THE HYDROGEN ECONOMY: OPPORTUNITIES, COSTS, BARRIERS, AND R&D NEEDS

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Committee on Alternatives & Strategies for
Future Hydrogen Production and Use

Board on Energy & Environmental Systems
Division on Engineering & Physical Sciences
National Research Council
National Academy of Engineering

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A Presidential Initiative

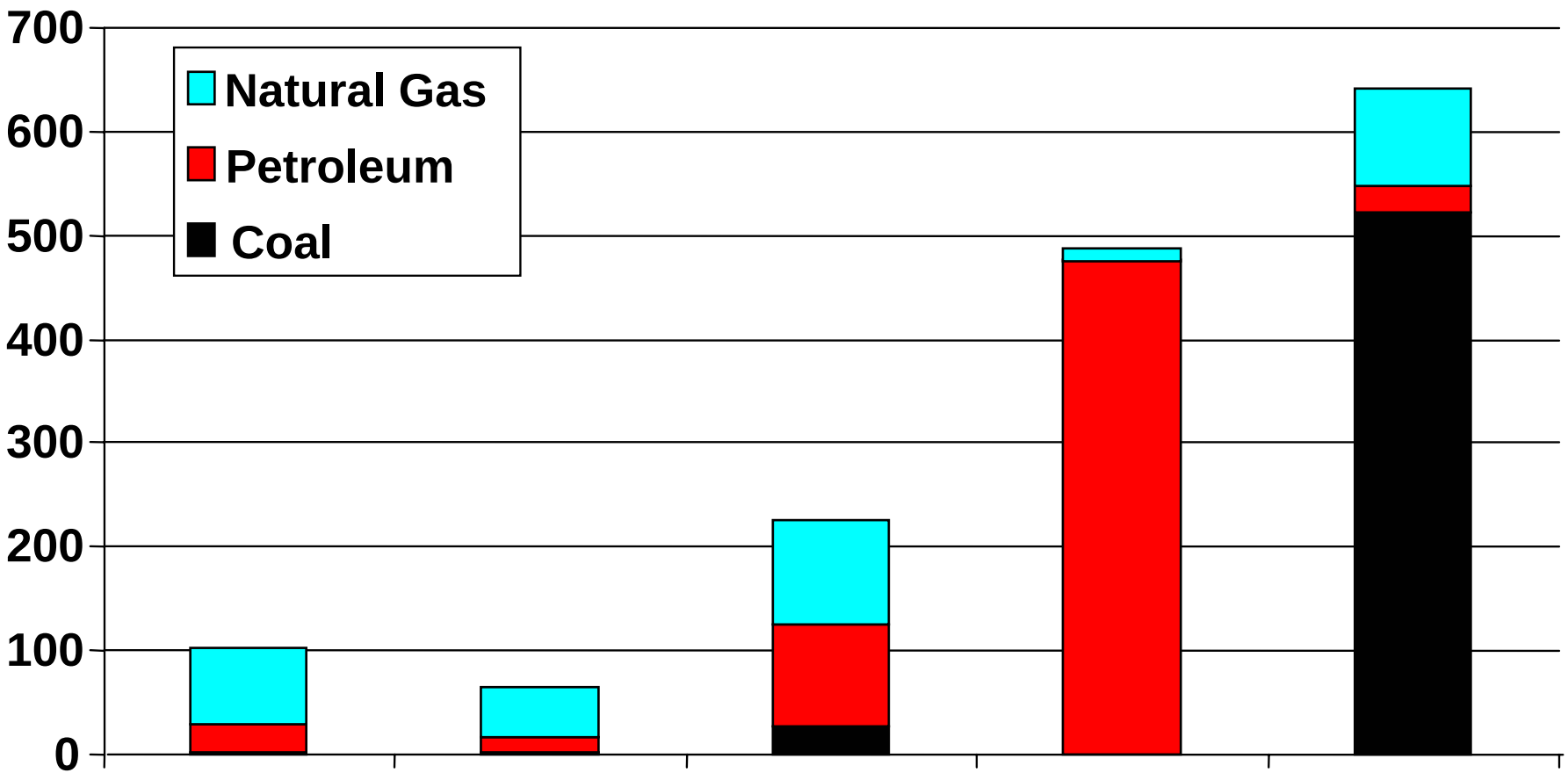
- January 2003 State of the Union
- President announces Hydrogen Fuel Initiative
- $1.2 billion program
- Set high expectations
  - Child born today could drive H_2 powered vehicle as first car

Motivation: Oil and Carbon

- In United States…
  - 2002 production 9 million bbl/day
  - 2002 consumption 20 million bbl/day
- Transportation: 13 million bbl/day
  - Autos and trucks: 11 million bbl/day
- Essentially all energy in transportation: oil

United States CO_2 Emissions by Sector and Fuels 2000

Millions of metric tons per year carbon equivalent



Source: U.S. EPA Inventory of Greenhouse Gas Emissions, April 2002

Road Transportation

- Energy security & carbon reduction intersect in road transportation
- Three competitors
  - Conventional ICV
  - Hybrid electric vehicles (GHEV)
  - Fuel cell vehicles (HFCV)
- For HFCV
  - Entire fuel/vehicle infrastructure must be replaced
  - Supply side v. demand side precedence

