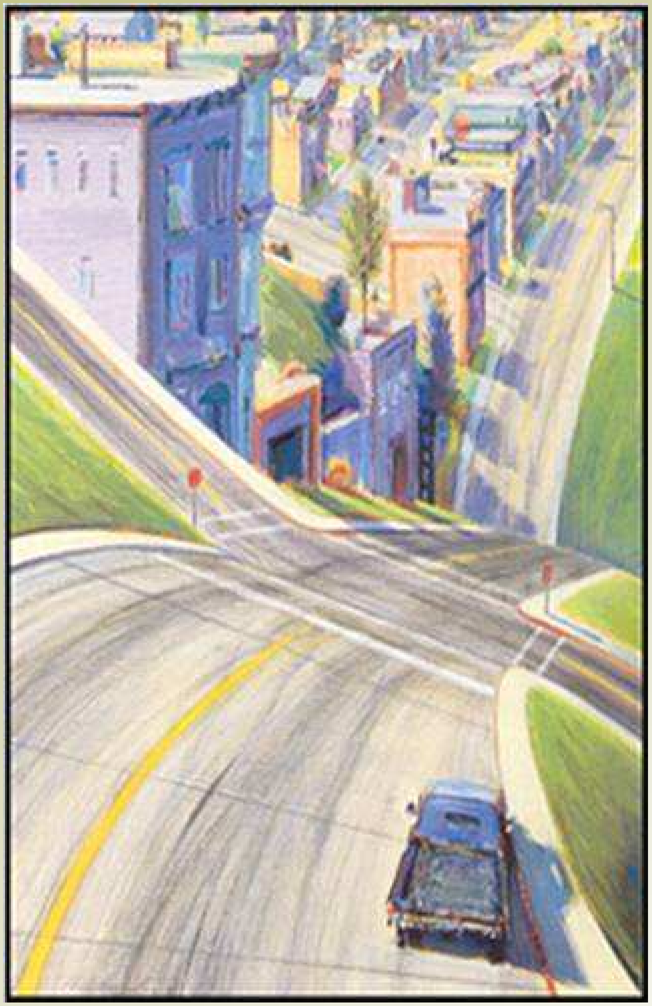
Institute of Transportation Studies
University of California, Davis



Strategies for Building a Hydrogen Infrastructure:

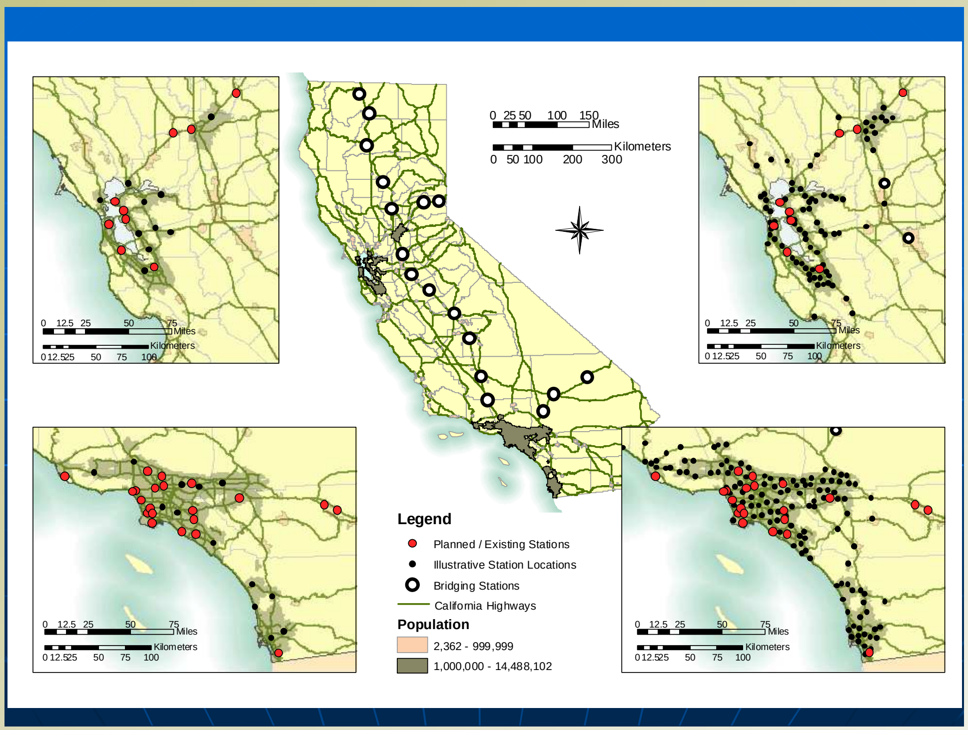
Insights from the H2 Pathways Program at UC Davis

Prof. Joan Ogden

presented at the
California Air Resources Board
Zero Emission Vehicle (ZEV)
Technology Symposium
Sacramento, CA

September 25, 2006

UCDAVIS ITS



- Multi-year interdisciplinary research program (began 2003)
- Strategies and Pathways for transportation sector Hydrogen
- OEMs, energy firms, government, environmental community
- Research
- Public Outreach
- Education

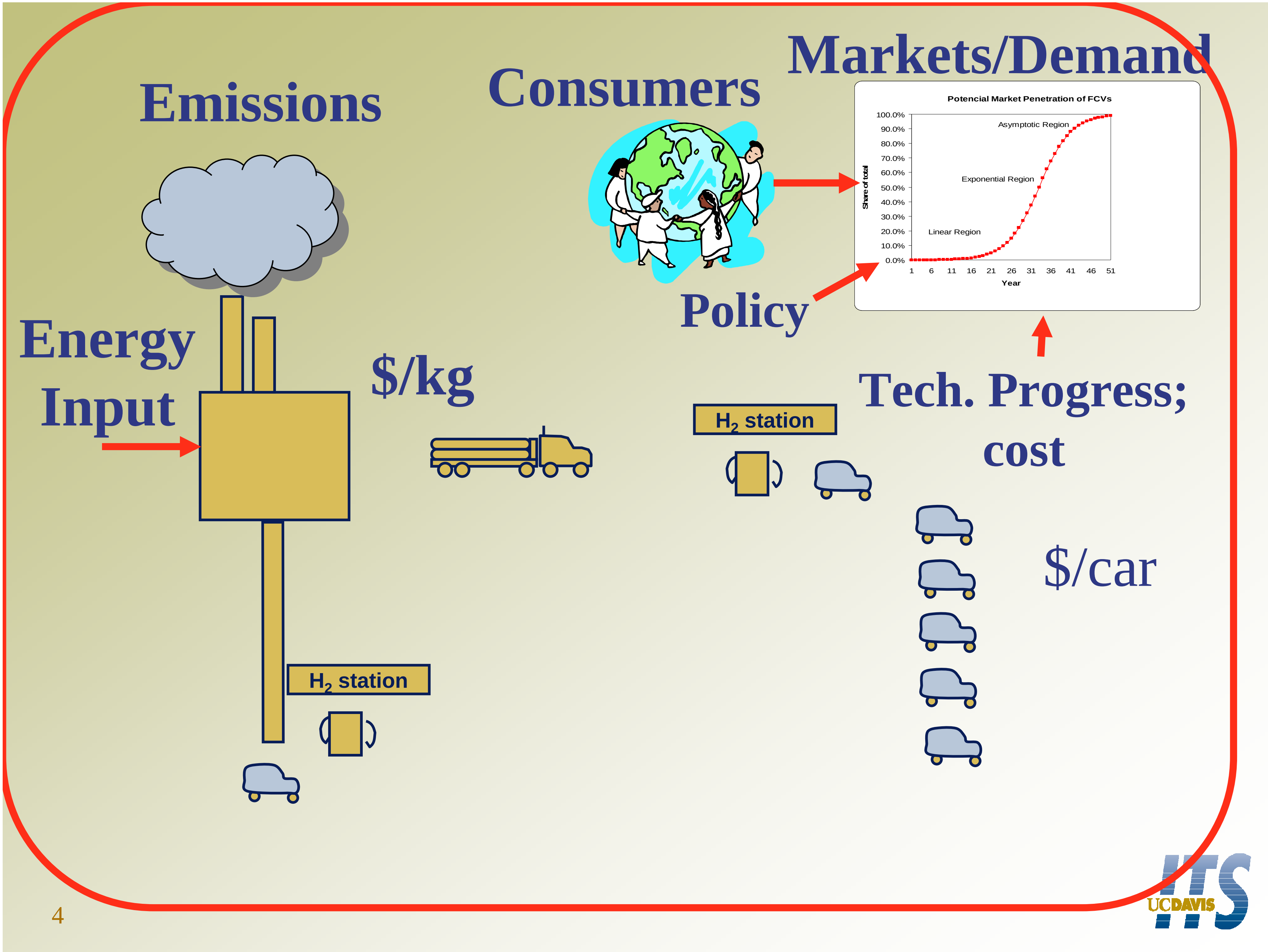
H2 Pathways Program Sponsors

Energy Industry	Automotive
▪Air Products & Chemicals ▪BP* ▪Chevron* ▪ConocoPhillips* ▪ExxonMobil* ▪Indian Oil Company ▪Petrobras ▪PG&E* ▪Shell Hydrogen* ▪Southern California Gas ▪Total*	▪Fuji Heavy Ind./Subaru ▪Honda* ▪General Motors* ▪Nissan* ▪Toyota*

Government

- California DOT*
- Federal Transit Authority*
- NR-Canada*
- US DOE*
- US EPA

*** Indicates full program sponsor with Advisory Board position**

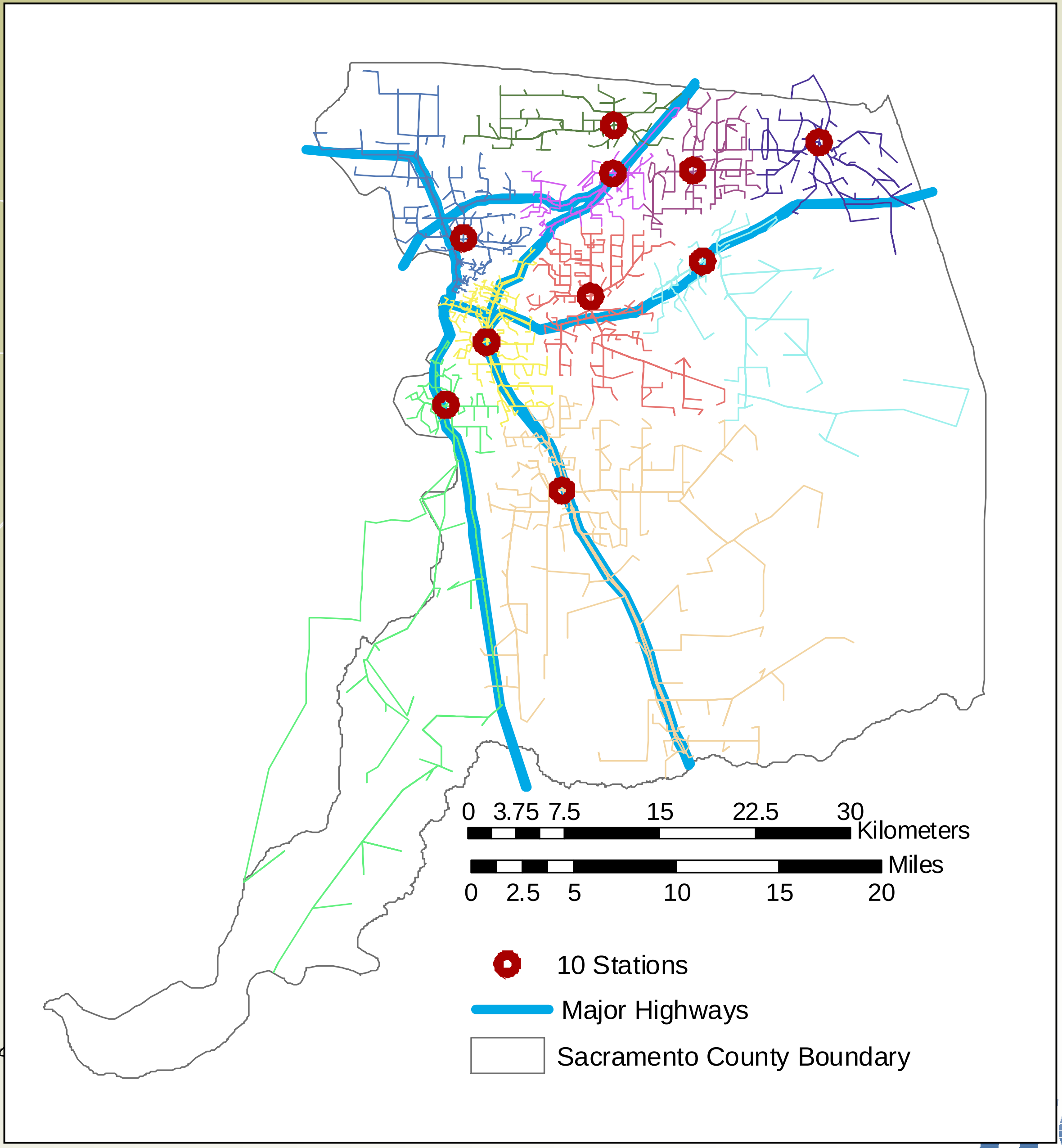

Emissions
Consumers
Markets/Demand
Potencial Market Penetration of FCVs
Asymptotic Region
Exponential Region
Linear Region
Share of total
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
1 6 11 16 21 26 31 36 41 46 51
Year
Policy
Energy Input
$/kg
H2 station
Tech. Progress; cost
$/car
H2 station

Key Questions for H_2 in Transportation

- **Who Will Buy a Hydrogen Car and Why?**
- **What Would a Hydrogen Infrastructure Look Like? (And where will the Hydrogen come from?)**
- **How and When Could We Make a Transition to Hydrogen?**
- **What are the Societal Costs and Benefits of Hydrogen (Compared to Alternatives)?**
- **What are Policy and Business Strategies for Hydrogen? What Should We Do Now?**

How many H2 stations do we need for customer convenience?

Geographic Information System (GIS) Analysis of Refueling Station Siting and sizing



Source: Nicholas, Handy and Sperling, 2004.

