 2012 Status*

HURDLE		REQUIRED STATE FOR REACHING WIDE-SCALE COMMERCIALIZATION	RATING	COMMENTS
ENGINES:				
🟩 COMBUSTION OPTIMIZATION	IN-CYLINDER PRESSURE & FUEL INJECTION	Robust & reliable, mass-manufactured fuel systems and valvetrains	🟡	Optimized ultra-high-pressure fuel systems are an enabling feature for highly-optimized combustion
	GAS EXCHANGE	Cost-effective reliable options to single turbocharging & fixed valve	🟡	Multiple technologies are in development including VVA, 2-stage turbo, EGR, supercharger, etc.
	HCCI	Life, torque, and convenience of traditional diesel engines	🔴	Largely confined to laboratory studies due to controllability issues; may require specialty fuels/blends
	FRICTION REDUCTION	Long-life, lead-free lubricants and bearings with proven long-term reliability	🔵	Low-friction oils and bearings are available. Some barriers to adoption, including cost and inertia
	PARASITIC & ACCESSORY LOADS	Highly-electrified trucks in mass-production	🟡	Electrification of accessories; some synergies with hybridization
HYBRIDS	🟩 BATTERY COSTS	Cost-effective hybrid batteries with 1 million mile life in real-world conditions	🔴	Cost breakthrough required to enable cost competitiveness in heavier applications
	MANUFACTURING SCALE	Dominant electric architecture that builds synergies with automotive scale	🔴	Cost competitiveness is hindered by low volumes and several competing hybrid architectures (e.g., parallel, series, etc.)
	WASTE HEAT RECOVERY	Integrated and cost-effective, reliable Rankine cycle and/or thermoelectric device	🟡	Rapidly developing technology, scale adoption will be needed to drive down costs
	AFTERTREATMENT	High efficiency, long-life, low-cost controls for both NOx and PM	🔵	Multiple technologies now on the market; cost and long-term reliability are still a major concern
	🟩 ADVANCED GASOLINE ENGINES	Long-term reliability coupled with low total cost of ownership to compete with diesel	🟡	Gasoline competes well on initial cost, but still must close a gap efficiency and reliability
VEHICLES:				
	TIRES	Wide availability of single-wide-base tires	🔵	Super-single and low-friction options available; but safety perception hinders super-single adoption
	TRANSMISSION	Cost effective DCT, CVT, and AMTs with proven field reliability	🟡	Complex picture created by existing and emerging technologies (AMT, DCT, CVT, etc.)
AERODYNAMICS	🟩 INTEGRATED TRACTOR/TRAILER APPROACHES	Harmonized tractor/trailer logistics and value chains	🔴	Mis-alignment of incentives between tractor purchasers and trailer purchasers; trailer turnover is very slow and trailer fleet is much larger than tractor fleet
	IDLE REDUCTION TECHNOLOGY/APU	Cost and convenience approaching the traditional idling approach for hotel loads	🟡	Various technology options available (e.g., APU, engine controls, etc.) but not widely adopted
	🟩 LCVs AND EXTENDED GROSS VEHICLE WEIGHT	Federal law supporting higher GVW and/or nationwide LCVs	🔴	Safety and road-wear challenges currently under study
FLEET OPERATIONS TECHNOLOGY:				
	TELEMATICS AND ROUTE OPTIMIZATION	Cost, simplicity, and value proposition comparable to home-use GPS	🟡	Tools to improve driver awareness & productivity; barriers to full adoption include cost and uncertainty of fleet buyers
	SPEED MANAGEMENT/ GOVERNORS	Simple and effective speed control measures for fleet-manager application	🔵	Widely adopted using conventional techniques; new telematics-based options now available

🟩 PRIORITY FOCUS AREA TO ENABLE WIDE-SCALE COMMERCIALIZATION

🔵 MINIMAL/NO BARRIERS

🟡 WILL TAKE INVESTMENT AND TIME, BUT PATHWAY FOR SUCCESS HAS BEEN IDENTIFIED

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Note: Engine technologies relate to diesel engines unless otherwise noted.

