Quadrennial Reviews Underway

- Quadrennial Energy Review: Called for by the President to analyze government-wide energy policy, particularly focused on energy infrastructure.

- Quadrennial Technology Review: Secretary Moniz requested the second volume be published in parallel with the QER to provide analysis of the most promising RDD&D opportunities across energy technologies in working towards a clean energy economy.

The resulting analysis and recommendations of the QTR 2015 will inform the national energy enterprise and will guide the Department of Energy's programs and capabilities, budgetary priorities, industry interactions, and national laboratory activities.

Expanded Scope of QTR 2015

- The QTR will evaluate major changes since the first volume of the QTR was published in 2011 and provide forward leaning analysis to inform DOE's strategic planning and decision making.

- In doing so, the QTR 2015 will provide three levels of analyses:
  - Systems Analyses – Uses systems frameworks to evaluate the power, buildings, industry, and transportation sectors, enabling a set of options going forward.
  - Technology Assessments – Examines in detail, the technical potential and enabling science of key technologies out to 2030.
  - Road Maps – Uses these analyses and assessments to extend R&D Roadmaps and frame the R&D path forward.

QTR 2015 Chapter Outline

Introduction

1. Energy Challenges
2. What has changed since QTR 2011
3. Energy Systems and Strategies

Assessments

4. **Advancing Systems and Technologies to Produce Cleaner Fuels**
5. Enabling Modernization of Electric Power Systems
6. **Advancing Clean Electric Power Technologies**
7. Increasing Efficiency of Buildings Systems and Technologies
8. Increasing Efficiency and Effectiveness of Industry and Manufacturing
9. **Advancing Clean Transportation and Vehicle Systems and Technologies**
10. Enabling Capabilities for Science and Energy

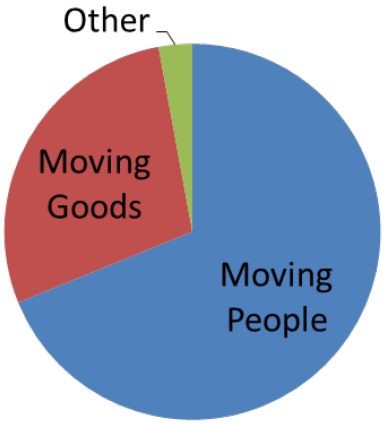
Integrated Analysis

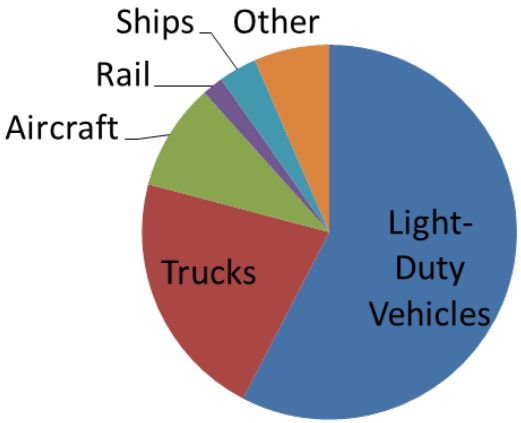
11. U.S. Competitiveness
12. Integrated Analysis
13. Accelerating Science and Energy RDD&D
14. Action Agenda and Conclusions; Web-Appendices

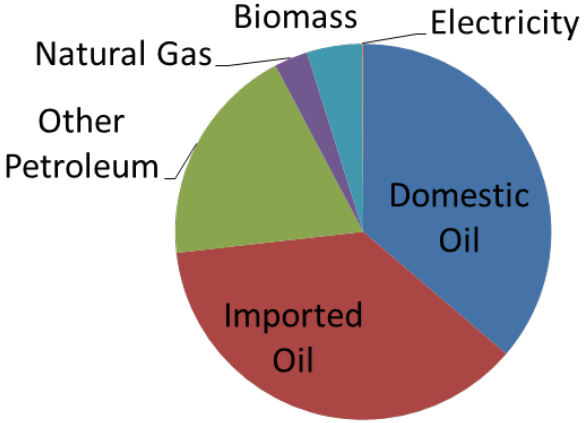
Web Appendices

Transportation Overview

- Transportation is 10% of GDP, and provides essential services for all aspects of the economy and quality of life
- But it is 93% petroleum dependent, represents 70% of all U.S. petroleum use, and produces 27% of U.S. emissions
- Overall, the U.S. uses 21% of the world's oil supply, accounts for 11% of the world's oil production, but has just 2% of the world's proven oil reserves







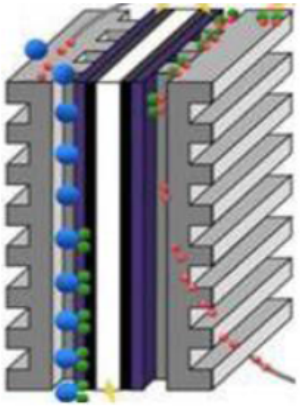
26.8 Quadrillion Btu of transportation energy use

(note: does not include approximately 2.2 quadrillion Btu for offroad equipment)

Fuel-Cell Electric Vehicles

- **FCEVs can be refueled in a few minutes, used for a wide range of vehicle sizes and performance requirements, achieve a >300 mile driving range and have zero emissions from the tailpipe.**
- **Key issues are fuel cell cost and durability and on-board hydrogen storage (hydrogen production, delivery and infrastructure covered in Ch. 4)**

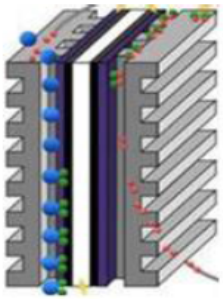
Fuel Cell Challenge



30% Cost Reduction

2X Durability Increase

40% Reduction in Platinum Group Metal



2014 Fuel Cell Technology

$55/kW*, 2,500 h durability, 0.2 g_{PGM}/kW

Fuel cells currently use high platinum group metal loadings for high performance and durability.

2020 Fuel Cell Technology

$40/kW, 5,000 h durability, 0.125 g_{PGM}/kW

Improved catalyst and electrode technology is required to reduce catalyst loading while simultaneously increasing durability and performance.

