DTIC FILE

IOUSE COMMITTEE REPOI

(11)

Date Referred to Committee: March 3, 2004

FURTHER REFERRALS:

Date of Committee Action: 4.22.04

The FINANCE Committee considered: HB 512

HOUSE BILL NO. 512 HYDROGEN ENERGY RESEARCH PROGRAM

"An Act establishing the Hydrogen Energy Partnership in the Department of Community and Economic Development; requiring the commissioner of community and economic development to seek public and private funding for the partnership; providing for the contingent repeal of an effective date; and providing for an effective date."

Recommends it be replaced with [ ] HCS *or* [X] CS for HB 512 (FIN)

For Senate Bills with new title: [ ] Technical Title [ ] New Title: HCR ______ [X] Same Title [ ] New Title

[ ] attach amendments

[ ] add new referral to ____________ Committee

[ ] Letter of Intent ____________ Committee

List of Abbrev for Depts.: ADM, CED, COR, CRT, EED, DEC, DFG, GOV, HSS, LEG, LAW, LWF, MVA, DNR, DPS, REV, DOT, UA

NEW **FISCAL NOTES**

*Assigned by Chief Clerk's Office

List by Dept(s):	*FN#	Fiscal	Indet.	Zero
CED		✓		

PREVIOUS **FISCAL NOTES**

List by Dept(s):	FN#	Fiscal	Indet.	Zero
UA	1			✓

Signing with recommendations	Printed Last Name	DP	DNP	NR	AM
[signature]	Joule	—			
[signature]	MOSES	✓			
[signature]	Chenault	✓			
[signature]	Fate	✓			
[signature]	FOSTER	X			
Chair:					
Chair: [signature]	Williams	X			

FISCAL NOTE

STATE OF ALASKA
2004 LEGISLATIVE SESSION

Fiscal Note Number: 1
Bill Version: HB 512
(H) Publish Date: 3/3/04

Revision Date/Time (Note if correction):
Dept. Affected: University of Alaska
Title: HYDROGEN ENERGY RESEARCH PROGRAM
RDU
Component
Sponsor: Representative(s) Crawford, Berkowitz, Gara, Morgan
Requester
Component No.

Expenditures/Revenues (Thousands of Dollars)

Note: Amounts do not include inflation unless otherwise noted below.

OPERATING EXPENDITURES	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Personal Services	0.0	0.0	0.0	0.0	0.0	0.0
Travel						
Contractual						
Supplies						
Equipment						
Land & Structures						
Grants & Claims						
Miscellaneous						
TOTAL OPERATING	0.0	0.0	0.0	0.0	0.0	0.0
CAPITAL EXPENDITURES						
CHANGE IN REVENUES ( )						

FUND SOURCE (Thousands of Dollars)

1002 Federal Receipts						
1003 GF Match						
1004 GF						
1005 GF/Program Receipts						
1037 GF/Mental Health						
Other (Specify Type--Do not abbreviate)						
TOTAL	0.0	0.0	0.0	0.0	0.0	0.0

Estimate of any current year (FY2004) cost: 0.0

Mark this box (X) if funding for this bill is included in the Governor's FY 2005 budget proposal: [ ]

POSITIONS

Full-time						
Part-time						
Temporary						

ANALYSIS: *(Attach a separate page if necessary)*

This is the estimated cost of participating in the Hydrogen Energy Partnership.

Prepared by: Paul Jenny
Phone 907-474-7958
Division: University of Alaska
Date/Time 2/23/04 4:19 PM
Approved by: Paul Jenny
Date 2/23/2004
Agency: University of Alaska

(Revised 12/2003 OMB)

FISCAL NOTE

STATE OF ALASKA
2004 LEGISLATIVE SESSION

Fiscal Note Number:
Bill Version: CSHB(FIN) 512
() Publish Date:

Revision Date/Time (Note if correction):
Title: Hydrogen Energy Research
Sponsor: Representatives Crawford, et al
Requester: House Finance

Dept. Affected: DCED
RDU: Executive Admin & Dev (119)
Component: Office of Economic Development
Component No. 2743

Expenditures/Revenues (Thousands of Dollars)

Note: Amounts do not include inflation unless otherwise noted below.

OPERATING EXPENDITURES	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Personal Services	65.0					
Travel	4.0					
Contractual						
Supplies	1.0					
Equipment	5.0					
Land & Structures						
Grants & Claims						
Miscellaneous						
TOTAL OPERATING	75.0	-	-	-	-	-
CAPITAL EXPENDITURES						
CHANGE IN REVENUES ( )						

FUND SOURCE (Thousands of Dollars)

1002 Federal Receipts	35.0					
1003 GF Match						
1004 GF						
1005 GF/Program Receipts						
1037 GF/Mental Health						
1108 Statutory Designated Program Rcpts	40.0					
TOTAL	75.0	-	-	-	-	-

Estimate of any current year (FY2004) cost: 0.0

Mark this box (X) if funding for this bill is included in the Governor's FY 2005 budget proposal: [ ]

POSITIONS

Full-time	1	-	-	-	-	-
Part-time						
Temporary						

ANALYSIS: *(Attach a separate page if necessary)*

This legislation creates the Hydrogen Energy Partnership to facilitate the development of a hydrogen fuel industry in Alaska. The partnership would consist of nine members and be housed in the department. The department is charged with securing federal and private funding sources to cover the costs of establishing and operating the partnership. If funding is secured, the department would appoint partnership members and continue to provide staff support.

DCED estimates needing a Development Specialist II to secure the federal or private funding sources and begin organizational work for the partnership. Because responsibilities could not be absorbed by existing staff, one new FTE would be required along with funds for a computer and supplies. Travel funds are included for partnership members to meet up to three times annually. After FY05, federal and/or private funding sources would fund partnership operations and staff.

Prepared by: Albert H. Clough, Deputy Commissioner — Phone (907) 465-2500
Division: Office of Economic Development — Date/Time 4/22/04 8:04 AM
Approved by: Edgar Blatchford, Commissioner — Date 4/22/2004
Agency: Department of Community & Economic Development

Alaska State Legislature

House of Representatives

Alaska State Capitol
Juneau, Alaska 99801-1182
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Representative Harry Crawford
District 21

SPONSOR STATEMENT FOR HB 512

House Bill 512 establishes a hydrogen energy partnership within the Department of Community and Economic Development. The partnership is tasked with facilitating the development of a hydrogen fuel industry in Alaska.

Hawaii has already established a similar commission in preparation for potentially using their geothermal energy resource for producing hydrogen for dispersal throughout the Pacific Rim. If Alaska is going to remain competitive in the field of energy in the United States and throughout the world, we must prepare for the possibility that hydrogen will become a viable fuel.

House Bill 512 addresses this eventuality and establishes the structure necessary for the State of Alaska to accept funding for a hydrogen project in the state.

E-mail: Representative_Harry_Crawford@legis.state.ak.us

FISCAL NOTE

STATE OF ALASKA
2004 LEGISLATIVE SESSION

Fiscal Note Number: 1
Bill Version: HB 512
(H) Publish Date: 3/3/04

Revision Date/Time (Note if correction):
Dept. Affected: University of Alaska
Title: HYDROGEN ENERGY RESEARCH PROGRAM
RDU
Component
Sponsor: Representative(s) Crawford, Berkowitz, Gara, Morgan
Requester
Component No.

Expenditures/Revenues (Thousands of Dollars)

Note: Amounts do not include inflation unless otherwise noted below.

OPERATING EXPENDITURES	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Personal Services	0.0	0.0	0.0	0.0	0.0	0.0
Travel						
Contractual						
Supplies						
Equipment						
Land & Structures						
Grants & Claims						
Miscellaneous						
TOTAL OPERATING	0.0	0.0	0.0	0.0	0.0	0.0
CAPITAL EXPENDITURES						
CHANGE IN REVENUES ( )						

FUND SOURCE (Thousands of Dollars)

FUND SOURCE	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
1002 Federal Receipts						
1003 GF Match						
1004 GF						
1005 GF/Program Receipts						
1037 GF/Mental Health						
Other (Specify Type--Do not abbreviate)						
TOTAL	0.0	0.0	0.0	0.0	0.0	0.0

Estimate of any current year (FY2004) cost: 0.0
Mark this box (X) if funding for this bill is included in the Governor's FY 2005 budget proposal: [ ]

POSITIONS

POSITIONS	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Full-time						
Part-time						
Temporary						

ANALYSIS: *(Attach a separate page if necessary)*
This is the estimated cost of participating in the Hydrogen Energy Partnership.

Prepared by: Paul Jenny — Phone 907-474-7958
Division: University of Alaska — Date/Time 2/23/04 4:19 PM
Approved by: Paul Jenny — Date 2/23/2004
Agency: University of Alaska

(Revised 12/2003 OMB)

Adopted w/o objection
4.22.04

23-LS1690\D.1
Craver
4/21/04

AMENDMENT 1

OFFERED IN THE HOUSE

TO: HB 512

BY REPRESENTATIVE WILLIAMS

4/22/04
called
8:45

Page 2, line 3, following "energy":

Insert ", hydropower, wind power, and tidal power"

Page 2, following line 21:

Insert a new paragraph to read:

"(6) the electric utility industry;"

Renumber the following paragraphs accordingly.

L

Requested new fiscal note from DCED

FISCAL NOTE

OF ALASKA
:GISLATIVE SESSION

Fiscal Note Number: 2
Bill Version: HB 512
(H) Publish Date: 3/3/04

Date/Time (Note if correction):
Hydrogen Energy Research

Dept. Affected: DCED
RDU: Executive Admin & Dev (119)
Component: Office of Economic Development

Sponsor: Representatives Crawford, et al
Requester: House Econ Dev. Int'l. Trade & Tourism

Component No. 2743

Expenditures/Revenues (Thousands of Dollars)

Note: Amounts do not include inflation unless otherwise noted below.

OPERATING EXPENDITURES	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010
Personal Services	65.0	0.0	0.0	0.0	0.0	0.0
Travel						
Contractual						
Supplies	1.0					
Equipment	5.0					
Land & Structures						
Grants & Claims						
Miscellaneous						
TOTAL OPERATING	71.0	0.0	0.0	0.0	0.0	0.0
CAPITAL EXPENDITURES						
CHANGE IN REVENUES ( )						

FUND SOURCE (Thousands of Dollars)

1002 Federal Receipts						
1003 GF Match						
1004 GF	71.0	0.0	0.0	0.0	0.0	0.0
1005 GF/Program Receipts						
1037 GF/Mental Health						
Other (Specify Type--Do not abbreviate)						
TOTAL	71.0	0.0	0.0	0.0	0.0	0.0

Estimate of any current year (FY2004) cost: 0.0

Mark this box (X) if funding for this bill is included in the Governor's FY 2005 budget proposal: [ ]

POSITIONS

Full-time	1	0	0	0	0	0
Part-time						
Temporary						

ANALYSIS: *(Attach a separate page if necessary)*

This legislation creates the Hydrogen Energy Partnership to facilitate the development of a hydrogen fuel industry in Alaska. The partnership would consist of eight members and be housed in the department. The department is charged with securing federal and private funding sources to cover the costs of establishing and operating the partnership. If funding is secured, the department would appoint partnership members and continue to provide staff support.

DCED estimates needing a Development Specialist II to write grant applications, secure the federal or private funding sources and begin organizational work for the partnership. Because responsibilities could not be absorbed by existing staff, one new FTE would be required along with funds for a computer and supplies. After FY05, federal and/or private funding sources would fund partnership operations and staff.

Prepared by: Albert H. Clough, Deputy Commissioner — Phone (907) 465-2500
Division: Office of Economic Development — Date/Time 2/24/04 10:38 AM

Approved by: Edgar Blatchford, Commissioner — Date 2/24/2004
Agency: Department of Community & Economic Development

(Revised 9/2003 OMB)

Combined Heat and Power

Case Study

Fuel Cells Provide Reliable Power to U.S. Postal Service Facility in Anchorage, Alaska

Combined heat and power project provides reliable power at reduced cost

Overview

Working together, the U.S. Postal Service (USPS) and Chugach Electric Association, partnering with the Department of Defense (DOD), Department of Energy (DOE), US Army Corps of Engineers Construction Engineering Research Laboratories (USA CERL), Electric Power Research Institute (EPRI), and National Rural Electric Cooperative Association (NRECA), developed and installed one of the largest fuel cell installations in the world.

The one-megawatt fuel cell combined heat and power plant sits behind the Anchorage U.S. Postal Service Mail Processing and Distribution Facility. Chugach Electric owns, operates, and maintains the fuel cell power plant, which provides clean, reliable power to the USPS facility. In addition, heat recovered from the fuel cells, in the form of hot water, is used to heat the USPS Mail Processing and Distribution Facility. By taking a leadership role, the USPS will save over \$800,000 in electricity and natural gas costs over the 5½-year contract term with Chugach Electric.

"Fuel cells solved a handful of problems."

—Cathe Grosshandler, Alaska District Environmental Coordinator, U.S. Postal Service

Background

The U.S. Postal Service Mail Processing and Distribution Facility, adjacent to the Anchorage International Airport, serves as the postal hub for all of Alaska. The facility processes, on average, over one million pieces of mail every day, operating 24 hours per day, 365 days per year. Annual energy costs for the 270,000-square-foot facility exceeded \$300,000 for electricity and \$35,000 for natural gas.

The facility faced a series of issues that needed to be addressed. To meet new environmental codes, the facility needed to upgrade an existing underground fuel oil tank serving the facility's 600-kW emergency generator. As a result of an expansion to the facility and adding new optical mail processing equipment, the facility's peak electric demand had grown larger than the existing emergency generator could support. Upgrades were also needed to the UPS (uninterruptible power supply). In addition, the two 80-horsepower boilers (2,700,000 Btu/h), which heat the facility, also needed some improvements.

The Mail Processing and Distribution Facility, adjacent to the Anchorage International Airport, is key to the Alaska mail system.

Rather than solving each issue separately, the District Environmental Coordinator wanted a comprehensive solution. The answer seemed to lie in a highly reliable, highly efficient combined heat and power plant.

Project Summary

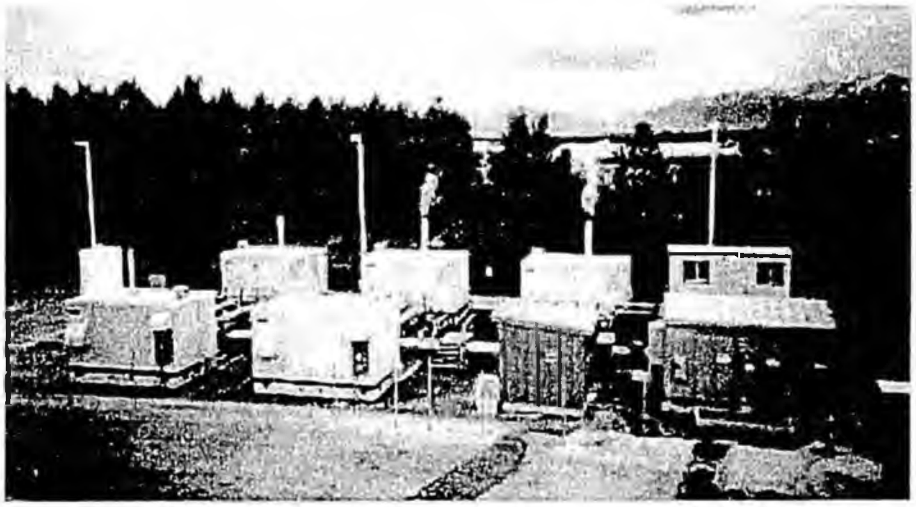
Initially, a combined heat and power plant using natural gas engine generators was proposed. However, after attending a local energy technology show, the USPS began to consider fuel cells. By coincidence Chugach Electric Association, the serving electric utility, was developing expertise in fuel cell technology and supported the USPS interest in the emerging technology.

Fuel cells produce electricity through an electrochemical reaction rather than combustion. While more expensive than conventional power generating equipment, fuel cells provide efficient, reliable power with minimal emissions. (For more information on fuel cells, see FEMP's Federal Technology Alert, "Natural Gas Fuel Cells," at http://www.eren.doe.gov/femp/prodtech/fed_techalert.html.)

To increase overall reliability, the combined heat and power plant consists of five fuel cells with room for a future sixth unit. Thus, the system can meet the facility's peak 800-kW demand even when one fuel cell is off-line. The resulting one-megawatt (1,000-kW) combined heat and power plant consists of five fuel cells, a nitrogen tank, heat recovery equipment, a pump house, and the site management system (SMS).

The fuel cells, manufactured by International Fuel Cells, Inc. (formerly ONSI), are rated at 200 kW each and are fueled by natural gas. Nitrogen is used to purge the fuel cells during startup and shutdown cycles. The pump house is used to move the heat generated by the fuel cells to either the facility for space heating or to the cooling modules, where the excess heat is rejected.

What makes the system a success is the site management system. The SMS includes fuel cell load control, grid interconnection, and a high-speed switching system. The SMS allows the multiple fuel cell system to transfer between grid-parallel and grid-independent in under 4 milliseconds (1/4 cycle in a 60-Hz system), fast enough that the highly sensitive computer systems in the USPS facility are not interrupted by the transfer. Normally, the fuel cells operate in parallel with the Chugach electric grid. Excess power generated by the fuel cells flows out into the Chugach grid. However, in the case of a grid outage, the SMS identifies the outage, isolates the USPS facility from the grid and allows the fuel cells to transfer to grid-independent mode seamlessly. The SMS was developed under this project but is now commercially available and being specified for use in other fuel cell power systems.



Set against the Chugach Mountains, five fuel cells supply reliable and clean power to the USPS facility.

The entire project cost $5.5 million, including the research and development for the SMS. Funding for the project came from the many partners involved in the effort. What made the project work economically for the U.S. Postal Service is a special contract between the USPS and Chugach Electric. Chugach Electric owns, operates, and maintains the fuel cell power plant, which is located on the USPS property. The plant is remotely operated by Chugach Electric. The only cost to the USPS was the $1 million up-front cost as part of a 5 1/2-year contract for baseline electrical service. In return Chugach Electric provides electricity to the mail processing facility for the 5 1/2-year term. If electricity requirements at the USPS facility grow above the set baseline, which the USPS believes is unlikely, additional electricity is purchased at standard rates.

In addition, the USPS facility owns the use of the heat recovered from the fuel cells. Heat energy from the fuel cells is available in the form of hot water at two temperatures: 240°F and 140°F. At this time, the higher temperature water is used for heating the facility. The lower temperature heat is rejected through the cooling modules.

Benefits

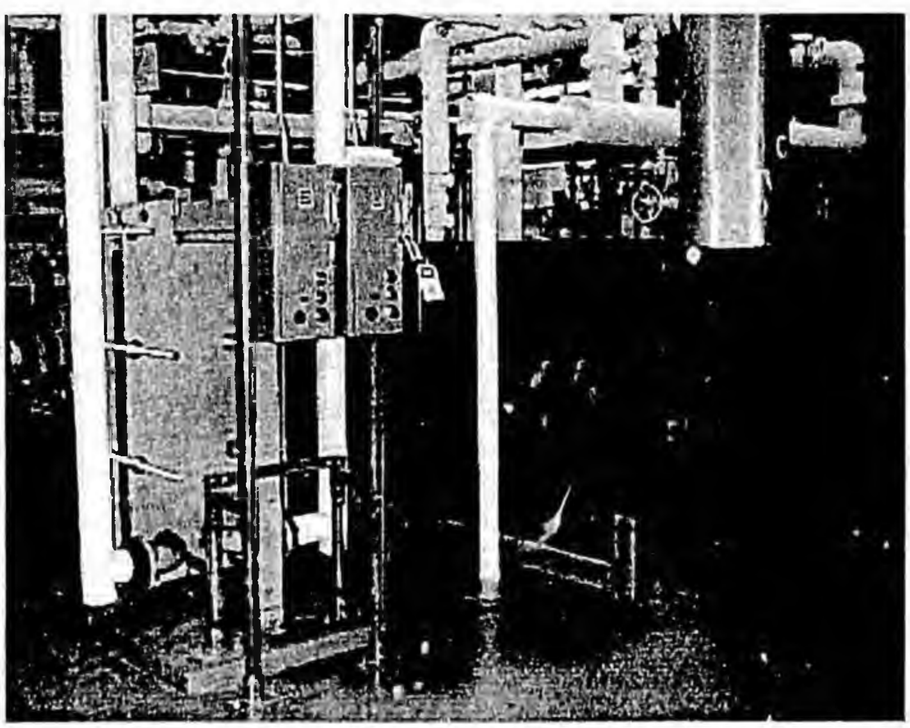
The fuel cell CHP plant provides a number of benefits to the USPS. The most significant benefit has been the increased reliability of electric service.

Restarting the mail processing equipment after a power outage requires a significant level of effort. The increased reliability results in fewer power outages, thereby avoiding unscheduled shutdowns and restarts. The fuel cell and SMS have worked flawlessly since commissioned. In fact, the week before Christmas, on one of the busiest days of the year, construction at the airport caused a local power outage. The entire area was without power for over 4 hours. All, except the U.S. Postal Service, that is. The SMS system automatically switched the facility to operate grid-independent with no interruption. The USPS facility went on to set records, processing over 1.4 million letters and parcels that day, while the neighbors were sitting in the dark.

While the combined heat and power project does not reduce electricity consumption at the USPS facility, it does significantly reduce USPS energy costs. The contract between the USPS and Chugach Electric provides baseline electrical service to the USPS facility for 5½ years at a cost of $1 million. Previously, electricity for the USPS facility averaged over $300,000 per year.

Heat recovered from the fuel cells is being used for space heating in the mail processing facility, thereby displacing the load on the original boiler heating system. In fact, savings have exceeded the original estimate. Initially, it was determined that the fuel cell heat energy could meet around 50% of the total facility space heating needs. During the first year of operation, the heat recovered has satisfied all the space heating needs. Although the winter of 2000-2001 was milder than average, heat recovered from the fuel cells has exceeded expectations.

Some capital cost reductions were also achieved. The demonstrated reliability of the fuel cell and site management system has eliminated the need to upgrade the existing emergency generator. However, the old 1000-gallon, single-wall, below-grade fuel oil tank still needed to be replaced. A new dual-wall, 500-gallon, above-ground fuel oil tank was determined to be sufficient because of the increased reliability of the new power supply system. In addition to the cost reduction from the less expensive, smaller tank, the environmental code features were also less expensive for the smaller tank size. Avoiding the need to upgrade the emergency generator and installing a smaller fuel oil tank saved the USPS an estimated $500,000 in capital costs.



Heat recovered from the fuel cells offsets heat supplied by the boiler system. The boilers were not needed during the winter of 2000–2001.

Lessons Learned

The USPS recommends that any site thinking about a similar project should consider the following:

- Projects of this nature require "champions." Each of the parties involved in the project recognized the value of local champions who could think outside the box, overcome barriers, and push the project through.
- Consult with the local utility, DOE regional office, and other organizations to investigate potential partnerships. Both the USPS and Chugach Electric Association believe a more effective solution was achieved as a result of the partnership.
- Take a holistic approach to solving facility needs. The USPS had to address a series of issues. Although each facility need could have been solved individually, the fuel cell combined heat and power plant solved several of the needs simultaneously and at a lower cost.

THE
FOLLOWING
DOCUMENT(S)
ARE
POOR
ORIGINAL
COPIES

Being the largest fuel cell installation of its time made this a distinctive installation. However, it will not remain unique. The development of the SMS will lead to more multi-unit fuel cell power plants with high-speed reliability.

Looking Ahead

The USPS facility is looking for additional uses for the heat recovered from the fuel cells. While the high temperature heat recovered is perfect for space heating, there is still significant heat energy available at 140°F, which has yet to be utilized. The USPS is still investigating several potential uses for this valuable heat energy.

The SMS has additional capabilities that the USPS may use in the future. In addition to controlling fuel cell operation, the SMS is also capable of controlling peak electrical demand through load shedding. This feature could be used to prevent overloading the power plant when the electric grid is down and the fuel cells are operating independent of the electric grid. The ability to load shed while operating grid-independent could prevent a shutdown of the fuel cell power plant as a result of an overload condition.

At the end of the contract period, the USPS and Chugach Electric will renegotiate the future of the fuel cell combined heat and power plant. No one knows what the future may bring, but all agree the project has been a success.

For More Information

FEMP Help Desk
(800) 363-3732
International callers please use
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Web site: www.eren.doe.gov/femp

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Rocky Mountain Institute Quest for Solutions (RMIQ) Public Lecture
Given Institute, Aspen, Colorado, 6 August 2003

Hydrogen: The Future of Energy

Amory B. Lovins

Chief Executive Officer
Rocky Mountain Institute
www.rmi.org

Chairman of the Board
Hypercar, Inc.
www.hypercar.com

ablovins@rmi.org

Why is hydrogen so important?

- New, highly versatile energy carrier
- Cleaner, safer *and* cheaper fuel choice
- When combined with super-efficient fuel cell vehicles, enables a profitable transition from oil — profitable even for oil companies
- In a hydrogen economy, U.S. energy needs can be met from North American energy sources (including local ones), providing real security
- Hydrogen can accelerate renewable energy sources, which also have stable prices
- Hydrogen-ready vehicles can revitalize Detroit

The hydrogen cacophony (see "Twenty Hydrogen Myths," www.rmi.org)

- Rapidly growing interest due to climate and security concerns
- Unfamiliar terms and concepts, many disciplines
- Speculation: winners, losers, hidden agendas?
  - Reinforce dominant incumbents, displace, or diversify?
  - Foolishness, panacea, or misleading and double-edged?
- Debate is overlaid on rancorous old debates
  - Oil, nuclear, renewables, climate, big business, right/left,...
- Unexpected realignments, strange bedfellows
  - Environmentalists: If President Bush, oil companies, and the nuclear industry like it, it must be bad
  - *Wall St. J.* editorial: If enviros like it, it must be bad
- Both advocates *and* opponents often poorly understand it!