Figure 4B-10. *Hurdles for Medium- and Heavy-Duty Engines and Vehicles*

APPENDIX 4C:
CRITICAL PATH CHARTS

Criteria for Priority Hurdles Selection							Relative Scale and Sequence of Investments		
		Techno-logy	Infra-structure	Scale Efficiencies	Barrier to Wide-Scale Material Volumes	Notes:	Short Term	Medium Term	Long Term
Vehicles Priority Hurdles	**Low Cost Light-weighting**	☑				New materials and supply chains, manufacturing and assembly processes, vehicle damage diagnostics and repair processes (note: competitive advantage issues)	Material technology and manufacturing process development	Initial vehicle applications; supply chain development	High volume, low cost application to mass market vehicles
	Technology and Vehicle Development Time	☑				Advanced design, development, testing and validation procedures (note: competitive advantage issues)		Pilot and local applications	Ubiquitous application
	Vehicle Inventory Turnover	☑				Fundamental change in vehicle and ownership economics to accelerate vehicle inventory turnover			Short life cycle vehicles
	Connectivity and Traffic Congestion/ Throughput		☑			Ubiquitous vehicle to vehicle/vehicle to infrastructure connectivity enabling “crash-less” vehicles and better traffic throughput management; significant impact on pertinent regulations	R&D and technology demos	Pilot and local applications	Ubiquitous application across multiple transportation modes and infrastructure

Table 4C-1. *Light-Duty Vehicles*

		Criteria for Priority Hurdles Selection					Relative Scale and Sequence of Investments		
		Tech-nology	Infra-structure	Scale Efficien-cies	Barrier to Wide-Scale Material Volumes	Notes:	Short Term	Medium Term	Long Term
Fuel Production	**Biotechnology to increase food and biomass**	☑				Biotechnology that will increase production of both biomass and food crop production	Breeding and biotechnology trait improvement	Breeding and biotechnology trait improvement	Breeding and biotechnology trait improvement
	Biochemical hydrolysis	☑				Biochemical Hydrolysis low dry solids – can we develop a higher dry solids that makes a more concentrated sugar solution	Improve enzyme relative to rate, temp. inhibition, and pH		
	Fermentation of C5 and C6 sugars	☑				Ethanol fermentation that can efficiently co-ferment C5 (xylose) and C6 (glucose) sugars at low yeast cell dosing is critical; alternatively, inoculating at high pitch has been shown to be effective and tolerant to inhibitors	Develop culture capable of simultaneous pentose and hexose fermentation	Biochemical hydrolysis	
	Capex and feedstock logistics associated with commercial scale gasification			☑		Limited economies of scale based on feedstock logistics. Capital costs of for direct, pressurized oxygen-blown biomass gasifiers are higher than low pressure, indirect biomass gasifiers primarily because air separation units are not cost effective at projected scales (2,000 tons per day) for biomass gasifiers	Develop low cost oxygen production or highly efficient small steam reformer	Deploy local gasifiers and mixed alcohol production	
	Gasification clean up and conditioning	☑					Gasification clean up and conditioning relative to steam reforming		
	Produce higher quality of pyrolysis oil	☑					Develop catalyst for high liquid fuel hydrotreatment for pyrolysis oil		
Infrastructure	**Crop collection/ densification/ storage**	☑	☑	☑		Crop collection – low density and concentration of biomass	Develop low cost pelletization or briqueting system for storage and transport crop collection		Crop collection/ densification/ storage

Table 4C-2. Biofuels

	Requirement for Wide-Scale Commercial Volumes	Criteria for Priority Hurdle Selection				Actions	Timing		
		Technology	Infrastructure	Scale Efficiencies	Barrier to Wide-Scale Material Volumes		Short Term	Medium Term	Long Term
	Lithium-Ion Energy Density	☑			☑	a) Advance battery production and conditioning processes b) Improve uniformity of performance from cell to cell c) Fundamental research on nanostructures, cell design, materials, cell geometric format d) Applied research on module packaging and battery enclosure, in order to reduce system burden e) Develop thermal management technologies/devices to improve heat transfer rate, temperature uniformity, and volume/mass burden	→	→	→
	Lithium-Ion Longevity	☑				a) Testing to validate calendar life of current lithium-ion batteries in real-world driving b) Develop new chemistries with longer expected calendar life than current lithium-ion chemistries	→	→	→
Fuels/Infrastructure Priority Hurdles	**MDU/ Commercial/ Public Charging Business Models**		☑		☑	a) Align business models, regulations, codes and standards, and processes to enable 3rd-party providers to install and charge for MDU, workplace, commercial, and public charging at a reasonable return on investment	→	→	
	Refuel Time (Time Required to Charge Battery)	☑			☑	a) Develop battery chemistries with greater ability to receive rapid charging without negatively impacting the battery		→	→
						b) Develop DC and L2 charging infrastructure to align with vehicle "dwell" time			
						c) Public Education and Outreach re: matching charging time to location	→	→	→

