ESTIMATING HYDROGEN DEMAND DISTRIBUTION USING GEOGRAPHIC INFORMATION SYSTEMS (GIS)

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ABSTRACT

Understanding the evolution of a hydrogen fuel delivery infrastructure depends on the spatial characteristics of the hydrogen demand. We have developed a GIS-based method to model the magnitude and spatial distribution of hydrogen demand based on exogenously-derived market penetration rates and population data. This approach is applied to a study of the state of Ohio, but can be applied to any region of interest.

Our methodology is based upon population density, which is mapped at the census-block level and used to calculate hydrogen demand density based on per-capita vehicle ownership, projections for daily hydrogen use per vehicle, and market penetration levels or profiles. Various methods (including buffers and thresholds) are used to identify and aggregate high demand density areas into demand clusters, since only those areas with sufficient hydrogen demand are assumed to be viable locations for refueling stations. The resulting demand clusters (or demand centers) represent the potential areas in which investment in hydrogen infrastructure may be warranted and can be fed into a supply infrastructure model.

Sensitivity analyses were conducted to test the impact on hydrogen demand of different market penetration levels, thresholds, and buffer sizes. (i.e. different scenarios) The results allow one to examine the tradeoff between meeting hydrogen demand and the associated projected infrastructure costs. Although this demand model contains many simplifying assumptions, it provides a means for identifying potentially viable locations for hydrogen infrastructure investment at various scenarios.

KEY WORDS:
Infrastructure, threshold, market penetration rate, buffer size, scenarios

1. Introduction

Modeling future hydrogen demand is an important issue in understanding a transition to a hydrogen economy. In particular, understanding the evolution of a hydrogen fuel delivery infrastructure depends on the spatial characteristics of the hydrogen demand. We have developed a GIS-based method to model the magnitude and spatial distribution of hydrogen demand based on exogenously-derived market penetration rates and population data. Under the umbrella of a larger research project[1], this approach is applied to a study of hydrogen demand in the state of Ohio. However, our method could be applied to any region of interest, where census data is available.

This paper details the hydrogen demand calculations, using GIS analysis, for the state of Ohio. First, we list GIS data sources used in the analysis. Next, we describe our methodology for estimating spatial demand using GIS techniques, including buffering and aggregation concepts. We present results, where hydrogen demand is estimated under different scenarios for market penetration levels, thresholds, and buffer sizes.. Finally, we present conclusions and a discussion about the future research work.

2. Data

The following describes the data and factors we used in our analysis:

- Our analysis begins with US census data (population, population density by census tract) for year 2000 (US Census Bureau, 2000).
- As hydrogen demand will occur in the future, a base year of 2030 was used for the analysis. Projected population growth factors from 2000 to 2030 were obtained for Ohio by county (Source: Ohio Department of Development, 2004). These were used to project population in the year 2030 for each county.
- Population density was calculated by dividing the population of each census block by its area (km^2) to arrive at people/km^2.
- An estimate of total light duty vehicles (LDV) per km^2 was calculated by multiplying the population density by an estimate of auto ownership per person. A statewide average factor of 0.7 LDV/person was derived from Ohio Department of Public Safety data, which indicates that 8.3 million

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[1] Dr. Joan M. Ogden, Dr. Christopher Yang, Nils Johnson, Jason Ni and Joshua Johnson: *"Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of Carbon Dioxide"*, DOE Award Number: DE-FC26-02NT41623

light duty vehicles are registered among approximately 11,353,140 people.

- Hydrogen vehicle density (H_2 vehicles/km^2) was calculated by multiplying the total LDV per km^2 by exogenously specified market penetration rates. We examined the case of 5%, 10% and 50% market penetration in our sensitivity analysis.
- Hydrogen demand density (kg H_2/day/km^2) was derived by multiplying the hydrogen vehicle density (H_2 vehicles/km^2) with an estimate of average vehicle fuel use of 0.6 kg H_2/day/vehicle. This estimate is based on the assumption that the average vehicle travels 15,000 miles/year and has a fuel economy of 65 miles/kg (roughly equivalent to a gasoline fuel economy of 65 miles per gallon).
- Hydrogen demand (kg H_2/day) in the region of interest can be calculated by multiplying the hydrogen demand density (kg H_2/day/km^2) by the area.

3. Methodology

Based on the data, we used the following formula to calculate the hydrogen demand density:

Hydrogen Demand Density (kg H_2/day/km^2) =
Population Density (people/km^2) x Vehicle Ownership (0.7 LDV/person) x
Market Penetration Rate (5%, 10%, 50%) x Fuel Use (0.6 kg H_2/day/vehicle)

After we calculated the census block level hydrogen demand density, we went through the following steps to identify the magnitude and spatial distribution of hydrogen demand centers:

- **<u>STEP 1</u>: Applying Density Threshold (DT)**

Given hydrogen demand density throughout the state, the next step was to identify census blocks with sufficient demand to warrant consideration for infrastructure. This was done by setting a demand density threshold (DT). Only areas with a demand density exceeding the threshold are considered. Three density thresholds (DT) (50, 100, and 150 kg H_2/day/km^2) were analyzed to examine their ability to capture hydrogen demand. A GIS tool (ArcMap 9.0) was used to select census blocks where the demand density exceeded the specified threshold. Upon examining the results, it was apparent that the selections did not result in uniform areas of high density; but rather concentrations of high density census blocks with holes caused by low density blocks. Figure 1 illustrates this phenomenon within the city of Columbus for the three thresholds (The most stringent threshold is shown in red, the middle case in green and the least stringent threshold in blue.).