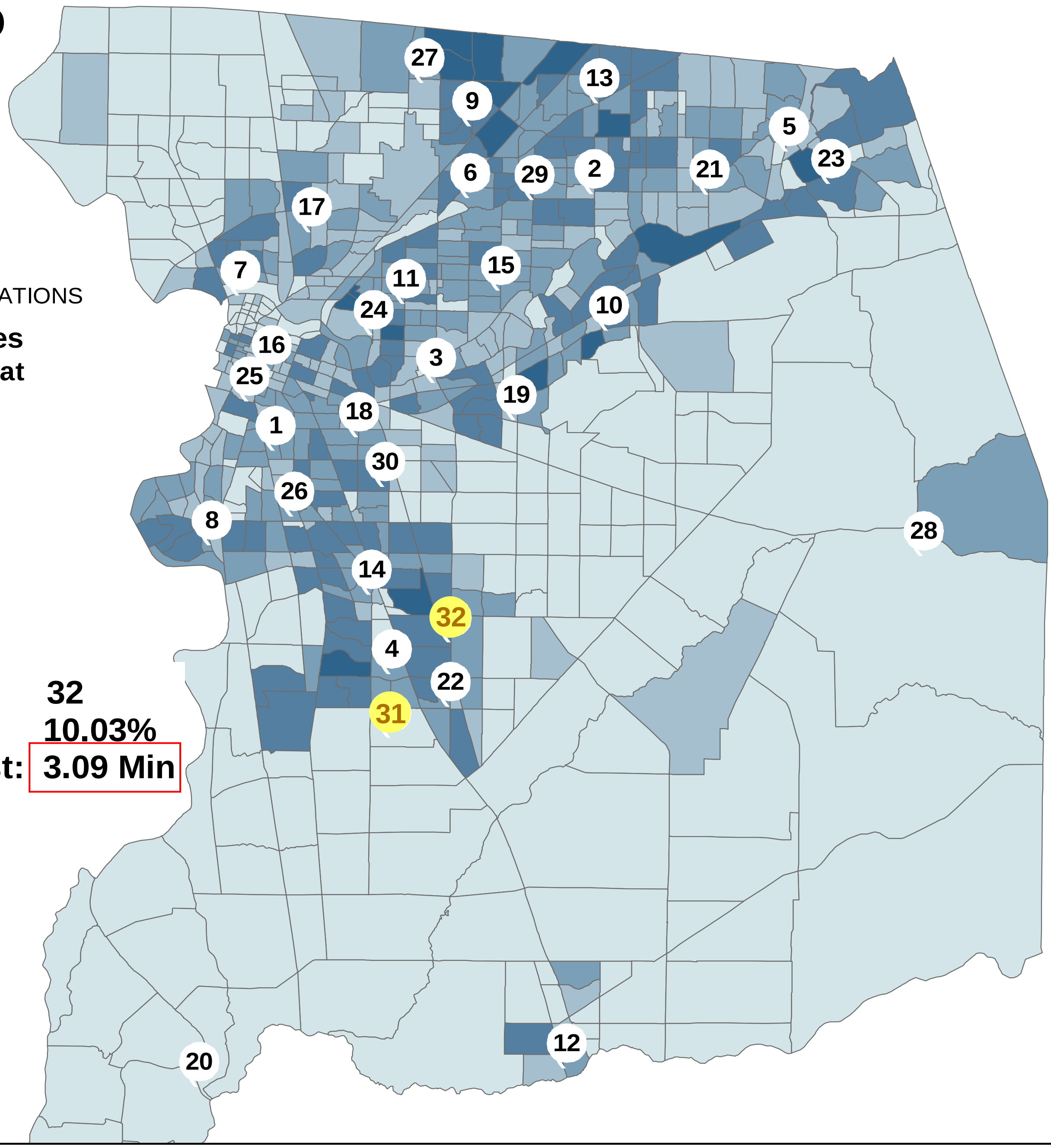
Sacramento County Analyses

Legend

(HYPOTHETICAL STATIONS

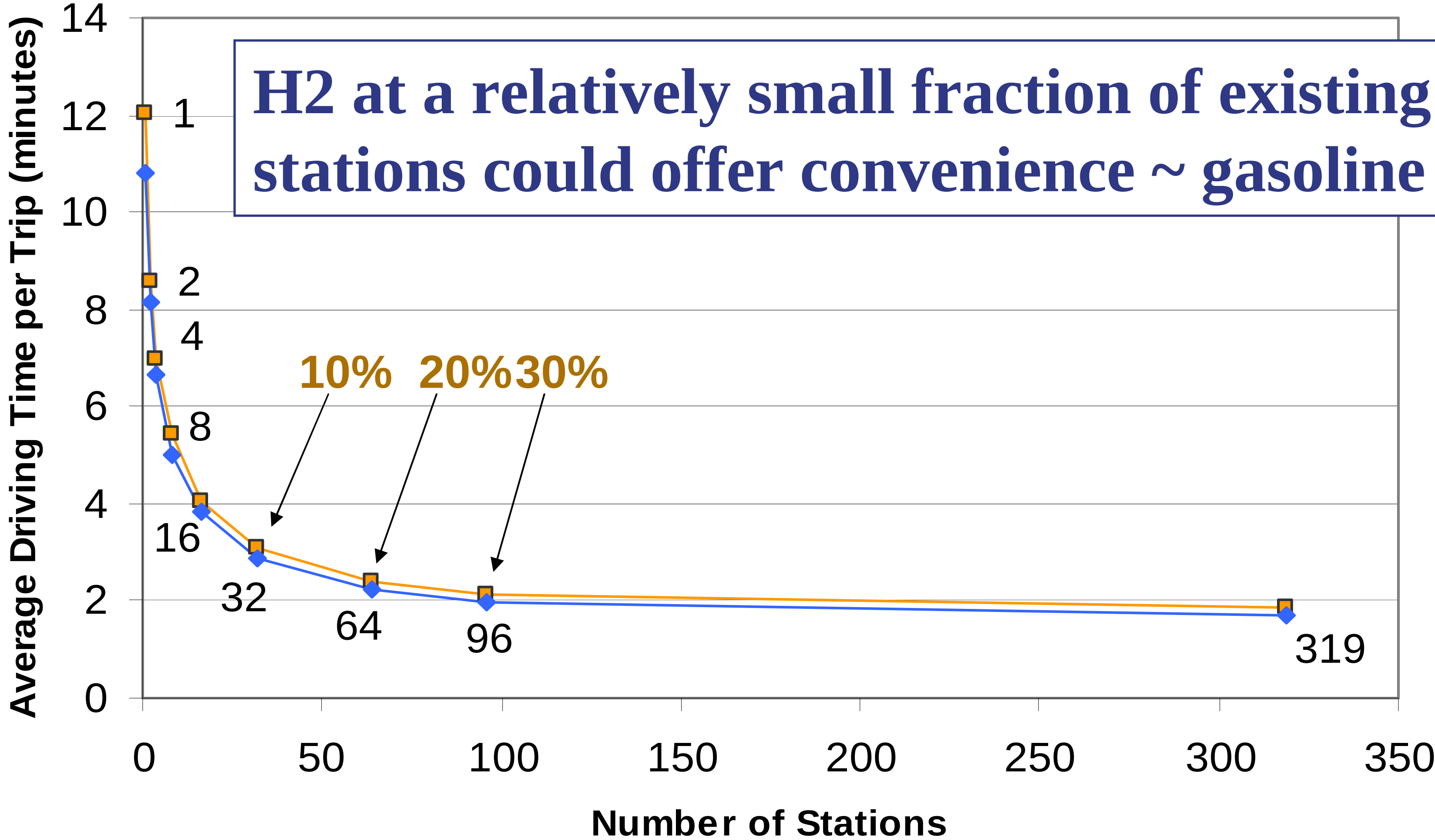
Traffic Analysis Zones
Vehicles leaving zone at 6:30 - 7:30

- 0 - 211
- 212 - 491
- 492 - 798
- 799 - 1259
- 1260 - 2125



Number of Stations: 32
Percent of Stations: 10.03%
Avg. Time to Nearest: 3.09 Min

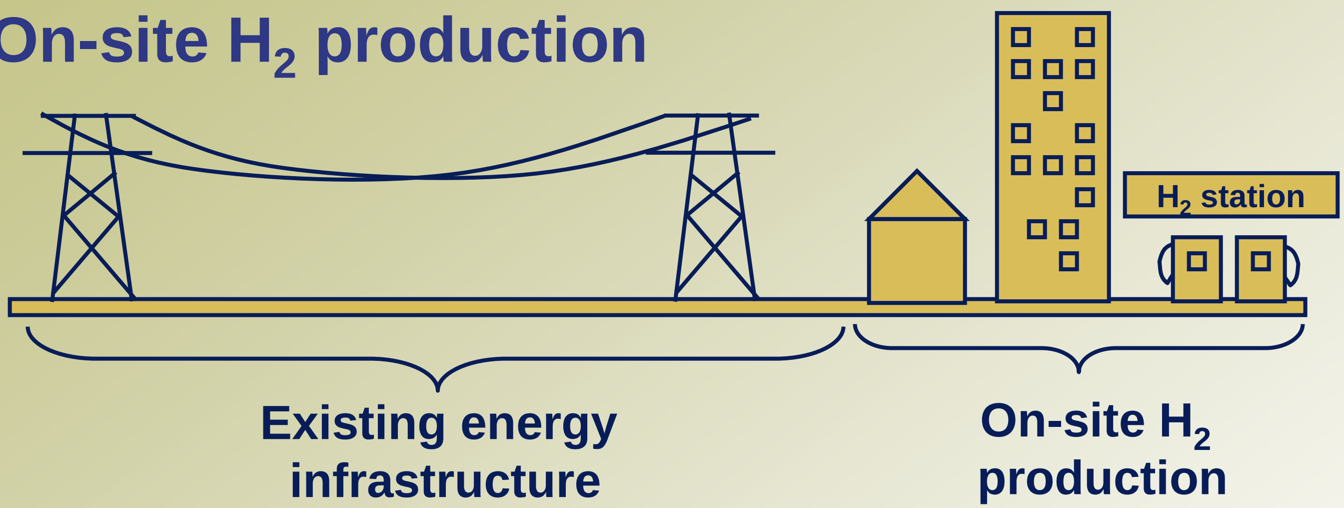
H2 at a relatively small fraction of existing stations could offer convenience ~ gasoline



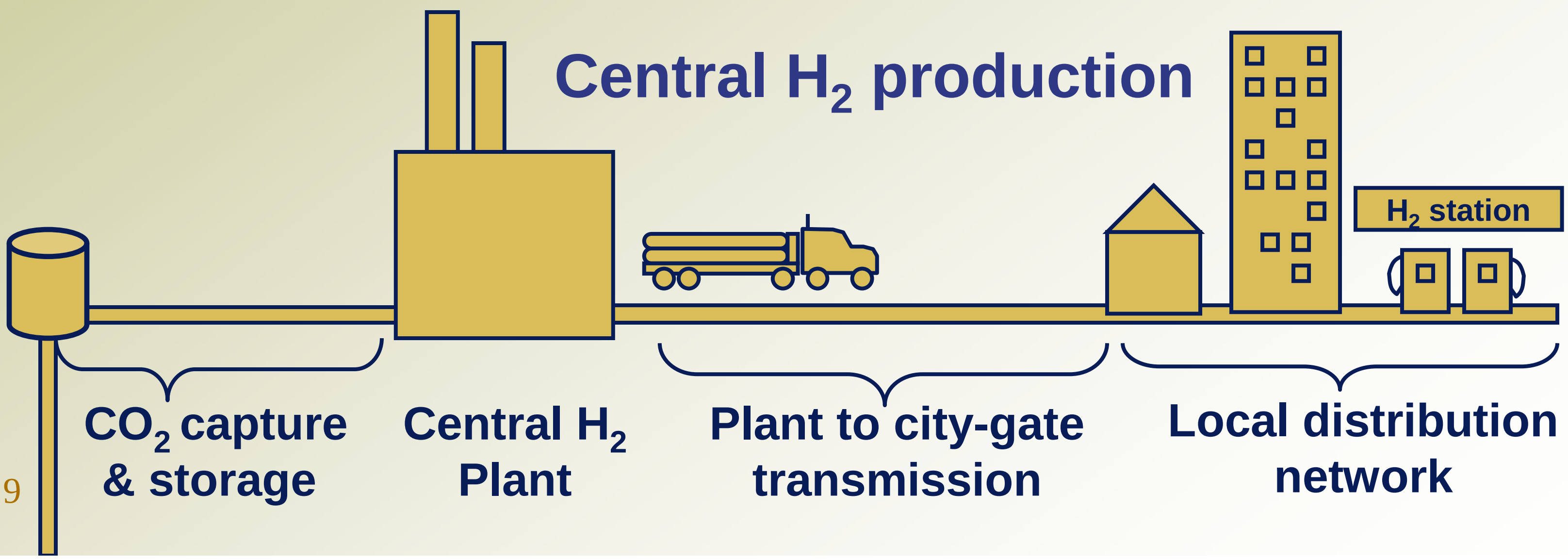
Relationship Between Number of Stations and Average Travel Time

What Will a H2 Infrastructure Look Like?

On-site H_2 production

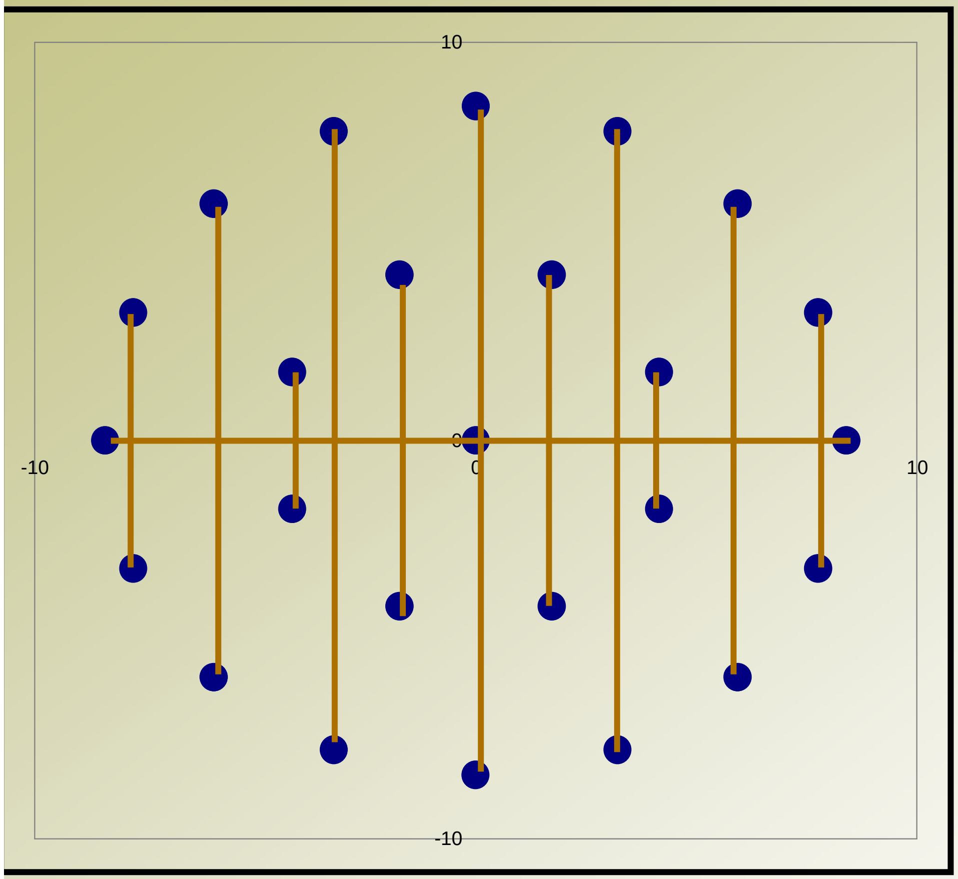


Central H_2 production

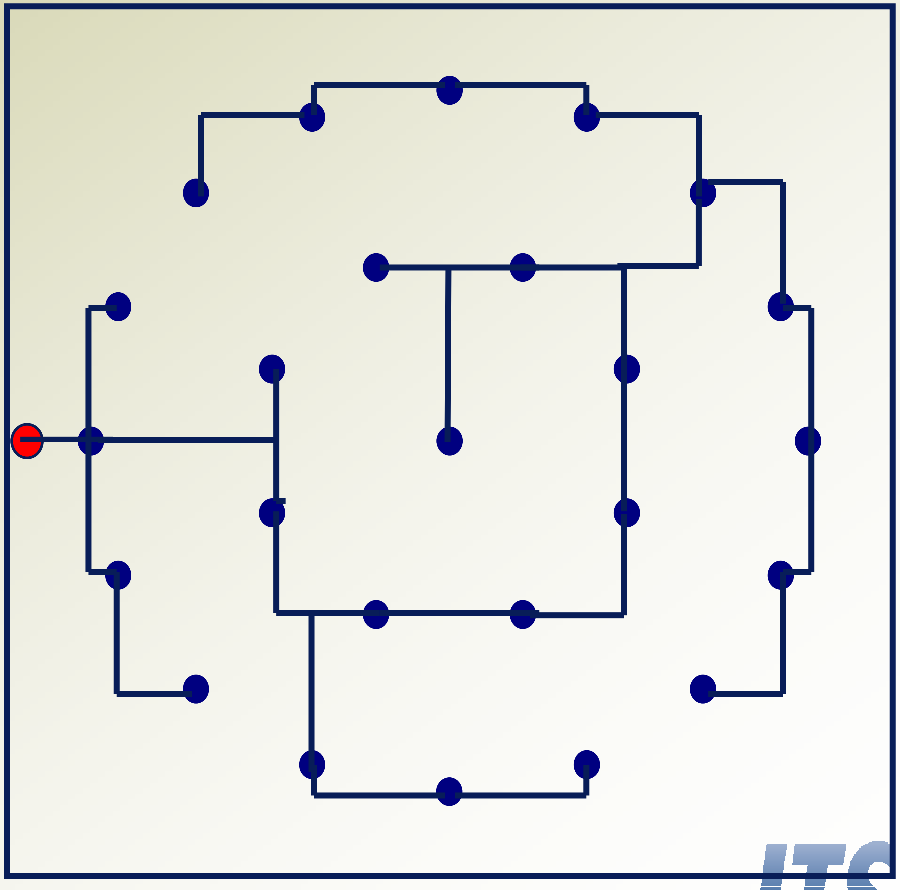


Analysis of H2 Delivery Systems:
UCD "Idealized City" Model
(Inputs: population density, city size, #of H_2 stations)

