CHAIN: Cost of Hydrogen under Alternative INfrastructures

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Operated by The University of Chicago

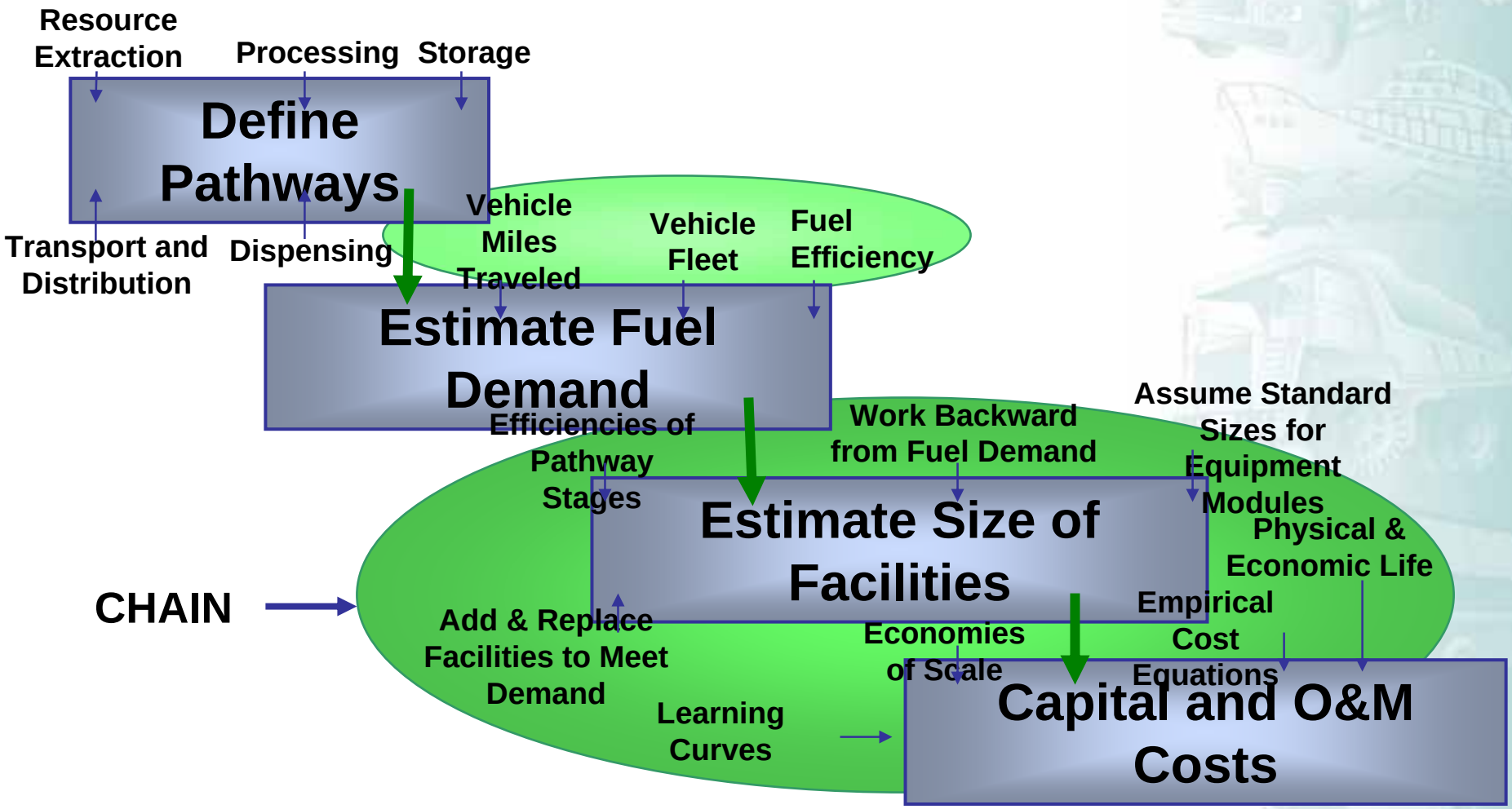
Topics

- **Cost modeling process**
- **"Well-to-pump" pathways**
  - Components
  - Arrangement
  - Key assumptions
- **Illustrative component cost analyses**
- **Results**

"Well-to-Pump" Pathways Include:

- **Feedstock acquisition**
  - Crude oil
  - Natural gas
  - Uranium
  - Coal
- **Feedstock transport and storage**
- **Processing**
  - Petroleum refining
  - Hydrogen production
  - Coal, natural gas or uranium processing
- **Product distribution and storage**
  - Pipelines
  - Compressor stations
- **Dispensing and retailing**

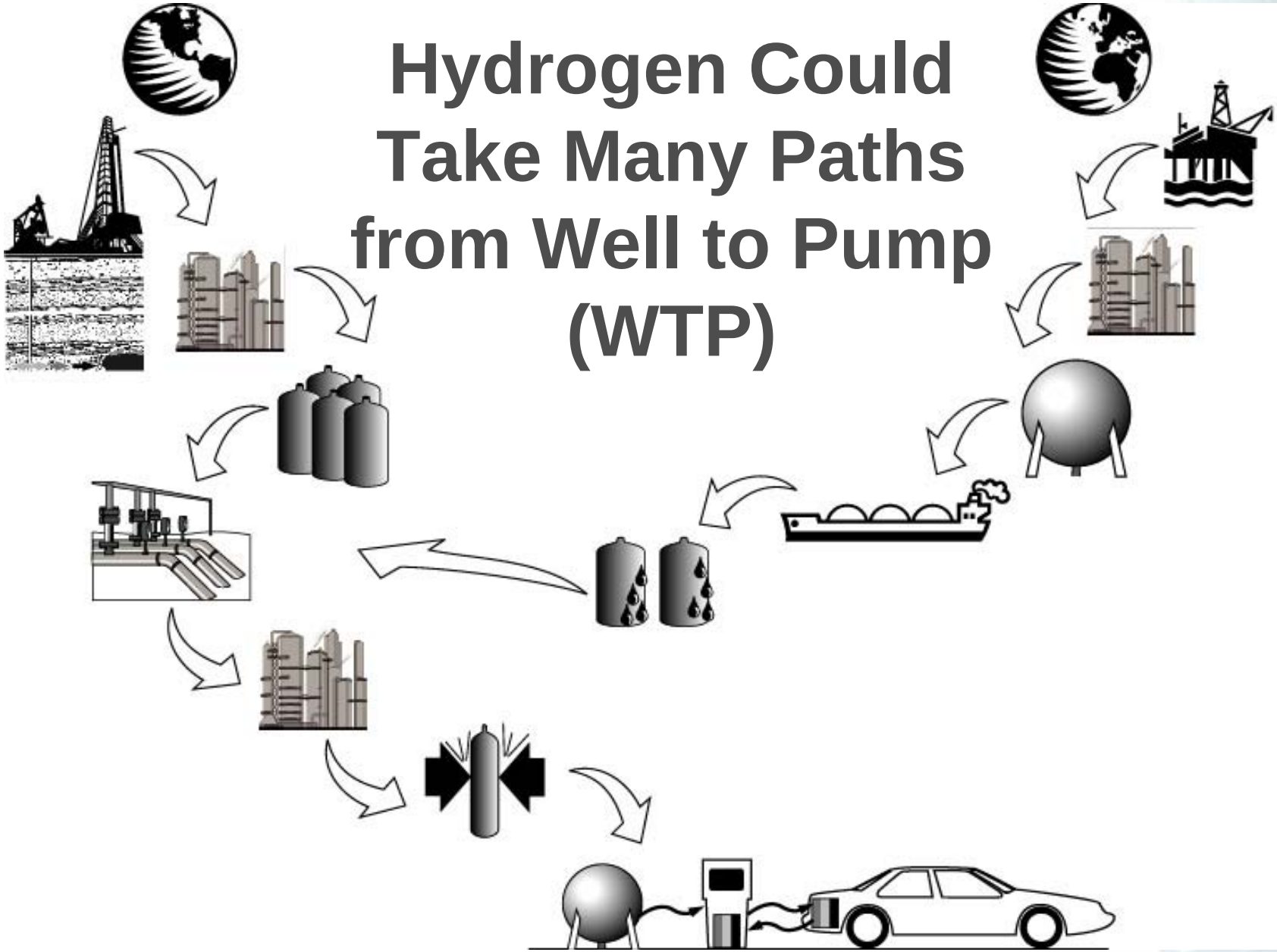
Stock Adjustment and Infrastructure Models Estimate Pathway Costs