*$55/kW at high volume, ~$280/kW at low volume

Key Areas of R&D

Stack:

- Catalysts, membranes, gas diffusion layers, bipolar plates

Balance of plant components

- Air management, humidification systems

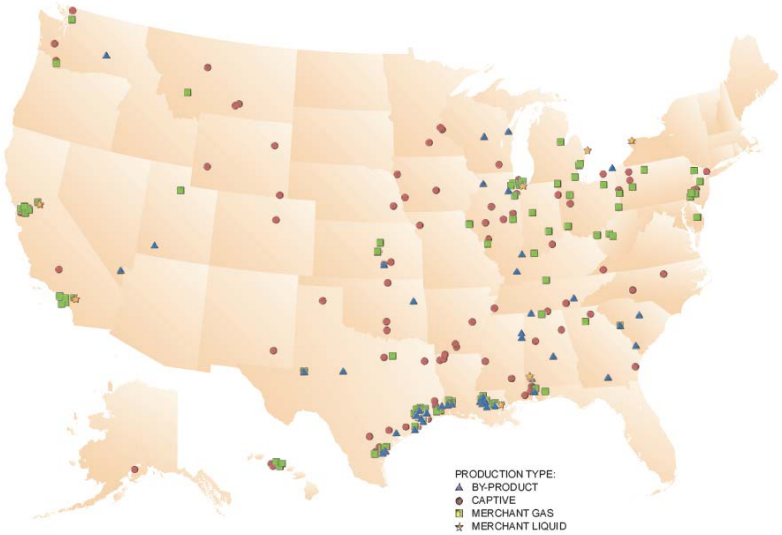
Hydrogen storage

- Tanks (carbon fiber)
- Materials R&D for long term low pressure storage

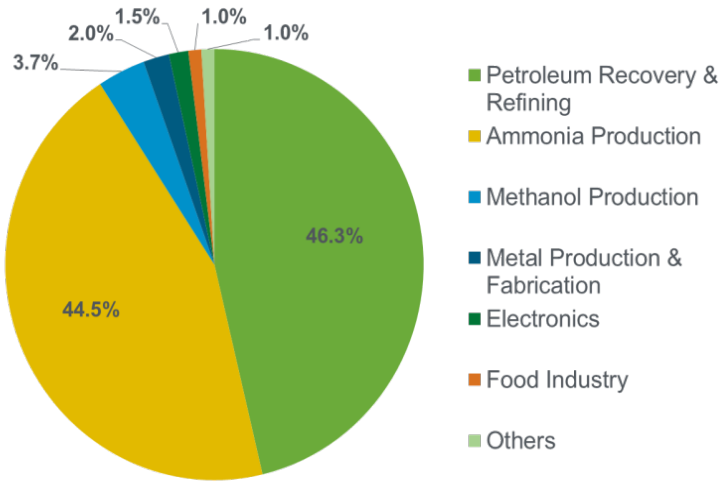
Vehicle-delivery interface & safety (materials compatibility- see Ch. 4)

Hydrogen Current Status

- **~10 million tonnes H_2 from NG reforming for petroleum refining, ammonia production, etc. today**
- **NG can provide near-term cost-competitive H_2 at scale:**
  - <$2/gge produced ($4.50/gge delivered)
- **>1,500 miles of H_2 pipeline**
- **~ 50 H_2 stations (10 public)**
- **Plans for H_2 stations:**
  - 100 in CA; 100 each in Germany, Japan (1,000 each by 2025)
- **Growing demand for electrolyzers for renewable H_2 at scale:**
  - >$5/gge produced ($7.50/gge delivered)



Existing centralized hydrogen production facilities



2010 hydrogen consumption market share by application

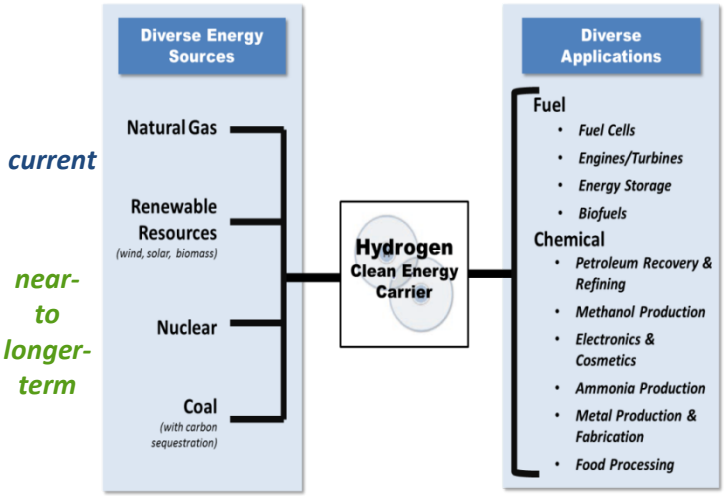
Note: NG reforming with CCS is another near-term low-carbon option

Hydrogen Challenges and Opportunities

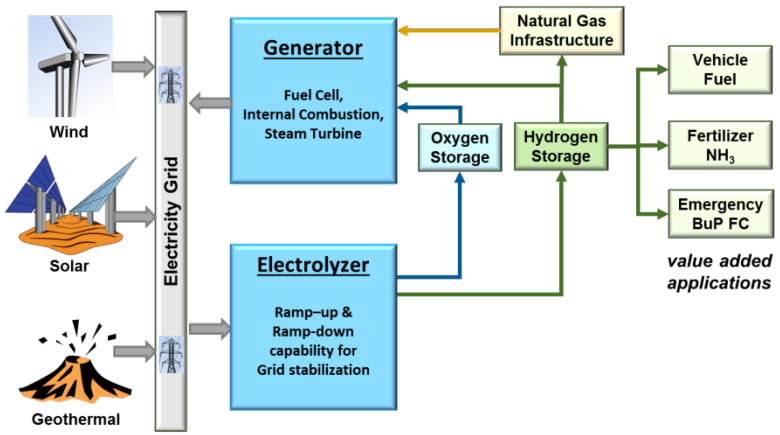
- **Major challenges:**
  Reduce the cost of producing and delivering H_2 from renewable/low-carbon sources for FCEV and other uses (capex, O&M, feedstock, infrastructure, safety, permitting, codes/standards)

- **Factors driving change in the technologies:**
  - FCEVs are driving requirements (e.g. high P tanks)
  - Need to reduce cost of 700 bar refueling stations for near-term FCEV roll-out

- **Where the technology R&D needs to go:**
  - Materials innovations to improve efficiencies, performance, durability and cost, and address safety (e.g. embrittlement, high pressure issues)
  - System-level innovations including renewable integration schemes, tri-generation (co-produce power, heat and H_2), energy storage balance-of-plant improvements, etc.
  - Cost reductions in H_2 compression, storage and dispensing components
  - Continued resource assessments to identify regional solutions to cost-competitive H_2



