CONCEPTUAL DESIGN OF OPTIMIZED FOSSIL H_2 ENERGY SYSTEMS WITH CAPTURE AND SEQUESTRATION OF CO_2

Joan Ogden and Elizabeth Kaijuka

Princeton Environmental Institute

Princeton University

ogden@princeton.edu

presented at the

National Carbon Sequestration Conference

Alexandria, VA

May 7, 2003

Why Consider H_2 As A Future Energy Carrier?

- Zero or near-zero emissions at point of use
- Low to zero full fuel cycle primary emissions of both air pollutants and greenhouse gases (e.g. H_2 fuel cell vehicles offer lowest well-to-wheels emissions of any fuel/engine option)
- Decarbonizing fuels sector is important for controlling Carbon emissions
- H_2 can be made from widely available primary resources (fossil, renewable, nuclear).
- Rapid progress in H_2 and fuel cell technologies

Potential Role of Fossil H_2 Energy Systems

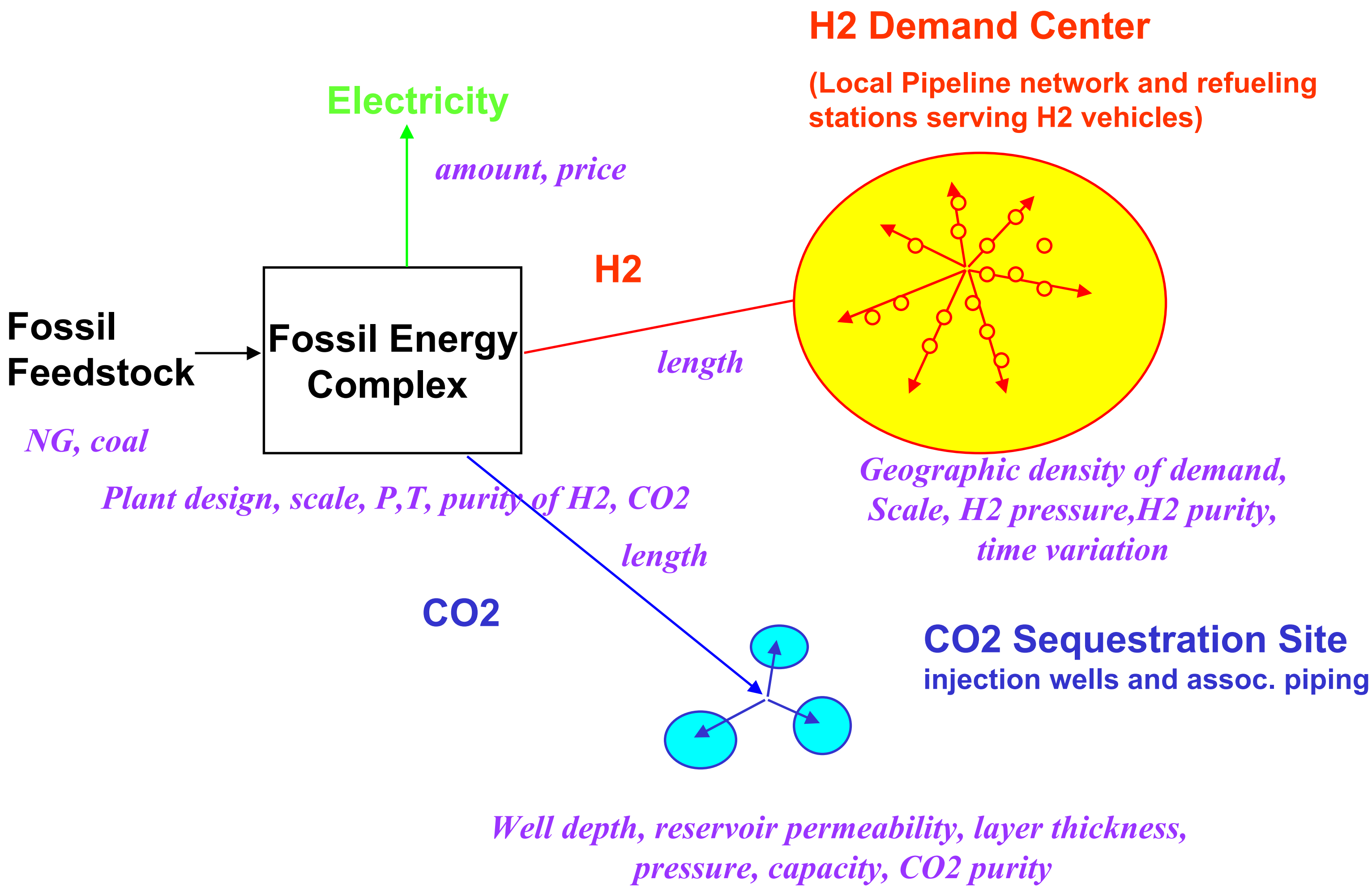
- Low cost fossil resources are available in many regions of the world.
- Fossil derived H_2 is likely to be lowest cost H_2 supply option for many decades in these areas.
- Production of H_2 from fossil fuels *with capture and sequestration of CO_2* offers a route toward near zero emissions in production and use of fuels.

THIS STUDY: Examine possible transition strategies to a future energy system based on production of H_2 and electricity from fossil fuels with capture and underground sequestration of CO_2. *This involves development of two new pipeline infrastructures, one for H_2 distribution and one for CO_2 disposal.*

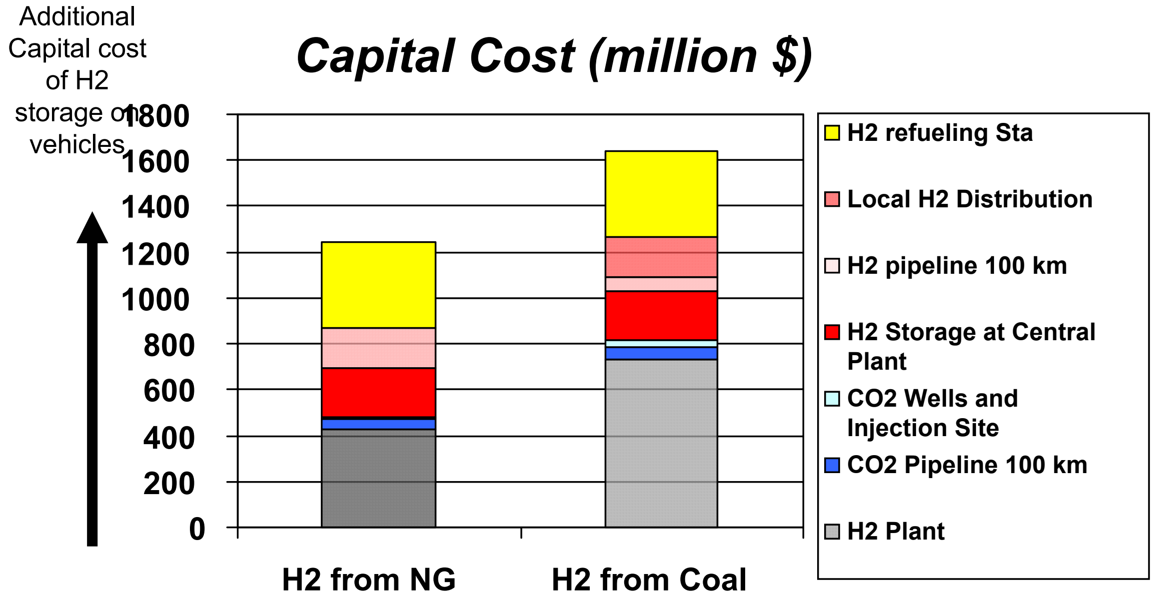
TECHNICAL APPROACH

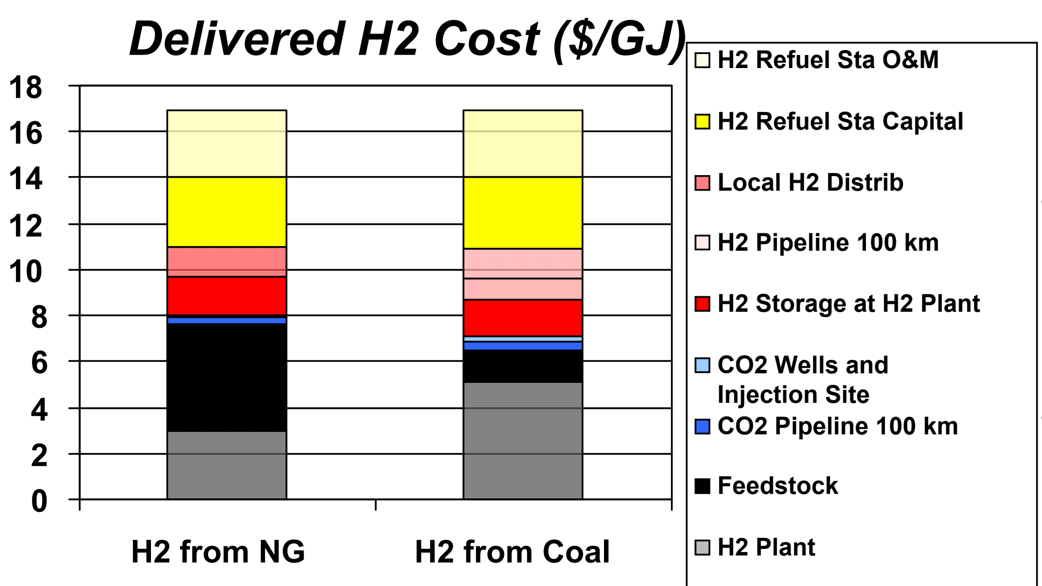
- **Develop engineering/economic models for components**: fossil energy complexes, CO_2 pipelines, CO_2 sequestration site, H_2 pipeline distribution, H_2 refueling stations, H_2 demand.
- Use a variety of analytic and simulation tools to **understand performance and economics of entire system**.
- Use **Geographic Information System (GIS)** data to study spatial relationships between H_2 demand, supply, resources, CO_2 sequestration sites, and existing infrastructure.
- Explore use of **mathematical programming** techniques to find the lowest cost strategy for building a widespread H_2 energy system with CO_2 sequestration. 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 study** of H_2 infrastructure development with CO_2 sequestration, involving multiple sources and sinks for CO_2 and multiple H_2 demand sites, using GIS data.

