Hydrogen Infrastructure

Pathways for the Transportation Sector

SAE Government/Industry Meeting

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Topics

- Evolution to hydrogen and electricity
- Current hydrogen production
- Alternative hydrogen pathways
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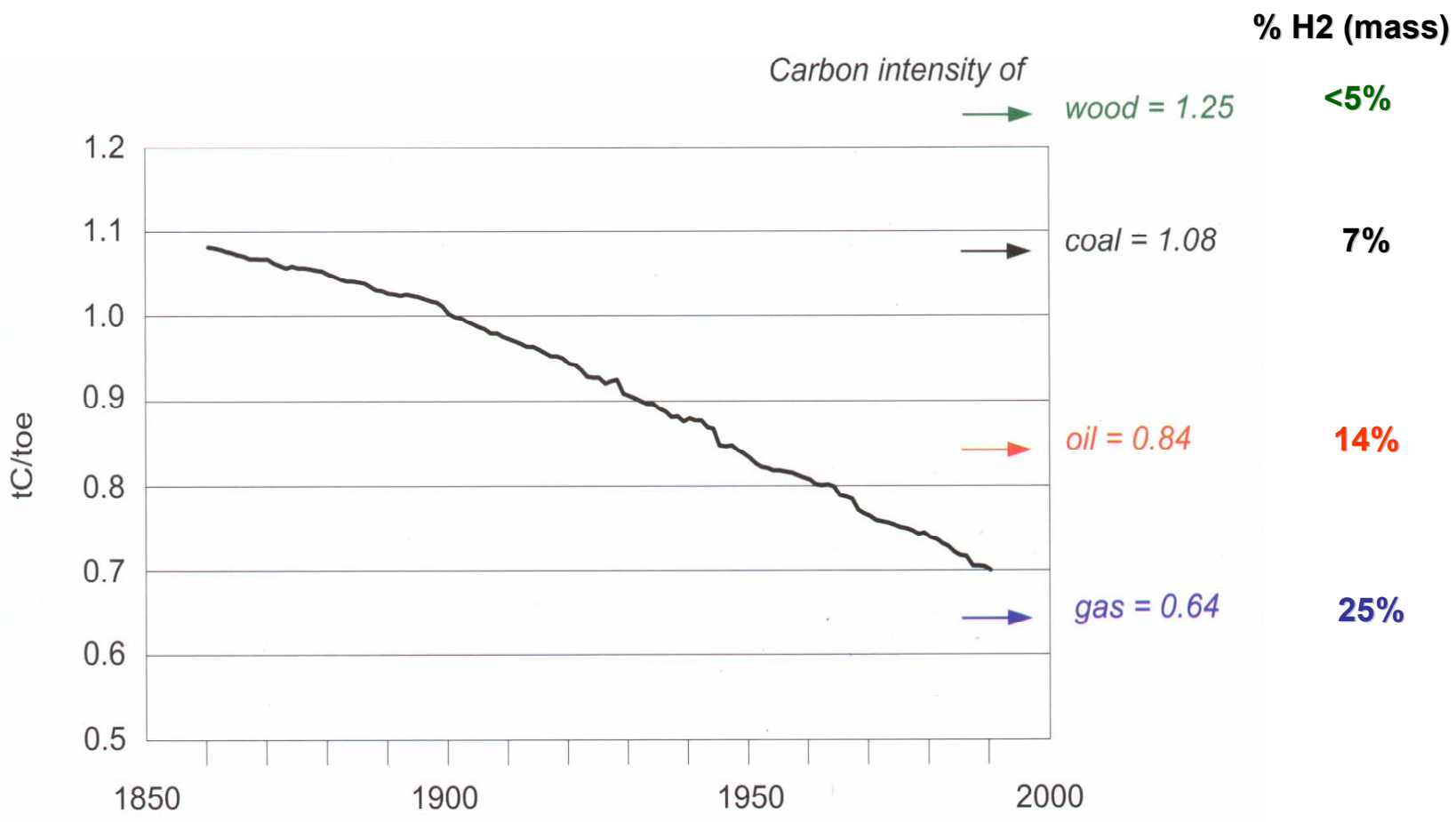
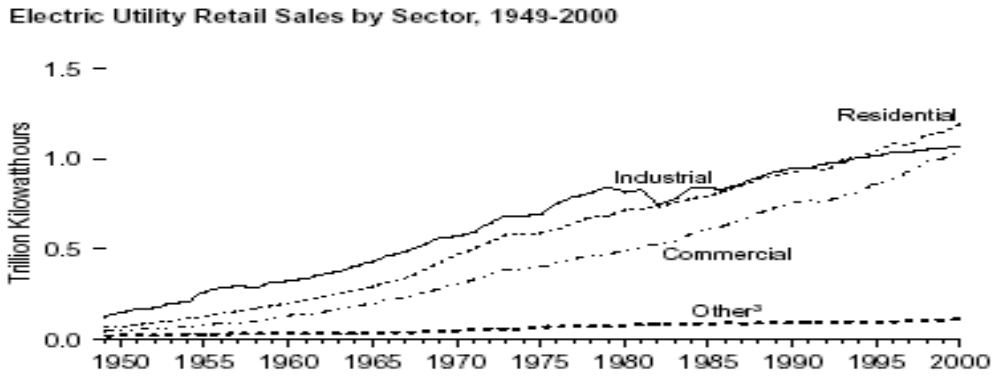
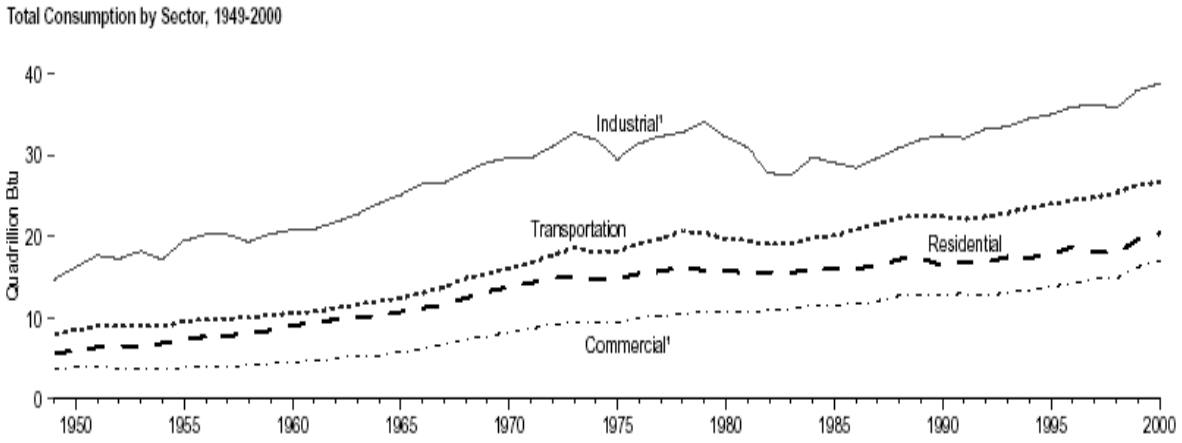
While Carbon Intensity of World Primary Energy Has Been Falling H_2 Intensity Has Grown



