Hydrogen Fuel

Well-to-Pump Pathways for 2050

Windsor Workshop 2002

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Center for Transportation Research

Transportation Technology R&D Center

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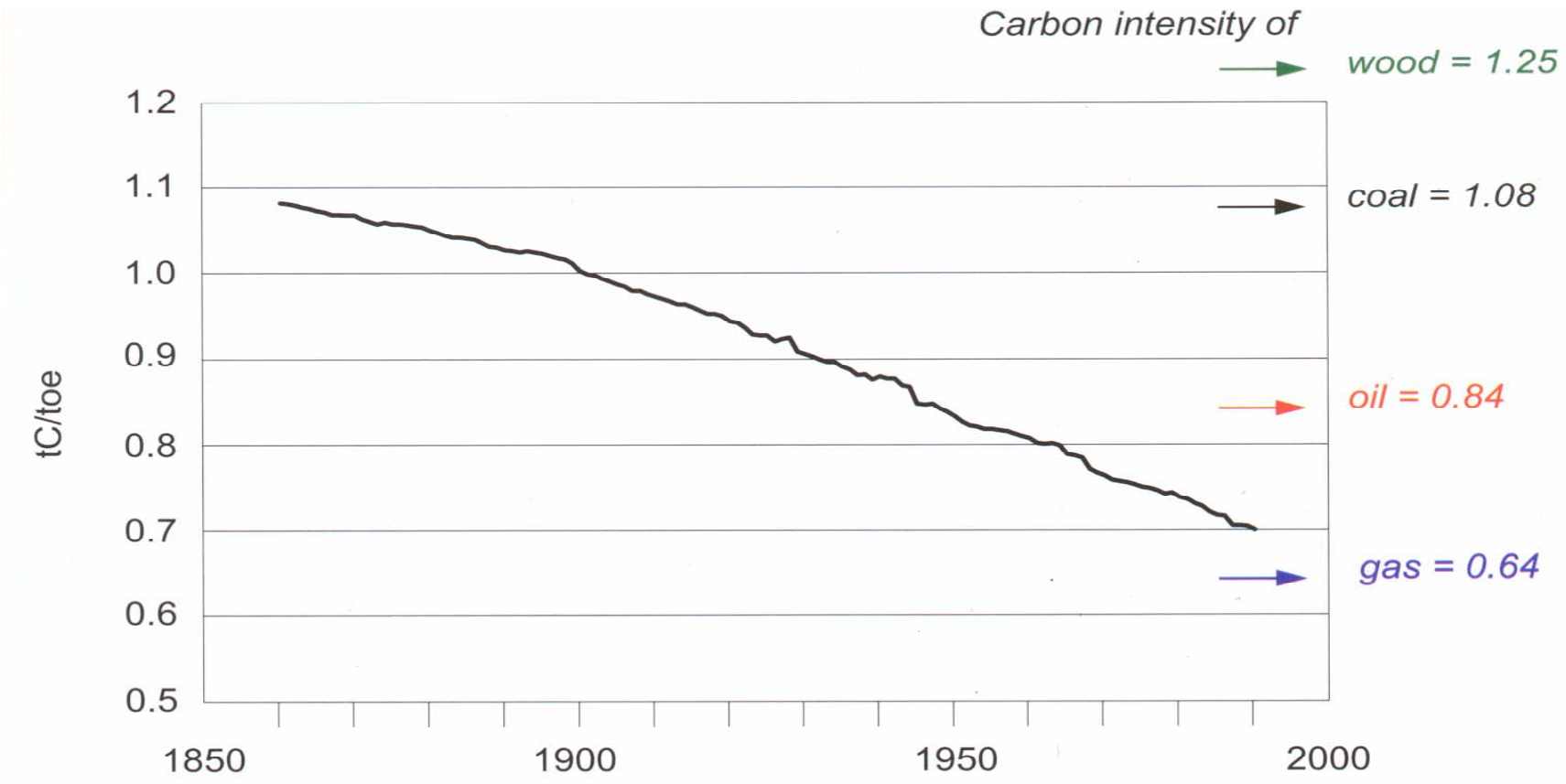
Topics