“SIMPLE” FOSSIL H_2 SYSTEM W/CO_2 SEQUESTRATION



Economics of Simple System: 1000 MW H_2



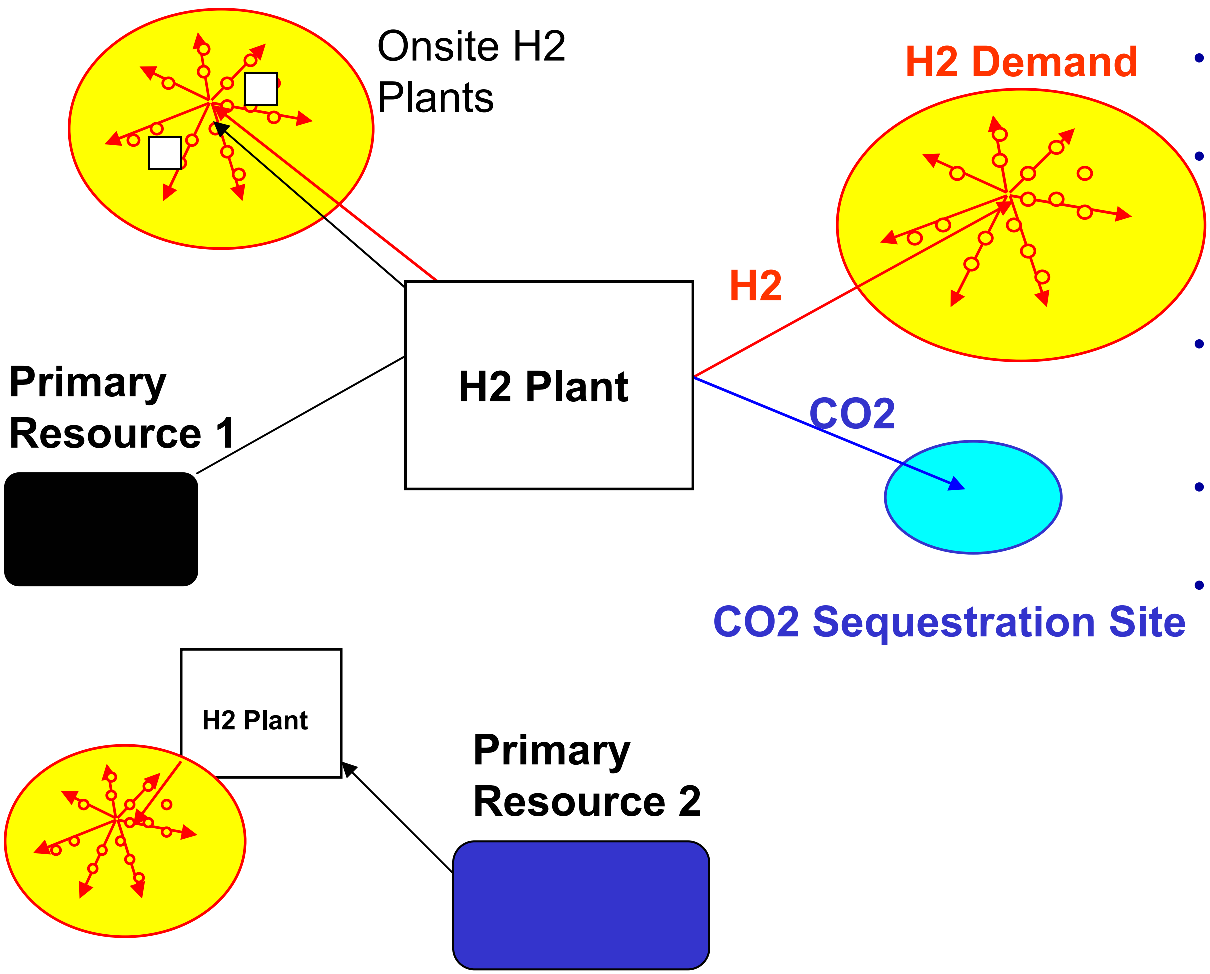


- For projected 2015 US NG and coal prices, delivered cost of H_2 from NG and H_2 from coal were comparable. The system capital cost was ~30% higher for coal.
- For base case (large CO_2 and H_2 flows; nearby reservoir for CO_2 sequestration with good injection characteristics; large, geographically dense H_2 demand), major contributors to the delivered H_2 cost are: H_2 production, H_2 transmission and distribution and H_2 refueling stations
- CO_2 capture, transmission and sequestration add only ~10% (CO_2 pipelines and injection site added ~2-3%)
- Better methods of H_2 storage would reduce refueling station and distribution system costs,

  and costs on-board vehicles.

More Complex System: 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**

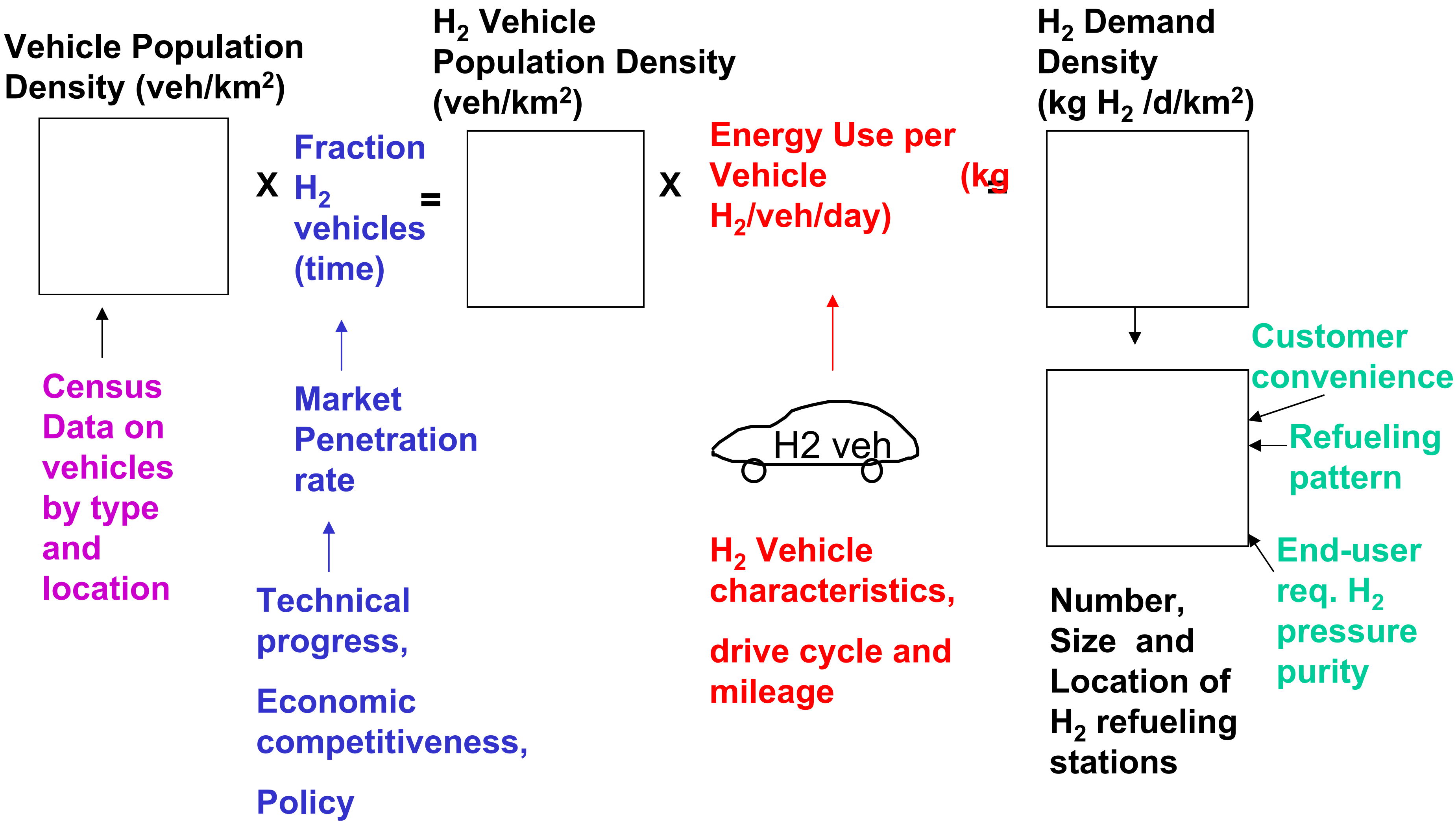
WHAT DO WE HOPE TO LEARN?

- Time constants and costs. How fast can we implement hydrogen fuel 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, characteristics of CO_2 sequestration sites, market growth, policies.
- Rules for thumb for optimizing H_2 and CO_2 infrastructure development.

CASE STUDY:
A FOSSIL 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 Light Duty Vehicles converted to H_2, (assuming H_2 LDVs have ave. fuel economy = 2-4X current gasoline vehicles)
  - NG use would increase by ~25-50% OR
  - Coal use would increase by ~20-40% (20-40 CO_2 injection wells, each disposing of 2500 tonne/day would be needed for CO_2 produced in 5-10 1000 MW coal->H_2 plants) OR
  - Electric power ~ 6.5-13 GWe continuous power. Or ~ 13-26 GWe off-peak power for 12 h/d.

CREATING A H_2 DEMAND MAP

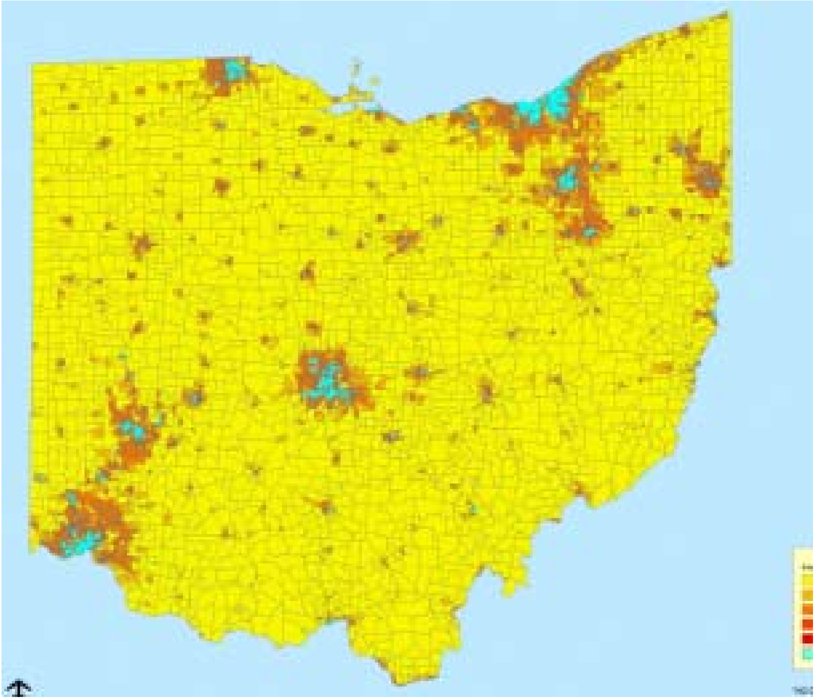


Fraction of H_2 cars in fleet vs. year and market penetration rate

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%

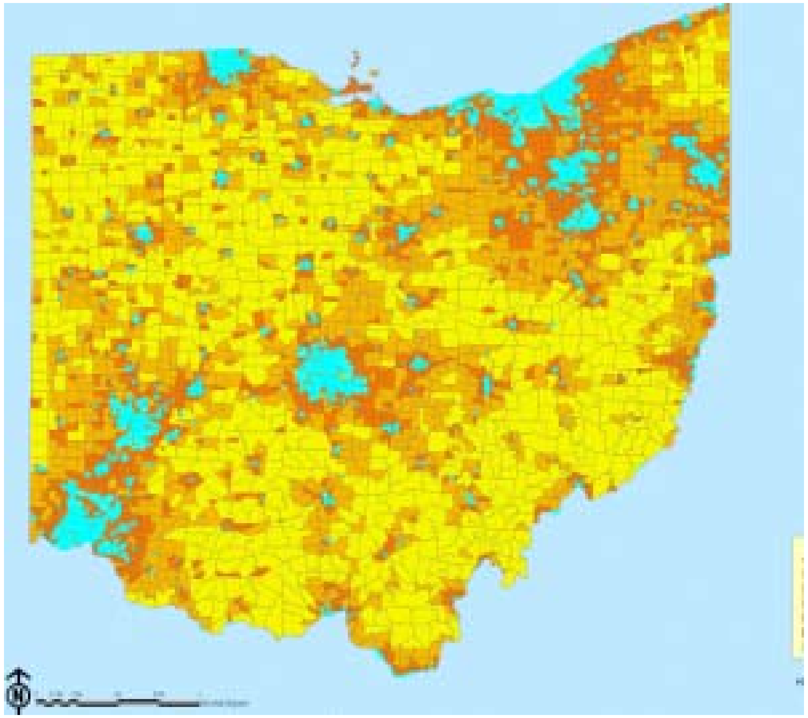
H_2 DEMAND DENSITY (kg/d/km^2): YEAR 1: 25% OF NEW Light Duty Vehicles = H_2 FCVs