FOCUS OF THE COMMITTEE'S STUDY

- Assessed the current state of technology for hydrogen production and use – focused on transportation (LDV)
- Evaluated potential future hydrogen technologies
- Estimated current and future projected costs, carbon dioxide (CO_2) emissions, and energy efficiencies
- Developed scenarios for future light-duty vehicles and associated impacts on oil imports & CO_2 emissions
- Addressed infrastructure issues
- Reviewed RD&D plan for hydrogen and recommended changes to DOE

IMPLICATIONS FOR NATIONAL GOALS

- Hydrogen could fundamentally transform the U.S. energy system
  - Enhance energy security
  - Reduce CO_2 and criteria emissions
- A robust, ongoing hydrogen program is important
- Hurdles to a hydrogen economy are more than technical and economic, also social and political
  - RD&D can potentially overcome the technical and economic hurdles
- Hedged strategy: maintain a robust, balanced energy RD&D program in areas other than hydrogen
- Natural Gas, as a hydrogen source, is a significant energy security issue

R&D PRIORITIES

For a viable hydrogen transportation system to emerge, the following four technological and economic challenges need priority:

1. *Development and introduction of cost-effective, durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems for LDV*

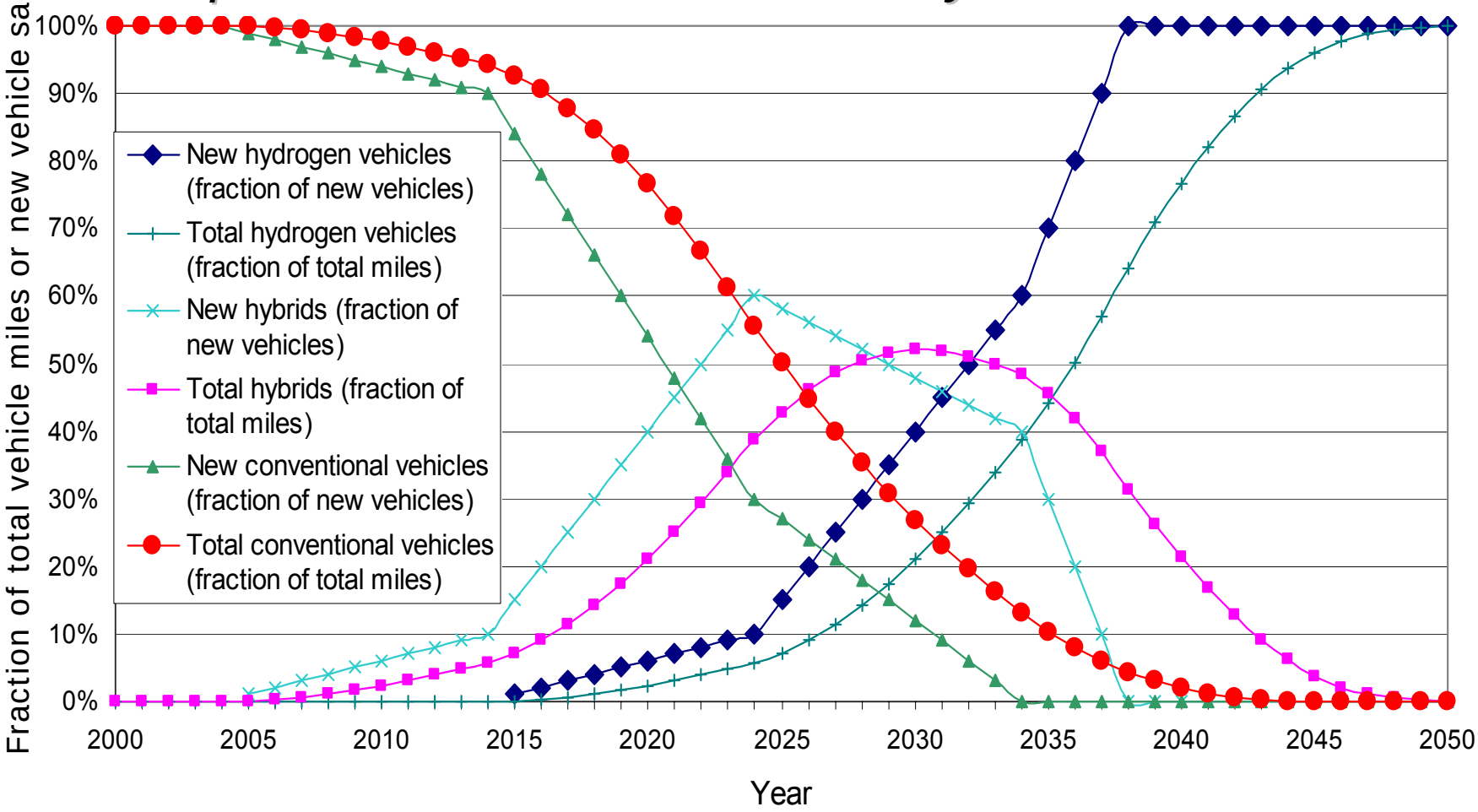
2. *Development of the infrastructure to provide hydrogen for the light-duty vehicle user*