H_2 offers important long-term value as a clean energy carrier



Renewable energy integration options with hydrogen

Note: H2 storage on-board FCEVs is addressed in Ch. 9

Hydrogen Analysis and Research Goals

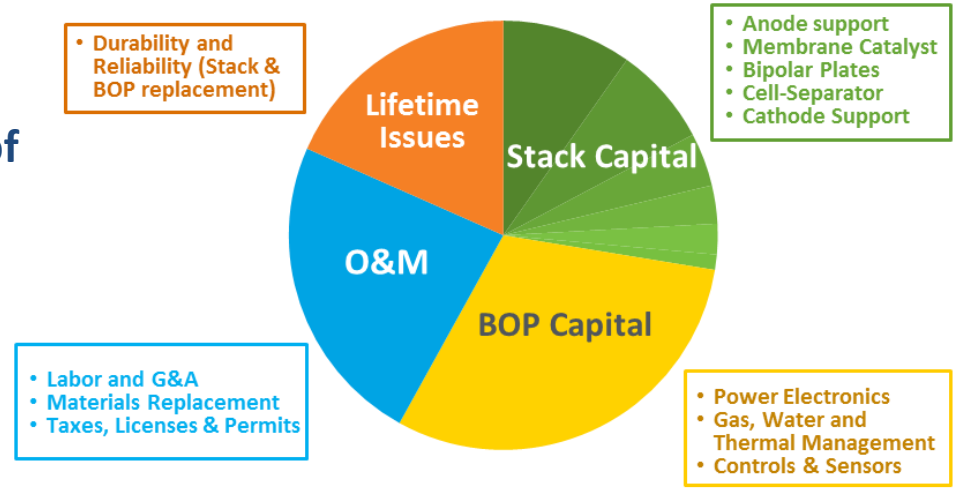
- **Reduce the cost of H_2 from renewable and low-carbon domestic resources to achieve a delivered & dispensed cost of <$4/gge** (Note: 1 kg H_2 ~ 1 gge)

  Pathways:
  - Electrolysis, high temperature thermochemical (solar/nuclear), biomass gasification/bio-derived liquids, coal gasification with CCS, biological & photoelectrochemical

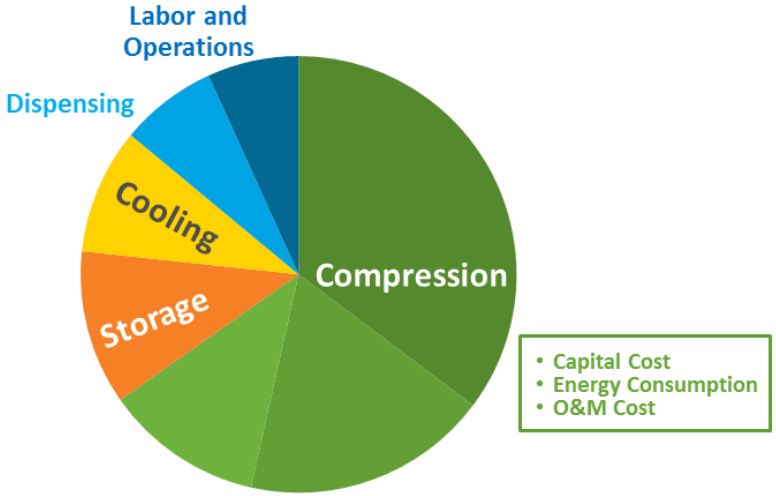
- **Need R&D in materials and components to improve efficiency, performance, durability, and reduce capital and operating costs for all pathways**
  - For many pathways, feedstock cost is a key driver of H_2 cost

- **Need strong techno-economic and regional resource analysis**

- **Opportunities for energy storage (e.g. curtailed wind for electrolyzing water)**



H_2 Production Example- Cost Breakdowns for PEM electrolysis, (excluding electricity feedstock costs)

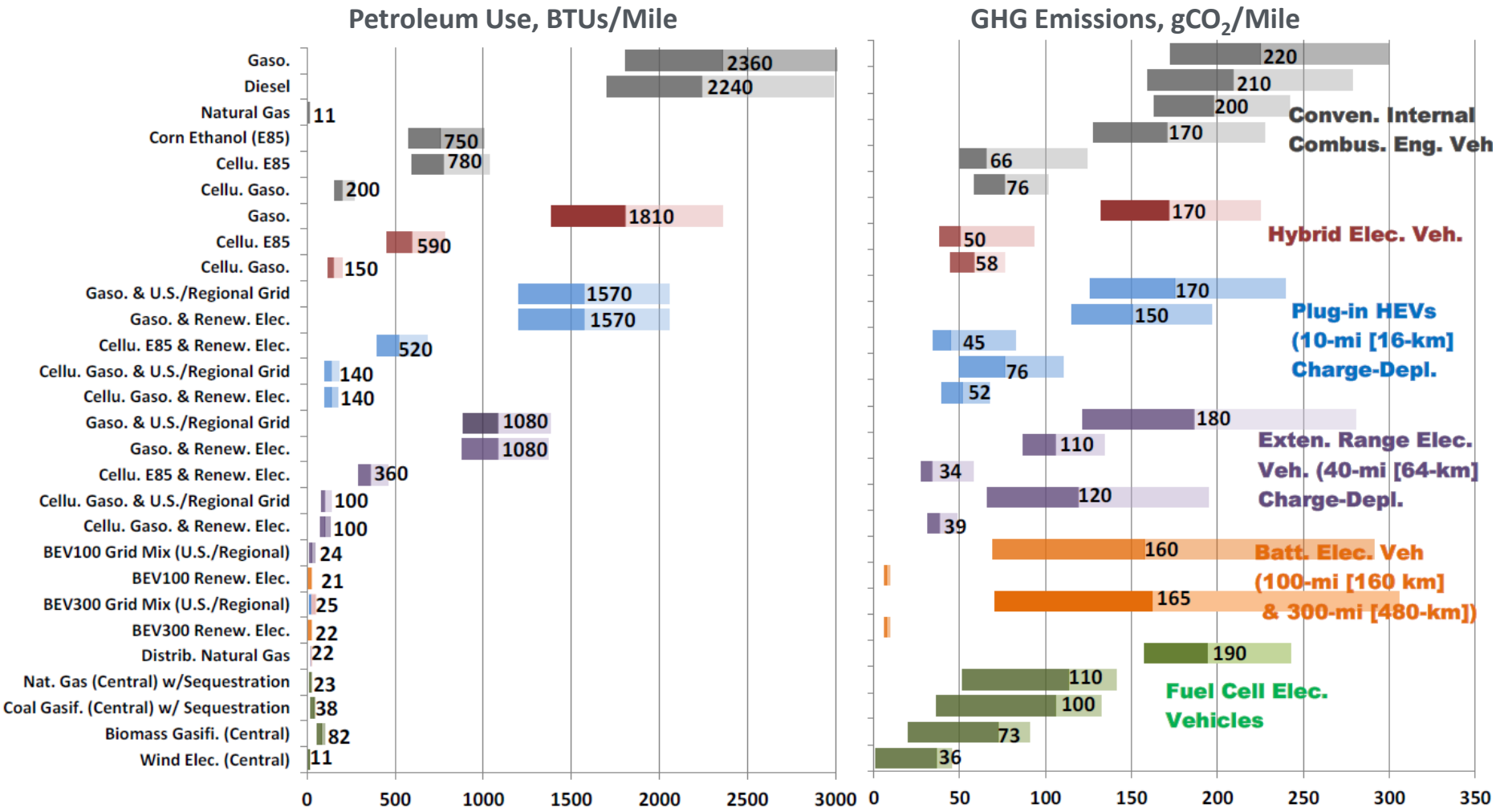


H_2 Delivery Example- Compression, Storage and Dispensing (CSD) Cost Breakdown for the Pipeline Delivery Scenario

8

Metrics

Metrics differ by technology, but all systems are evaluated based on the potential cost competitiveness (ROI), impacts on petroleum use, and greenhouse gas emissions.



