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Regional Consumer Hydrogen Demand and Optimal Hydrogen Refueling Station Siting

M. Melendez and A. Milbrandt

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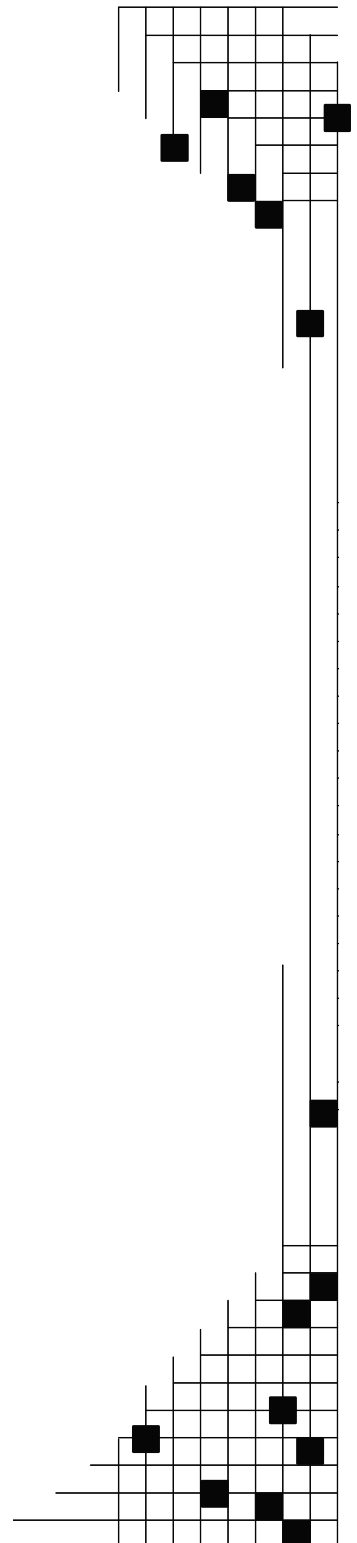
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Introduction

Infrastructure development analysis explores the benefits and drawbacks of various options for installing refueling hardware to serve an emerging hydrogen demand. Most alternative fuel experts agree that infrastructure issues have been among the top barriers to transitioning to alternative transportation fuels. Therefore, infrastructure analysis is a key component in the development of a hydrogen transportation system. Understanding consumer demand on a geographic basis is an important part of this analysis. Matching emerging hydrogen demand with emerging infrastructure is critical to a successful transition.

In fiscal years (FY) 2004 and 2005, the National Renewable Energy Laboratory (NREL) developed a proposed minimal infrastructure to support nationwide deployment of hydrogen vehicles by offering infrastructure scenarios that facilitated interstate travel.[1] In FY 2006, additional analyses quantified projected hydrogen vehicle demand nationwide and in targeted metropolitan areas and projected hydrogen fuel demand to inform infrastructure decisions (e.g., siting hydrogen refueling stations and selecting between centralized and distributed hydrogen production).[2]

The current (FY 2007) project builds on this previous work by analyzing projected hydrogen demand at a finer (subregional) scale and proposing hypothetical locations for hydrogen refueling stations based on optimal demand characteristics. The following are the objectives of this analysis:

1. Identify the minimum hydrogen infrastructure needed to gain consumer buy-in for purchasing hydrogen vehicles .
2. Demonstrate a method for siting hydrogen stations based on the unique demand characteristics of select urban areas.

Research Methodology

There are two general types of vehicle purchasers: 1) consumers and 2) fleets. Both groups have unique characteristics that affect how they choose vehicles to purchase and drive. This study examines hydrogen infrastructure demand based on anticipated hydrogen vehicle owners.

Various factors influence a consumer's vehicle purchase decision, including purchaser characteristics (e.g., income and age) and external factors (e.g., vehicle rebates, interest

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[1] See Melendez, M.; Milbrandt, A. *Analysis of the Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles: Preprint*. NREL Report No. CP-540-37903. Golden, CO: National Renewable Energy Laboratory, 2005.

[2] See Melendez, M.; Milbrandt, A. *Geographically Based Hydrogen Consumer Demand and Infrastructure Analysis: Final Report*. NREL Report No. TP-560-40373. Golden, CO: National Renewable Energy Laboratory, 2006.

rates, and tax incentives). To match emerging consumer demand for hydrogen vehicles with transitional hydrogen infrastructure, the spatial/geographic component of consumer demand must be understood. This analysis projects the geographic distribution of consumer demand for hydrogen vehicles and the corresponding infrastructure requirements.