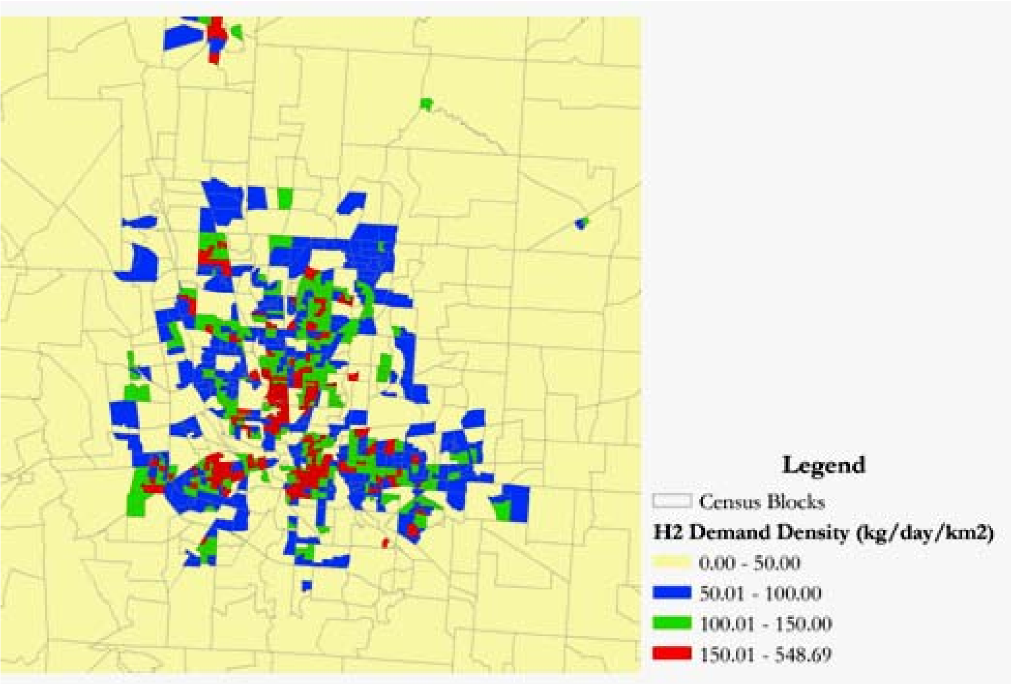


Figure 1 Census blocks under different density thresholds,
City of Columbus, Ohio

- **<u>STEP 2</u>: Buffering and Aggregating Demand**

In designing an optimized infrastructure, it was decided to identify contiguous demand clusters rather than the disjointed census blocks shown in Figure 1. A 5-kilometer buffer was used to aggregate these clusters into uniform, consolidated shapes. The buffer was applied from each of the high demand density blocks and then all census blocks that were *completely contained within* the buffer were aggregated to form the demand clusters. Figure 2 illustrates the results from this analysis for the city of Columbus. The buffer could be regarded as a measure of allowed distance from the center of each high density block. For example, this approach would allow low density urban areas like parks to be aggregated into the whole city.

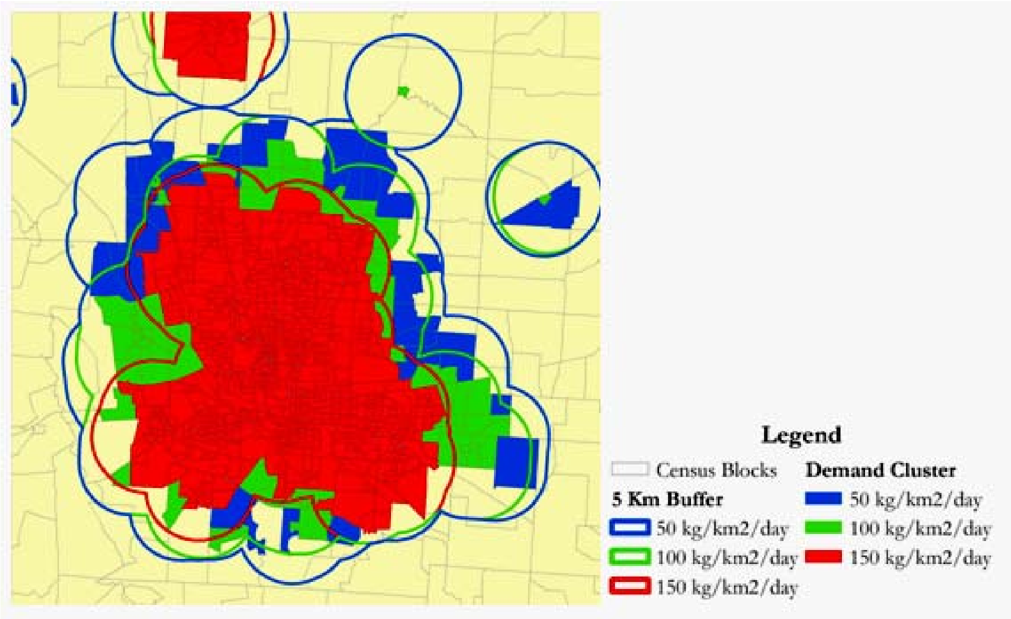


Figure 2 Demand clusters under different density thresholds,
City of Columbus, Ohio

- **<u>STEP 3</u>: Applying Aggregation Threshold (AT)**

Given the demand clusters in Step 2, the next step was to identify a subset of clusters that have sufficient aggregate hydrogen demand (kg H_2/day) to support a single fueling station. To calculate aggregate demand, total hydrogen demand was identified for each census block by multiplying the hydrogen demand density (kg H_2/day/km^2) with the area (km^2) of each block. Aggregate demand for each demand cluster was then calculated by summing the demand for all component blocks. The aggregation threshold (AT) was then used to eliminate clusters that do not have sufficient demand to support one fueling station. Three aggregation thresholds were tested, including 1,000, 3,000, and 5,000 (kg H_2/day).