The only options that achieve very high petroleum reductions and very low carbon emissions combine electric drive with low carbon fuels. Contributions of vehicle cycle (manufacturing), fuel production, and vehicle operations are given in the technology assessments.

http://www.hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf

Chapter 6 – Stationary Fuel Cells

Major Challenges:

- Reduce manufacturing cost
- Increase efficiency and durability
- Reduce cost of biogas cleanup subsystem to reduce total CO_2 emissions

Current Status:

- Reliability and electrical efficiency offset by current high capital costs
- Prototypes and demonstrations built, operated, retired in U.S.
- Early commercial units deployed by private sector and government agencies, including DOD
- U.S. is a net exporter of fuel cells

Factors driving change in the technologies:

- Increasing need to educate and facilitate integration with electric grid
- Expansion in CHP applications to support buildings and reduce cost
- Synergy with distributed generation and support to plug-in vehicles

Where the technology R&D needs to go:

- Drive down component and system capital costs
- Focus on gas cleanup for increased fuel flexibility, advanced materials, hydrogen production, and manufacturing technology
- Modeling and simulation with technology validation to demonstrate performance of components and full systems

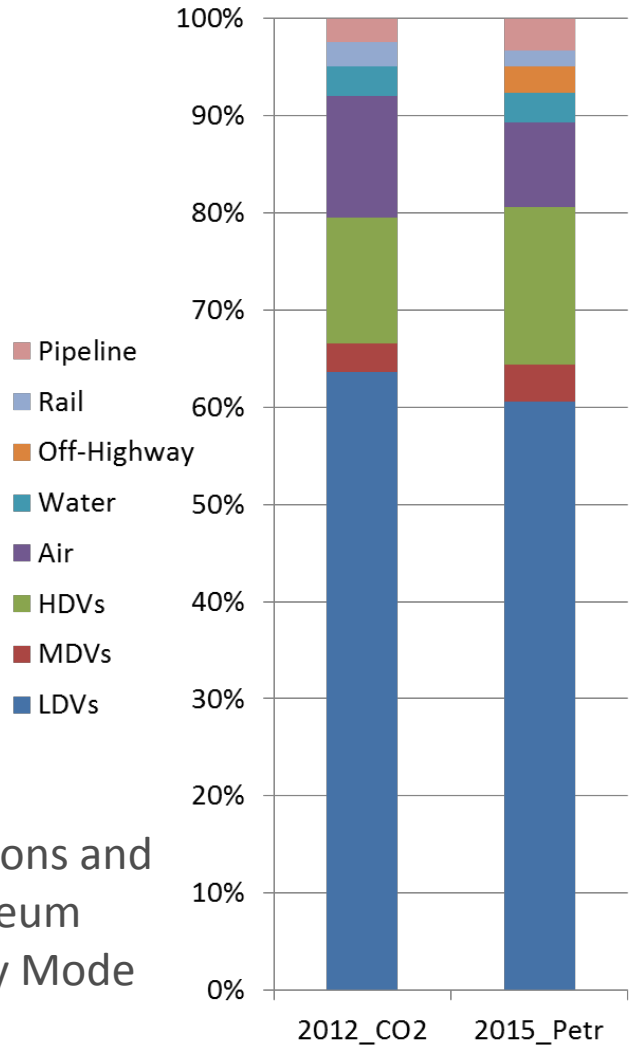
Backup Slides

DOE Current Investments

- **Investments so far have been strategically focused on LDV and trucks.**
- **Some technologies, if developed for one mode, may benefit other modes.**

Key Findings

- **Technologies evaluated can significantly impact transportation GHG emissions and petroleum use in key modes.**



Emissions and Petroleum Use by Mode

Potential for impacts of technology at full penetration (up to 2050 timeframe) relative to current vehicles.

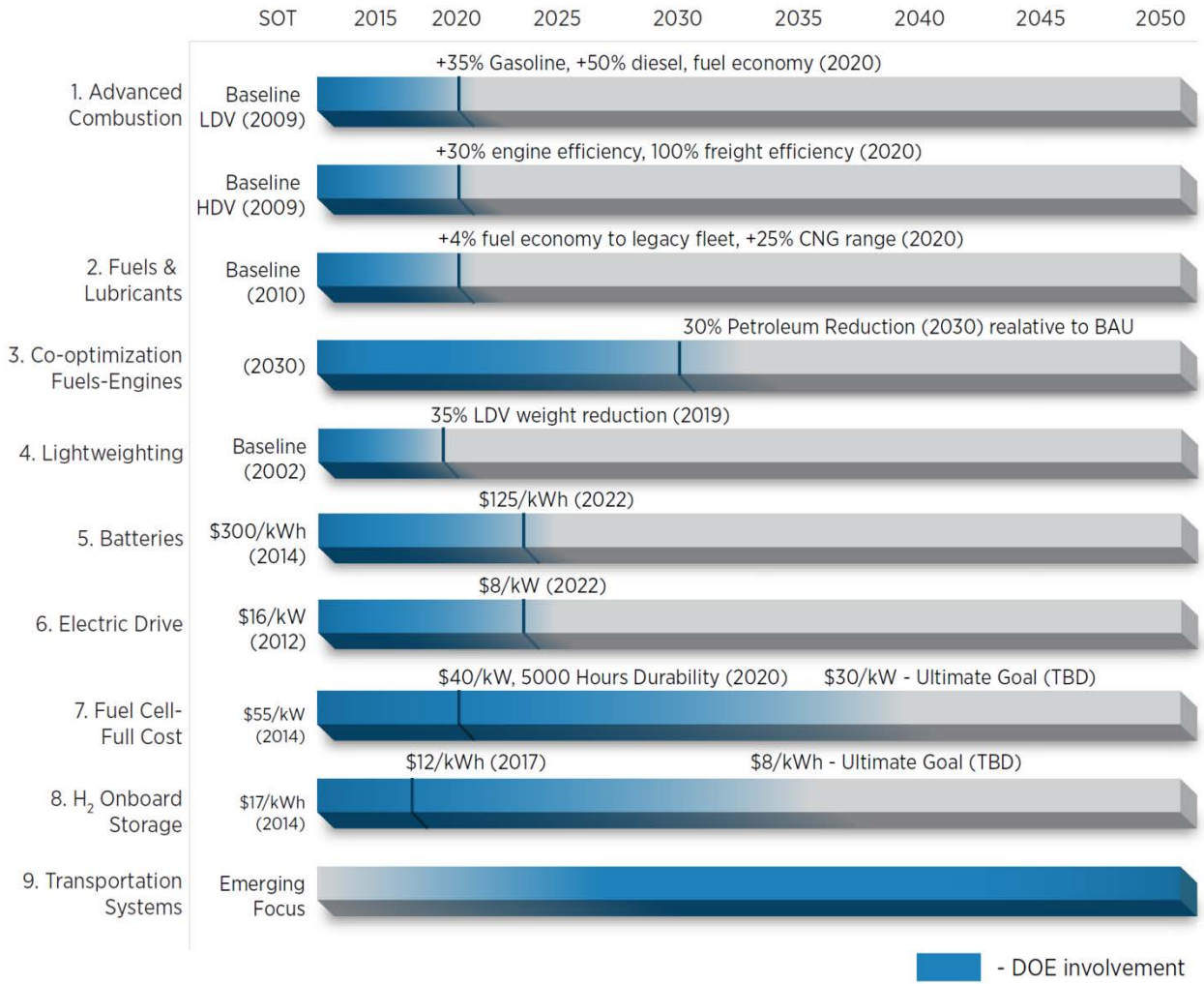
HDV	GHG Benefit	Petrol'm Benefit	Timing
Combustion	→ 25%	→ 25%	Near
Systems	→ 20%	→ 20%	Near