- Evolution to hydrogen and electricity
- Current hydrogen production
- Alternative hydrogen pathways
- Results of the DOE/NRCan 2050 Study
- Conclusions and next steps
- Transition strategies

While Carbon Intensity of World Primary Energy Has Been Falling …



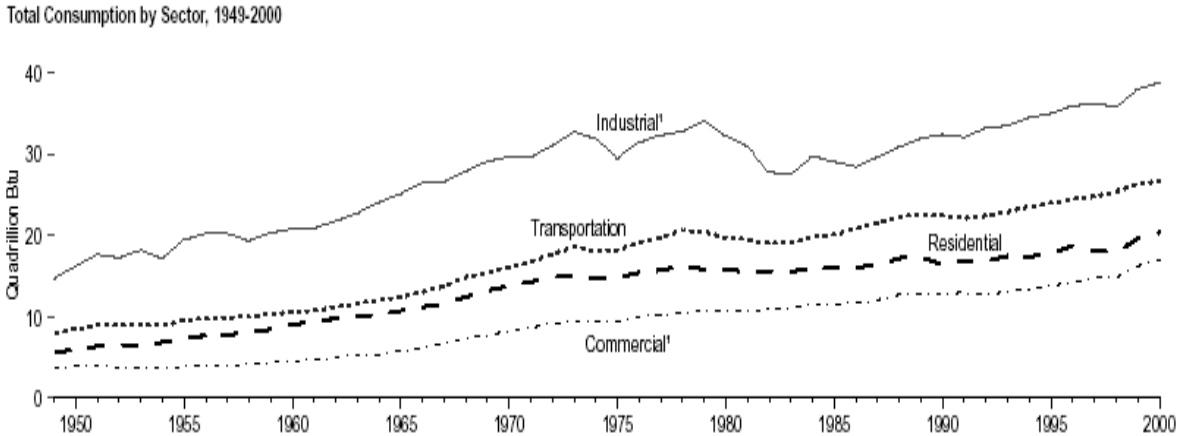
Hydrogen Intensity Has Been Rising

Fuel	Physical State	% Carbon	% Hydrogen
Dry Wood	solid	90%	10%
Coal	solid	62%	38%
Oil	liquid	36%	64%
Natural Gas	gas	20%	80%
Hydrogen	gas	0%	100%

Source: De Jong and Van Wechem 1995, Marchetti 1985, Cannon 1997.

Carbon Declines Have Come from Efficiency Gains and Fuel Switches

Across all sectors, electricity accounts for an increasing share of total energy use

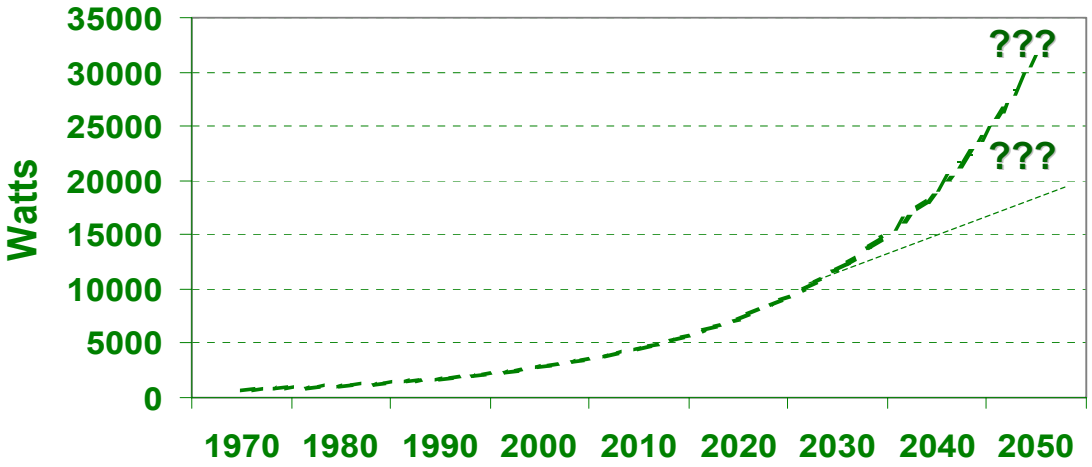


Industry and residential/commercial sectors switched to lower-carbon natural gas and electricity. Transportation remains almost completely oil dependent, but …