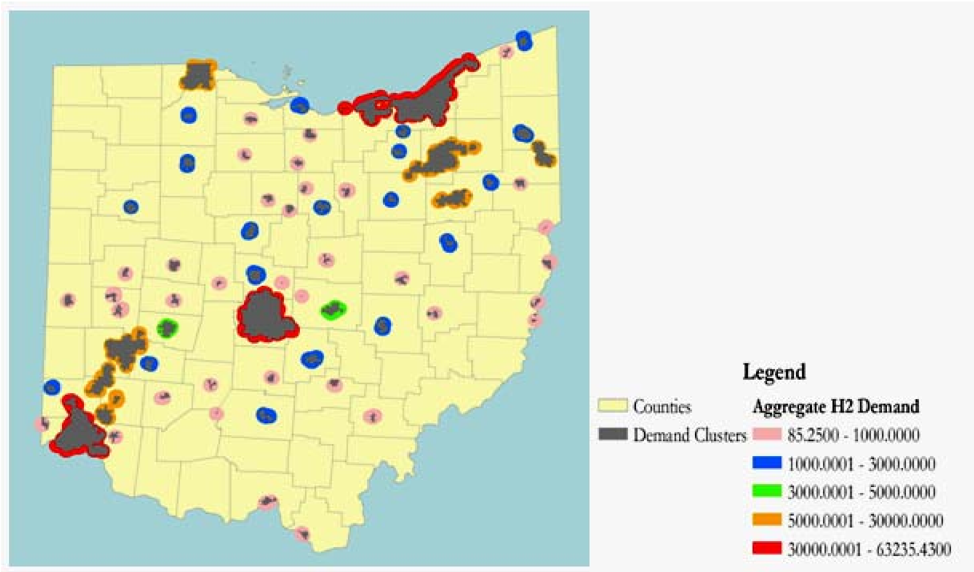


Figure 3 Demand clusters prior to applying an aggregation threshold

Figure 3 shows demand clusters prior to application of an aggregation threshold. For the "base" case that used a density threshold of 100 (kg H_2/day/km^2), we found that the hydrogen demand in individual clusters varied from 85 to 63,235 (kg H_2/day) under the 10% scenario and from 115 to 754,836 (kg H_2/day) under the 50% scenario. Figure 3.shows the results for the 10% scenario.

Using the "base" case aggregation threshold of 3,000 (kg H_2/day), all demand centers with a demand below this threshold were erased, leaving 12 demand centers under the 10% market penetration and 39 under the 50% market penetration. The final demand centers using the "base" thresholds (DT = 100 kg H_2/day/km^2; AT = 3000 kg H_2/day) are illustrated for the 10% and 50% scenarios in Figure 4 and Figure 5.

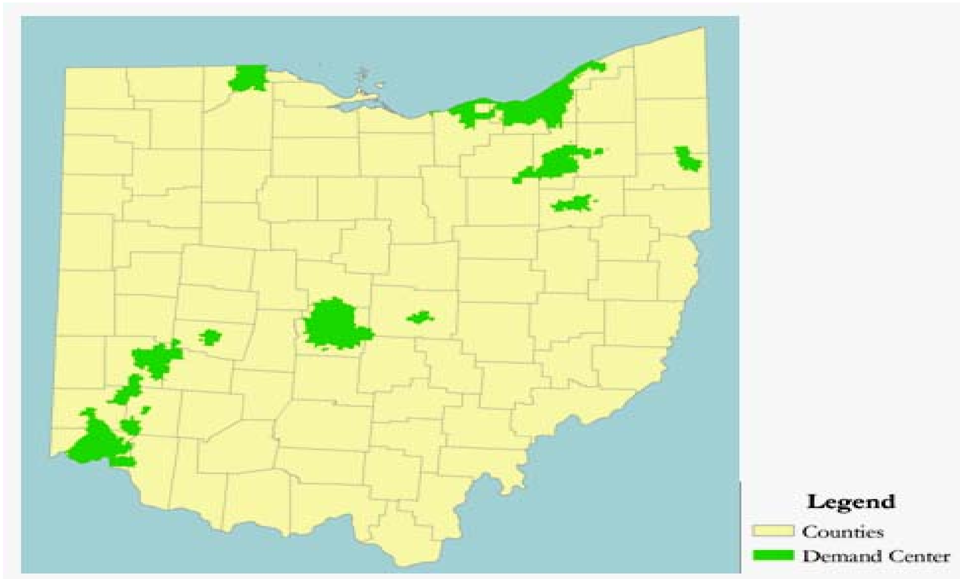


Figure 4 Demand centers (DT = 100 kg H_2/day/km^2; AT = 3000 kg H_2/day) with 10% market penetration

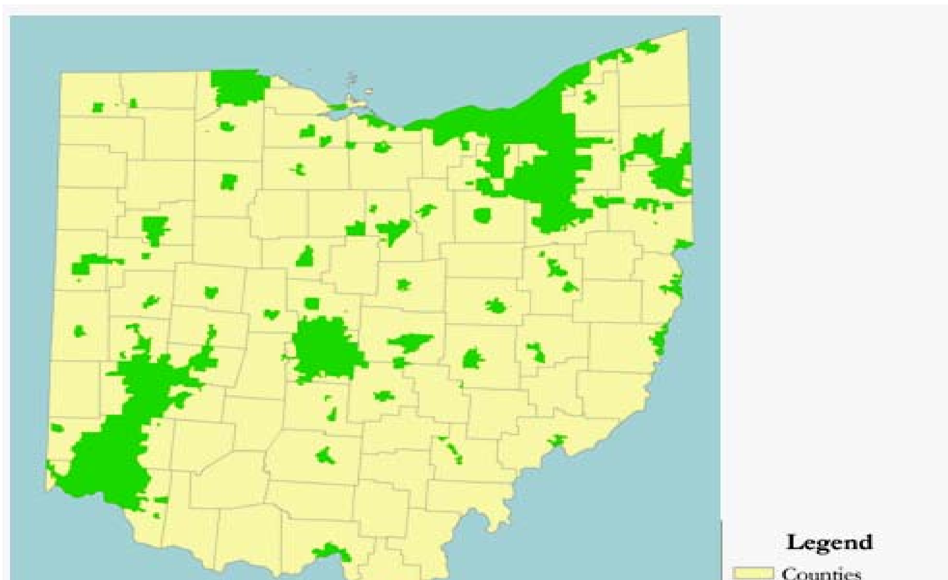


Figure 5 Demand centers (DT = 100 kg H_2/day/km^2; AT = 3000 kg H_2/day) with 50% market penetration

As we can see from above, the final demand centers actually share the same boundary with the original census blocks. The following flow chart (Figure 6) summarizes the procedures of hydrogen demand calculation and GIS process.