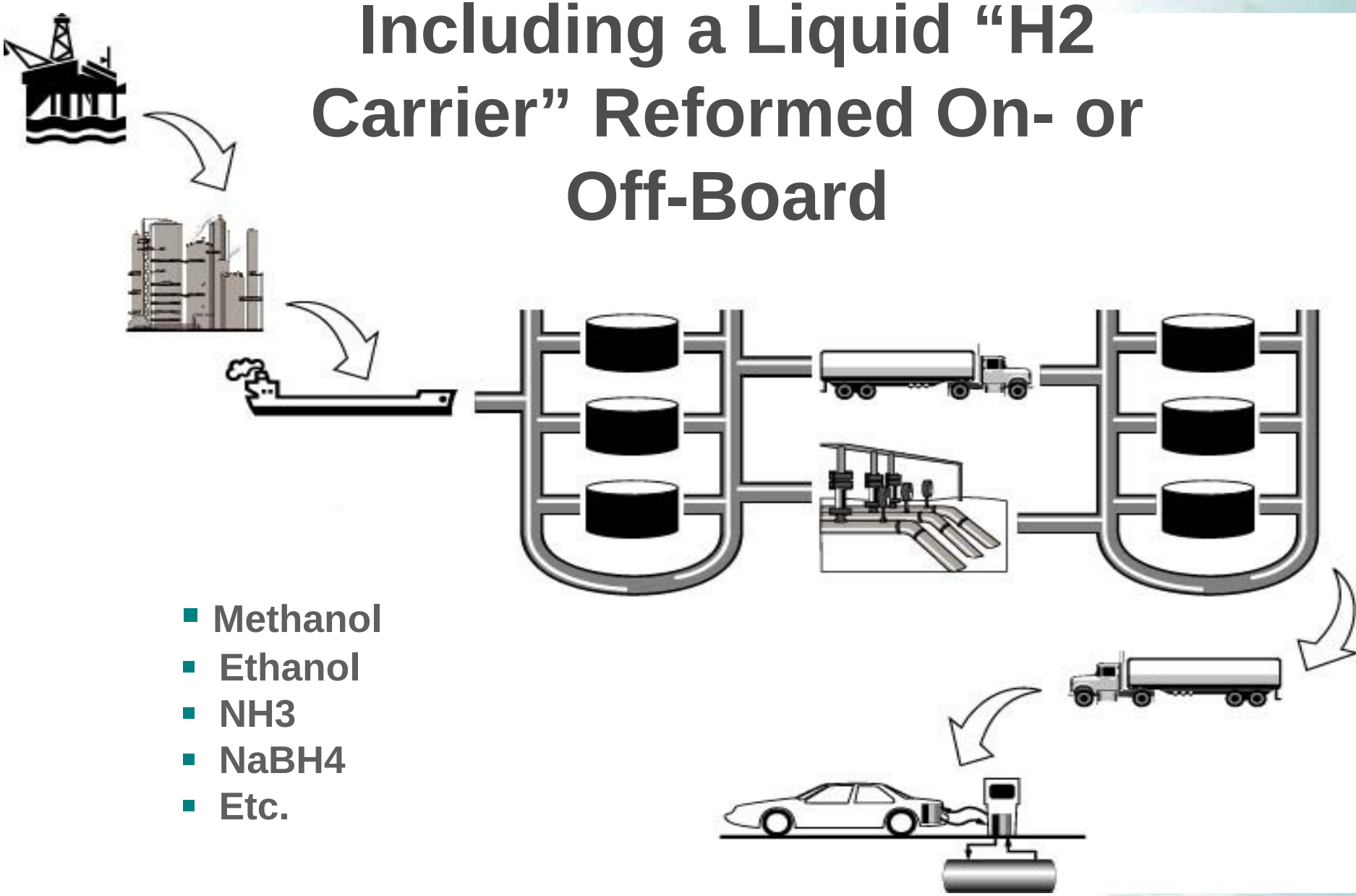
Cost Modeling Is a Five-Step Process

- Define "well-to-pump" (WTP) paths
  - NG compression, storage and transport
  - Hydrogen production
  - H_2 compression, storage and transport
  - Hydrogen dispensing
- Determine "tank-in" fuel requirement
  - HFCV market penetration & efficiency
- Size pathway components
- Estimate component costs
- Calculate pathway costs (CHAIN model)

Hydrogen Could Take Many Paths from Well to Pump (WTP)