Blue shows good locations for refueling station



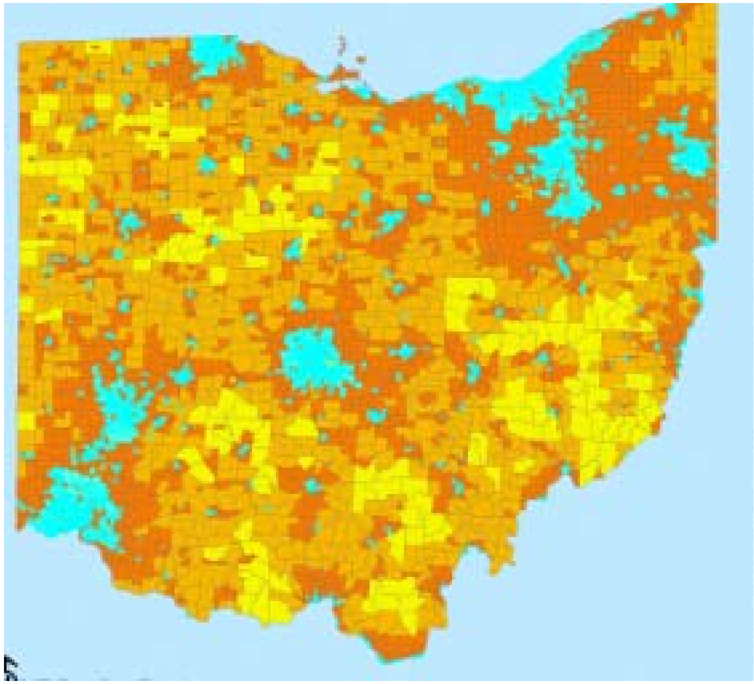
H_2 DEMAND DENSITY ($kg/d/km^2$):

YEAR 5: 25% OF NEW LDVs = H_2 fueled



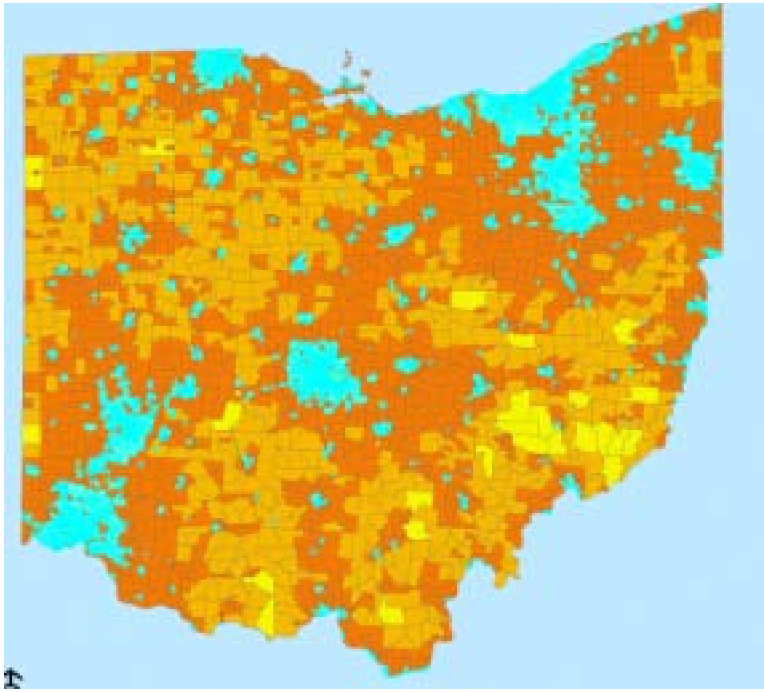
H_2 DEMAND DENSITY ($kg/d/km^2$):

YEAR 10: 25% OF NEW LDVs = H_2 fueled



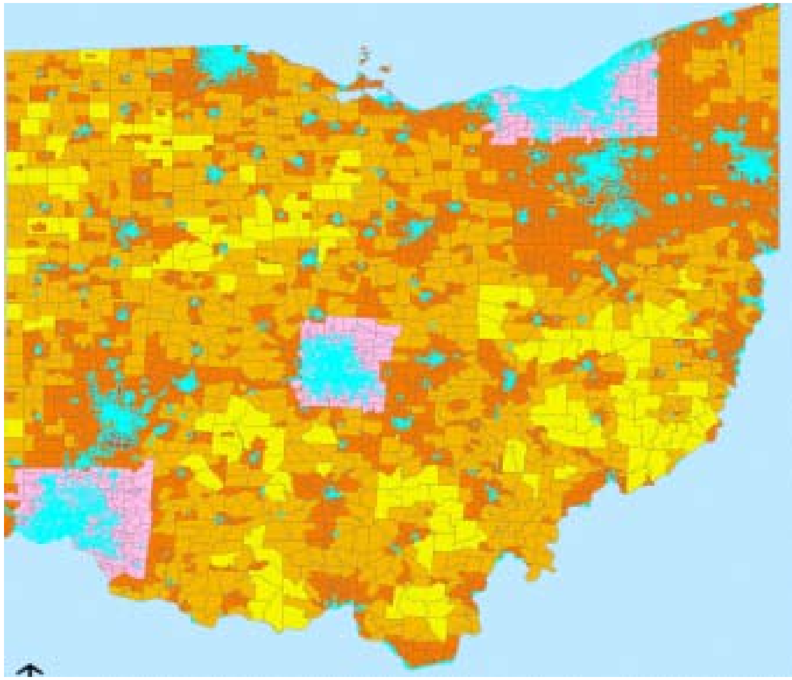
H_2 DEMAND DENSITY (kg/d/km^2):

YEAR 15: 25% OF NEW LDVs = H_2 fueled



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: 60-120 tonne/d

(25-50 million scf/d or 100-200 MW)

Columbus: 44-88 tonne/d

(18-36 million scf/d or 71-142 MW)

Cincinnati: 46-92 tonne/d

(19-38 million scf/d or 75-150 MW)

State: 384-768 tonne/d

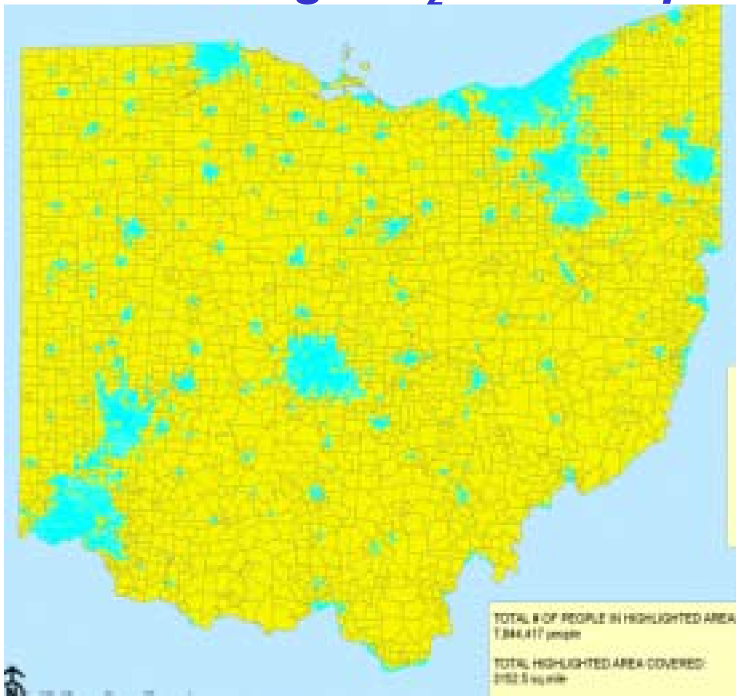
(159-318 million scf/d or 630-1260 MW)

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, ~10-20% the size of a large coal -> H_2 plant. One large 380-770 t/d (630-1260 MW) coal->H_2 plant could serve entire state, but long, inter-city pipelines would be needed. This suggests that local, smaller scale H_2 production might be preferred for this H_2 demand.

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

Assume All Light Duty Vehicles Use H_2, and Threshhold for Building a H_2 Local Pipeline is 200 Cars/km^2



Highlight areas where H_2 vehicles>200/km^2

Sum population in highlighted areas = 7.8 million people

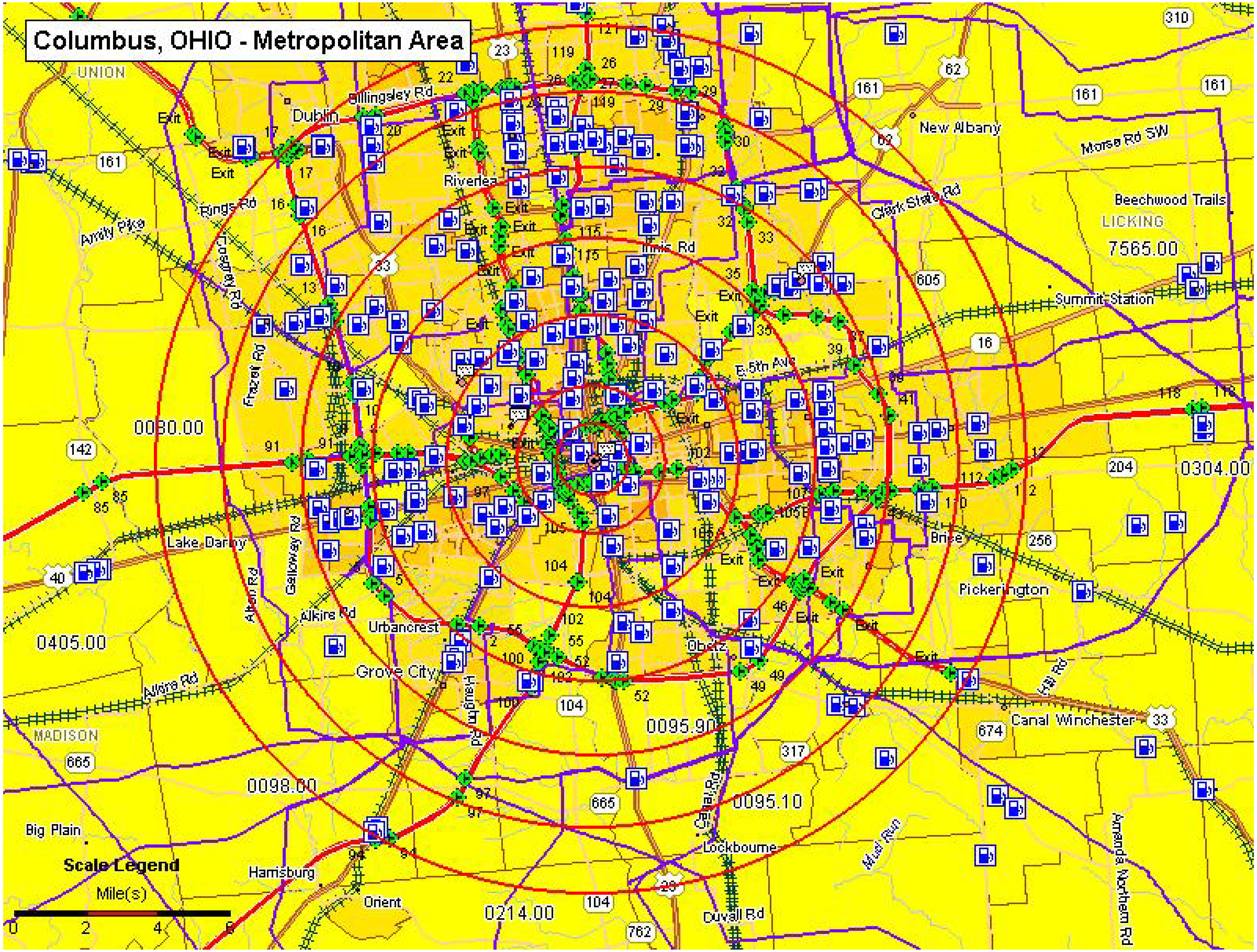
This is ~70% of the total state population