Truck delivery



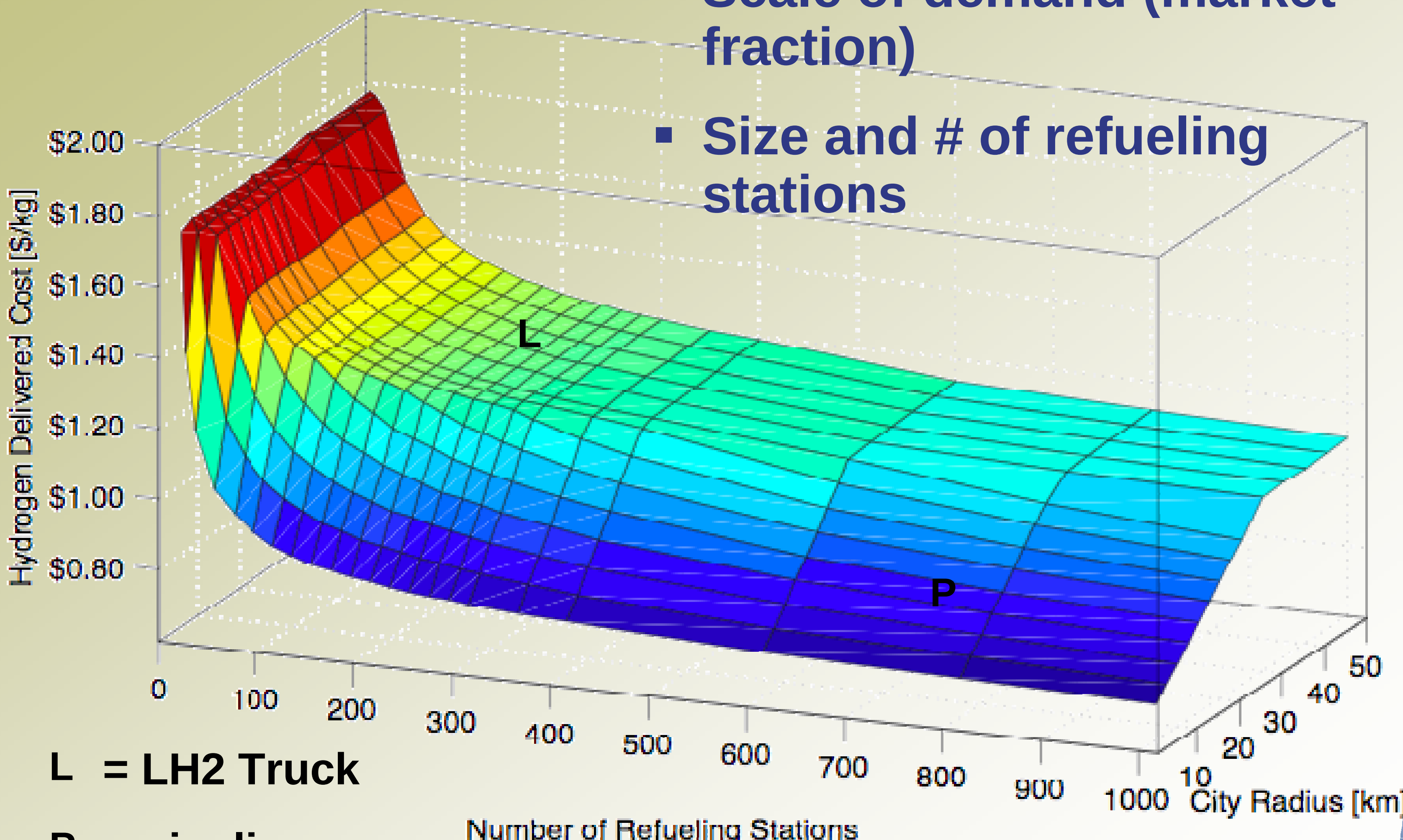
Pipeline



Source: Yang and Ogden, submitted to IJHE, 2005

Lowest Cost Delivery Mode to Network of Stations Depends on

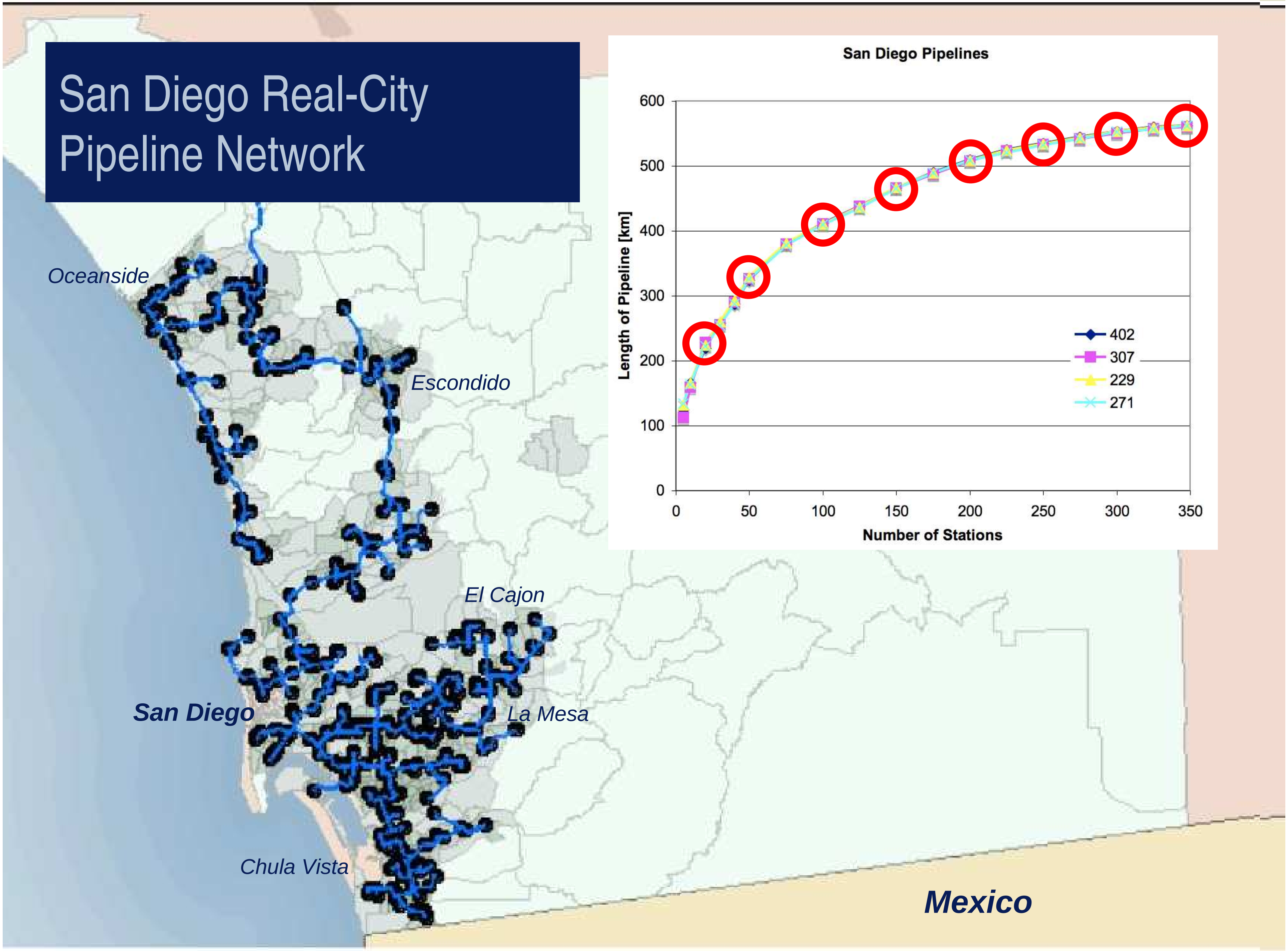
- City size and density
- Scale of demand (market fraction)
- Size and # of refueling stations



L = LH2 Truck

P = pipeline

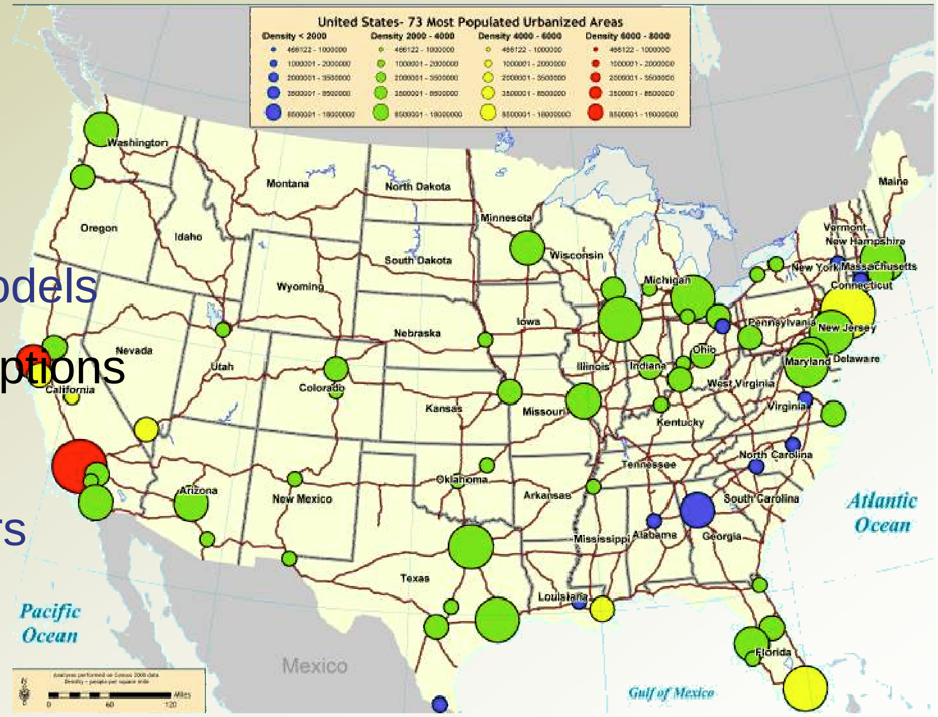
San Diego Real-City Pipeline Network



City Hydrogen Infrastructure Model

Christopher Yang, Joel Bremson, Jason Ni

- Steady State City Hydrogen Infrastructure System Model (SSCHISM)
- Simplified national case study
  - User-friendly interface
  - 73 US census defined urban areas
  - Simplified engineering/economic models
    - NAS, H2A, User-defined assumptions
  - Energy and feedstock prices
  - Demographic and geographic factors
- Estimate costs, energy and emissions
  - Pathway
  - Market penetration
- Understand factors that affect hydrogen infrastructure design

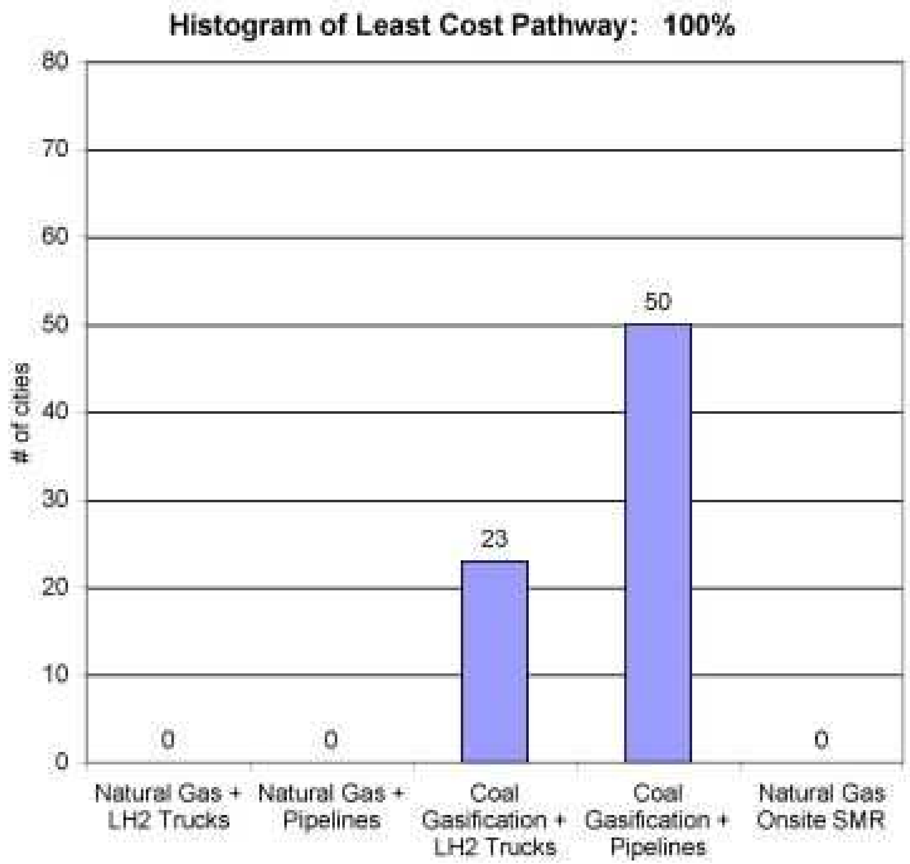


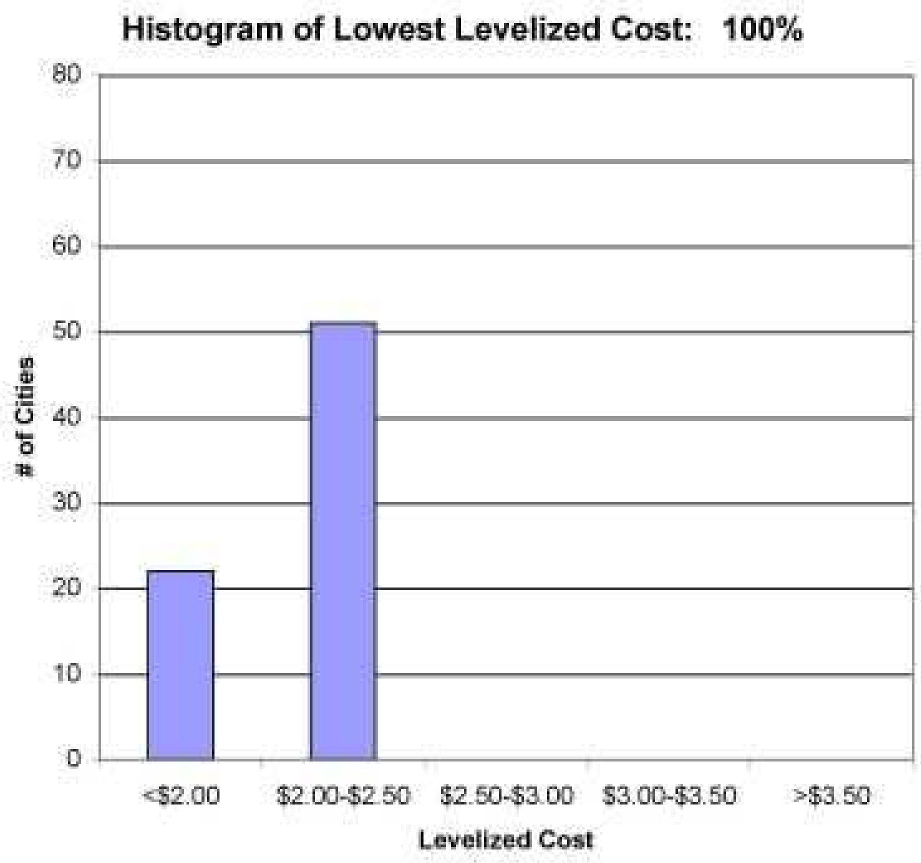
Lowest Cost Pathway

- Less dense cities favor LH2 trucks
- High density cities favor pipelines

5 Pathways Considered

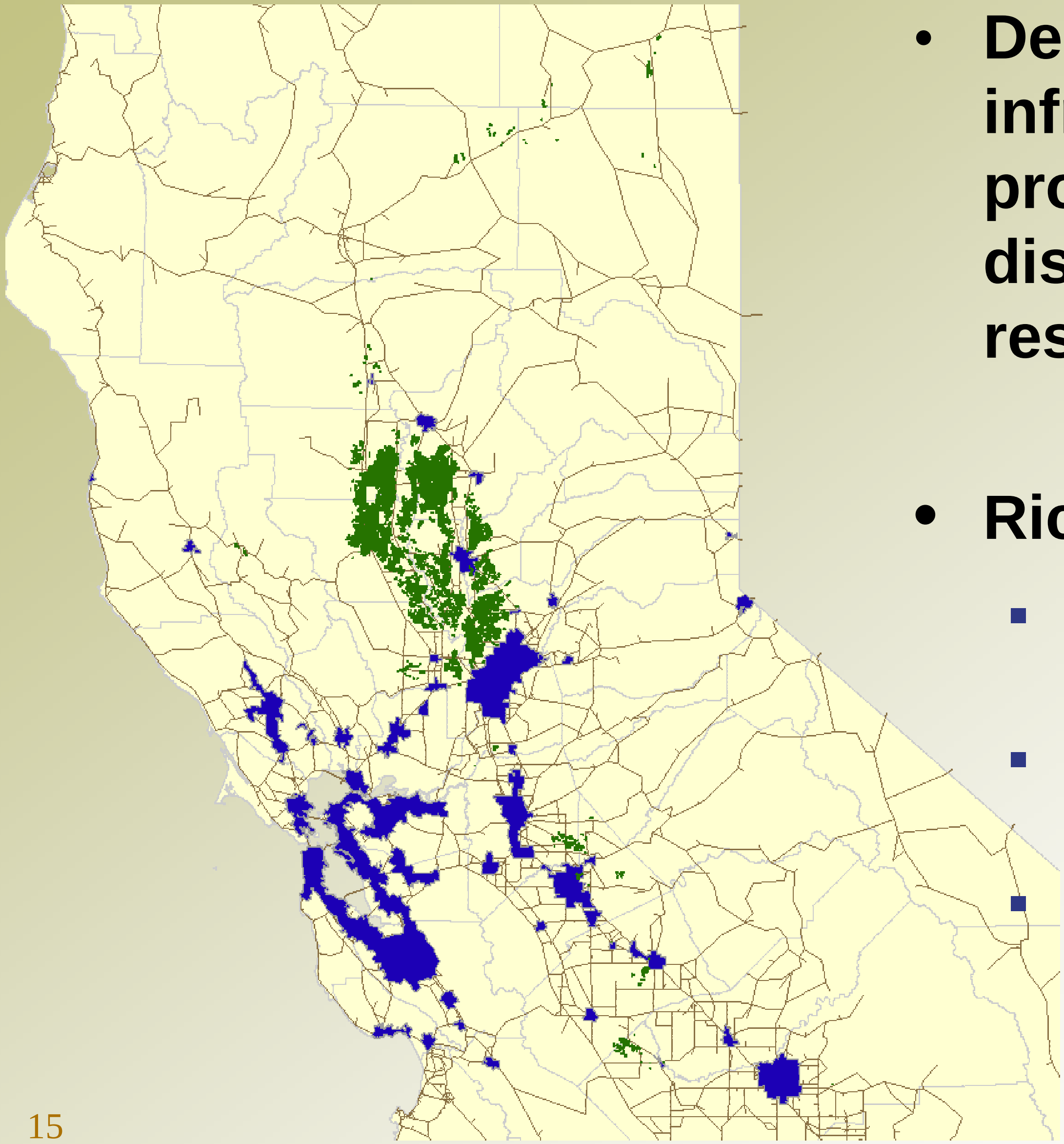
NG-LT	Natural Gas Liquid Truck
NG-P	Natural Gas Pipeline
C-T	Coal Liquid Truck
C-P	Coal Pipeline
NG-Dist	Natural Gas Onsite





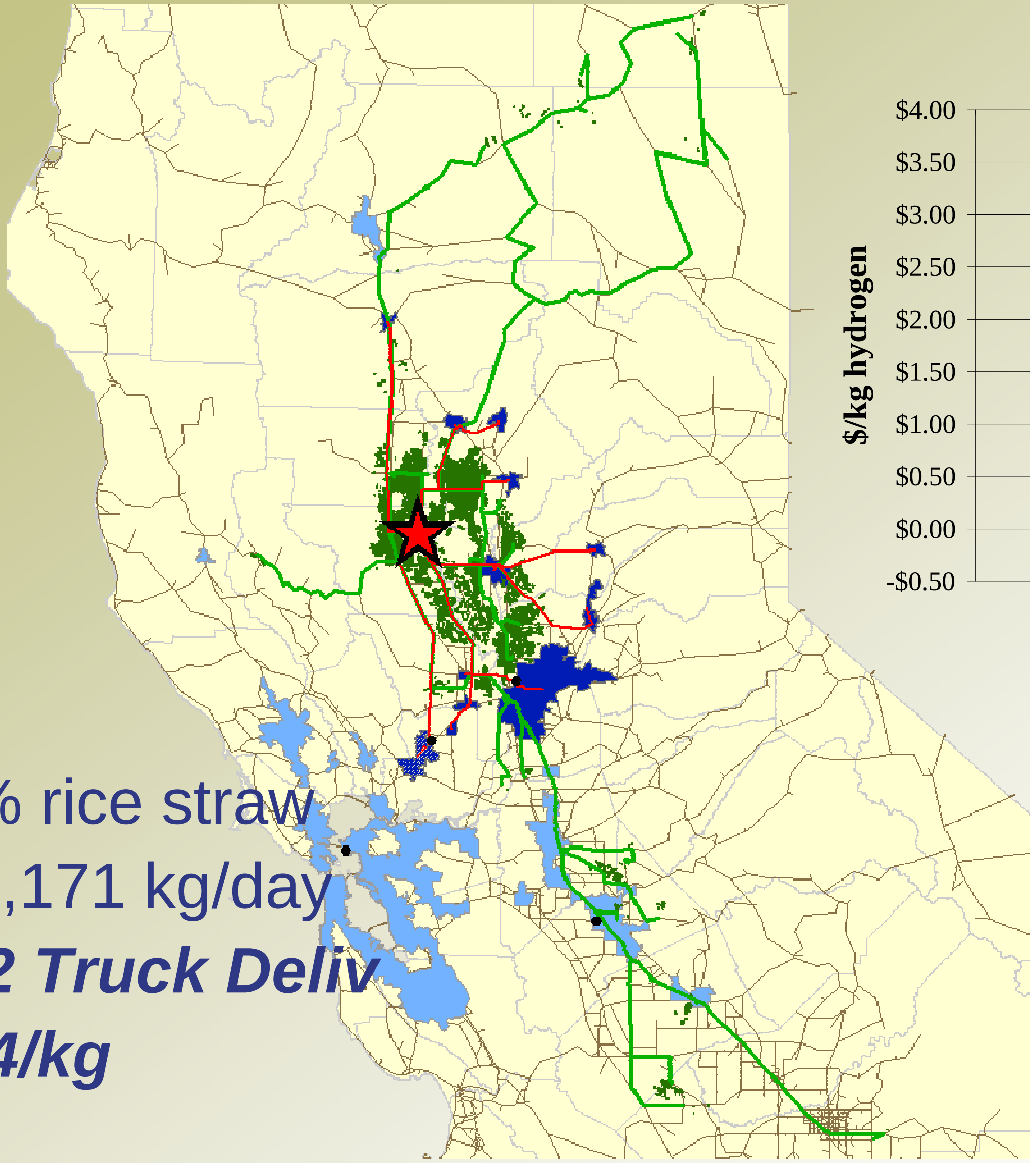
Coal gasification is predicted as the lowest cost production method for all cities