We already *have*, invisibly, a partly hydrogen economy

- Two-thirds of the fossil-fuel atoms being burned today are hydrogen...as a part of hydrocarbons
- A large hydrogen industry exists today: it produces 1/4 the annual volume of the natural-gas industry worldwide
- The debate is about:
  - Whether we also need to combust the last third (carbon)
  - Whether it might be cheaper and more attractive not to burn the carbon, but to use only the hydrogen
  - To what degree and at what speed the fossil-fuel hydrogen should be replaced by renewable hydrogen
  - How renewable hydrogen will compete with hydrogen produced by nuclear fission (or eventually fusion?) power
  - At what scale
  - Who does it
  - Who decides and how

I'll address pervasive myths with answers to eight questions:

- What is hydrogen?
- Is hydrogen safe?
- Why is hydrogen cheaper to use for vehicles?
- How is hydrogen now produced and used?
- What is the least-cost way to make and deliver hydrogen?
- What technologies are needed to enable a hydrogen transition?
- How can the U.S. profitably transition from oil to hydrogen?
- Are there enough North American primary energy sources for this transition?

What is it? Basic hydrogen facts

- Hydrogen is ~75% of the known universe
- On earth, it's not an energy *source* like oil or coal
  - Only an energy *carrier* like electricity or gasoline — a form of energy, derived from a source, that can be moved around
- The most versatile energy carrier
  - Can be made from any source and used for any service
  - Readily stored in large amounts
  - Fungible with the other highest-quality carrier, electricity
- Almost never found by itself; must be liberated
  - "Reform" HCs or CHs with heat and catalysts
  - "Electrolyze" water (split H_2O with electricity)
  - Experimental methods: photolysis, plasma, microorganisms,…
- Can be made and used at any scale

Physical attributes of hydrogen

- Transparent, colorless, odorless, nontoxic
- Molecular hydrogen (H_2) is the lightest element and molecule
  - Per unit of energy contained, H_2 is 64% lighter than natural gas or 61% lighter than gasoline
- 1 kg of H_2 contains same energy as 1 U.S. gallon of gasoline, which weighs not 2.2 but 6.2 pounds
- The flip side of lightness is bulk
  - H_2 has 30% the energy of CH_4, both at atmospheric pressure
  - H_2 at 170 bar pressure has 6% the energy/volume of gasoline
- **H_2 is advantaged if lightness is worth more than compactness**

Is it safe?: A primer on Hydrogen safety

- ◇ All fuels are hazardous, but…
- ◇ Hydrogen is comparably or less so, but different
  - Buoyant (8× CH_4), diffusive (4×CH_4, 12× gasoline)
  - Clear flame can't sear you at a distance; no smoke
  - Hard to make explode; can't explode in free air; burns first
  - 4× gasoline-fume concentration required to burn; 22× less explosive power
  - Rises, doesn't puddle
  - *Hindenburg* myth (1937) — *nobody* was killed by hydrogen fire
  - Completely unrelated to hydrogen bombs

Demonstrating hydrogen *vs.* gasoline safety

M.R. Swain, "Fuel Leak Simulation," www.eren.doe.gov, 2002.

3 s: Ignition. H_2 @ 28 L/min, gasoline @ 0.68 L/min

60 s: H_2 flow subsiding; max 47°C on rear window, 19.4°C on tray behind rear seat. Zooming in on gasoline car…

90 s: H_2 plume nearly stopped.

140 s: Gasoline-car interior alight. Tires later burst.

Why is it cheaper? Basic hydrogen economics

- The most common fallacy is comparing hydrogen to other fuels in cost per unit of *energy contained*
- What matters is cost per unit of *service provided*
- *E.g.*, a hydrogen fuel cell can propel a car 2–3× as efficiently as a gasoline engine car, so even if H_2 cost twice as much per unit of energy, it would cost the same or less *per mile driven*
- Recovered heat from the fuel cell (and reformer), clean and silent operation, high-quality and ultra-reliable power supply, and many other "distributed benefits" may also have a big value

Hydrogen cars will be cheaper per mile driven

◇ Gasoline

= 5¢ per mile

- Gasoline
- Diesel

$1.00/gallon (pretax)

Avg. 20 mpg

Hydrogen cars will be cheaper per mile driven

- **Gasoline**

liquid fuel → retail site → vehicle = 5¢ per mile

liquid fuel	retail site	vehicle
• Gasoline • Diesel	$1.00/gallon (pretax)	Avg. 20 mpg

- **Reformation**

liquid or gas fuel → retail site reformer → hydrogen → vehicle = $2^1/_2$¢ per mile

liquid or gas fuel	retail site reformer	hydrogen	vehicle
• Natural Gas • Biofuel	72% (LHV) conversion eff.	$2.5/kg of H_2 ~$2.5/gallon gasoline	5× efficient 100 mpg

Well-designed hydrogen cars will be cheaper per mile driven

◇ Gasoline

= 5¢ per mile

- Gasoline
- Diesel

$1.00/gallon (pretax)

Avg. 20 mpg

◇ Reformation

= 2½¢ per mile

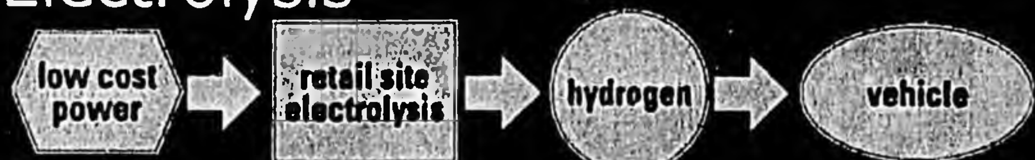
- Natural Gas
- Biofuel
- $6/million Btu

72% (LHV) conversion eff.

$2.5/kg of H_2
~$2.5/gallon gasoline

5× efficient
100 mpg

◇ Electrolysis



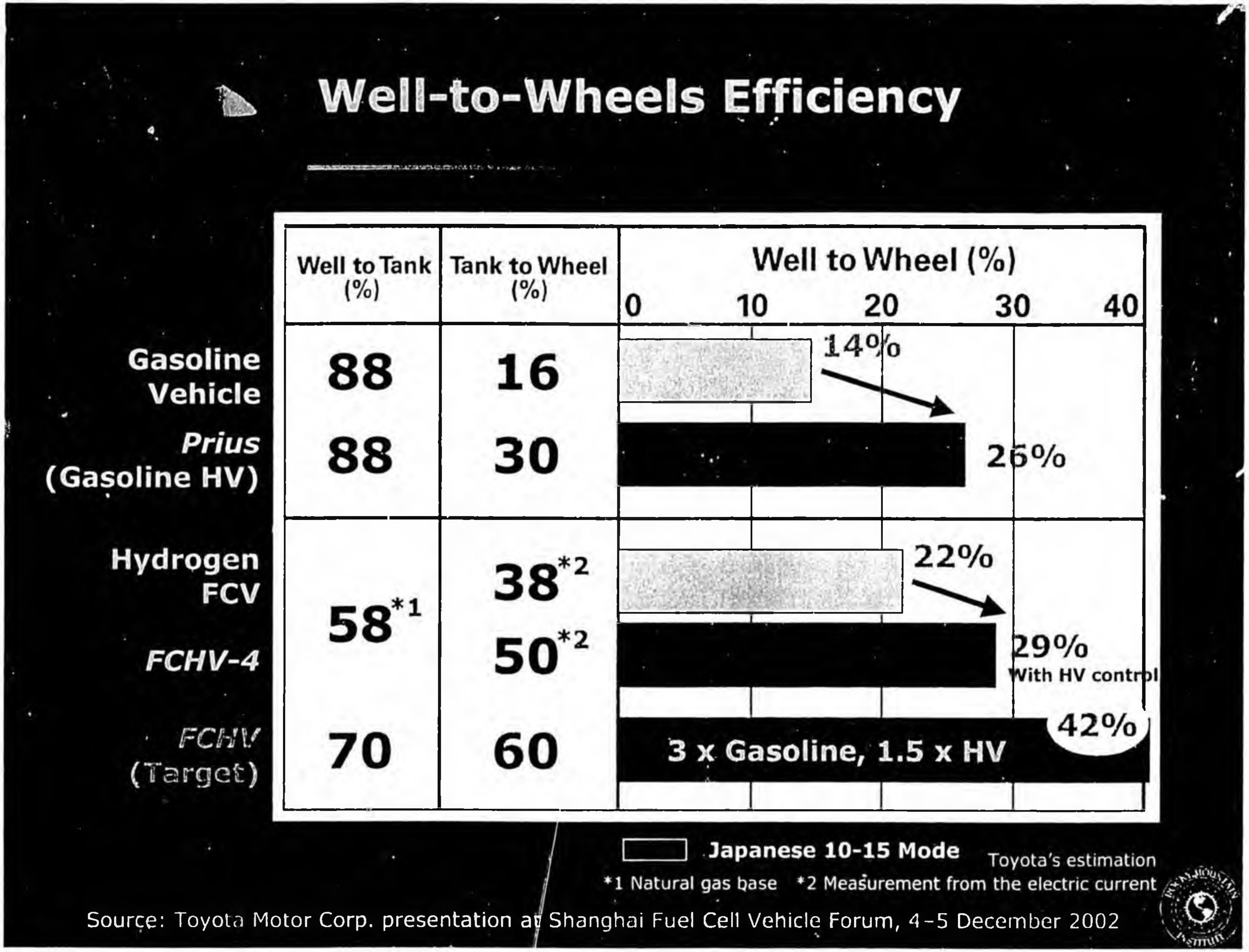
= 3¢ per mile

- Hydro
- Offpeak wind 3¢/kWh del.'d.

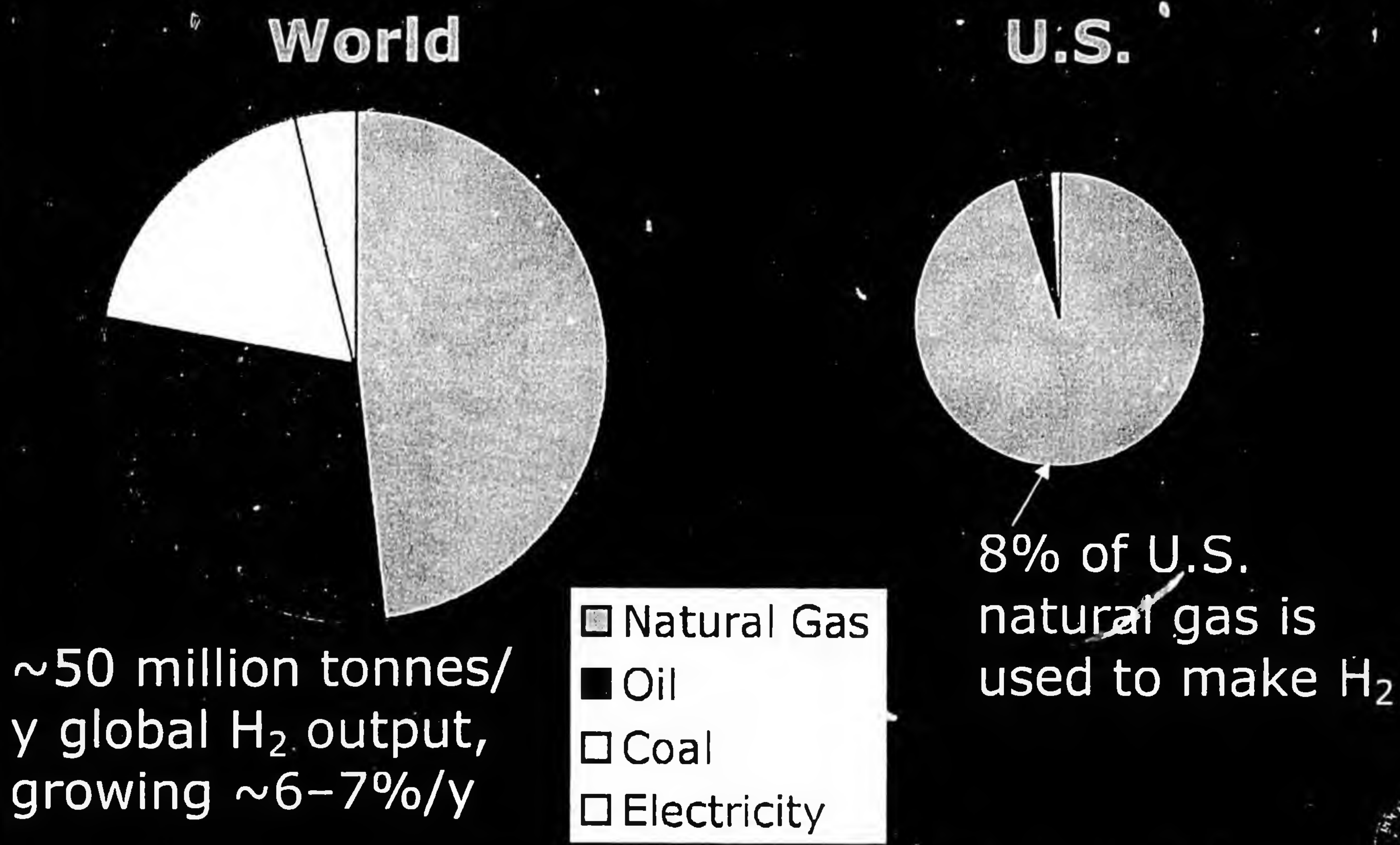
70% (LHV) conversion efficiency

$3.2/kg of H_2
~$3.2/gallon gasoline

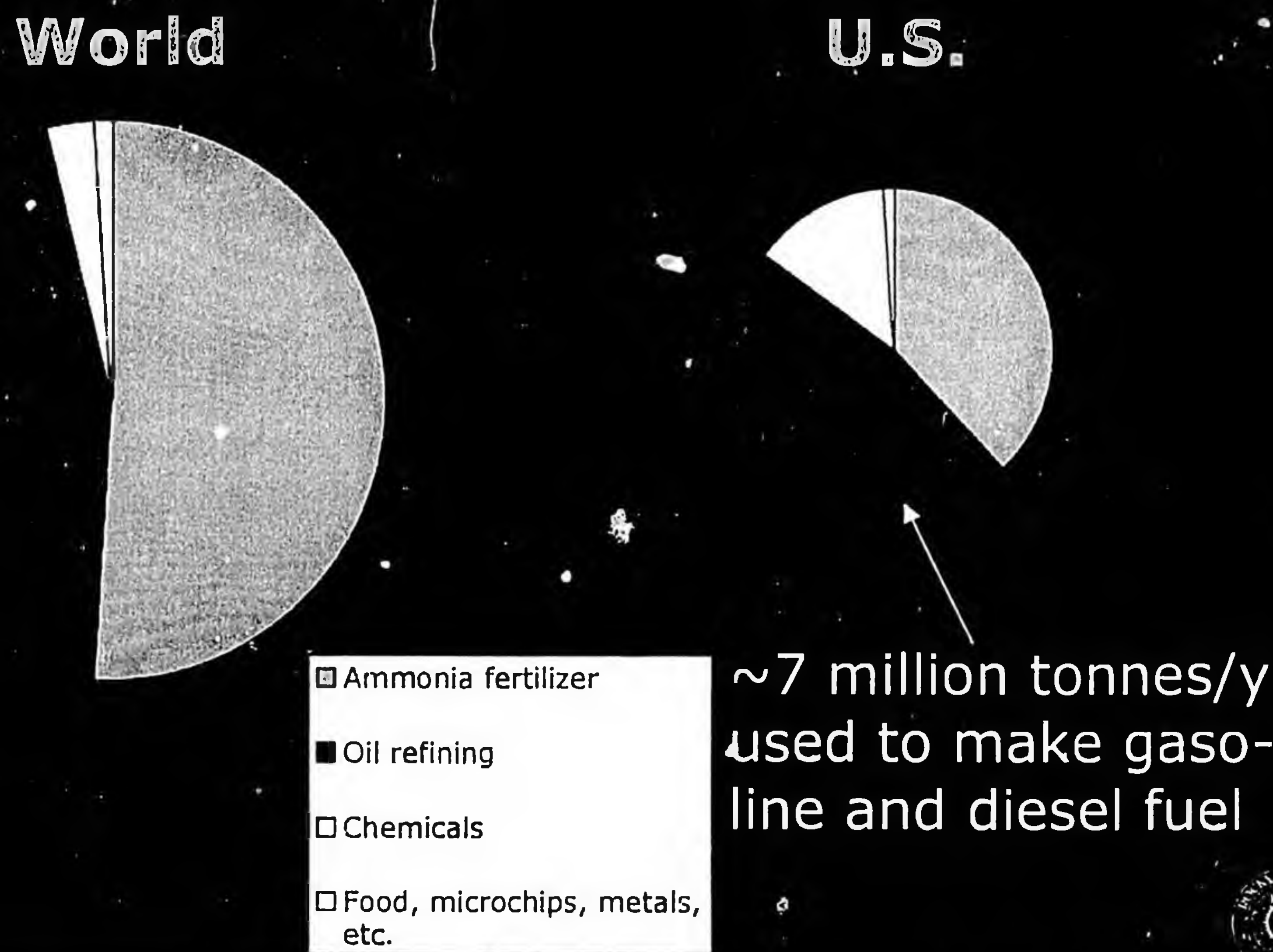
5× efficient
100 mpg


Well-to-Wheels Efficiency
Well to Tank (%)
Tank to Wheel (%)
Well to Wheel (%)
0
10
20
30
40
Gasoline Vehicle
88
16
14%
Prius (Gasoline HV)
88
30
26%
Hydrogen FCV
38*2
22%
58*1
FCHV-4
50*2
29%
With HV control
FCHV (Target)
70
60
42%
3 x Gasoline, 1.5 x HV
Japanese 10-15 Mode
Toyota's estimation
*1 Natural gas base
*2 Measurement from the electric current
Source: Toyota Motor Corp. presentation at Shanghai Fuel Cell Vehicle Forum, 4-5 December 2002

How is hydrogen now produced?



How is hydrogen now used?



"Making hydrogen uses more energy than it yields"

- Of course! The laws of physics require that *any* conversion from one form of energy to another yield less useful energy than you start with — otherwise it'd be a perpetual-motion machine
  - Making gasoline from crude oil is ~73–91% efficient
  - Making coal into delivered electricity is ~29–35% efficient
  - We make these energy carriers because they're worthwhile
- Hydrogen production is quite efficient
  - ~70–82% efficient from natural gas, 75–80+% from electricity (but ×1.15 to measure the same way as for fossil fuels)
  - The rest is heat that may also be recaptured and reused
  - Conversion efficiencies continue to rise; losses may be halved
- H_2's 2–3× greater end-use efficiency in fuel cells richly justifies the costs and losses of producing it

How to make least-cost H_2

- ◇ Proven, cost-effective, climate-safe methods already exist

1. Reform natural gas at the wellhead and reinject the CO_2
   - Reforming (~8% of U.S. gas now) & reinjection (32 MT/y) are mature
     - › Potentially three profit streams: H_2, $+CH_x$, $-C$
2. Electrolyze with climate-safe electricity (hydropower, offpeak windpower)
   - Greatly improves renewable economics if electricity is converted to H_2 and sold as motor fuel
     - › U.S. gasoline at $1.25/gallon is equivalent at the wheels to $0.09–0.14/kWh electricity with a proton attached to each electron — so run dams in "Hydro-Gen" mode, shipping compressed hydrogen (a value-added product) instead of kWh (a raw commodity)
     - › H_2 storage makes wind/PV power firm and dispatchable
3. In the future, hydrogen from coal, oil, and biomass (and perhaps experimental solar methods) will further hone competition...but we need only one solution and have at least two

"Hydrogen takes too much energy to deliver"

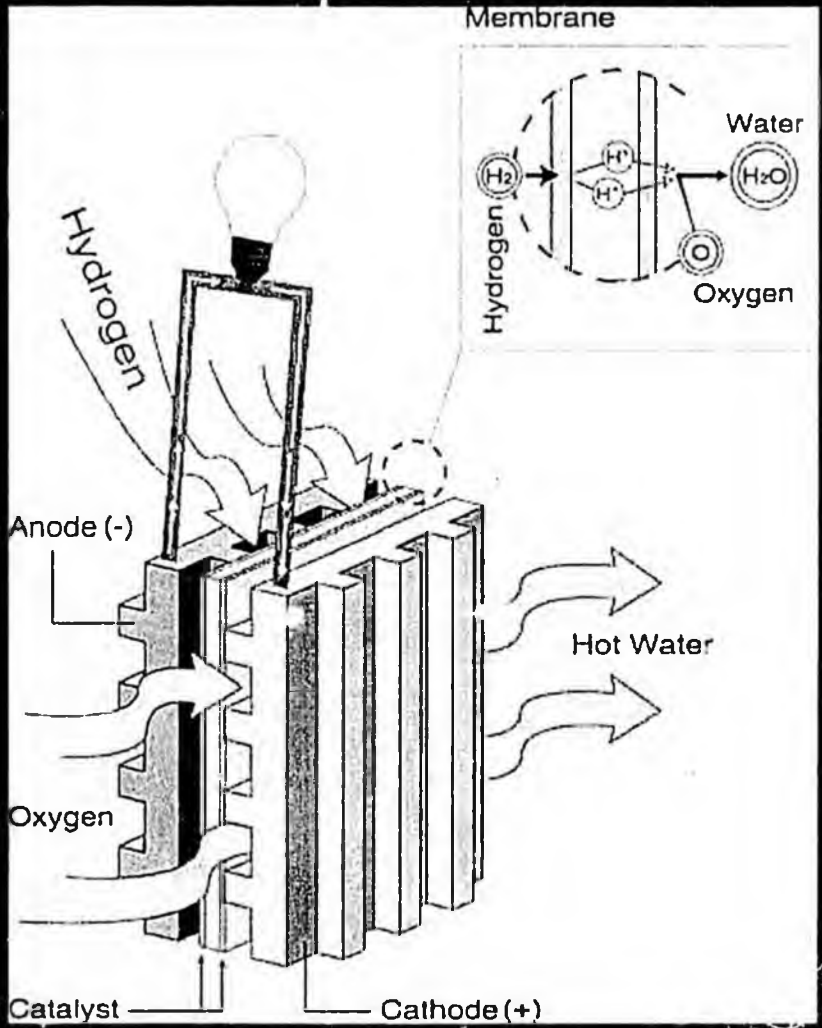
- The Myth: since H_2 is so light, "its physical properties are incompatible with the requirements of the energy market...because production, packaging, storage, transfer and delivery...are so energy consuming...." — Bossel & Eliasson
  - They catalogued the delivery methods that the industry has already rejected for this reason (outside special niche markets) — very long pipelines, liquid H_2, steel tube trucks,...
  - They considered only the costliest production method (electrolysis, which has 4% of the world market)
  - They considered only centralized production, incurring its high distribution costs
  - Their assessment is useful for helping others to understand (as hydrogen experts already do) how *not* to design a hydrogen economy, but gives no reasons not to design one correctly

How should we deliver hydrogen?

- Use the cheapest method by fully utilizing the existing, paid-for gas and electricity infrastructure
- Both centralized and distributed architectures
  - Centralized natural-gas reformers may or may not ultimately prove cheaper and more efficient than miniature ones
  - Distributed solution: small-scale reformers and electrolyzers
  - Cost <10% of a gas station's capital cost, or ~2½% of the investment in the station *plus* its upstream oil supply
  - As with diesel fuel, fewer than one-third of filling stations need conversion
  - Deutsche Shell said it could install hydrogen in all German stations in two years
  - Integrate with deployment of fuel cells in buildings
- Central solution: merchant hydrogen production at refineries near urban centers with pipelines

Fuel cells — key to the hydrogen transition

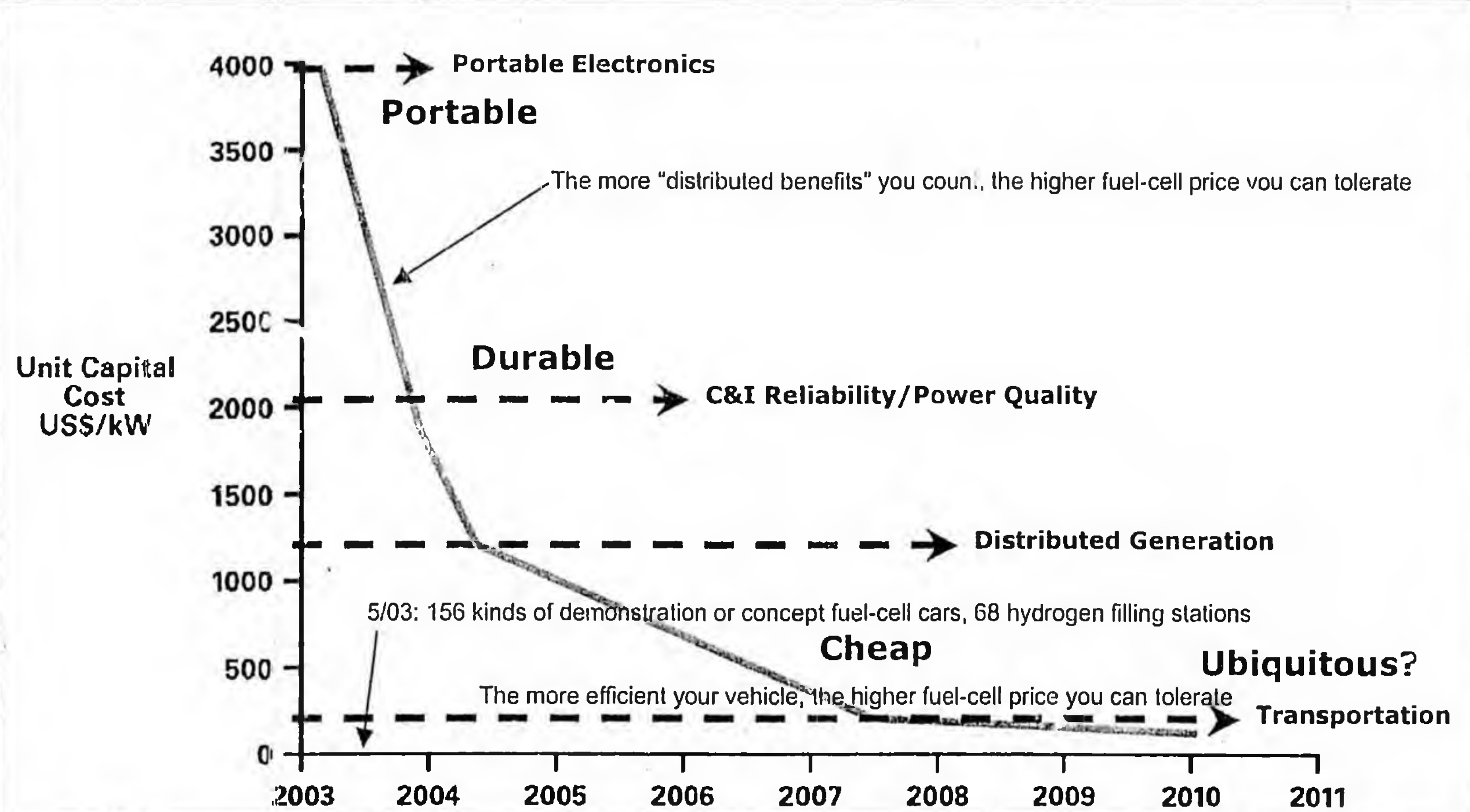
- The most efficient way to make electricity; ~50–70% efficient (the rest is recoverable heat)
- Extremely reliable, virtually silent, few or no moving parts, no combustion
- Fully scaleable



Fuel cells are already viable

Fuel Cell Competitive Price Points

(1993–2003 Cost Reduction: % catalyst÷20, cost ÷10, vol./kW ÷10)



We can make the price drop happen faster and more surely...