LDV	GHG Benefit	Petrol'm Benefit	Timing
Combustion	→ 25%	→ 25%	Near
LDV Systems	→ 20%	→ 20%	Near
Adv. Matls.	→ 20%	→ 20%	Mid
Electrification	→ 99%	→ 99%	Mid
Fuel Cell	→ 99%	→ 99%	Long

Note: "→" indicates up to.

R&D Potential and Timing

- **R&D potential as determined in roadmapping and tech assessments gives improvement potential over a variety of timescales.**
- **DOE has current investments in many of these technologies. End of blue area is targeted reassessment of further potential. Discussion in the QTR can support use in future planning.**



DOE Current Investments Notes

1. Low-temperature combustion strategies to achieve higher engine efficiencies; more efficient lower cost approaches for reducing NOx, HC and PM in low temperature exhaust. System level technologies to improve vehicle fuel economy through a combination of combustion strategies, emission control, fuel injection, air handling, waste heat recovery, and control systems; advanced materials to address limitations for advanced combustion regimes and engines.
2. Alternative and renewable fuels; unique non-conventional fuel properties to improve efficiency; lubricant technologies that can reduce friction losses in new and legacy vehicles.
3. High performance, low carbon fuels for high efficiency engines

   Integration into production, distribution, and dispensing infrastructure
4. All vehicle systems (Body, Chassis, Powertrain, Closures, Tires, Bumpers) using advanced high strength steels, aluminum and magnesium alloys, carbon fiber composites, and mixed material systems
5. High voltage, high capacity cathodes; advanced metal alloy and composite anodes; electrolytes; separators; surface films; cell fabrication, pack integration
6. Cost, performance, reliability, efficiency, packaging, weight, manufacturing of Electric Motors and Power Electronics . Wide Band Gap semiconductors, high temp passive devices, interfaces, interconnects, laminations, windings, packaging, capacitors, magnetic materials, reduced rare earth materials
7. Lower cost, more durable, non-PGM catalysts and MEAs
8. Lower cost, spatially/volumetrically efficient storage
9. Connected, intelligent, integrated, multi-scale, multi-modal, multi-fuel, urban sciences, behavioral sciences, overall mobility (people & goods)

Transportation System Highlights

Current Status of the Transportation System	
Total number of light-duty vehicles:	232 million (126 million cars, 106 million LTs)
Total number of PEVs:	260,000 PEVs 2010-present
Average efficiency of the fleet	Cars: 23.6 MPG LTs: 17.5 MPG
Number of heavy trucks	10 million
Average efficiency of class 7-8 combination trucks	5.8 MPG (supertruck demonstrated 10.7 MPG)
Miles travelled per person	10,000 (almost 3 trillion total in 2011)
Transportation fuel expenditure per household	$4000

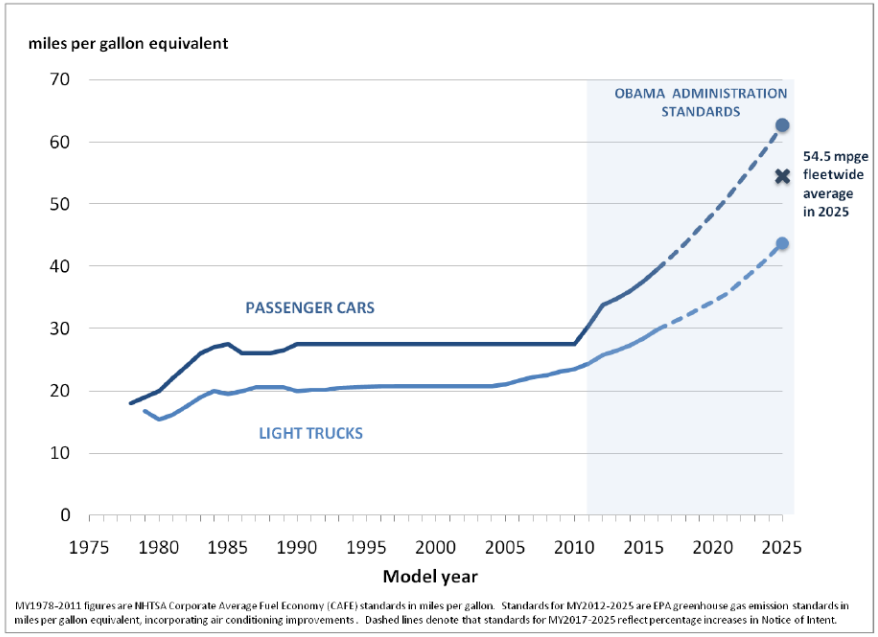
Facts from "Transportation Energy Data Book" 32nd edition