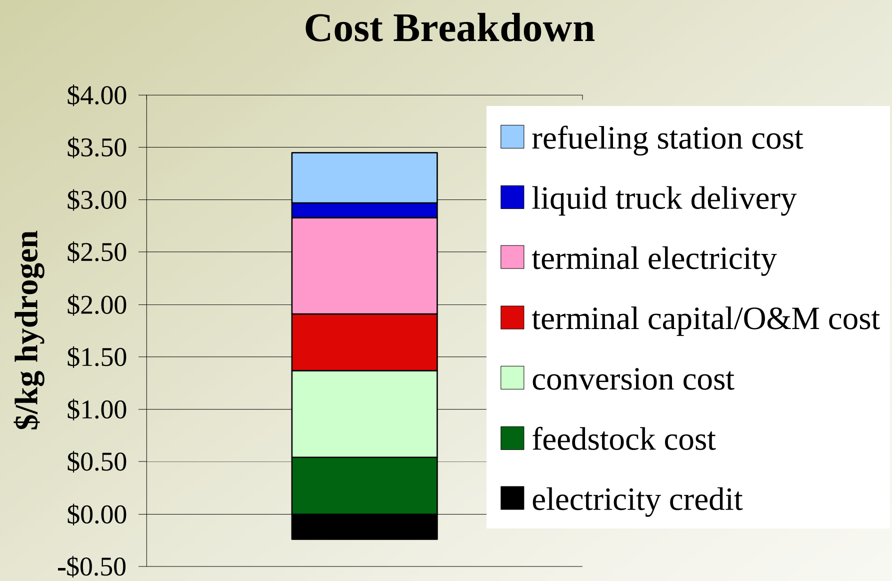
Renewable H2 from Agricultural Wastes: Rice Straw Case Study (N. Parker)



- **Design optimal infrastructure for producing H_2 from dispersed waste biomass resources.**
- **Rice Straw**
  - **Regionally significant resource**
  - **Capable of supporting about 250,000 FCVs**
  - **Potential for competitive near to mid term renewable H2**

H2 from Rice Straw : 25% LDVs





50% rice straw

169,171 kg/day

LH2 Truck Deliv

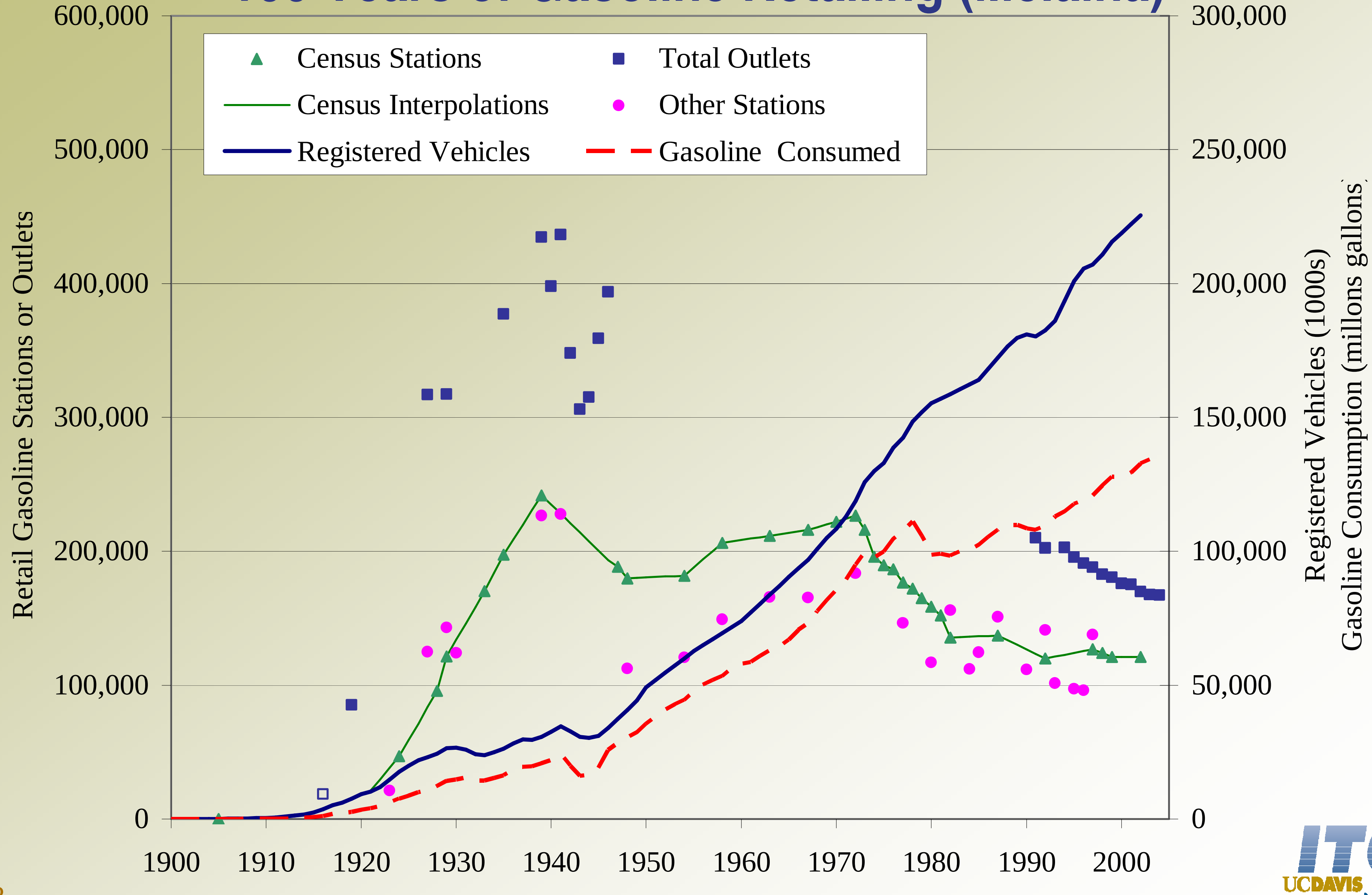
$3.4/kg

Methods for studying transitions

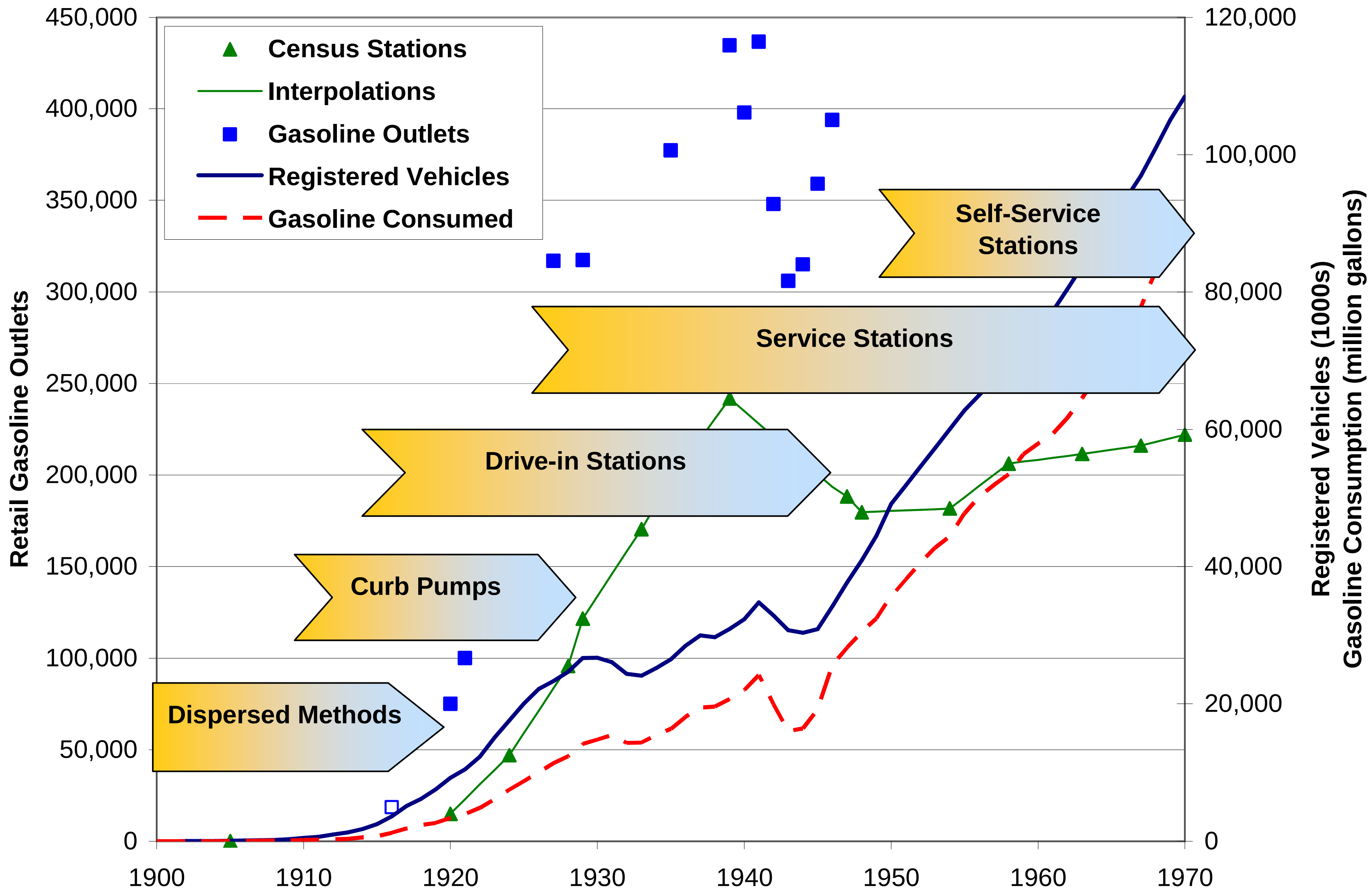
- **Historical analysis**
- **Studies of markets and consumers**
- **Engineering/economic infrastructure system models with dynamics**
  - **Scenario evaluation**
  - **System optimization (in space, time)**
- **Regional transition case studies**
  - **GIS data**

What Can Gasoline History Teach Us About H2?

100 Years of Gasoline Retailing (Melaina)

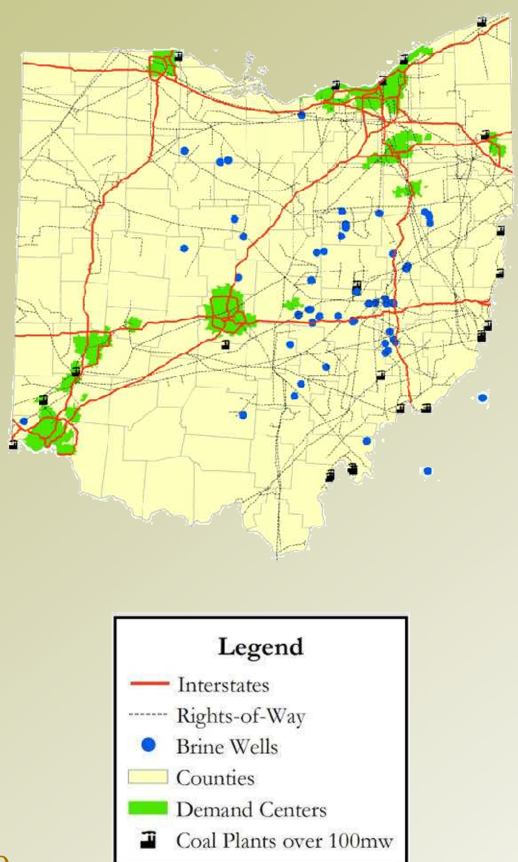


History Reveals a *Phased* Introduction of Different Refueling Methods

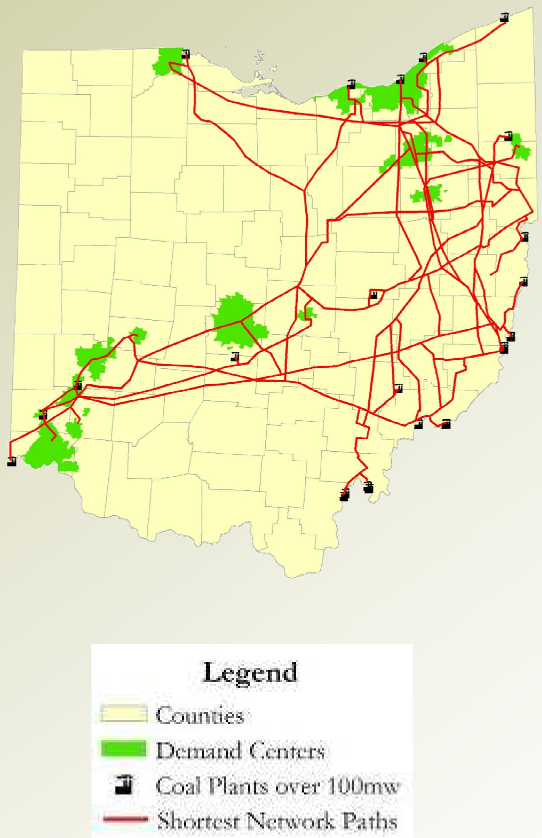


Building a Coal-Based H_2 Infrastructure w/ CO_2 Capture & Sequestration: Ohio Case Study (N. Johnson et al.)