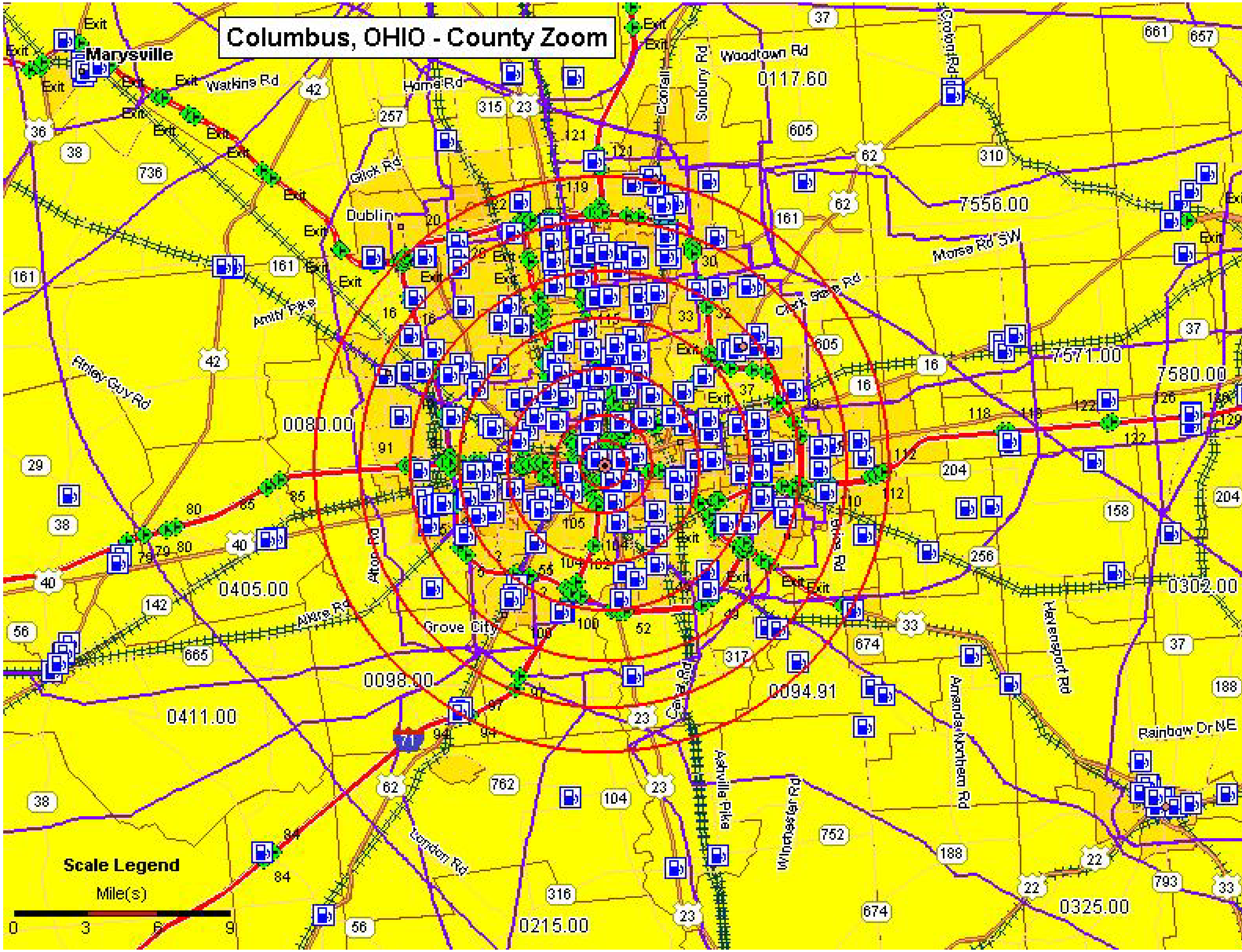
If all LDVs used H2, large cities like Columbus, Cleveland, Cincinnati could each support a large coal H2 plant dedicated to fuel production.

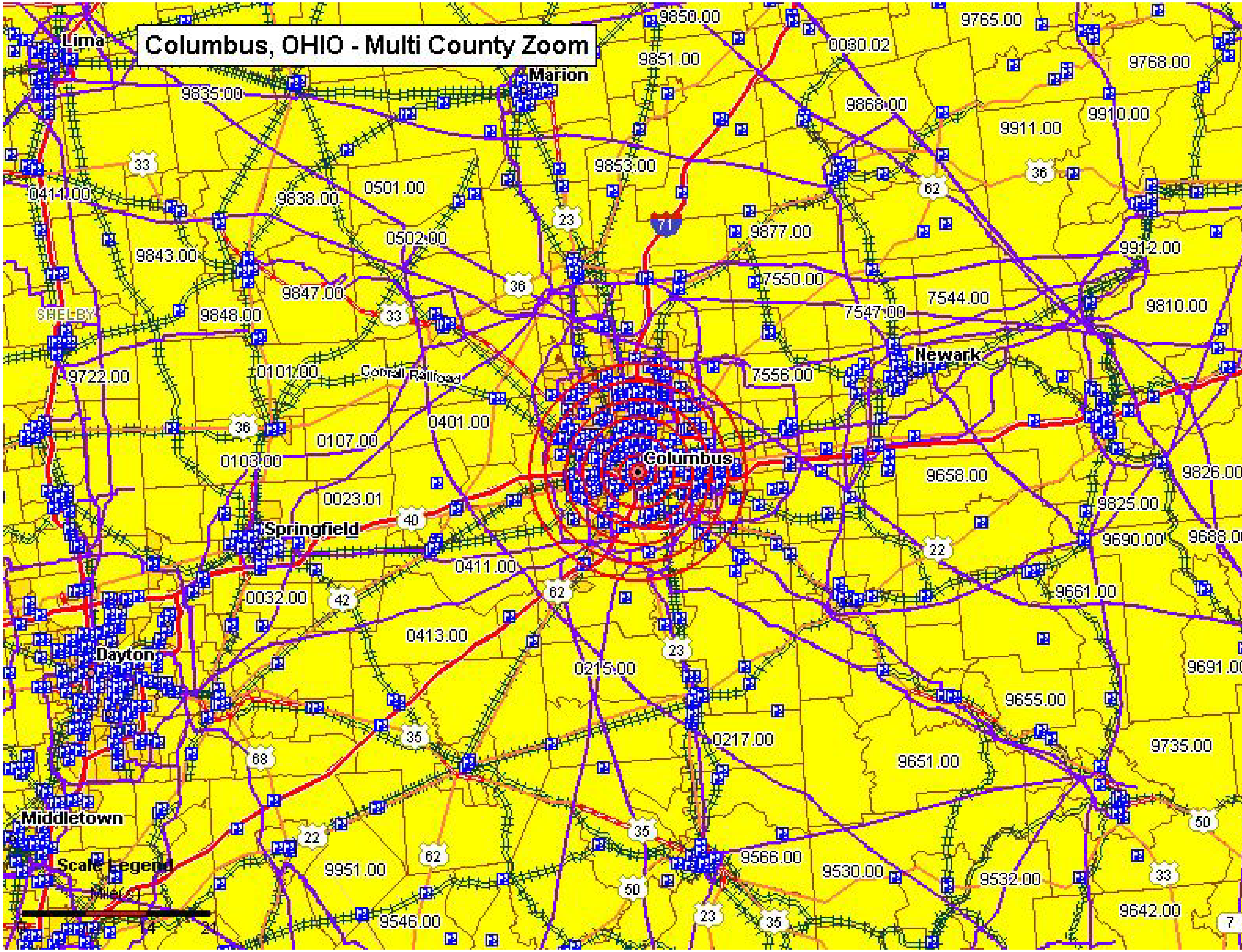
Many smaller cities have demand <u>dense</u> enough for local H2 distribution, but not <u>large</u> enough for their own coal H2 plant. Make H2 at smaller scale (from NG or elec) or pipe or truck H2 to these cities.

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 - Metropolitan Area
UNION
Dublin
New Albany
Morse Rd SW
Beechwood Trails
LICKING
Summit Station
Riverlea
Amity Pike
Rings Rd
Clark State Rd
E 5th Ave
Lake Darby
Alkire Rd
Urbancrest
Grove City
Obetz
Brice
Pickerington
Canal Winchester
MADISON
Big Plain
Harrisburg
Orient
Lockbourne
Duvall Rd
Scale Legend
Mile(s)
0 2 4 6


Columbus, OHIO - County Zoom
Marysville
Dublin
Grove City
Watkins Rd
Home Rd
Glick Rd
Amity Pike
Finley Guy Rd
Alkire Rd
Alton Rd
London Rd
Cornell
Sunbury Rd
Woodtown Rd
Morse Rd SW
Clark State Rd
Havensport Rd
Amanda Northern Rd
Winchester Rd
Ashville Pike
Canal Rd
Rainbow Dr NE
0117.60
7556.00
7571.00
7580.00
0080.00
0405.00
0411.00
0098.00
0094.91
0302.00
0215.00
0325.00
Scale Legend
Mile(s)
0
3
6
9


Columbus, OHIO - Multi County Zoom
Lima
Marion
Newark
Columbus
Springfield
Dayton
Middletown
Scale Legend
SHELBY
Conrail Railroad
9850.00
9765.00
0030.02
9851.00
9768.00
9835.00
9868.00
9910.00
9911.00
9853.00
0411.00
9838.00
0501.00
9843.00
0502.00
9877.00
9912.00
9847.00
7550.00
7544.00
9848.00
7547.00
9810.00
9722.00
0101.00
7556.00
0401.00
0107.00
0103.00
9658.00
9826.00
0023.01
9825.00
9690.00
9688.00
0411.00
9661.00
0032.00
0413.00
0215.00
9691.00
9655.00
0217.00
9735.00
9651.00
9566.00
9530.00
9532.00
9951.00
9546.00
9642.00

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
- Ave. 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/cluster every 2-4 mi)
  - Interstate ~ 90% (typically 3 to 4 stations per cluster)
- Fraction of gasoline stations near rail lines,electric lines, natural gas lines, or limited access highways (possible rights of way for H_2 local pipelines) = almost all.

