MODELING REGIONAL HYDROGEN INFRASTRUCTURE DEVELOPMENT

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BACKGROUND

- Current lack of an extensive H_2 infrastructure is seen as a serious barrier to the introduction of H_2 as a energy carrier, and commercialization of H_2 vehicles (chicken and egg problem).
- H_2 can be made at a wide range of scales (from household to large city) and from a variety of primary sources (fossil, renewable and nuclear).
- There are many possible pathways for producing and distributing H_2 to users.

DESIGN, ECONOMICS AND EVOLUTION OF A H_2 ENERGY INFRASTRUCTURE DEPEND ON:

- Location, size, type, time variation and geographic density of the H_2 demand.
- Cost and performance of technologies making up a H_2 energy system.
- Cost, location and availability of resources for H_2 production. (And, for fossil derived H_2, location and capacity of sites for sequestering CO_2.)
- The capacity and location of existing energy infrastructure and rights of way.

GEOGRAPHY IS IMPORTANT IN UNDERSTANDING TRANSITION TO WIDESPREAD USE OF H_2

- Many of the factors that determine the system design are geographically specific => regional issues are likely to be very important in determining the design, cost and evolution of a H_2 energy infrastructure
- Most earlier technical/economic studies of H_2 infrastructure have estimated costs in a general way, rather than designing system for a particular region

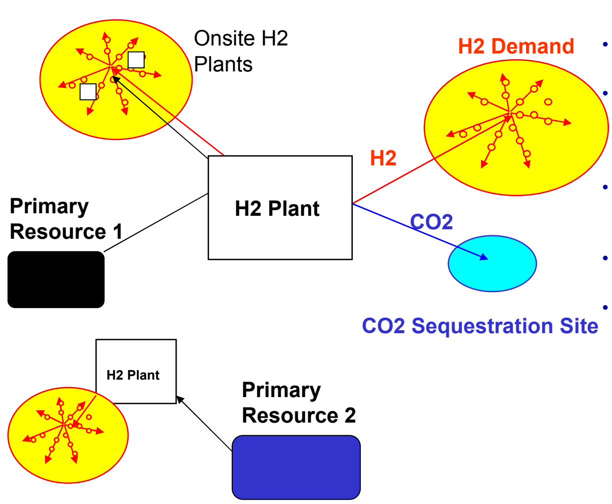
THIS STUDY: ***Assess alternative transition strategies toward widespread use of H_2 under different regional conditions.***

APPROACH

- Develop **engineering/economic models** of system components: H_2 production systems, H_2 transmission and distribution, H_2 refueling stations, H_2 demand, CO_2 sequestration.
- Use **Geographic Information System (GIS)** data to study spatial relationships between H_2 demand, supply, primary resources, CO_2 sequestration sites, and existing infrastructure in particular region.
- Explore use of various techniques **(GIS analysis, mathematical programming)** to find the lowest cost strategy for building a widespread H_2 energy system. Given a specified H_2 demand and resources for H_2 production, design a system to deliver H_2 to users at the lowest cost. Examine which transition paths give the lowest overall cost.
- Carry out **regionally specific case studies** of H_2 infrastructure development, involving multiple H_2 plants, multiple H_2 demand sites, using GIS data.

Optimization for Low Delivered H_2 Cost

What is the lowest cost system for producing and delivering H_2 to serve a growing demand ?



- **H_2 Plants: Size and Location?**
- **Resources for H2 production: Characteristics, distance from H_2 plant?**
- **Use existing energy infrastructure/rights of way?**
- **Optimum paths for H_2 infrastructure over time?**
- **Design problem is different than typical oil or gas pipeline systems w.r.t time frame and complexity**

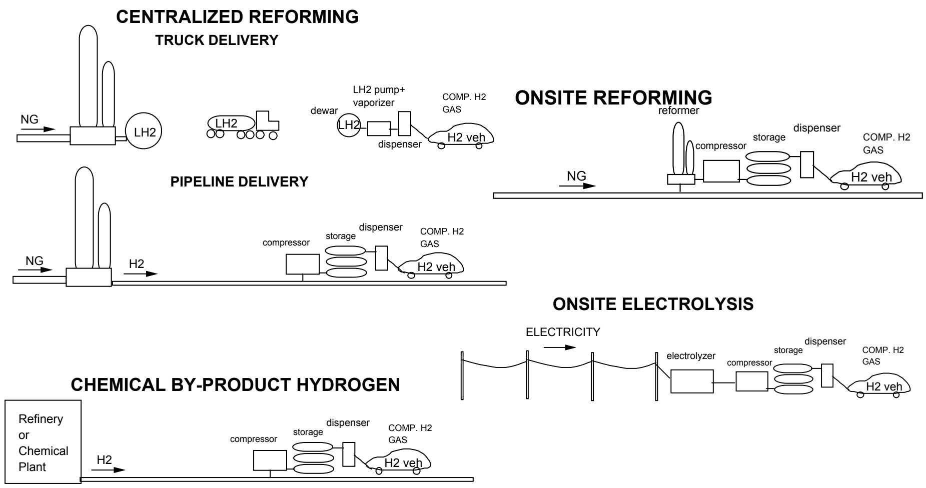
WHAT DO WE HOPE TO LEARN?

- Time constants and costs. How can H2 demand be characterized in space and time? Which supply options are preferred as demand grows? How fast can we implement H2 infrastructure? How much will it cost? What are the best strategies? What level of demand is needed for widespread implementation of H_2 energy system?
- Sensitivities to: technology performance and costs, size and density of demand, local availability of primary sources(and for fossil H2 CO_2 sequestration sites), market growth, policies.
- Rules for thumb for optimizing H_2 infrastructure development.