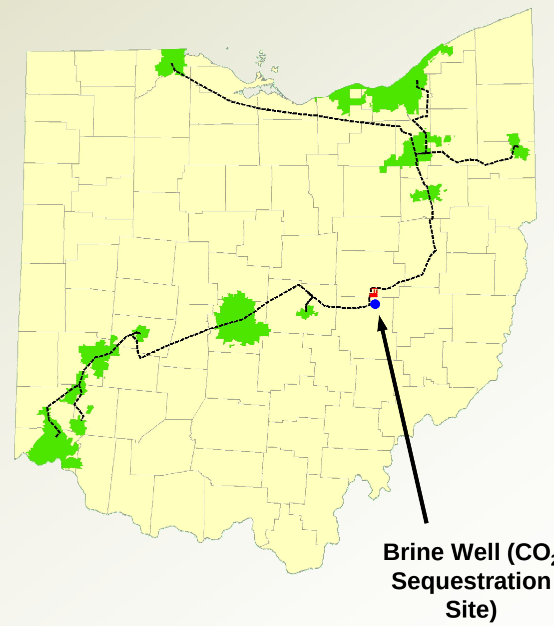
GIS Database



Identify Shortest Pathways Between Demand Centers and Coal Facilities



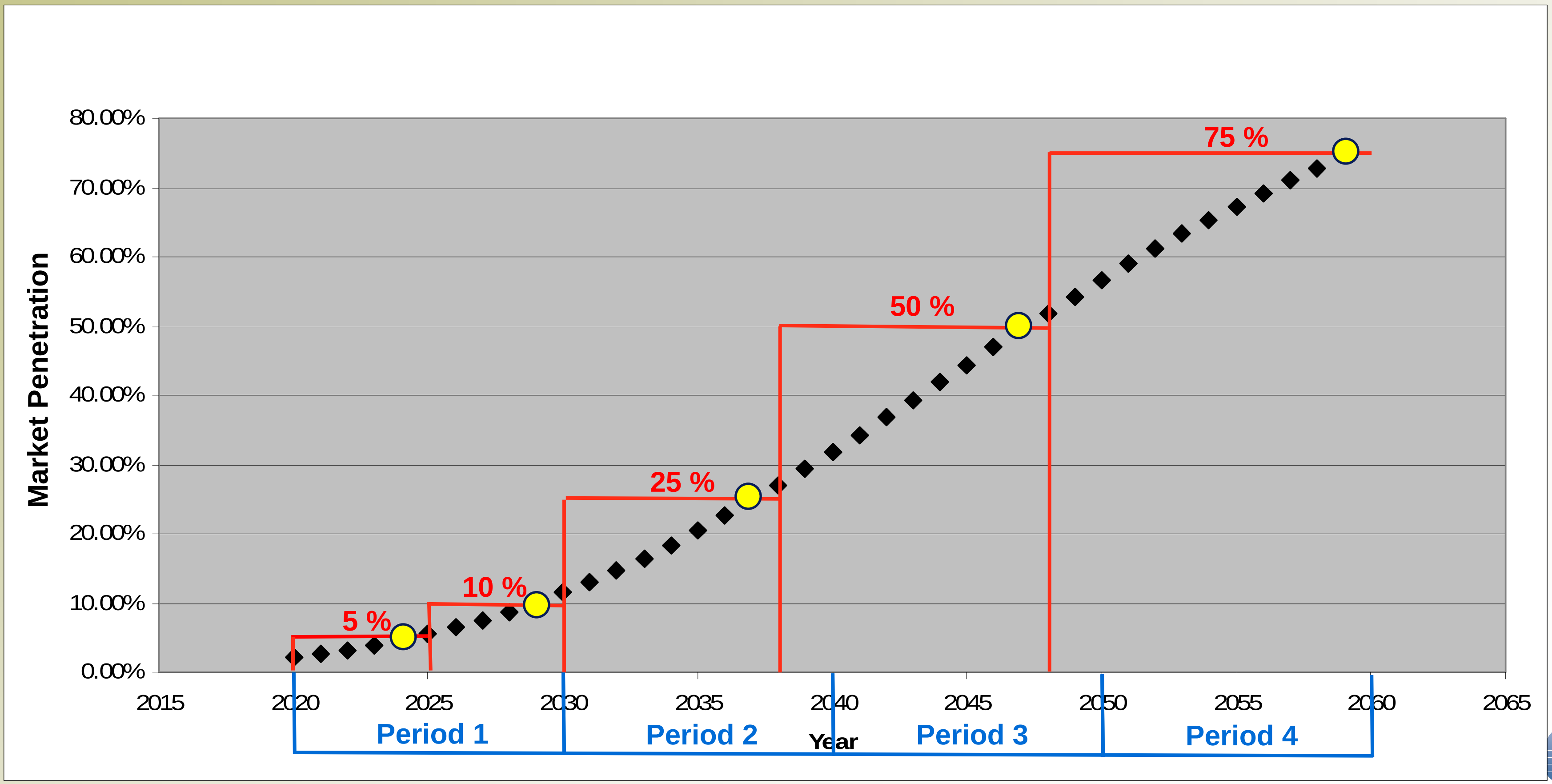
Optimal Supply Network



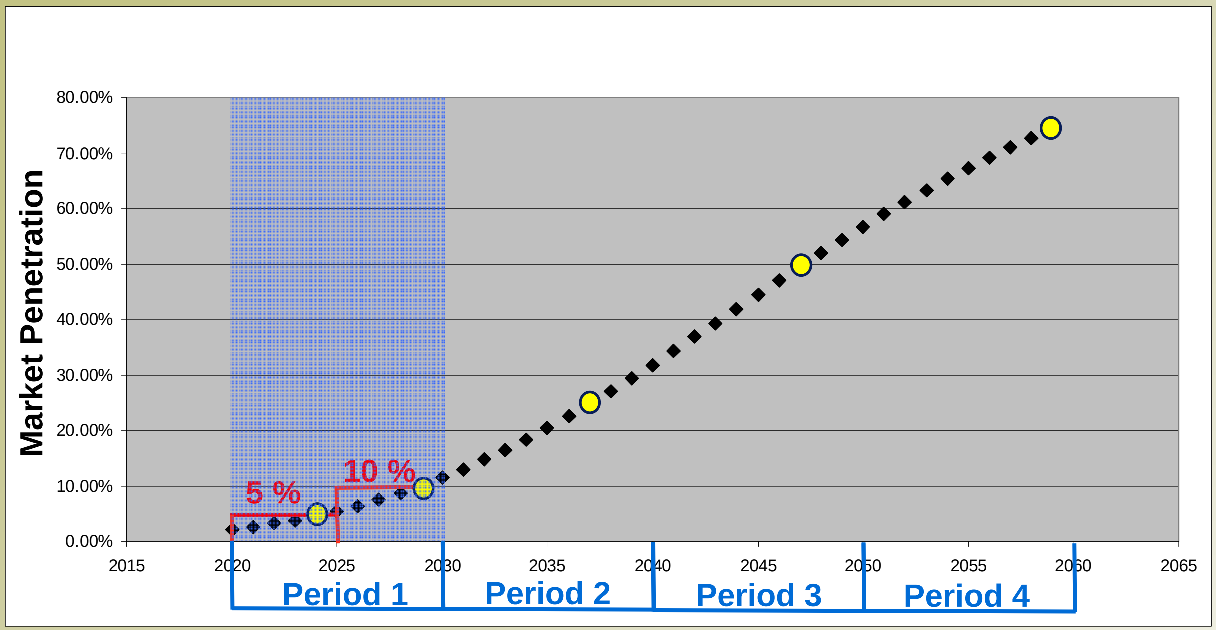
Hydrogen Infrastructure Build-Out Scenarios

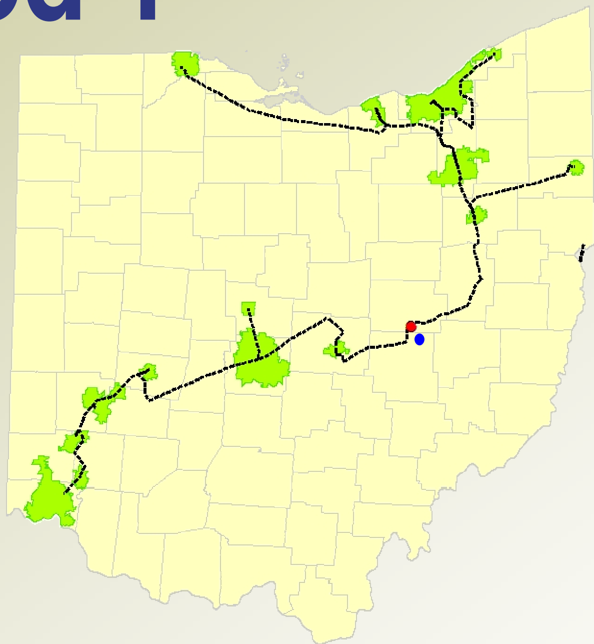
Hydrogen Vehicle Market Penetration

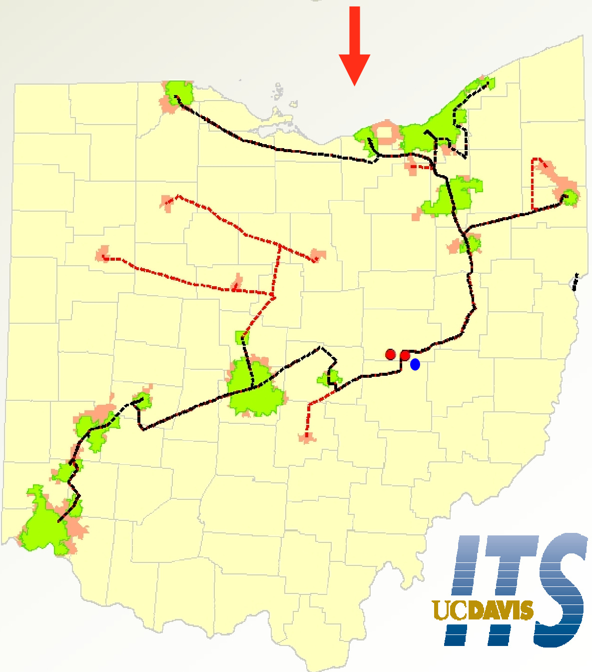
(Miller et al., 2005)



Pipeline Scenario: Period 1







Market Penetration Range: 2.1 - 9.6%

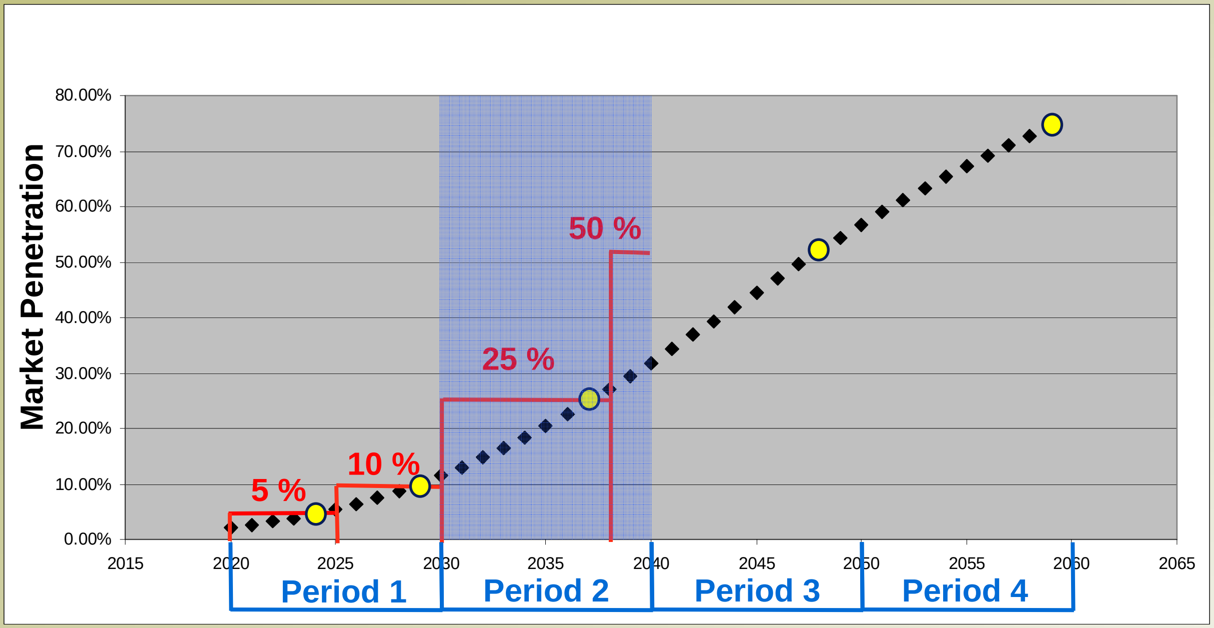
Infrastructure Installed: Years 1 and 6

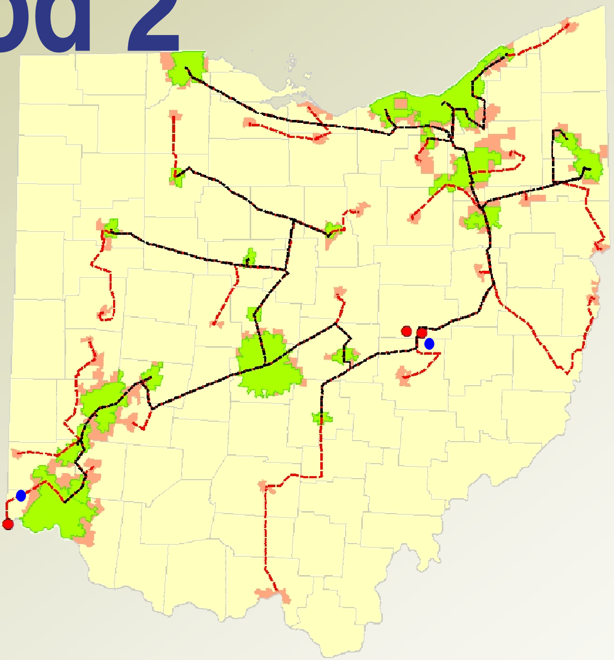
Capital Cost: $2.66 Billion

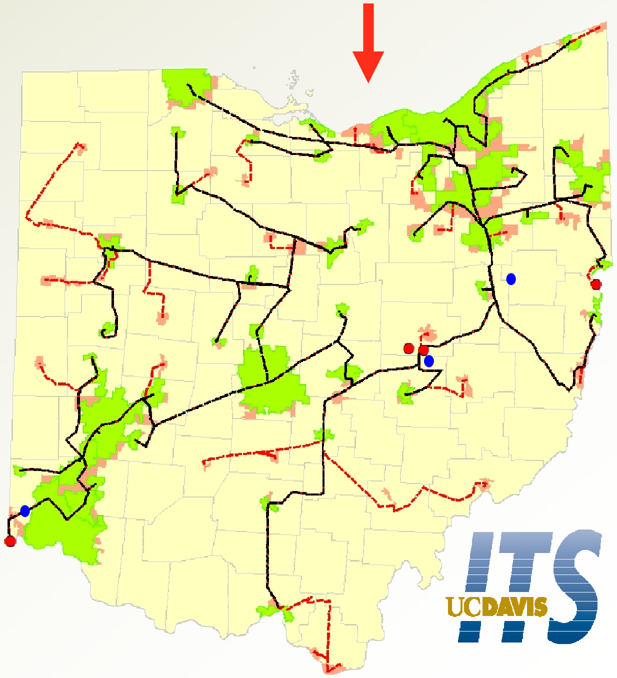
Average Utilization: 73%

Levelized Cost of Hydrogen: $4.29/kg

Pipeline Scenario: Period 2







Market Penetration Range: 11.5 – 29.4%

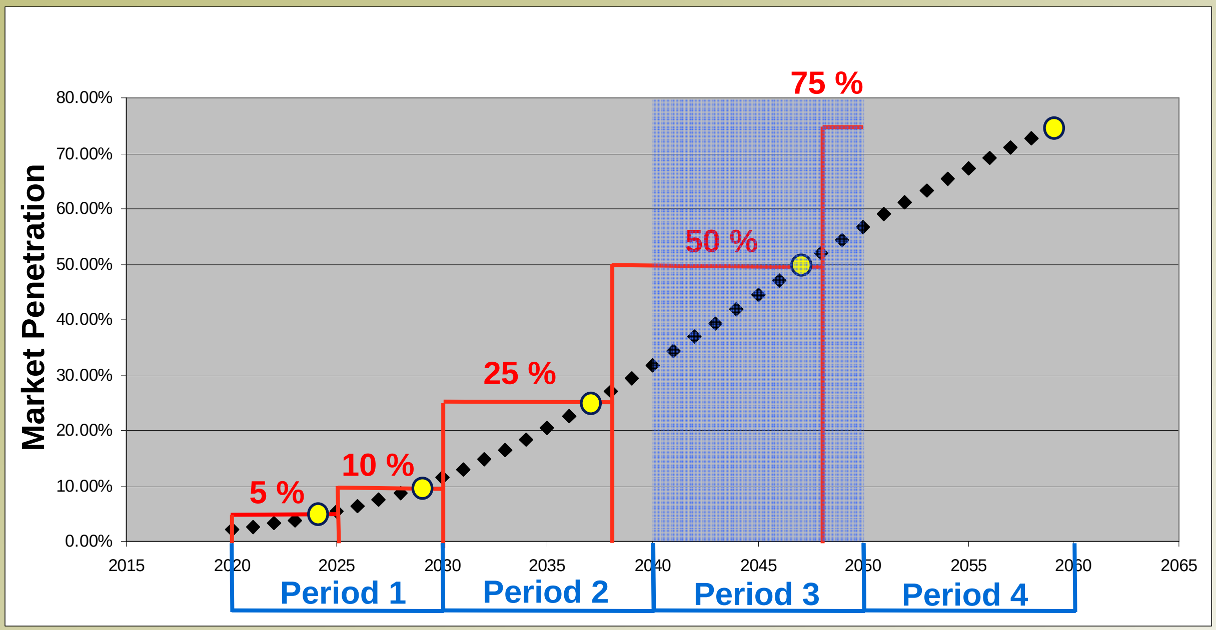
Infrastructure Installed: Years 11 and 19