3. *Reduction in the costs of hydrogen from renewables*

4. *Viable CO_2 capture and storage, particularly for coal*

PENETRATION CURVES FOR FUEL CELL VEHICLES

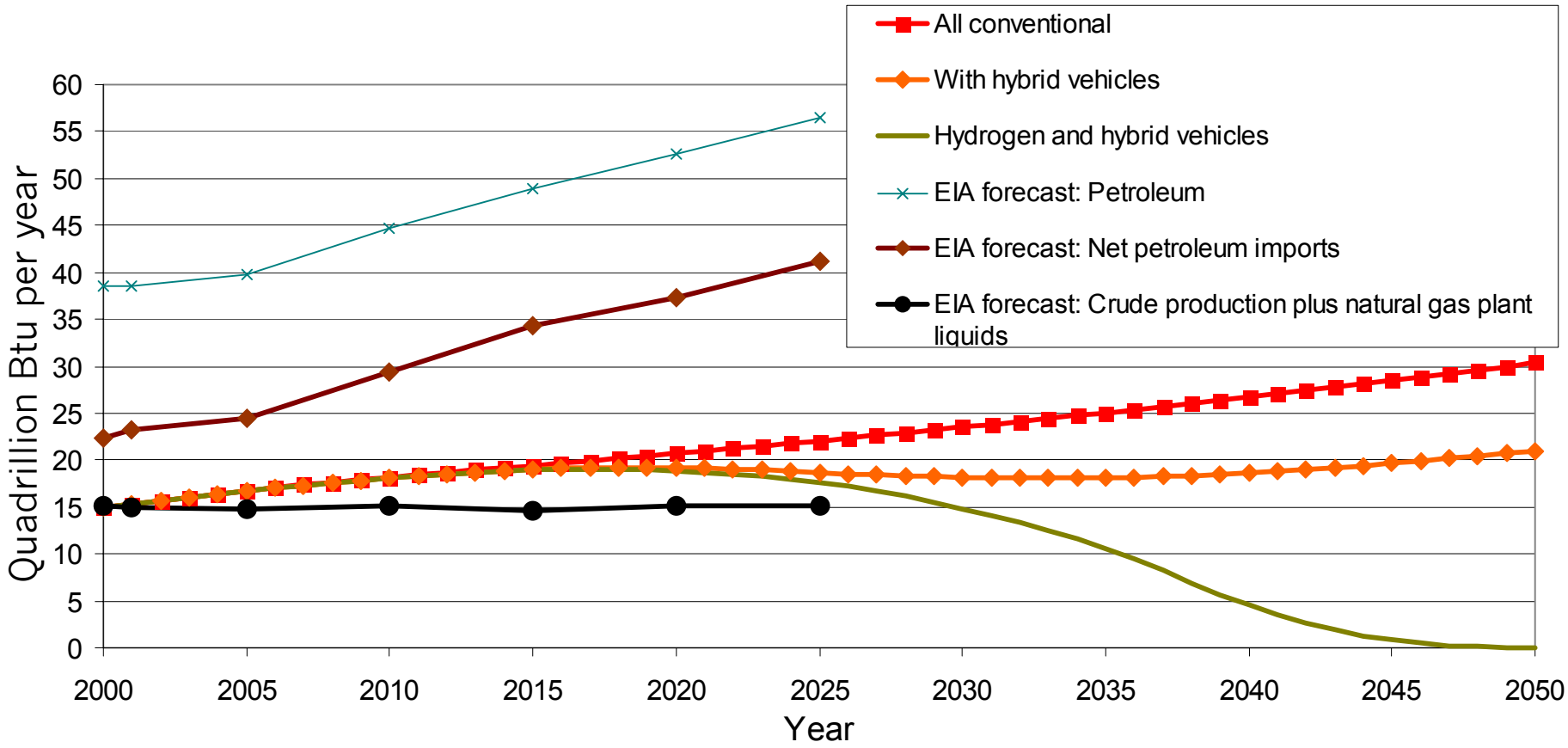
Optimistic Case Postulated by Committee



- *Complete replacement of ICE vehicles with fuel cell vehicles in 2050*