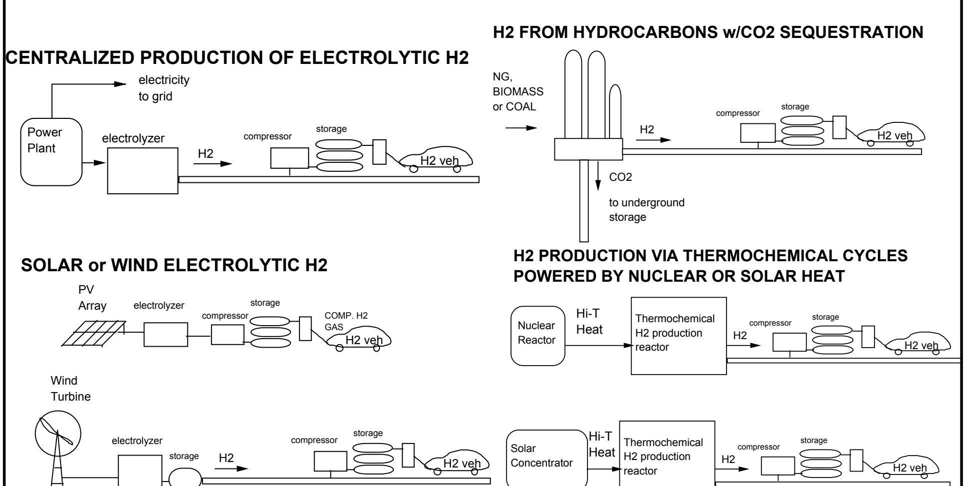
MODELING H_2 ENERGY SYSTEM COSTS

- Develop engineering/economic cost and performance estimates for H_2 production systems, H_2 storage, H_2 transmission and local distribution, H_2 refueling stations, CO_2 sequestration, as function of scale.
- Future feedstock/energy prices (natural gas, electricity, coal, wind etc.) use EIA projections for particular regions. *(More generally, one could calculate the cost of increasing supply of primary energy resources to make H_2 for vehicles. For example, increase the natural gas supply for H_2 from steam reforming or build wind power systems.)*

Near term H_2 Supply Options



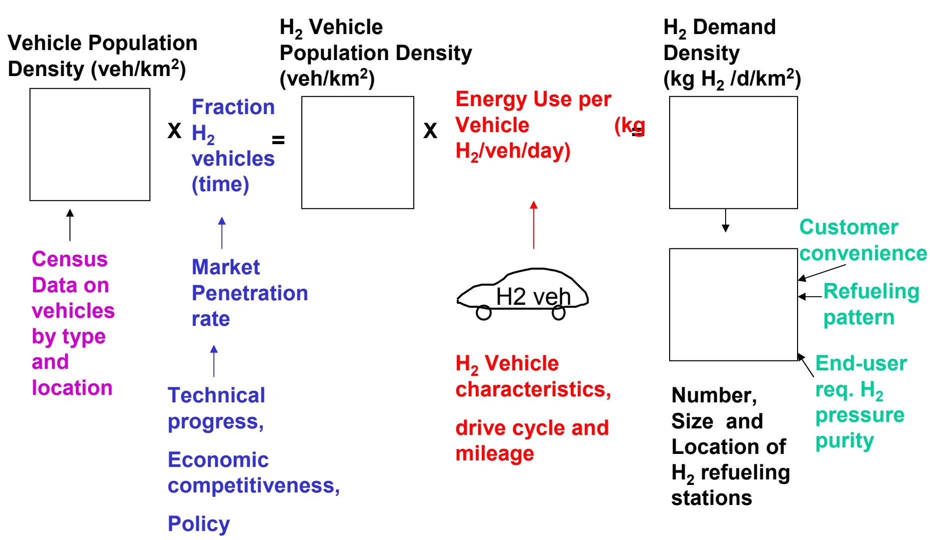
Long term H_2 Supply Options



MODELING H_2 DEMAND

- Numbers, geographic location and density of vehicles
- H_2 use by different types of vehicles
- Market penetration rate
- Location and size of refueling stations to serve projected demand

CREATING A H_2 DEMAND MAP



Fraction of H_2 cars in fleet vs. year and market penetration rate

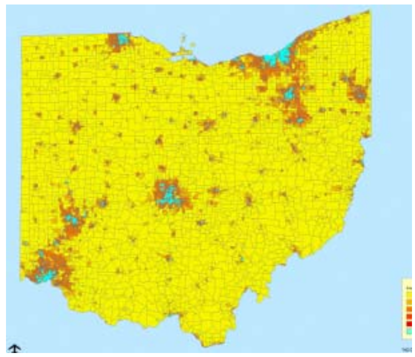
H_2 Cars (fraction of all new cars)	Year 1	Year 5	Year 10	Year 15
10%	0.7%	3.5%	7%	10%
25%	1.8%	9%	18%	25%
50%	3.5%	18%	35%	50%
100%	7%	35%	70%	100%

CASE STUDY: A H_2 ECONOMY IN OHIO

- Population = 11.1 million people
- 6.7 million cars; 3.0 million light trucks; 3.4 million heavy trucks and buses (Ave. miles/yr/vehicle = 10,250; ave. fuel economy for Light Duty Vehicles (LDVs) = 20 mpg)
- Energy use 4300 Trillion BTU/y (32% coal, 20% NG, 15% gasoline, 7% Distillate fuel)
- Installed Electric capacity = 27,000 MWe, 90% coal-fired, ~2.5 kWe/person; ave. coal plant capacity factor ~ 65%
- If all LDVs converted to H_2, statewide
  - NG use would increase by ~25% OR
  - Coal use would increase by ~20% (statewide, 16-20 CO_2 injection wells, each disposing of 2500 tonne/day would be needed for CO_2 produced in 4-5 1000 MW coal->H_2 plants) OR
  - Electric power ~ 6500 MWe would be needed on continuous basis. Or ~ 13,000 MWe off-peak power for 12 h/d.