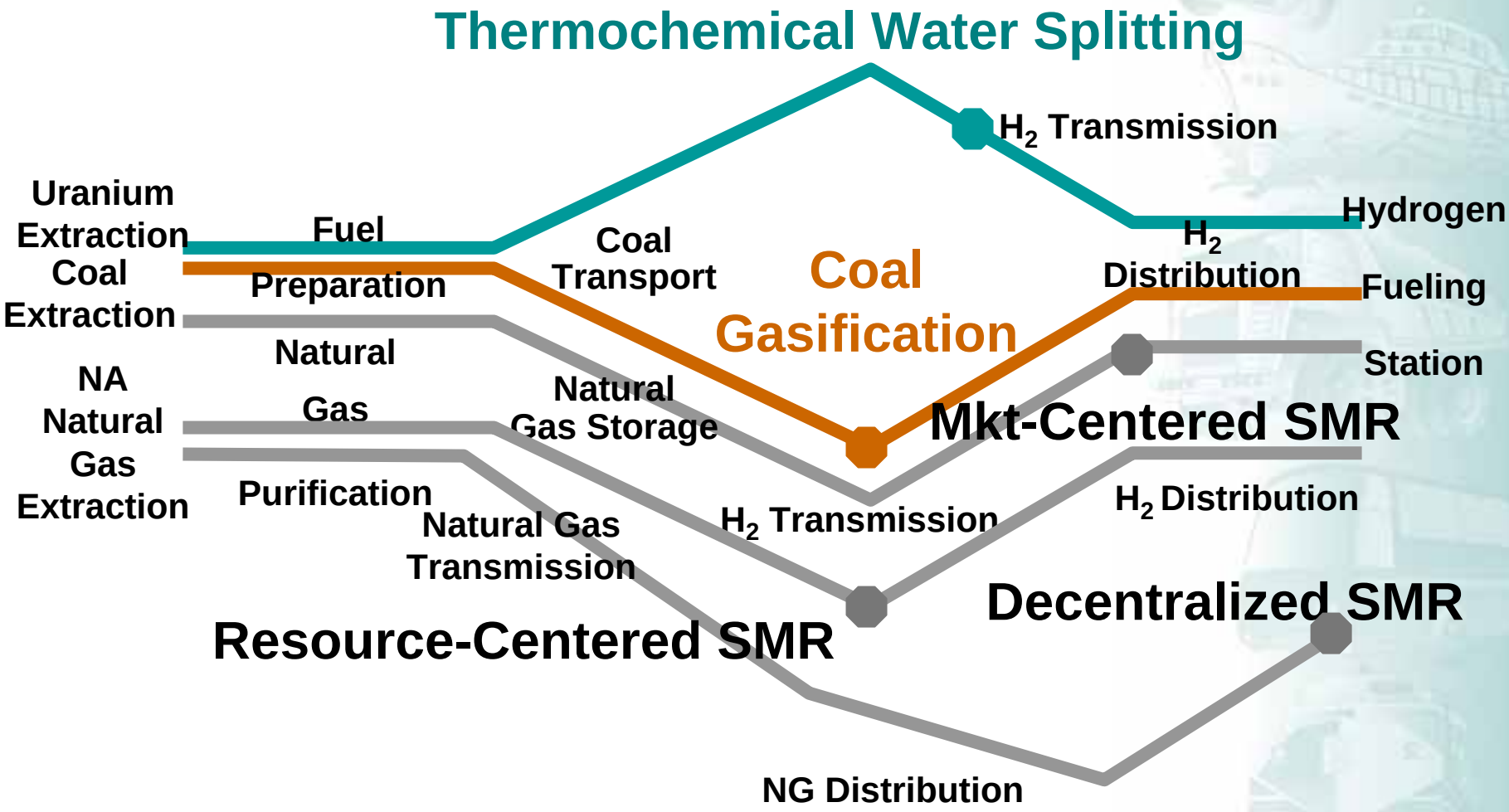


Including a Liquid “H2 Carrier” Reformed On- or Off-Board

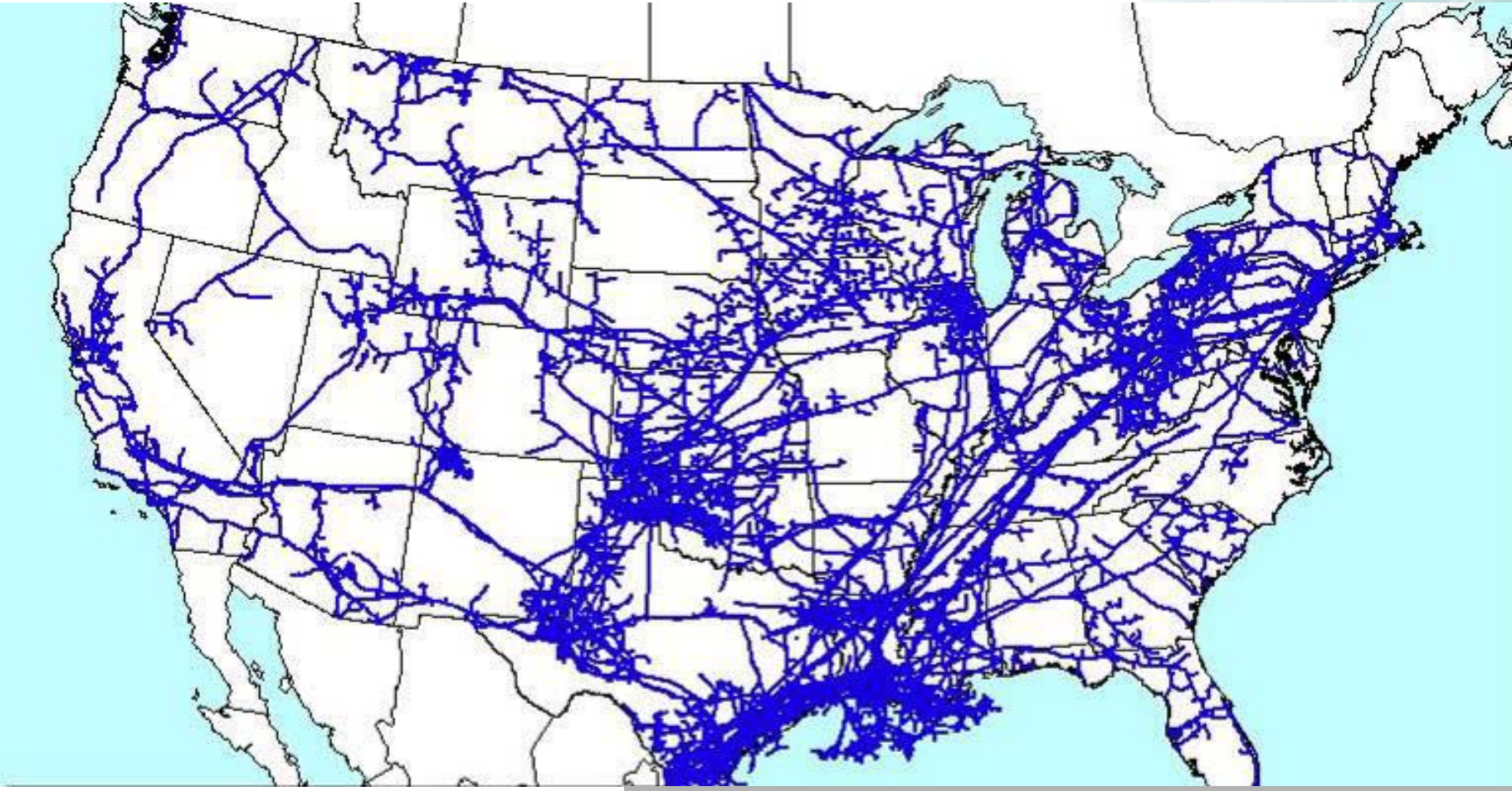


- Methanol
- Ethanol
- NH3
- NaBH4
- Etc.

Infrastructure Costs Have Been Estimated for Several Pathways



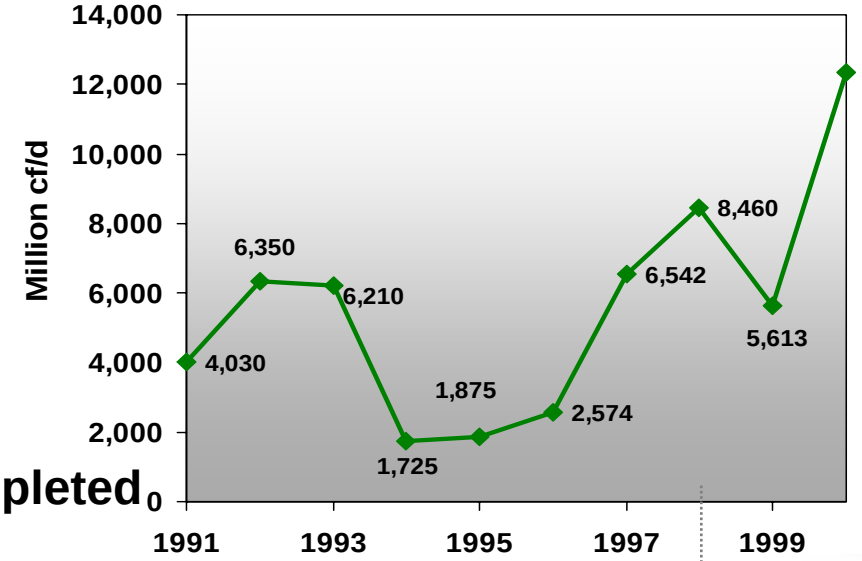
Natural Gas-Based Pathways Require Additional NG Transmission Lines

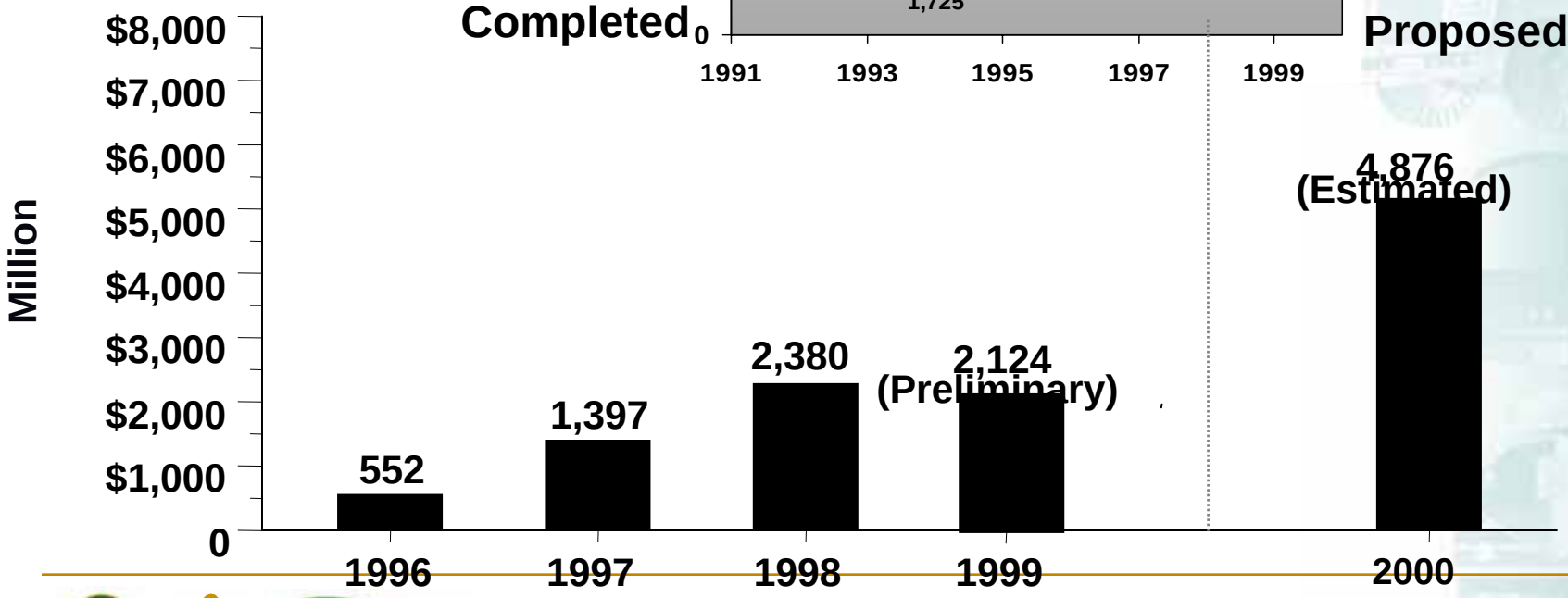


The US has an extensive in-place NG transmission infrastructure …..