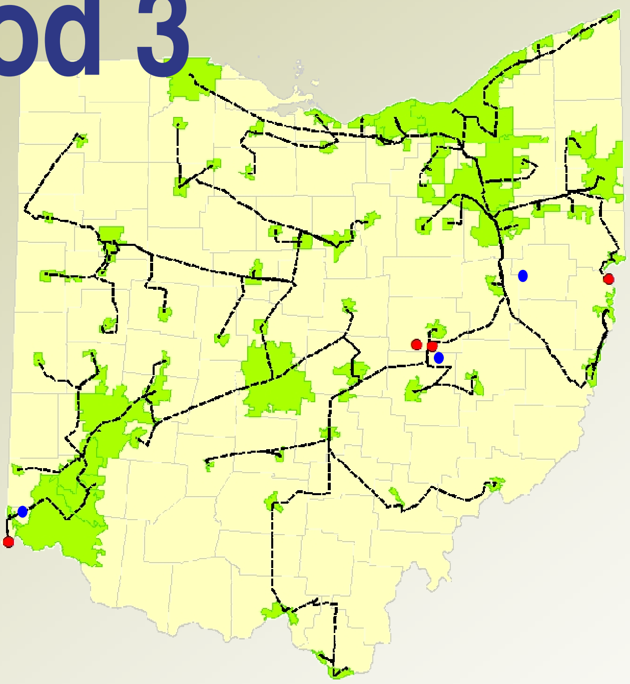
Total Capital Cost: $10.75 Billion

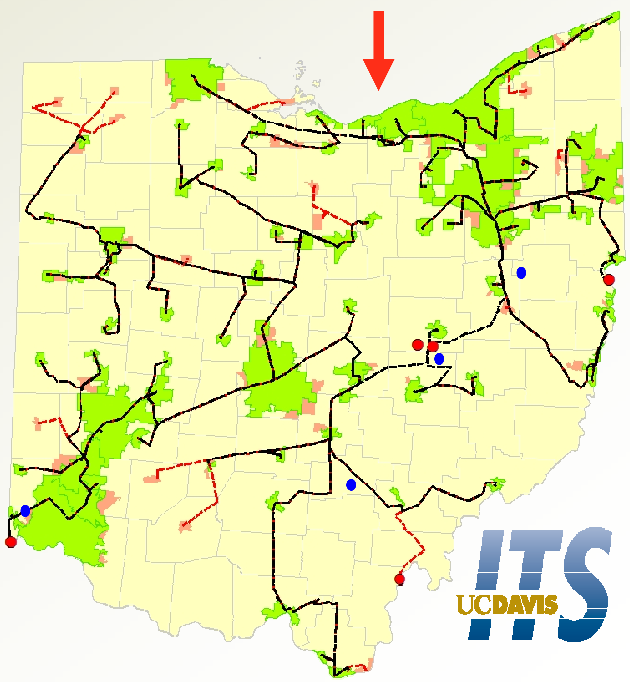
Average Utilization: 68%

Levelized Cost of Hydrogen: $3.70/kg

Pipeline Scenario: Period 3







Market Penetration Range: 31.8 - 54.3%

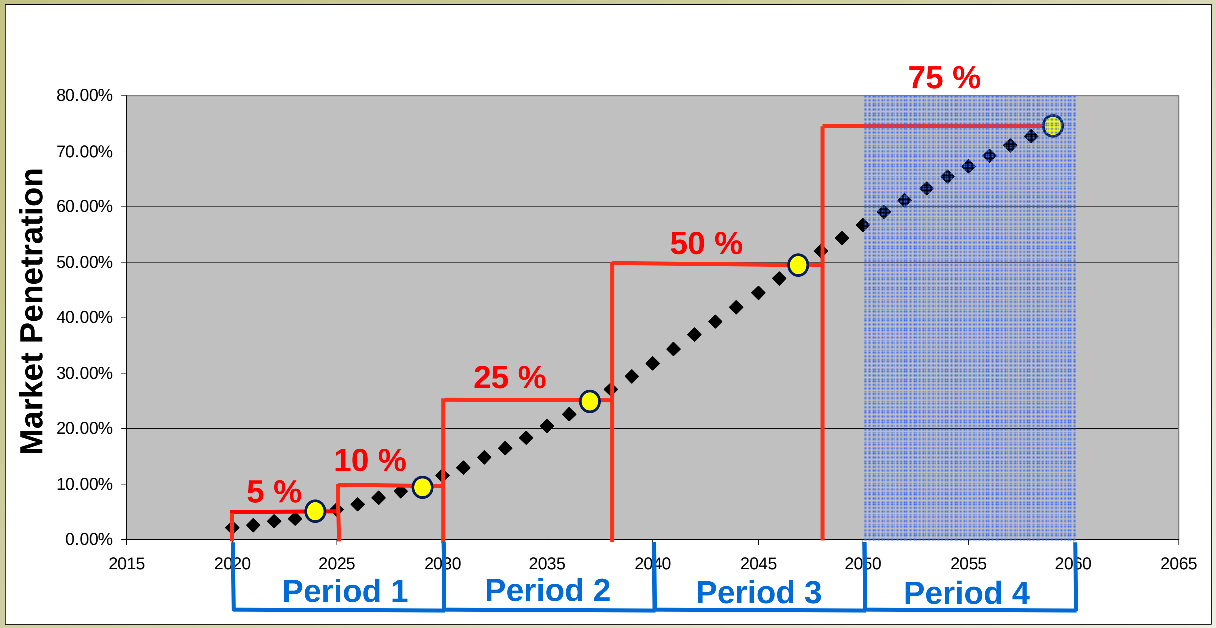
Infrastructure Installed: Year 29

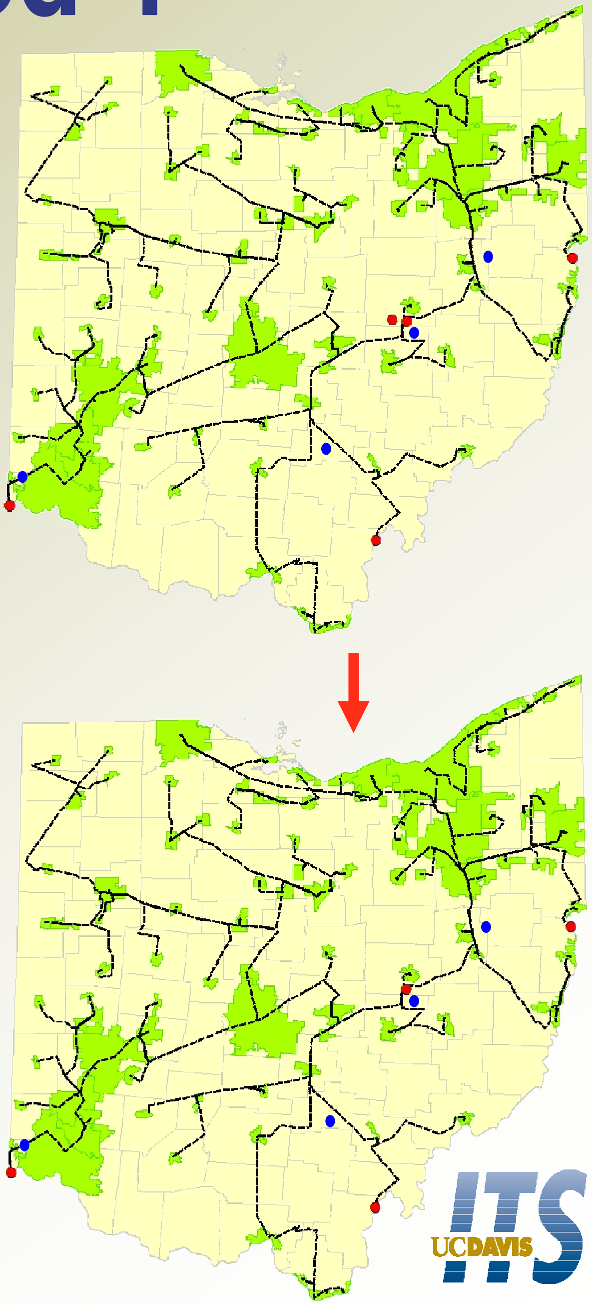
Total Capital Cost: $15.6 Billion

Average Utilization: 80%

Levelized Cost of Hydrogen: $3.02/kg

Pipeline Scenario: Period 4





Market Penetration Range: 56.7 – 74.9%

Infrastructure Installed: None

Total Capital Cost: $15.6 Billion

Average Utilization: 88%

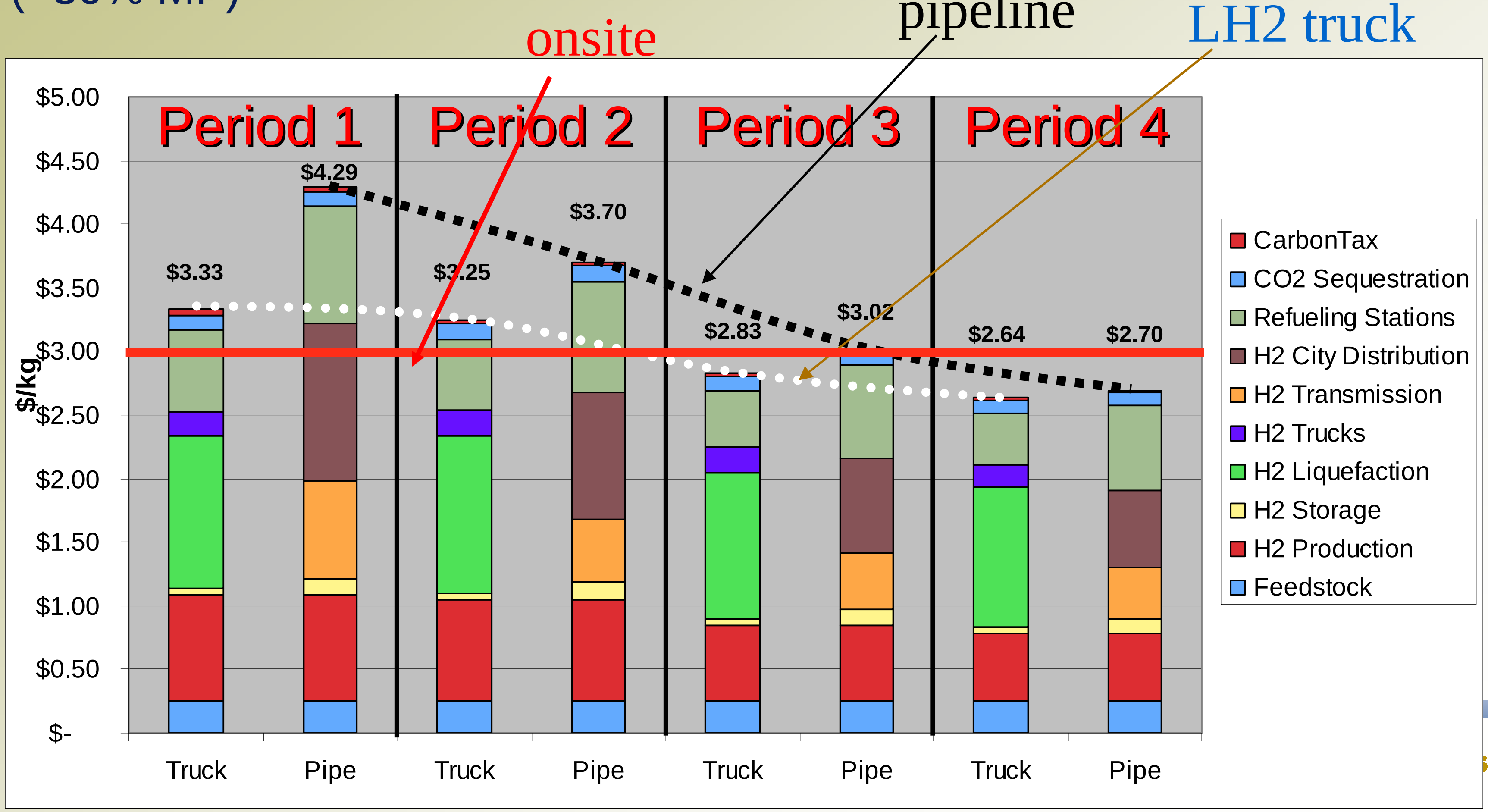
 Levelized Cost of Hydrogen: $2.70/kg

Build-Out Scenarios

Summary of Results

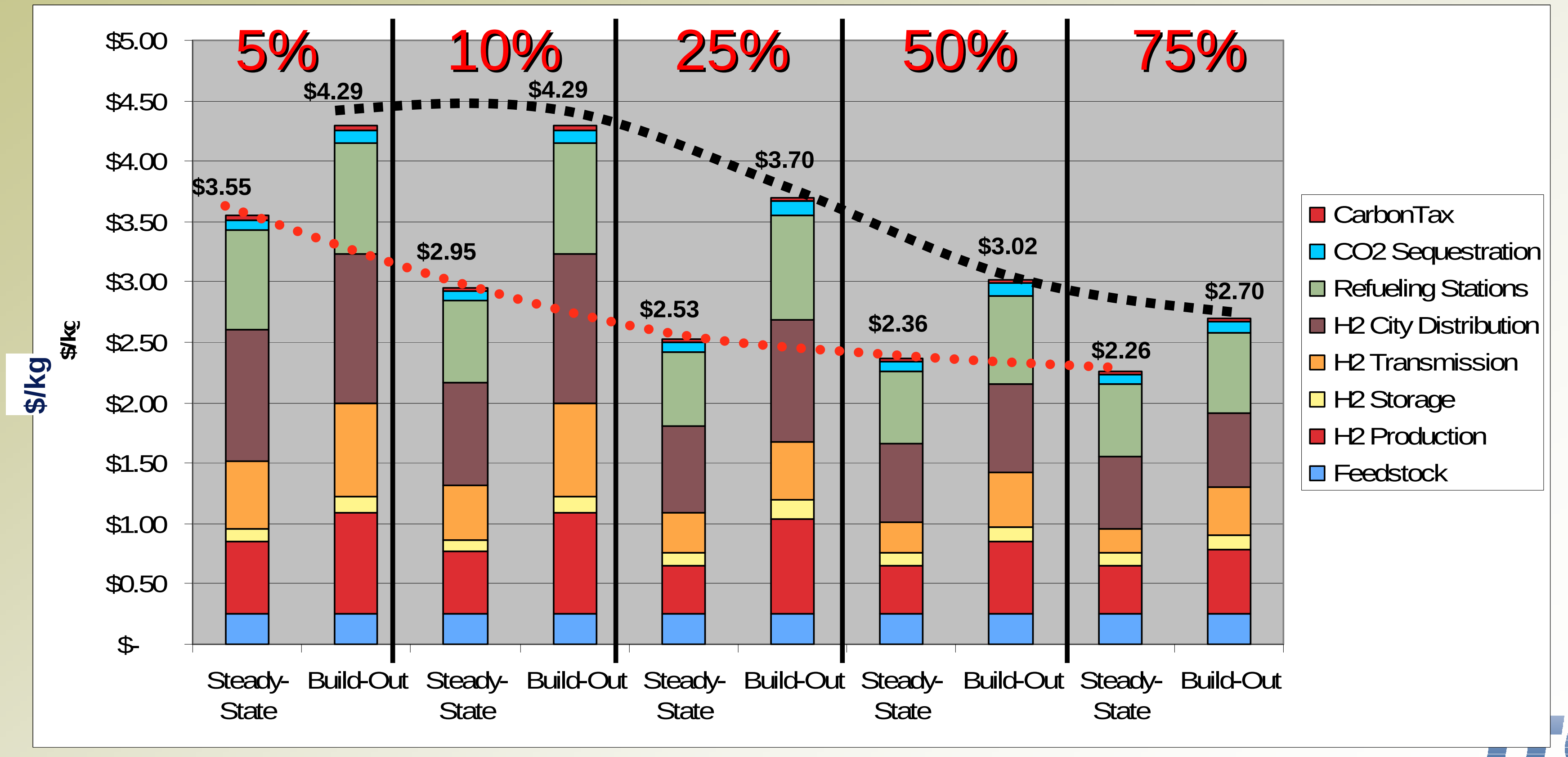
Liquid truck delivery is lower cost than pipelines throughout transition

Distributed production is lowest cost in first two periods @ $7/mmBtu (~30% MP)

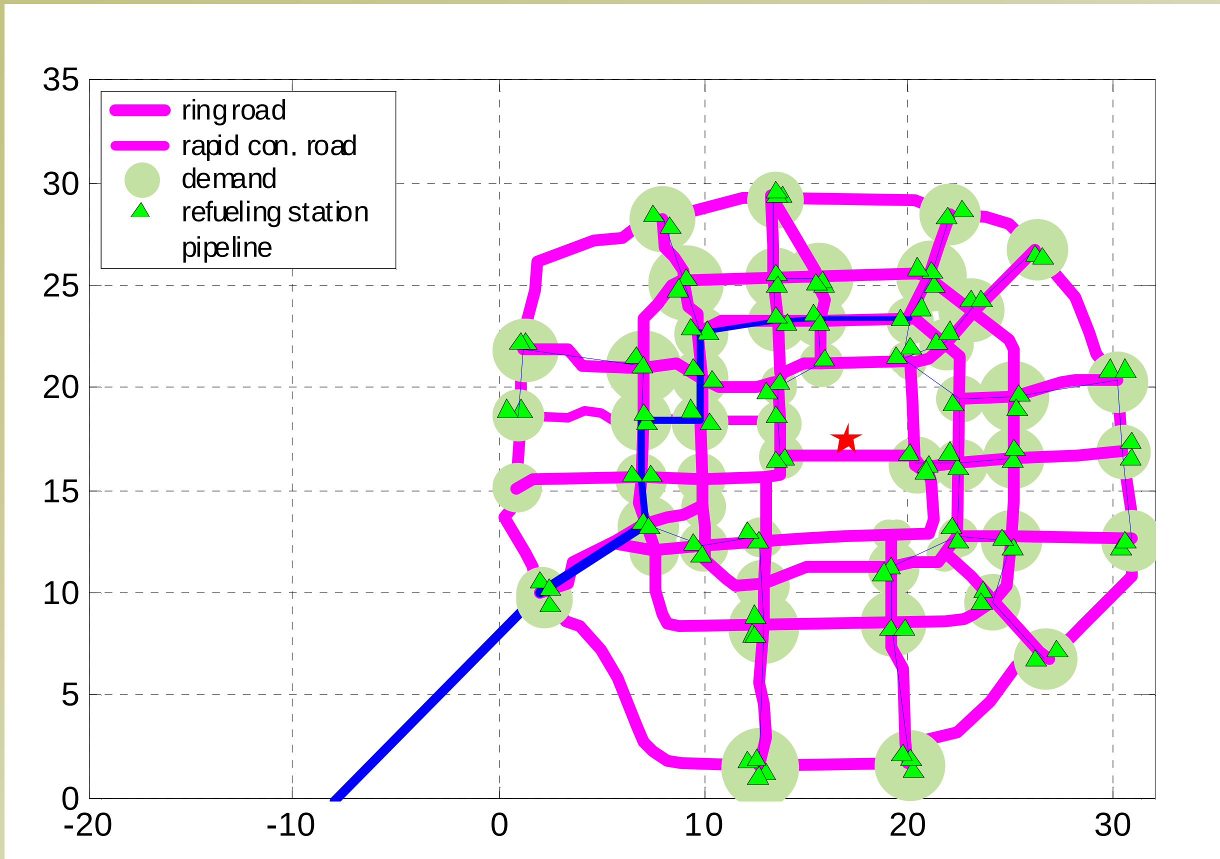


Comparison of Steady-State and Build-Out Scenarios (Pipelines)

Levelized costs associated with steady-state scenarios are consistently lower (underutilization and legacy effects)