Table 4C-3. Electric

		Criteria for Priority Hurdle Selection					Critical Path / Timing		
		Technology That Reduces Cost	Ease Infrastructure Development	Drive Scale Efficiencies	Wide-Scale Material Volumes	Notes:	Near Term	Medium Term	Long Term
Vehicles Priority Hurdles	**Full OEM Production**			☑		Plant investments to retool for natural gas engines and vehicles	Support for full OEM production of vehicles – move away from retrofit		
	Increased Engine & Vehicle Option Availability				☑	Broader range of engines required to fulfill market requirements and avoid perception that NG engines are low power/low torque	Engineering demonstration	Product line integration	Product line integration
	Advanced Fuel Economy Potential	☑			☑	R&D and demonstration of NG long-term technology compatibility with heavy truck fuel economy technology	Engineering demonstration	Product line integration	Product line integration
	NG Optimized Engine Designs	☑				Including combustion systems to avoid need for Diesel Particulate Filters with CI NG engines	Combustion optimization	Engineering demonstration	Product line integration
Fuels Priority Hurdles	**Fuel Station Availability**		☑			Limited infrastructure today. Growing but pace of acceleration is key to market growth	Investment in refueling to support major freight corridors	Infrastructure expansion to support broader markets	
	LNG Liquefaction Capacity Expansion				☑	Expanded availability of LNG required, primarily through new liquefaction plants	Investment to support fuel throughput		
	Small Scale Liquefaction	☑				Cost reduction of small scale liquefaction systems to support fuel availability	Engineering demonstration	Deployment scale up	
		Additional Technology Opportunities							
		Technology That Reduces Cost	Ease Infrastructure Development	Drive Scale Efficiencies	Wide-Scale Material Volumes	Notes:	Near Term	Medium Term	Long Term
Additional Technology Opportunities	**Low Cost/ Lightweight Fuel Storage**	☑				Even at scale, the cost of fuel storage remains a premium over diesel HD vehicles	Technology R&D	Manufacturing demonstration	Incorporate in future product architectures
	Cryogenic System Robustness				☑	Continued development and improvement of vehicle components associated with fuel delivery systems for LNG	Technology and material R&D	Cost reduction and product implementation	
	LNG Fuel Recovery and Re-Use				☑	R&D into more effective methods of vapor pressure management on LNG fuel tanks, e.g., supplemental combustion fuel, use in aftertreatment, etc.	Technology R&D	Engineering demonstration	Product line integration
	Cost Effective On Board NG Compression		☑			Could facilitate use of CNG in High Pressure Direct Injection Systems that currently rely on LNG. Cannot increase product cost		Technology R&D	
	Increased Energy Density (On Board Fuel Storage)	☑				Long term path to increase range, reduce packaging, reduce mass	Technology R&D	Manufacturing demonstration	Incorporate in future product architectures
	RNG Production and Clean Up	☑				Improved anaerobic digesters and thermal gasification technology for lower cost RNG		Technology R&D	

Table 4C-4. *Natural Gas*

	Criteria for Priority Hurdle Selection				Notes/Actions	Critical Path/Timing		
	Tech-nology	Infra-structure	Scale Efficien-cies	Barrier To Wide-Scale Commercial Volumes		Short Term	Medium Term	Long Term
Fuel Cell Durability	☑				>150,000 mile life has been demonstrated in the lab and must be proven in field trials	Fuel cell lasts life of vehicle		
Up Front Price Premium	☑		☑		Current costs for fuel cell and storage system are high; lower costs can be achieved with scale production and lower platinum requirements		Vehicle priced to attract early adopter consumers	Vehicle costs decrease through incremental advancements and scale
Compression and Storage Technologies	☑	☑	☑		Land requirements for compression, storage equipment, and permitting/setback requirements can limit scale up of fueling capacity	Fueling equipment fits into most existing stations	Fueling capacity scales within real estate limitations	
Distribution Technology	☑		☑		On-road truck deliveries, which are likely in the near and long term, require incremental increases in payload capacity		Truck payload capacity increases to leverage economies of scale	Truck payload capacity continues to increases to keep up with demand
Fuelling Station Availability		☑			Insufficient fueling locations for material consumer adoptions and lack of compelling economics for early infrastructure deployment	Sufficient early stations for demonstration fleets	Sufficient early stations to avoid consumer concerns of fuel availability	
Capital Investment for Stations				☑	Significant capital required for wide scale dispensing capacity with limited first mover benefits		Capital requirements are not entry barrier, particularly when demand is low	Demand is sufficient to provide return on capital
Dispensed Fuel Cost				☑	Fuel cost per mile expected to be higher in the near term; future increased station utilization and fueling capacity can improve economics			Fuel costs decrease through advancements and scale