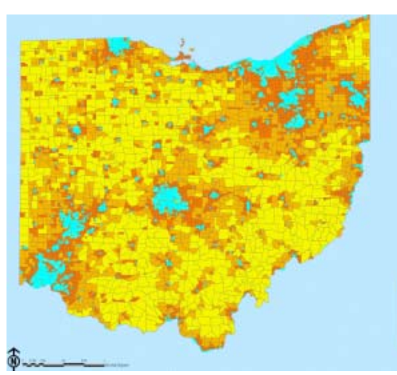
H$_2$ DEMAND DENSITY (kg/d/km^2): YEAR 1:
25% OF NEW Light Duty Vehicles = H$_2$ FCVs

Blue = high demand density = good location for refueling station



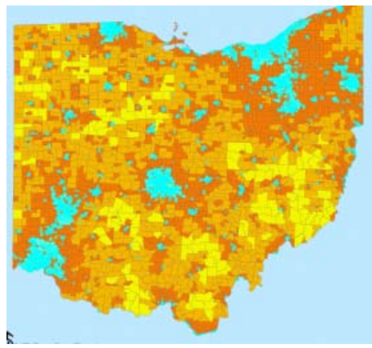
H$_2$ DEMAND DENSITY (kg/d/km^2):

YEAR 5: 25% OF NEW LDVs = H$_2$ FCVs



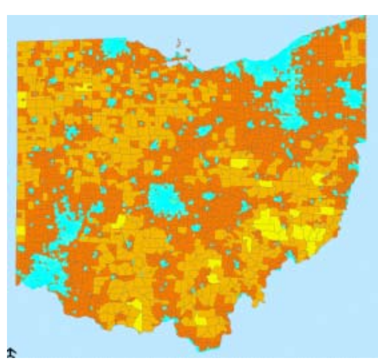
H$_2$ DEMAND DENSITY (kg/d/km^2):

YEAR 10: 25% OF NEW LDVs = H$_2$ FCVs



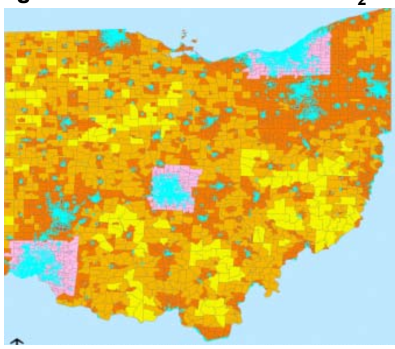
H$_2$ DEMAND DENSITY (kg/d/km^2):

YEAR 15: 25% OF NEW LDVs = H$_2$ FCVs



TOOLS FOR ESTIMATING H_2 DEMAND

Highlight urban areas to find total H_2 demand in a city



For example, in year 10 of 25% market penetration rate (18% of LDVs use H2):

Cleveland: 60,000 kg/d
(25 million scf/d or 100 MW)

Columbus: 44,000 kg/d
(18 million scf/d or 71 MW)

Cincinnati: 46,000 kg/d
(19 million scf/d or 75 MW)

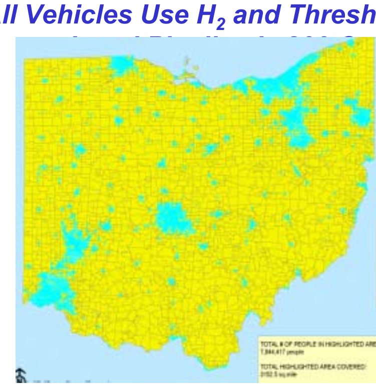
State: 384,000 kg/d
(159 million scf/d or 630 MW)

OBSERVATIONS: The 3 largest urban areas account for ~40% of state H_2 demand, but many people live in areas with lower demand density, where infrastructure might be more expensive -- at least at this level of demand (10 years into a 25% H_2 vehicle market penetration rate).

Each city has relatively small H_2 demand, ~10% of the size of a large fossil H_2 plant. One 380 t/d (153 million scf/d) central H_2 plant could serve the entire state, but long, inter-city pipelines would be needed => local, smaller scale H_2 production might be preferred at this level of H_2 demand.

HOW MANY PEOPLE LIVE IN AREAS WHERE LOCAL H_2 PIPELINE DISTRIBUTION MIGHT BECOME VIABLE IN THE LONG TERM?