"Gasoline-like" convenience in Columbus

Number of H_2 cars served/station

(convenience =>1/3 of stations = 80 stations have H_2)

H_2 Cars (fraction of all new cars)	Year 1	Year 5	Year 10	Year 15
10%	**60**	**280**	**560**	**810**
25%	**140**	**730**	**1450**	**2010**
50%	**280**	**1450**	**2820**	**4030**
100%	**560**	**2820**	**5640**	**8060**

H_2 refueling options for "Gasoline-like" convenience at public H_2 refueling stations

(assume each vehicle uses ave. of 0.3-0.7 kg H_2/day)

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

▲ **Comp.Gas Truck = 420 kg**

● **LH2 Truck = 3600 kg**

■ **Onsite electrolyzer = 2.4-2400 kg/d**

⬢ **Onsite reformer = 240-4800 kg/d**

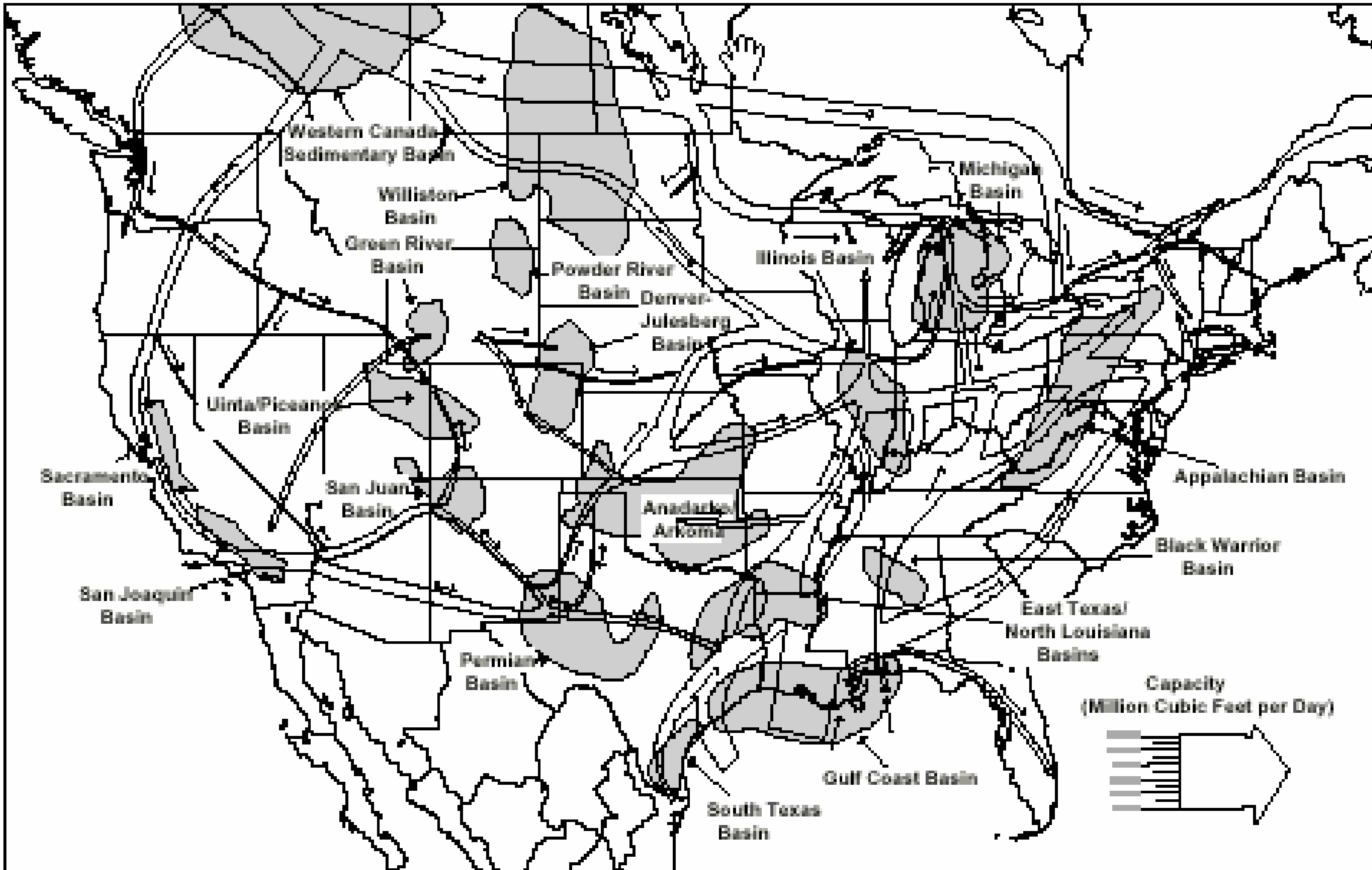
★ **Pipeline delivery of (CO_2 free H_2) = 240-4800 kg/d per station;** (pipeline viable, for hi demand & hi demand density)

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

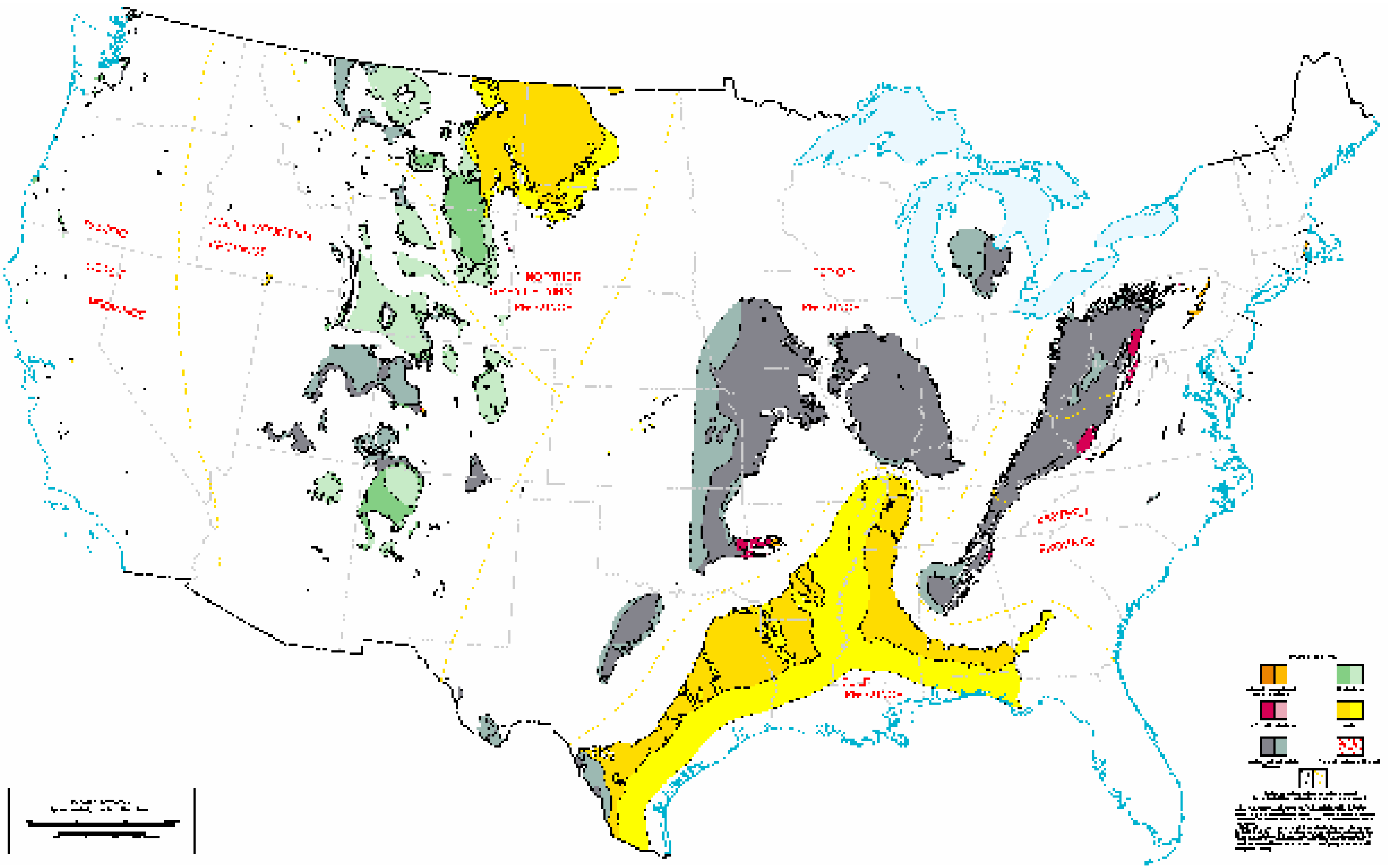
Onsite electrolysis might compete with onsite NG reforming depending on electricity & NG prices, and could use CO_2 free electricity.

RESOURCES FOR H_2 PRODUCTION

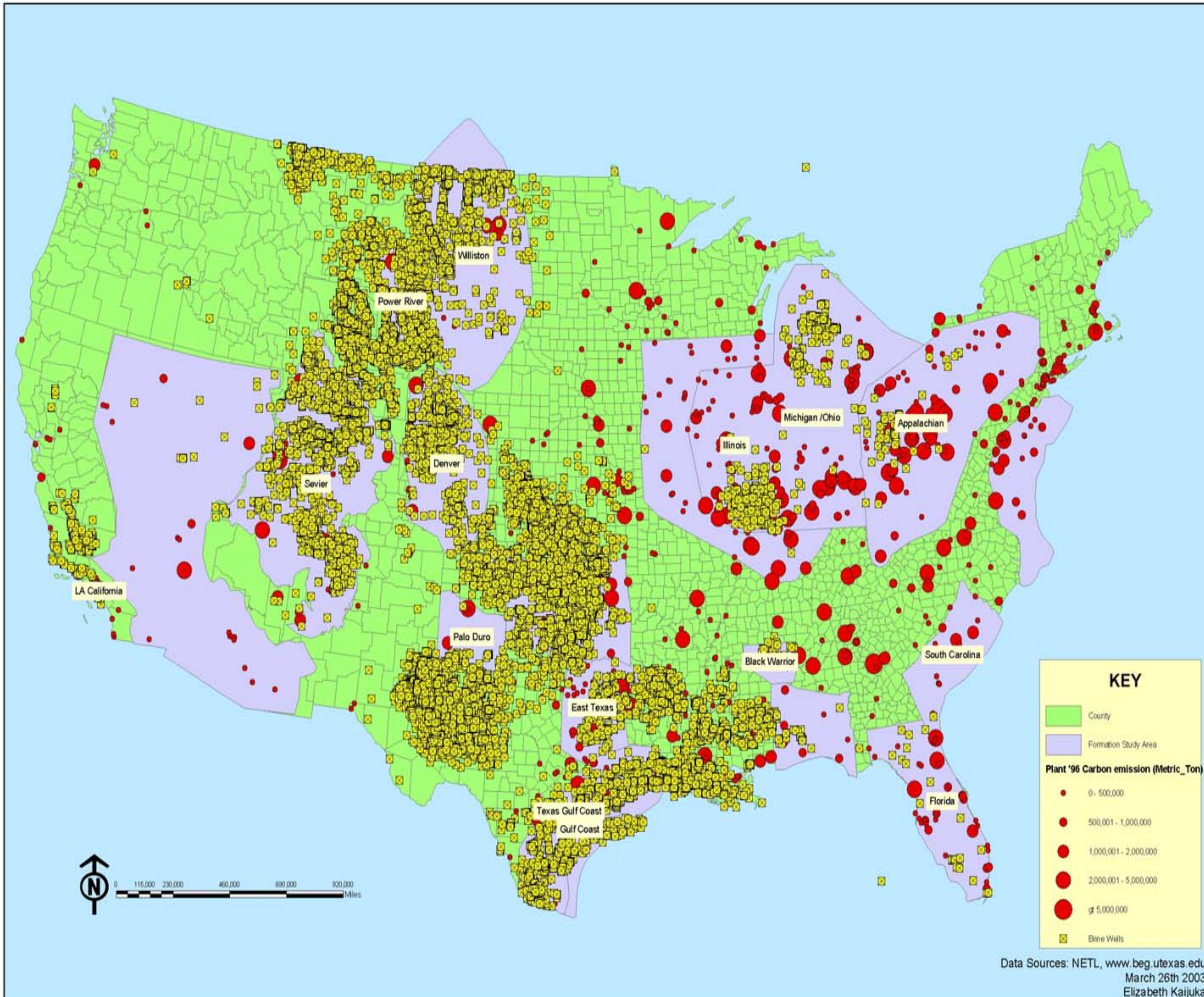
Figure 2. Major Natural Gas Producing Basins and Transportation Routes to Market Areas