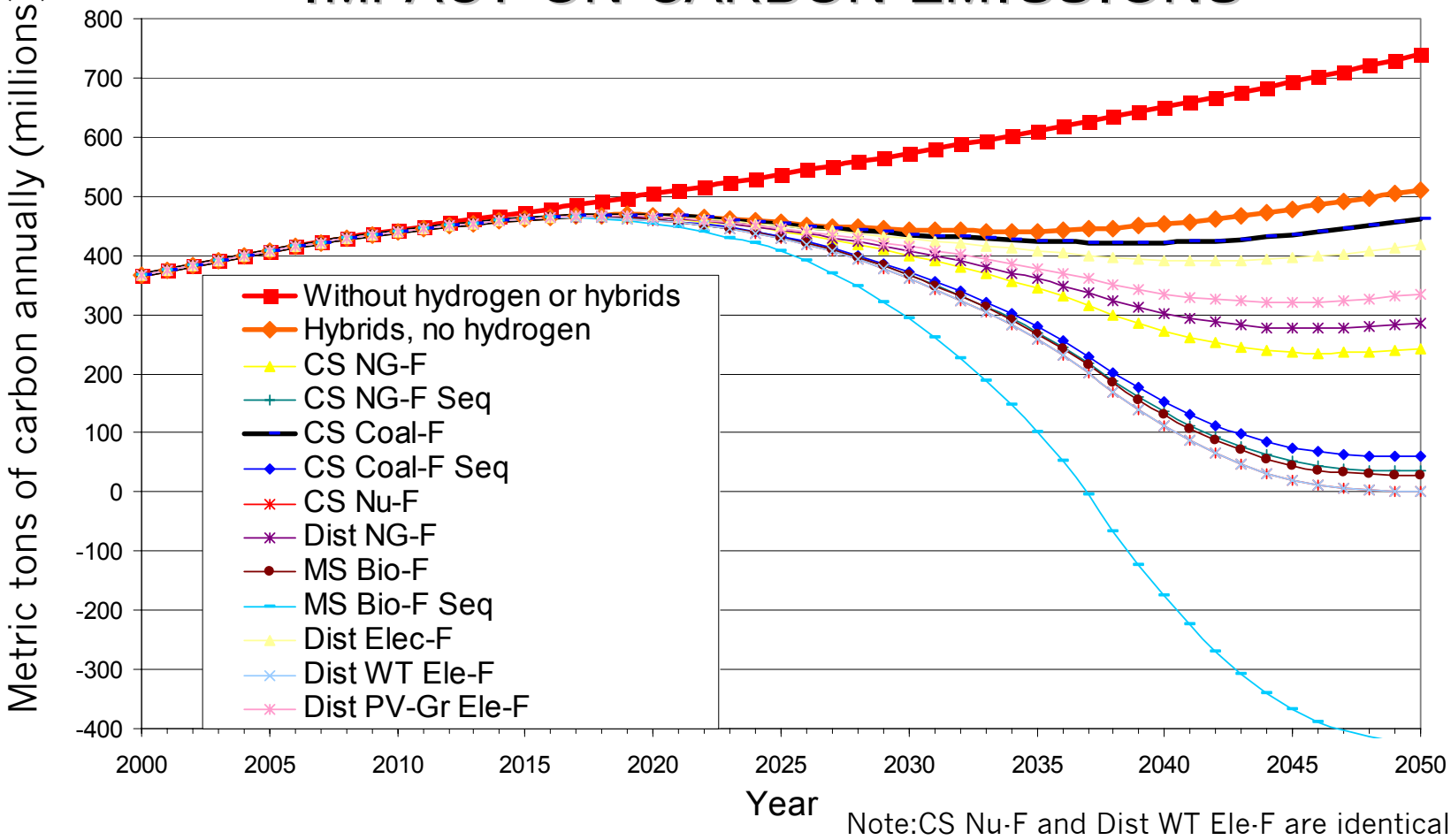
SECURITY IMPACTS

Petroleum Use Decreases with Penetration of FCV versus HEV or Conventional ICE



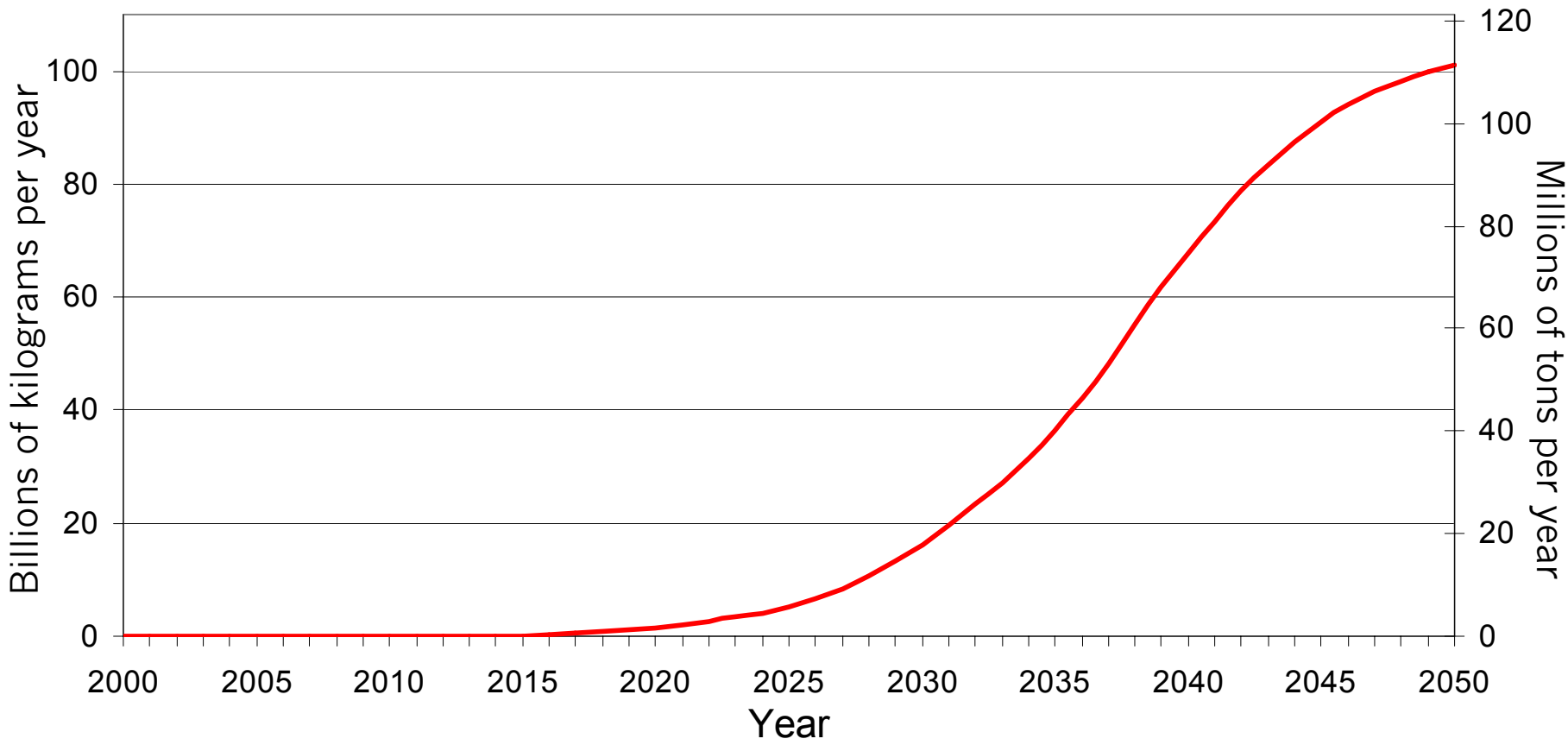
- *EIA reference projections of U.S. consumption, production, and imports of oil also shown*