Carbon Declines Have Come from Efficiency Gains and Fuel Switches

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



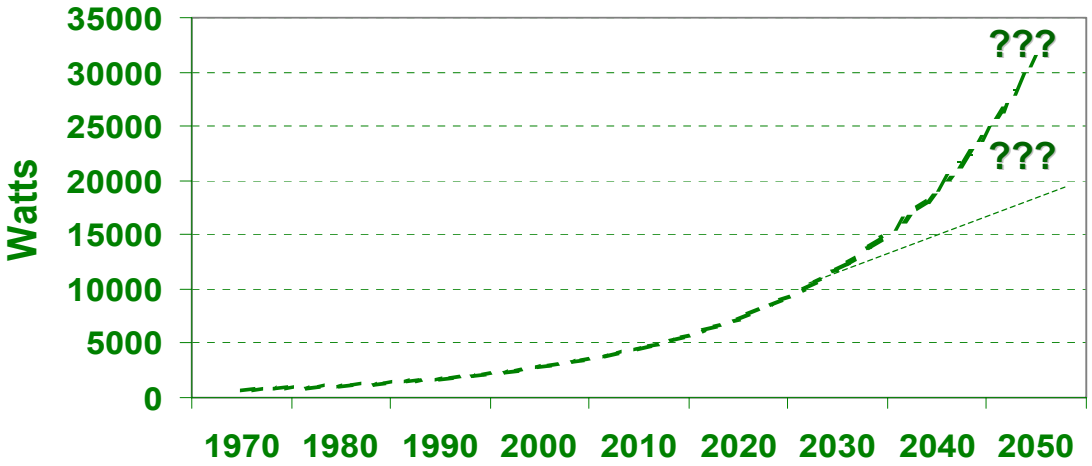


Industry and residential/commercial sectors switched to lower-carbon natural gas and electricity. Transportation remains almost completely oil dependent, but …

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???)

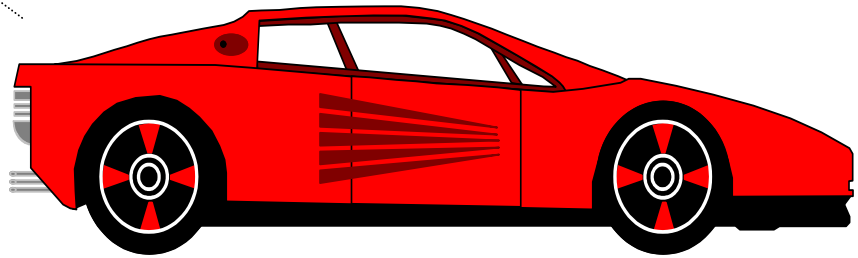
Fuels Could Also Evolve – With or Without On Board Reforming

Gasoline

CNG ??

CNG/Hydrogen ?

Hydrogen



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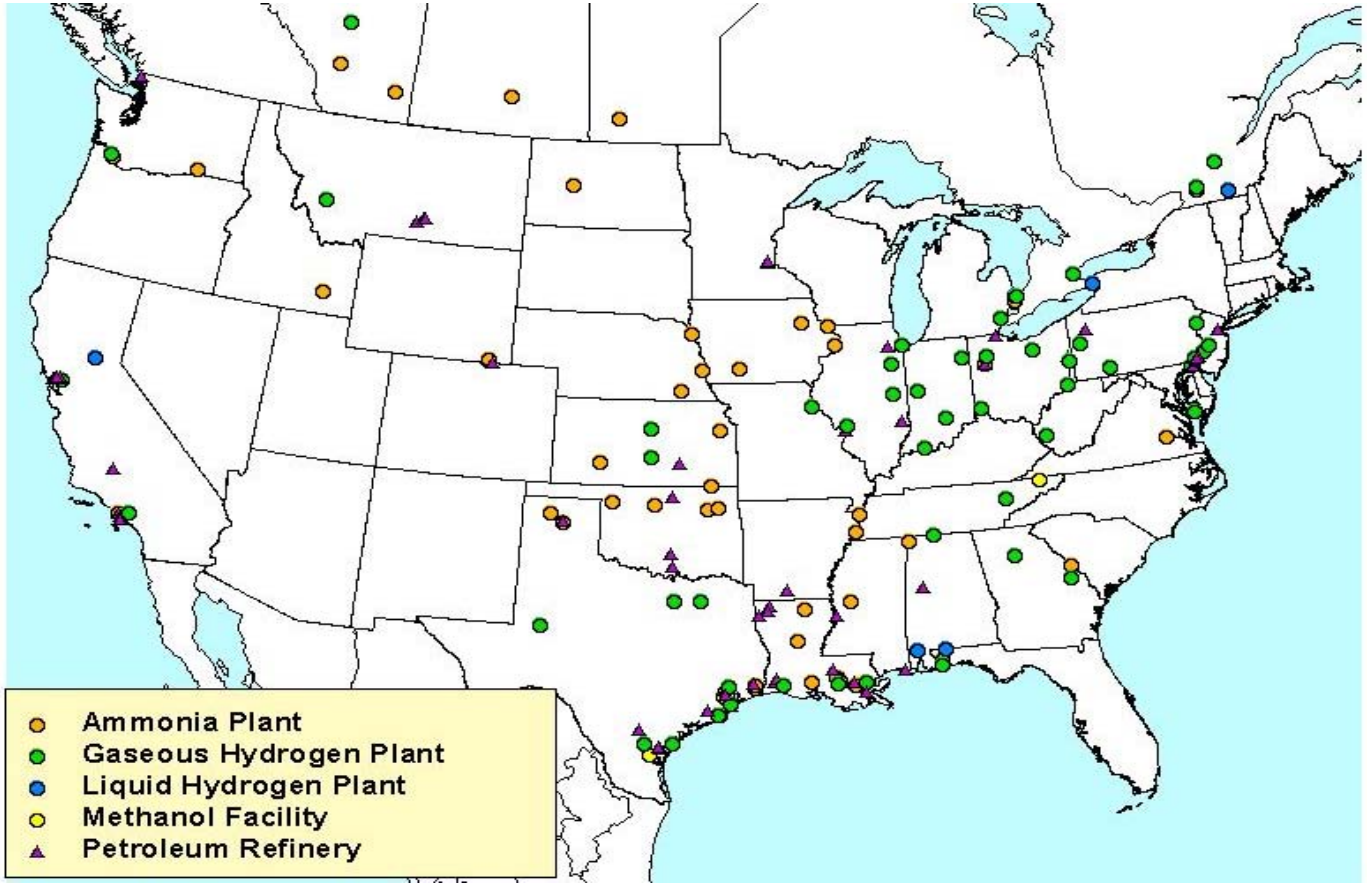
In 1999 the US Accounted for 3.2 tcf (1 quad) or 20% of Global H_2 Consumption