Assume All Vehicles Use H_2 and Threshhold for Building a H_2
s/km^2



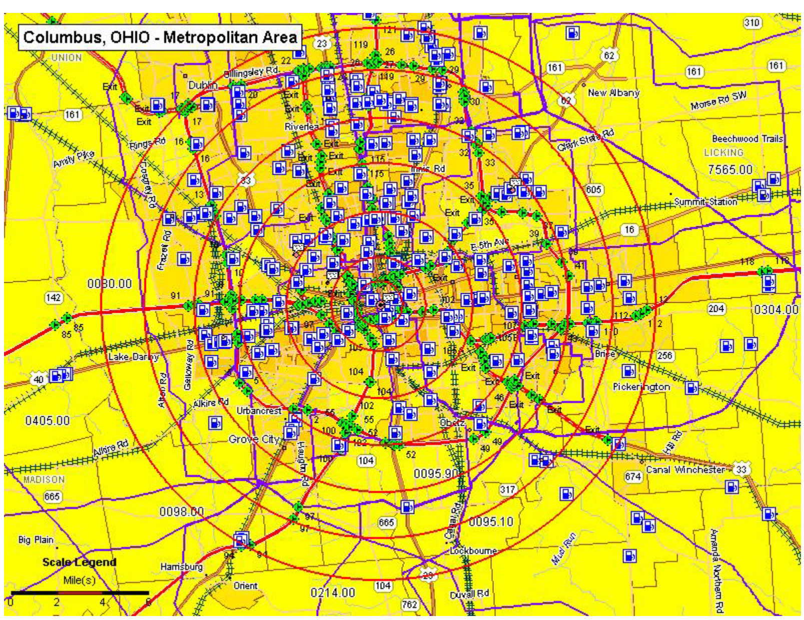
Highlight areas where H_2 cars>200/km^2

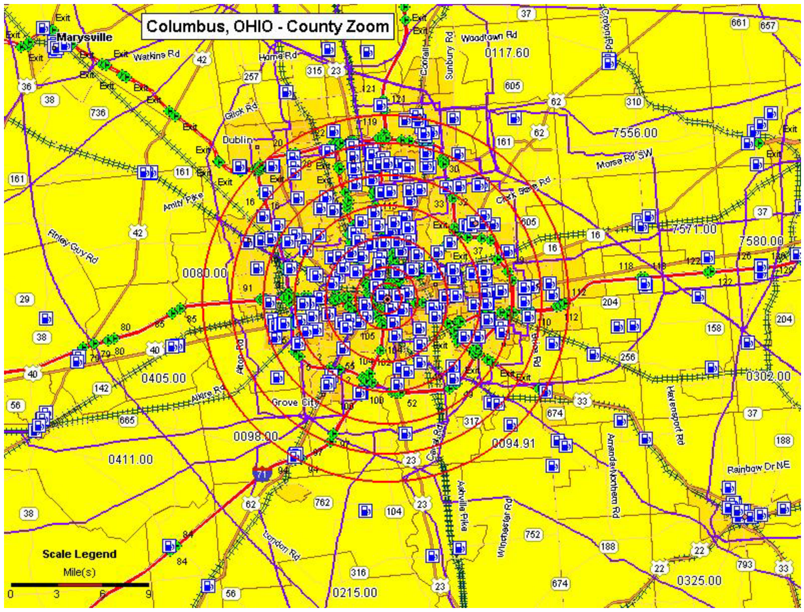
Sum population in highlighted areas = 7.8 million people

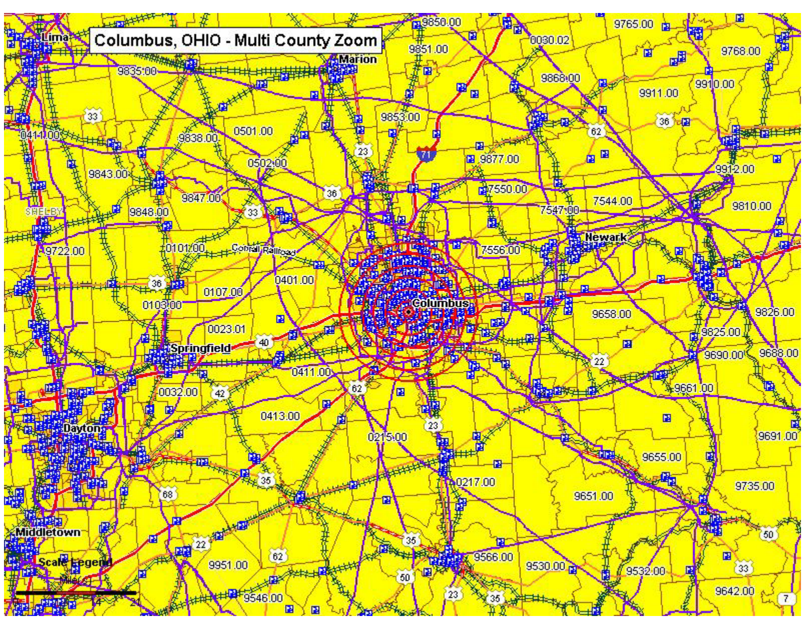
This is ~70% of the total state population

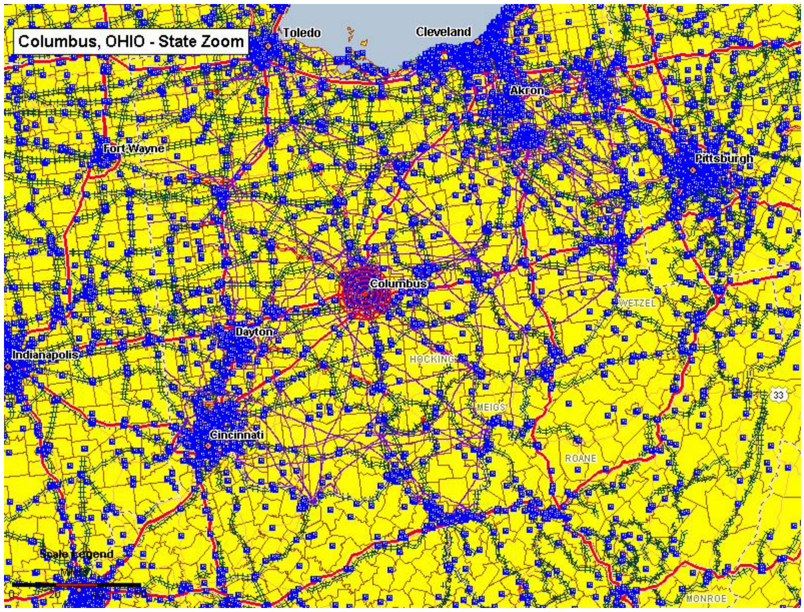
H_2 REFUELING STATIONS

- Where should H_2 refueling stations be located? *(Early H_2 stations might serve fleets, possibly co-located with CNG stations or buildings; later stations serve general transportation markets)*
- How many H_2 stations are needed and how many cars should each station serve? *(A large number of stations offers more convenience, but the infrastructure might cost more per car, and limit the possibility for carbon capture, if many small stations are needed. Can H_2 be acceptably convenient at a reasonable cost?)*
- What level of convenience is needed? *(How convenient are gasoline stations today? Or are home, neighborhood or workplace refueling preferred?)*




Columbus, OHIO - County Zoom
Scale Legend
Mile(s)


Columbus, OHIO - Multi County Zoom
Scale Legend

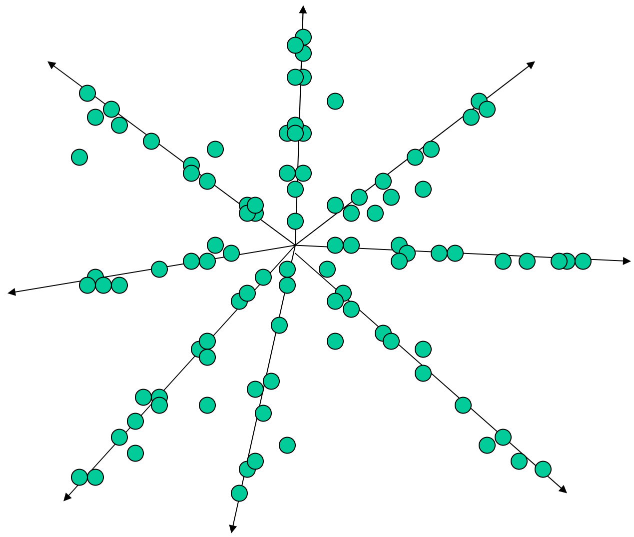


HOW CONVENIENT ARE GASOLINE STATIONS IN OHIO?