On Board Systems Are Increasingly Electric

2000-2010

Infotronics; ABS; rear defrost; heated steering wheel; heated seats; power seats/sunroof/ door locks, trunk closer; steer/brake by wire; electro-mechanical valve control; active suspension



2010-2020

Entertainment (mobile Internet, video, gaming); navigation; collision avoidance; power electronics (42 v, integrated starter/alternator)

2020+

Power management, ISA+APU (fuel cell?? ultracapacitor???)

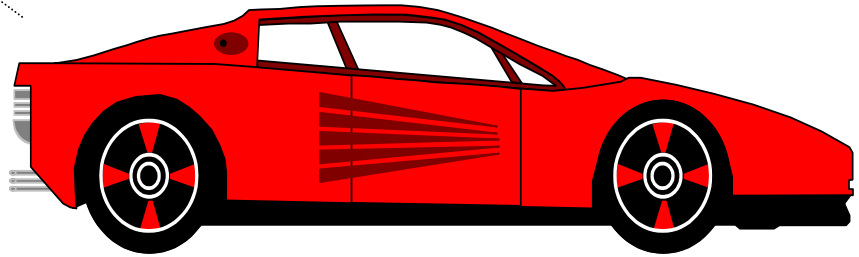
Fuels Could Also Evolve – With or Without On Board Reforming

Gasoline

CNG ??

CNG/Hydrogen ?

Hydrogen



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In 1999 the US Accounted for 3.2 tcf (1 quad) or 20% of Global H_2 Consumption

Captive Users	United States	Total World[1]
- NH_3 Producers	1.185	9.662
- Oil Refiners[2]	1.164	3.721
- MeOH Producers	0.303	1.428
- Other	0.121	0.482
Merchant Users	0.379	0.570
Total	3.153	15.864

[1] Including US.
[2] Excluding byproduct hydrogen.

Source: SRI Chemical Economics Handbook 2001.

Most of the Refinery and Merchant Hydrogen Production Is Concentrated in Major Refining Centers

Source: Centers for Transportation Research and Infrastructure Assurance, Argonne National Lab