And a Track Record of Continually Expanding Capacity (line & compression additions, looping)

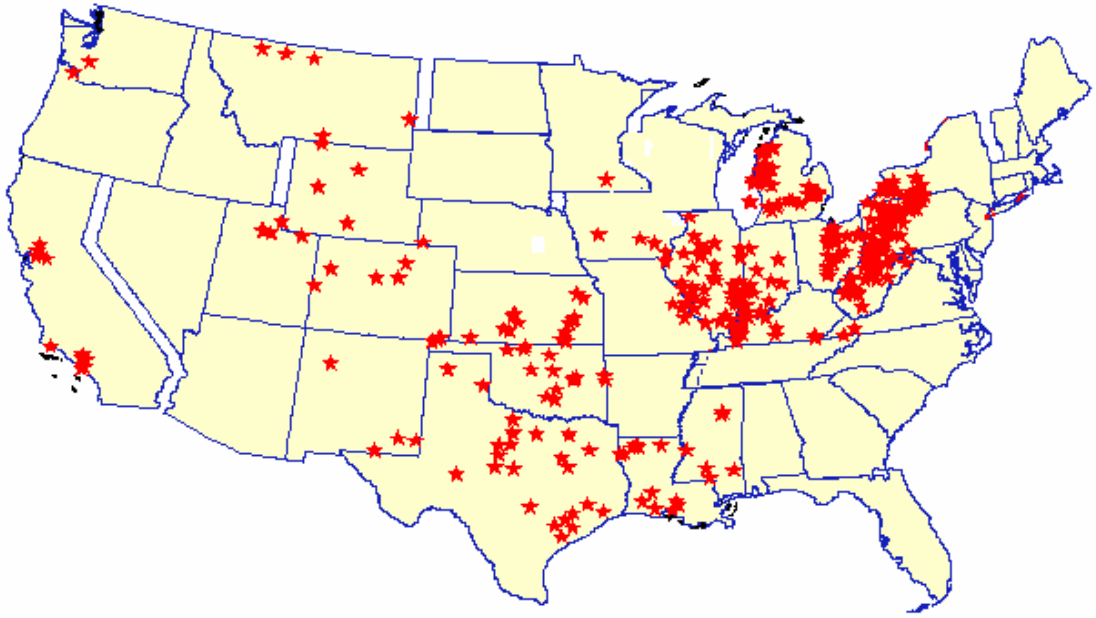
Since the mid-1990's transmission capacity has grown by > 4 bcf/d each yr





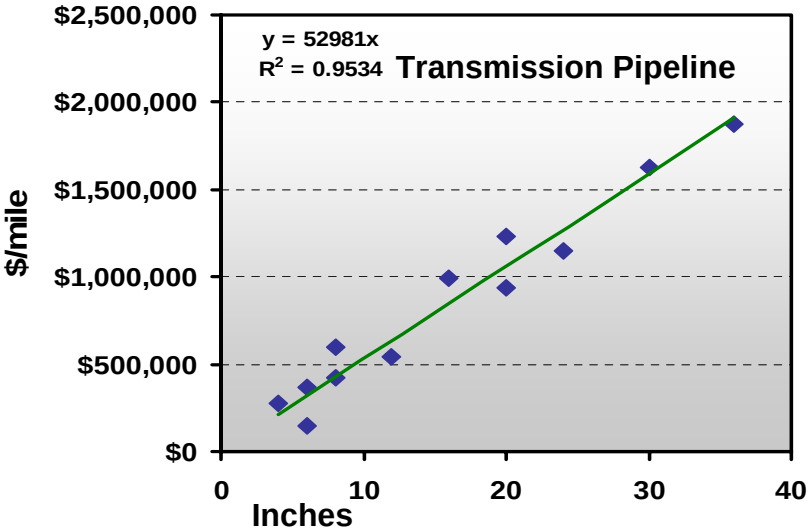
And Underground Storage

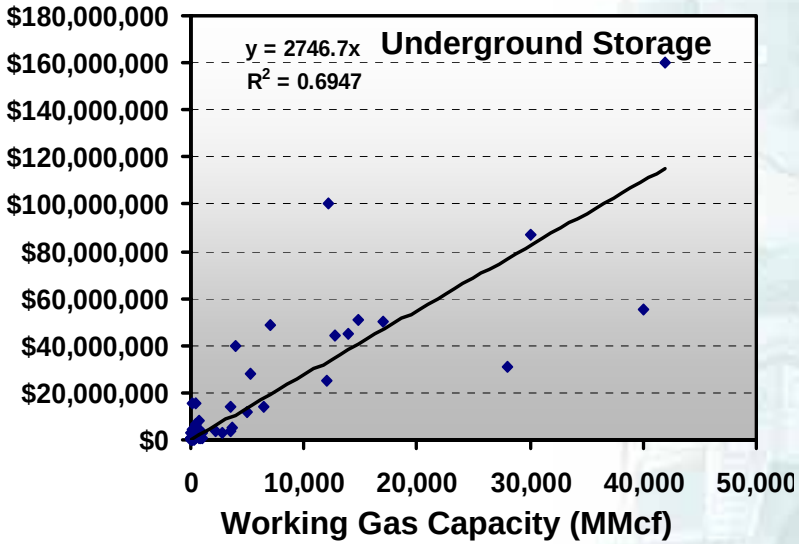
At the end of 1998 there were 410 underground natural gas storage sites in the U.S.

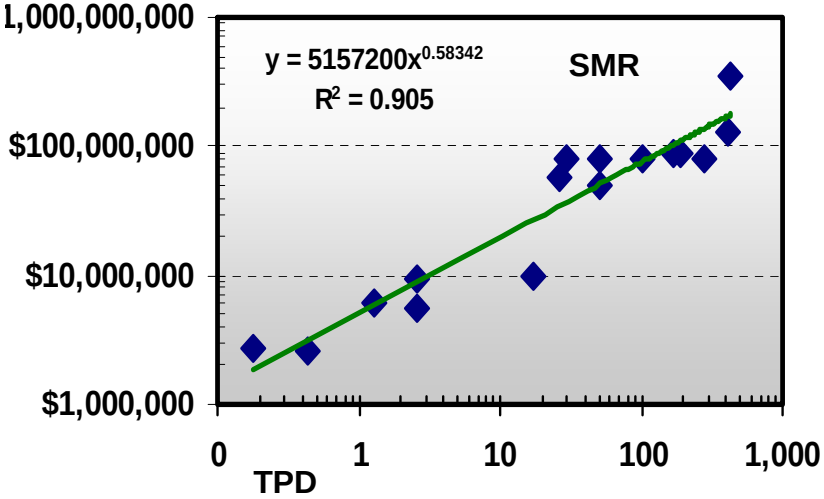


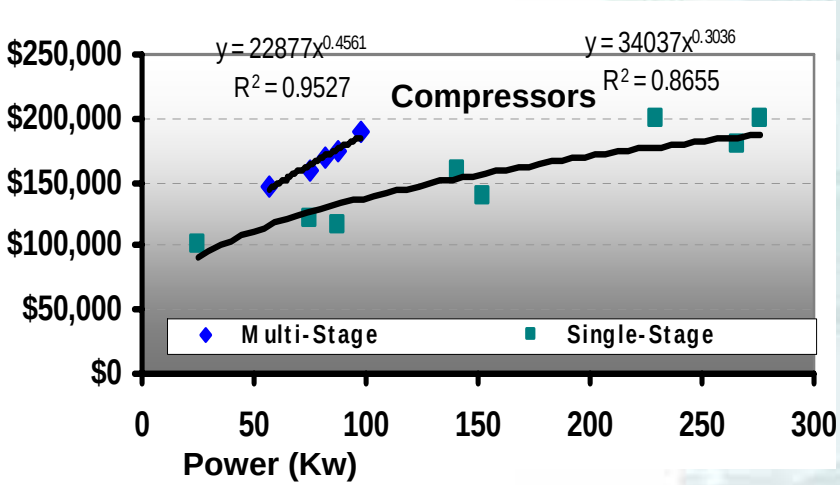
With 76 Bcf per day of Withdrawal Capability and 3,933 Bcf of Working Gas Capacity