Making cars ready for hydrogen

- **Standard fuel-cell car:** insert fuel cell in near-normal, high-tractive-load platform
- Fuel cell is too big and costly, so must sell many units at a loss (or wait a long time) to bring cost down
- H_2 tanks are too big to package, so need onboard methanol or gasoline reformer
- Reformer hell

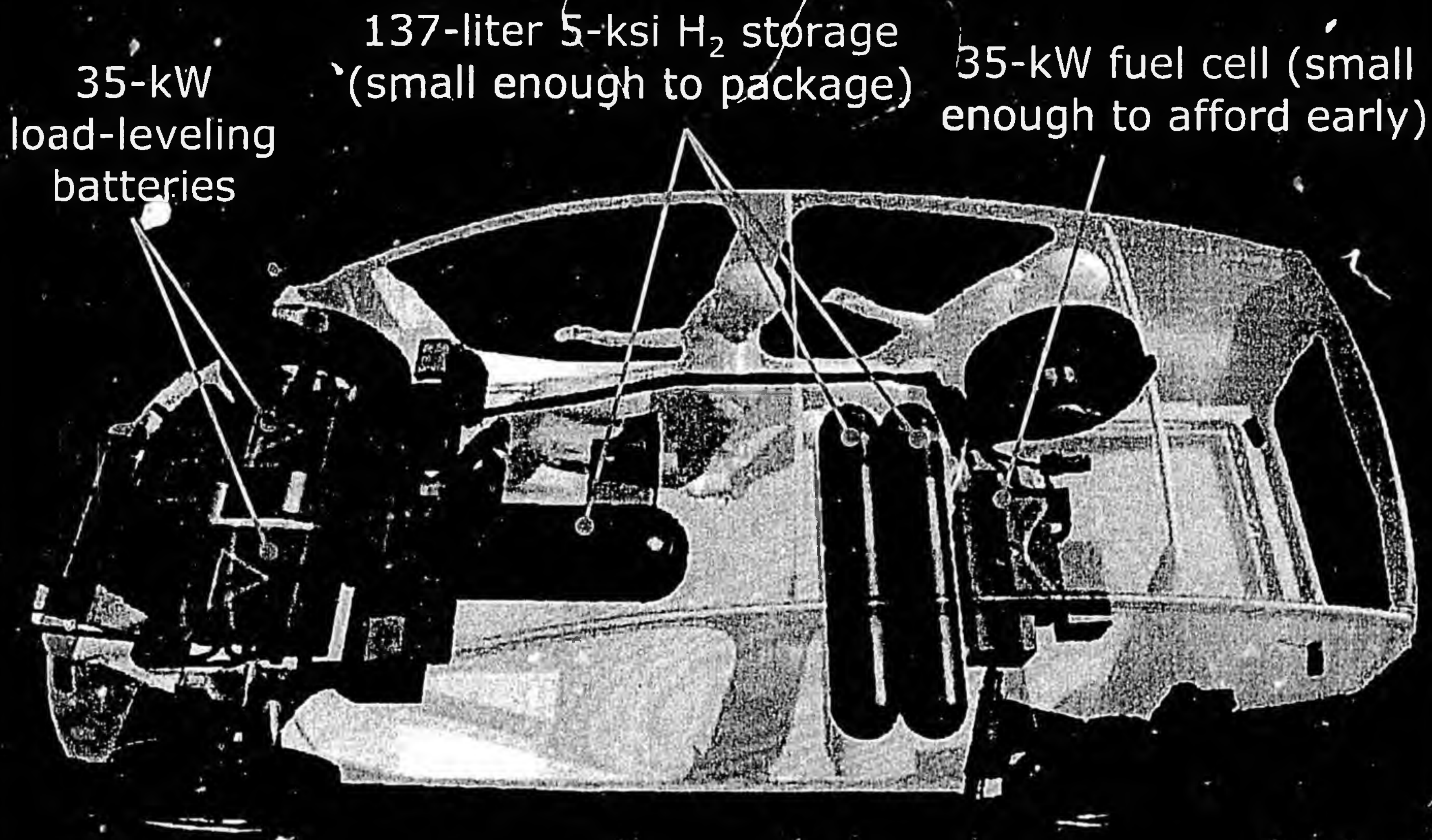
- **Direct-hydrogen fuel-cell car:** ultralight, ultra-low-drag platform can use any driveline and fuel, but is peculiarly well suited to direct-hydrogen fuel cell
- Fuel cell is small enough to afford, even at early prices
- Now-commercial H_2-gas tanks for normal range are small enough to package — **no storage problem**
- No reformer, high efficiency
- Can produce cars as soon as fuel cells are ready

An uncompromised, same-cost, 5×-efficiency midsize SUV

an illustrative, production-costed, manufacturable concept car *developed for a few million dollars in eight months in 2000 by Hypercar, Inc. (www.hypercar.com) — on time, on budget, with attributes never before combined in a single vehicle*

- 5 adults in comfort, up to 69 ft^3 of cargo
- hauls 1,012 lb up a 44% grade
- 1,889 lb (47% mass of Lexus *RX300*)
- sim. head-on wall crash @ 35 mph doesn't damage passenger compartment
- sim. head-on collision with car 2× its mass, each @ 30 mph, prevents serious injury
- 0–60 mph in 8.2 seconds
- 99mpg (2.38L/100 km, 42km/L, 5×*RX300*)
- 330 mi on 7.5 lb safely stored 5-kpsi H_2
- 55 mph on just normal a/c energy
- zero-emission (hot water)
- sporty, all-wheel digital traction
- ultra-reliable, software-rich, flexible
- wireless diagnostics/upgrades/tuneups
- 200k-mi warranty; no fatigue, dent, rust
- competitive manufacturing cost expected
- decisive mfg. advantages—≤90% less capital, space, assembly, parts count
- initial production could ramp up ~2007

55 mph on same power as normal a/c, so ready now for direct hydrogen fuel cells



Ready or not, here it comes

- The chairs of four major oil companies and several major car companies have said we're entering the oil endgame and starting the hydrogen era
- Royal Dutch/Shell Group Planning scenario in 2001 envisaged a China-led hydrogen leapfrog
  - H_2 would fuel 1/4 of the industrialized world's vehicles in 2025
  - World oil remains stagnant to 2025, then falls
  - China is already on this path, for compelling strategic reasons
- U.S. & E.U. committed >$3b to H_2 R&D in 2003
- Private sector has committed far more

"Insoluble chicken-and-egg problem" to get to H_2 cars

- Nobody would want a H_2 car with nowhere to fuel it, nor invest to make H_2 with nobody to buy it
- It's normally assumed to be too costly to cover the country with H_2 infrastructure before selling H_2 cars — probably hundreds of billions of dollars
- This actually costs less than normal investments in *oil*-based infrastructure — and can be self-financing
- Key to transition: *integrate* deployment of fuel cells in buildings and in vehicles

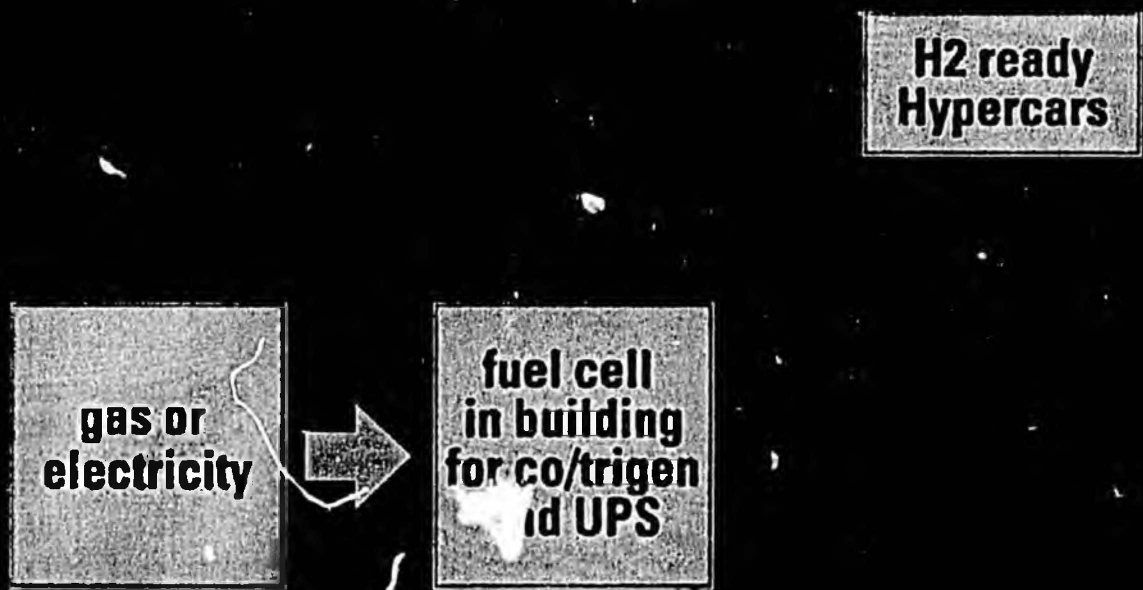
How a rapid, profitable H_2 transition would work

gas or electricity

How a Rapid Profitable H_2 Transition would work

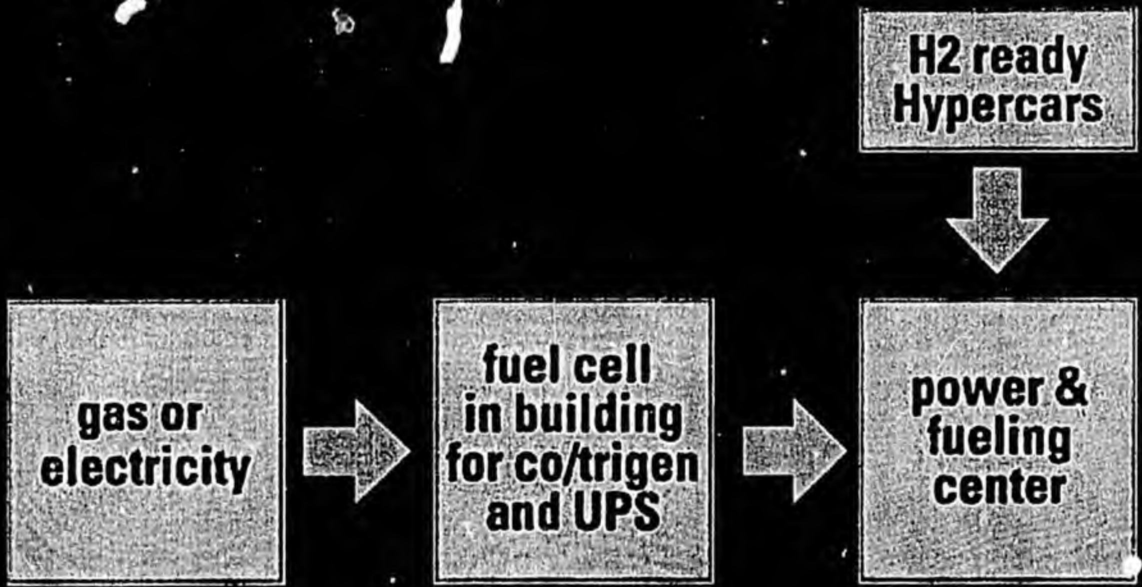
Buildings use 2/3 of US electricity

How a rapid, profitable H_2 transition would work



Buildings use 2/3
of US electricity

How a rapid, profitable H_2 transition would work



First fleets, then drivers who work in or near buildings that have fuel cells

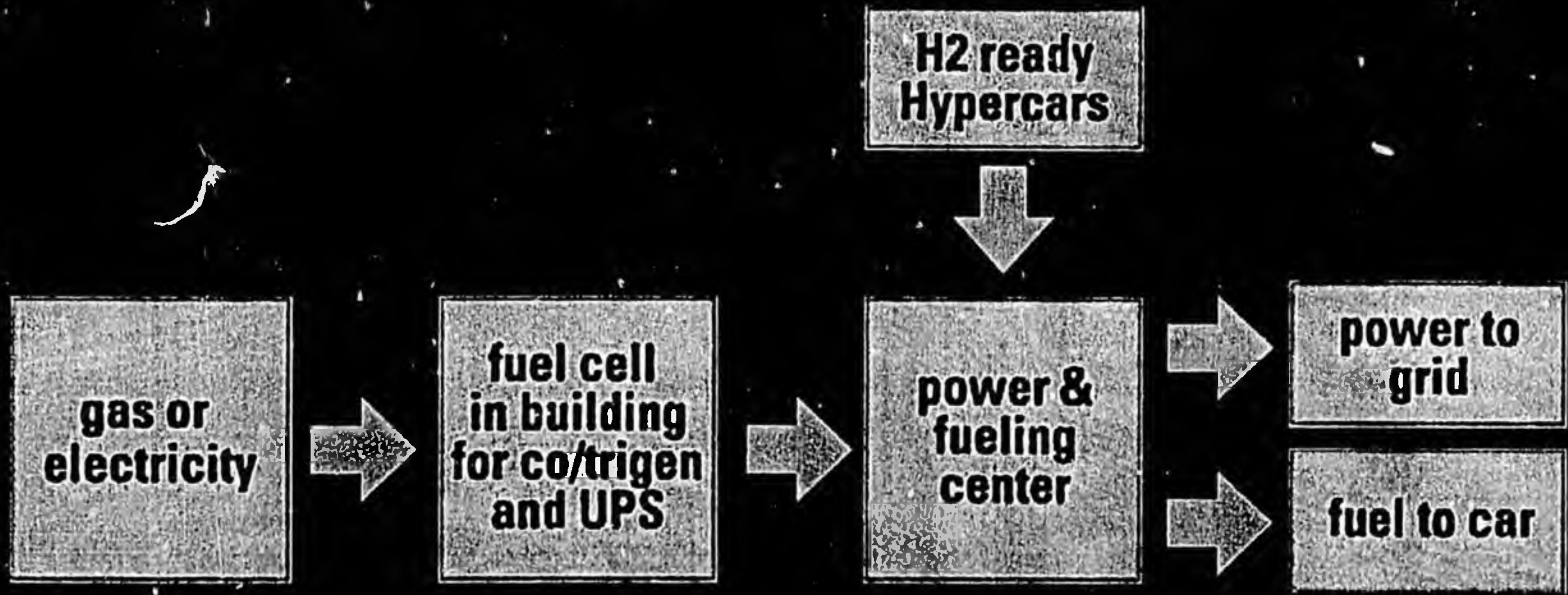
Buildings use 2/3 of US electricity

Hydrogen appliance is sized for peak building loads that seldom occur

Marginal investment in H_2 compression, storage, and fueling, car-to-grid connection, and more durable fuel cell

US fleet has potential of 5–10 TW (6–12x US capacity)

How a rapid, profitable H_2 transition would work



Buildings use 2/3 of US electricity

Marginal investment in H_2 compression, storage, and fueling, car-to-grid connection, and more durable fuel cell
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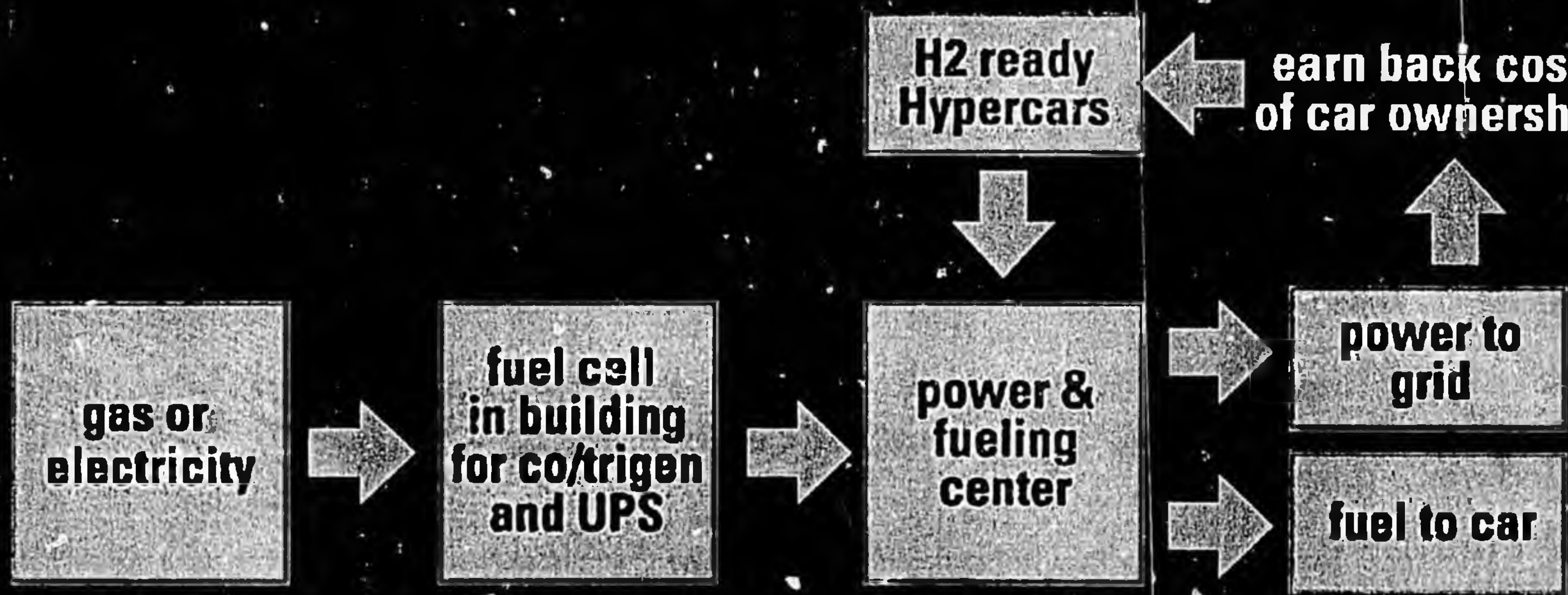
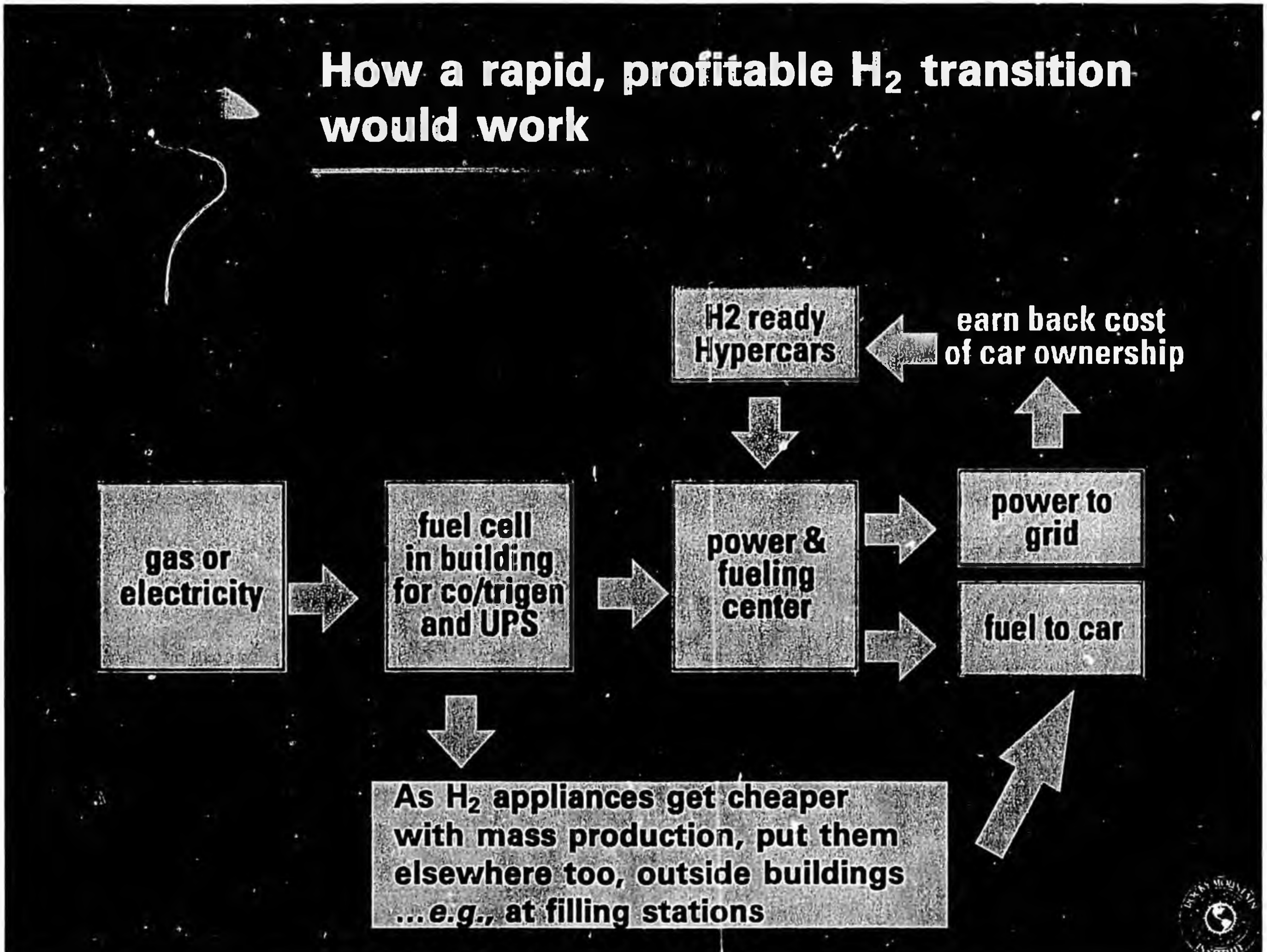
How a rapid, profitable H_2 transition would work



Buildings use 2/3 of US electricity

Marginal investment in H_2 compression, H_2 fueling and grid connection
US fleet has potential of 5–10TW (6–12x US capacity)


How a rapid, profitable H_2 transition would work
H2 ready Hypercars
earn back cost of car ownership
gas or electricity
fuel cell in building for co/trigen and UPS
power & fueling center
power to grid
fuel to car
As H_2 appliances get cheaper with mass production, put them elsewhere too, outside buildings ...*e.g.*, at filling stations

Hydrogen-ready cars + integrated with buildings = hydrogen transition

- No technological breakthroughs required (*e.g.*, onboard reformers) — just durable and cheaper fuel cells
- Can market fuel-cell cars as soon as durable fuel cells become available, and can do so profitably many years earlier than inefficient vehicles would allow
- Meanwhile, engine or engine-hybrid Hypercar vehicles would impress (*e.g.*, ~70$^+$ mpg for a midsize SUV)
- No need for new liquid-fuel infrastructure (methanol, ultrapure gasoline,...) nor for liquid hydrogen
- Integrating mobile and stationary deployment makes the transition profitable at each step (>10%/y real return)
- It doesn't matter whether durable stacks come first (favoring buildings) or cheap stacks (favoring cars); whichever comes first accelerates both markets

New supply strategy for B.C., California, and the Pacific NW?

- Import oil for transportation
- Heat with electricity and BC gas
- Electricity from hydro and thermal (coal being phased out, gas combined-cycle phased in)
- Minor renewables
- Key energy carrier is *grid* electricity

- Import no oil
- Fuel-cell vehicles, buildings, most industries
- Hydrogen as main energy carrier, from gas, "Hydro-Gen," wind, and PVs
- Minor direct gas use for heat, mainly industrial
- Minor central hydro*electric* supply; still onpeak el. sales; mostly onsite gen.; fish water

Intensive integrated superefficiency + distributed-generation experiments are emerging: Iceland, NZ, Yakushima, Vanuatu, Utsira,...Vancouver Island?

Do we have enough primary energy to make the hydrogen we need?

($\eta \equiv$ efficiency)

- If fueling 5η light and 2η heavy vehicles, ~50 MT/y H_2 could displace all U.S. highway-vehicle fuel
- U.S. refineries use ~7 MT/y H_2 — enough to displace 1/4 of U.S. gasoline (2× Gulf share)
- ~10 MT/y H_2 could be made from 2.0 TCF of natural gas freed up by efficient end-use of gas and electricity and by electric load management
- Alternatively, 50 MT/y H_2 could be made by the Dakotas' cost-effective windpower potential, with turbines on a few percent of the windiest available lands, leaving the rest for farming/ranching/wildlife

"Won't we just run out of natural gas even faster? Or of capital?"

