CONCEPTUAL DESIGN OF OPTIMIZED FOSSIL H₂ ENERGY SYSTEMS WITH CAPTURE AND SEQUESTRATION OF CO₂

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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 $\text{H}_2$ and electricity from fossil fuels with capture and underground sequestration of $\text{CO}_2$. *This involves development of two new pipeline infrastructures, one for $\text{H}_2$ distribution and one for $\text{CO}_2$ disposal.*
TECHNICAL APPROACH

• **Develop engineering/economic models for components**: fossil energy complexes, CO₂ pipelines, CO₂ sequestration site, H₂ pipeline distribution, H₂ refueling stations, H₂ 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 H₂ demand, supply, resources, CO₂ sequestration sites, and existing infrastructure.

• Explore use of **mathematical programming** techniques to find the lowest cost strategy for building a widespread H₂ energy system with CO₂ sequestration. Given a specified H₂ demand and resources for H₂ production, design a system to deliver H₂ to users at the lowest cost. Examine which transition paths give the lowest overall cost.

• Carry out **regionally specific case study** of H₂ infrastructure development with CO₂ sequestration, involving multiple sources and sinks for CO₂ and multiple H₂ demand sites, using GIS data.
“SIMPLE” FOSSIL H₂ SYSTEM W/CO₂ SEQUESTRATION

Fossil Feedstock → Fossil Energy Complex

- Fossil Energy Complex
  - Electricity
    - amount, price
  - H₂
    - length
  - CO₂
    - length
  - NG, coal
  - Plant design, scale, P,T, purity of H₂, CO₂
  - Geographic density of demand, Scale, H₂ pressure, H₂ purity, time variation

H₂ Demand Center

- (Local Pipeline network and refueling stations serving H₂ vehicles)

CO₂ Sequestration Site

- Injection wells and associated piping
  - Well depth, reservoir permeability, layer thickness, pressure, capacity, CO₂ purity
Economics of Simple System: 1000 MW H₂

- For projected 2015 US NG and coal prices, delivered cost of H₂ from NG and H₂ from coal were comparable. The system capital cost was ~30% higher for coal.
- For base case (large CO₂ and H₂ flows; nearby reservoir for CO₂ sequestration with good injection characteristics; large, geographically dense H₂ demand), major contributors to the delivered H₂ cost are: H₂ production, H₂ transmission and distribution and H₂ refueling stations.
- CO₂ capture, transmission and sequestration add only ~10% (CO₂ pipelines and injection site added ~2-3%).
- Better methods of H₂ storage would reduce refueling station and distribution system costs, and costs on-board vehicles.
More Complex System: Optimization for Low Delivered H₂ Cost

What is the lowest cost system for producing and delivering H₂ to serve a growing demand?

Primary Resource 1

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

Primary Resource 2

- H₂ Plant
- CO₂ Sequestration Site
- CO₂

H₂

Diagram: Connections between primary resources, H₂ plants, CO₂ sequestration sites, and demand points.
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 H₂ energy system?

• **Sensitivities** to: technology performance and costs, size and density of demand, local availability of primary sources, characteristics of CO₂ sequestration sites, market growth, policies.

• **Rules for thumb for optimizing H₂ and CO₂ infrastructure development.**
CASE STUDY:
A FOSSIL H₂ 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 H₂, (assuming H₂ 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 CO₂ injection wells, each disposing of 2500 tonne/day would be needed for CO₂ produced in 5-10 1000 MW coal->H₂ plants) OR
  – Electric power ~ 6.5-13 GWe continuous power. Or ~ 13-26 GWe off-peak power for 12 h/d.
CREATING A H₂ DEMAND MAP

Vehicle Population Density (veh/km²) \( \times \) Fraction H₂ vehicles (time) \( \times \) Energy Use per Vehicle H₂/veh/day = H₂ Demand Density (kg H₂/d/km²)

Census Data on vehicles by type and location

Market Penetration rate

Technical progress, Economic competitiveness, Policy

H₂ Vehicle Population Density (veh/km²)

H₂ Vehicle characteristics, drive cycle and mileage

Number, Size and Location of H₂ refueling stations

Customer convenience

Refueling pattern

End-user req. H₂ pressure purity
Fraction of H₂ cars in fleet vs. year and market penetration rate

<table>
<thead>
<tr>
<th>H₂ Cars (fraction of all new cars)</th>
<th>Year 1</th>
<th>Year 5</th>
<th>Year 10</th>
<th>Year 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.7%</td>
<td>3.5%</td>
<td>7%</td>
<td>10%</td>
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<tr>
<td>25%</td>
<td>1.8%</td>
<td>9%</td>
<td>18%</td>
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<tr>
<td>50%</td>
<td>3.5%</td>
<td>18%</td>
<td>35%</td>
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<tr>
<td>100%</td>
<td>7%</td>
<td>35%</td>
<td>70%</td>
<td>100%</td>
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</tbody>
</table>
$H_2$ DEMAND DENSITY (kg/d/km$^2$):  
YEAR 1:  
25% OF NEW Light Duty Vehicles = $H_2$ FCVs  
Blue shows good locations for refueling station
H₂ DEMAND DENSITY (kg/d/km²):
YEAR 5: 25% OF NEW LDVs = H₂ fueled
H₂ DEMAND DENSITY (kg/d/km²):

YEAR 10: 25% OF NEW LDVs = H₂ fueled
H₂ DEMAND DENSITY (kg/d/km²):

YEAR 15: 25% OF NEW LDVs = H₂ fueled
TOOLS FOR ESTIMATING H₂ DEMAND

Highlight urban areas to find total H₂ 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 H₂ 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% H₂ vehicle market penetration rate).