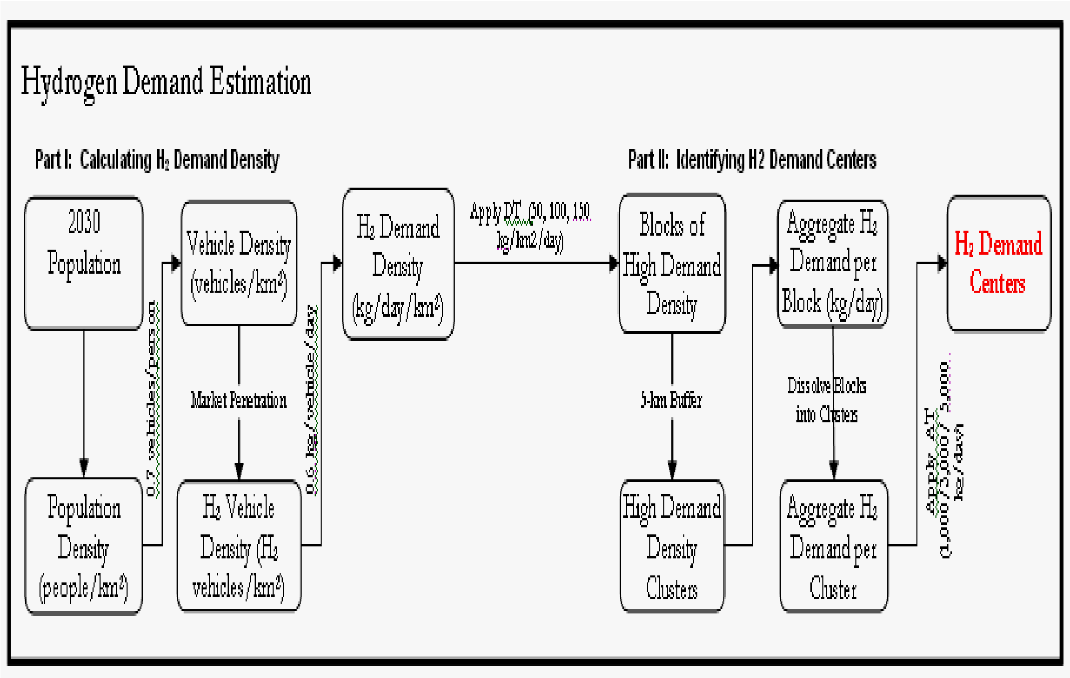


Figure 6 Flow chart of hydrogen demand estimation

4. Results and Sensitivity Analysis

Several input variables are used to determine the spatial location and size of hydrogen demand centers from raw census data. In this section we study the sensitivity of our results to changes in these variables. We consider several metrics for characterizing demand centers, such as the fraction of statewide hydrogen demand captured in the demand centers.

- **Sensitivity to Density and Aggregation Thresholds.**

As mentioned, in order to understand the spatial distribution and quantity of hydrogen demand, we used two thresholds to identify areas of high demand. The first threshold (density threshold) was used to identify high demand density and develop demand clusters. The second threshold (aggregate threshold) was used to highlight areas with sufficient aggregate demand to warrant investment in infrastructure (i.e. fueling station). As a result, it served to identify the optimized demand centers as a subset of the initial demand clusters. In order to determine appropriate thresholds, we conducted a sensitivity analysis using three threshold scenarios to analyze their impact on the extent and quantity of hydrogen demand. The three scenarios are shown in the following table:

	Scenario 1 [low threshold]	**Scenario 2 [base]**	**Scenario 3 [high threshold]**
Density Threshold	50 (kg H_2/day/km^2)	100 (kg H_2/day/km^2)	150 (kg H_2/day/km^2)
Aggregate Threshold	1000 (kg H_2/day)	3000 (kg H_2/day)	5000 (kg H_2/day)

Table 1 Threshold values for 3 scenarios

To compare these scenarios, we calculated the percent of statewide hydrogen demand (kg H_2/day) captured within the demand centers, the percent of statewide land area (km^2) captured, and the number of demand centers identified, as summarized in the following table:

	Scenario 1 [low threshold]	**Scenario 2 [base]**	**Scenario 3 [high threshold]**
H_2 Demand (% of Ohio total)	63.65%	47.21%	32.32%
Area (% of Ohio total)	8.83%	4.84%	2.59%
Number of Demand Centers	25	12	8

Table 2 Sensitivity analysis results for 3 scenarios

As expected, a greater percentage of hydrogen demand is captured over a larger land area and in more demand centers as the threshold is lowered. The following figures illustrate the results for demand centers with varying levels of hydrogen demand. We categorized the demand centers into five groups based on the quantity of aggregate hydrogen demand: 0~5,000 kg/day, 5,000~10,000 kg/day, 10,000~20,000 kg/day, 20,000~40,000 kg/day, and greater than 40,000 kg/day. Figure 7 identifies the number of demand centers in each group.

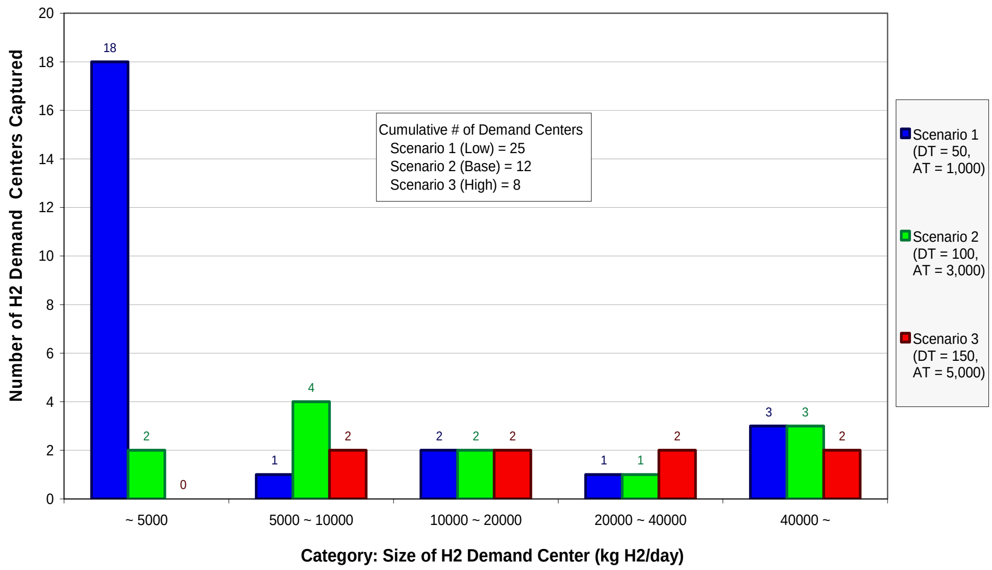


Figure 7 Number of hydrogen demand centers
(3 scenarios, 5 groups of demand centers)