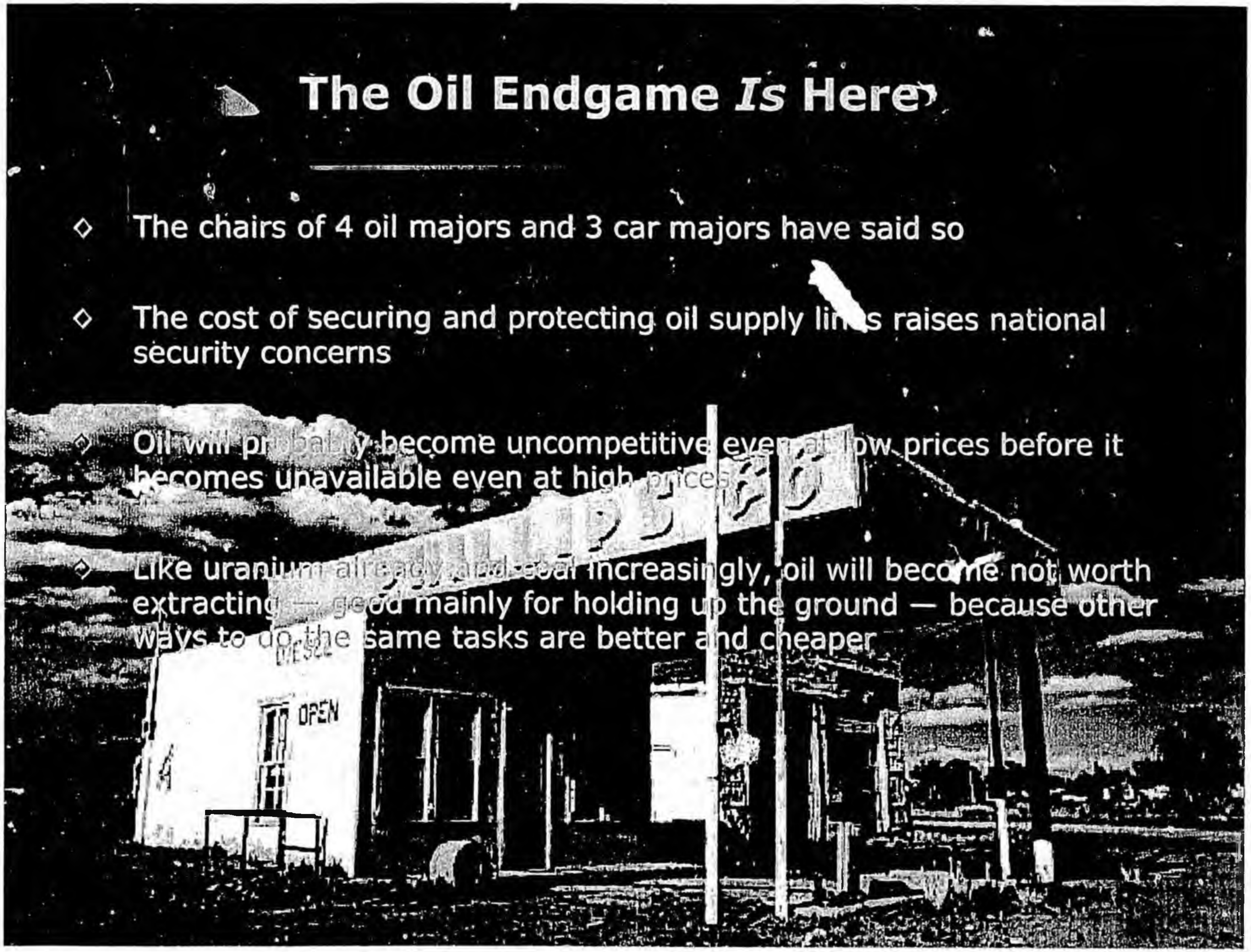
- GM thinks U.S. use of natural gas would be *lower* with a miniature-gas-reformer H_2 transition
- RMI is checking, but can see how any net increase in natural-gas use could at worst be very small
  - Natural gas used to make H_2 could be approximately offset by gas saved in power plants, in boilers and furnaces, and in making H_2 for gasoline
  - Peak electricity demand is served by extremely inefficient gas-fired turbines...so shaving peak electric loads by 5% would save around 9% of the total U.S. use of natural gas
- Sandy Thomas (www.h2gen.com) argues that global capital investment in a gas-based H_2 hydrogen fueling infrastructure over the next 40 y would be ~$1 trillion *less* than for gasoline, saving ~$600 of investment per car served; RMI is refining this estimate too

"Hydrogen is just a shill for nuclear power and fossil fuels"

- Even if electrolysis were a competitive way to make H_2, new nuclear plants are a hopelessly uncompetitive way to make electricity — forget it
  - Delivered cost of new nuclear el. would be ~2–3× new wind-power, 5–10× gas cogen/trigen, 10–30⁺× end-use efficiency — so nuclear-el. H_2 would cost 2–3× more/mi than record oil price
  - Far from saving nuclear power, H_2 will hasten its extinction
- It's OK to use responsibly extracted fossil fuels to make hydrogen...
  - Temporarily to make H_2 from natural gas without carbon sequestration, because CO_2 released per mile would fall by ~2–5× (DOE: 2.5×)...
  - And long-run to make H_2 *with* carbon sequestration (at large or probably, with emerging methods, small scale) — or its backstop technologies, which don't require geological success

Renewables will compete well too — even better with hydrogen

- As already noted, H_2 boosts renewables' economics
- Fuel cells' distributed benefits are synergistic with those of renewables such as photovoltaics
- Reversible fuel cells go especially well with PVs
- DOE should fully fund both H_2 *and* renewables — not swipe H_2 funding from renewables as now
- Huge stranded renewables, such as Dakotas wind, will require substantial delivery investments (but will still be very worthwhile)
- Synergies from combining H_2 with renewables
  - *All* Danish *energy* — not just el. — could be cost-effectively, reliably obtained from windpower with two weeks' H_2 storage


The Oil Endgame *Is* Here
The chairs of 4 oil majors and 3 car majors have said so
The cost of securing and protecting oil supply lines raises national security concerns
Oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices
Like uranium already and coal increasingly, oil will become not worth extracting — good mainly for holding up the ground — because other ways to do the same tasks are better and cheaper
DIESEL
OPEN

More profitable for hydrocarbon owners too? Just try this quiz...

- (H – C) > (H + C)?
- Is the hydrogen worth more without the carbon than with the carbon?
- Is hydrogen plus negacarbon (which someone may pay you *not* to put into the air) worth more than hydrocarbon? What if carbon is worth zero?
- Is a hydrocarbon worth more feeding a refinery or a reformer?
- Should refineries become merchant H_2 plants?

(Left as an exercise for the reader. Then run, do not walk, to the hydrogen economy.)

The dawn of the hydrogen era has begun

- Hydrogen-fueled superefficient vehicles will be safer and cleaner, cost less to drive, cost about the same to buy, and offer the potential to repay most or all of their cost from power sell-backs
- Fuel cell and vehicle technology enablers are within reach
- Enough hydrogen can be made cost-effectively from North American energy sources (even from just regional renewables) to eliminate gasoline and diesel use — creating real security
- A fast transition to a hydrogen economy is already starting and can be profitable at each step

It's time — we just need leadership

"People and nations behave wisely —
once they have exhausted all other alternatives."
— Churchill

"Sometimes one must do what is necessary."
— Churchill

"We are the people we have been waiting for."
— Hopi Elders

www.hypercar.com

www.rmi.org

ROCKY MOUNTAIN INSTITUTE

U.S. DEPARTMENT OF ENERGY

OFFICE OF FOSSIL ENERGY - HYDROGEN PROGRAM PLAN

Hydrogen from Natural Gas and Coal: The Road to a Sustainable Energy Future

HYDROGEN COORDINATION GROUP

JUNE 2003

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The President's National Energy Policy calls for conducting a review of funding for alternative energy supplies, including hydrogen. In response, the Office of Fossil Energy (FE) established a Hydrogen Coordination Group to develop the FE Hydrogen Program Plan. The coordination group was comprised of FE personnel from the Offices of Coal & Power Systems and Natural Gas & Petroleum Technology in Germantown, MD and Washington, DC and the NETL Pittsburgh and Tulsa offices. The FE Hydrogen Program Plan, along with input from the Offices of Energy Efficiency and Renewable Energy, Nuclear, and Science and the two documents – *A National Vision of America's Transition to a Hydrogen Economy – to 2030 and Beyond* and the *National Hydrogen Energy Roadmap* – provided the input to the Department of Energy's (DOE) Hydrogen Posture Plan. The Posture Plan, with the Office of Energy Efficiency and Renewable Energy (EERE) as lead, was DOE's response to the NEP recommendations, which was used to support DOE's FY04 budget to Congress.

Hydrogen is seen by many as the energy carrier of the future that will lead to efficient and clean fuel for use by utilities and especially in transportation systems. The use of hydrogen in fuel cells to electrochemically produce electricity and for combustion in heating and/or engine systems is seen as a means to provide an important part of the Nation's need for power, heat, and transportation while achieving very low emissions of criteria pollutants as well as greenhouse gases.

This FE Hydrogen Program Plan focuses on the research, development and demonstration (RD&D) activities that are required to develop advanced hydrogen production, storage and delivery technologies from fossil fuels. The result of these activities will improve current technology and make available new, innovative technology that can produce and deliver affordable hydrogen from natural gas and coal with significantly reduced or near-zero emissions.

Natural gas and coal have the potential to be affordable resources that can produce the large amounts of hydrogen needed in the near to mid term for the Nation to begin the transition to a hydrogen economy. Hydrogen produced from these resources and used in advanced technologies, especially in efficient fuel cell vehicles (FCVs), will improve energy security by reducing the United States' oil imports by over 3 million barrels per day for every 100 million FCVs or nearly half of the U.S. fleet. Even without sequestration, production and use of coal-derived hydrogen in 100 million FCVs is estimated to also reduce carbon dioxide, a greenhouse gas (GHG), by 278 million tons per year, a reduction of 24 percent of the carbon dioxide emissions associated with the current U.S. light-duty vehicle fleet. Nitrogen oxide (NOx) emissions will be reduced by about 100,000 tons per year, while sulfur oxides (SOx) and particulate matter emissions would be reduced by 43 thousand tons and 40 thousand tons, respectively. Criteria pollutants and carbon dioxide emissions would be reduced by about the same or a greater amount for natural gas-derived hydrogen in FCVs.

When hydrogen production from fossil fuels is combined with carbon sequestration, carbon dioxide emissions will be reduced by over 530 million tons per year for each 100 million FCVs, a reduction of 45 percent for the current U.S. light-duty vehicle fleet. Also, the use of the Nation's domestic natural gas, its huge potential resource of methane hydrates (estimated at 320,000 trillion cubic feet), and 250-year supply of coal to produce hydrogen ensures that there will be a clean and affordable alternative to imported oil. This will enable the transition to a hydrogen economy until other sustainable energy resources for hydrogen production become economic.

Where do we get hydrogen?

Molecular hydrogen does not occur on Earth but must be produced from other hydrogen-containing materials. This process requires a primary energy source, such as fossil fuels, nuclear, or renewables. Fossil fuels (e.g., natural gas and coal) as that energy source can provide the transition to a hydrogen economy by delivering a near- to mid-term source of hydrogen. With sequestration, it is envisioned that natural gas and coal could be used to produce hydrogen for many decades. A sustainable hydrogen supply in the future may come from renewables and nuclear energy-supplied heat and electricity used to split water into hydrogen and oxygen.

Need for hydrogen research

While some hydrogen production technologies are commercial now and others are making rapid progress, hydrogen faces many technical, economic, and infrastructure challenges before it can become a significant energy carrier. The Bush Administration has initiated major efforts in research and development that will lead to a hydrogen economy. The President's budget calls for increases in funding for hydrogen-related research, development and demonstration (RD&D) activities, with a shift in emphasis to higher risk, longer term issues. This includes, for example, the FreedomCAR program, the FutureGen project, and the Hydrogen Fuel Initiative.

The FreedomCAR program is focused on the development of fuel cell technology for automobiles to efficiently convert hydrogen's electrochemical energy into electric power. Hydrogen fuel cell vehicles consume only one-third the energy of a current gasoline internal combustion engine per mile driven while achieving zero emissions. Natural gas and coal can provide the most affordable source of abundant hydrogen to allow early introduction of fuel cell vehicles in the FreedomCAR program and can continue to provide hydrogen as an energy carrier until hydrogen from renewable and nuclear energy becomes affordable. In this way, the Nation's imports of petroleum can be reduced and our air and environment can become cleaner.

FutureGen is a $1 billion, 10-year verification project that will build the world's first, coal-based, near zero-emission electricity and hydrogen plant integrated with sequestration. FutureGen will enable cutting-edge technologies, such as revolutionary separation membranes, to leapfrog mature technologies to lower the cost to separate hydrogen from mixed gas streams while demonstrating greenhouse gas capture and sequestration technologies.

The long-term vision of a hydrogen economy looks attractive for a number of reasons including: (1) the gradual transformation of the U.S. economy from one that currently relies on significant quantities of imported energy, primarily oil for the transportation sector, to one that will be able to harness domestic resources to a greater and greater extent, while being less damaging to the environment; (2) the potential for significant reductions in criteria pollutants (e.g., particulate matter, oxides of nitrogen, and oxides of sulfur) and corresponding improvements in air quality; and (3) the potential for reduced emission of greenhouse gases, especially carbon dioxide.

Fossil Fuel Research

Fossil fuels are an obvious choice as energy resources from which the large quantities of hydrogen needed to begin the transition to a sustainable hydrogen economy can be produced. Currently, hydrogen for industrial and commercial use is produced from steam reforming of natural gas with attendant water-gas shift reactions. This is a mature technology widely used in the petroleum processing industry. Significant opportunities exist for development of new technologies with potential to reduce the costs of hydrogen production from natural gas. Another fossil fuel, coal, is the Nation's largest domestic energy resource, and can also be an energy source for producing hydrogen. With associated carbon dioxide capture and sequestration technologies, hydrogen from natural gas and coal can make significant contributions toward achieving an improved environment.

Hydrogen from Natural Gas Program

This program will develop new technologies that lower the cost of producing hydrogen from natural gas and allow capture of associated carbon dioxide. In keeping with the National Energy Policy and relevant climate change initiatives, research will develop those technologies that will provide a primary source of hydrogen in the near to mid term, allowing development of infrastructure and end-use applications that will transition the Nation to a sustainable hydrogen economy. One technology, membrane reactors, will revolutionize the way hydrogen is produced from natural gas. When developed, this technology will simplify the process of producing hydrogen from natural gas by combining the process of air separation to produce oxygen with partial oxidation of natural gas to produce synthesis gas into a single step that will lower costs and increase efficiencies.

Hydrogen from Coal Program

Coal resources offer a viable mid-term energy resource for producing the large quantities of hydrogen that will be required to fuel the Nation's needs. Initially, hydrogen would be produced via coal gasification-based facilities also capable of co-producing electric power, reformable liquid fuels, and high-value chemicals. These multiple-product, co-production plants will be less costly, competitive, more efficient, and less polluting than current technology. Additionally, they will produce a concentrated stream of carbon dioxide that will facilitate its economic capture and sequestration.

To accelerate the development of hydrogen from coal production technologies, President George W. Bush and Secretary of Energy Spencer Abraham announced on February 27, 2003, a $1 billion, 10-year government/industry integrated sequestration and hydrogen research initiative titled

FutureGen. FutureGen would be designed, built, and operated as a large-scale, prototype plant that will serve as an engineering verification test-bed for many cutting-edge coal technologies, including technologies such as advanced catalysts and reactors and membrane separation units developed in the hydrogen from coal program. The prototype plant will become a model for future hydrogen from coal production facilities that will produce the necessary amount of hydrogen for the transportation sector.

Commonalities and Differences

There appears to be much similarity in the technology and processing concepts used to produce hydrogen from natural gas or hydrogen from coal, and indeed there is a need for coordination in the effort to develop the respective technologies.

At the same time, there are significant system differences in these concepts that make R&D planning and implementation more effective on a resource-specific basis. A synthesis gas mixture from coal is carbon monoxide-rich and the synthesis gas mixture from natural gas is hydrogen-rich, making it necessary to explore whether the same production/separation membranes will be effective. Coal-derived synthesis gases, even after a primary clean-up stage, have more impurities than their natural gas counterparts that may require different clean-up systems. In addition, integration of the hydrogen separation technology into the coal gasification-based hydrogen production facility is more complex, requiring different system integration efforts.

Hydrogen Delivery

Today, most hydrogen used in refineries and chemical facilities is produced on site. In addition, merchant hydrogen producers who supply the refining and chemical industries locate generation facilities near end-users, use dedicated hydrogen pipelines and storage facilities, and, for low-volume users at greater distances from the supplier, use on-road trucks for delivery. The unique properties of hydrogen may make the use of existing natural gas delivery infrastructure difficult because of potential material and valve incompatibility resulting in hydrogen leakage and embrittlement of components. Therefore, systems analyses and research are needed to determine the viability of using natural gas pipelines to transport hydrogen. From a larger perspective, this same approach must be extended to other options to determine the most optimum system that can be used to deliver hydrogen. The analyses should consider the trade-off between large capital investments in central location hydrogen plants, associated pipelines, and delivery versus the use of liquid and natural gas infrastructure to deliver hydrogen-rich fuels that can be converted on site.

One promising option for the delivery of hydrogen uses the current fuel infrastructure to transport synthesis gas-derived liquids. At or near the point of end use, the hydrogen can be produced from the liquid by a reforming process. The technologies for producing these liquids from natural gas are commercial or near commercial. However, for the conversion of coal-derived synthesis gas to a liquid, R&D is necessary to make the process economically viable for deployment in this country. In addition, for these hydrogen-carrier liquids, whether produced from coal or natural gas, further research is needed to determine the optimum fuel(s) for reforming and the associated reaction chemistry database required to develop economic, small-scale reforming systems for mobile and small-scale distributed power generation.

Associated Programs

The successful development of low-cost, affordable hydrogen production from fossil fuels, with sequestration of carbon dioxide, is dependent on technologies being developed in a number of ongoing associated RD&D programs within the Office of Fossil Energy (FE). These technologies are needed for:

- carbon dioxide capture and sequestration;
- advanced coal gasification, including feed handling systems;
- efficient gasifier design and materials engineering;
- advanced synthesis gas clean-up technologies;
- advanced membrane separation technology to produce a lower-cost source of oxygen from air; and
- fuel cell modules that can produce electric power at coal-fired integrated gasification combined-cycle power plants.

Key Hydrogen R&D Milestones

A future hydrogen economy will require multiple energy supply sources. Natural gas and coal will provide the transition to a sustainable energy supply. The key milestones of FE's Hydrogen Program are:

- By 2011, an alternative hydrogen delivery system utilizing hydrogen-rich synthesis gas-derived liquid fuels will be optimized and available,

- By 2013, modules to reduce the cost of hydrogen and synthesis gas production from natural gas by 25 percent will be available,

- By 2015, a zero-emission, coal-based plant that co-produces hydrogen and electric power with sequestration to reduce the cost of hydrogen by 25 percent when compared to existing coal-based technology will be demonstrated.

Testing of coal-based technologies developed by the program in the FutureGen prototype plant will significantly reduce the technical and economic risk associated with program RD&D activities, helping the FE hydrogen program achieve its key goals and milestones.

Benefits

Hydrogen from fossil fuel energy sources is an obvious near- to mid-term economic and technically feasible method to transition from fossil fuel to hydrogen as an energy carrier. Specific benefits of the Office of Fossil Energy's Hydrogen Program activities are discussed below.

- Production of lower cost hydrogen from natural gas could provide the earliest transitional source of hydrogen for the FreedomCAR program. It can provide the transition between the current economy and a hydrogen economy.

- Production of low-cost hydrogen from coal or synthesis gas-derived liquid fuels will reduce reliance on imported oil, increase the proportion of domestic energy resources used in the total domestic energy mix, and provide a cost-effective source of hydrogen for the FreedomCAR program.

- The production of hydrogen from domestic coal and natural gas along with natural gas from secure foreign energy resources and from abundant methane hydrates will be a significant step towards achieving energy security in the near term as well as the long term.

- The use of hydrogen in fuel cells and other efficient applications will reduce pollution compared to other alternatives and ially reduce greenhouse gas emissions. This technology will improve human h environment.

- The hydrogen from coal technol tegrates long-range R&D goals for innovative technology development of a co-production, highly efficient facility for the combined production of power and hydrogen while achieving the objectives of a zero-emissions fossil energy plant.

- Successful development and implementation of carbon dioxide sequestration technology, an R&D effort supporting the hydrogen from natural gas and coal effort, will ensure the continued availability of coal and natural gas as viable sources of hydrogen while moving toward a sustainable hydrogen economy.

Hydrogen could eventually be produced from fossil energy resources, renewables, including biomass, and nuclear energy. Analyses have shown that an aggressive fossil fuel-based hydrogen production program can yield a sufficient supply of hydrogen to meet projected market demand for fuel cell vehicles. When utilized in these vehicles, hydrogen will substantially reduce emissions of sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NOx), Volatile organic compounds (VOC), and particulate matter 10 microns in diameter (PM10). In this way, hydrogen from natural gas and coal provides a near- and mid-term transitional fuel source until the long-term goal of producing hydrogen from nuclear and renewable energy is realized. Successful development of carbon dioxide capture and sequestration technology will eliminate public concerns over projected increases of greenhouse gas emissions from fossil fuels and will make coal an option for the longer term.

In conclusion, within DOE, the Office of Fossil Energy already has considerable expertise in the production, separation, storage, delivery and end-use applications of hydrogen from natural gas and coal. This expertise includes production of clean synthesis gas from coal and natural gas, gas separations and purification, fuel cells, and novel hydrogen storage and delivery technologies. However, there are significant technical and economic barriers that must be surmounted before hydrogen can seriously be considered as a candidate energy carrier in the United States. This document discusses the rationale for using hydrogen as an energy carrier, reviews the current and future technology options, and provides a strategic framework for overcoming the current barriers to large-scale hydrogen production and utilization.

As a result of synergism in R&D activities, the currently ongoing and planned fossil energy associated programs (gasification, carbon sequestration, and fuel cells) will reduce the development time and cost of the proposed hydrogen initiative and will greatly contribute to the ultimate development of more efficient, less costly, environmentally preferred, hydrogen production and delivery processes from natural gas and coal.

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INTRODUCTION

Two of the major concerns in the U.S. energy sector today are energy security and the environmental impact of energy use. To address these issues, the President's 2001 National Energy Policy and the U.S. Department of Energy's Strategic Plan call for expanding the development of new and diverse energy supplies. Hydrogen - a promising solution for the future - holds the potential to provide a virtually limitless carrier of clean energy supplies in the long term.

The U.S. Department of Energy (DOE) is implementing an initiative that could eventually lead to domestic energy sustainability for the transportation and power sectors through the widespread use of hydrogen. Hydrogen is the ultimate clean fuel with a wide range of uses - from direct combustion to efficient fuel cells. The conversion/combustion by-product of hydrogen is essentially water. An economy that uses hydrogen derived from domestic fossil (with carbon dioxide capture and sequestration), nuclear, and renewable resources will have increased energy security and reduced emissions.

To begin the implementation of the hydrogen initiative, DOE convened meetings among representatives from industry, the National Laboratories, public interest groups and the Federal Government to develop *A National Vision of America's Transition to a Hydrogen Economy – to 2030 and Beyond* and the *National Hydrogen Energy Roadmap*. These documents introduce actions that will be needed to implement a national hydrogen economy, one in which hydrogen is used for both mobile and stationary applications. Subsequently, using these documents as a guide, DOE's Offices of Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy and Office of Science prepared a Hydrogen Posture Plan. The Hydrogen Posture Plan encompasses all elements in the hydrogen energy system - production, delivery, storage, conversion, and application. This Office of Fossil Energy Hydrogen Program Plan includes the contributions that the Office of Fossil Energy will make in the implementation of the National Hydrogen Vision, the Roadmap, and the DOE Hydrogen Posture Plan.

Before the vision of producing hydrogen from nuclear and renewable energy becomes a reality, a technology bridge must be developed to connect near- to mid-term technology to the technologies of the future. Hydrogen is not a primary source of energy, but an energy carrier. Consequently, it must be produced from a primary energy source, such as fossil fuels, nuclear, or renewables, and subsequently converted to energy at or by the utilization device.

Fossil fuels are the obvious transitional source of hydrogen for the near and mid term. Natural gas has the lowest carbon intensity of all fossil fuels and is the cleanest burning. Its existing infrastructure and its current economic availability are important factors to ensure successful development and public acceptance of a hydrogen energy system. Development of the large potential resource of methane hydrates can provide a stable, domestic supply of natural gas that will enhance energy security. Utilization of our abundant, domestic supply of coal resources to produce hydrogen will reduce U.S. reliance on foreign imports of petroleum. When utilized in FCVs, hydrogen from fossil fuel resources will reduce emissions of greenhouse gases and criteria pollutants such as NOx, SOx, and particulate matter less than 10 microns in diameter (PM10).

Of the five elements of a hydrogen energy system - production, storage, conversion, delivery, and applications - the Office of Fossil Energy's Hydrogen Program Plan focuses on the development of advanced production, storage, and delivery technologies. These developments will be coordinated and collaborated with the Office of EERE and other appropriate DOE organizations including co-sponsorship and funding. These activities will improve current technology and develop new innovative technology that can produce, store, and deliver affordable hydrogen from natural gas and coal while achieving significantly reduced or near-zero emissions. Successful development of carbon dioxide capture and sequestration technology will remove public concern over greenhouse gas emissions and will also make coal an option for the longer term.

Testing and evaluation of these advanced technologies in the FutureGen prototype plant will help the FE Hydrogen Program reduce the technical and economic risk associated with new, innovative technology development. The FutureGen project will design, build, and operate a large-scale, integrated, coal-based prototype plant that will provide the opportunity to test new, cutting-edge, clean power and hydrogen from coal technologies along with carbon capture and sequestration.