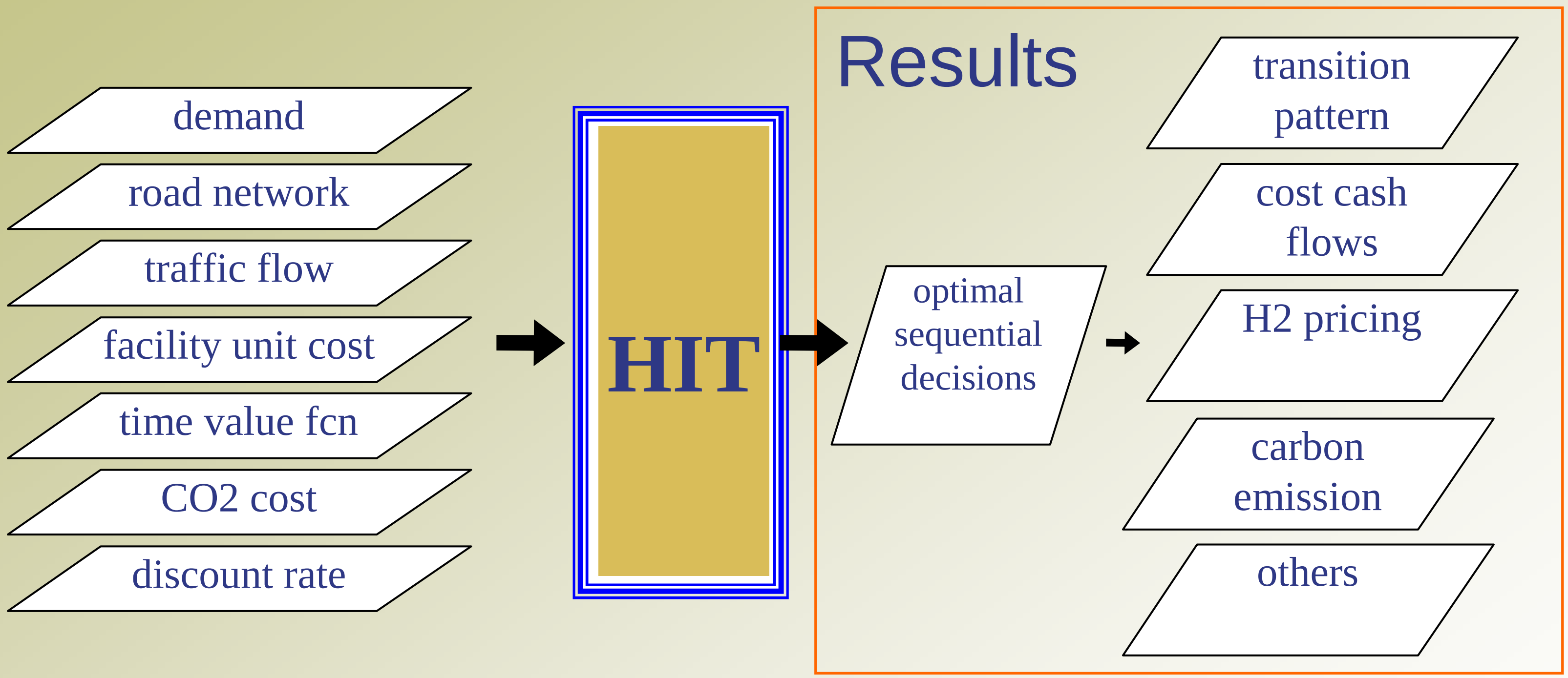
Modeling H_2 Transitions



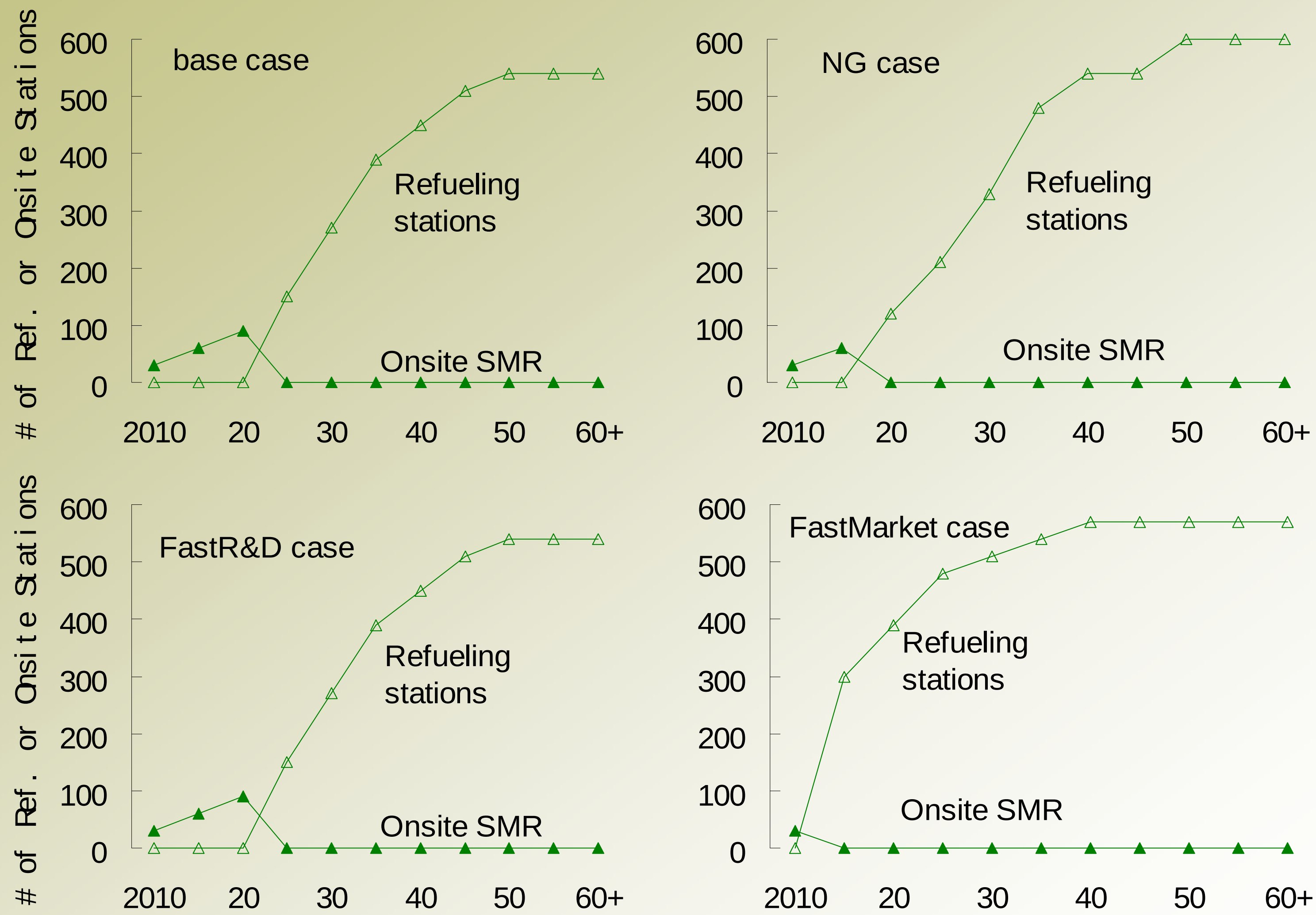
HIT (Hydrogen Infrastructure Transition) Model (D.Z..Lin)

- Consider cost, emissions, travel time
- Geographic specific
- Dynamic programming
- Considers optimal build-up in space and time

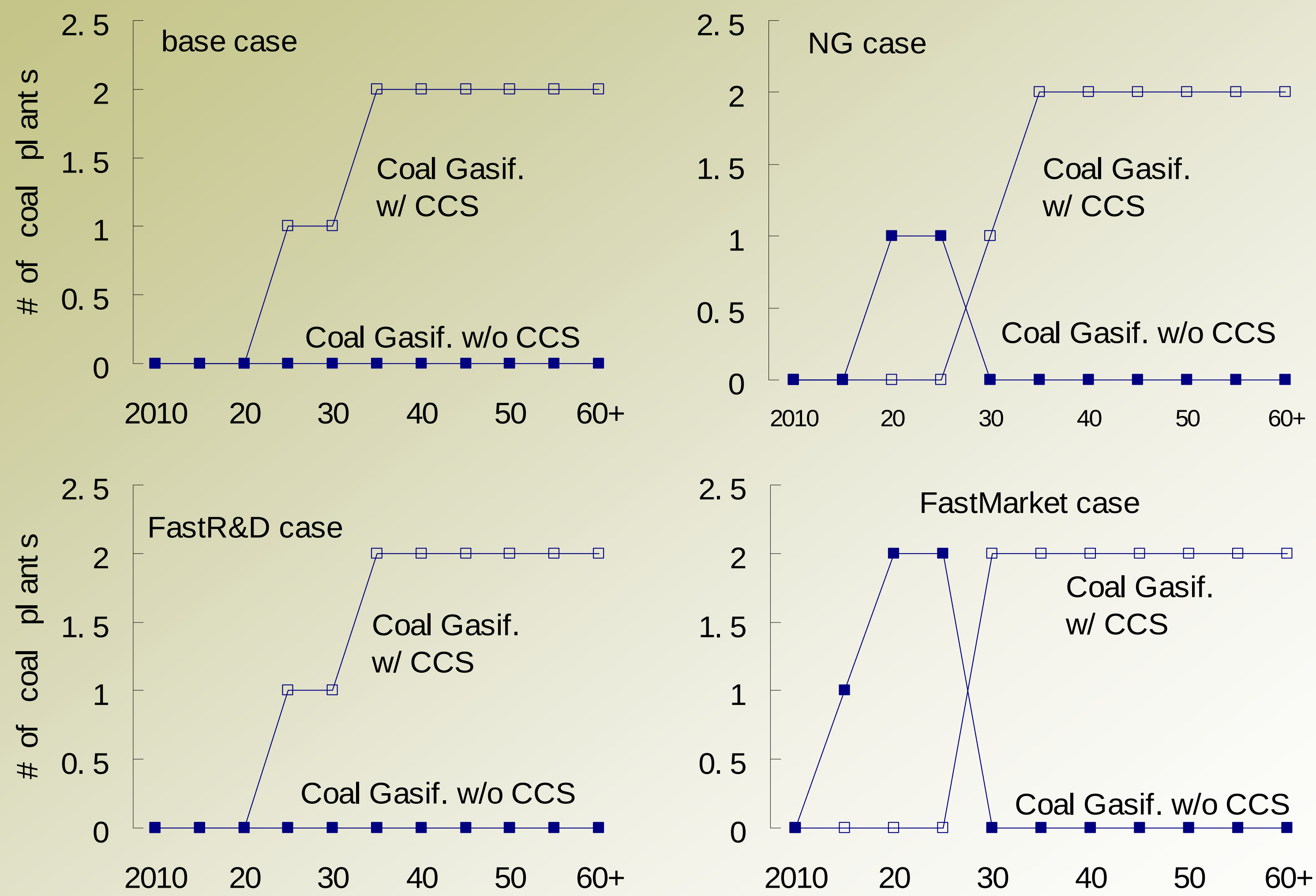
Hydrogen Infrastructure Transitions Model



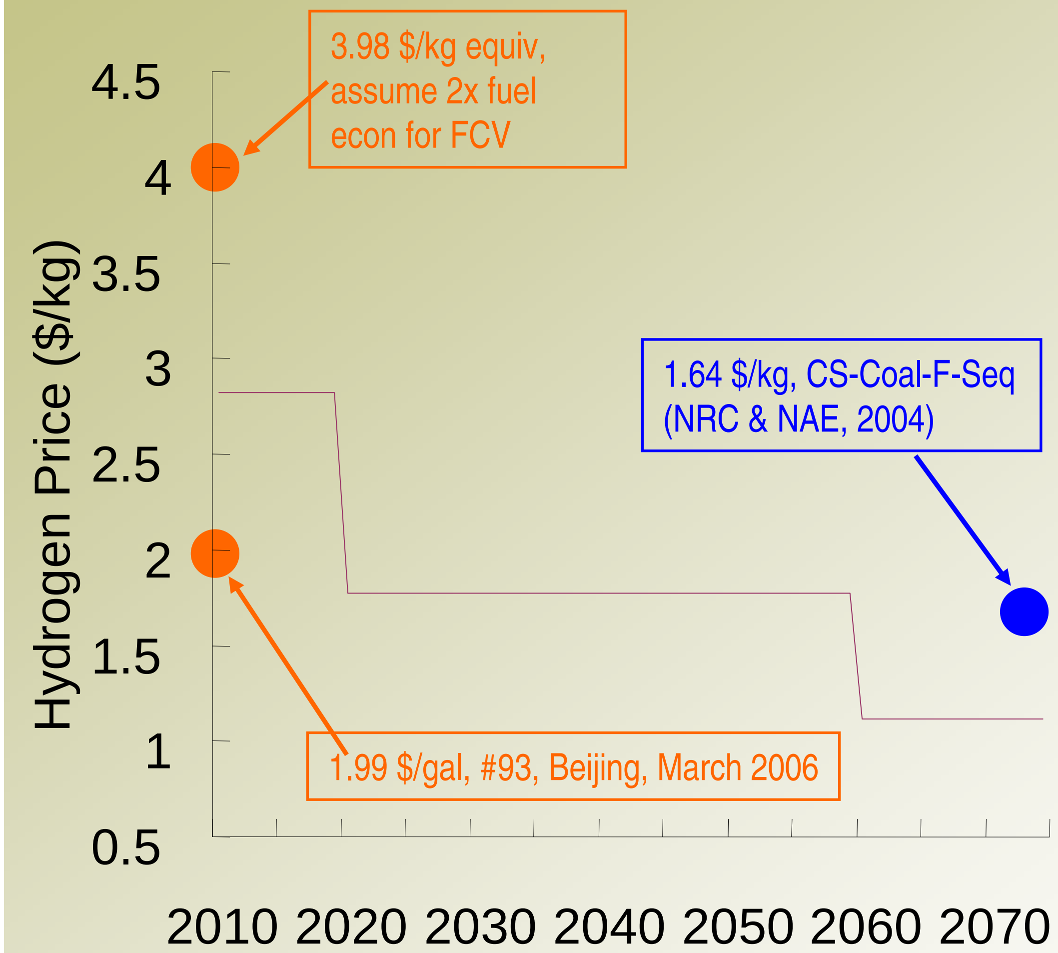
Optimal Decisions:
Transition from Distributed to Central Production



Optimal Decisions:
Implementing Carbon Sequestration



H2 Pricing Strategy for 12% IRR



- Price H2 higher initially to pay for more costly early infrastructure
- Lower price over time
- 12% IRR at ~$3/kg for first 10 years; $2/kg for next 40 years.
- About $1.2/kg from 2060 on
  - Lower than other estimates?
  - High demand density in Beijing
  - Optimization
  - 0.7 location factor

Lessons from H2P Transition Studies

What is required to initiate a H2 transition?

- Adequate consumer convenience with H2 offered at a small fraction of today's gasoline stations.
- History of early gasoline infrastructure suggests a range of possible early supply pathways

Lessons from H2P Transition Studies

How might the system evolve?

- **Distributed v. central H2 production?**
  - In most cases for cities, distributed hydrogen production offers lowest cost in early stages, but system generally evolves to central production, as the demand grows.
  - However, move to central supply happens <u>later</u> than steady-state models would predict.

Lessons from H2P Transition Studies

- **Fossil -> Low-C supply? (role of policy)**
  - Carbon tax => CCS for coal H2 plants.
  - Low carbon sources become lowest cost option in carbon-constrained world, but policy is needed
  - Renewable supplies (biomass gasification) can become competitive in mid term
  - CCS is key for coal, but needs large scale – co-production strategy?
- **Scale: Local -> Regional -> National**
  - Sparse city network of H2 stations plus a few stations on interstates may be sufficient for convenience
  - Regional supply can give lower costs because of scale economies in production and storage.

Lessons from H2P Transition Studies

What is the "end state?" LH2? Pipelines? Mix?

- Depends on geographic density of demand, energy prices, scale.
- Onsite, central with trucks can match demand better during transition.

- **Fast v. slow market growth**
  - Lower transition costs with fast market growth
  - Fast growth can lead to period of higher carbon emissions unless policy keeps up with market

Lessons from H2P Transition Studies

How much will it cost?

- Steady-state infrastructure models tend to underestimate the cost of hydrogen during a transition.
  - Do not account for under-utilization of capital
    - Pipelines happen too soon
    - Central plants displace distributed too soon
  - Trade-off between underutilization of capital and scale economies
- In mid to long term delivered hydrogen costs become cost competitive with gasoline (cents/km)
- There may be pricing strategies for hydrogen that yield a good rate of return throughout a transition.

Questions Going Forward

- **How are decisions made during transition?**
  - **Consumer behavior**
  - **Energy supply companies**
  - **Automakers**
  - **Competition among firms**
  - **Policy**
- **What are potential impacts of technology advances?**
  - **H2 storage**
  - **FCVs**
  - **Low-C H2 supply**

Questions Going Forward

- **What are the best regional strategies toward low-C H2 systems?**
- **H2 Interactions with rest of energy system**
  - **Merchant H2 and refinery**
  - **Electricity**
  - **Natural gas**
- **How does the cost of H2 transition compare to, interact with other fuels? Compare fuel/vehicle pathways**

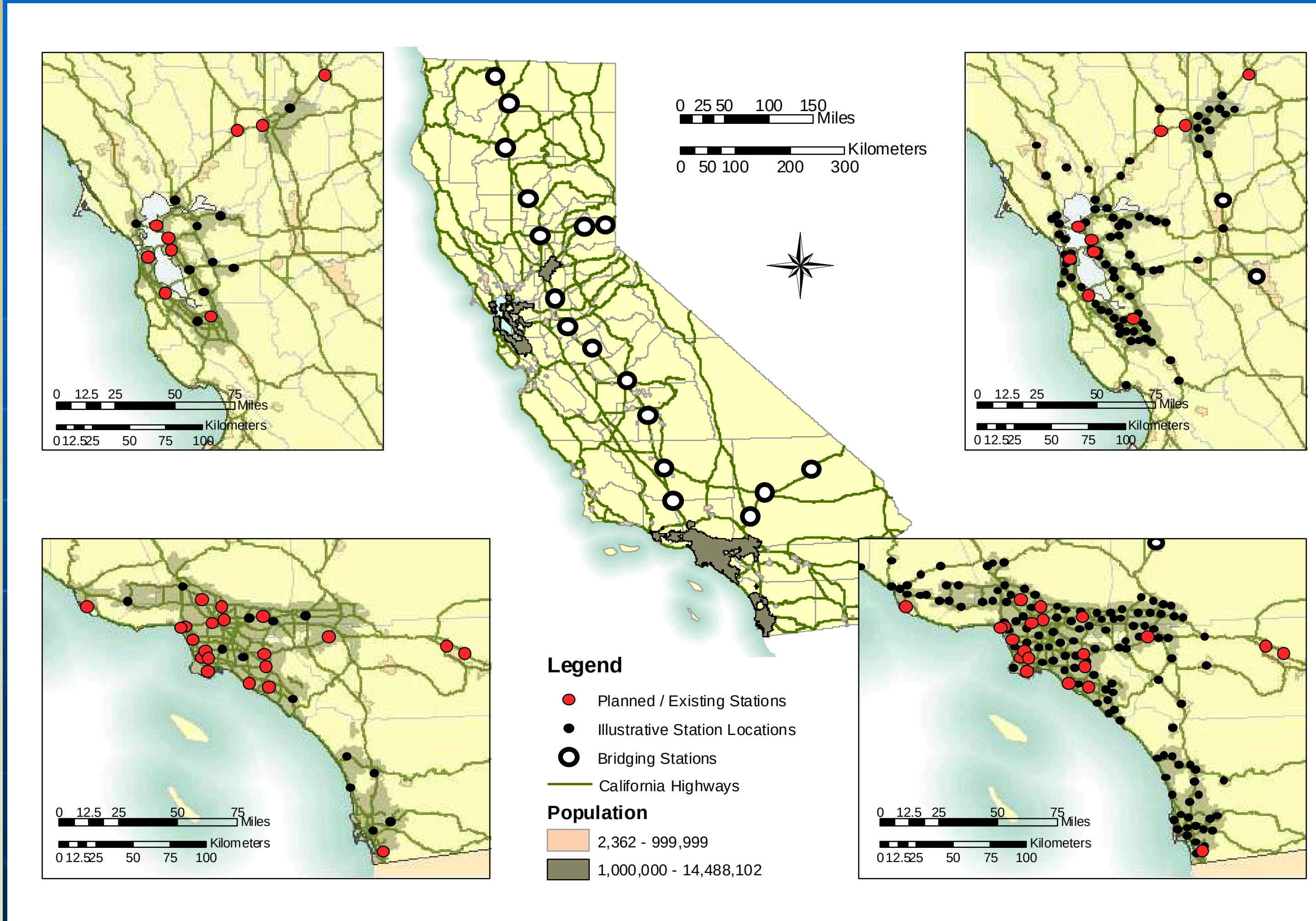
H2 Pathways Infrastructure Researchers

Prof. Joan Ogden	Obadiah Bartholomy
Dr. Chris Yang	Joel Bremson
Prof. Yueyue Fan	Steven Chen
Dr. Marc Melaina	Anthony Eggert
Dr. Tim Lipman	Nils Johnson
Dr. Andy Burke	David Zhenhong Lin
Dr. Marshall Miller	Ryan McCarthy
	David McCollum
	Jason Ni
	Michael Nicholas
	Nathan Parker
	Stephenie Ritchey
	Jonathan Weinert

extras

What's needed to initiate infrastructure?