IMPACT ON CARBON EMISSIONS



- *Curves show emissions due to H_2 supply chain for each production technology, assuming each is sole supplier of vehicles in fleet – future technology*

HYDROGEN PENETRATION SCENARIO



CRITERIA FOR THE TRANSITION
A Strategy

- Best accomplished initially through distributed production at fueling site
- Use natural gas reforming or electrolysis
- Wind or solar energy might provide electricity → onsite hydrogen
- Structure of mature hydrogen economy is difficult to imagine – let it evolve, plan the transition
- Allows time for development of new technologies/ breakthroughs/concepts for large scale hydrogen production and infrastructure
- Allows time for the market to develop and non technical hurdles to be overcome

MAJOR RECOMMENDATIONS
Fuel Cell Vehicle Technology

- DOE should emphasize breakthrough research in PEMFC
  - On-board storage systems
  - Fuel cell costs
  - Materials for durability
  - Functionality
- DOE should discontinue work on compression and cryogenic approaches to on-board storage
- Discontinue PEM stationary RD&D and reallocate $ to FCV
- Sponsor independent lessons learned study on past alternative fuels programs

MAJOR RECOMMENDATIONS
Infrastructure

- DOE infrastructure program requires greater emphasis and support
- Technical program should focus on materials issues
- Create better linkages between programs in large-scale and small-scale hydrogen production
- Clarify conditions under which large-scale and small-scale hydrogen production will become competitive, complementary, or independent
- Provide additional funding for exploratory research on new concepts for hydrogen delivery

MAJOR RECOMMENDATIONS
Transition

- Strengthen DOE's policy analysis capability with respect to the hydrogen economy
- Increase understanding of government role in facilitating industry investments
- Increase R&D on distributed small-scale natural gas and water electrolysis
- Initiate a program to develop new concepts in distributed production systems

MAJOR RECOMMENDATIONS
Carbon Dioxide-Free Hydrogen

- Set more aggressive electricity cost targets for nuclear and renewable energy
- Increase emphasis on electrolyzer development by setting aggressive targets for cost reduction
- Emphasize research in direct hydrogen production

MAJOR RECOMMENDATIONS
Carbon Capture and Storage

- Tighten coupling between hydrogen program and carbon capture and storage program
- The hydrogen program should be involved in all early carbon capture and storage projects, even those that do not involve hydrogen production
- Address CO_2 infrastructure issues early in transition

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (1 of 4)

- Continue to develop the hydrogen RD&D Plan
- Improve the integration and balance of activities among the various DOE offices
- Production/distribution/storage/dispensing portion probably underfunded – particularly with earmarked funds
- More prioritizing is needed within and across programs
- Establish more milestones and go/no-go decisions
- Adjust the program on the basis of ongoing results
- Partner with a broad range of academic, industrial, and government organizations, both domestic and international
- Establish an independent program review process and board

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (2 of 4)

- Shift some development areas toward more exploratory work
- Establish DOE-sponsored academic energy research centers
  - Focus on interdisciplinary areas of new science and engineering with opportunities for breakthrough solutions to energy issues (e.g. materials research, nanostructures, modeling for materials design, biosciences)

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (3 of 4)

The committee recommends increased emphasis in the following five areas:

1. *Fuel cell vehicle development*
   - R&D to facilitate breakthroughs in fuel cell costs, durability of materials, and on-board hydrogen storage systems
2. *Distributed hydrogen generation*
   - R&D in small-scale natural gas reforming, electrolysis, and new concepts for hydrogen production systems
3. *Infrastructure analysis*
   - Accelerate and increase efforts in systems modeling and analysis for hydrogen delivery to develop options and help guide R&D in large-scale infrastructure development