KEY DRIVERS

The FE Hydrogen Program strives to create public benefits for the Nation by addressing three key drivers: energy security, the Clear Skies Initiative that addresses air pollution, and global climate change. Each of these drivers has or potentially could have a significant impact on the Nation and the economy. The FE Hydrogen Program will address these drivers by performing RD&D that will:

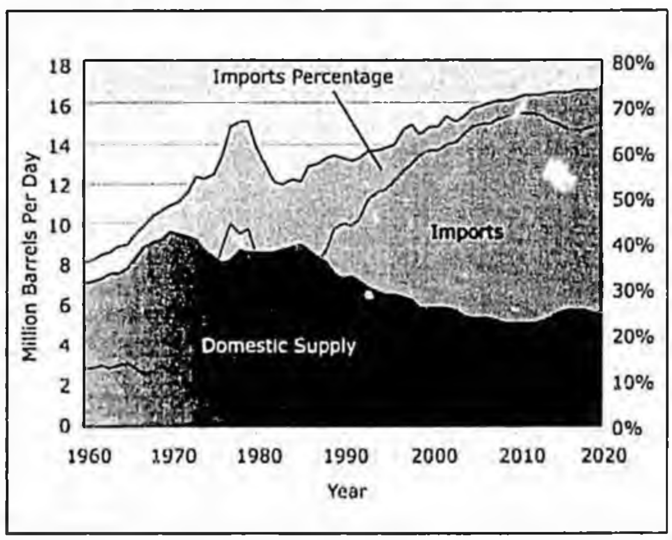
- develop advanced clean and efficient technologies that will produce hydrogen from natural gas and coal, enhancing the use of domestic energy resources;
- eliminate environmental concerns associated with the production of hydrogen from fossil fuels; and
- partner with industry to promote the commercialization of these technologies.

By developing new and innovative technology to produce hydrogen from natural gas and coal, the FE Hydrogen Program will benefit the public by enhancing U.S. energy and environmental security in a cost-effective manner through the use of domestic resources.

Energy Security

The Nation's energy consumption is directly linked to economic growth. However, the Nation's production of domestic fossil fuels, particularly petroleum, is expected to be insufficient to meet the needs of our growing economy. Therefore, a secure supply of affordable energy is critical for the continued economic growth and prosperity of the United States. Maintaining energy security in the future may be difficult because: 1) the United States is forecast to increase the volume of already large oil imports in the coming years, and 2) there is concern expressed by some analysts that world conventional oil production may peak in the next few decades before it begins a long decline.

Figure 1: Historic and Projected Domestic Crude Oil Supply and Imports (1960 – 2020)

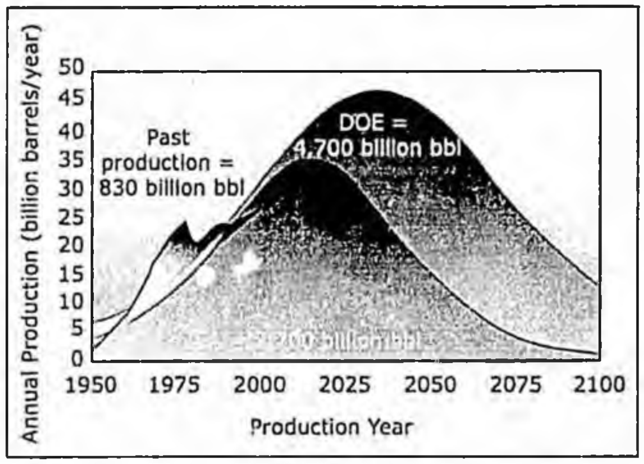


Source: EIA

Currently, the United States imports about nine million barrels per day of crude oil. Natural gas imports are increasing as well. By 2020, the Energy Information Administration (EIA) projects that imports will rise to 11 million barrels per day of crude oil, excluding petroleum products, accounting for nearly 67 percent of supply (see Figure 1). Over this period, world oil consumption is projected to rise from 76 to 119 million barrels per day. In China and India alone, consumption is expected to increase by over nine million barrels per day during this period, with a corresponding increase in imports in those countries.

Conventional petroleum is a finite resource and its production will eventually peak and irreversibly decline in the face of predicted increasing demand. Some analysts estimate that the world's average ultimately recoverable conventional oil resource is 2,700 billion barrels, which implies that the peak world conventional oil production would occur around the year 2015. Even if the remaining recoverable resource of conventional oil were nearly double this estimate so that the ultimately recoverable resource was 4,700 billion barrels, the production peak would occur only about 20 years later (Figure 2). For both estimates, alternative energy resources need to be available to ensure the Nation's future energy security.

Figure 2: World Conventional Oil Production.

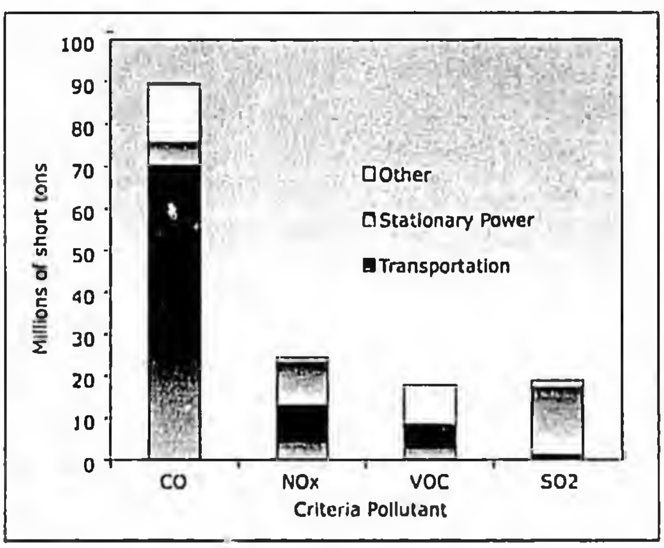


Source: J.H. Laherrere, Oil and Gas Journal, February 1999.

Environment

Other challenges facing energy use are the issues surrounding emissions from fossil fuel utilization (e.g., combustion, conversion), increased levels of greenhouse gases, especially carbon dioxide, and their impact on urban/regional air pollution and climate.

Figure 3: Transportation and Stationary Power Contributions to Criteria Air Pollutant Emissions



Source: ORNL, Transportation Energy Data Book, Edition 22.

Air Pollution

Of the man-made emissions, U.S. transportation and power production are responsible for over 84 percent of the carbon monoxide, 95 percent of the NOx, 48 percent of the VOCs, and over 92 percent of SO_2 emissions (Figure 3). There have been improvements in emissions, as the NEP states: "An individual car meeting 2004 Federal requirements will emit 95 percent less carbon monoxide, 94 percent fewer NOx emissions, and 98 percent fewer hydrocarbons than an average car did before laws limiting such vehicle pollution were implemented." Even so, these remaining emissions can have a significant impact on human health and the environment.

Climate Change

Fossil fuels account for over 70 percent of the electricity generated in the United States and nearly all of the fuel consumed in the transportation sector. The continued use of fossil fuels in these sectors presents many environmental challenges, particularly global climate change. To address this environmental challenge, the President has proposed the Climate Change Research and National Climate Change Technology Initiatives to improve scientific understanding of the global climate system and to work toward long-term reductions of carbon dioxide emissions resulting from the use of fossil fuels. The production of hydrogen from domestically available and economic fossil fuels and subsequent capture and sequestration of carbon dioxide directly respond to these initiatives.

FE HYDROGEN FROM FOSSIL FUELS – TODAY'S TECHNOLOGY

Today's hydrogen production technologies are adequate to produce and deliver hydrogen in sufficient quantities to meet refining and chemical industries' needs. However, before large-scale hydrogen use can be a clean, affordable option, there is a need for considerable cost reduction and technical improvements throughout the entire hydrogen system - production, delivery, storage, conversion, and application.

It is anticipated that coordination among Office of Fossil Energy R&D programs will be needed to lower cost, improve efficiency, and accomplish carbon dioxide capture and sequestration when fossil resources are used to produce hydrogen. The most economic and environmentally responsive process for the production of hydrogen will be one utilizing the potential of advanced technologies now in, or being proposed as part of, the FE RD&D programs. Table 1 compares the cost to produce hydrogen from selected technologies and resources. A more detailed version of Table 1 and the analyses cited can be found in the Appendix (Table A-1). Table 1 shows that natural gas and coal are the most economical choices to provide the hydrogen necessary to begin the transition to a sustainable energy system. If the technology development objectives of the FE Hydrogen Program are achieved, the production cost of hydrogen from natural gas and coal, including carbon capture and sequestration, will be about $4.00 per million Btu or lower by 2020.

Table 1: Cost Comparison of Selected Hydrogen Production Technologies

Resource	Technology	Hydrogen Cost ($/MMBtu) / ($/kg)	Year Technology is Available
Natural Gas*	Steam Methane Reforming, PSA, No Sequestration	5.54 / 0.75	Current
Natural Gas*	ITM Synthesis Gas Generation, Advanced Membrane Separation, CO_2 capture	4.15 / 0.56	2013
Coal	Gasification, Shift, PSA, No Sequestration	6.83 / 0.92	Current
Coal	Advanced Gasification, Membrane Separation, CO_2 Sequestration	5.89 / 0.79	2015+
Coal**	Advanced Gasification, Membrane Separation, Co-Production of Power, CO_2 Sequestration	3.98 / 0.54	2015+
Biomass	Pyrolysis to bio-oil followed by steam reforming	(9 – 16) / (1.21 – 2.16)	2015+
Nuclear	Sulfur-Iodine Cycle (Thermochemical Process)	9.70 / 1.31	2020+
Electrolysis	Electricity Cost at 4 cents/kWh	(19 – 22) / (2.56 – 2.97)	Current

*These two cases are based upon a natural gas price of $3.15/MMBtu. Hydrogen costs will increase or decrease from these values at roughly 1.5 times the change in natural gas price above or below $3.15/MMBtu.
**The hydrogen cost in this case is based upon achievement of the associated Vision 21 Program goals. The value of power produced in the process is assumed to be 53.6 mils/kWh.

It should be noted also that the success of the R&D effort to economically utilize fossil fuels as a source of hydrogen is dependent upon successfully achieving the goals of a number of associated R&D efforts of the FE program. These associated programs include, but are not limited to:

- carbon dioxide capture and sequestration,
- conversion of hydrogen to power through fuel cells, and
- improvements in gasification technologies to improve efficiency of producing synthesis gas.

Hydrogen Industry Today

It has been estimated by Air Products and Chemicals, Inc. that the U.S. demand for hydrogen currently is about 9 million tons per year.[1] Of this amount, about 1.5 million tons is merchant hydrogen production that is sold to refineries and chemical plants.

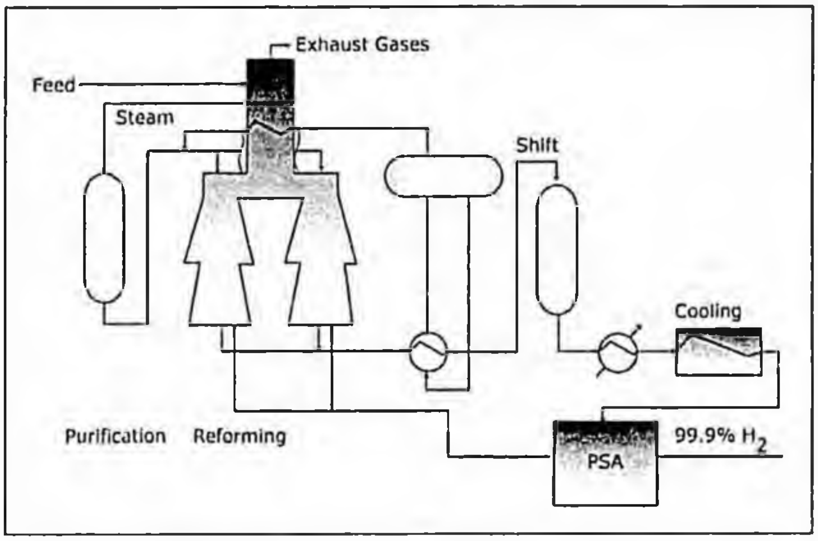
In refineries, hydrogen is produced as a by-product of naphtha reforming, and any supplemental hydrogen is produced from steam reforming of natural gas. The chemical industry also utilizes hydrogen, mostly in the manufacture of ammonia and other nitrogen-based fertilizers. Hydrogen for the chemical industry is also produced from steam reforming of natural gas, although some chemical plants use coal gasification (i.e., partial oxidation) to produce hydrogen. In total, about 95 percent of U.S. hydrogen production for supplemental refinery needs and in the chemical industries is produced from natural gas utilizing steam reforming technology.

Current Technology — Steam Reforming of Natural Gas

Steam reforming is a catalytic process that involves a reaction between natural gas or other light hydrocarbons and steam (Figure 4). The result is a mixture of hydrogen, carbon monoxide, carbon dioxide and water that is produced in a series of three reactions. The first reforming step catalytically reacts methane with steam to form hydrogen and carbon monoxide in an endothermic reaction. The carbon monoxide is then "shifted" with steam to form additional hydrogen and carbon dioxide in an exothermic reaction. The carbon dioxide is removed using one of several adsorption processes. Trace amounts of carbon monoxide and carbon dioxide are removed by exothermically reacting the compounds with hydrogen to form methane and water. Finally, hydrogen is separated in preparation for its final use.

[1] Katsaros, Arthur. Air Products and Chemicals, Inc. *U.S. Industrial Hydrogen Infrastructure Presentation.* November 2001.

Figure 4: Steam Methane Reforming Technology

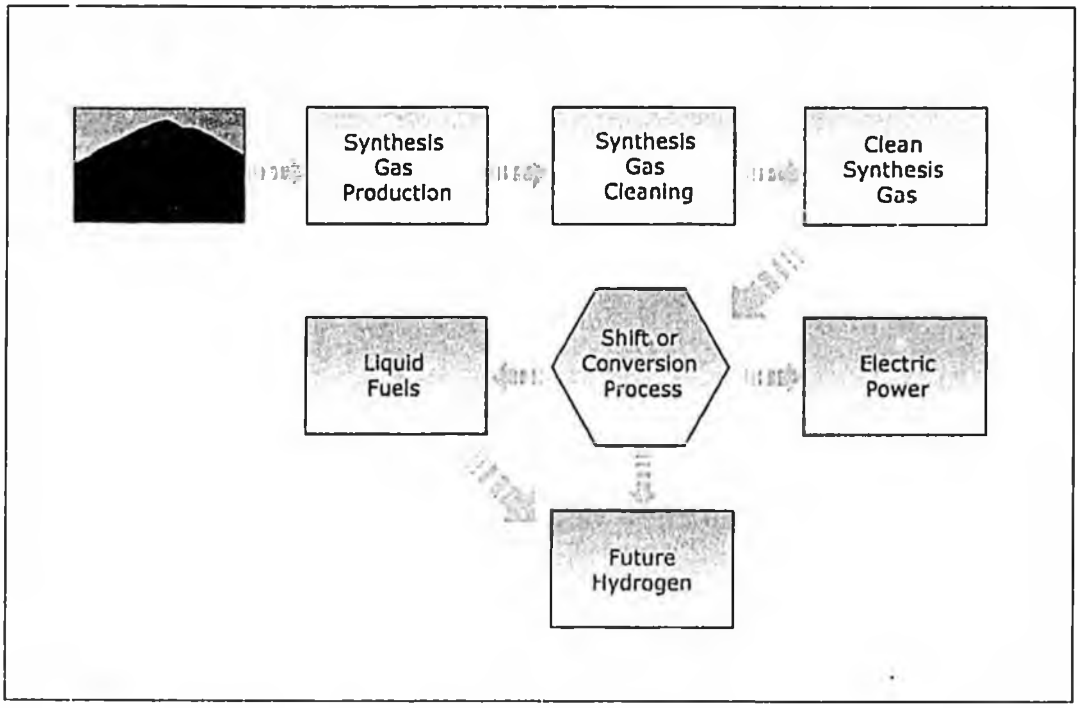


Current Coal Technology — Gasification and Conversion

Today, hydrogen is produced from coal by gasification and the subsequent processing of the resulting synthesis gas, and is used primarily to produce ammonia for fertilizer. Another market is being developed whereby coal-derived synthesis gas is being converted to methanol for use as an intermediate for chemical production, but which could also be used as a hydrogen carrier for subsequent reforming applications. This methanol production technology is being demonstrated successfully at the Eastman Chemical Complex in Kingsport, Tennessee.

In its simplest form, the overall technology used to produce hydrogen from coal is shown schematically in Figure 5. The coal is first gasified with oxygen and steam to produce a synthesis gas consisting essentially of carbon monoxide and hydrogen. This synthesis gas is cleaned to remove all impurities and shifted to produce additional hydrogen. The clean gas is then sent to a separation system to recover hydrogen. The residual gas from this separation can be recycled or combusted for its heat. The synthesis gas can also be converted into hydrocarbons and oxygenates for upgrading to liquid transportation fuels, or reformable fuels to produce hydrogen for fuel cell applications.

Figure 5: Current Hydrogen from Coal Production Process



HYDROGEN FROM FOSSIL FUELS — THE RD&D PROGRAM

Hydrogen Demand Scenarios

Hydrogen derived from fossil fuels and consumed in advanced fuel cell vehicles (FCVs) will have a significant benefit to the Nation's energy security and the environment. When light duty FCVs reach 50 million vehicles, petroleum imports will be reduced by 1.5 million barrels per day, and by 3 million barrels per day when FCVs reach 100 million vehicles. The Nation currently has about 210 million light duty vehicles that consume about 8.1 million barrels per day of petroleum in the production and use of gasoline and diesel fuels.

Emissions will be reduced significantly with fossil fuel-derived hydrogen use in these advanced hydrogen-powered FCVs, which are estimated to use one-third the energy per mile traveled compared with future gasoline internal combustion engine (ICE) vehicles. For example, even without carbon sequestration, domestic hydrogen from coal production and use in FCVs is estimated to reduce carbon dioxide emissions by 278 million tonnes per year for every 100 million FCVs. This reduction is equal to about 24 percent of the Nation's current carbon dioxide emissions associated with all of today's light duty vehicle fleet. When combined with sequestration, this same hydrogen from coal production and use in FCVs is estimated to reduce carbon dioxide emissions by 537 million tonnes per year, an amount that equals about 45 percent of current carbon dioxide emissions associated with today's light duty vehicles.

These estimates are based on a comparison of the production of the fuel (either hydrogen or petroleum products) and delivery to the service station, followed by use in either advanced FCVs or advanced gasoline ICE vehicles. This system pathway therefore includes the manufacture, transportation and consumption of fuel in these two transportation system technologies (FCV and ICE).

Table 2 shows the impact that centrally produced hydrogen from coal and natural gas, used in FCVs, will have on criteria pollutants, imports of oil, greenhouse gas emissions, energy use, and other criteria. For the case in which FCVs reach 100 million vehicles, if all hydrogen is produced from natural gas, SOx, NOx, and particulate matter less than 10 microns in diameter (PM10) are estimated to be reduced by 68,000 metric tonnes per year, 96,000 metric tonnes per year, and 28,000 metric tonnes per year, respectively. In the case of coal-derived hydrogen, reductions of SOx, NOx and PM10 are estimated to be 22,000 metric tonnes per year, 51,000 metric tonnes per year, and 20,000 metric tonnes per year, respectively.

The Nation currently consumes about 1,050 million tons of coal per year, all of which is produced domestically. Coal demand is estimated to increase only 14 percent, or 145 million tons annually, to produce the 20 million tons of hydrogen needed to fuel 100 million FCVs. In this case, energy savings are estimated at nearly $35 billion annually as coal is used instead of 3 million barrels per day of petroleum imports to fuel these light duty vehicles.

Energy savings estimated at $23 billion annually could be realized with efficient natural gas-to-hydrogen production and use in FCVs. The natural gas needed to produce 20 million tons of hydrogen per year to fuel 100 million advanced FCVs is 3.1 trillion cubic feet (tcf). However, natural gas consumption will be reduced by about 1.6 tcf/year in the refining sector and fuel production/blending operations. As a result, net annual natural gas consumption is estimated to increase by 1.5 tcf, or about 7 percent of the Nation's current annual natural gas demand of 23 tcf.

This analysis assumes hydrogen from natural gas plants have a nominal capacity of about 150 million standard cubic feet (MMscf) per day. The technology used is efficient steam methane reforming (SMR) with heat recovery but without sequestration. A total of 148 SMR plants are estimated to be needed to produce 20 million tons of hydrogen needed to fuel 100 million FCVs. In the case of hydrogen from natural gas with sequestration, advanced ITM syngas reactors are assumed to have equal thermal efficiency with SMR technology, but with sequestration. The size of these ITM syngas reactor hydrogen plants is assumed the same as SMR hydrogen plants.

Hydrogen from coal technology benefits analysis assumes that hydrogen plants also have a capacity of about 150 MMscf/day. These efficient 3,000 tons of coal per day plants use integrated gasification combined-cycle (IGCC) technology with carbon capture and sequestration, as shown in Table 4, Case 2 (p. 35). A total of 156 of these hydrogen from coal plants would be required to provide enough hydrogen to fuel 100 million advanced FCVs.

Assumptions for both advanced FCVs and ICE vehicle operation efficiency and fuel delivery are from Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, version 1.5a. Technology assumptions are based on "Long-Term Technologies" in the model, instead of current technology. In addition, this model estimates each portion of the full fuel-cycle energy use and emissions associated with various transportation fuels and advanced vehicle technologies applied to motor vehicles. The GREET model has been used in numerous joint government and industry studies, such as the June 2001 study "Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis".

The emission reductions and benefits shown in Table 2 and previously discussed, are based mainly on the GREET 1.5a model. In that model, FCVs are three times as efficient as future gasoline ICE vehicles. Using these estimates, 20 million tons of hydrogen would be consumed annually to fuel 100 million FCVs. Since FCV technology has not yet been developed, there is uncertainty in its ultimate efficiency. Some have estimated that FCVs may only have twice the energy efficiency of future ICE vehicles. If that scenario were to occur, some benefits shown in Table 2 would be reduced, but petroleum imports would still decrease by the same amount when hydrogen is produced from natural gas or coal. However, if FCVs were only twice as efficient as ICE vehicles, hydrogen demand would increase to 30 million tons per year for each 100 million FCVs. Criteria pollutants and greenhouse gas emissions from fossil fuel-derived hydrogen use in FCVs would increase by 50 percent, but they would still be significantly lower than gasoline use in future ICE vehicles, even without sequestration. With carbon capture and sequestration, these emissions will be virtually eliminated. Table A-2 in the Appendix provides more detail on the emissions reductions and benefits associated with FCVs that have twice the energy efficiency of future ICE vehicles.

Table 2: Impact of Centrally-Produced Hydrogen from Natural Gas and Coal and Use in Light-Duty FCVs that are Three Times as Efficient as ICE Vehicles in the Long Term (a)

	Hydrogen from Coal		Hydrogen from Natural Gas	
Number of Light Duty FCVs	50 million	100 million	50 million	100 million
Number of Hydrogen Plants	78	156	74	148
Hydrogen Production, million short tons per year	10.1	20.2	10.1	20.2
Capital Cost of Hydrogen Plants; $ billion (current dollars)	33	66	11	21
Emissions Reductions				
SO_x, thousand tonnes per year	22	43	34	68
NOx, thousand tonnes per year	51	102	48	96
PM10, thousand tonnes per year	20	40	14	28
CO_2, million tonnes per year (no sequestration)	139	278	189	377
CO_2, million tonnes per year (with sequestration)	269	537	278	555
Other Impacts				
Energy Savings, $ billion per year (current dollars)	17	35	12	24
Reduce Petroleum Imports, million barrels per day	1.5	3.0	1.5	3.0
Natural Gas Displaced trillion cubic feet per year	0.8 decrease	1.6 decrease	0.8 increase	1.5 increase

(a) Based on a system analysis from a central hydrogen plant, pipeline delivery of hydrogen to refueling stations and use in efficient FCVs, compared with oil refining, delivery of gasoline and use in ICE vehicles.

Sources:

Argonne National Laboratory GREET 1.5a model, Per-Mile Fuel-Cycle Energy Use and Emissions for long-term technology light duty vehicles, assumed to be 55% passenger cars, 25% Light Duty Truck Class 1, and 20% Light Duty Truck Class 2. The GREET 1.5a model provides Btu/mile use of energy, broken down by fossil energy, petroleum energy and non-fossil energy, and SOx, NOx, and PM10, among other emissions, on a fuel-cycle basis. Except for the hydrogen from coal plant analysis, GREET 1.5a assumptions were used in the above table, including the assessment that FCVs use one third the energy per mile driven as ICE vehicles.

Hydrogen from Coal, Mitretek Technical Paper, MTR 2002-31, July 2002. This case is also used in this Office of Fossil Energy Hydrogen from Natural Gas and Coal Program Plan as Case 2 in Table 4 (p. 35). This case defines the quantity of coal, and therefore carbon, used to produce hydrogen.

SAIC, March 2003 presentation, which indicates advanced coal-fired IGCC plants emit 0.09 lbs NOx/MMBtu of coal, and 0.08 lbs of SO2/MMBtu at 98 percent recovery. Estimates used in the above analysis assume SO_2 recovery is 99 percent with emission of only 0.04 lbs SO_2/MMBtu through more severe operation of a Rectisol unit.

Hydrogen Production Facilities Plant Performance and Cost Comparisons, Parsons Infrastructure and Technology Group, Final Report, March 2002. Use of current steam methane reforming technology case. This case defines the quantity of natural gas, and therefore carbon used to produce hydrogen. Since both the Parsons and GREET 1.5a natural gas to hydrogen energy efficiency were essentially identical, the GREET 1.5a assumptions were selected for use.

FE Program Goal

The overall goal of the Hydrogen from Natural Gas Program and the Hydrogen from Coal Program is to demonstrate the capability and viability of producing hydrogen from our domestic natural gas and coal resources in an economic, reliable, safe, and environmentally sound manner. In addition, the program will evaluate the options available to achieve the most efficient and effective low-cost methods for distribution of the produced hydrogen.