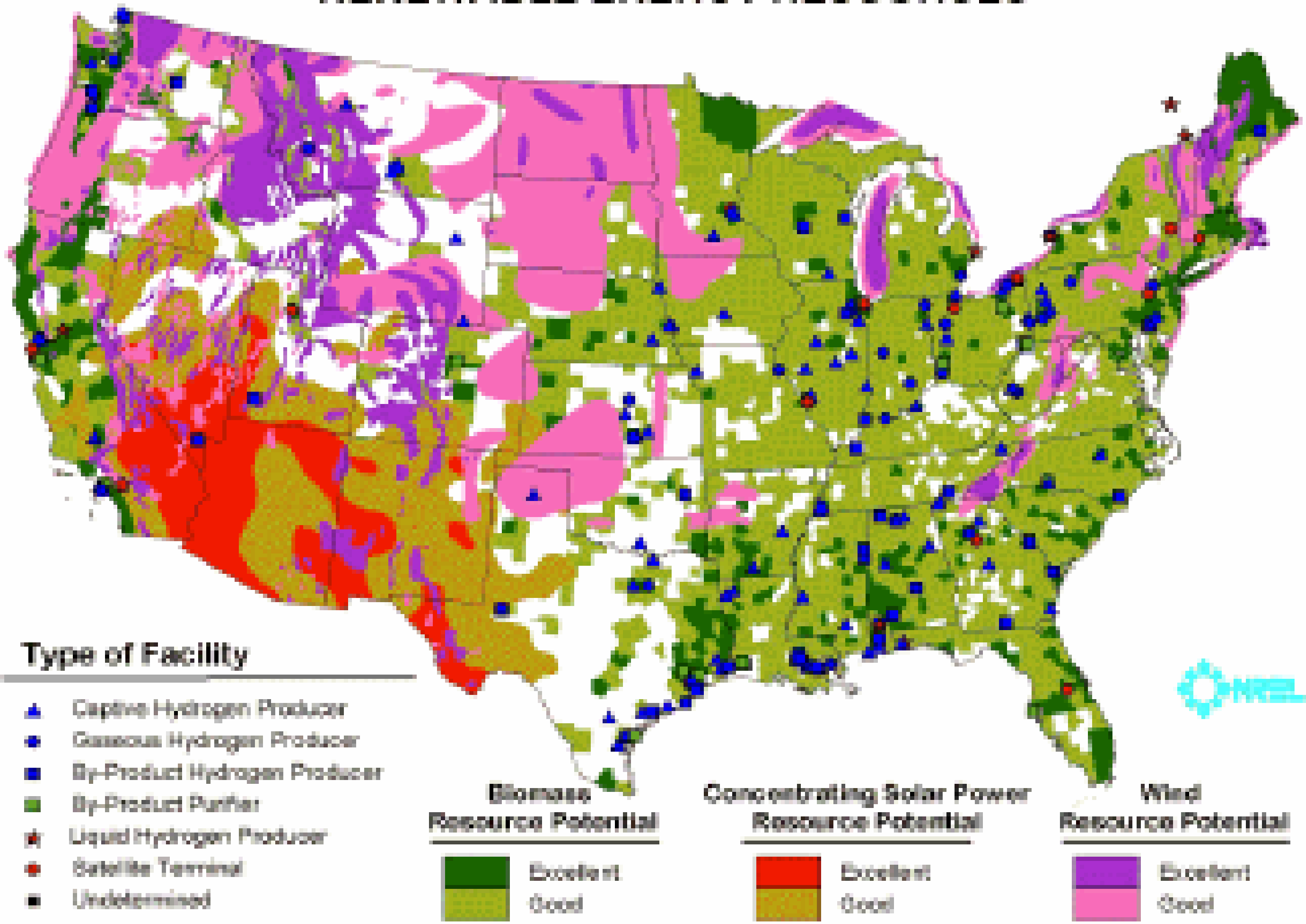
MAJOR US COAL FIELDS



CO2 SEQ. SITES & BRINE WELLS

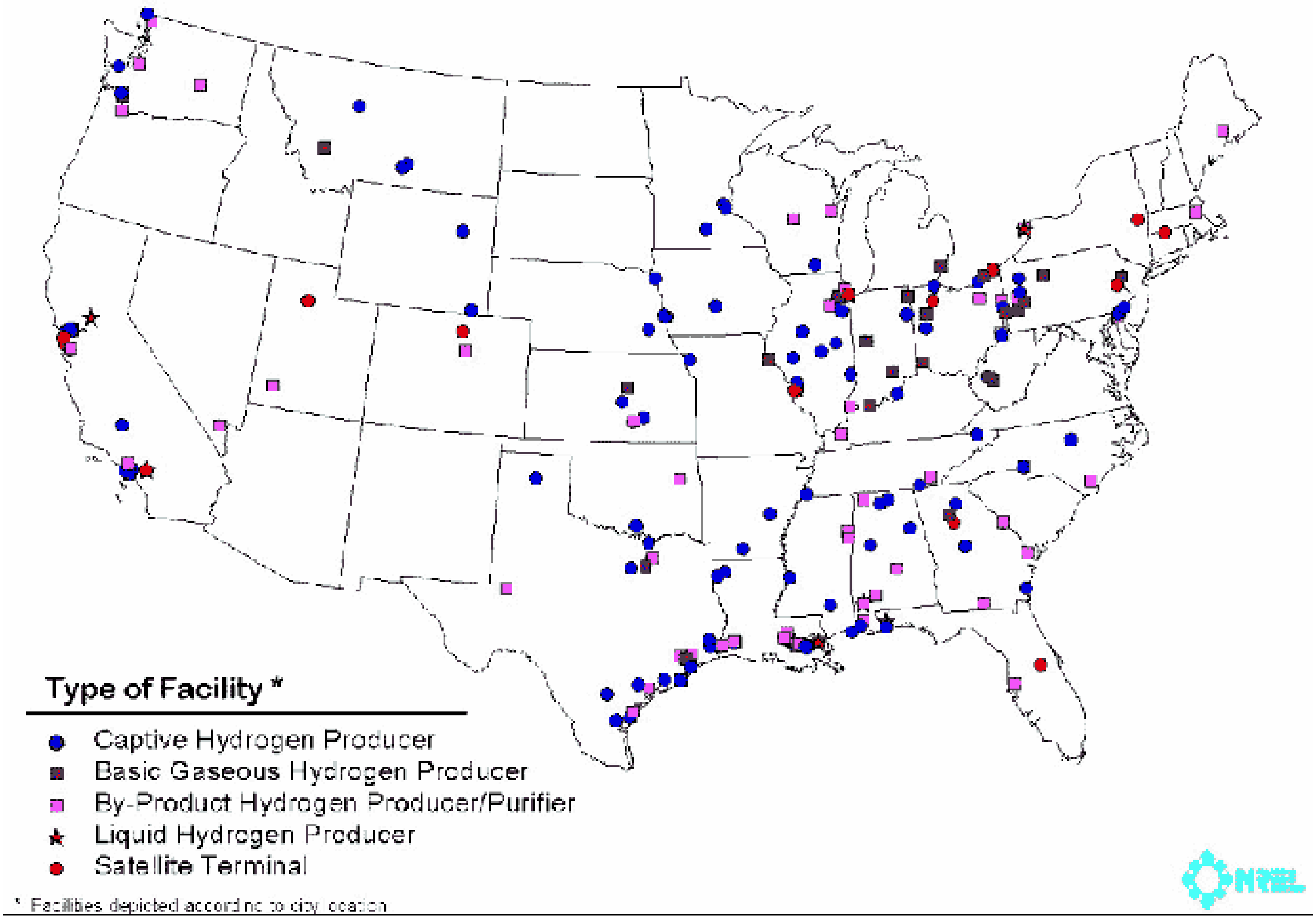


HYDROGEN FACILITIES AND GOOD TO EXCELLENT RENEWABLE ENERGY RESOURCES

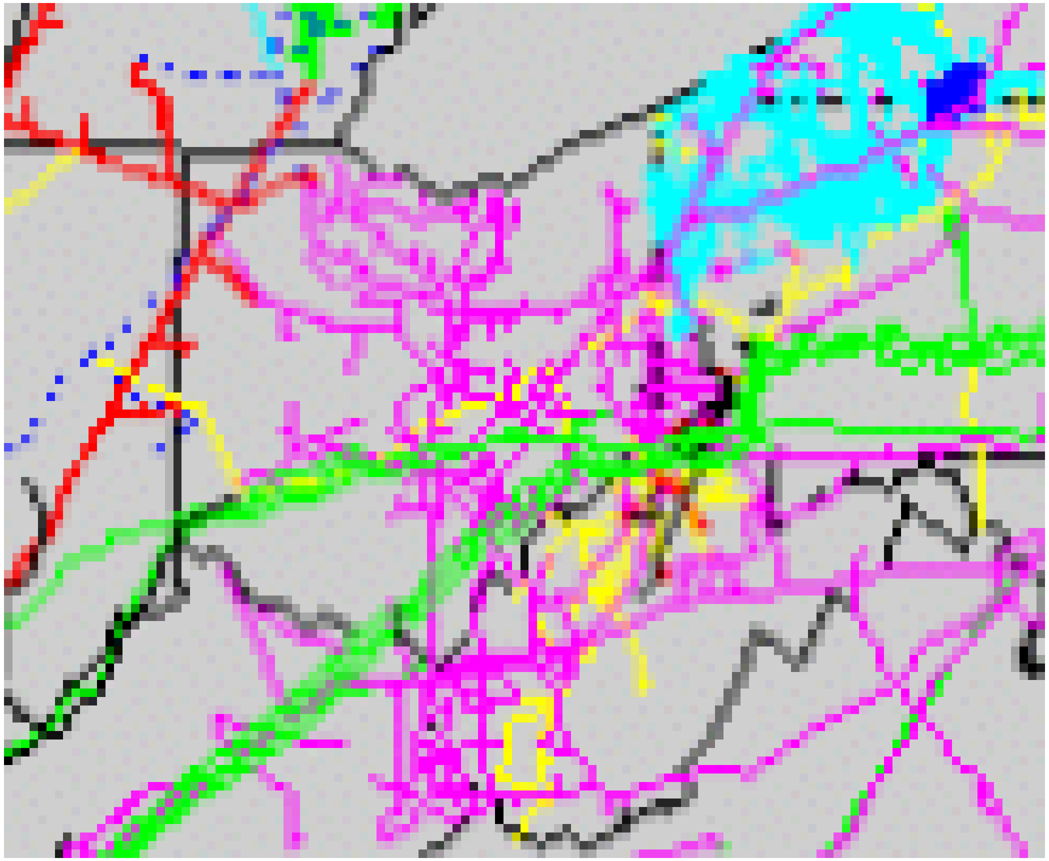


ROLE OF EXISTING ENERGY INFRASTRUCTURE AND RIGHTS OF WAY

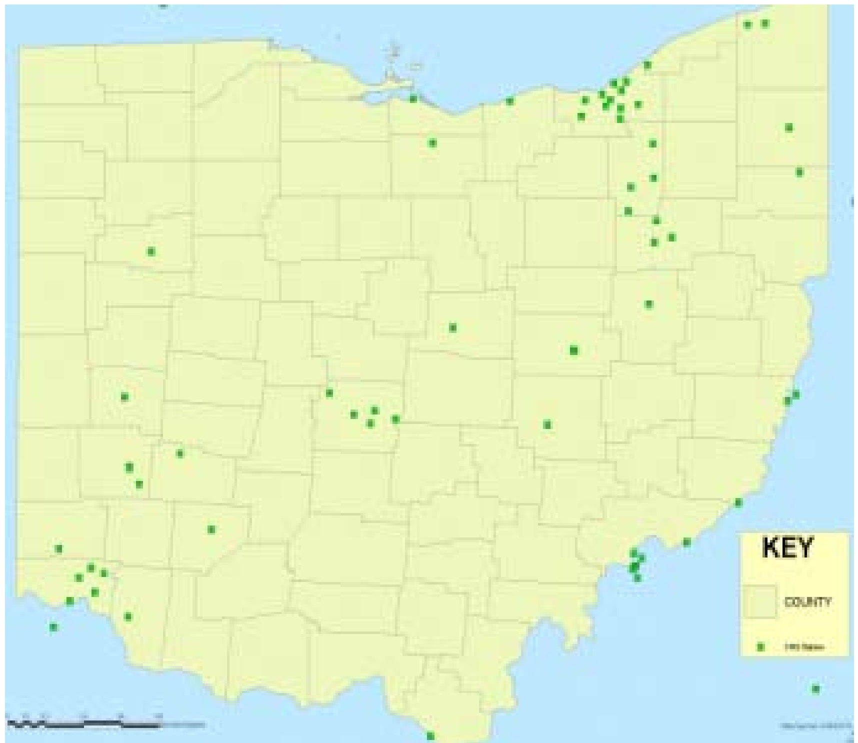