As shown in above figure, “low” threshold (the blue bars) results in a large number of centers with low hydrogen demand (less than 5,000 kg H_2/day, for example). Depending on the location of these small centers, it may be cost prohibitive to supply them with hydrogen given such low demand. Consequently, it may be preferable to use a “high” threshold to eliminate some of these smaller demand centers. Besides, the “low” threshold scenario not only results in more low-demand centers, but also results in more high-demand centers (> 40,000 kg H_2/day) as we can observe from Figure 7.

Figure 8 illustrates the percent of statewide hydrogen demand for different group of demand center.

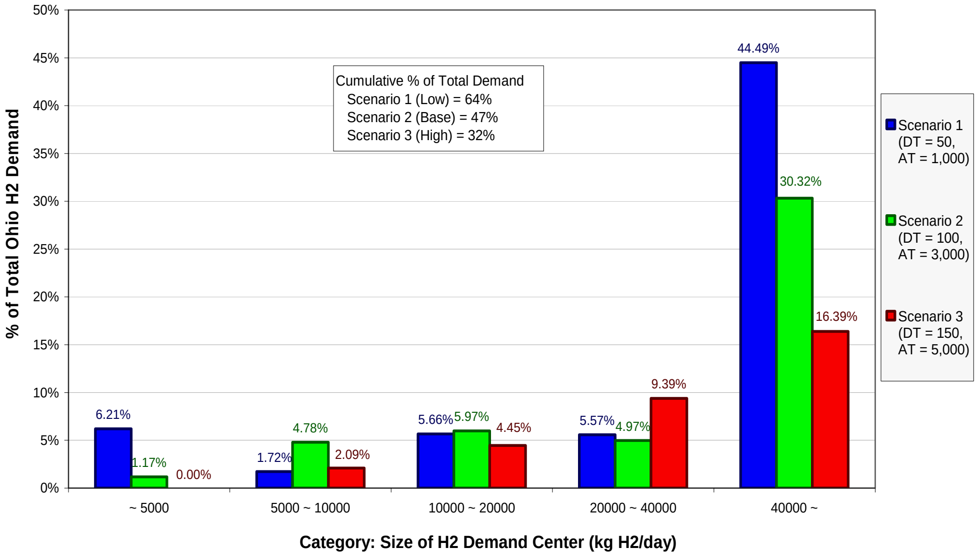


Figure 8 Percent of statewide hydrogen demand captured
(3 scenarios, 5 groups of demand centers)

Figure 8 indicates that the "low" threshold captures more of the hydrogen demand (64% of state total) as compared to the "base" threshold (47% of state total) and the "high" threshold (32% of state total). In particular, it captures more demand in small and large demand centers, which is a similar phenomenon as in Figure 7.

Synthesizing the results of Figure 7 and Figure 8, although low threshold scenario does result in a 36% increase in the capture of demand over the "base" scenario, it requires infrastructure to be installed to over twice as many demand centers. (25 demand centers vs. 12 demand centers) The "high" scenario captures about 50% of the demand met by the "low" threshold, but it only requires one third of demand centers in the "low" threshold. (8 demand centers vs. 25 demand centers)

Figure 9 indicates the percent of total Ohio land area captured within different group of demand center.

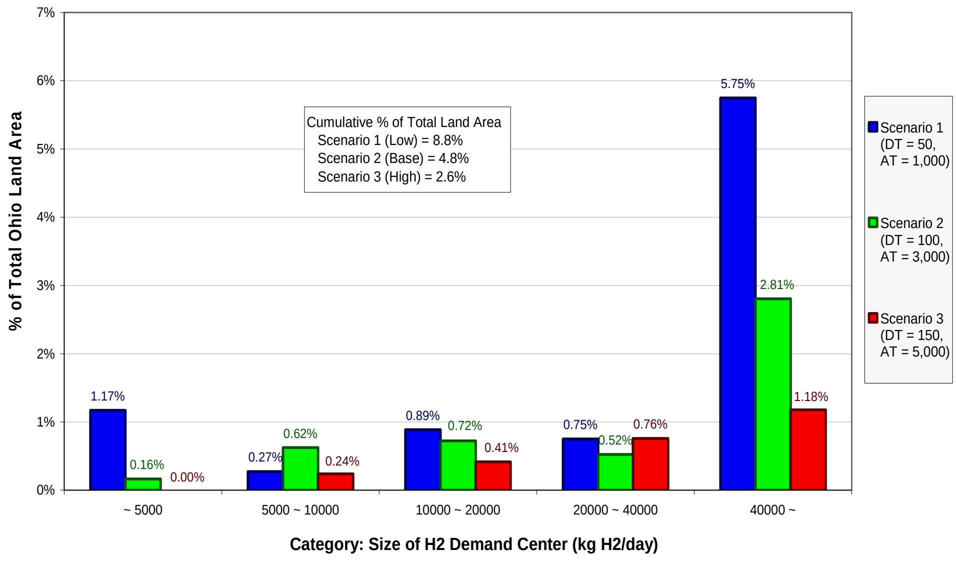


Figure 9 Percent of statewide land area captured
(3 scenarios, 5 groups of demand centers)

As in Figure 9, the “low” threshold scenario captures significantly more land area (especially in small and large demand centers). This result suggests that the “low” threshold would require more extensive intra-city infrastructures, resulting in higher costs. The “low” scenario occupies 83% more land than the “base” scenario and 238% more land than the “high” threshold. In summary, Figure 10 illustrates the spatial distribution of the three scenarios under the 10% market penetration.