To reach these overarching program goals, the FE hydrogen from natural gas and coal programs have set the following three significant long-range goals:

- By 2011, an alternative hydrogen delivery system will be optimized and available,
- By 2013, natural gas-based hydrogen systems will be capable of producing hydrogen with capture of carbon dioxide at 25 percent lower costs than current commercial means, and
- By 2015, coal-based hydrogen systems including carbon dioxide capture will be capable of producing hydrogen at 25 percent lower costs than current coal-based commercial means.

The achievement of these goals will result in technologies and processes for affordable hydrogen from fossil fuels in adequate volumes to provide a pathway to a long-term, hydrogen-fueled infrastructure, subsequently reducing urban and regional air pollution and greenhouse gas emissions.

Hydrogen from Natural Gas

Goal

2013 - Natural Gas Technology Modules Reduce the Cost of Hydrogen Produced from Natural Gas by 25 percent

Milestones

Major milestones are presented below. Figure 6 provides all intermediate and final milestones for the Hydrogen from Natural Gas Program.

- 2005: A 0.5 million standard cubic feet per day (MMscfd) hydrogen ITM production unit demonstrated
- 2010: Pre-commercial ITM technology unit producing 15 MMscfd of hydrogen demonstrated
- 2011: Low-cost, small-footprint plant for hydrogen production demonstrated
- 2013: Modules to reduce cost of hydrogen (and synthesis gas) production from natural gas by 25 percent available

Barriers

Steam reforming of natural gas is a mature technology, operating at or near the theoretical limits of the process that is used to produce nearly all the hydrogen (in the form of synthesis gas, a mixture of hydrogen and carbon monoxide) in the chemical industry and for supplemental hydrogen production in refineries. Once synthesis gas is produced and shifted, hydrogen is separated from the mixed gas stream using another mature technology, pressure swing adsorption (PSA). The associated cost to produce and deliver hydrogen with these technologies is too high for it to compete economically with conventional liquid fuels, such as gasoline or diesel fuel. Also, these hydrogen production system technologies are mature, and there is limited opportunity for cost and/or efficiency improvements.

During the steam reforming process, some natural gas is burned with air (80 percent nitrogen and 20 percent oxygen) in the furnace to produce the high temperatures required in the reactor. The furnace flue carries the combustion by-products of carbon dioxide, NOx, and inert nitrogen through the stack where it is emitted into the atmosphere. Capture of carbon dioxide from the mixed flue gas stream would be expensive. The development of novel technologies that could reduce the cost to produce hydrogen or capture carbon dioxide are not undertaken by industry without government joint support because of the associated high financial risk and the absence of promising candidate technologies.

Solutions

The economic barrier represented by the current use of steam methane reforming and PSA separation is being reduced and/or eliminated through the development and potential use of the Ion Transport Membrane (ITM) syngas reactor system. In a single reactor, these systems are capable of separating air to produce oxygen and subsequently use the oxygen in the partial oxidation of natural gas to generate synthesis gas. This technology offers the potential to be scalable without an associated significant increase in the unit cost. With the advanced ITM syngas reactor systems, after shifting and hydrogen separation, the remaining concentrated carbon dioxide can be captured or sequestered or used for industrial or other applications.

The mature steam reforming process, by contrast, burns a portion of the natural gas feed with air to generate the high temperatures needed for the process, which produces a mixed carbon dioxide, nitrogen and NOx gas stream that is emitted to the air through the flue. Separation of carbon dioxide from this flue gas stream is too costly to be an economic alternative. In addition, PSA hydrogen separation is an expensive technology that can be avoided if advanced membrane separation of synthesis gas technology is developed. Joint government/industry research is needed to identify, design, demonstrate, and commercialize these new and advanced technologies. An alternative technology with potential applications in small plants also being considered is advanced autothermal reforming.

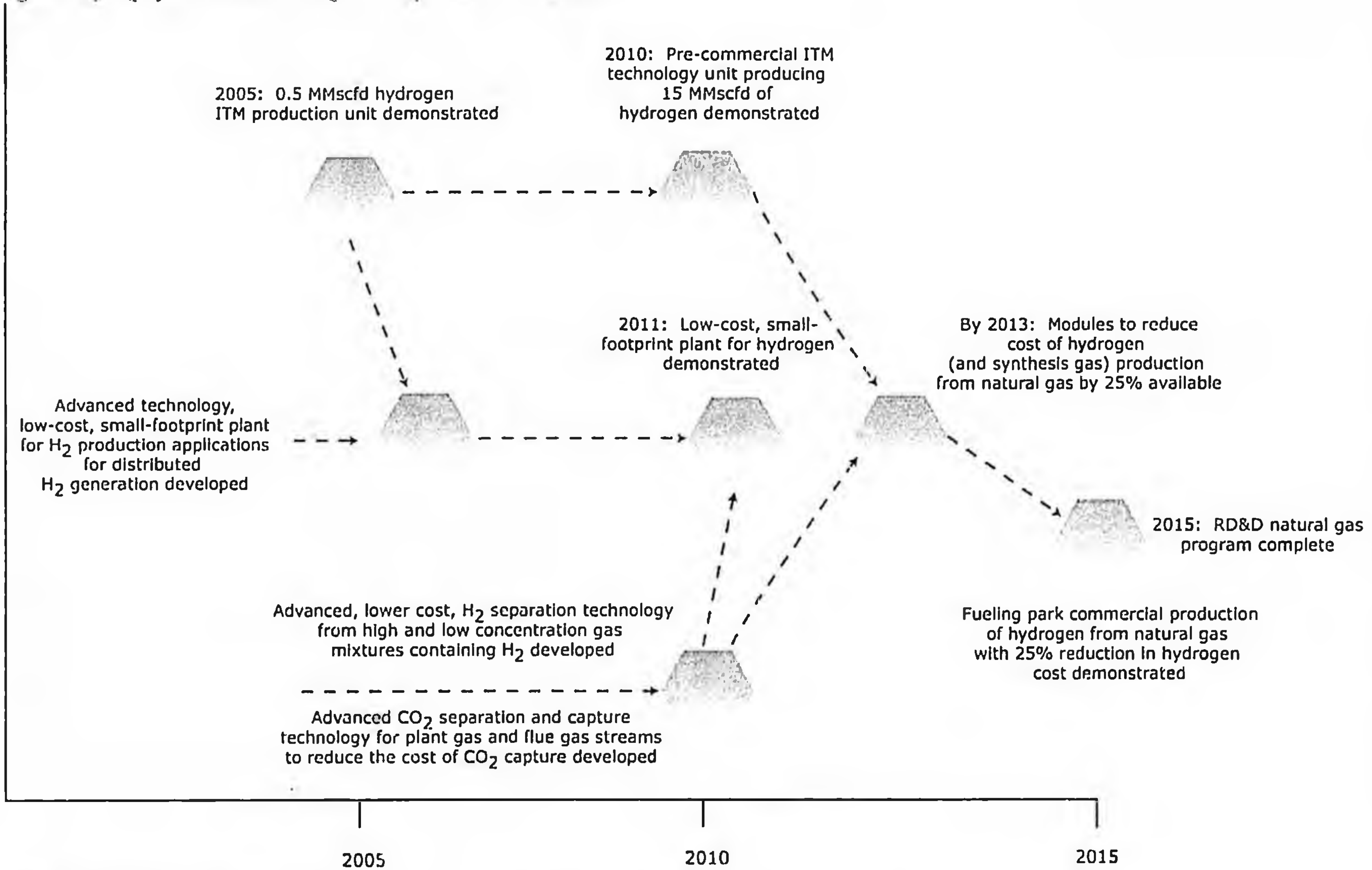
Benefits

Development of technologies to lower the cost of hydrogen from natural gas will enable the early transition to use clean hydrogen technologies, such as fuel cell vehicles (FCVs). The benefits of using low-cost hydrogen from natural gas and, in the future, potential resources of methane hydrates in advanced hydrogen utilization technologies would be improved energy security due to reduced petroleum imports, reduced criteria pollutants and reduced greenhouse gas emissions. Advanced FCVs powered by natural gas-derived hydrogen can replace gasoline internal combustion engine vehicles. For every 100 million FCVs fueled by natural gas-derived hydrogen, oil imports will be reduced by 3 million barrels per day and carbon dioxide emissions will be reduced by over 375 million tonnes per year, with carbon capture, 550 million tonnes. Criteria pollutants such as SOx, NOx, and PM10 will also be reduced by significant amounts (see Table 2, page 18).

Introduction of small-scale, lower capital cost hydrogen plants will allow earlier production of low-cost hydrogen. Because of the small footprint, construction time is shorter than for large hydrogen plants. Use of small-footprint facilities will reduce the need for significant delivery and transportation infrastructure. Large hydrogen plants that use novel ITM reactor systems will have even lower costs to produce hydrogen because of the economy-of-scale benefits and can become a significant source of hydrogen in the near to mid term.

The low-cost hydrogen production from natural gas technology can be the bridging technology to enable not only early transition to the hydrogen economy but also provide a platform for wider distribution of hydrogen production facilities that will support technologies such as fuel cell vehicles in a shorter period of time. For example, both large-scale and small-footprint plants producing hydrogen from natural gas can provide the earliest, low-cost transitional source of hydrogen for the FreedomCAR program reducing the Nation's energy consumption and reducing pollution compared to transportation alternatives. It is the integration of this innovative technology with the results of associated technology that allows capture of carbon dioxide and reduces NOx.

Figure 6: Hydrogen from Natural Gas Program – Major Technical Milestones



Associated Fossil Energy Programs

* Carbon dioxide sequestration.

Hydrogen from Coal

Goal

2015 - 60 Percent Efficient, Zero Emissions, Coal-Fueled Hydrogen and Power Co-production Facility Operational

Milestones

Major milestones are presented below. Figure 7 provides all intermediate and final milestones for the Hydrogen from Coal Program.

- 2006: Advanced hydrogen separation technology including membranes tolerant of trace contaminants identified
- 2011: Hydrogen modules for coal gasification combined-cycle co-production facility demonstrated
- 2015: Zero-emission, coal-based plant producing hydrogen and electric power (with sequestration) which reduces cost of hydrogen by 25 percent compared to current coal-based plants demonstrated

Spotlight on FutureGen

On February 27, 2003, Secretary of Energy Spencer Abraham announced the $1 billion FutureGen initiative to design, build, and operate the world's first coal-fired, zero emissions plant integrated with carbon sequestration. The goal of the project is to produce electricity at a cost increase no greater than 10 percent higher than non-sequestered systems, and hydrogen at a cost of $4.00/MMBtu. The FutureGen prototype plant may provide a venue in which project researchers have the opportunity to gain large-scale, real-world experience for technologies developed by the Hydrogen from Coal Program. This experience can help reduce the technical and economic risks associated with developing new, innovative technologies while successfully meeting the program's goals and milestones. The advanced technologies developed under the Hydrogen from Coal program will support the FutureGen initiative.

Barriers

Partial oxidation of coal is a promising technology for the production of electric power that uses integrated gasification combined-cycle (IGCC) technology. However, there currently are no commercial demonstrations of these joint power and hydrogen production plants. Partial oxidation, or gasification, combines coal, oxygen and steam to produce synthesis gas that is cleaned of impurities such as sulfur or mercury. To produce hydrogen, this synthesis gas is shifted using mature water-gas shift reactor technology to generate additional hydrogen and convert carbon monoxide to carbon dioxide. Hydrogen is subsequently separated from the gas stream. Currently, this separation is accomplished through the use of mature PSA technology which operates near its theoretical limit. In order to reduce costs, novel and advanced technology must be developed in all phases of the gasification/hydrogen production and separation process. Carbon dioxide produced in the hydrogen production process would be removed utilizing capture and sequestration technology now being developed in an associated program.

Solutions

Within the Hydrogen from Coal Program, R&D activities are focused on the development of novel processes that include:

- advanced water-gas shift reactors using sulfur-tolerant catalysts to produce more hydrogen from synthesis gas at lower cost;
- novel membranes for advanced, lower cost separations of hydrogen from carbon dioxide and other contaminants;
- advanced technology concepts that combine hydrogen separation and the water-gas shift reaction; and
- technologies that utilize fewer steps to separate carbon dioxide, hydrogen sulfide, and other impurities from hydrogen.

Novel catalysts and materials must be developed for this to succeed. Technology and engineering studies are also required for co-production and integration of coal gasification for power production with hydrogen production and separation. At the same time, cost reduction and process efficiency improvement are dependent upon R&D successes in a number of associated coal gasification technologies. These include:

- advanced ITM technology for oxygen separation from air;
- advanced cleaning of raw synthesis gas;
- improvements in gasifier design, materials and feed systems, and
- carbon dioxide capture and sequestration technology.

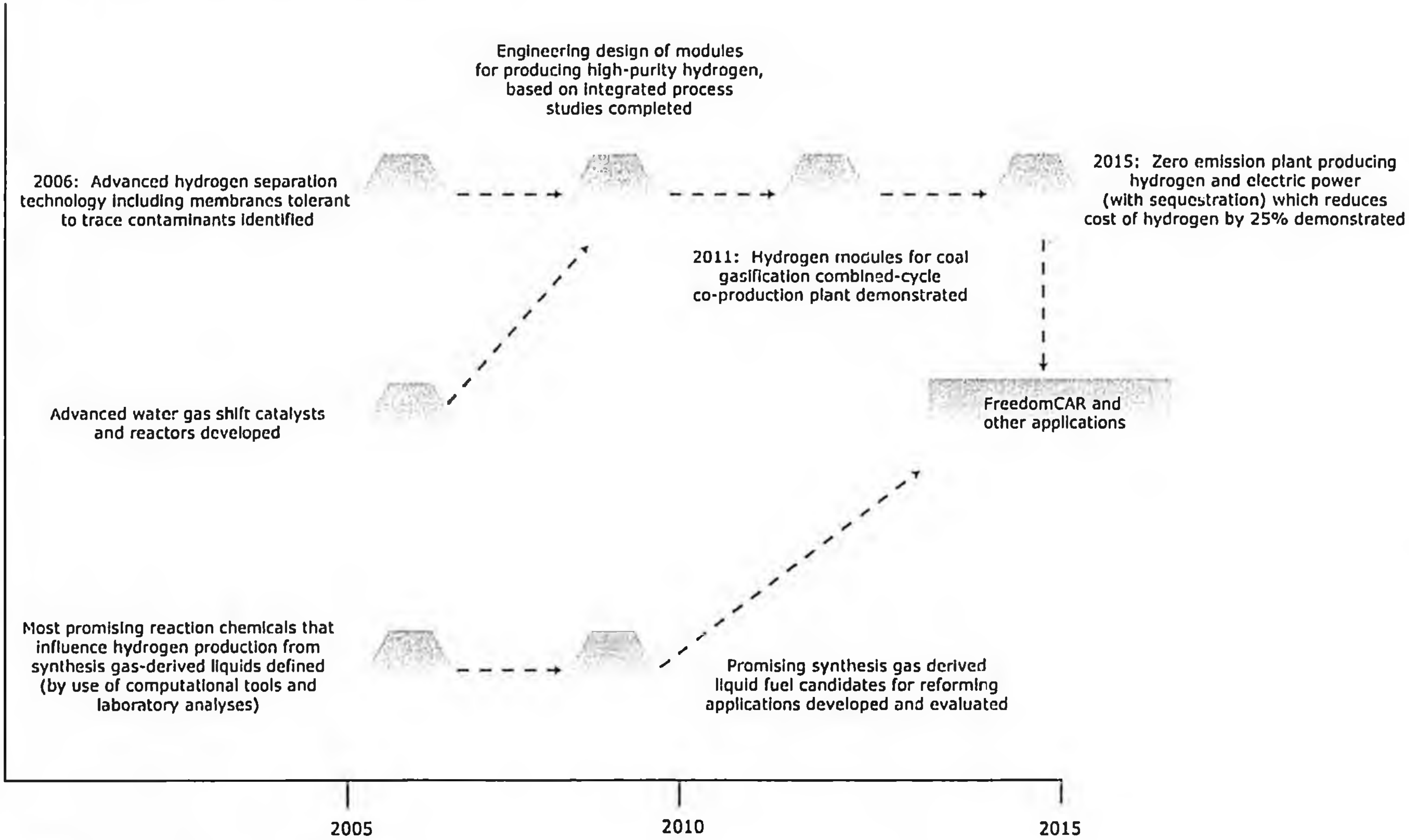
Joint government/industry research is needed to identify, design and demonstrate these new and advanced technologies if an economic alternative to current, mature technology is to be realized.

Benefits

Low-cost, hydrogen from coal technologies will allow the Nation's 250-year supply of domestic coal to replace imported oil and improve the Nation's energy security when used in advanced hydrogen technologies such as fuel cell vehicles (FCVs). The benefit of producing enough hydrogen in efficient coal-to-hydrogen technologies to power 100 million FCVs will be a reduction of 3 million barrels per day of imported oil. Even without carbon sequestration, carbon dioxide emissions will be reduced by over 275 million tonnes per year, and nearly 540 million tonnes per year with sequestration. Criteria pollutants of SOx, NOx, and PM10 will be reduced significantly (see Table 2, page 18).

Production of low-cost hydrogen from coal will reduce reliance on imported oil, increase the proportion of domestic energy resources that compose the Nation's energy mix, and provide a cost-effective source of hydrogen for the transportation sector and the associated FreedomCAR program. In this way, hydrogen from coal provides a mid-term transitional source of energy until the long-term goal of producing hydrogen from renewable and nuclear energy is realized. Successful development of carbon dioxide capture and sequestration technology will eliminate public concerns over any greenhouse gas emissions that may be generated by this technology.

Figure 7: Hydrogen from Coal Program – Major Technical Milestones



Associated Fossil Energy Programs

- Incorporates technology being developed under the associated Advanced IGCC Technology and Sequestration for carbon dioxide capture and storage programs

Delivery

Goal

2011 - Alternative Hydrogen Delivery System Optimized and Available

Milestones

- 2005: Identify and evaluate the most promising approaches and options for economic storage, handling and delivery of hydrogen
- 2008: Complete bench-scale tests of storage, handling and delivery technologies that, when integrated with the entire fuel production and delivery cycle, provide a cost to the consumer of no greater than $1.50 per gallon of gasoline equivalent (gge) by 2015.
- 2011: Complete tests and evaluations of the most promising hydrogen-rich, synthesis gas-derived liquid fuel candidates for reforming applications.

Barriers

Currently, hydrogen delivery infrastructure exists only for the small merchant hydrogen market that currently exists in the chemical and refining industries. This limited system lacks the scope or scale needed to deliver hydrogen outside of these limited industrial areas to potential large-volume end-user applications such as the FreedomCAR program. The existing liquid fuel (e.g., gasoline, diesel fuel, and jet fuel) delivery infrastructure is an entrenched, capital-intensive network that consists of pipelines, intermediate product storage, import terminals, and rail, barge and on-road truck delivery to end-use distribution stations that links the entire Nation. The existing natural gas delivery infrastructure is also a capital-intensive network that consists of import LNG terminals; significant storage to build inventory during low-demand, off-peak seasons; and pipelines to deliver product to end-users. Hydrogen has physical properties that may cause embrittlement of some high-strength steel piping materials and components (e.g. compressors and valves) currently used for natural gas. These systems would require modification for use in the delivery and distribution of hydrogen. In addition, natural gas pipelines may not be available or able to handle the additional volume. Therefore, it is likely that significant capital investment in dedicated hydrogen delivery infrastructure will be required before a hydrogen economy can be realized. The evaluation of options and the identification of the most optimum delivery system to include an alternative liquid fuel as consideration for a hydrogen carrier is a critical issue. In any consideration of advanced or modified hydrogen delivery systems, the unique characteristics of hydrogen must be considered.

Solutions

Computational studies and analysis of optimal, early-introduction hydrogen carriers is required in order to evaluate the most promising reaction catalysts and chemical process routes. Analysis is also needed to evaluate the trade-off between massive capital investments in central location hydrogen plants, associated pipelines, and delivery in a dedicated hydrogen infrastructure against the use of liquid and natural gas infrastructure to deliver hydrogen-rich fuels. It may be the case that these fuels can be reformed at end-use locations, instead of central locations, and the cost of small-scale, on-site reforming must be evaluated against the large capital costs of a ded' ed hydrogen infrastructure.

Benefits

Identification and development of the best alternatives to produce and deliver hydrogen in the near term is needed to achieve the early introduction of efficient fuel cell technology. The efficient fuel cell will reduce the overall amount of fossil fuels consumed, thereby reducing greenhouse gas emissions and pollution from conventional fossil fuels. Utilization of synthesis gas to produce liquid hydrocarbons as hydrogen carriers will enable the use of abundant coal resources and reduce oil imports. Some synthesis gas-derived liquids can use existing refined liquid fuel infrastructure, which will reduce the need for significant capital investments in dedicated hydrogen infrastructure. The combination of carbon dioxide removal at the production site of the liquid hydrogen carrier with the significantly higher potential efficiency of fuel cell vehicle technology could result in substantially lower emissions per mile in the transportation sector.

HYDROGEN FROM FOSSIL FUELS — A BUDGET FOR THE HYDROGEN FROM FOSSIL FUELS PROGRAM

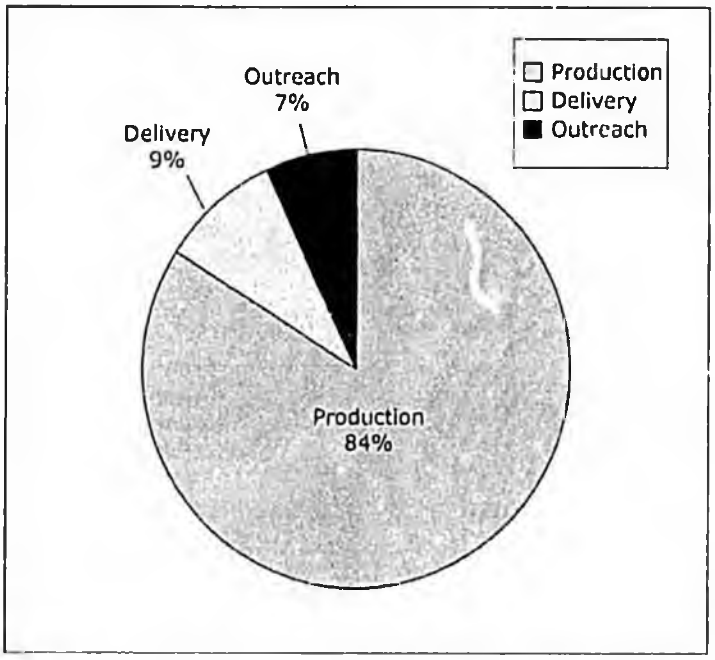
Office of Fossil Energy Hydrogen Program Budget

The budget for the FE hydrogen program for FY04 as currently planned is $11.6 million, with $5.0 million provided to the Hydrogen from Coal Program and $6.6 million to the Hydrogen from Natural Gas Program. Table 3 and Figure 8 show the breakout of the FE hydrogen budget for FY04 by category and what percentage has been allocated for each of these categories.

Table 3: FE Hydrogen Budget Breakout for FY04 ($million)

FE Hydrogen Budget	Category			
	Production	Delivery	Outreach	Total
Coal	4.3	0.5	0.2	5.0
Natural Gas	5.4	0.6	0.6	6.6
Total	9.7	1.1	0.8	11.6

Figure 8: FE FY04 Hydrogen Budget Breakout Percentage by Category



Figures 9 and 10 are Gantt charts that show a more detailed program planning breakout for the hydrogen from natural gas and coal programs, which is required to meet the program milestones and metrics. These charts also show some of the potential areas for research that will be conducted by the programs.