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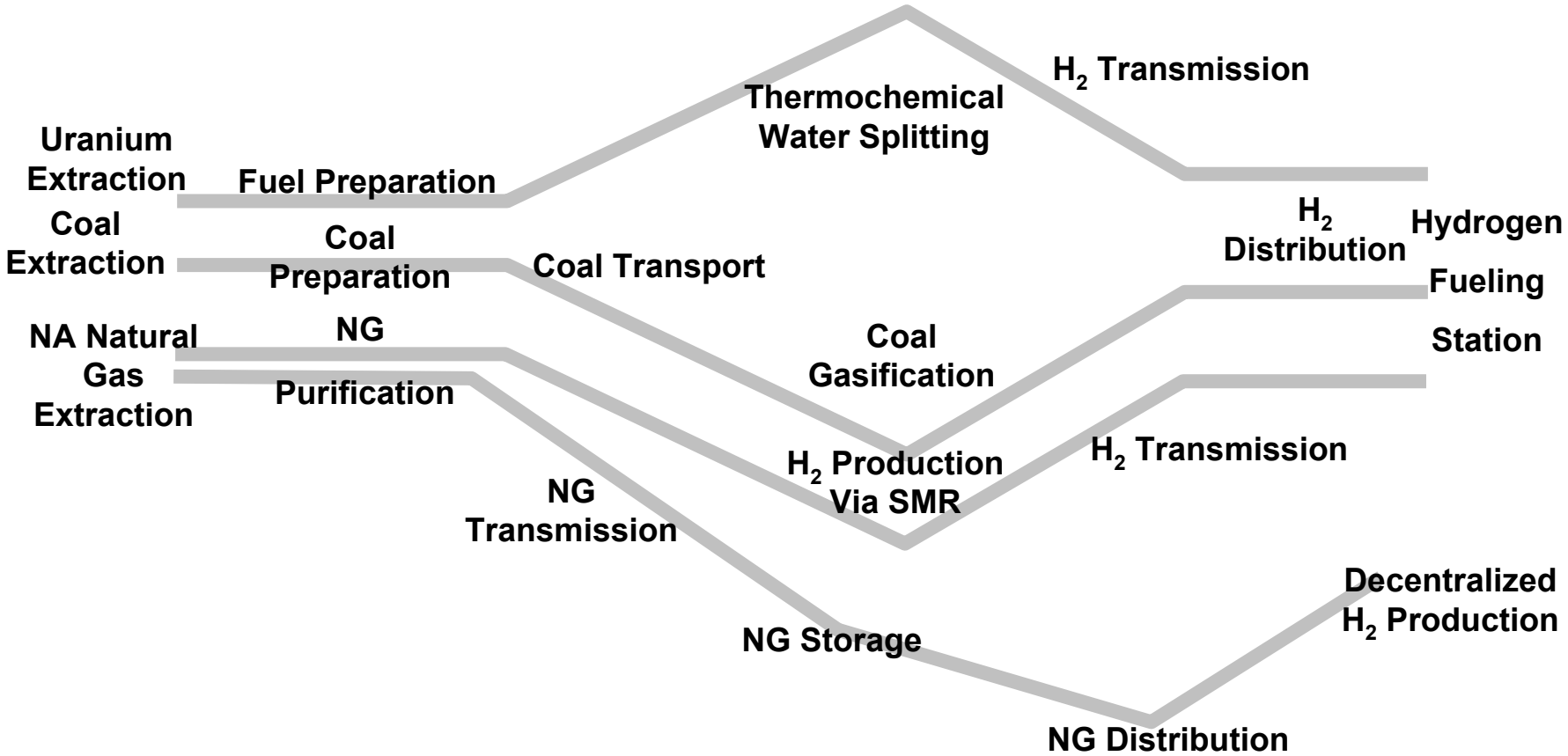