The analysis consists of the following steps:

- Project Hydrogen Demand at Census Tract Level: Key attributes affecting consumer acceptance of hydrogen vehicles are identified and spatially analyzed at the census tract level using geographic information systems (GIS).

- Site Hydrogen Refueling Stations: Specific sites for hydrogen refueling stations are suggested based on locations with optimal demand characteristics.

- Quantify Hydrogen Refueling Station Coverage: The proportions of the target populations served by the proposed hydrogen refueling stations are calculated.

A regional framework was used for the analysis. Regions are states grouped together based on physical, demographic, and transportation characteristics (Figure 1). These regions are slightly modified versions of the regions defined by the U.S. Census Bureau (e.g., the Rocky Mountain and Great Plains states are combined into a single Central Region owing to their low population, small urban areas, and relative isolation from highly populated areas).
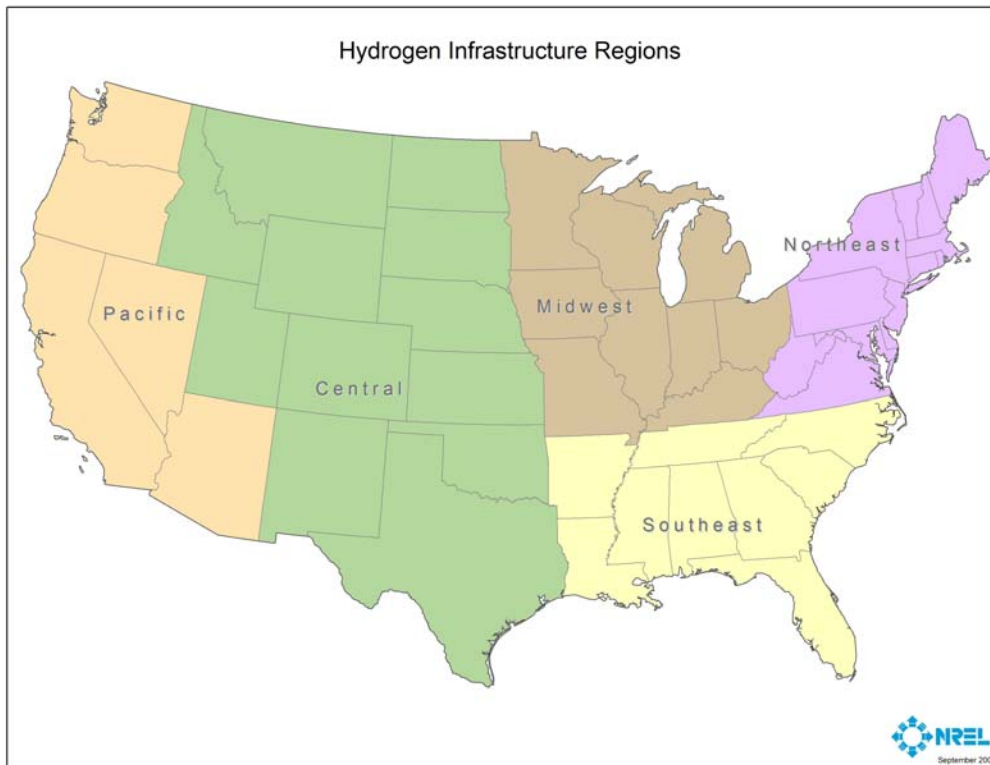
Figure 1. Regions Used in the Analysis

Once projected hydrogen demand is calculated, subregions are identified within the regions. Subregions are large urban areas or clusters of urban areas with contiguous "good" and higher hydrogen demand and well-established traffic corridors. This regional/subregional framework balances the demand analysis and proposed hydrogen infrastructure throughout the nation and ensures that geographically diverse urban areas are examined.

Hydrogen Demand Projections

Demographics
Key attributes affecting hydrogen vehicle penetration into the consumer market were identified through a literature search (from the FY 2004 and 2005 work described in the Introduction above) and interviews with vehicle technology transition experts, then reviewed and ranked by a focus group consisting of NREL personnel with expertise in advanced technology vehicle deployment (Table 1). These assumptions were also confirmed by various market studies and analyses related to hybrid and hydrogen vehicles conducted by researchers at UC Davis and Synovate.