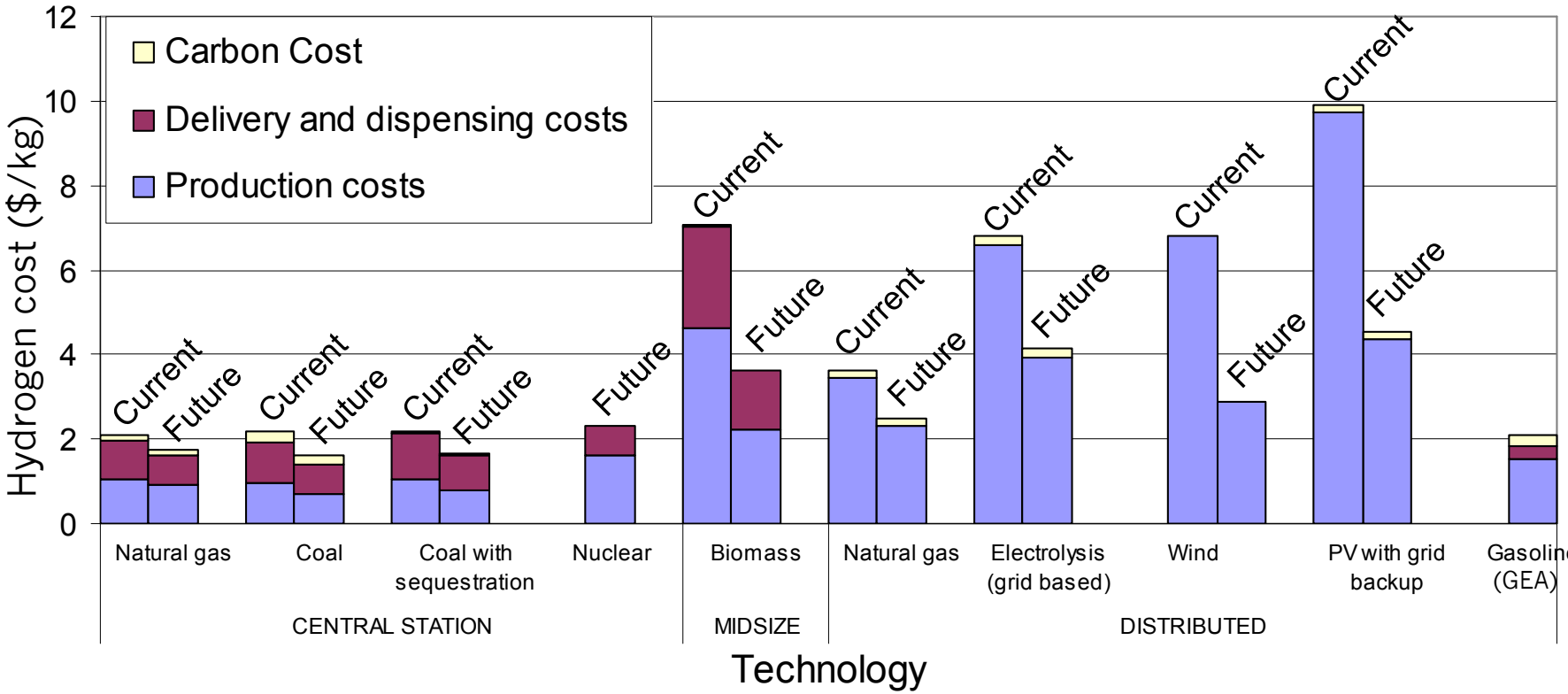
(continued)

MAJOR RECOMMENDATIONS
DOE's Hydrogen RD&D Plan (4 of 4)

4. *CO_2-free energy technologies*
   - Wind-energy-to-hydrogen for transition & potentially longer term
   - Exploratory and fundamental research on hydrogen from photobiological, photoelectrochemical, thin-film solar, and nuclear heat processes

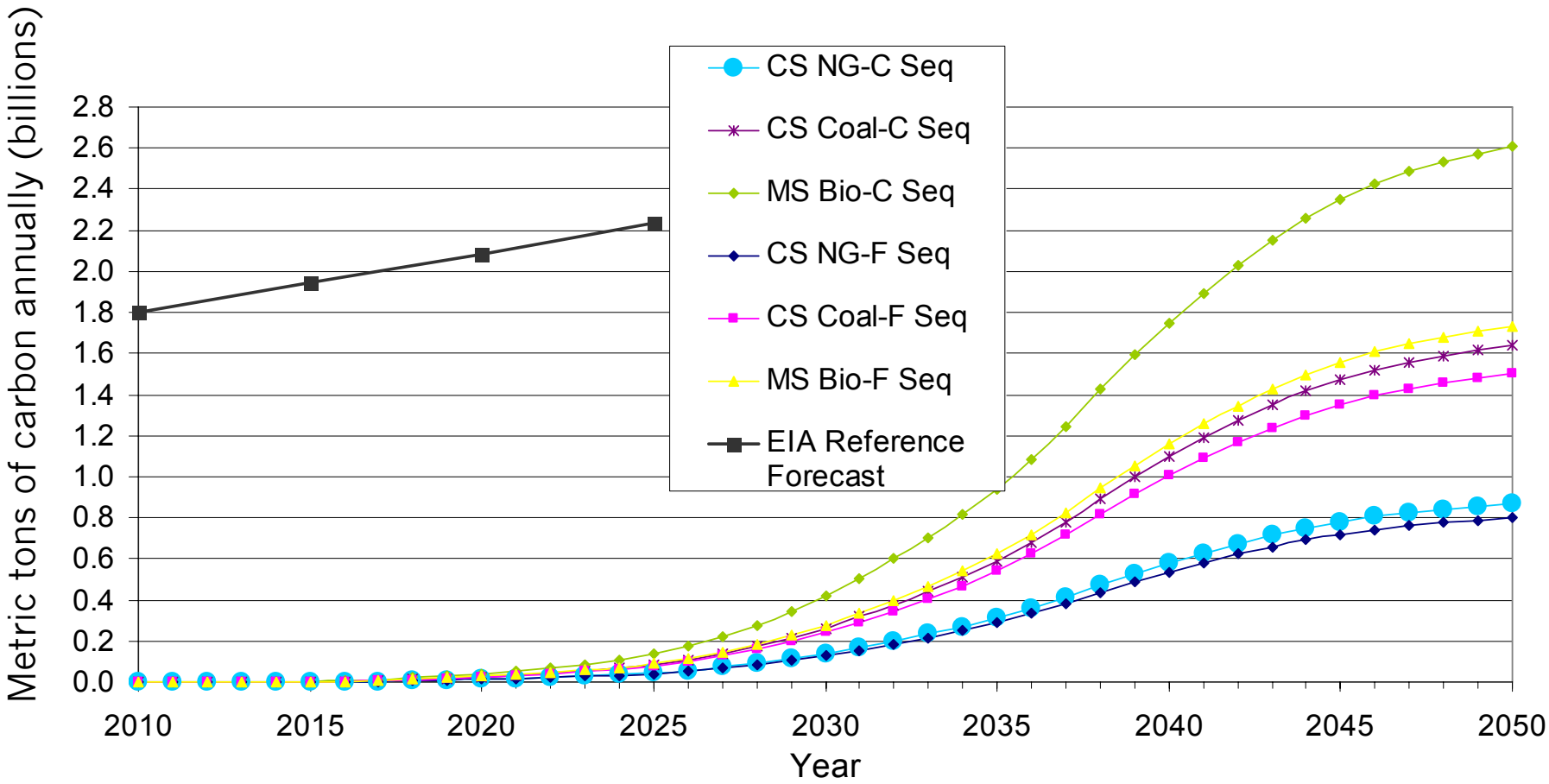
5. *Carbon sequestration*
   - Accelerate development and early evaluation of carbon capture and sequestration
   - Continue FutureGen Project as a high-priority task