Each city has relatively small H₂ demand, ~10-20% the size of a large coal -> H₂ plant. One large 380-770 t/d (630-1260 MW) coal->H₂ plant could serve entire state, but long, inter-city pipelines would be needed. This suggests that local, smaller scale H₂ production might be preferred for this H₂ demand.
HOW MANY PEOPLE LIVE IN AREAS WHERE LOCAL H₂ PIPELINE DISTRIBUTION MIGHT BECOME Viable IN THE LONG TERM?

Assume All Light Duty Vehicles Use H₂, and Threshold for Building a H₂ Local Pipeline is 200 Cars/km²

Highlight areas where H₂ vehicles >200/km²

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 dense enough for local H₂ distribution, but not large enough for their own coal H₂ plant. Make H₂ at smaller scale (from NG or elec) or pipe or truck H₂ to these cities.
H₂ REFUELING STATIONS

• Where should H₂ refueling stations be located? (Early H₂ stations might serve fleets, possibly co-located with CNG stations or buildings; later stations serve general transportation markets)

• How many H₂ 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 H₂ 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?)
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 mi² (1.3/mi² ctr city; 0.7/mi² 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 H₂ local pipelines) = almost all.
“Gasoline-like” convenience in Columbus
Number of H₂ cars served/station

(convenience =>1/3 of stations = 80 stations have H₂)

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<tr>
<td>10%</td>
<td>60</td>
<td>280</td>
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<td>810</td>
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<td>140</td>
<td>730</td>
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<td>2010</td>
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<td>50%</td>
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<tr>
<td>100%</td>
<td>560</td>
<td>2820</td>
<td>5640</td>
<td>8060</td>
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H₂ refueling options for “Gasoline-like” convenience at public H₂ refueling stations

(assume each vehicle uses ave. of 0.3-0.7 kg H₂/day)

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Other convenient scenarios for H₂ refueling at work or home could be envisioned.

Onsite electrolysis might compete with onsite NG reforming depending on electricity & NG prices, and could use CO₂ free electricity.
RESOURCES FOR H₂ PRODUCTION
Figure 2. Major Natural Gas Producing Basins and Transportation Routes to Market Areas
HYDROGEN FACILITIES AND GOOD TO EXCELLENT RENEWABLE ENERGY RESOURCES

Type of Facility
- Captive Hydrogen Producer
- Gaseous Hydrogen Producer
- By-Product Hydrogen Producer
- By-Product Propane
- Liquid Hydrogen Producer
- Satellite Terminal
- Undetermined

Biomass Resource Potential:
- Excellent
- Good

Concentrating Solar Power Resource Potential:
- Excellent
- Good

Wind Resource Potential:
- Excellent
- Good
ROLE OF EXISTING ENERGY INFRASTRUCTURE AND RIGHTS OF WAY
HYDROGEN PRODUCTION FACILITIES

Type of Facility *
- Captive Hydrogen Producer
- Basic Gaseous Hydrogen Producer
- By-Product Hydrogen Producer/Purifier
- Liquid Hydrogen Producer
- Satellite Terminal

* Facilities depicted according to city location
NATURAL GAS TRANSMISSION SYSTEM IN OHIO
CNG REFUELING STATIONS
ELECTRIC TRANSMISSION SYSTEM
COAL-FIRED POWER PLANTS
LIMITED ACCESS HIGHWAYS AND RAILROADS
MATCHING H₂ SUPPLY AND DEMAND: COLUMBUS, OHIO

• Columbus Population ~ 1 million; ~700,000 light duty vehicles, metro region ave. vehicle population density = 600 cars/km²; center city higher.
• Projected H₂ Demand (if all LDVs use H₂) = 400-800 MW (100-200 million scf H₂/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 CO₂/yr (~ 20 CO₂ 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\textsubscript{2} FROM COAL FOR COLUMBUS

- To make enough H\textsubscript{2} for all Columbus cars in a coal->H\textsubscript{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\textsubscript{2} 150 km to city. The H\textsubscript{2} pipeline itself should add a relatively small amount to the delivered cost of H\textsubscript{2}, \(<1/GJ. H\textsubscript{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\textsubscript{2} capture, and run at a higher capacity factor, then it might be possible to supply electric needs and make enough H\textsubscript{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
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 > threshold)
FUTURE WORK

• Develop models and tools for system cost optimization using data in GIS format
• Examine how H₂ 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 H₂ interact with other parts of the energy economy and environment?
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