Figure 9: Hydrogen from Natural Gas Program

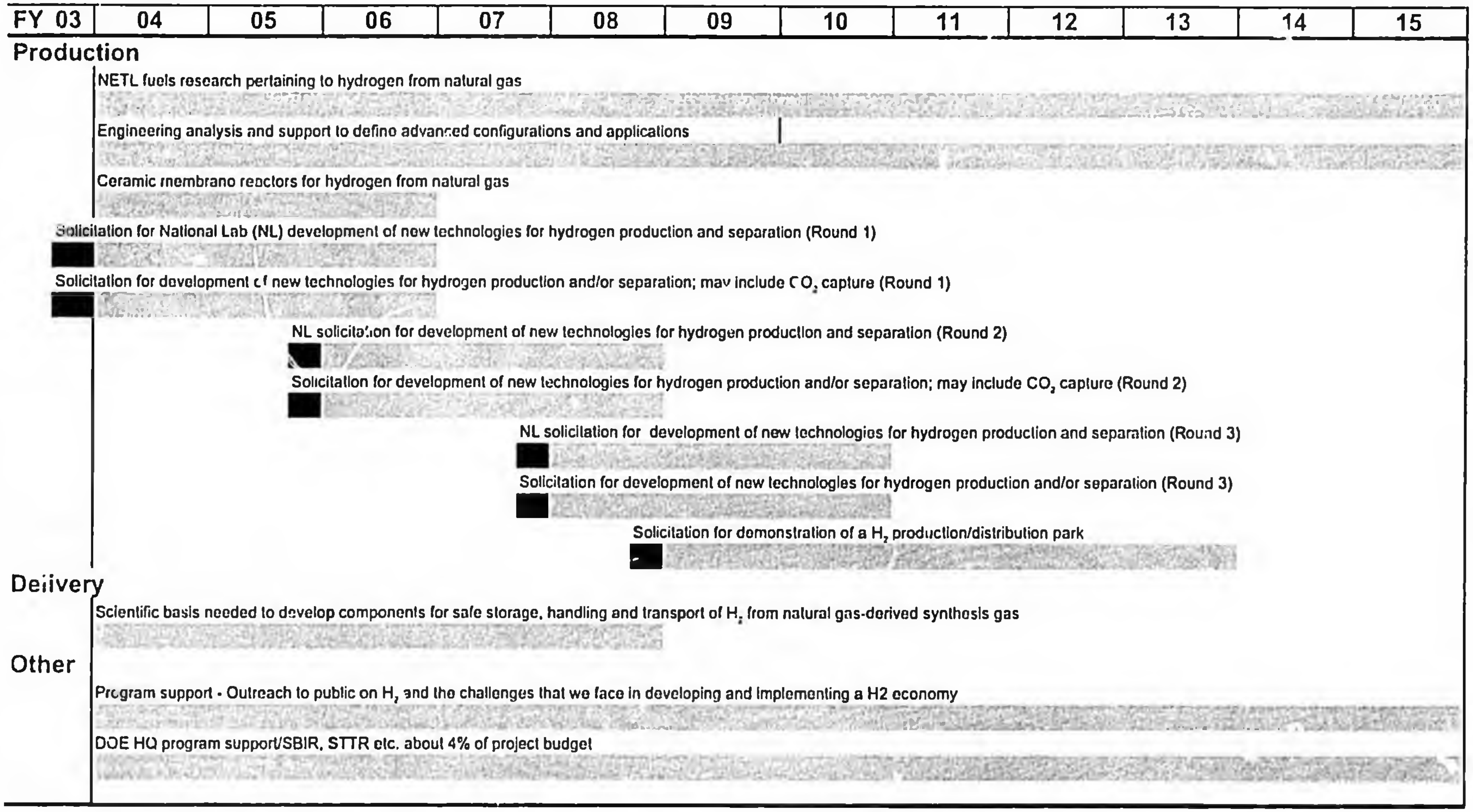
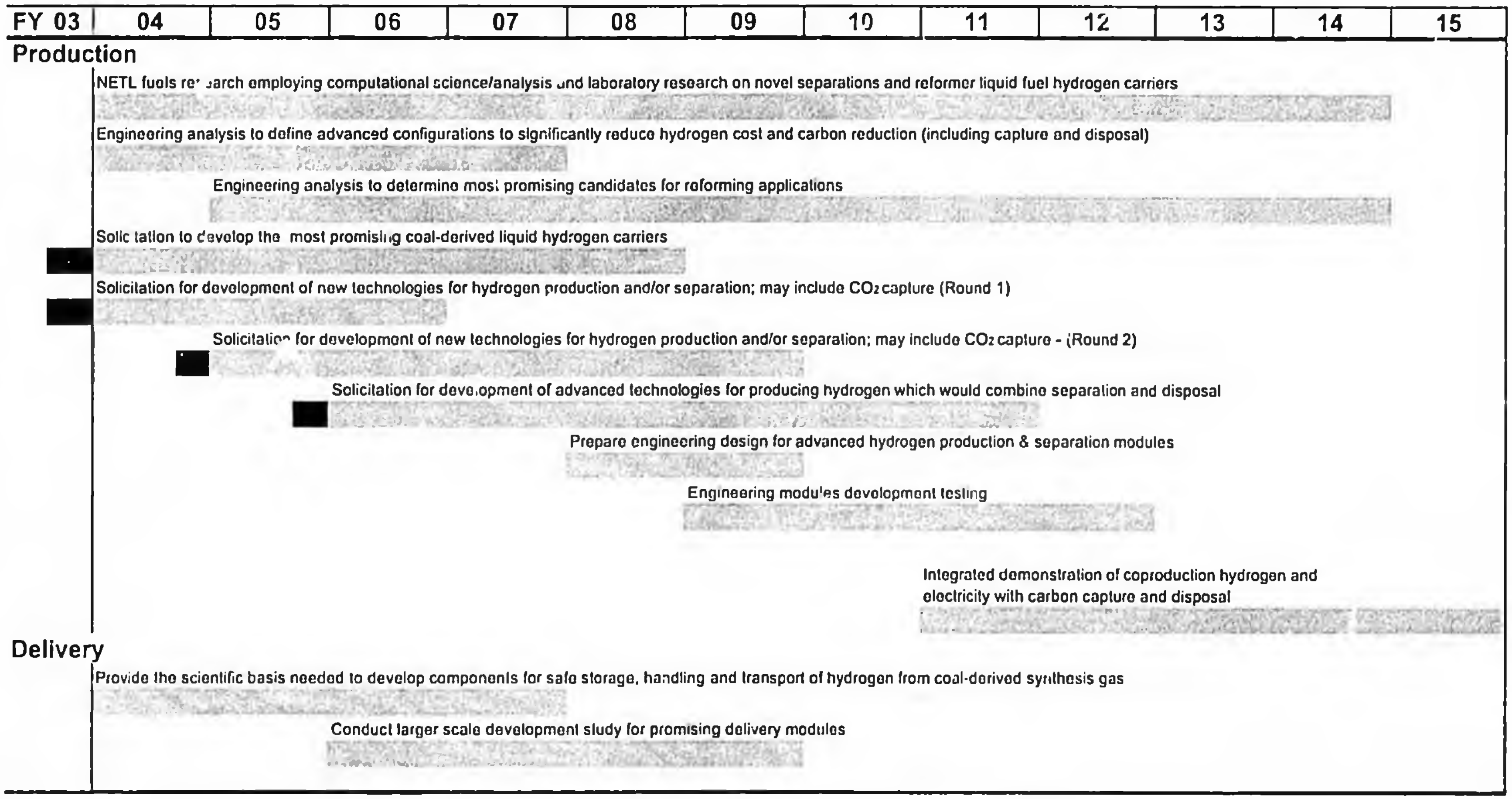


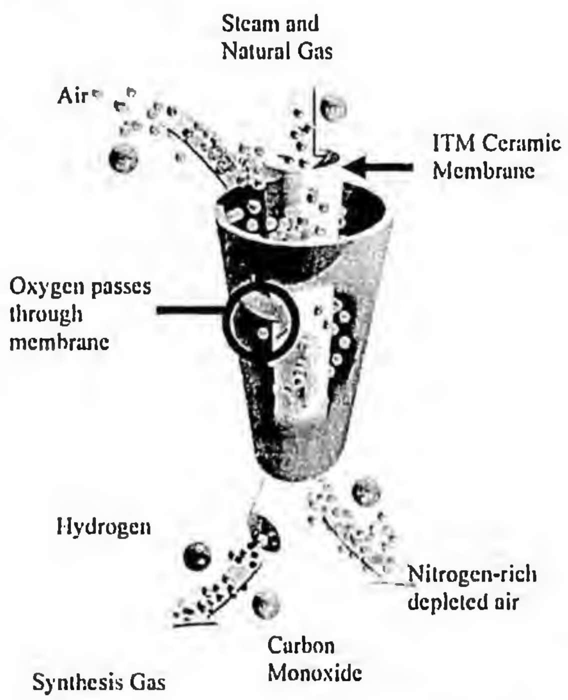
Figure 10: Hydrogen from Coal Program



FUTURE TECHNOLOGIES TO PRODUCE HYDROGEN FROM NATURAL GAS[2,3,4]

Steam reforming of natural gas is a mature process approaching its maximum theoretical process efficiency and is the primary one used to produce hydrogen from natural gas. However, there are advanced technologies, currently in various stages of development, which have the potential to reduce the cost to produce hydrogen from natural gas on both large and small scale.

Figure 11: Schematic of the ITM Synthesis Gas Generation Process



One of the promising technologies under development that shows significant potential in reducing the cost of producing hydrogen from natural gas is the application of ITM technology to generate synthesis gas. This technology combines the processes of oxygen separation from air and partial oxidation of natural gas into one, compact step (Figure 11). ITM synthesis gas generation technology utilizes non-porous ceramic membranes fabricated from multicomponent metallic oxides that conduct both electrons and oxygen ions at temperatures greater than 700°C. During operation, oxygen from a hot air stream is reduced by catalysts at one surface of the membrane to create oxygen ions. The oxygen ions flow through the membrane under a chemical gradient to the opposite membrane surface where they partially oxidize a pre-reformed hot mixture of steam and natural gas to form synthesis gas, a mixture of carbon monoxide and hydrogen. The ratio of hydrogen to carbon monoxide is partly dependent upon the amount of steam that is used. The synthesis gas then proceeds to a water-gas shift reactor where additional steam is added to convert the steam and carbon monoxide to more hydrogen and carbon dioxide. This mixture of hydrogen, carbon dioxide, and trace amounts of carbon monoxide is subsequently separated to produce a hydrogen product stream and a concentrated carbon dioxide stream. The carbon dioxide can be captured and eventually sequestered. Currently, the comparatively expensive PSA technology is used to separate hydrogen from synthesis gas. However, advanced membrane technologies that are under development have the potential to reduce the cost of this process step. Figure 12 is a schematic of the advanced technology process.

[2] Office of Fossil Energy and the National Energy Technology Laboratory Project Factsheets, 2002.
[3] Air Products and Chemicals, Inc. technical literature, 2002.
[4] Proceedings of the 2000 to 2002 DOE Hydrogen Program Reviews.

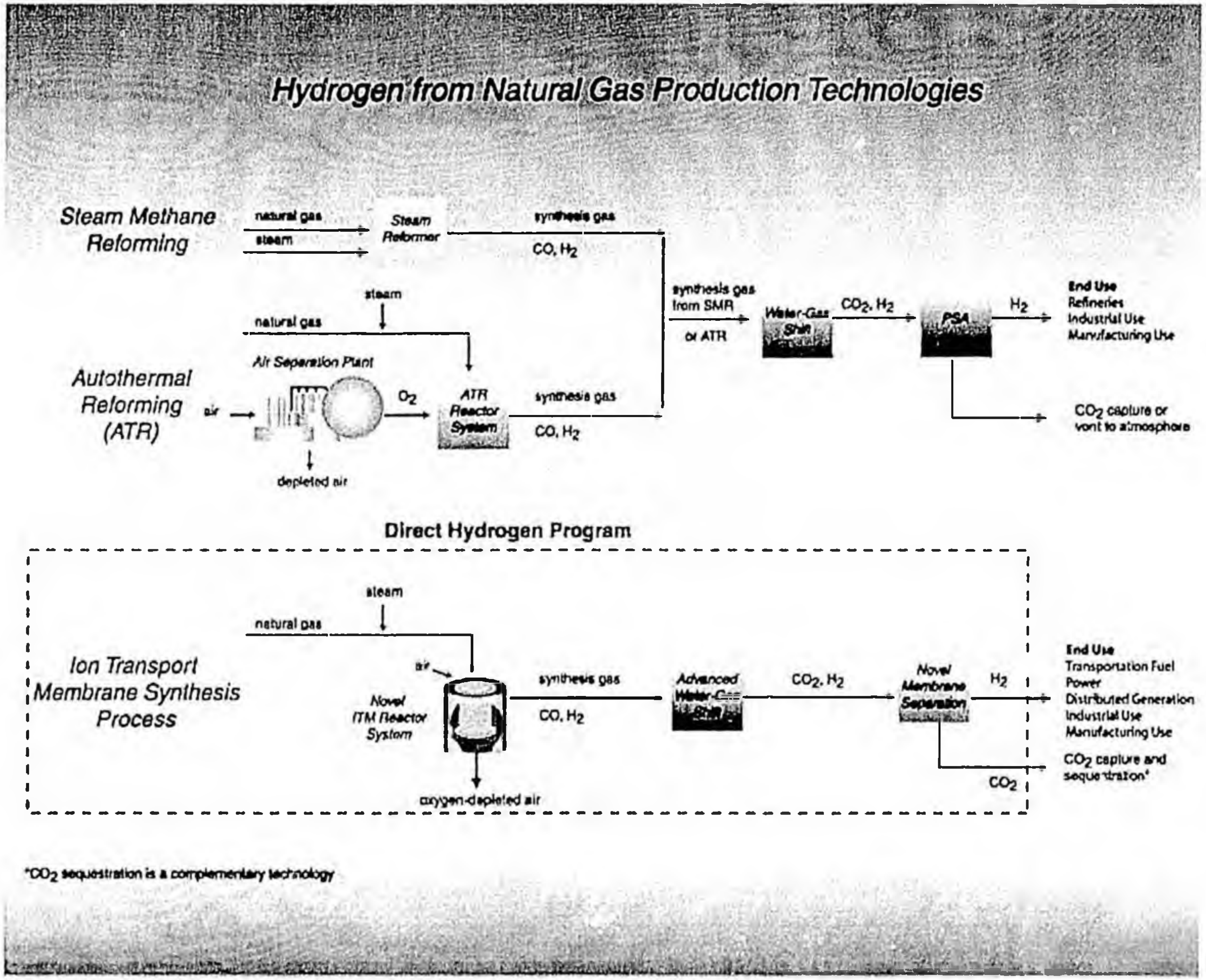
There are several key challenges that the ITM synthesis gas generation technology needs to address to reach its potential as a compact, low-cost hydrogen production process alternative to steam reforming. The membrane material used must show long-term stability in both reducing and oxidizing environments. The membrane must also allow large fluxes of oxygen to pass through so that optimal oxidation of the natural gas occurs. Long-term compatibility between the oxidation and reforming catalysts along the surface of the membrane must be exhibited. Reliable, leak-proof, metal-ceramic seals are also required.

In addition to the potential cost benefits of ITM synthesis gas generation technology, another benefit is its versatility due to its compact size. The technology has the potential to be used in small-footprint plants for distributed hydrogen generation purposes, as well as in large-scale industrial plant applications.

Distributed generation of hydrogen from small-footprint plants allows hydrogen to be produced near the end-user for fuel cell vehicle applications or industrial uses. The benefit of producing hydrogen near the end-user is that hydrogen delivery capital costs can be avoided. A small-footprint plant based on ITM synthesis gas reactor technology that produces 0.5 MMscfd of hydrogen at 5,000 pounds per square inch (psi) for FCVs was compared to trucked-in liquid hydrogen. Including the costs of hydrogen compression, storage, and dispensing, a recent industry study estimated that the small-footprint ITM plant could save 27 percent of the high-pressure hydrogen production costs compared to trucked-in liquid hydrogen.

Large-scale hydrogen production using ITM synthesis gas generation technology also has the potential to achieve cost benefits. An ITM synthesis gas generation process that produces 760 MMscfd of hydrogen at 100 bars (1,450 psi) and 14,000 tonnes/day of carbon dioxide at 80 bars (1,160 psi) for sequestration was compared to a conventional oxygen-blown autothermal reformer with a cryogenic air separation unit to supply oxygen. The comparison indicated that the ITM synthesis gas generation process could potentially save over 30 percent of the capital cost of synthesis gas generation and over 20 percent of the capital cost for the overall process. In addition, the process has a predicted thermal efficiency of 74 percent compared to 71 percent for the autothermal reformer process.

Figure 12: Schematic of Technology Process for Hydrogen Production from Natural Gas



FUTURE TECHNOLOGIES TO PRODUCE HYDROGEN FROM COAL[5]

At the present tim·, no coal-based facilities based on modern entrained gasification have been constructed that produce both hydrogen and electric power. Conceptual commercial plants have been simulated using computer models to estimate the technical performance and economics of a co-production plant producing hydrogen and power, based on current technology. Computer simulations have also been developed for conceptual plants that produce hydrogen and some excess power, based on advanced technologies that are presently not available for commercial deployment. The status of these advanced technologies varies. Some are already close to commercialization and others are further back in the R&D pipeline. Table 4 summarizes the information developed from two of these computer simulations. A more detailed evaluation of additional co-production cases can be found in the Mitretek report (5), and these cases are included in the hydrogen production cost table in the Appendix.

Table 4: Summary of Hydrogen from Coal Cases

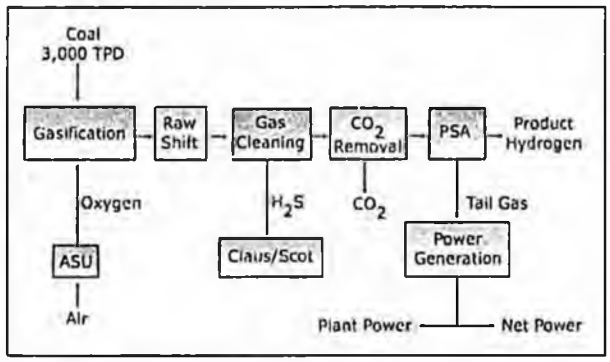
	CASE 1	CASE 2
Carbon Sequestration	YES (87%)	Yes (100%)
Hydrogen (MMscfd)	119	158
Coal (Tons/day) (AR)	3000	3000
Efficiency (%HHV)	59	75.5
Excess Power (MW)	26.9	25
Power Value (mills/kWh)	53.6	53.6
Capital ($million)	417	425
RSP of Hydrogen ($/MMBtu)	8.18	5.89

Notes:
1) Coal cost is $29/ton (and is assumed to de-escalate at 1.5 percent below general inflation), and the assumed plant capacity factor is 85 percent.
2) For carbon sequestration, the co-produced power is assumed to have a value of $53.6/MWh, based on an additional cost of power production from Natural Gas Combined-Cycle (NGCC) plants with sequestration of 18 mills/kWh (reference EPRI report 1000316).
3) For sequestration, it is assumed that $10 per ton of carbon is added for sequestration after the concentrated carbon dioxide stream has been isolated, and the carbon dioxide stream is compressed to 200 bars (2,900 psi).
4) Financial assumptions used for these simulations: 25-year plant life; 67/33% debt/equity financing; 15% return on equity; 8% interest for a 16-year term; 3% inflation with coal de-escalation of 1.5% per annum below general inflation; 16-year double declining balance depreciation; 40% combined Federal and State tax rate; 3-year construction with 50% output in start-up year; carbon sequestration cost of $10/ton.

[5] Hydrogen from Coal, Mitretek Technical Paper MTR 2002-31, July 2002.

Case 1, shown schematically in Figure 13, is a process to produce hydrogen based on conventional technology utilizing carbon sequestration. The process assumes that a Texaco quench gasification system with conventional acid removal and a PSA system for hydrogen recovery is used. All of the carbon dioxide is removed prior to the PSA unit, is compressed to 200 bars (2,900 psi), and is assumed to be sequestered for an additional cost of $10 per ton of carbon. In this configuration, 87 percent of the carbon in the feed is sequestered. The capital cost of the plant is estimated at $417 million with a retail selling price (RSP) of the hydrogen at $8.18/MMBtu. The amount of hydrogen produced is 119 MMscfd, and there is 27 MW of excess power.

Figure 13: Schematic of Current Technology to Produce Hydrogen from Coal with Carbon Sequestration



Case 2 represents a process for hydrogen production from coal that uses advanced gasification technology, advanced membrane technology for hydrogen separation with carbon dioxide removal, and carbon sequestration. A schematic of the process is shown in Figure 14. In this configuration, advanced E-gas gasification with hot gas cleanup is used in combination with a ceramic membrane system operating at nearly 600°C that is capable of shifting and separating hydrogen from clean synthesis gas. It is assumed that 90 mole percent of the synthesis gas is converted in this membrane system, assumed to be similar to the K25 system under development by Oak Ridge National Laboratory (ORNL). The hydrogen produced is separated at low pressure and must be compressed. The remaining synthesis gas, containing mostly carbon dioxide with some carbon monoxide and hydrogen, is then combusted with oxygen in a gas turbine to provide power for the plant. Oxygen is used so that a concentrated stream of carbon dioxide is produced for sequestration. Heat is recovered from both the gas turbine exit gas and from the hot hydrogen in heat recovery steam generators (HRSGs) where the steam produced is sent to a steam turbine to provide additional power. The capital cost for the facility is $425 million, with the required selling price of hydrogen estimated at $5.89/MMBtu.

Advanced concepts are planned to be developed after 2015 which would employ advanced gasification, combustion and turbine systems, membrane separation, and carbon capture and sequestration in a co-production plant producing hydrogen and electric power. These highly efficient, hydrogen and electricity co-production plants could provide significant additional reductions in the cost of hydrogen, reducing the cost to $4.00/MMBtu.

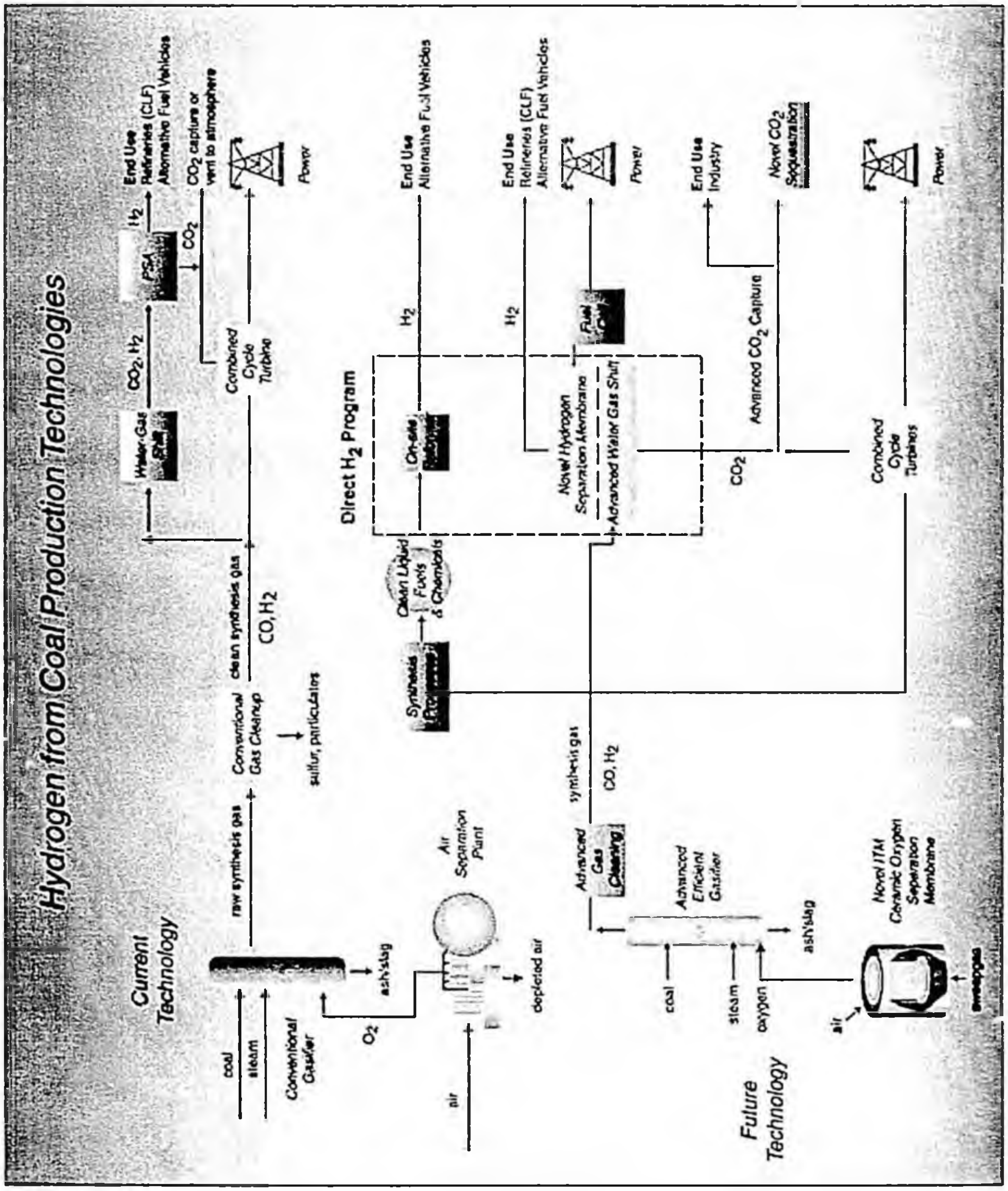


Figure 14: Schematic of Advanced Technologies to Produce Hydrogen from Coal

FE ASSOCIATED PROGRAMS

The successful development of low-cost, affordable hydrogen production from fossil fuels with sequestration of carbon is dependent on successful completion of several associated RD&D programs within the Office of Fossil Energy. The technologies are discussed below.

Gasification

Advanced coal gasification technologies will reduce the cost to produce electric power from coal using Integrated Gasification Combined-Cycle (IGCC) technology. The initial IGCC process technology produces synthesis gas that is cleaned and used to efficiently produce electric power in advanced combined-cycle turbines. Hydrogen from coal is produced from the synthesis gas generated by IGCC technology. Improved technologies developed in RD&D in the FE program will complement, and are necessary to produce, low-cost hydrogen from coal. These technologies include: improved feed handling systems, efficient gasifier design and materials engineering, advanced synthesis gas clean-up technologies, and advanced membrane separation technology to produce a lower cost source of oxygen from air.

Carbon Dioxide Sequestration

While hydrogen is a clean fuel with water as essentially its only by-product, emissions of greenhouse gases will be generated during its production from natural gas and coal. The hydrogen from natural gas program will investigate technologies to capture carbon dioxide as part of its activities to augment the carbon dioxide sequestration program where appropriate, because there is a difference in the concentration and pressures of the carbon dioxide in its effluent streams compared to process streams of coal-derived hydrogen systems. The Hydrogen from Coal Program will separate carbon dioxide from mixed hydrogen streams and will collaborate with, and take advantage of, the capture technologies being developed by the Office of Fossil Energy carbon sequestration program. Both the Hydrogen from Natural Gas Program and the Hydrogen from Coal Program, however, will utilize these sequestration technologies.

The FE carbon sequestration program is currently investigating technologies to inject carbon dioxide into enhanced oil and gas production systems and enhanced coalbed methane projects; to store carbon dioxide in underground reservoirs; to utilize the natural ability of vegetation and soils to store carbon; and to convert carbon dioxide into safe, harmless minerals. Development of carbon sequestration technology will also benefit the FE hydrogen program by sequestering carbon dioxide that is removed from the concentrated product streams that result during hydrogen production.

The goals of the FE carbon sequestration program are to provide economically and environmentally safe sequestration technologies. These technologies will offset projected growth in carbon dioxide emissions by 2015 at a cost of $10/ton of avoided carbon, with the potential to eventually offset at least one-half of any required reductions in emissions of global greenhouse gases. The development of cost-effective, safe sequestration methods will provide the United States with the opportunity to fully utilize its domestic fossil fuel resources to produce hydrogen during the Nation's transition to a sustainable hydrogen economy.

Fuel Cells

Solid State Energy Conversion Alliance (SECA) fuel cell technology is in its initial stages of development and requires improvements in all aspects of system technology. In distributed generation, a primary market for stationary fuel cell applications, the market risk and market potential are higher because of uncertainty surrounding the slow deregulation of the U.S. electric power industry.