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.

Hydrogen Production Is Concentrated in Refining Centers and the Farm Belt



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

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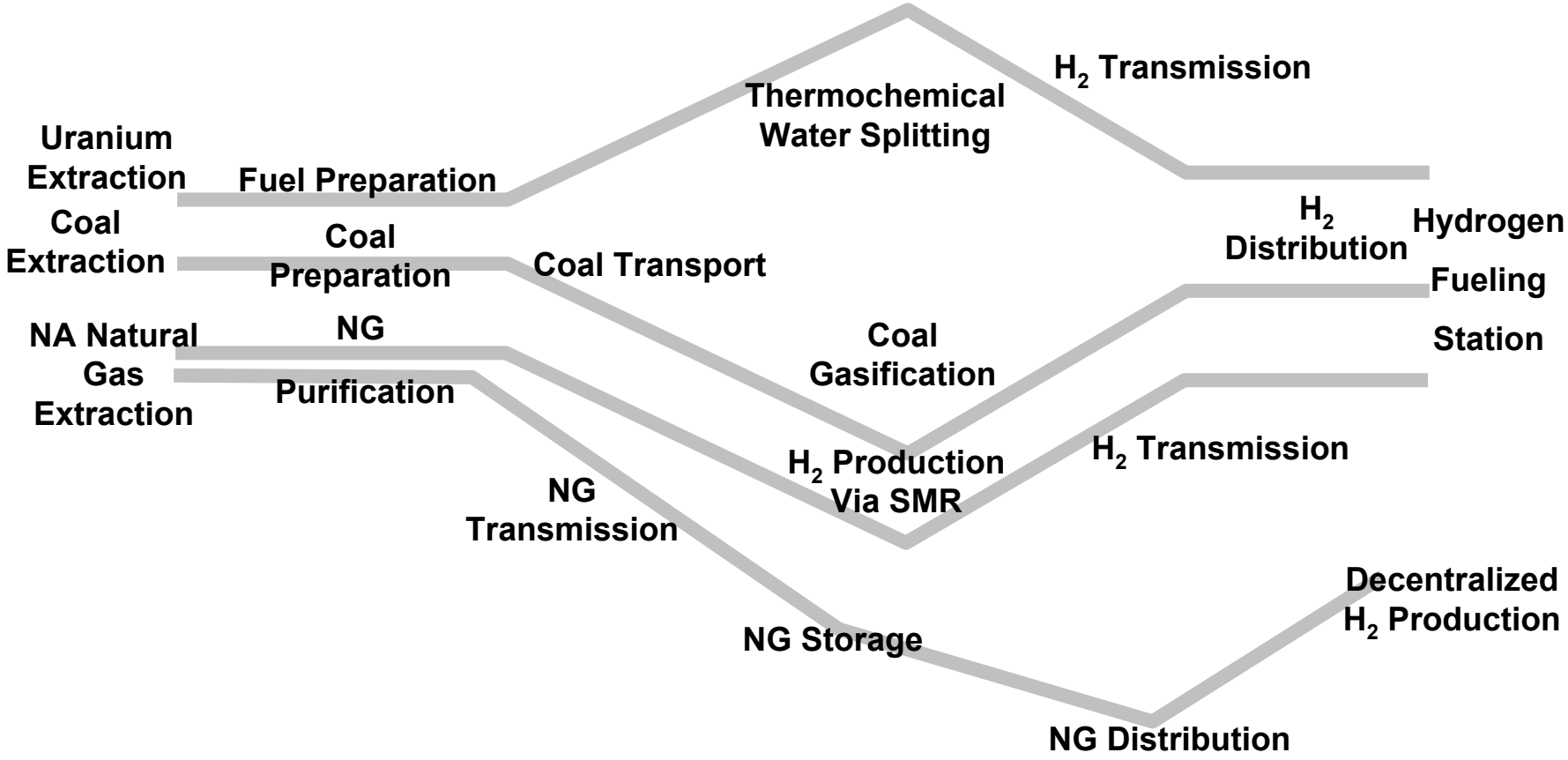