From analysis of GIS data, we find for Columbus, Ohio area gasoline stations:

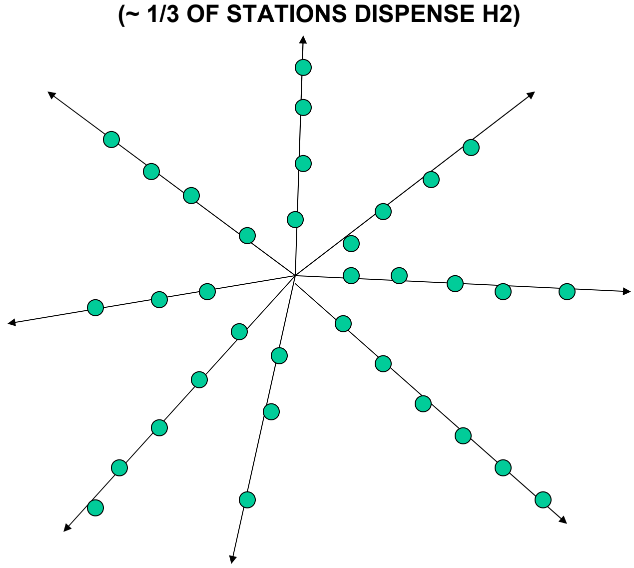
- ~240 gasoline stations. Density of urban gasoline refueling stations ~1 per mi^2 (1.3/mi^2 ctr city; 0.7/mi^2 suburbs)
- Fraction of gasoline stations on main roads ~ virtually all
- Distance between gasoline stations along roads
  - Urban roads ~ 1 per mi
  - Rural Interstates ~ 1 per 6-10 mi
- Fraction of gasoline stations in “clusters” (arbitrarily defined as several stations within 0.5 mi of each other)
  - Urban ~ 60-70% (typically 2 to 4 stations per cluster)
  - Interstate ~ 90% (typically 3 to 5 stations per cluster)
- Fraction of gasoline stations in near rail lines,electric lines, natural gas lines, or limited access highways (possible rights of way for H_2 local pipelines) = almost all.

LOCATION OF GASOLINE STATIONS TODAY



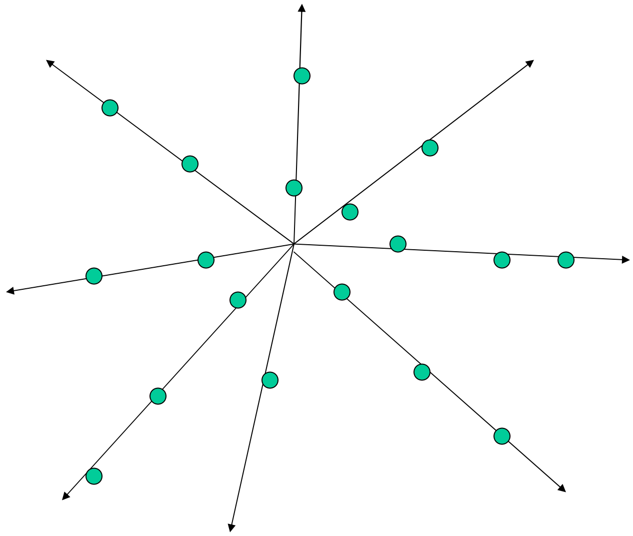
EQUIVALENTLY CONVENIENT LAYOUT (?)

(~ 1/3 OF STATIONS DISPENSE H2)



ACCEPTABLY CONVENIENT LAYOUT (?)

(~ 1/6 OF STATIONS DISPENSE H2)



Convenience trade-off

Acceptable Distance between urban stations (mi)	#(fraction) of gas stations that offer H_2	H_2 Cars served per station = (fraction H_2 cars in fleet) *(3000 cars per station)/ (fraction of stations w/ H_2)	H_2 dispensed in each station kg/day
1 (~same as today's gas stations)	80(33%)	90 (1% H2 cars) 900 (10% H2 cars) 9000 (100% H2 cars)	30 300 3000
2 (~ half as convenient)	40 (17%)	180 (1% H2 cars) 1800 (10% H2 cars) 18000 (100% H2 cars)	60 600 6000
Acceptable Distance between interstate stations (mi)			
10	25%		
20	12%		

“Gasoline-like” convenience in Columbus (80 stations):

Number of H_2 cars served

(kg H_2/day dispensed*)

H_2 Cars (fraction of all new cars)	Year 1	Year 5	Year 10	Year 15
10%	56 21	282 106	564 211	806 302
25%	145 54	725 272	1450 540	2014 755
50%	282 106	1450 544	2820 1057	4029 1510
100%	564 211	2820 1057	5640 2115	8057 3020

Comp.Gas Truck = 420 kg

LH2 Truck = 3600 kg

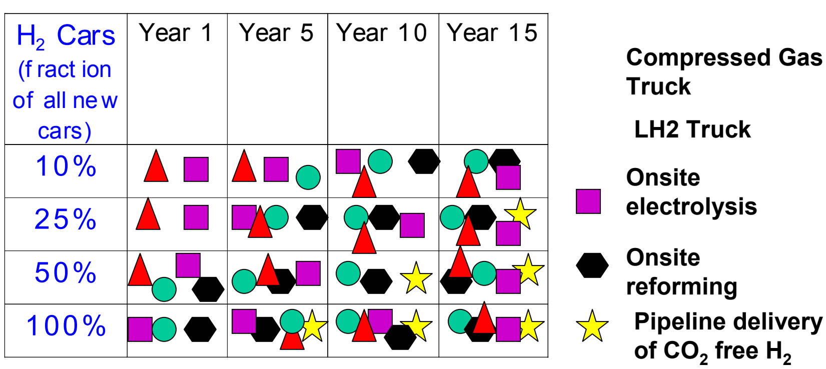
Onsite reformer = 240-4800 kg/d

Onsite electrolyzer = 2.4-2400 kg/d

Pipeline delivery = 240-4800 kg/d per station; (pipeline viable, only if high demand and high demand density)