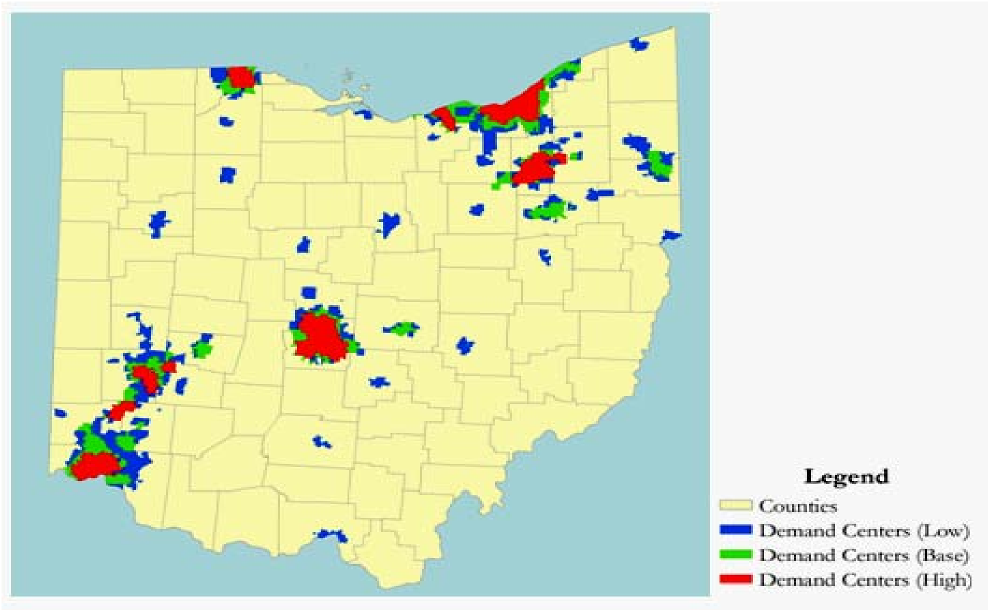


Figure 10 Spatial distribution of demand centers (3 scenarios)

Figure 10 illustrates how the demand centers expand in size and number as the thresholds are lowered. In comparison with the “base” scenario, the “low” scenario captures 36% more of the state hydrogen demand, but requires service to twice as many demand centers and 83% more land area. However, it does capture 64% of hydrogen demand in less than 10% of the land area. In contrast, the “high” scenario captures 32% less hydrogen demand than the “base” and requires 46% less land area and 33% fewer demand centers. It captures 32% of the hydrogen demand in only 2.6% of the land area. The last, the “base” scenario captures 47% of hydrogen demand in less than 5% of the land area.

- **Sensitivity to Buffer Size**

Here we examine the impact of changing the buffer size. This corresponds to increasing the “influence distance” of each high density census tract. In this case, we started from a “base” scenario (DT/AT = 100/3000, buffer size = 5 km, and 10% market penetration rate). We vary the buffer size from 1 km to 10 km. Results are shown in Figure 11, for three buffer sizes (1 km, 5 km (the base case), and 10 km). The number of demand centers and fraction of total statewide demand are shown in the table below. As buffer size is increased, a significantly larger fraction of demand is captured.

- **Sensitivity to Market Penetration Rate.**

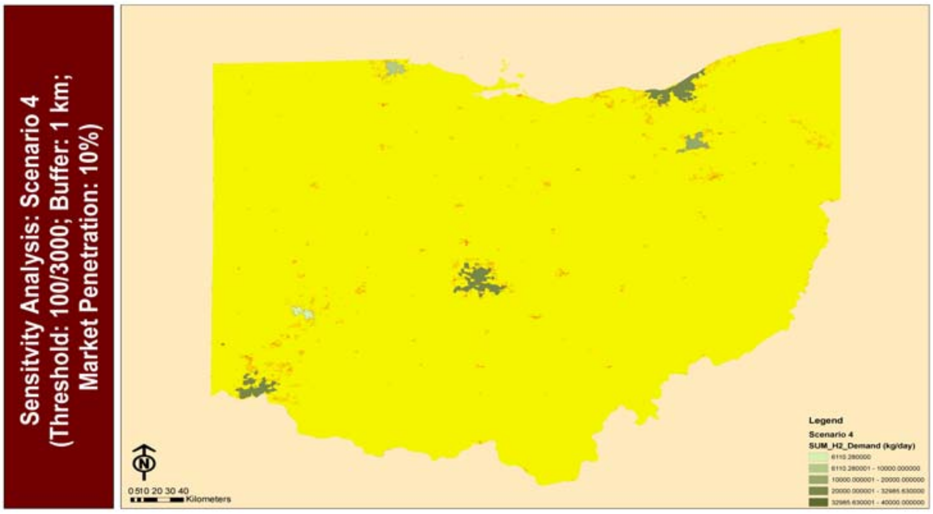
In Figure 12, we show the impact of market penetration rate on the demand centers. At higher market fractions, demand centers expand and spread, and a larger fraction of demand is captured.

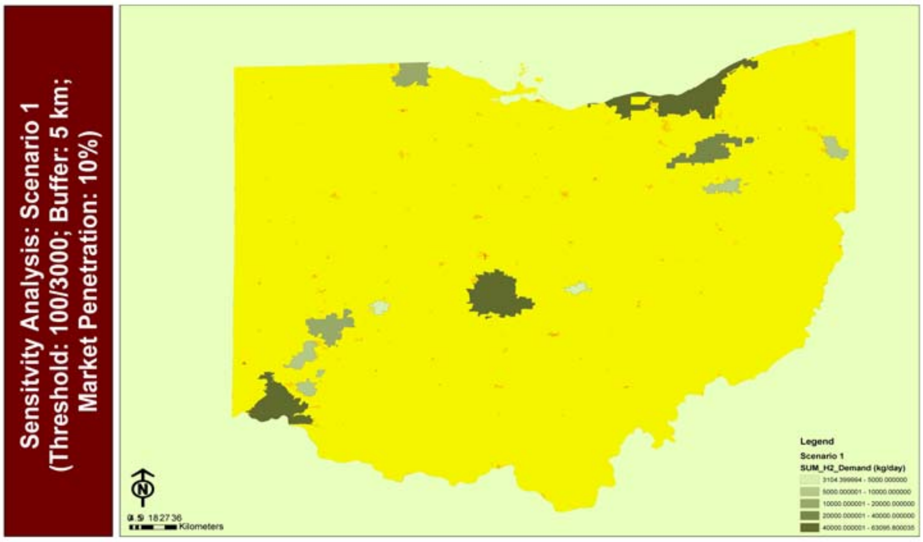
- **Summary**

Table 3 summarizes out sensitivity studies. Increasing the buffer size and increasing the market penetration rate all had similar impacts on the hydrogen demand captured and number of demand center identified. More hydrogen demand and more demand centers will be included, if we either lower the threshold, increase the buffer size or raise the market penetration rate.