No fuel cell type has been successfully commercialized. Early fuel cell marketers have had to rely on high-price, limited-niche markets to support the high cost of the technology. The SECA program is a joint government/private cost-shared program that has low fuel cell cost targets. SECA has identified fuel cell technologies to meet those low-cost targets that include: fuel processing, manufacturing, controls and diagnostics, power electronics, modeling and simulations, and materials. Successful development of novel and advanced low-cost processes will allow the SECA industry partners to have a wider, deeper market penetration from the start. In SECA, a 5- to 10-fold cost reduction and mass-customization manufacturing are required over existing technology to achieve widespread national deployment of fuel cells.

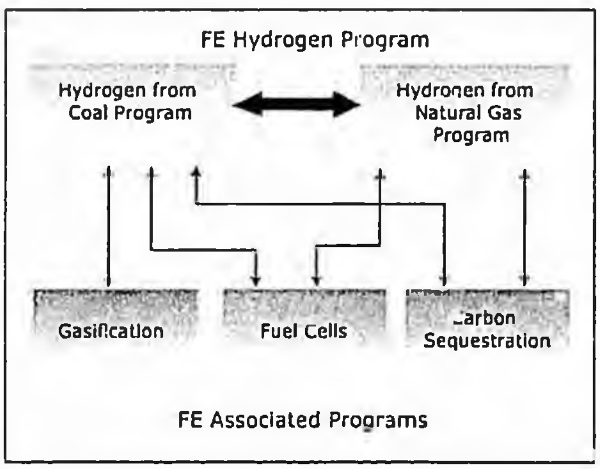
The key milestones for the SECA fuel cell program are: by 2010, 3 to 10 kW SECA fuel cells at $400/kW with target efficiencies of 40 to 60 percent demonstrated, and by 2015, hybrid SECA fuel cell/turbines that meet $400/kW system requirements with 70 to 80 percent efficiencies demonstrated.

INTEGRATED PROGRAM MANAGEMENT AND COORDINATION

The Hydrogen from Natural Gas Program and the Hydrogen from Coal Program will be managed separately by their respective program managers. However, the programs will be coordinated so that the potential for duplication of efforts is eliminated and better leveraging of resources occurs. It is expected that coordination of the hydrogen from natural gas and coal programs within FE will occur through the Hydrogen Coordination Group.

In addition, the hydrogen from natural gas and coal programs will coordinate their efforts with associated programs within the Office of Fossil Energy. Success of the FE hydrogen program is directly tied to the success of the following FE programs: coal gasification, carbon sequestration, and fuel cell development. Each of these programs will play a vital role in achieving the overall economic and environmental goals of the hydrogen energy system. To ensure a smooth and successful transition to a hydrogen energy system, it is important that there is communication between these programs. Figure 15 shows a schematic of one option that these programs may use to coordinate.

Figure 15: Coordination of Relevant FE Programs



The FE hydrogen program will also need to coordinate its activities with the hydrogen programs in the Office of Energy Efficiency and Renewable Energy, the Office of Nuclear Energy, and the Office of Science within DOE. Coordination of efforts and sharing of information and experience will help ensure the successful transition to a hydrogen energy system.

ACRONYMS

gge – gallon gasoline equivalent
kg – kilogram
kW – kilowatt
kWh – kilowatt-hour
mills – one-tenth of one cent
psi – pounds per square inch
tcf – trillion cubic feet
tpy – tons per year

ATR – autothermal reforming
CO – carbon monoxide
CO2 – carbon dioxide
DOE – Department of Energy
EIA – Energy Information Administration
EPRI – Electric Power Research Institute
FCV – fuel cell vehicle
FE – Office of Fossil Energy
FY – fiscal year
GHG – greenhouse gas
GREET – The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
H2 – hydrogen
HHV – higher heating value
HRSG – heat recovery steam generator
ICE – internal combustion engine
IGCC – integrated gasification combined-cycle
ILWG – Interlaboratory Working Group
ITM – ion transport membrane
LNG – liquefied natural gas
MW - megawatt
MWh – megawatt-hour
MMBtu – million British thermal units
MMscfd – million standard cubic feet per day
NEMS – National Energy Modeling System
NEP – National Energy Policy
NETL – National Energy Technology Laboratory
NGCC – natural gas combined-cycle
NL – National Laboratories
NOx – nitrogen oxides
ORNL – Oak Ridge National Laboratory

PM10 – particulate matter 10 microns in diameter or less
PSA – pressure swing adsorption
R&D – research and development
RD&D – research, development, and demonstration
RSP – retail selling price
SBIR – Small Business Innovative Research
SECA – Solid State Energy Conversion Alliance
SMR – steam methane reforming
SO_2 – sulfur dioxide
SOx – sulfur oxides
SOFC – solid oxide fuel cell
STTR – Small Business Technology Transfer
TPD – tons per day
U.S. – United States
VOC – volatile organic compounds

APPENDIX

HYDROGEN PRODUCTION COST COMPARISON

The following table provides a summary of hydrogen production cost comparisons for various resources and technologies and an estimate of when these technologies could be available. References to the sources of the information and notes on some of the relevant assumptions used for each resource and technology are also included at the end of the table. These tables are representative only, and other analyses of these costs might be found for the same pathway, which could be lower or higher.

Table A-1: Hydrogen Production Cost Comparisons from Various Sources

Resource	Technology	Efficiency (%HHV)	Cost ($/MMBtu)	Notes	Estimated Timeframe	Data Source	Notes
Coal	Gasification/Shift/PSA	63	6.83	Current Technology No Sequestration	Current	Mitretek (1)	1,2,3
		-	6.20	•	•	Williams (2)	4
	Gasification/Shift/PSA	59	8.18	Current Technology Sequestration	2005+	Mitretek (1)	
		-	7.90	•	•	Williams (2)	5
		60	6.91	•	•	Parsons (3)	
	Advanced Gasification/Shift/PSA	62	5.42	Co-production of Hydrogen & Power No Sequestration	2005	Mitretek (1)	
	Advanced Gasification/Shift/PSA	56	5.64	Co-production of Hydrogen & Power Sequestration	2015+	Mitretek (1)	
	Advanced Gasification/Membrane Separation	59	3.98	Co-production of Hydrogen & Power Sequestration	2015+	Mitretek (1)	6
	Advanced Gasification/Membrane Separation	75	5.89	Production of Hydrogen Sequestration	2015+	Mitretek (1)	
		80	5.06	•	2015+	Parsons (3)	
	Advanced Gasification/SOFC/ Membrane Separation	65	2.40	Co-production of Hydrogen & Power Sequestration	2020+	Mitretek (1)	7

Resource	Technology	Efficiency (%HHV)	Cost ($/MMBtu)	Notes	Estimated Timeframe	Data Source	Notes
Coal	Water Electrolysis from electric power derived from Advanced IGCC	40	14.00	No sequestration	2005	Mitretek (1)	
	Water Electrolysis from electric power derived from Advanced IGCC	35	17.50	Sequestration	2015+	Mitretek (1)	
Petroleum Coke	Current Gasification/Shift/PSA	54	4.50	Co-production of Hydrogen & Power No Sequestration	Current	Mitretek (4)	8
Natural Gas	Steam Methane Reforming (SMR)/PSA	83	5.54	Includes export steam No Sequestration	Current	Parsons (3)	9
Natural Gas	Steam Methane Reforming (SMR)/PSA	78	5.93	Sequestration	2015+	Parsons (3)	10
Natural Gas	ITM Synthesis Gas Generation, Advanced Membrane Separation, CO_2 capture		4.15	Sequestration	2015+	FE Hydrogen Program Plan Goal	11
Gravity	Hydropower Water electrolysis	-	21.90	Hydropower capital cost of $3260/kW		Ogden (5)	12
Nuclear	Water electrolysis	-	14.50	Assuming capital cost of nuclear $1620/kW		Ogden (5)	13
	Sulfur-Iodine cycle	45-55	9.70	Preliminary estimate	2020+	General Atomics (6)	14
Biomass	Gasification	-	9 – 18	Feedstock cost range: $1.0 - $2.7 per MMBtu		NREL Survey (7)	
	Pyrolysis to bio-oil/Steam reforming	-	9.4 – 16.3	Bio-oil cost of $7.1 per MMBtu		NREL Survey (7)	
Wind	Wind Water electrolysis	-	21	1998 estimate for the year 2000	Current	NREL Survey (7)	

Resource	Technology	Efficiency (%HHV)	Cost ($/MMBtu)	Notes	Estimated Timeframe	Data Source	Notes
Wind	Wind Water electrolysis	-	11.6	Assumes technology improvements that will reduce the cost	2010	NREL Survey (7)	
Geothermal	Geothermal Water electrolysis	-	25 – 45	Based on current electricity cost of 5 to 8 cents/kWh	Current	EERE/TMS estimates (8)	15
	Geothermal Water electrolysis	-	13 – 15	Based on electricity cost of 3 cents/kWh	2010+	EERE/TMS estimates (8)	16
Sunlight	Photovoltaics Water electrolysis	-	44	1998 estimate for the year 2000	Current	NREL Survey (7)	
	Photovoltaics Water electrolysis	-	20	Assumes technology improvements that will reduce the cost	2010	NREL Survey (7)	
	Concentrated Solar Water electrolysis	-	43 – 68	Ambient Temperature Electrolysis	2010	Glatzmaier et al, 1998 (9)	
Sunlight	Concentrated Solar Water electrolysis	-	36 – 64	Ambient Temperature Electrolysis	2020	Glatzmaier et al, 1998 (9)	
	Concentrated Solar Water electrolysis	-	52 – 66	High-Temperature Electrolysis		Glatzmaier et al, 1998 (9)	
Water and Sunlight	Photobiological - Algal growth process	-	10.6	Highly speculative preliminary estimate	2020+	Benemann (10)	
Secondary Electricity	Electrolysis	-	10 – 13	Electricity cost at 2 cents/kWh	Current	NREL Survey (7)	17
	Electrolysis	-	19 – 22	Electricity cost at 4 cents/kWh	Current	NREL Survey (7)	17
	Electrolysis	-	41 - 45	Electricity cost at 8 cents/kWh	Current	NREL Survey (7)	17

Data Source:

1) Hydrogen from Coal, Mitretek Technical Paper MTR 2002-31, July 2002

2) Hydrogen Production Costs with Alternative Technologies, Robert H. Williams, Princeton Environmental Institute, Presentation, Washington, D.C. July 17, 2002

3) Hydrogen Production Facilities Plant Performance and Cost Comparisons, Parsons Infrastructure and Technology Group, Final Report, March 2002

4) Opportunities for Petroleum Coke Gasification under Tighter Sulfur Limits for Transportation Fuels, Mitretek Paper MP 2000-61, December 2000

5) Ogden, Joan, M. & Williams, Robert. H., Solar Hydrogen, Moving Beyond Fossil Fuels, World Resources Institute Report, October 1989.

6) Schultz, Ken, General Atomics, Economic Production of Hydrogen from Nuclear Energy, Presentation to DOE, September 2002.

7) Padro, C.E.G. & Putsche, V., National Renewable Energy Laboratory, Survey of the Economics of Hydrogen Technologies. Technical Report, September 1999.
    a. Note: This survey includes information from the following sources: Larson, 1992; Mann et al, 1995; Mann et al, 1998; Andreassen 1998.

8) EERE Geothermal Program Website (http://www.eren.doe.gov/geothermal/); Williams, Hydrogen Production Costs with Alternative Technologies, 2002; and Technology & Management Services, Inc., Hydrogen Production Cost Comparison Spreadsheet Estimates, 2002.

9) Glatzmaier, Greg (Peak Design), Blake, Dan (National Renewable Energy Laboratory), & Showalter, Steve (Sandia National Laboratory), Assessment of Methods for Hydrogen Production Using Concentrated Solar Energy, January 1998.

10) Benemann, John R., Consultant, Process Analysis and Economics of Biophotolysis of Water, IEA Report, March 1998.

Notes:

1) Coal cost is $29/ton (and is assumed to de-escalate at 1.5 percent below general inflation) and the assumed plant capacity factor is 85 percent.

2) For those cases with no sequestration, the co-produced power value is assumed to be \$35.6/MWh, based on the cost of power production from Natural Gas Combined-Cycle (NGCC) plants if natural gas costs \$3.75/MMBtu. In cases where there is carbon sequestration, the co-produced power is assumed to have a value of \$53.6/MWh, based on an additional cost of power production from Natural Gas Combined-Cycle (NGCC) plants with sequestration of 18 mills/kWh (reference EPRI report 1000316).

3) For cases with sequestration, it is assumed that \$10 per ton of carbon is added for sequestration after the concentrated carbon dioxide stream has been isolated and the carbon dioxide stream is compressed to 200 bars.

4) Coal cost is \$0.95/ MMBtu (\$20/ton with coal at 20.8 MMBtu/ton).

5) Coal cost is \$0.95/MMBtu. Includes carbon dioxide capture and disposal cost of \$1.70/million, but excludes reported H2 storage cost of \$0.43/MMBtu (for consistency with Mitretek reported costs).

6) Assumes ceramic membrane hydrogen separation device operating at 600 degrees Centigrade.

7) Assumes operation of a solid oxide fuel cell (SOFC) topping cycle operating at 2,000 degrees Fahrenheit with an efficiency of 60 percent with a capital cost of the SOFC stack at \$400/kW.

8) Assumes current gasification with pet coke at \$10 per ton.

9) Assumes natural gas cost of \$3.15/MMBtu.

10) Assumes carbon dioxide capture by Amine Process.

11) Based upon a natural gas price of \$3.15/MMBtu. Hydrogen costs will increase or decrease from this value as natural gas price fluctuates above or below \$3.15/MMBtu.

12) Capacity factor for hydropower assumed to be 47 percent.

13) Assumed capacity factor for nuclear of 65 percent.

14) Based on using 800 degrees Centigrade nuclear heat for the sulfur-iodine water splitting cycle.

15) Based on current geothermal electricity cost of 5 to 8 cents/kWh and electrolysis cost estimates from NREL survey.

16) Based on future geothermal electricity cost estimate from EERE and electrolysis cost estimates from NREL survey.

17) Based on a plant size of 50 - 250 million standard cubic feet of hydrogen produced per day.

HYDROGEN FROM FOSSIL FUEL — BENEFITS SENSITIVITY CASE

The benefits of using hydrogen from fossil fuel in advanced hydrogen powered fuel cell vehicle (FCV) technology are discussed throughout the FE Hydrogen Program Plan with specific impacts shown in Table 2. These benefits are based on Argonne National Laboratory's GREET 1.5a model assumption that long-term fuel cell vehicles (FCVs) will use one third the energy per mile driven as future internal combustion engine (ICE) vehicles. As a sensitivity case, an analysis has been made to assess the impact if FCVs use only one half the energy per mile driven as future ICE vehicles. Table A-2 below provides a summary of that analysis. The table shows that, even at twice the efficiency of future ICE vehicles, compared to Table 2 in which FCV efficiency is three times an ICE vehicle, centrally-produced hydrogen from natural gas and coal used in light-duty FCVs provides significant benefits.

Table A-2: Impact of Centrally-Produced Hydrogen from Natural Gas and Coal and Use in Light-Duty FCVs that are Twice as Efficient as ICE Vehicles in the Long Term (a)

	Hydrogen from Coal		Hydrogen from Natural Gas	
Number of Light Duty FCVs	50 million	100 million	50 million	100 million
Number of Hydrogen Plants	117	233	111	221
Hydrogen Production, million short tons per year	15.1	30.3	15.1	30.3
Capital Cost of Hydrogen Plants; $ billion (current dollars)	50	99	16	31
Emissions Reductions				
SO_x, thousand tonnes per year	10	19	26	52
NOx, thousand tonnes per year	28	55	12	25
PM10, thousand tonnes per year	17	33	7	14
CO_2, million tonnes per year (no sequestration)	69	139	144	288
CO_2, million tonnes per year (with sequestration)	264	528	238	476
Other Impacts				
Energy Savings, $ billion per year (current dollars)	16	32	8	16
Reduce Petroleum Imports, million barrels per day	1.5	3.0	1.5	3.0
Natural Gas Displaced trillion cubic feet per year	0.8 decrease	1.6 decrease	1.5 increase	3.1 increase

(a) Based on a system analysis from a central hydrogen plant, pipeline delivery of hydrogen to refueling stations and use in efficient FCVs, compared with oil refining, delivery of gasoline and use in ICE vehicles.

Table A-2 Sources:
Argonne National Laboratory GREET 1.5a model, Per-Mile Fuel-Cycle Energy Use and Emissions for long-term technology light duty vehicles, assumed to be 55% passenger cars, 25% Light Duty Truck Class 1, and 20% Light Duty Truck Class 2. The GREET 1.5a model provides Btu/mile use of energy, broken down by fossil energy, petroleum energy and non-fossil energy, and SOx, NOx, and PM10, among other emissions, on a fuel-cycle basis. Except for the hydrogen from coal plant analysis, and adjusting FCV efficiency to twice instead of three times ICE efficiency in the model, GREET 1.5a assumptions were used in the above table.

Hydrogen from Coal, Mitretek Technical Paper, MTR 2002-31, July 2002. This case is also used in this Office of Fossil Energy Hydrogen from Natural Gas and Coal Program Plan as Case 2 in Table 4. This case defines the quantity of coal, and therefore carbon used to produce hydrogen.

SAIC, March 2003 presentation, which indicates advanced Coal fired IGCC plants emit 0.09 lbs NOx/MMBtu of coal, and 0.08 lbs of SO2/MMBtu at 98 percent recovery. Estimates used in the above analysis assume SO_2 recovery is 99 percent with emission of only 0.04 lbs SO_2/MMBtu through more severe operation of a Rectisol unit.

Hydrogen Production Facilities Plant Performance and Cost Comparisons, Parsons Infrastructure and Technology Group, Final Report, March 2002. Use of current Steam Methane Reforming Technology case. This case defines the quantity of natural gas, and therefore carbon used to produce hydrogen. Both the Parsons and GREET 1.5a natural gas to hydrogen energy efficiency were essentially identical, the GREET 1.5a assumptions were selected for use.

Hydrogen Cars May Hit Showrooms by 2005

Janet Ginsburg
for National Geographic Today
January 29, 2003 (Originally published on October 16, 2001)

Future Trans[...]

The Revolution, a lightweig[...] powered by a hydrogen fu[...] is as much as eight tin[...] efficient as most sta[...] models, according [...] desi[...]

Photograph by Clasen/Hypercar Inc.

National Geographic T[...]

This story airs on our U.S. television daily news *National Geographic Toda[...]* details of how to get the broadcast weekdays at 7 ET/PT, please visit the Ch[...] Web si[...]

Viewers of National Geographic Today *in the United States can watch an update on hydrogen-car technology in tonight's broadcast, which follows yesterday's announcement by President Bush that he proposes U.S. $1.2 billion in funding for this research over the next few years.*

In the clean, "green" future envisioned by energy expert Amory Lovins, cars not only get 99 miles per gallon emissions-free, but they may also play a key role in providing electricity to a power-hungry world.

The solution, according to Lovins, is a "hypercar"—a lightweight vehicle powered by a hydrogen fuel cell, with enough style and space to compete with luxury sport utility vehicles (SUVs). Lovins is with the Rocky Mountain Institute, a think tank in Colorado.

and chairman of its corporate spin-off venture Hypercar, Inc.,.

Some of the giant car companies are also designing hydrogen-powered cars. Hypercar Inc. hopes to have its first model ready to roll off the production line by 2005.

Today, an estimated 210 million vehicles are stuck in traffic on America's roadways. Collectively they spew nearly a billion and a half tons of greenhouse gases into the atmosphere each year. According to a recent EPA report, the latest conventional models average a little more than 20 miles per gallon—the worst showing since 1980.

While some blame America's love affair with the fuel-hungry SUVs, Lovins says the problem comes down to design.

A decade ago, Lovins was asked to address a National Academy of Sciences meeting about how to build cars with greater fuel efficiency. The general thinking was that fuel efficiency could be increased by only 10 percent because otherwise the car would become too expensive, says Lovins.

He was unconvinced of that assertion, however, and set up an informal team to rethink the automobile from the tires up. "I'm not a car guy, which actually was a bit of an advantage because I didn't know too much about how it ought to be done," said Lovins.

The result is a car that is as much as eight times as efficient as most standard models.

Map
Map Machine: North America >>

Lightweight Parts, Heavy Results

How did the Lovins team do it? They began by "light-weighting" the car.

They started with the body, which is made from a composite of carbon fibers set in a plastic matrix. It's a stronger version of the material used in skis and tennis rackets—and, per pound, five times as strong as steel.

Although carbon composites are a lot more expensive than steel, a smaller quantity is needed. Even more important, Lovins pointed out, "it's cheaper to manufacture."

While the Hypercar weighs less than 2,000 pounds (907 kilograms), it is still tough enough to meet federal safety standards, based on a computer-simulated 30-miles-per-hour fixed barrier crash. In a cyber smash-up with a Ford Explorer—a vehicle twice the weight—all the damage to the Hypercar occurred in the front end.

There are other, less obvious, ways to lightweight. Special low-rolling resistance tires developed with Michelin, not only cut down on friction—which can use up to a third of a car's fuel energy—but are also designed to run flat. If a tire blows, the car can still be driven for another 100 miles, more than enough to get to a gas station. The need to carry a spare is eliminated, further reducing weight.

Soon the savings in weight starts to snowball. A lighter car requires a smaller engine to power it, less braking to stop it, and less suspension to hold it up. And because the Hypercar runs on an electricity-producing fuel cell rather than an internal

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Hydrogen Safet

For many people, of hydrogen as a up images of the Hindenberg explo flames. But hydro actually safer tha gasoline and had to do with the 19 disaster. Instead, research has sho the outer membr the dirigible, whic made of a volatil combination of al and iron oxide co caught fire from a spark—possibly fr lightning or even electricity. Becau hydrogen is light air, it flowed up a of harm's way.

Likewise, recent s have shown that hydrogen gas tar would be much le than a gasoline le hydrogen dissipa quickly and dispe upward, while ga tends to pool—re for an explosion.

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RELATED LESSO

Use this National Geographic News in your classroom the *Xpeditions* le electricity-producing fuel cell rather than an internal combustion engine, certain parts, including the starter, alternator, clutch, and transmission, are eliminated.

"The car gets radically simplified. And then it costs less to make," said Lovins.

David Cole, president of the Center for Automotive Research in Ann Arbor, Michigan, said it's important to be cautious about expectations. "The potential on paper looks awfully good," he said. "But getting it into production—things don't necessarily turn out as you might expect."

"If you think of this as a ten-step program, the first step is showing technical feasibility," said Cole. "They still need to do this. Then it's nine more steps to commercial feasibility."

"Brains," Not Bulk

Brains replace bulk in a Hypercar. "Think of it like a computer with wheels, not a car with chips," Lovins explained.

The car can diagnose, upgrade, and, to a certain extent, fix itself. It can also be programmed for a variety of new features, such as recording everything that happened at the time of a crash, like an airplane's "black box."

Two years ago, Hypercar,Inc., was spun off from the Rocky Mountain Institute. The nine-person start-up team, based in Basalt, Colorado, intends to "create the DNA of the next generation of vehicles," according to Hypercar's Michael Brylawksi.

To do that, they're trying to sell not only the Hypercar

plan: "On the Ro
Again": Moving P
Products, and Ide

itself, but also the ideas that make it run so efficiently—the "intellectual property." By working with automakers and suppliers, the company hopes to get the technologies on the road faster.

While none of its fuel-efficient, smart features are unique to Hypercar, what's special is how they're combined and optimized.

For example, at least half a dozen automakers, including Ford, Daimler-Chrysler, and BMW, are developing fuel cell-powered cars. But because those vehicles are still fairly heavy, they need fuel cells, which are about three times bigger and heavier—and three times more expensive—as that used by the Hypercar.

Cole thinks the Hypercar is "a huge step" in the right direction. "My guess is where they [Hypercar Inc.] would make the most contribution is in a few of the ideas," said Cole. "The real role of the Hypercar is unleashing the imagination—that's one of the real values of it."

Double Duty

Perhaps the biggest hurdle to overcome with fuel cell-powered cars is setting up a distribution network to supply the hydrogen gas that runs them.

A fuel cell works by combining hydrogen with oxygen from the air in a chemical process to generate electricity. The only by-products are heat and pure water. Hydrogen can be extracted from natural gas, using a device called a reformer, or through a process called "electrolysis," which splits water into hydrogen and oxygen atoms.

While there are only a handful of hydrogen gas stations in the world, Lovins has a plan for making it easy to fill up. "Many people assume that before you can sell the first hydrogen car, you have to put in $100 billion worth of hydrogen generating and delivery stations and pipelines," said Lovins. "That's not correct."

He says the first Hypercars should be leased to people who work in buildings where fuel cells have already been installed. The Hypercars could tap into the buildings' supply of hydrogen to refuel. But they could also be hooked up to the grid.

As "portable power plants on wheels," the cars' fuel cells could be put to work during the day when they're parked, generating—and selling—electricity.

"It doesn't take many people wanting to be paid to park, rather than the other way around...to put the coal and nuclear people out of business," said Lovins. And of course, using fuel cells would dramatically decrease the need for oil.

Cole disagrees with Lovins' conclusions, arguing that the hydrogen infrastructure would take billions of dollars to establish. But he does support the direction of the project. "I say, 'More power to them.' My only reservation is to be careful about generating unrealistic expectations," he said.

"It does get people to think out of the box," said Cole. "You don't want to clamp down on these people who are dreaming at the edge."

Eventually, the Hypercar could change ideas about what people come to expect from automobiles. Fittingly, the first model to come off the drawing boards is called the Revolution.

Watch continued television coverage of this event on National Geographic Today, *only on the National Geographic Channel, at 7 p.m. ET/PT in the United States.* *Click here to request it.*

Related Websites

- Hypercar
- Rocky Mountain Institute
- National Hydrogen Association

Comments? Contact the news desk.