* assumed 80 mpge H2 FCV driven 11,000 mi/y

Possible H_2 refueling options for “Gasoline-like” convenience at public H_2 refueling stations: match by capacity



Select lowest cost H_2 refueling options for "Gasoline-like" convenience at public H_2 refueling stations over time:

(don't quote this slide yet: work in progress!)

H_2 Cars (fraction of all new cars)	Year 1	Year 5	Year 10	Year 15
10%	▲ ■	▲ ■ ●	■ ● ⬢	⬢
25%	▲ ■	■ ● ⬢	⬢	⬢ ☆
50%	▲ ■ ● ⬢	● ⬢	⬢ ☆	☆
100%	● ⬢	⬢ ☆	☆	☆

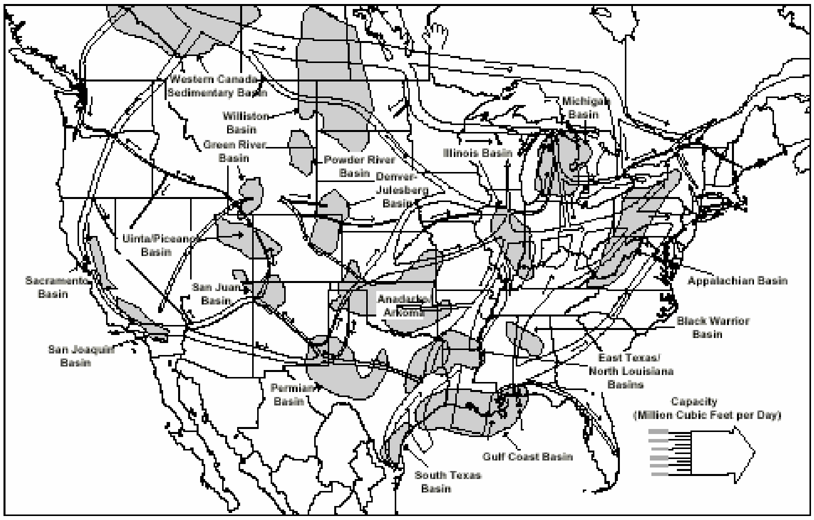
- ▲ **Compressed Gas Truck**
- ● **LH2 Truck**
- ■ **Onsite electrolysis**
- ⬢ **Onsite reforming**
- ☆ **Pipeline delivery of CO_2 free H_2**

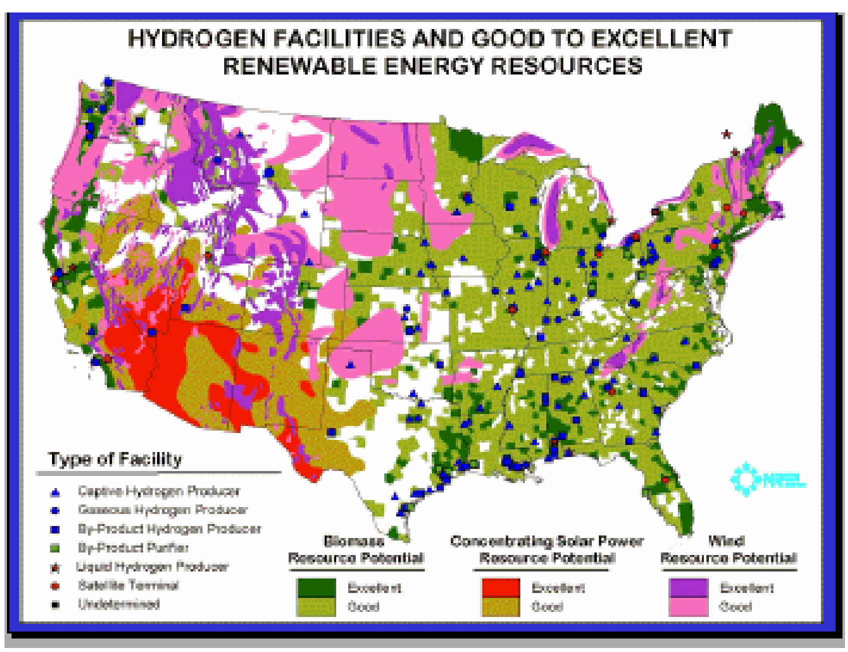
Other convenient scenarios for H_2 refueling at work or home could be envisioned.

Onsite electrolysis might compete with onsite SMR depending on electricity, NG prices, and could use CO_2 free electricity.

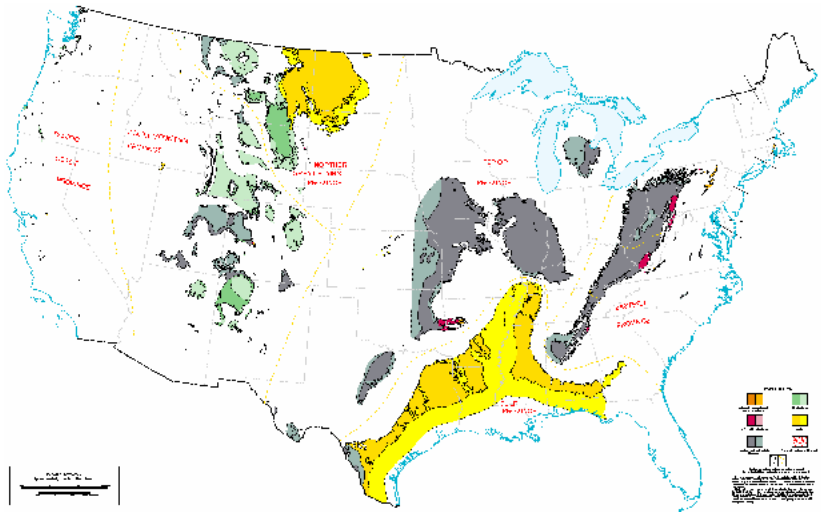
RESOURCES FOR H_2 PRODUCTION

Figure 2. Major Natural Gas Producing Basins and Transportation Routes to Market Areas