DELIVERED H_2 COSTS OF VARIOUS TECHNOLOGIES



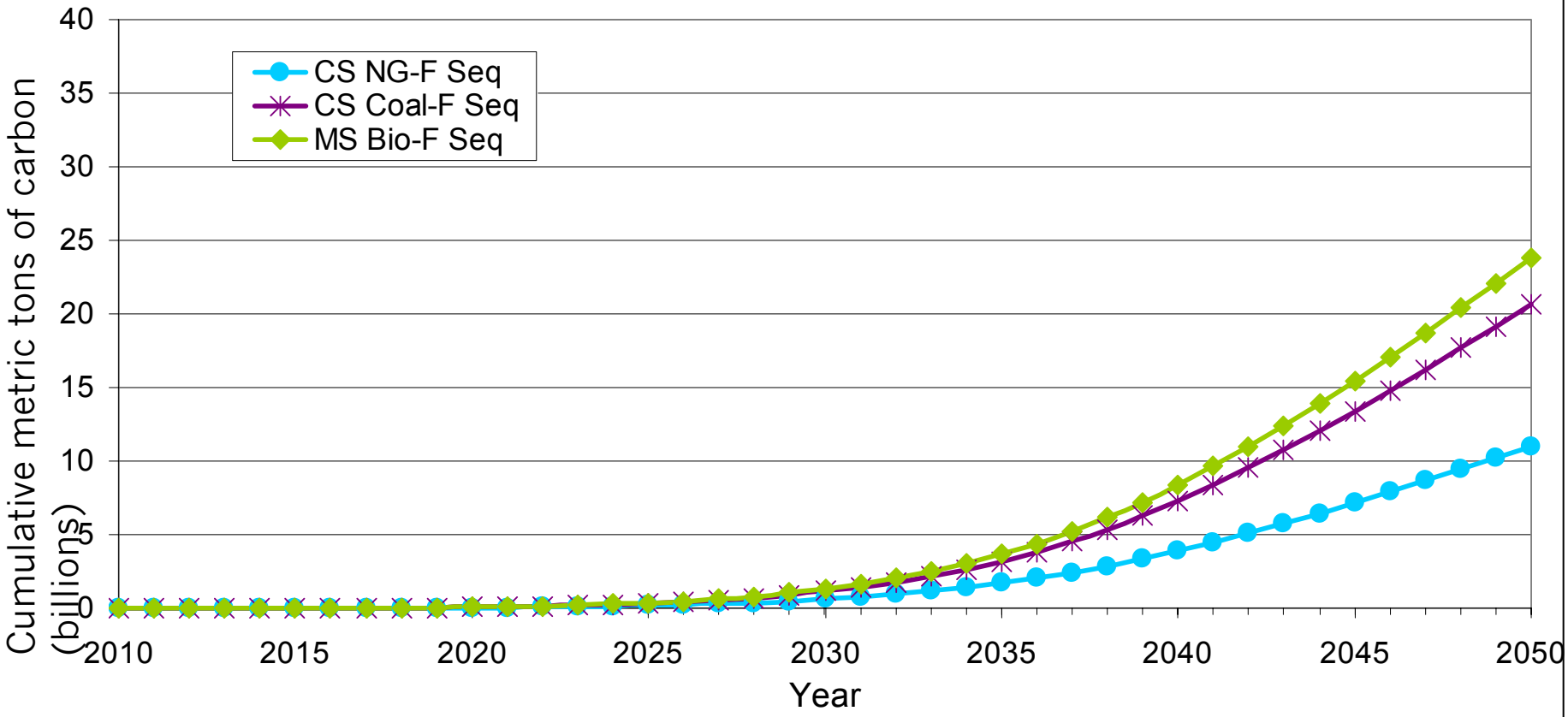
- *GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency*