Table 4C-5. *Hydrogen*

<table>
<tr><th colspan="7">Criteria for Priority Hurdle Selection</th><th colspan="4">Timing/Sequence of Investments</th></tr>
<tr><th colspan="2"></th><th>Technology Advancement That Reduces Cost</th><th>Ease Development of Infrastructure</th><th>Drive Scale Efficiencies</th><th>Wide Scale Material Volumes</th><th>Notes:</th><th>Short Term</th><th>Medium Term</th><th colspan="2">Long Term</th></tr>
<tr><th rowspan="4">Vehicles Priority Hurdles</th><th>Combustion and Exhaust Aftertreatment Optimization</th><td>☑</td><td></td><td></td><td></td><td>Improve existing engine platforms through mechanical, thermodynamic, and combustion improvements</td><td>Optimization with high-efficiency SCR; waste heat recovery; high-pressure fuel injection</td><td>VVA, advanced boosting systems, emerging compression ignition technologies (HCCI, PCCI, RCCI)</td><td colspan="2">Specialized combustion systems based on HCCI, RCCI, advanced biofuels – dependent on fuel infrastructure</td></tr>
<tr><th>Battery Capability for Medium- & Heavy-Duty Hybrids</th><td>☑</td><td></td><td>☑</td><td>☑</td><td>Cost effective hybrid batteries for MD/HD trucks. Power: Energy priority depends on duty cycle</td><td colspan="3">Battery technology breakthrough (cost, life, power density)</td><td>Battery manufacturing scale-up</td></tr>
<tr><th>Advanced Gasoline Engines</th><td>☑</td><td>☑</td><td></td><td>☑</td><td>Develop durable, efficient, low-cost gasoline engines for medium-duty (Class 3-6) applications.</td><td>Direct-injection technology</td><td>VVA, advanced boosting systems, high-energy ignition systems</td><td>Ethanol/ "X"-anol boosting technology</td><td>Future incremental improvements</td></tr>
<tr><th>Integrated Tractor & Trailer Aerodynamics</th><td></td><td></td><td>☑</td><td></td><td>Integrated trailer and truck combination; requires new safety standards and market structure</td><td colspan="2">Regulatory standards for trailer aerodynamics</td><td colspan="2">Change in trailer ownership model; "Future Truck" Integrated Aero R&D; New safety standards to allow vision systems, eliminate multiple external mirrors</td></tr>
</table>

Table 4C-6. *Medium- and Heavy-Duty Vehicles*

APPENDIX 4D:
LIST OF SUPPLEMENTAL TOPIC PAPERS AVAILABLE ON NPC WEBSITE

	Paper	Subgroup	Paper Authors/Reviewers
1	Air Transportation Demand	Air Travel Demand	Jeff Cumpata, United Airlines Robert Sturtz, United Airlines David Lee, Air Transport Association of America John Heimlich, Air Transport Association of America Nancy Young, Air Transport Association of America Shauna Bassett, Boeing Commercial Airplanes Bob Petersen, Boeing Commercial Airplanes Robert Schaufele, Federal Aviation Administration Laurent Rouaud, GE Aviation Steve Csonka, GE Aviation Mike Farina, GE Energy
2	Rail Transportation Demand	Rail Transportation Demand	John Gray, Association of American Railroads Frank Hardesty, Association of American Railroads Michael Goetzke, EMD Martha Lenz, EMD
3	Truck Transportation Demand	Truck Transportation Demand	Jeff Short, American Transportation Research Institute Glen Kedzie, American Trucking Associations Rich Moskowitz, American Trucking Associations
4	Alcohol Boosted Turbo Gasoline Engines	Engines & Vehicles (HD and LD)	Leslie Bromberg, MIT and EBS Daniel R. Cohn, MIT and EBS John B. Heywood, MIT and EBS
5	The Connected Car: Smart Technologies to Reduce Congestion (Intelligent Transport Systems)	Light-Duty Engines & Vehicles	Elaine Horn, Accenture Clay Phillips, General Motors
6	Low Temperature Combustion	Engines & Vehicles (HD and LD)	David E. Foster, UW–Madison
7	Mass-Market Adoption of Ultralightweight Automobiles	Light-Duty Engines & Vehicles	Amory Lovins, Rocky Mountain Institute
8	Production of Alternative Liquid Hydrocarbon Transportation Fuels from Natural Gas, Coal, and Coal Biomass (XTL)	Hydrocarbon Liquids	David Gray, Noblis Harold Schobert, Penn State University
9	Analysis of the Fatty Acid Biosynthetic Pathway for the Production of Fuels in Genetically Engineered Bacteria	Biofuels	Padma Sengodon, Texas A&M University Dirk B. Hays, Texas A&M University Eric Steen, Joint BioEnergy Institute
10	Are We Going to be Able to Meet World Food and Biofuel Demands in 2050? (Long Term Food and Biofuels Projections)	Biofuels	Swatilekha Bhattacharjee, Iowa State University John Miranowski, Iowa State University
11	Genetic Engineering to Add Traits Not Natural to the Feedstock	Biofuels	Tom Binder, Archer Daniels Midland Company