Equipment/Facility Sizing Are Critical for Estimating Scale Economies

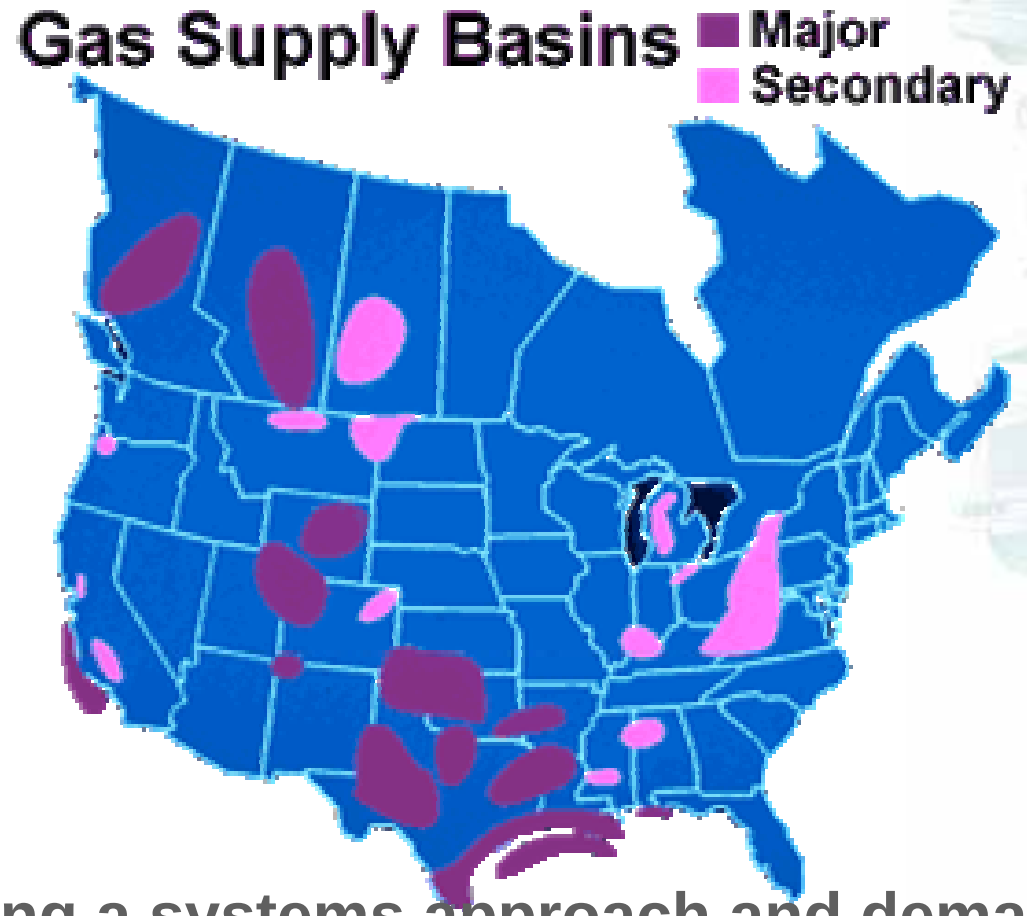






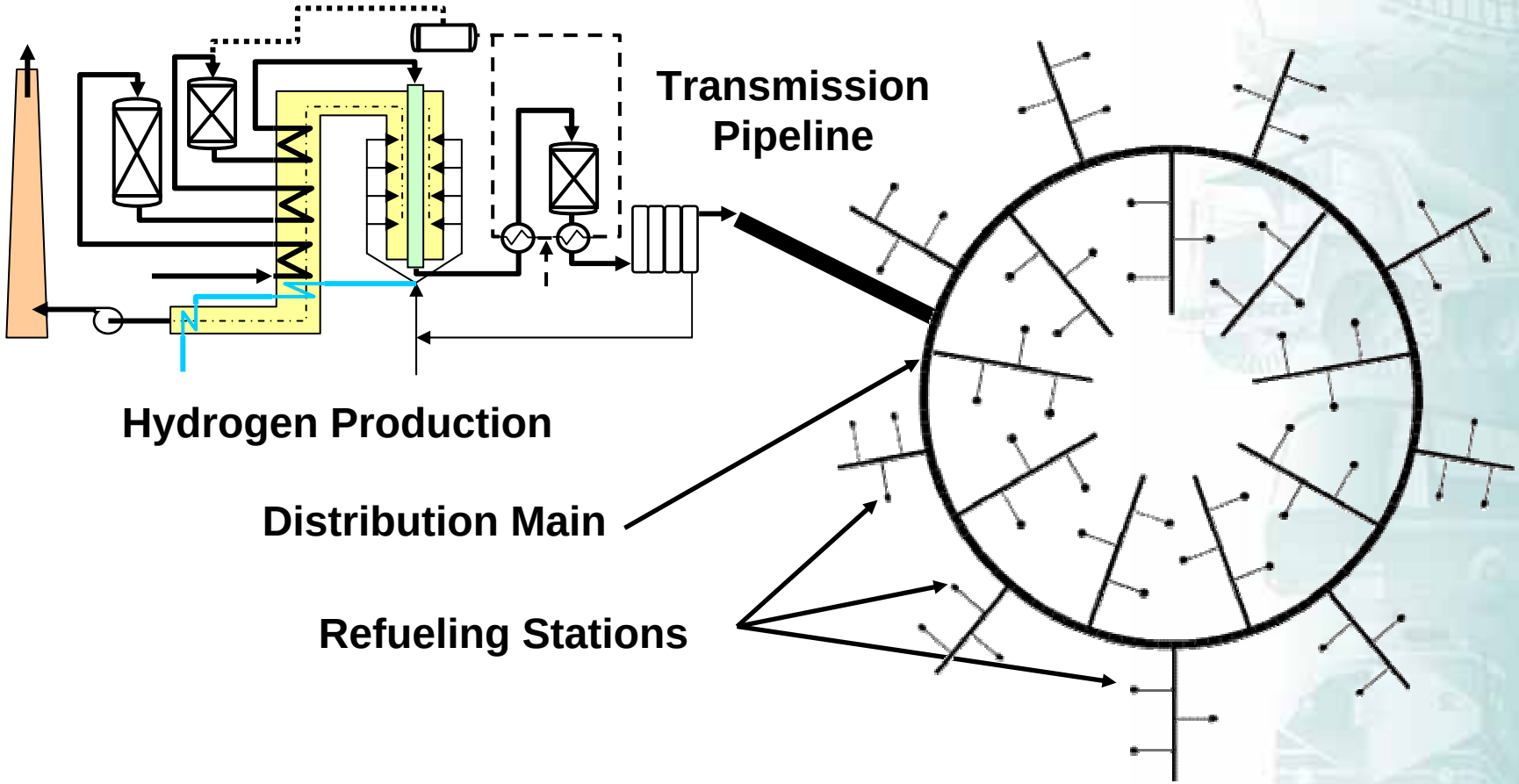


But Scale Economies May Be Offset by Increased Transport Costs



Necessitating a systems approach and demand analysis

In CHAIN Pipelines Support Local Hydrogen Delivery in Centralized Pathways



Results are Sensitive to Production Volume and Feedstock Cost

Efficiency Increase of H_2 Fuel Cell Vehicles Relative to Conventional Vehicles (nX)	*3.000*	← *Please Input!*
NOTE: General cases are 2.25X, 2.755X, and 3X.		