(base)	Thresholds (DT/AT)	Buffer Size	Market Penetration Rate	% of total Ohio H2 Demand	# of demand center
Scenario 1	100/3000	5 km	10%	47%	12
Scenario 2	50/1000	5 km	10%	64%	25
Scenario 3	150/5000	5 km	10%	32%	8
Scenario 4	100/3000	1 km	10%	22%	6
Scenario 5	100/3000	10 km	10%	65%	10
Scenario 6	100/3000	5 km	5%	22%	5
Scenario 7	100/3000	5 km	50%	74%	39

Table 3 Summary of Results





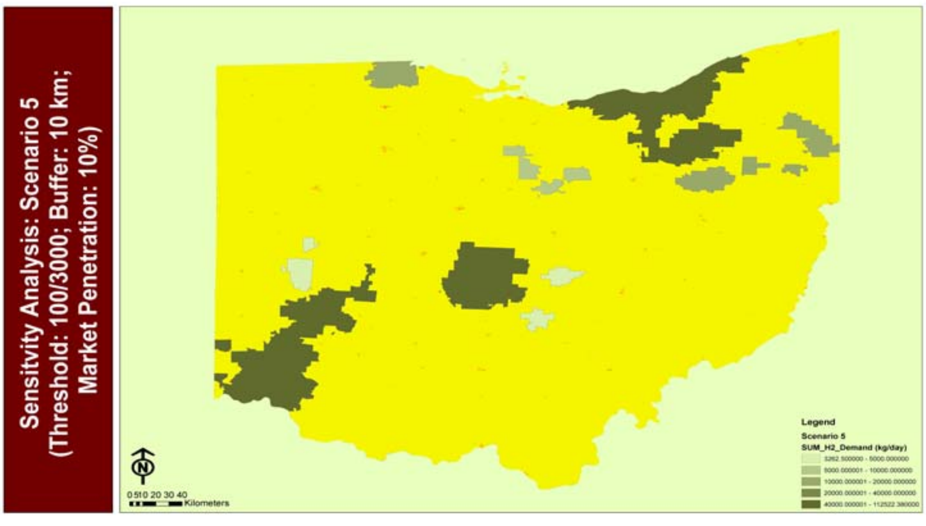


Figure 11 Effect of changing the buffer size: 1 km (top), 5 km (middle), 10 km (bottom)

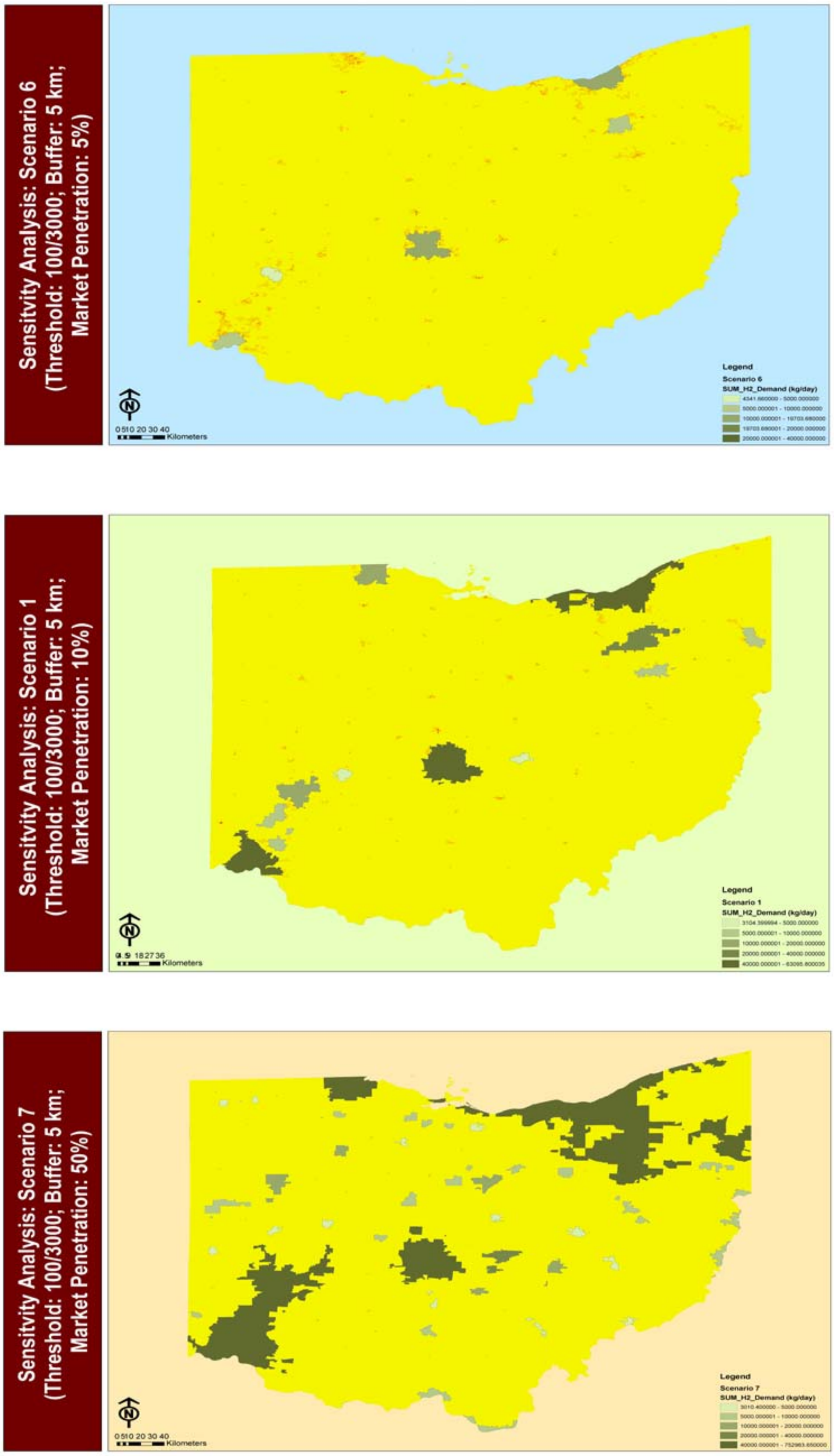


Figure 12 Effect of changing the market penetration 5% (top), 10% (middle), 50% (bottom)