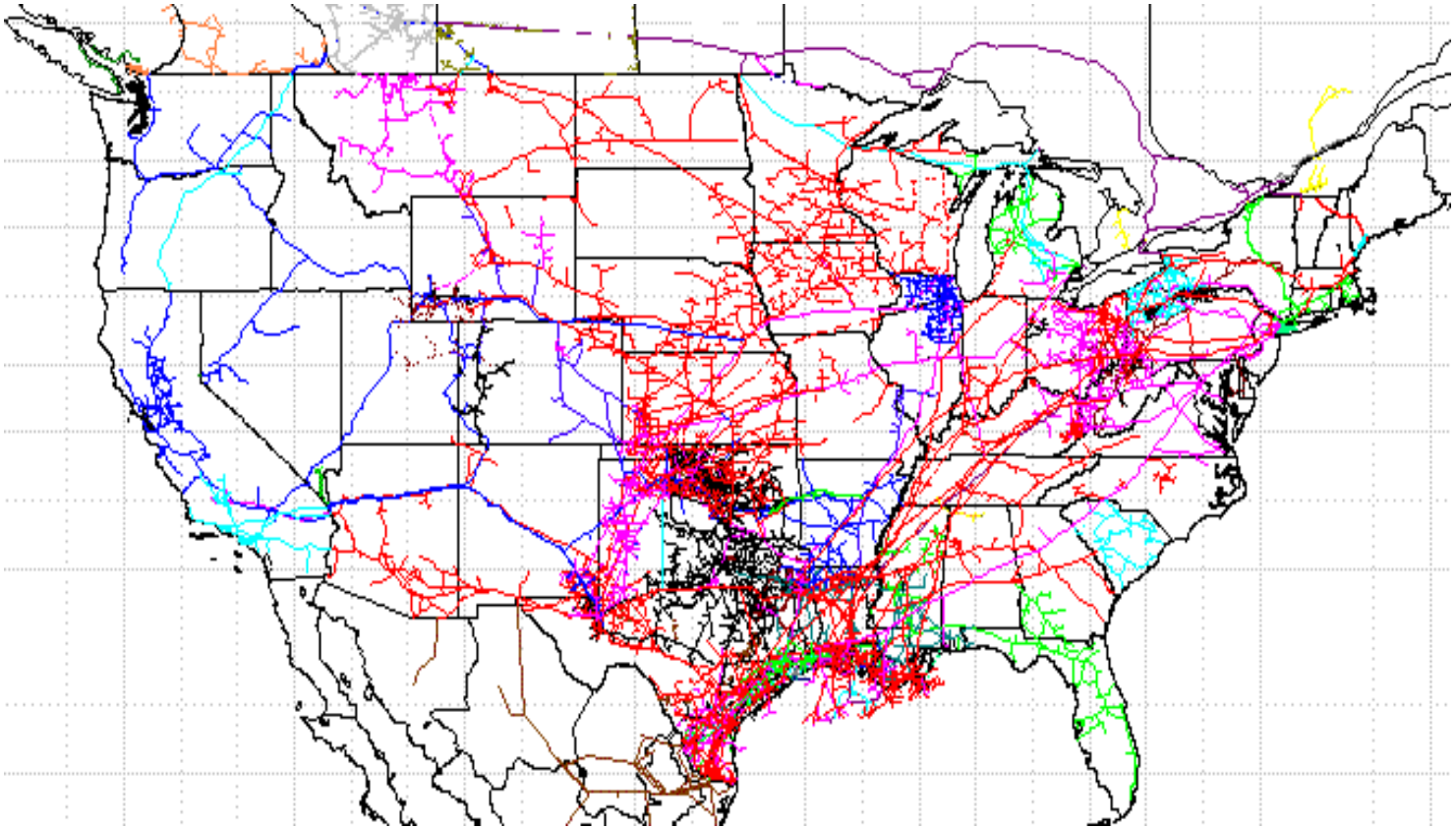
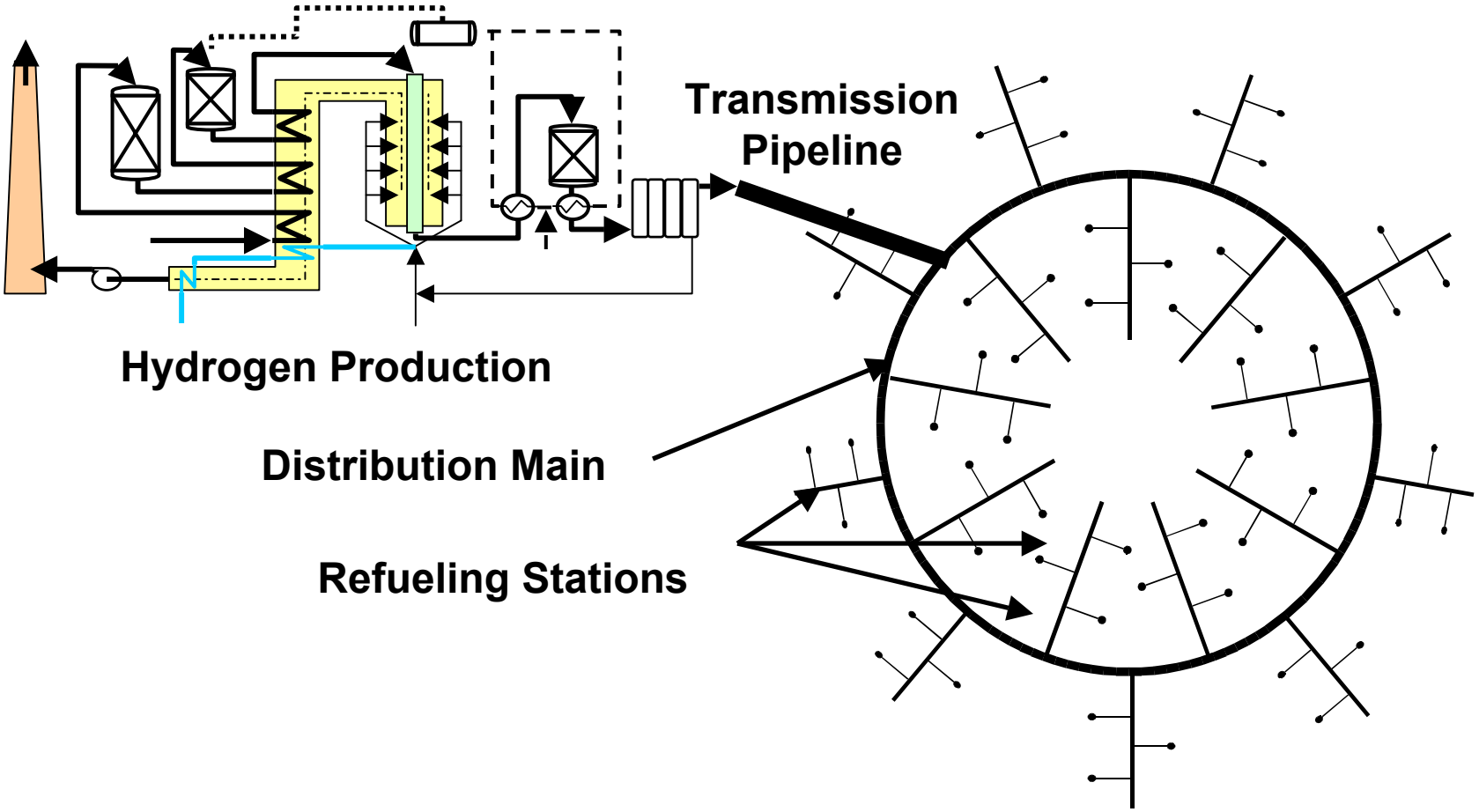
Four Hydrogen Pathways Were Modeled