Energy efficiency of NG-to-H_2 reforming by SMR	*72%*	← *Please Input!*

Natural Gas Cost ($/million Btu)	*$3.00*	← *Please Input!*

Number of H_2 Production Plants in U.S. at year 2050???	*228*	←	*Please Input ONLY any of the following numbers: 1, 2, 19, 38, 76, 114, or 228*	
H_2 Plant Capacity (thousand scf/d H_2)	207,200	HIGH	578	TPD H_2
	104,700	LOW	292	TPD H_2
	1.72E+13	scf/yr	*LOW*	
	8.71E+12	scf/yr	*HIGH*	

Ratio of Baseline Length of H_2 Transmission Pipeline	*0.6*	→	No. of Major Communities Served per H_2 Plant	1
			Miles of H_2 Pipeline Between Plant and Community	18

Assumed Total Mileage of Pipeline (natural gas plus hydrogen)	*1,000*	→	Miles of NG Transmission Pipeline	982
			Miles of H_2 Pipeline Between Plant and Community	18
			NG Infrastructure Required?	YES

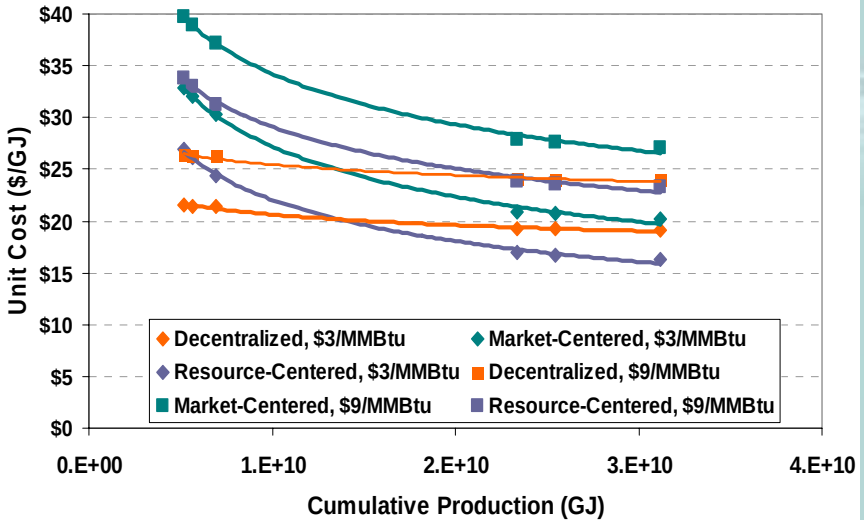
Base Year for Discounting Costs	*2000*	← *Please Input!*
Assumed Economic Life (years)	*20*	← *Please Input!*

General Inflation Rate	*2.7%*	← *Please Input!*
Corporate Income Tax Rate	*38%*	← *Please Input!*
After-Tax Real Rate of Return	*10%*	← *Please Input!*
After-Tax Rate of Return (including inflation)	13%	
Pre-Tax Rate of Return (including inflation)	21%	

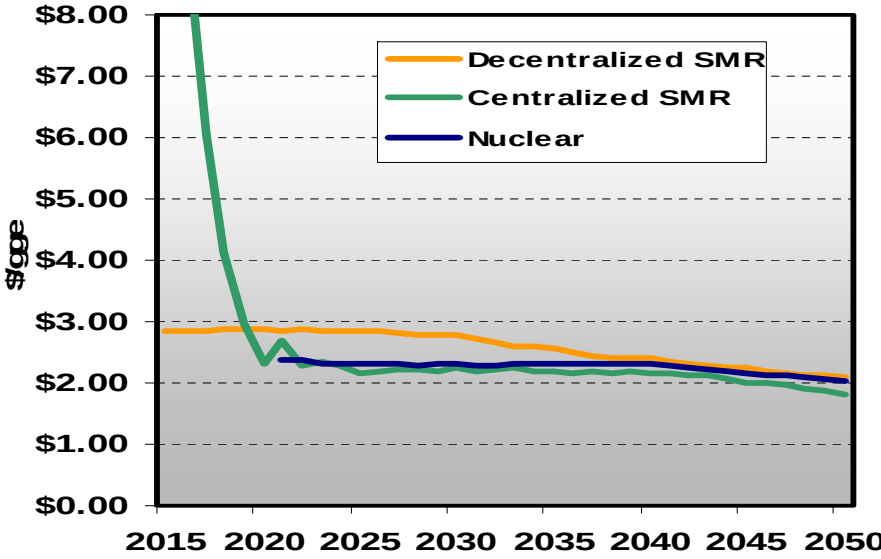
Which method to estimate discount rate?	*1*	← *Please Input!*
Discount Rate (%)	10%	

In the above, please indicate which discount rate should be used: "1" for the "After-Tax Real Rate of Return"; "2" for the "After-Tax Rate of Return (inc. inflation)"; "3" for the "Pre-Tax Rate of Return (inc. inflation)"

H2 Delivered Cost Varies by Pathway and Feedstock Price



Annualized H2 Cost Declines with Scale and Investment Amortization



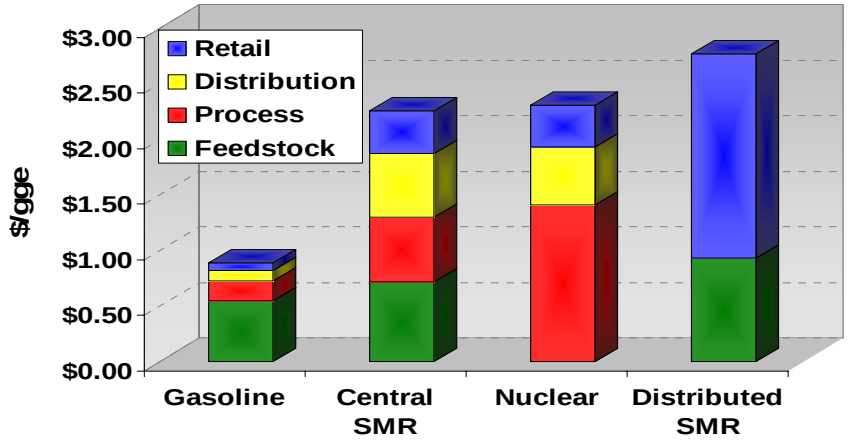
CHAIN Assumptions and Sources Are Documented in the Model