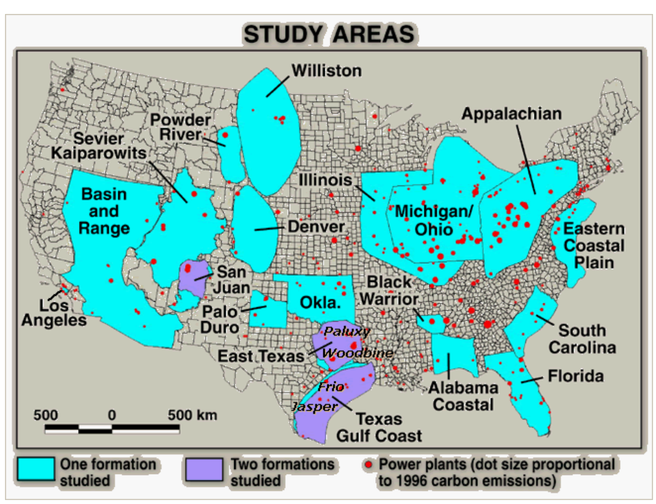




MAJOR US COAL FIELDS

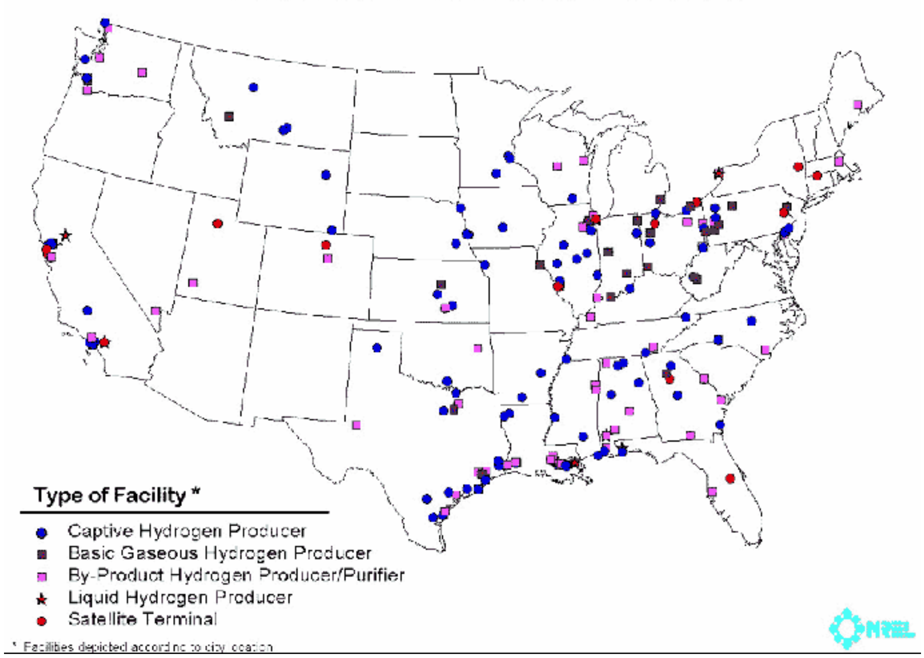


Potential Sites for Underground CO_2 Sequestration Widely Available

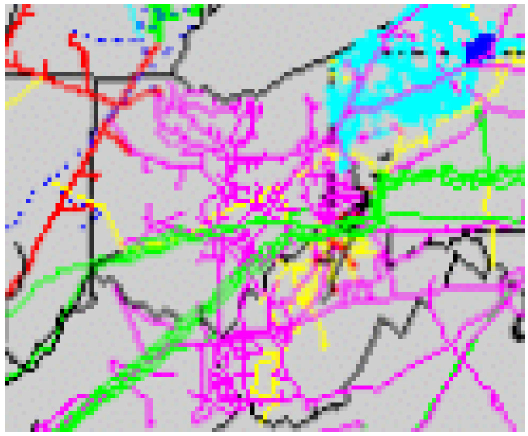


ROLE OF EXISTING ENERGY INFRASTRUCTURE AND RIGHTS OF WAY

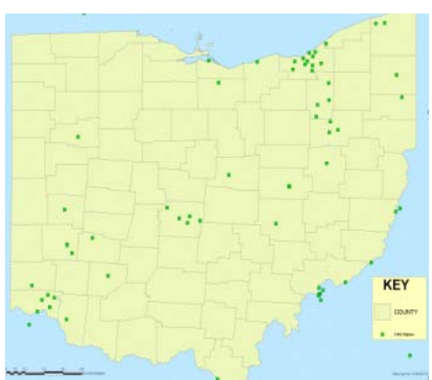
HYDROGEN PRODUCTION FACILITIES



NATURAL GAS TRANSMISSION SYSTEM IN OHIO

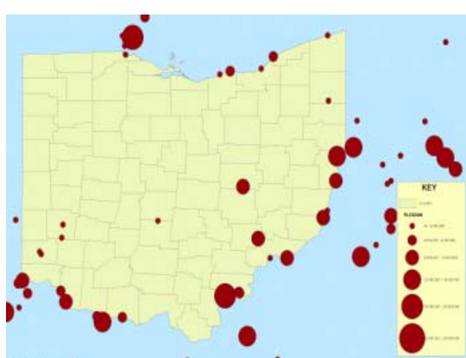


CNG REFUELING STATIONS

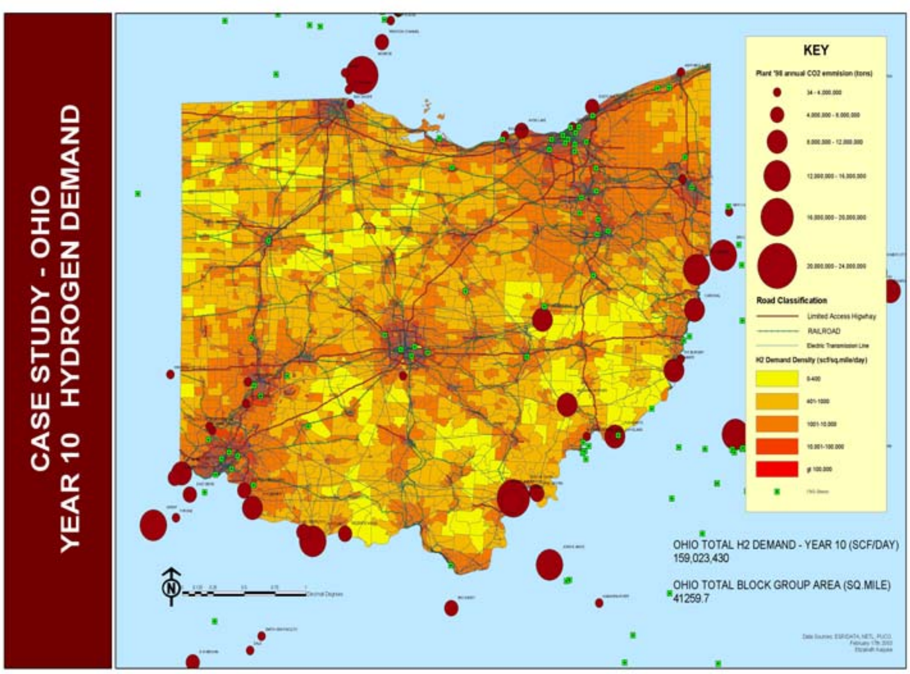


ELECTRIC TRANSMISSION SYSTEM

COAL-FIRED POWER PLANTS



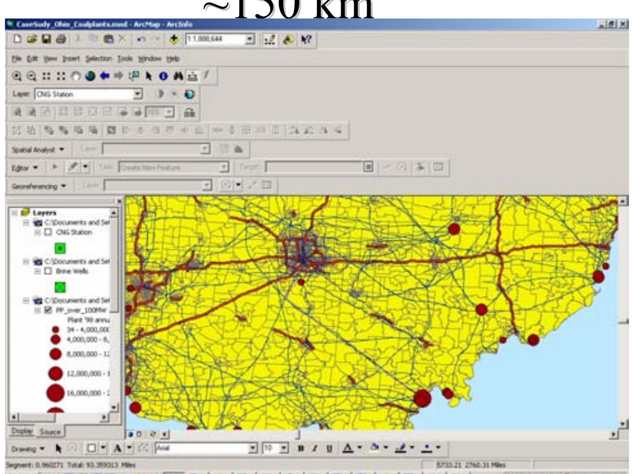
LIMITED ACCESS HIGHWAYS AND RAILROADS



Connecting H_2 Supply and Demand: Columbus, Ohio

- Columbus Population ~ 1 million; ~700,000 light duty vehicles, metro region ave. vehicle population density ~600 cars/km^2; center city higher.
- Projected H_2 Demand (if all LDVs use H_2) = 400 MW
  (100 million scf H_2/d or 240 t/d)
- Nearest large coal plant is “General Gavin”, built 1974, pulverized coal steam plant, with flue gas desulfurization, Low NOx burners, SCR.
  - 2600 MW capacity
  - 17 million MWh/y
  - 7.2 million tons coal/yr (~6400 MW coal on ave.)
  - 18.6 million tons CO_2/yr (~ 20 CO_2 wells @ 2500 tonnes/d/well)
  - kWhe/kWhcoal = 30%
  - ave. annual capacity factor = 74%
  - All coal is barge delivered
  - ~~

GIS Tool =>Measured Distance Coal Plant -> Downtown Columbus ~150 km



Making H_2 from Coal for Columbus

- To make H_2 for all Columbus cars (via coal gasifier with 65% energy conv. efficiency), use ~10% of present of coal flow at General Gavin, then pipe 240 t/d (100 million scf/d) H_2 150 km to city. The H_2 pipeline itself might cost about $40-50 million and adds a relatively small amount to the delivered cost of H_2, ~ $0.15/kg. H_2 compression and storage at the central plant might add ~$0.5/kg.