Both Natural Gas Pathways Required Additional NG Transmission and Storage



Conceptual Representation of Hydrogen Pipeline Loop Supporting Local H_2 Delivery



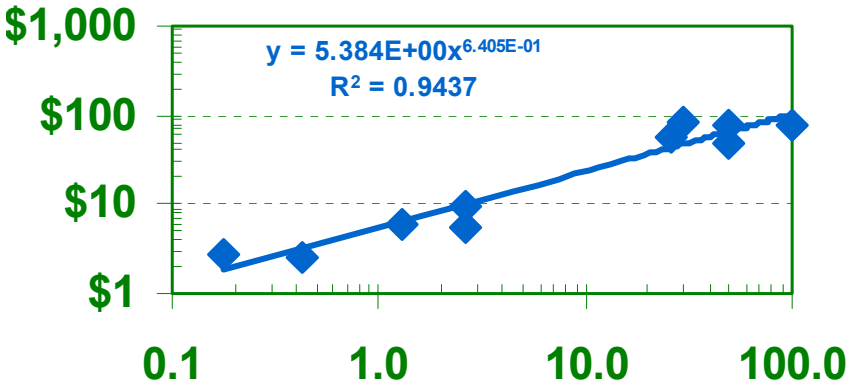
Hydrogen Distribution Assumptions for Centralized Hydrogen Production