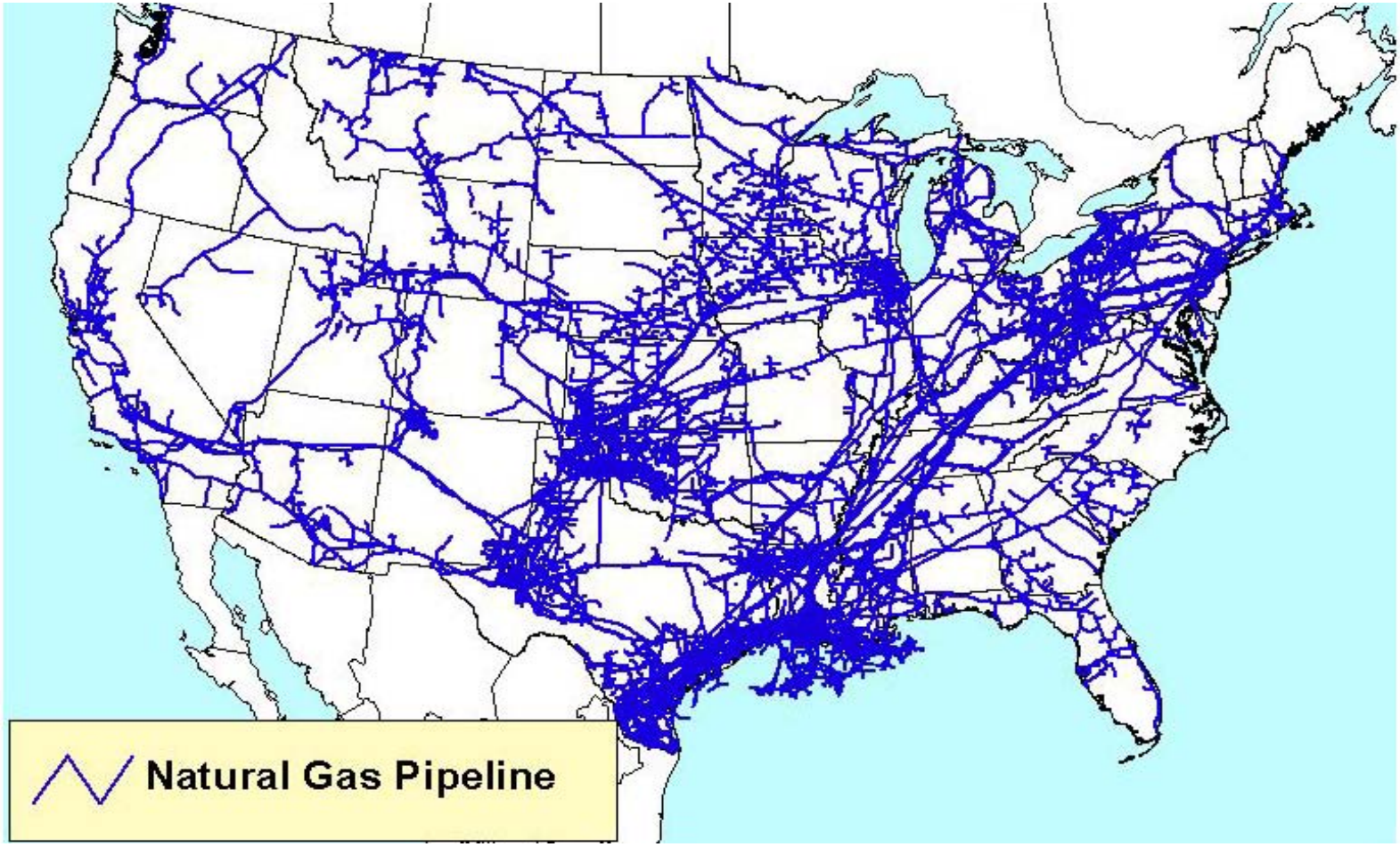
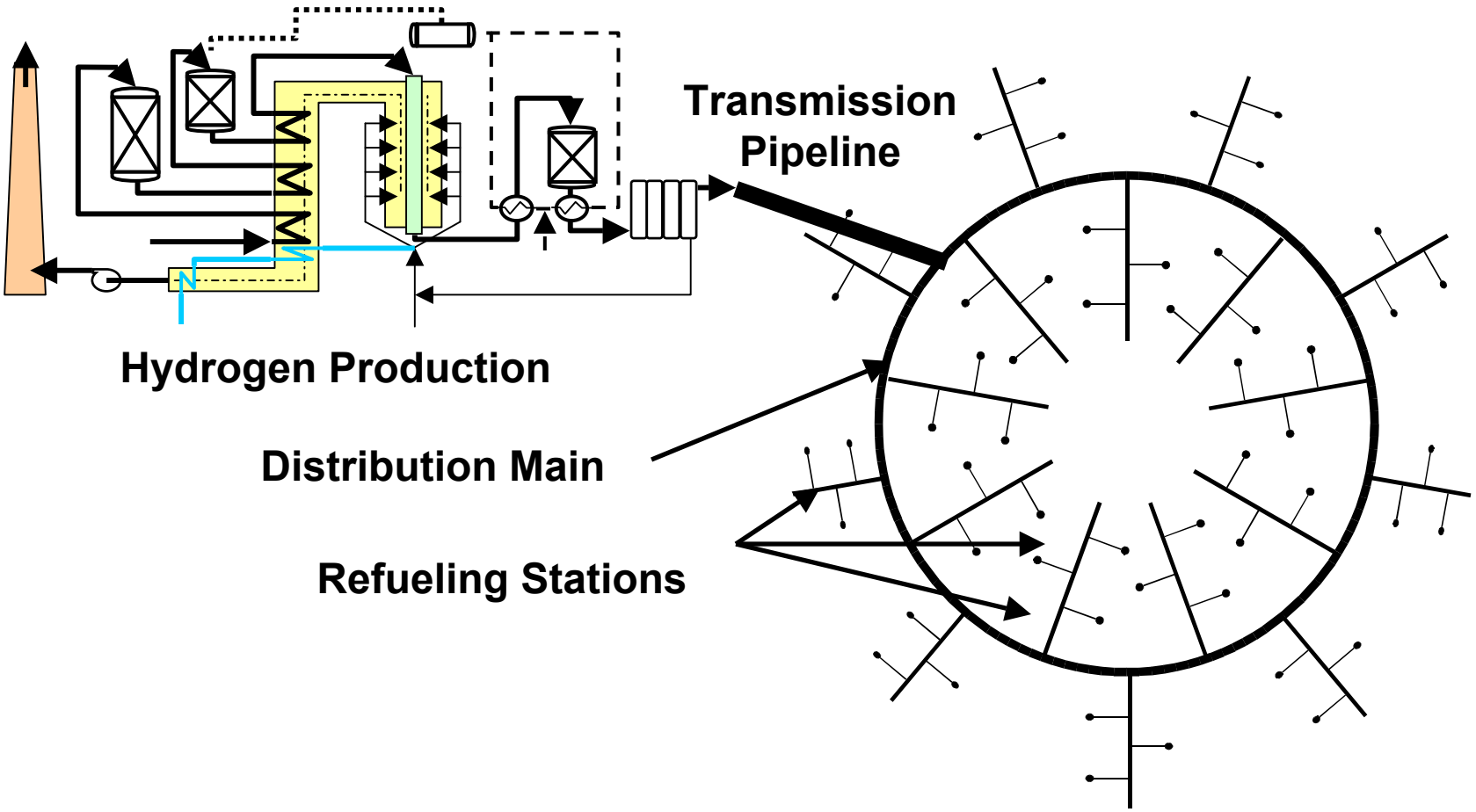
Four Hydrogen Pathways Were Modeled