HYDROGEN PRODUCTION FACILITIES



NATURAL GAS TRANSMISSION SYSTEM IN OHIO

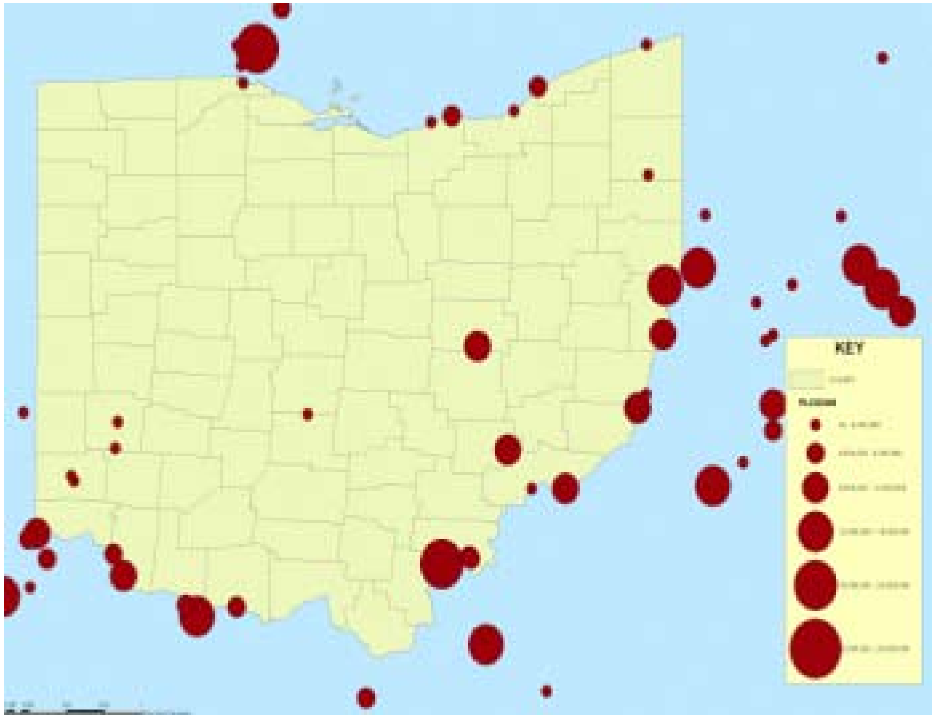


CNG REFUELING STATIONS



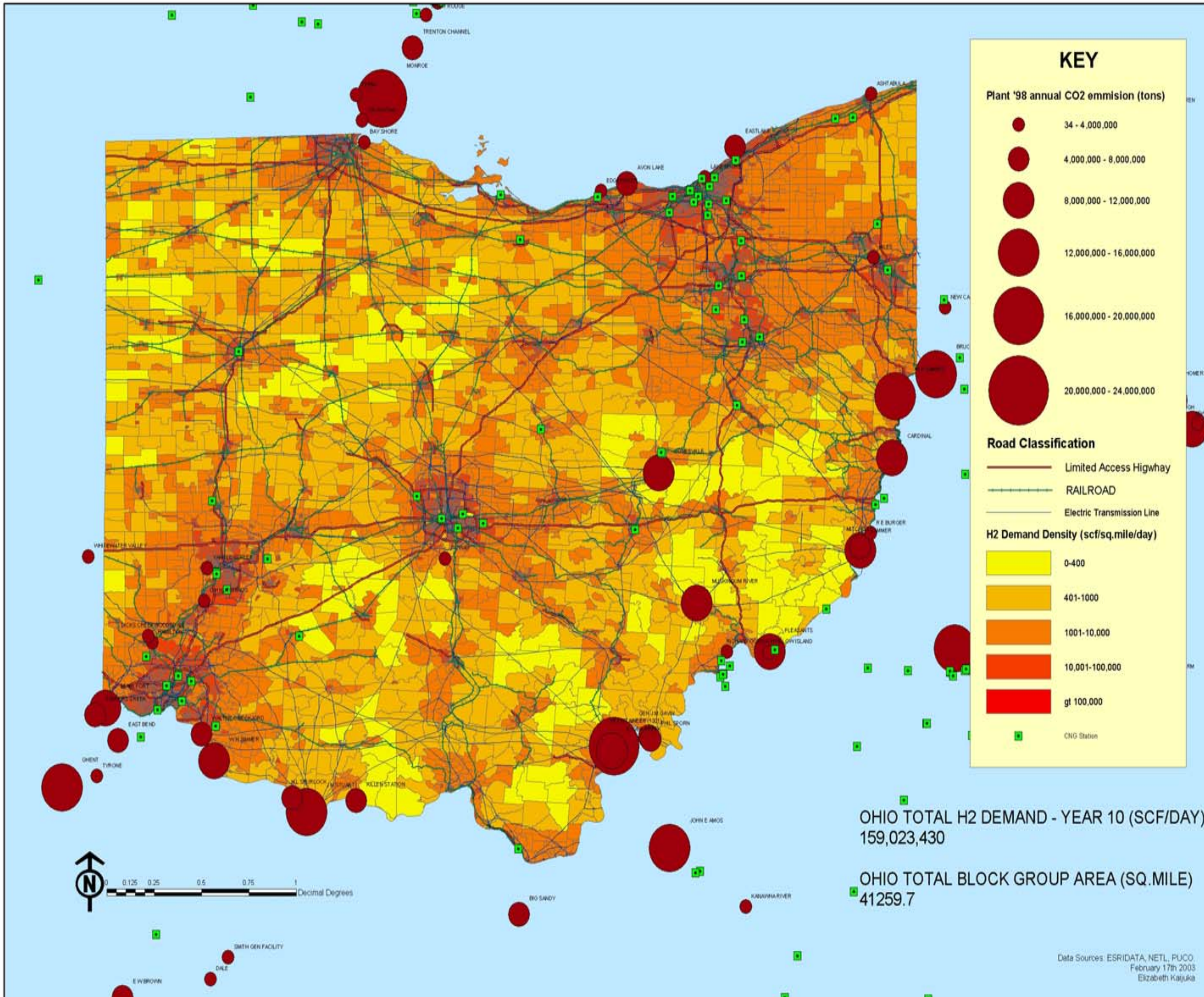
ELECTRIC TRANSMISSION SYSTEM

COAL-FIRED POWER PLANTS



LIMITED ACCESS HIGHWAYS AND RAILROADS

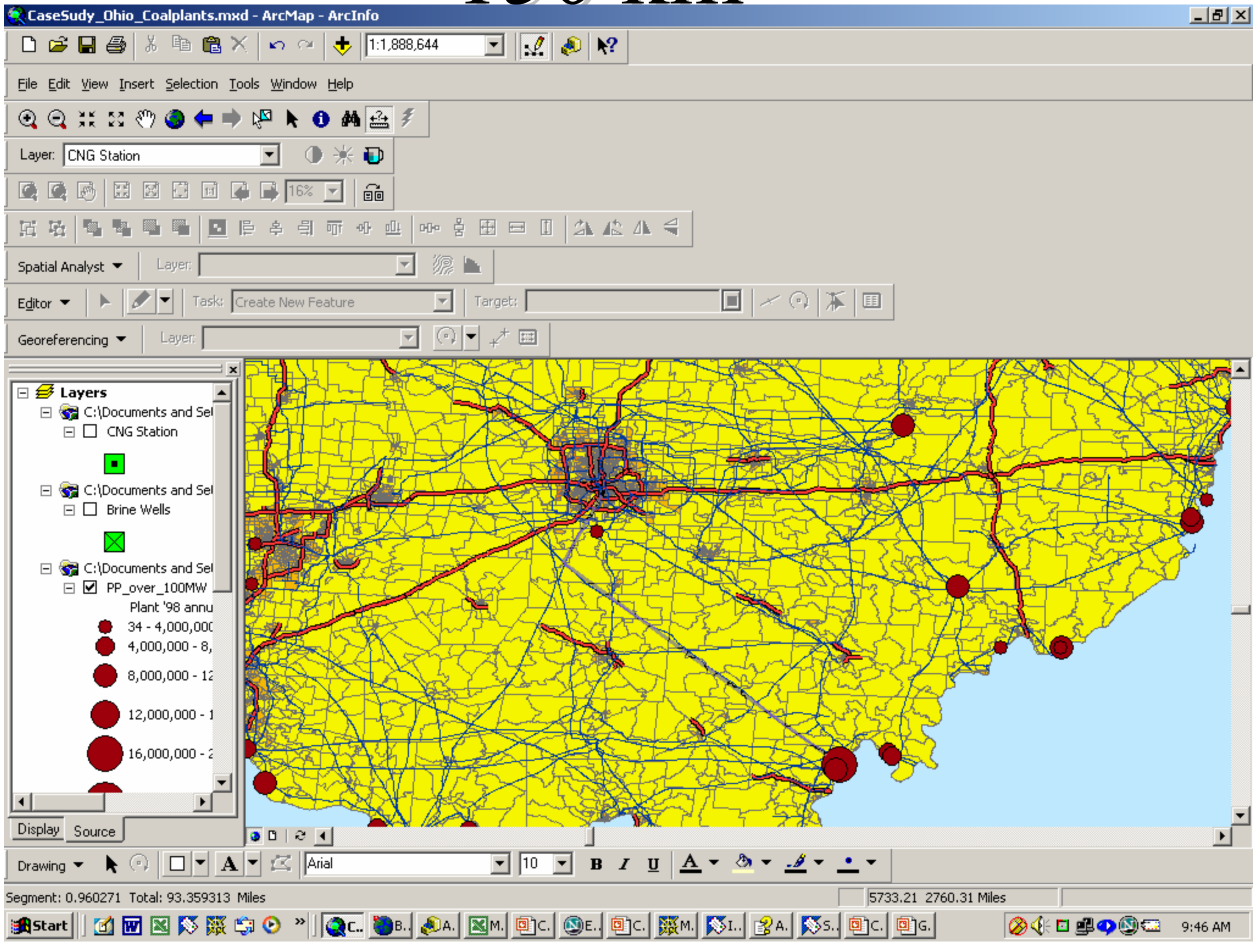
CASE STUDY - OHIO
YEAR 10 HYDROGEN DEMAND