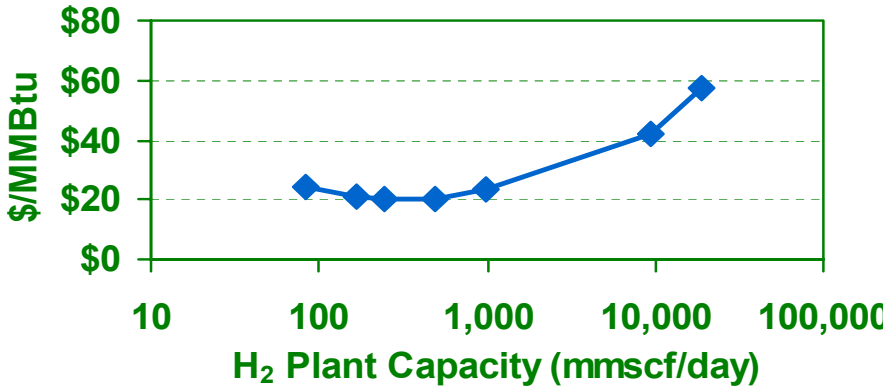
Component	Unit Cost ($/mi)	Diameter (in)	Length (mi)
H_2 Pipeline Connecting Pipeline Ring with H_2 Production Plant	$1,000,000	12	100
H_2 Pipeline Ring Encompassing Community	$1,000,000	12	157
H_2 Pipeline Connecting H_2 Refueling Stations with H_2 Pipeline Ring	$400,000	3	900 [a]

[a] Assumes 180 refueling stations, a service pipeline unit length of 15 miles, and 3 refueling stations per service pipeline.

Trading Off SMR Economies of Scale with Pipeline Costs Produced a "Large Market Centered" Case

- Plotting construction cost (10^6 \$) vs. capacity (tpd, 100t=37 mmscf) of steam methane reforming plants shows strong economies of scale (note log scale).
- For a given delivery volume, plotting relatively few high-output plants with more pipeline mileage vs. more low-output plants with less pipeline mileage shows the dependence of unit cost (in \$/mmBtu) on the combination of production scale and transport cost.





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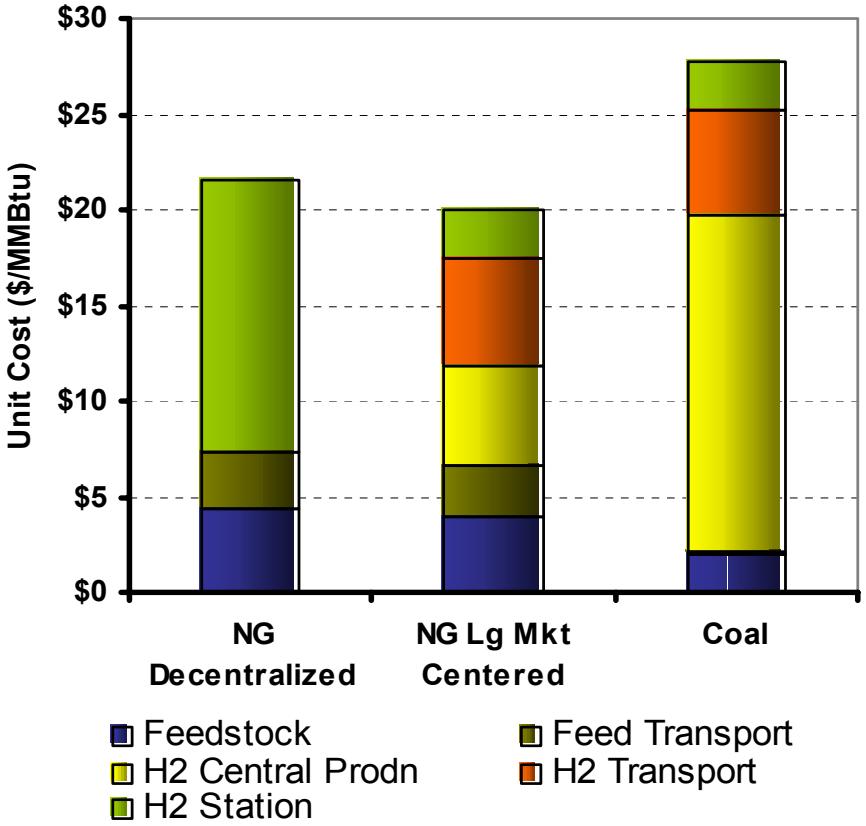
Cost Modeling Procedure

- Define paths
  - ✓ North American (NA) or non-North American (NNA) natural gas
  - ✓ NG production, compression, storage and transport; conversion to alternative fuel, transport and dispensing
- Determine "tank-in" fuel requirement
  - ✓ Market penetration
  - ✓ Vehicle and pathway efficiencies
- Size pathway components
- Estimate component costs
- Calculate pathway costs (NICC model)