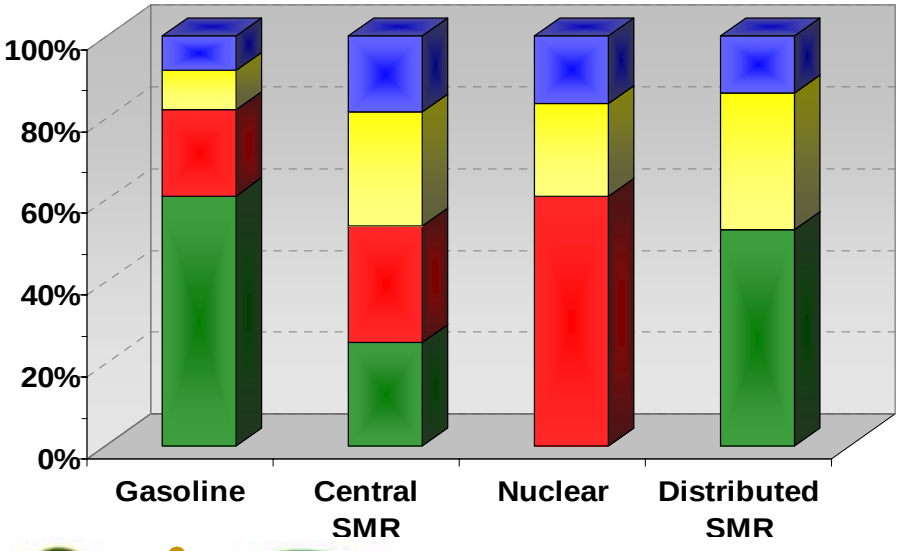
Component	Economic Lifetime (years)	Source / Reference
NG Underground Storage Facility	**20**	A value of 20 years is recommended for "Pipelines and Related Storage" (SIC Code 492-20) based on http://www.window.state.tx.us/taxinfo/proptax/faguide00/sic1.html
NG Transmission Pipeline	**20**	A value of 20 years is recommended for "Pipelines" (SIC Code 4923) based on http://www.window.state.tx.us/taxinfo/proptax/faguide00/sice_f.html
NG Distribution Pipeline	**20**	A value of 20 years is recommended for "Pipelines" (SIC Code 4923) based on http://www.window.state.tx.us/taxinfo/proptax/faguide00/sice_f.html
NG Compressor Station	**20**	There could be two values for NG compressor stations: 20 years (SIC Code 4923) and 35 years (SIC Code 4922), both based on http://www.window.state.tx.us/taxinfo/proptax/faguide00/sice_f.html. A value of 20 years is assumed, because an economic lifetime of 35 years would be greater than the replacement lifetime of 30 years.
H_2 SMR Production Facility	**10**	SMR production of H_2 is a standard process used in "Industrial Gas Manufacturing" (SIC Code 2813) and a value of 10 years is applied (http://www.window.state.tx.us/taxinfo/proptax/faguide00/sice_f.html)
H_2 Transmission Pipeline	**20**	A value of 20 years is assumed, equal to that applied for NG Transmission Pipeline, based on similarity in design and operation.
H_2 Compressor Station	**20**	A value of 20 years is assumed, equal to that applied for NG Compressor Stations, based on similarity in design and operation.
H_2 Underground Storage Facility	**20**	A value of 20 years is assumed, equal to that applied for NG Underground Storage, based on similarity in design and operation.
H_2 Distribution Pipeline	**20**	A value of 20 years is assumed, equal to that applied for NG Distribution Pipeline, based on similarity in design and operation.
CNG Refueling Station	**8**	A value of 8 years is recommended for a typical "Gasoline Service Station" (SIC Code 5541; http://www.window.state.tx.us/taxinfo/proptax/faguide00/sicg_i.html) and it is assumed in this analysis that a similar value would be applied for a CNG refueling station.
H_2 Refueling Station	**8**	A value of 8 years is recommended for a typical "Gasoline Service Station" (SIC Code 5541; http://www.window.state.tx.us/taxinfo/proptax/faguide00/sicg_i.html) and it is assumed in this analysis that a similar value would be applied for a H_2 refueling station.

NAICS Code	SIC Code	Industry Description
221210	4924	Distribution of natural gas
221210	4924	Natural gas distribution systems
234910	N/A	Natural gas compressing station construction
325120	2813	Hydrogen manufacturing
486210	4922 / 4923	Booster pumping station, natural gas transportation
486210	4923	Gas, natural, pipeline operation
486210	4922 / 4923	Natural gas transmission (i.e., processing plants to local distribution systems)
486210	4922 / 4923	Storage of natural gas

Component	Potential Cost Reduction		SOURCE / REFERENCE
	Capital Cost	Annual Cost	
NG Transmission Pipeline	0%	----	Mature technology, no decrease expected (although increased annual cost may be possible due to more stringent regulatory environment, etc.)
NG Distribution Pipeline	0%	----	As above
H2 Transmission Pipeline	0%	----	Although the number of miles of H2 pipeline in the U.S. is limited, the experience with NG pipeline construction and operation is great. Would expect similar situation as with NG pipelines.
H2 Distribution Pipeline	0%	----	As above
H2 Production Plant	0%	0%	
NG Underground Storage Facility	0%	0%	Mature technology, no decrease expected (although increased annual cost may be possible due to more stringent regulatory environment, etc.)
H2 Underground Storage Facility	0%	0%	
NG Compressor Station	0%	8%	Based on Intercooled Recuperative Cycle Gas Turbines design in document "Compressor Station Technologies: Options for the Next 20 Years, Final Report," AGA Contract PR-215-9129 (Dec. 1993). In general, increased efficiency requires more exotic materials which increases capital cost.
H2 Compressor Station	0%	8%	Assuming similar decreases in H2 compressor station design
CNG Refueling Station	50%	0%	A capital cost of $1,000 per scfm has been targeted by GRI and the NGV-IWG, which represents a 50% reduction in station cost (http://38.144.192.166/reports/1999-10_500-99-019.PDF). The operating costs can be expected to increase if only due to elevated electric and water costs with time.
NG compressor	50%	50%	Based on projected H2 compressor improvements
NG steam reformer (SMR)	20%	20%	According to Praxair, Inc., the new small on-site hydrogen plants, which use steam reforming of commercially available natural gas, offer cost savings of 20 percent or more over conventional steam methane reformers (http://www.us-tech.com/Jan97/news/news001.htm)
H2 storage compressor	50%	50%	Dave Livengood of ANL believes that the compressor design he has been evaluating will be 1/2 to 1/3 the cost of conventional compressors. A 50% reduction in capital and operation costs is applied in this analysis - SF, 4/26/01
H2 dispensing stations	0%	20%	
High-pressure storage cylinders	0%	0%	

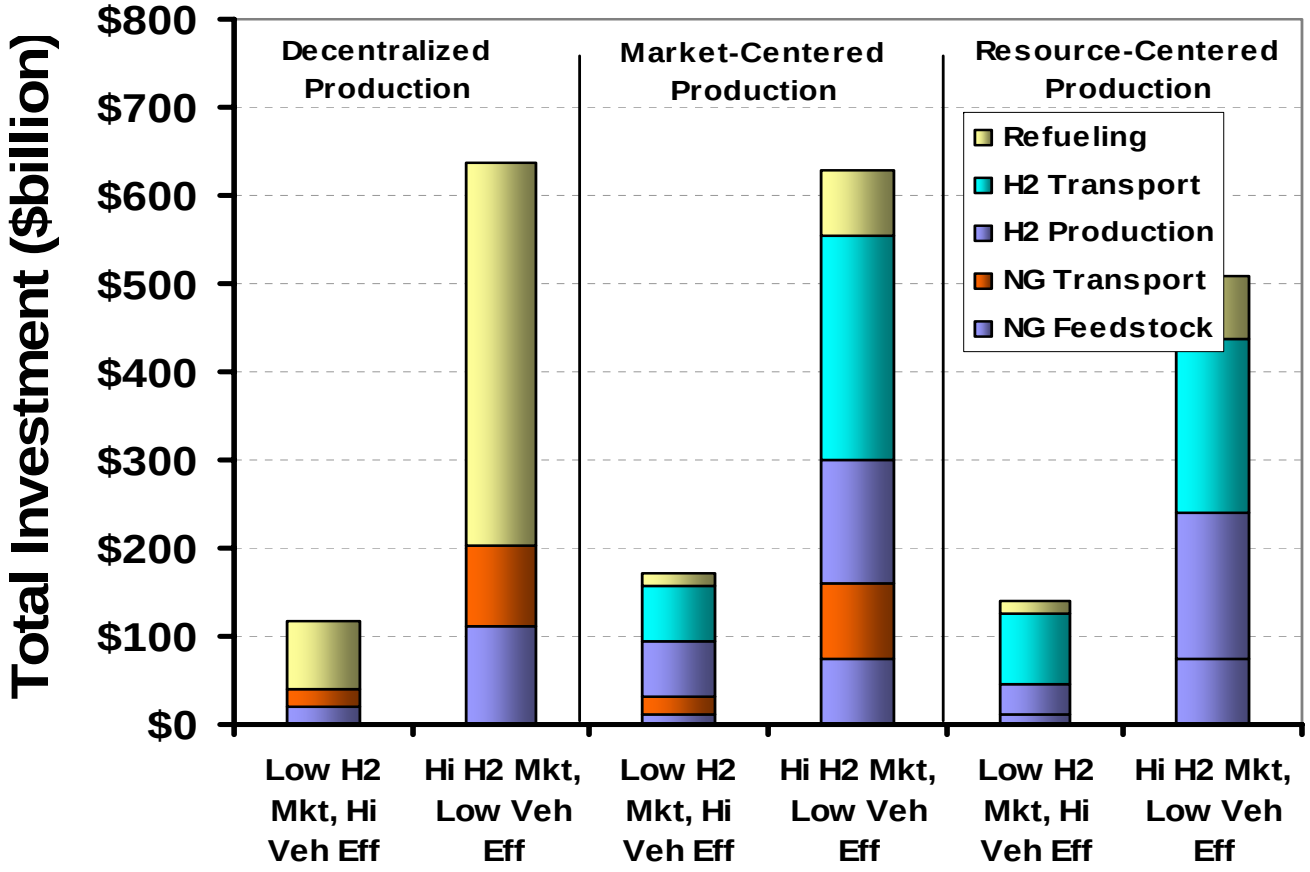
Gasoline Depends Feedstock Cost; H_2 Depends on Processing and Distribution