5. Conclusion and Future Work

We developed a methodology based upon GIS census data, for calculating hydrogen demand density spatially, and identifying hydrogen demand centers. Sensitivity analyses were conducted to test the impact on hydrogen demand of different market penetration levels, thresholds, and buffer sizes. Although this demand model contains many simplifying assumptions, it provides a means for identifying potentially viable locations for hydrogen infrastructure investment. This model of demand can be coupled to a hydrogen supply infrastructure model.

In this paper, GIS was shown to be a powerful new research tool for tasks such as: data managing and visualization in the hydrogen demand modeling process. In addition, the results of our sensitivity analyses suggest that there may be a trade-off between serving more hydrogen demand and the cost of building a more extensive infrastructure to expand the service area.

In the future, it will be interesting to investigate in the levelized cost of hydrogen under each scenario in order to determine which thresholds are the most cost-effective. For example, although the "low" threshold scenario requires extensive expansion of infrastructure for a relatively small gain in the capture of hydrogen demand, it may allow for the capture of economies of scale, resulting in favorable economics.

We have coupled estimates of the infrastructure cost to estimates of hydrogen demand. In a recent study [Ogden et al. 2004; Johnson et al. 2005] we optimized the infrastructure network based on hydrogen demand, CO_2 sequestration and pipeline cost. Eventually, it is assumed that the optimization process will be able to provide some feedback on the spatial distribution. (Figure 13)

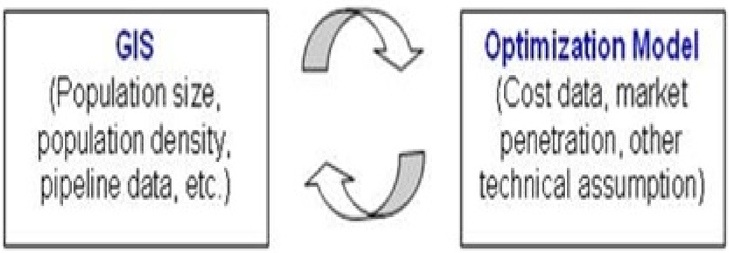


Figure 13 Interaction between GIS and Optimization of Infrastructure

6. Reference

1. Dr. Joan M. Ogden, Dr. Christopher Yang, Nils Johnson, Jason Ni and Joshua Johnson: *"Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of Carbon Dioxide"*, Final Report to US Department of Energy, September 30 2004, DOE Award Number: DE-FC26-02NT41623
2. Dr. Joan M. Ogden, Dr. Christopher Yang, Nils Johnson, Jason Ni, Zhen-Hong Lin and Joshua Johnson: *"Optimal Design of a Fossil Fuel-Based Hydrogen Infrastructure with Carbon Capture and Sequestration: Case Study in Ohio"*, Presentation of NHA Conference, March 31, 2005
3. N. Johnson, C. Yang, NHA 2005 paper.

7. Authors' Bios

Jason Ni is graduate student researcher at the Institute of Transportation Studies. He got his BS. degree from the department of Civil Engineering of National Taiwan University, and his master degrees from the dual-degree program of Transportation Engineering and City Planning at UC Berkeley. Jason joined UC Davis in Fall 2003 as Ph.D. student in Transportation Technology and Policy program. He started working for Professor Joan Ogden on hydrogen demand modeling since Spring 2004. The major work he has done so far is the GIS demand modeling for the State of Ohio.

Nils Johnson is a project manager within the Hydrogen Pathways Program at the Institute of Transportation Studies at the University of California, Davis. He is primarily involved with the management of the Transitional Hydrogen Infrastructure Modeling (THIM) project, which is an ongoing modeling effort to evaluate how a hydrogen infrastructure might develop through time. Mr. Johnson has a BA in political science from Haverford College and a Master of Forestry and Master of Environmental Management from the Nicholas School of the Environment at Duke University.

Dr. Joan Ogden is Associate Professor of Environmental Science and Policy at the University of California, Davis and Co-Director of the Hydrogen Pathway Program at the campus's Institute of Transportation Studies. Her primary research interest is technical and economic assessment of new energy technologies, especially in the areas of alternative fuels, fuel cells, renewable energy and energy conservation. Her recent work centers on the use of hydrogen as an energy carrier, hydrogen infrastructure strategies, and applications of fuel cell technology in transportation and stationary power production. She participated in the U.S. DOE Hydrogen Vision process in 2001, and headed the systems integration team for the National Hydrogen Roadmap in 2002. She is active in the H2A, a group of hydrogen analysts convened by the Department of Energy to develop a consistent framework for analyzing hydrogen systems, and serves on the Blueprint Plan advisory panel for the California Hydrogen Highway Network.

Dr. Christopher Yang is a Research Engineer at the Institute of Transportation Studies at the University of California, Davis. His primary research focus is on modeling of hydrogen production and distribution infrastructure and understanding how a hydrogen economy might evolve over time. Other research topics include a study on the interactions between fuel and electricity production in a hydrogen economy. He recently completed his PhD from Princeton University in the Mechanical and Aerospace Engineering Department where he collaborated with faculty in a multidisciplinary lab focused on fuel cell membrane research.

Joshua Johnson is a GIS Research Analyst at the Information Center for the Environment at the University of California, Davis. He specializes in the application of GIS to the study of environmental issues.