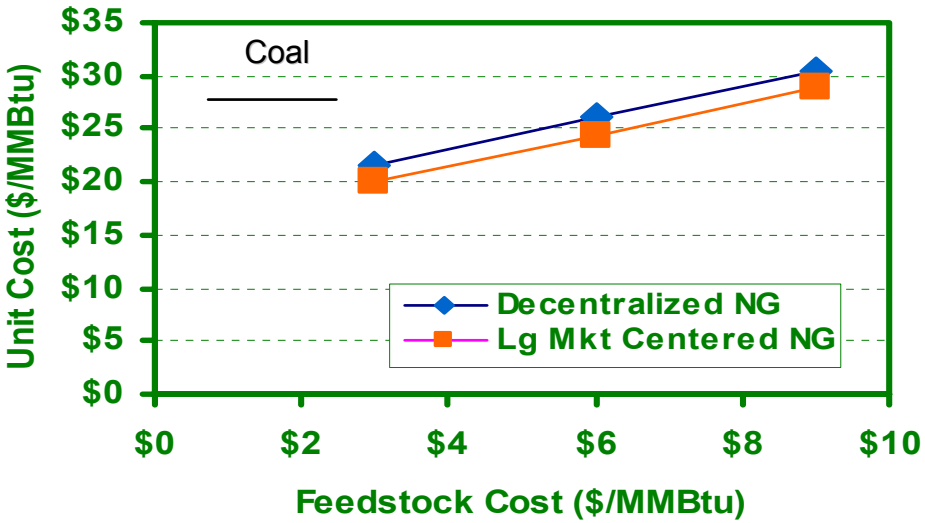
With Current Technology, Unit Cost of GH_2 in All Pathways Is $20-27/mmBtu

- Feedstock accounts for about 20% of delivered cost in both NG-based pathways; less than 10% in coal pathway.
- In Large Market-Centered pathway, hydrogen production and transport (assuming 100 mi average distance) account for 54% of delivered cost.
- In Decentralized pathway, station cost (production and refueling) accounts for 66% of delivered cost.
- In Coal pathway, gasification accounts for over 60% of delivered cost.



NG-Based Pathways Are Sensitive to Feedstock Cost, Coal and Nuclear Are Not

- Delivered cost of gaseous hydrogen (GH_2) is $20-23/mmBtu for NG pathways, $27 for coal.
- By comparison, gasoline costs roughly $7/mmBtu, excluding taxes and markups.
- Doubling feedstock cost increases GH_2 cost in NG-based pathways by roughly 25%; virtually nothing in coal pathway.



- Thermochemical water cracking aims to produce GH_2 at 1.5 times SMR. Production cost increment offsets NG transport, making unit cost $20-23.

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Some Conclusions:

- With current technologies, on a well-to-pump basis, the unit cost of hydrogen is likely to be 2-3 times that of gasoline.
- To offset this, the mpge of hydrogen-fueled vehicles must be more than double gasoline.
- H_2 transport and production are the largest components of all paths examined, hence appropriate focus for cost reduction.

Next Steps

Focus on transition

- Total and unit costs through study timeframe
- Penetration of hydrogen blends
- Niche markets

Compare “apples to apples”

- Cost of infrastructure components over time
- Learning curves

Re-examine pathways/scenarios

- Truck, rail, marine market penetration
- Hydrogen carrier pathways

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"Disruptive" Technologies

Personal vehicles
- Coaches, autos, SUV/auto "hybrids"
- ICE, electric drive
- Kerosene, gasoline, RFG, blends

Computers
- Mainframes, tape drives
- PCs, PDAs, CD/DVD
- Internet, LAN, wireless networks

Telecommunications
- Analogue networks, land lines
- Fiber optic networks, wireless

… Evolve Incrementally Over Decades

New Infrastructure May Be Expected to Evolve from Existing:

- Production facilities
- Fuel distribution networks
- Fueling procedures

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