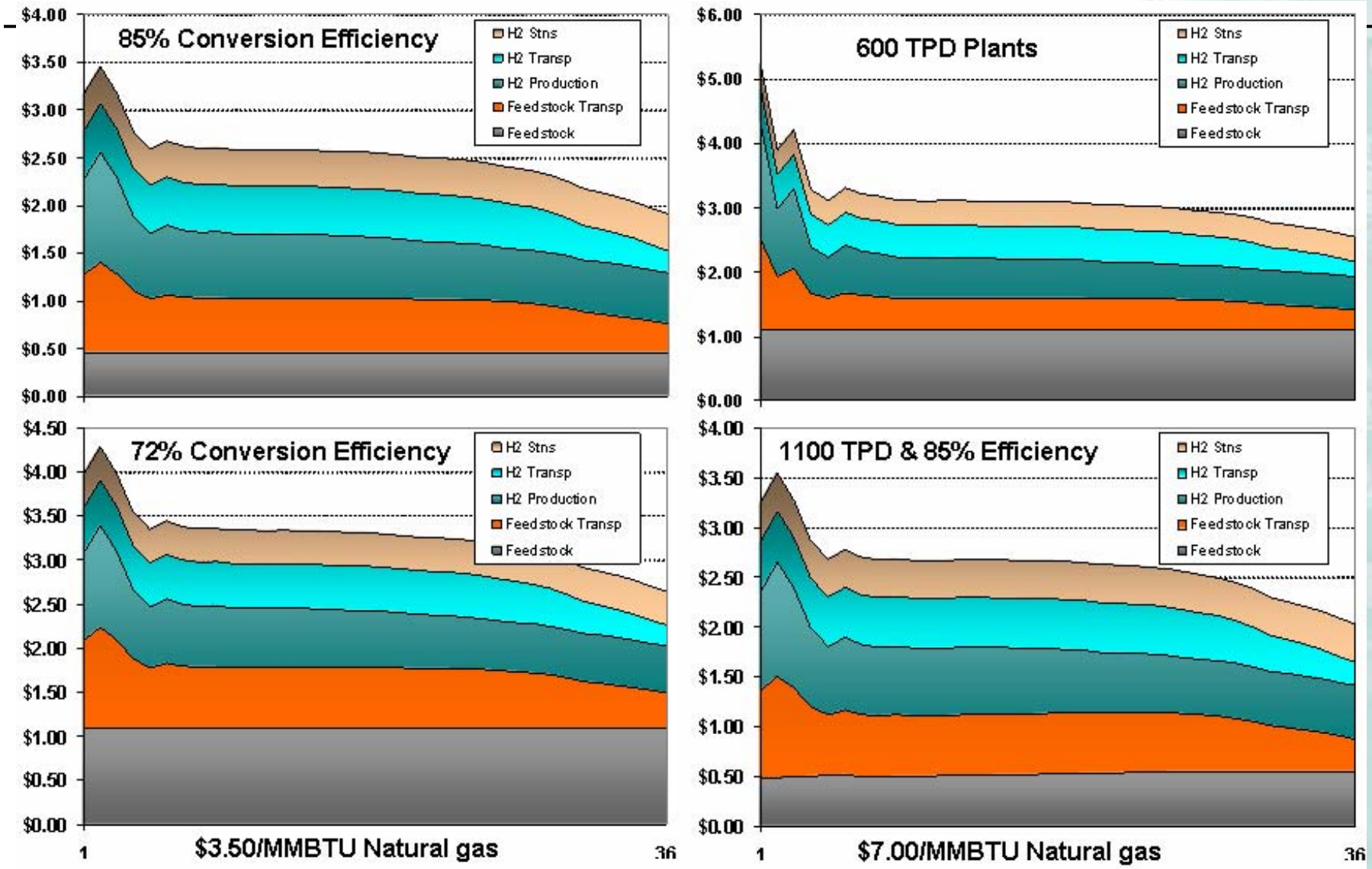


- Gasoline ~$1.00-1.25/gal untaxed ($28-40/bbl crude)
- H_2 >$2.50/gge at high volume, much more at low volume
- Feedstock >60% for gasoline vs. 25-35% for NG-based H_2, much less for coal or nuclear
- Distribution <10% for gasoline vs. 20-25% for centralized H_2
- Production ~20% for gasoline vs. >60% for H_2 from nuclear, ~25% from NG.
- Levelized costs decline as infrastructure is “built out”

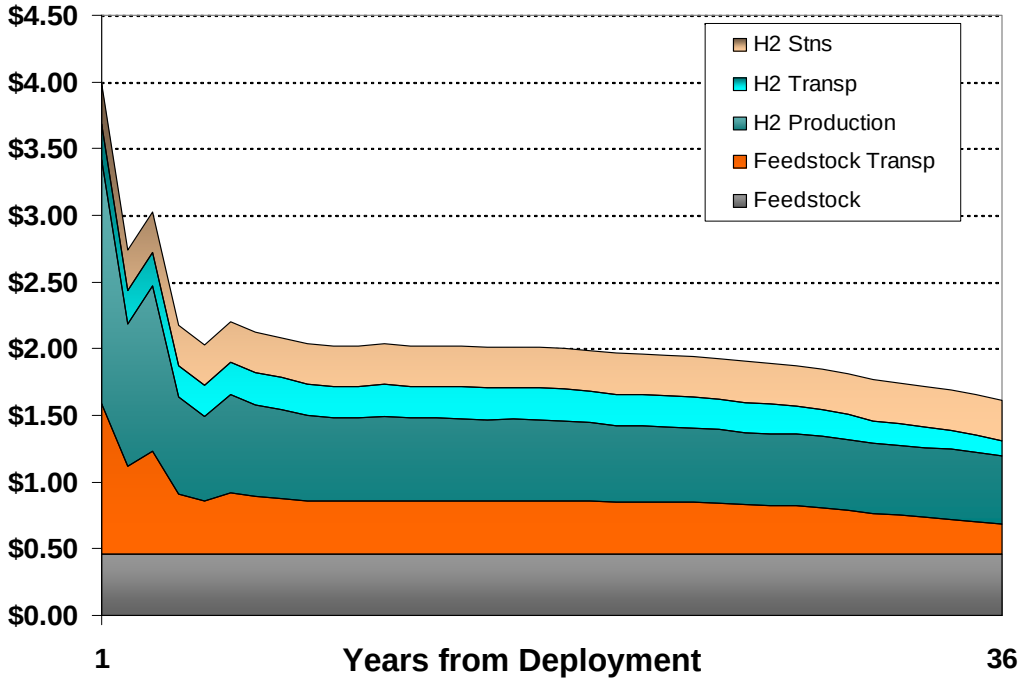
H_2 Infrastructure to Fuel 100 Million+ FCVs Could Cost $500 Billion or More



What Would It Take to Produce $1.50/gge H2?



With Very Optimistic Assumptions Delivered Cost of Hydrogen Approaches DOE's Program Goal



- Large plants (1100 tpd)
- Low natural gas price ($3.50/mmBtu)
- 50% cut in H/NG pipeline cost increment
- 85% SMR efficiency
- 50% cut in H2 service pipeline miles
- 75% cut in H2 main pipeline (ring) miles
- 50% cut in hydrogen refueling station cost

Some Conclusions:

- With current production and delivery technologies, on a WTP annualized basis, H_2 is likely to be at least twice as costly as gasoline.
- Although the decentralized path costs less initially, centralized paths become more economical at higher production volumes (scale economies)
- Of the centralized options, the resource-centered path is consistently lower cost (scale economies).
- H_2 transport and production are the most costly components of all paths examined (co-production and co-distribution?)
- WTP analysis provides a systematic rubric for examining impacts along the entire supply chain

Future Research Directions and Questions

- Additional pathways
  - **Biomass gasification**
  - **Tube trailers**
  - **Mobile refuelers**
  - **LH2 delivery**
- Pipeline assumptions and model
- Regional opportunities/differences
  - **Southeast US**
  - **West of Rockies**

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