- **Structure:**
  - 5 Technology Assessments, supporting strategy, and several boxes / sidebars
- **What is in?**
  - Assessment of R&D needs for technologies that can replace conventional vehicles and reduce petroleum use and GHG emissions
  - Overview of potential benefits of these technologies and R&D to improve benefits
- **What is out?**
  - Regulatory and market policy recommendations (QER)
  - Bulk fuel infrastructure questions (QER)
  - Market forecasts of vehicle technologies

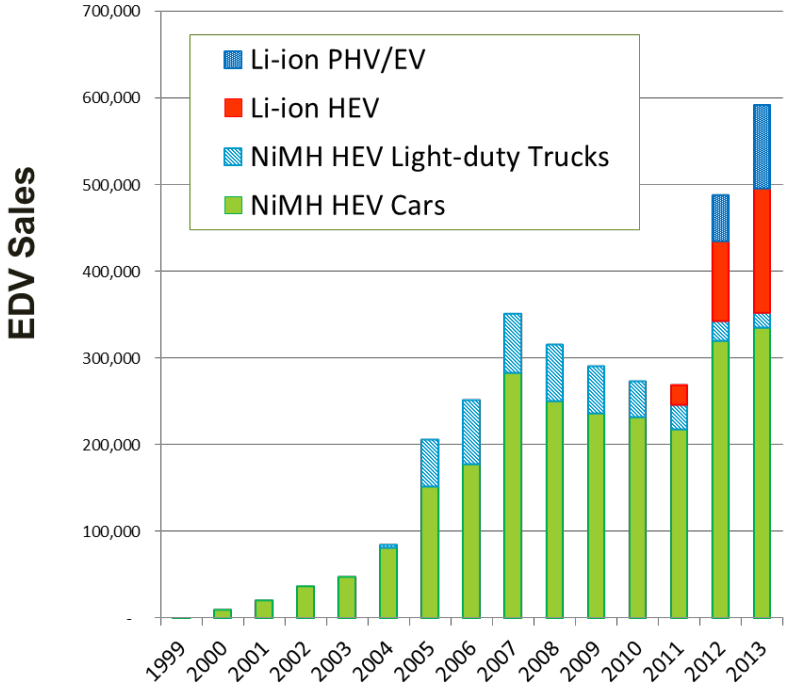
Context

- CAFE is driving increased efficiency for light-duty vehicles and heavy trucks
- Electric drivetrain and alternative fuel vehicles are now widely available
- Available vehicle, fuel, and system options define an 'option space' for improvements in energy efficiency, carbon intensity, and use intensity to meet national goals

CHART 2: LIGHT-DUTY VEHICLE FUEL ECONOMY STANDARDS, 1978-2025



U.S. Electric Drive Vehicle Sales, by Technology (1999-2013)



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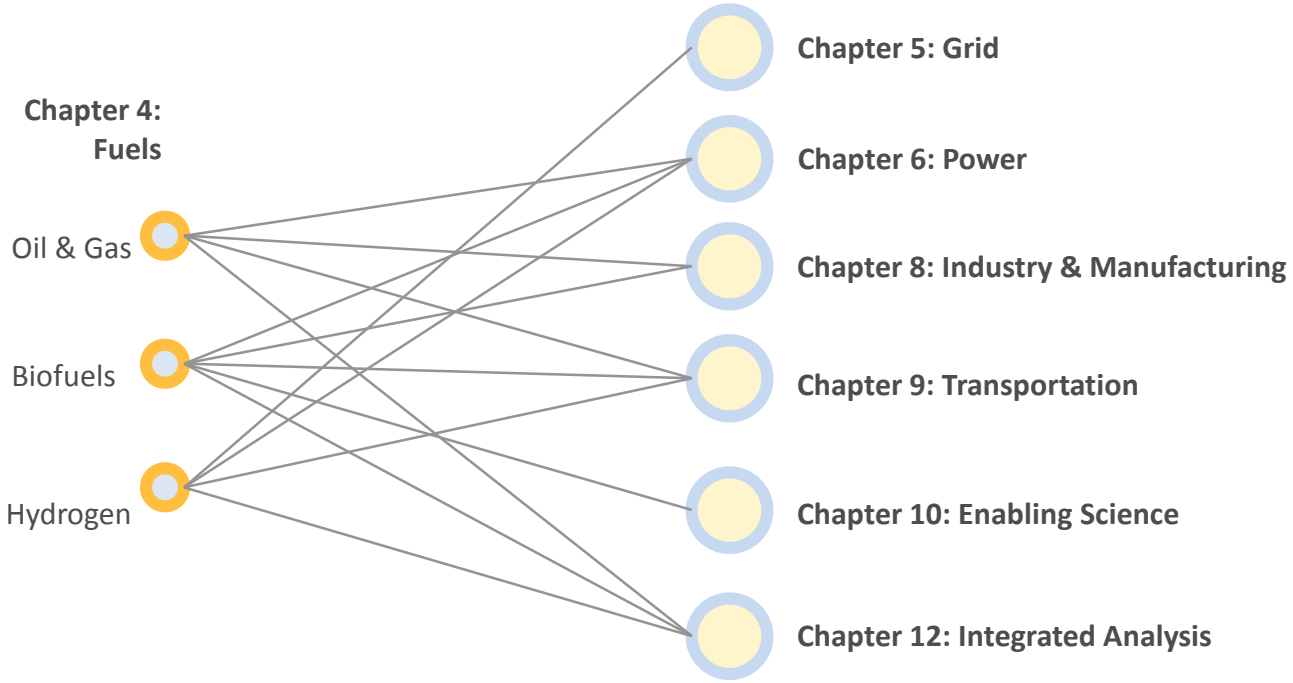
Conclusions and Cross Linkages

Major Challenges:

- Oil & Gas: Prudent development for maximum value of domestic resources, and minimizing the negative impacts on air, water, and local communities.
- Biofuels: RD&D in feedstocks, logistics, and conversion technologies can enable widespread deployment of low-carbon biofuels to displace petroleum use.
- Hydrogen: RD&D to address H_2 production and delivery infrastructure challenges can enable significant emissions and energy security benefits. Opportunities for synergies between NG and H_2 can be leveraged in the near term, but low cost H2 from renewable and low carbon sources is needed in the long term.