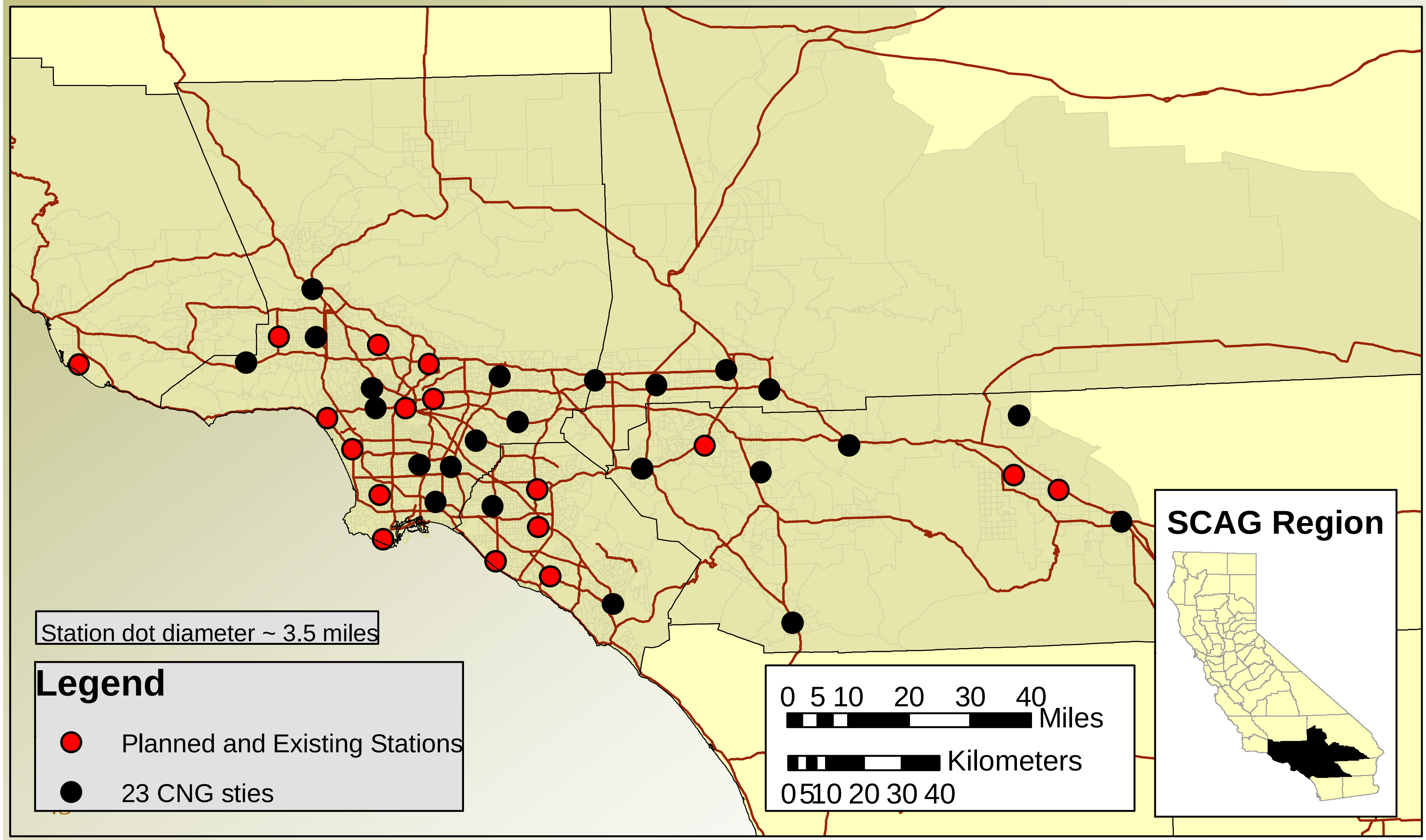
So. Cal. Case study for CA H_2 Highway Network



Michael Nicholas

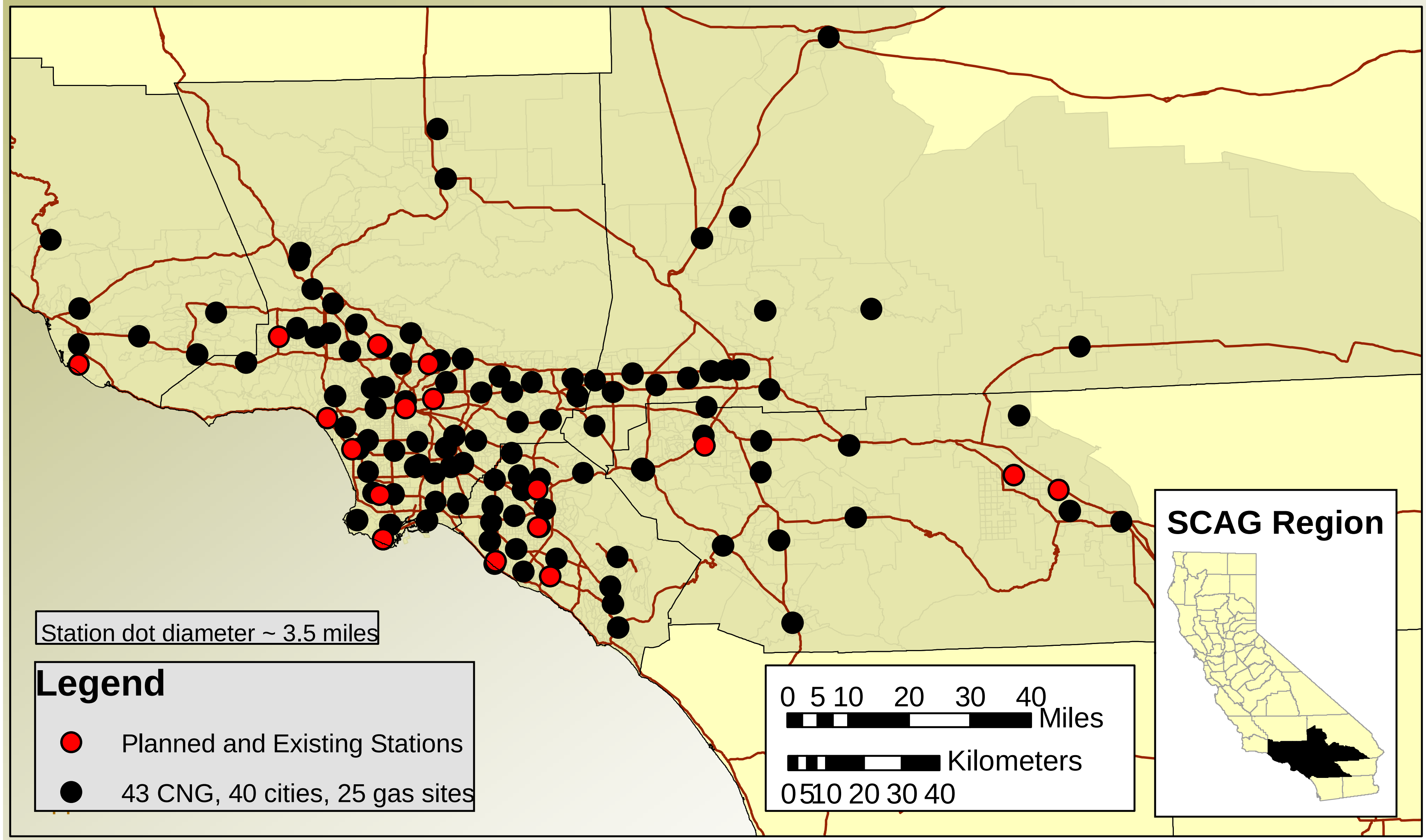
1% of stations in LA (40 stations total):

17 planned H2 stations + 23 fleet sites



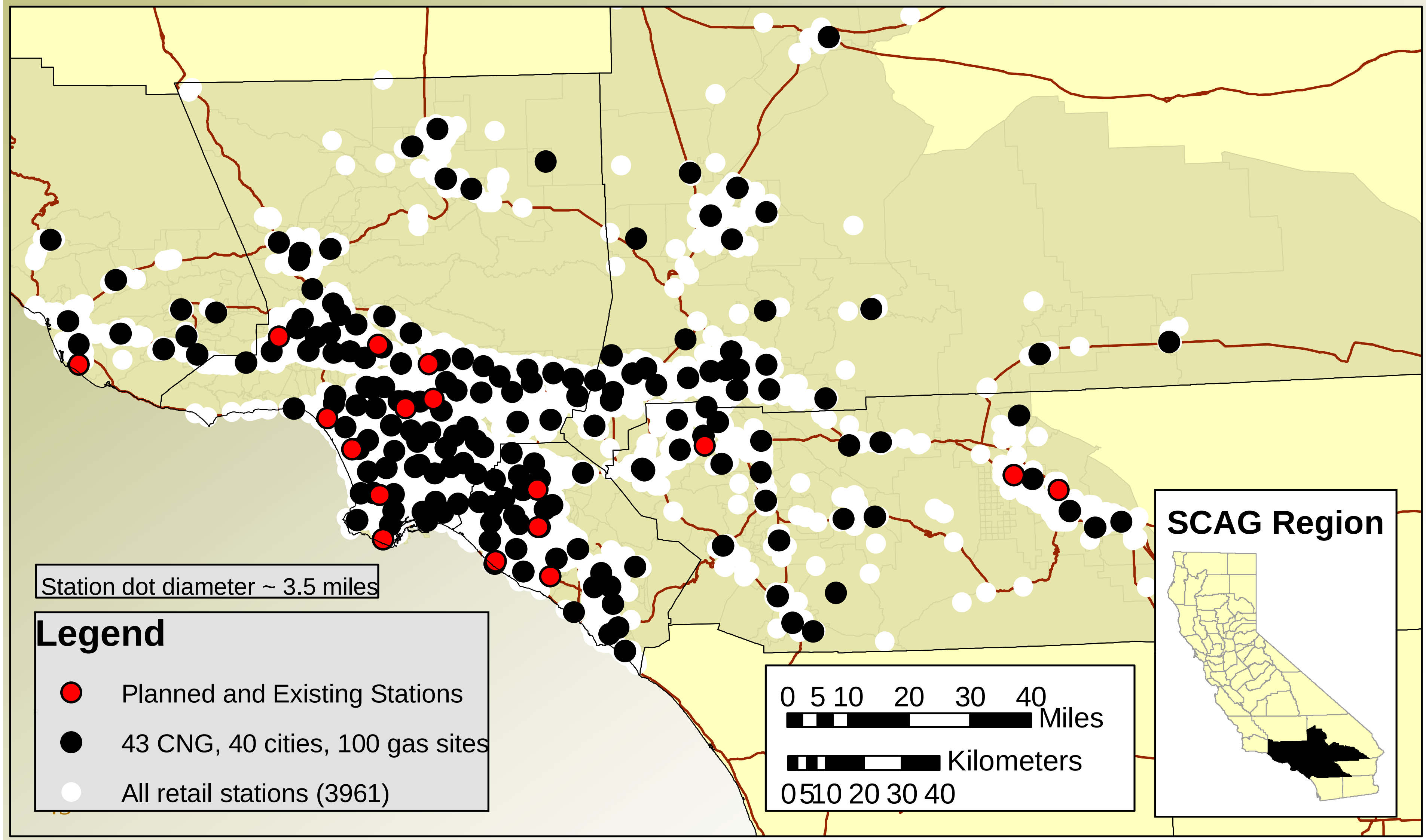
3% of stations in LA (125 stations total):

17 planned, 43 CNG fleet sites, 40 largest cites, 25 gasoline locations

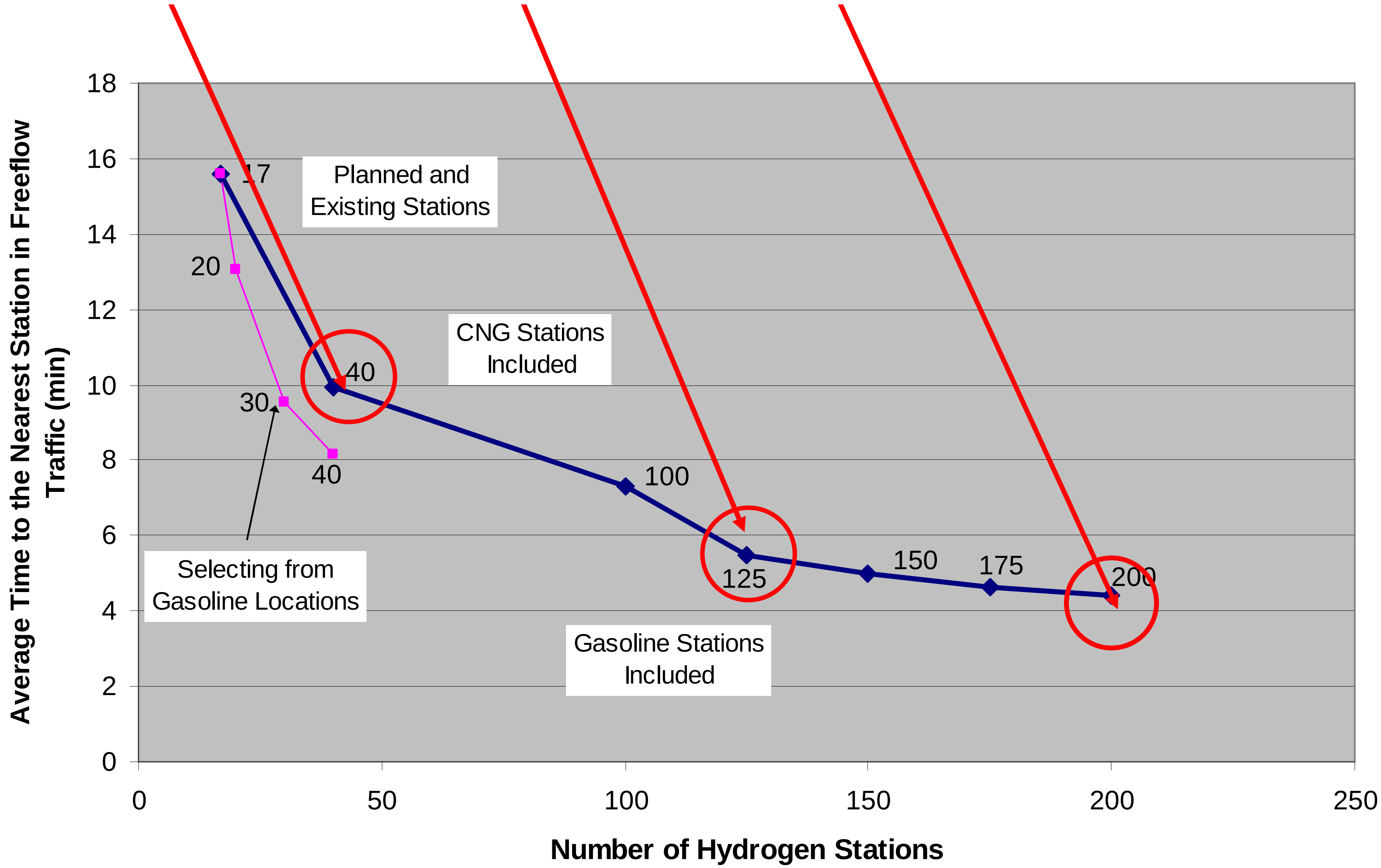


5% of stations in LA (200 stations total):

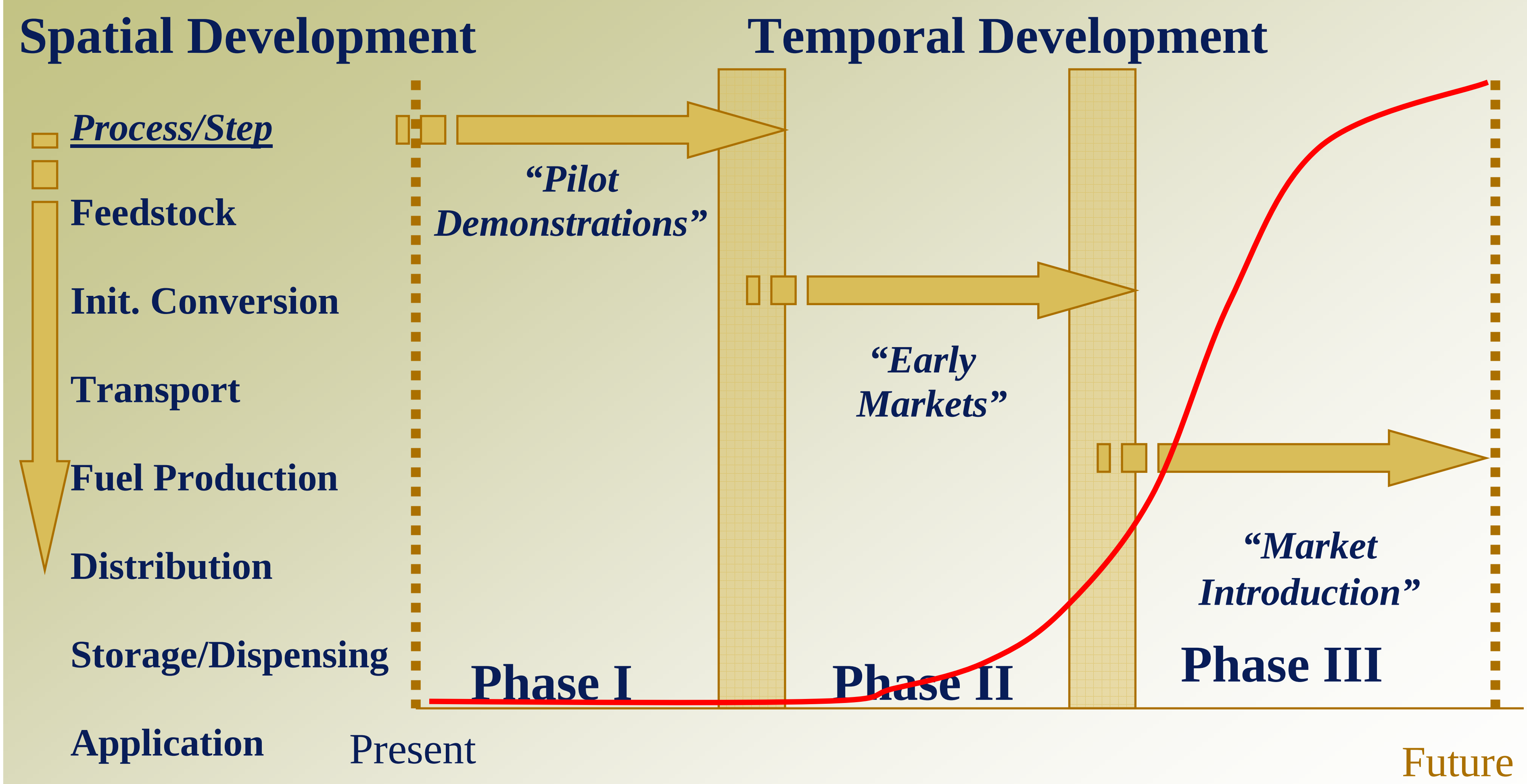
17 planned, 43 CNG fleet sites, 40 largest cites, 100 gasoline locations



Average Travel Time to the Nearest Station:
1% ~ 10 min; 3% ~ 6 min, 5% < 5 min



Hydrogen Pathways



Focus on "Transitions"!