Paper		Subgroup	Paper Authors/Reviewers
12	Macroalgae (Seaweeds)	Biofuels	Julie Rothe, Texas A&M University Dirk B. Hays, Texas A&M University John Benemann, Benemann Associates
13	Microbial Fuel Cells	Biofuels	Padma Sengodon, Texas A&M University Dirk B. Hays, Texas A&M University
14	Separations Landscape for the Production of Biofuels	Biofuels	Jose L. Bravo, Royal Dutch Shell
15	U.S. Woody Biomass Yields at the State and Regional Level	Biofuels	Jesse Caputo, SUNY ESF Tim Volk, SUNY ESF
16	Yield Projections for Major U.S. Field Crops and Potential Biomass Crops	Biofuels	Alicia Rosburg, Iowa State University John Miranowski, Iowa State University
17	Advanced Batteries: “Beyond Li-ion”	Electric	William H. Woodford, MIT R. Alan Ransil, MIT Yet-Ming Chiang, MIT
18	Emerging Electric Vehicle Business Models	Electric	Eric Cahill, Adaptive Consulting Mike Waltman, Better Place Elaine C. Horn, Accenture
19	The Interaction Between Plug-in Electric Vehicles, Distributed Generation, and Renewable Power	Electric	Tim Brown, University of California, Irvine Scott Samuelsen, University of California, Irvine
20	Vehicle to Grid (V2G)	Electric	Gary Helm, PJM Interconnection, LLC
21	An Initial Qualitative Discussion on Safety Considerations for LNG Use in Transportation	Natural Gas	Tom Drube, Chart Industries Bill Haukoos, Chart Industries Peter Thompson, UC Berkeley/Accenture Graham Williams, GP Williams Consulting
22	Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and GHG Emission Reduction Benefits of RNG as a Low-Carbon Fuel	Natural Gas	Karen Hamberg, Westport Innovations Don Furseth, Acorn Solutions Jim Wegrzyn, Brookhaven National Labs Anthony LaRusso, National Grid Donald Chahbazpour, National Grid Gail Richardson, Energy Vision Barry Carr, Clean Communities of Central New York Harrison Clay, Clean Energy Fuels Chris Cassidy, U.S. Department of Agriculture Michael Ippoliti, Calstart Jack Lewnard, Gas Technology Institute Graham Williams, GP Williams Consulting Brian Chase, Chevron
23	Development of Non-Precious Metal Catalyst for Oxygen Reduction in PEM Fuel Cells	Hydrogen	Branko Popov, University of South Carolina
24	Advanced Storage Technologies for Hydrogen and Natural Gas	Hydrogen Natural Gas	Peter Thompson, UC Berkeley/Accenture
25	Hydrogen-Compressed Natural Gas (HCNG) Transport Fuel	Hydrogen	Peter Thompson, UC Berkeley/Accenture
26	Artificial Photosynthesis	Biofuels	Victoria L. Gunderson, Northwestern University Michael R. Wasielewski, Northwestern University

	Paper	Subgroup	Paper Authors/Reviewers
27	Carbon Capture & Storage (CCS)	GHG Emissions	Robert Bailes, ExxonMobil Steve Crookshank, API Nick Welch, GCCSI
28	Criteria Air Pollutants	GHG Emissions	Karen Hamberg, Westport Innovations Don Furseth, Acorn Solution Development Services
29	Greenhouse Gas Life Cycle Assessment/Analysis	GHG Emissions	Mike Leister, Marathon Petroleum Corporation
30	Data Variability and Uncertainty in Greenhouse Gas Life Cycle Assessment	GHG Emissions	Robert Bailes, ExxonMobil Mike Leister, Marathon Petroleum Corporation Phillip Heirigs, Chevron Global Downstream Laura E. Verduzco, Chevron Gib Jersey, ExxonMobil Venkatesh Vasudevan, ExxonMobil
31	Water Usage	GHG Emissions	John Wind, Chevron Ray Dums, Chevron

Note: Topic paper abstracts can be found in Appendix C at the back of Part 2 of this report.