Bioenergy and Hydrogen Key Contributors

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Ch. 4: Hydrogen Technology Assessment

based on foundational information from sources including:

Peer-Reviewed Technology Reports utilized for the Hydrogen Technology Assessment :

- **Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios (2013) -** *http://www.nrel.gov/docs/fy14osti/60528.pdf*
- **Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs (2014) -** *http://www.hydrogen.energy.gov/pdfs/58564.pdf*
- **Report of the Hydrogen Production Expert Panel: A Subcommittee of the Hydrogen & Fuel Cell Technical Advisory Committee (2013) -** *http://www.hydrogen.energy.gov/pdfs/hpep_report_2013.pdf*
- **Cost of Ownership and Well-to-Wheels Carbon Emissions/Oil Use of Alternative Fuels and Advanced Light-duty Vehicle Technologies –** *Energy for Sustainable Development 17 (2013) 626-641*

Fuel Cell Technologies Office Peer-Reviewed Technology Records

http://www.hydrogen.energy.gov/program_records.html

- **Early Market Hydrogen Cost Target Calculation (#14013)**
- **Hydrogen Production Status 2006–2013 (#14005)**
- **Hydrogen Delivery Cost Projections—2013 (#13013)**
- **Hydrogen Production Cost Using Low-Cost Natural Gas (#12024)**
- **Hydrogen Threshold Cost Calculation (#11007)**
- **Hydrogen Production and Delivery Cost Apportionment (#12001)**
- **Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles (#13005)**

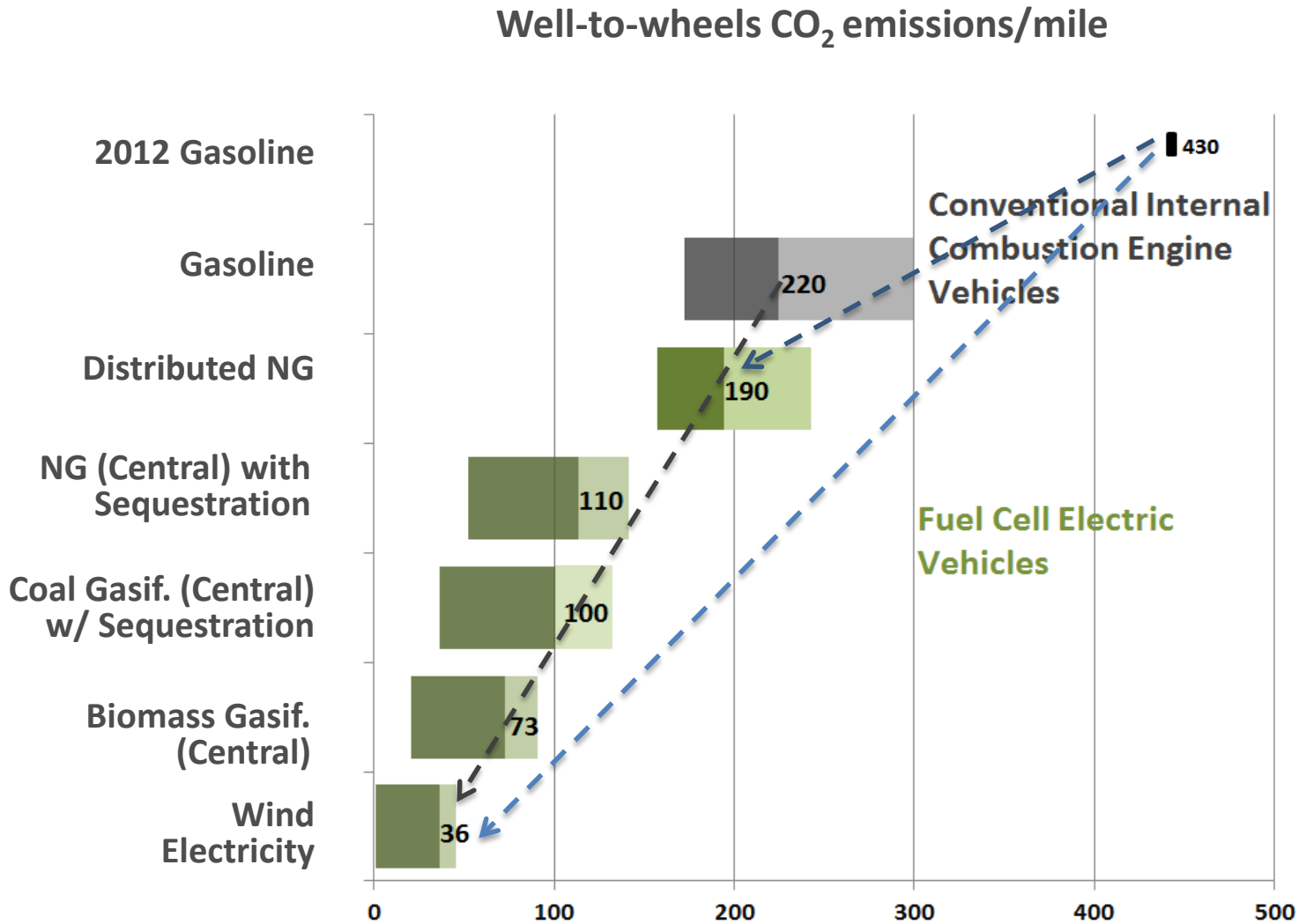
These assessments, separate from the main report, will contain the data and analysis that supports the technology discussion in the chapter. They will be available on the web.

Greenhouse Gas Emissions Reductions with H2 FCEVs

>50% from Distributed Natural Gas*

>80% from Renewables** (Wind)