CARBON SEQUESTRATION RATES



- *EIA reference forecast shown*

CUMULATIVE CARBON SEQUESTRATION



- *Capacity of depleted U.S. oil and gas reservoirs = 25-50+ billion metric tons C*
- *Capacity of unminable U.S. coal seams = 15 billion metric tons C*

DEMAND SIDE
Transportation

- Only light duty highway vehicles considered
- Target: $50/kW with 4,000 – 5,000 hours of operation
- Today
  - Infrastructure: large, distributed, inexpensive, liquid fuel
  - Over 200 million vehicles need existing parallel infrastructure
  - "No compromise vehicles": range, refueling, safety, cargo space, park anywhere
- H_2 vehicle demand won't justify infrastructure by 2020:
  - "Best case scenario": analogy with HEVs
  - 1st HEV in 1997; 159,100 sold world-wide by end of 2002
  - Still slow because of cost; ~ 100,000 in US in 2004
  - FCV "not close" to $100/kw today; still, assumed 1% in 2015
  - With this optimistic assumption: Less than 4 million in 2020

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE

- The current energy carrier of choice is molecular hydrogen and it has the advantage that it can be produced using many feedstocks
- Significant energy lost in hydrogen distribution and dispensing
- Getting hydrogen to and on-board the vehicle in a practical manner are formidable technology challenges
  - H_2 is difficult to transmit through pipelines because of embrittlement and a propensity to leak
  - In even the best case of improved compression efficiency and higher pressure on board tanks, the energy, space, cost and weight penalties are formidable

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE
On-board Storage

- No approach to on-board storage—physical or chemical—is close to DOE/FreedomCAR target for energy density (on a total storage system basis)
- Physical storage of H_2 (i.e., pressurized, liquefied) can't reach DOE energy density target due to thermodynamic properties of H_2. Safety of high pressure storage systems may be an issue when used by untrained personnel such as consumers
- Development of new methods for carrying hydrogen, such as carbon, metal hydrides, or chemical hydrides, is needed

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE
Recommendations

- DOE infrastructure program requires greater emphasis and support
- Technical program should focus on materials issues
- Create better linkages between programs in large-scale and small-scale hydrogen production
- Clarify conditions under which large-scale and small-scale hydrogen production will become competitive, complementary, or independent
- Needs additional funding for exploratory research on new concepts for hydrogen delivery

REPORT SECTIONS

HYDROGEN STORAGE AND INFRASTRUCTURE
Recommendations

- Increase R&D investment in support of breakthrough approaches on small-scale electrolyzers and natural gas reformers to facilitate transition phase
- Halt efforts on high-pressure tanks and cryogenic liquid storage
  - Both approaches have reached pre-commercial development
  - Neither approach can reach DOE target for energy density
- Invest in new approaches to onboard storage of hydrogen such as solid state carriers (e.g., hydrides)

REPORT SECTIONS

CARBON CAPTURE AND STORAGE

- Fossil fuels will be one of the principal sources of hydrogen for the hydrogen economy
- Carbon capture and storage technologies will be required for successful utilization of fossil fuels in production of hydrogen

REPORT SECTIONS

CARBON CAPTURE AND STORAGE
Findings

- Only a modest incremental cost is incurred at plants that produce H_2 from coal or natural gas, if these plants also capture instead of venting the byproduct CO_2
- There appears to be abundant geological storage capacity for CO_2 below ground in hydrocarbon reservoirs and in deep brine aquifers, but sufficient storage integrity has not been established
- All CO_2 storage projects (not just hydrogen) have common and difficult institutional issues and issues of public acceptance

REPORT SECTIONS

CARBON CAPTURE AND STORAGE
Recommendations

- Integration of carbon capture and storage with H_2 production from fossil fuels starts with the integration of R&D programs
- Address CO_2 infrastructure issue early in transition
- The national H_2 R&D program should be involved in all of the early carbon capture and storage projects, even those that do not involve H_2 production, including:
  - Projects where CO_2 is captured as impurity in natural gas
  - Projects where CO_2 is captured during electricity production

REPORT SECTIONS

TRANSITION MATTERS
The Problem

- The "first mover problem"
  - H_2 suppliers won't invest without demonstrated demand
  - Without ubiquitous supply, risk increases for customers of devices that use H_2
- Policy issue: how to stimulate both sides of the H_2 market

REPORT SECTIONS

TRANSITION MATTERS
The Lessons of Experience

- In other industries, a compelling customer application drove market change
- Personal computer
  - Spreadsheet application (Visi-calc) enabled transition for PC to become working tool
- Automobile
  - Superior customer value enabled gasoline engine to win over electric (no long trip capability) and steam (affordability)

REPORT SECTIONS

TRANSITION MATTERS
The Value of Market Intelligence

- Observation of energy markets can inform transition strategies
- Niche markets most important
  - Every technology starts there
  - Most also finish there
- Observe early-stage investment markets
- Integrate with systems analysis capability

REPORT SECTIONS

TRANSITION MATTERS
Implications for Strategy

- Government as first customer
  - Defense applications?
  - Army program: http://www.onpoint.us/
- Distributed generation of H_2 matches supply with demand
- Buy-down for H_2 using technologies
- Remove safety as an issue

REPORT SECTIONS

TRANSITION MATTERS
Questions to be Resolved

- Should the DOE seek to guide the transition into selected pathways, or let development be guided by industrial stakeholders?
- Which transitional technologies to pursue?
- What incentives will entrepreneurs and investors need before they commit capital?

REPORT SECTIONS