Despite an Extensive Network, NG Pathways Require Additional Transmission and Storage



Conceptual Representation of Hydrogen Pipeline Loop Supporting Local H_2 Delivery



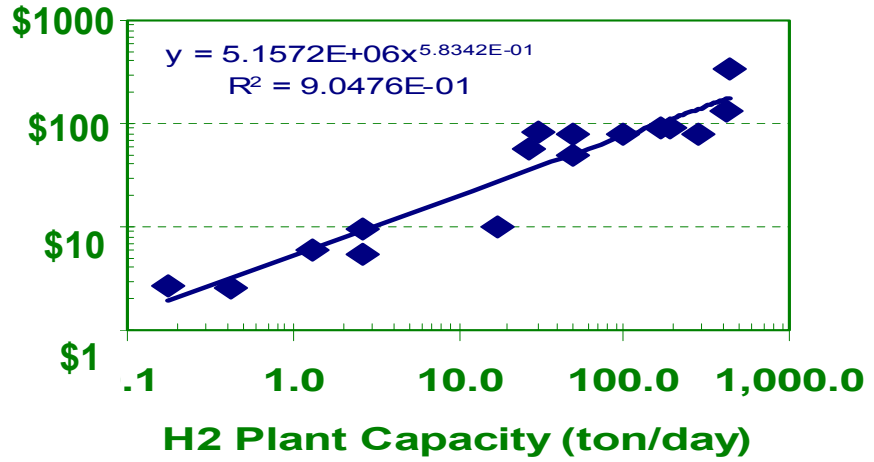
Hydrogen Distribution Assumptions for Large Market Centered H_2 Production

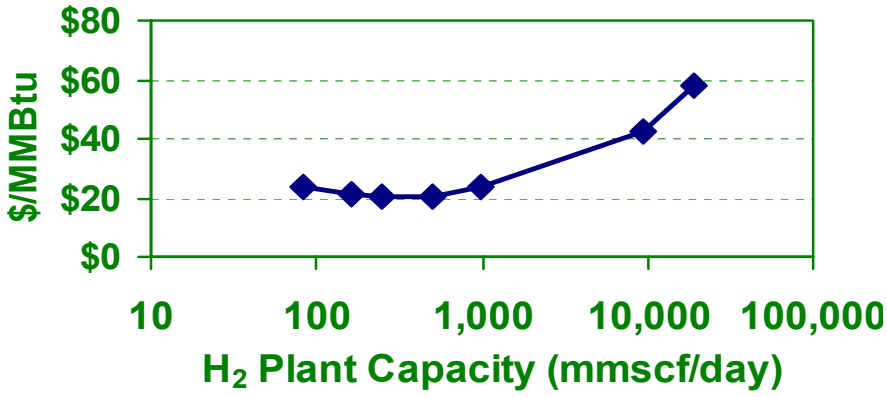
Component	Unit Cost ($/mi)	Diameter (in)	Length (mi)
H_2 Transmission Pipeline Connecting Pipeline Ring with H_2 Production Plant	$1,000,000	12	100
H_2 Distribution Pipeline Ring Encompassing Community	$1,000,000	12	157
H_2 Service Pipeline Connecting H_2 Refueling Stations with H_2 Pipeline Ring	$400,000	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

- SMR construction cost (10^6 $) vs. capacity (tpd, 100 t=37 mmscf) shows strong economies of scale (note log scale).
- For a "built out" H_2 delivery volume, 76 relatively high-output plants (with 100 miles of transmission pipelines per plant) resulted in the lowest unit cost ($/mmBtu).