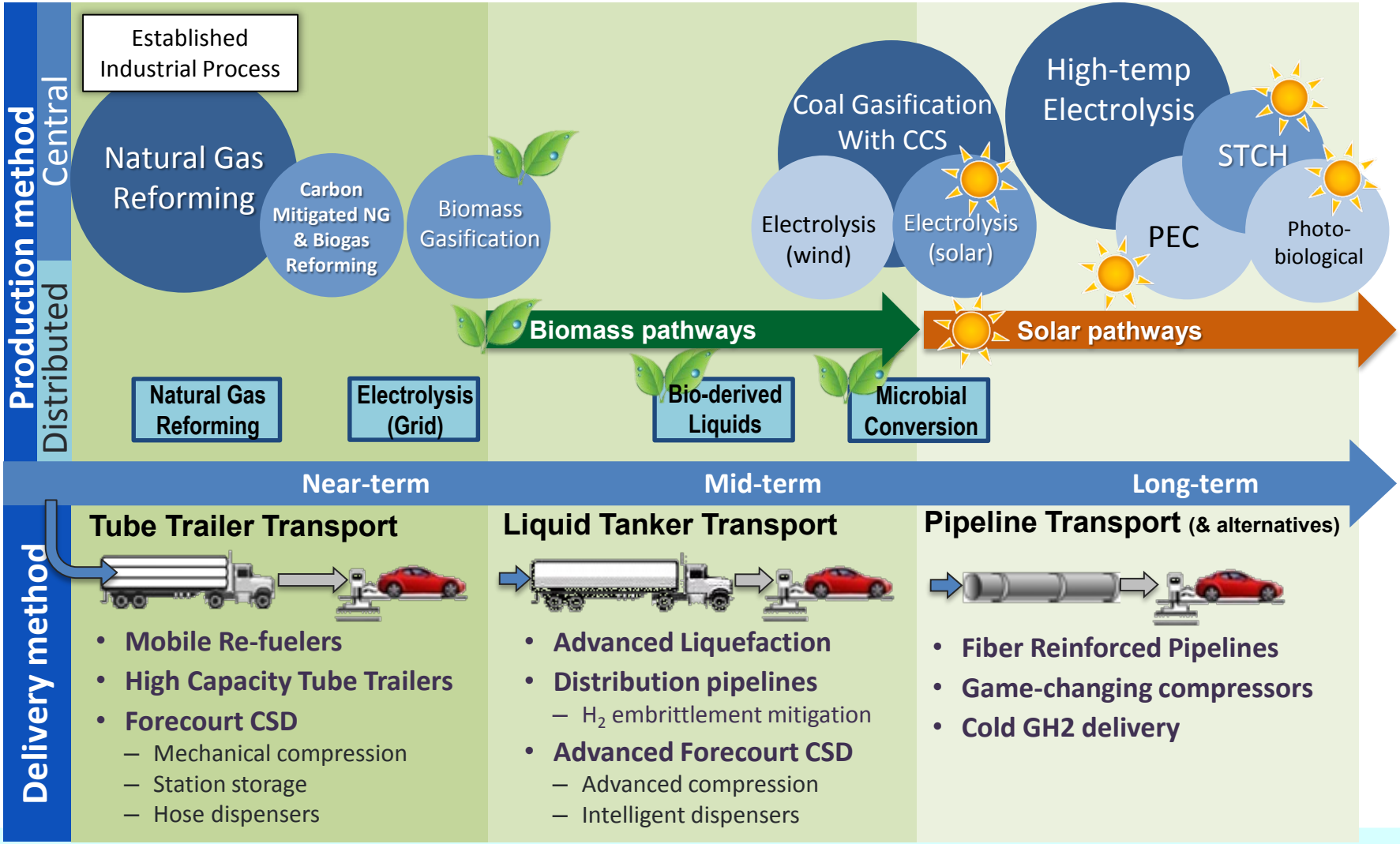
>90% from Renewables* (Wind)



*Compared to 2012 gasoline vehicle
**Compared to 2035 gasoline vehicle

Note: NG reforming with CCS is an option today

H_2 Production & Delivery Technology Strategies



The portfolio must consider near-term infrastructure rollout needs as well as the longer-term transition to large-scale renewable hydrogen

Hydrogen Challenges & Strategy

Materials durability, efficiency improvements, and capital cost reductions are key challenges for all production and delivery pathways

Challenge

Reduce the cost of sustainable low-carbon hydrogen production & delivery while meeting safety and performance requirements

- Feedstock costs
- Capital costs
- O&M costs

Strategies

Near-term

Minimize cost of 700 bar hydrogen at refueling stations

Long-term

Improve performance and durability of materials and systems for production from renewable sources

RD&D Focus

- Technoeconomic analysis
- Reliability and cost of compression, storage and dispensing
- Renewable integration
- Advanced materials and systems for H_2 delivery
- Innovations in materials, devices and reactors for renewable H_2 production
- Improved balance of plant for P&D systems

Key Areas

Delivery

- Polymers & composites for delivery technologies
- Liquefaction technologies
- Compressor reliability
- Low cost onsite storage

Production

- Advanced electrolysis
- Biomass/biogas conversion
- Hybrid fossil/renewable approaches
- Solar water splitting: PEC, STCH, biological

Chapter 6 Key Findings - Technology Opportunities

Technology	Where the technology R&D needs to go:
Carbon Capture and Storage	• 2nd generation pilot demonstrations • Retrofit plants w CCS • Application to Natural Gas and Industrial plants • International Partnerships
Nuclear Power	• Light water reactors: Characterize reactor material aging, Drive down costs of new construction, Analysis tools to characterize safety margins • High Temp and Fast Reactors: Advanced materials/fuels, modeling and simulation with validation experiments to demonstrate performance • Fuel Cycle Technology: Improved understanding of material degradation under extended storage of high-burnup fuels, Assessing alternate repository geologies and long-term interaction effects with waste forms, Research and testing of actinide-bearing fuels • Hybrid systems: Dynamic modeling and demonstration of subsystem interfaces
Solar (PV & CSP)	•PV: Innovation that will enable low cost manufacturing in the U.S. •CSP: Lower capital cost for large-scale deployment. •Systems Integration: Integration with storage solutions and energy management systems. •Non-hardware Soft Cost: Solutions to streamline processes and drive down costs of permitting, interconnection, finance, and customer acquisition.
Wind Power	• Access to high performance computing (HPC) capabilities and development of high-fidelity physics-based atmospheric and complex flow models to run on them • Effective grid integration, including high resolution short term resource forecasting
Hydropower	• Materials and turbine designs, modularization, technology-based footprint reduction • Supporting research needed in hydrologic, ecological, environmental, hydrodynamic, hydro-mechanical, operations, and power system data collection, monitoring, modeling, and analysis

Chapter 6 Technology Opportunities

Technology	Where the technology R&D needs to go:
Marine Hydrokinetic Power	• Next-generation component technology R&D designed specifically for the challenges of the marine environment - including advanced controls to tune devices to optimize energy extraction, compact high-torque low-speed generator technologies, and corrosion and biofouling resistant materials and coatings • Development of open source, fully validated MHK modeling and simulation codes • Collection of technology performance and cost data through device demonstrations
Geothermal Energy	• Resource characterization • Purposeful control of subsurface fracturing and flow • Improved and lower $/MW subsurface access technologies • Additive value through mineral recovery and hybrid systems
Fuel Cells	• **Drive down costs** • **Focus on gas cleanup for increased fuel flexibility, advanced materials, hydrogen production, and manufacturing technology** • **Modeling and simulation with technology validation to demonstrate performance**
Biopower	• Utility-scale BGCC with CCUS will jointly improve power production efficiency and may offer a cost-competitive GHG reduction alternative • BGCC is a dispatchable renewable power option • Use and integration of bio-gas processes
Supercritical CO2	• Dynamic modeling of system to assess feasibility and economics • Demonstration of subsystem interfaces including instrumentation and control
Water-Energy System	• Alternative cooling and heating fluids for fluid use in heat pipes and liquid metal coolants • Enhanced cooling systems coupled with non-traditional power generation cycles • Enhanced condensation and cooling in electricity power generating systems including hybrid or mechanical assist systems • Waste heat recovery technologies (e.g. solid state Thermo-electrics)