MATCHING 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) = 400-800 MW
  (100-200 million scf H_2/d or 240-480 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

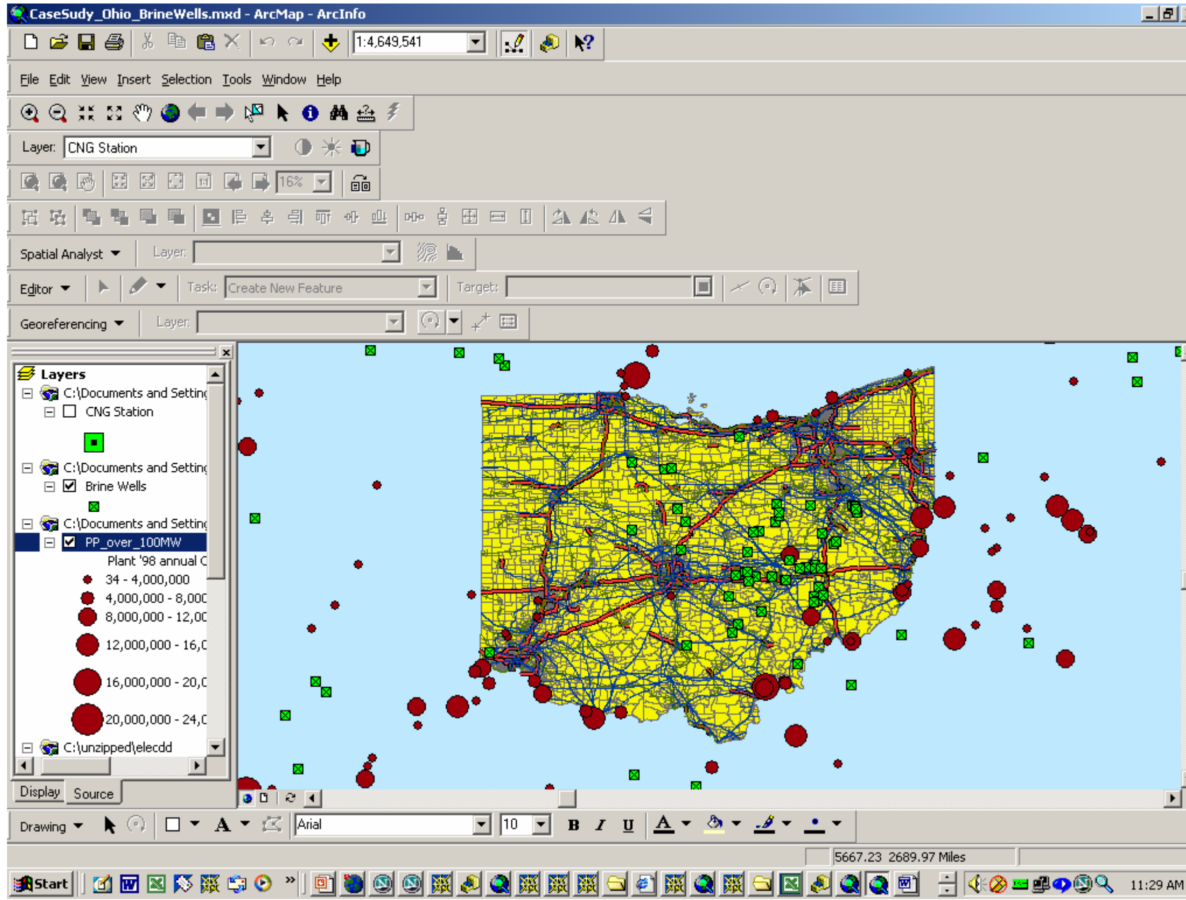
- To make enough H_2 for all Columbus cars in a coal->H_2 plant with 65% energy conv. efficiency, would need to use ~12-22% of present of coal flow at General Gavin, then pipe 240-480 t/d (100-200 million scf/d) H_2 150 km to city. The H_2 pipeline itself should add a relatively small amount to the delivered cost of H_2, < $1/GJ. H_2 storage at the central plant might add another $1.5/GJ.
- 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.

CO_2 DISPOSAL

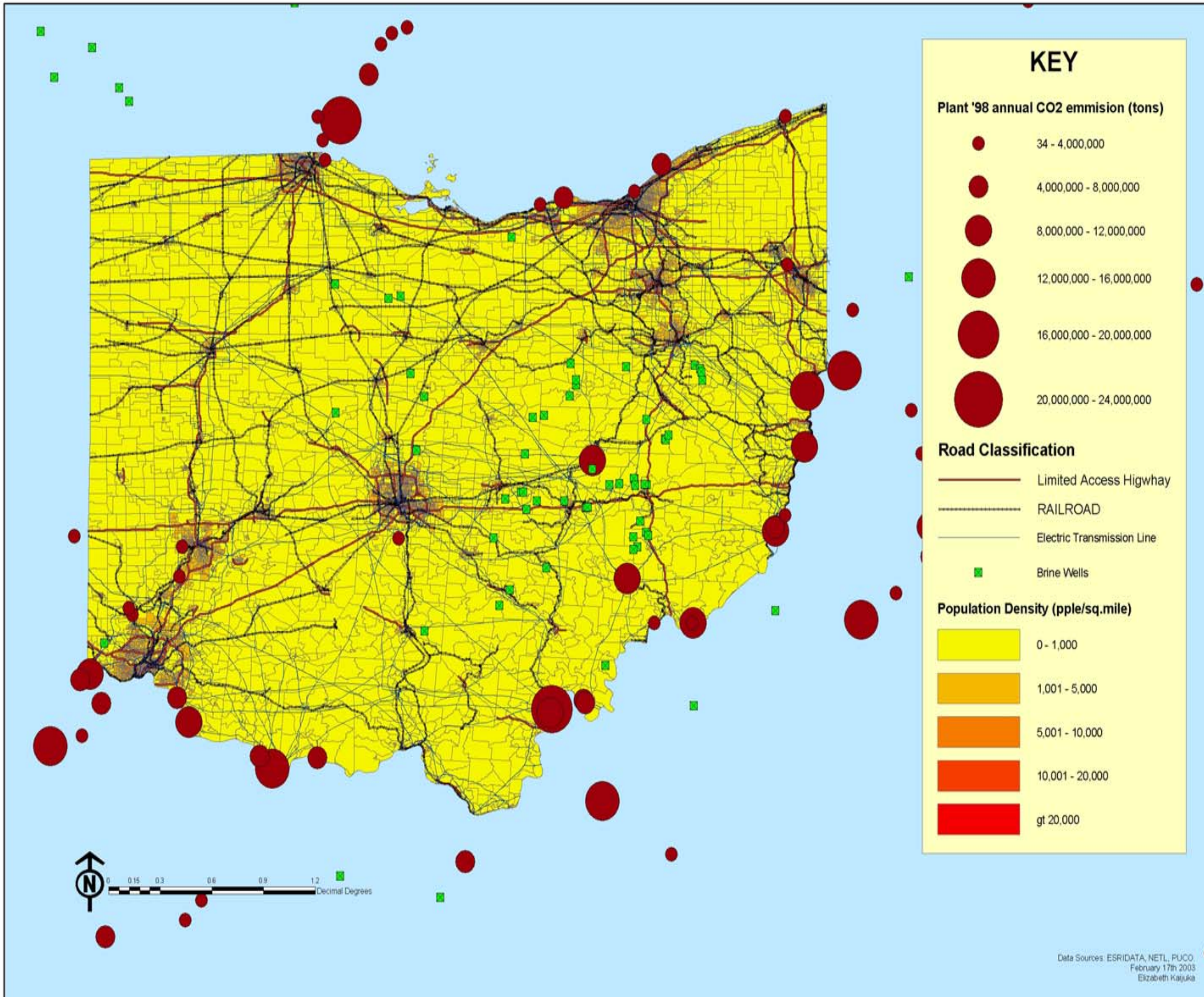
- ~20 CO_2 injection wells each handling 2500 tonnes/day would be needed to dispose of CO_2 associated with a fossil energy complex at the General Gavin (using the same amount of coal as present).
- Most coal consumption would be associated with electricity production. The ratio of electric energy demand to H_2 energy demand for LDVs is about 8:3 (4:3) for H_2 vehicles with 4X (2X) current gasoline fuel economy.
- Only about 12% (22%) of current coal input would be needed for H_2 production.

Ohio – Coal Plants/Brine Wells

- Total # Brine Wells = 83
- ~80% Owned by Ohio Dept of Natural Res.
- ~20% Owned by Oil Co.
- Each well has specific characteristics documented incl. Lower/upper depth



CASE STUDY - OHIO
POP DENSITY & INFRASTRUCTURE



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

For example:

•Distances between supply, demand, resources, seq. sites

•Mass and Energy flows => match supply and demand

•Shortest path along rights of way

•Characteristics of “features” like power plants, sequestration sites, H_2 demand centers, etc.

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

FUTURE WORK

- Develop models and tools for system cost 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?

ACKNOWLEDGMENTS

- We are grateful for research support from:
  - United States Department of Energy
    - National Energy Technology Laboratory
    - National Renewable Energy Laboratory
  - BP and Ford Motor Company (through the Carbon Mitigation Initiative at Princeton University).
- Colleagues at Princeton University
  - GIS Modeling Assistance
    - Bill Guthe
    - Wangyal Tsering
  - For useful conversations
    - Professor Robert Socolow
    - Professor Stefano Consonni
    - Dr. Robert Williams
    - Dr. Tom Kreutz
    - Dr. Eric Larson
    - Ms. Wei Wang
    - Professor Robert Vanderbei
- Information on energy use and infrastructure in Ohio
  - Kurt Waltzer (Ohio Environmental Council)
  - Dr. Curt White (NETL)