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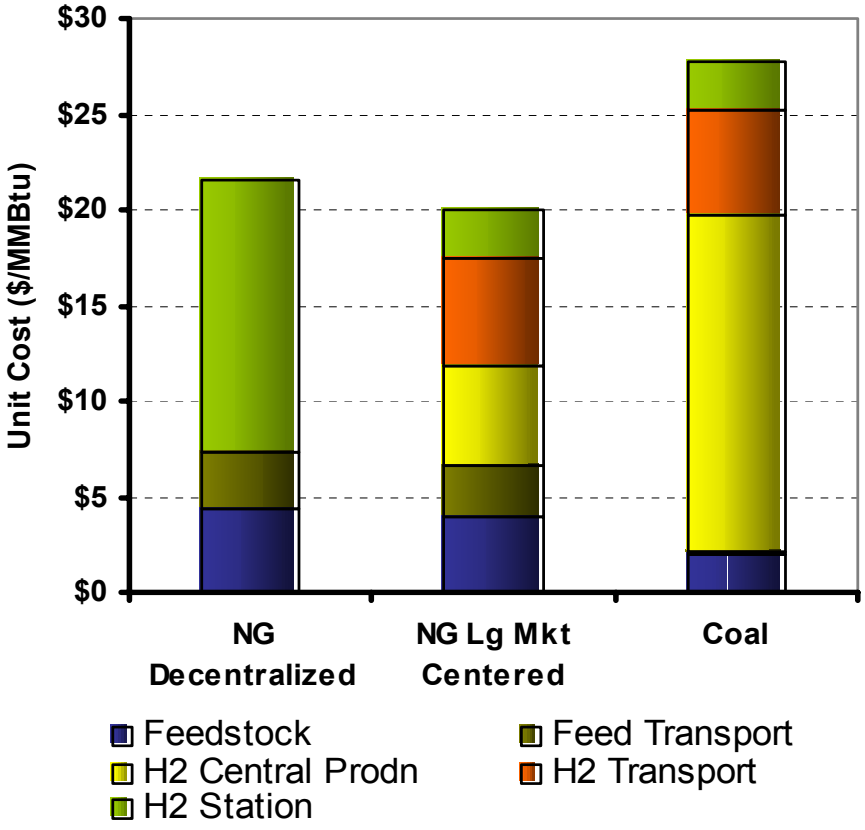
Cost Modeling Procedure

- 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)

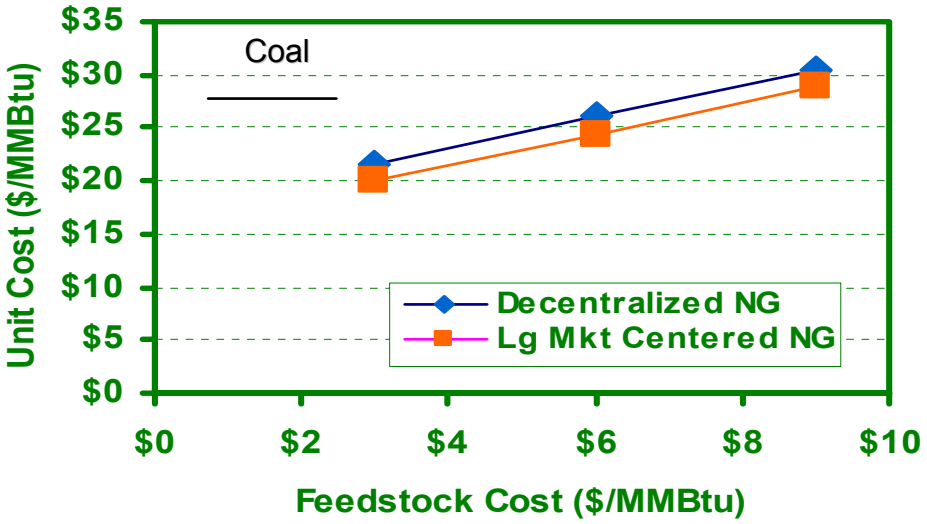
With Current Technology, Unit Cost of GH_2 in All Pathways Is $20-27/mmBtu

- 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

… but be transparent to the consumer and require little incremental adaptation

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