- Observation: General Gavin power plant is operated at only ~ 74% capacity factor today (because it follows electricity load). If this plant is "repowered" with a coal IGCC, with CO_2 capture, and run at a higher capacity factor, then it might be possible to supply electric needs and make enough H_2 during off-peak electric demand hours for light duty vehicles. (Onsite electrolysis using off-peak vs. central H_2 production w/pipeline distribution?) *Important to understand interaction of electric grid and H2 grid.*
- ~20 CO_2 injection wells each handling 2500 tonnes/day would be needed to dispose of CO_2 associated with a fossil energy complex at the General Gavin (using the same amount of coal as present).

GIS GIVES THE H_2 INFRASTRUCTURE DESIGNER A DATA BASE THAT CAN BE QUERIED IN A MYRIAD OF USEFUL WAYS

For example:

•Distances between supply, demand, resources

•Mass and Energy flows => match supply and demand

•Shortest path along rights of way

•Characteristics of "features" like power plants, H_2 demand centers, etc.

•Select features with specified characteristic (e.g. all areas with a H_2 demand density > threshhold)

FUTURE WORK

- Develop tools for system cost comparisons and optimization, using data in GIS format
- Examine how H_2 infrastructure design and cost depends on geographic factors. Study design space to find low cost transition strategies
- Take this “60,000 foot” look down to earth
- This type of model might eventually provide insights useful for
  – Integrated Assessment models.
  – Energy economy models. How does H_2 interact with other parts of the energy economy and environment?
  – Sustainable urban planning.