Table 1. Attributes Affecting Hydrogen Vehicle Adoption by Consumers

Attribute	Impact	Rationale
Household Income	High	Higher incomes lead to earlier adoption
Households with Two or More Vehicles	High	Households with multiple vehicles more likely to adopt hydrogen vehicles
Air Quality	Medium	Low air quality leads to educated consumers and incentives
Clean Cities Coalitions	Medium	Coalitions pull funding opportunities together and create alternative fuel awareness
Commute Distance	Medium	More time spent commuting in a vehicle interests consumers in newer and more efficient vehicles
Education	Medium	Higher education leads to earlier adoption
Hybrid Vehicle Registrations	Medium	Early adopters of new gasoline vehicle technologies could be early adopters of new hydrogen vehicle technologies
State Incentives	Medium	Alternative fuel vehicle incentives could indicate future or existing hydrogen incentives
Zero-Emission Vehicle (ZEV) Sales Mandate	Medium	Hydrogen vehicles qualify for these mandates

These attributes apply to a strategy where the general public consumer, limited to the contiguous United States, is the primary focus of early hydrogen vehicle deployment. Hydrogen vehicle demand can be described as a function of these attributes:

$$\text{Consumer hydrogen vehicle demand} = F \text{ (attributes)} \qquad (1)$$

The data to support analysis of these attributes were collected from various sources, including the U.S. Census Bureau, the U.S. Department of Energy's (DOE) Clean Cities Alternative Fuels Data Center (AFDC), and the U.S. Environmental Protection Agency.

Attribute Scores and Weights
The original datasets of each attribute have varying spatial presentations—some are at census tract level[3], whereas others are at county or state levels or actual locations. For each subregion, all these datasets were aggregated or disaggregated to the census tract level using two standard GIS techniques:

- **Area-weighting**—Area-weighting is a common form of quantitative aggregation. Data values are multiplied by the percentage of the area a component covers and then divided by the total of the area percentages.

- **Dominant component**—Dominant component is applied to qualitative datasets such as air quality and state incentives. It takes the data value for the component covering the largest area of the tract and assigns that value to the entire tract.

As outlined in Table 1, not all attributes have an equal impact on hydrogen vehicle demand. To incorporate these inequalities into the analysis, preferences were incorporated into the corresponding model developed in ArcGIS 9.1 Model Builder. The Model Builder Spatial Analyst extension evaluates multiple attributes through classification, ranking, and weighted-overlay techniques to produce the results for each demand scenario. The Model Builder is very flexible. Models can be saved and rerun with different parameters. In addition, data can be added or replaced, and other modules can be attached.

In order to perform the analysis effectively, attribute datasets had to be first ranked internally to value the data within the dataset. The attributes were then weighted in relation to other attributes.

Internal Dataset Ranking
There is no single best data classification method; each has advantages and disadvantages depending on the nature of the data and the type of information and analysis desired. In general, a classification method should maximize the between-class differences and minimize the within-class differences.

The natural breaks classification was chosen for this study. This method identifies break points by looking for groupings and patterns inherent in the data. ArcGIS uses a complex statistical formula (Jenk's Optimization) to identify break points by choosing the class breaks that best group similar value and maximize the differences between classes. The features are divided into classes with boundaries set where there are relatively big jumps in the data values. The major disadvantages are that the concept behind the classification may not be easily understood by all map users, and the legend values for the class breaks may not be intuitive. The advantage, however, is that it is one of the best ways to classify data that model natural human behaviors and patterns. The natural break method best applies to projected hydrogen demand because hydrogen demand patterns are not uniform by nature.

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[3] A census tract is a small, relatively permanent statistical subdivision of a county, which is relatively homogeneous with respect to population characteristics, economic status, and living conditions. The population of census tracts averages about 4,000. (The U.S. Census Bureau)

Using the natural break classification method, five classes were created within each data layer. Five classes were chosen because of the depth of analysis and the refinement of results they would provide. Then, a ranking system of 1 to 5 was employed to rate the values within each class used in the hydrogen demand model. A class was ranked 1 if its values had a "low" influence on the chosen strategy (e.g., people with the lowest income would generate the lowest hydrogen vehicle demand). A class was ranked 5 if its values had a "very high" influence (e.g., people with the highest income would generate the highest hydrogen vehicle demand).

Attribute Descriptions, Rankings, and Weightings

Based on the value placed on the attributes by transportation experts (Table 1), attributes were weighted in relation to each other in ArcGIS in terms of low, medium, or high impact on hydrogen vehicle adoption. These are normalized so the weightings of all the attributes are equal to 100%. The following section describes each attribute as well as the attribute classifications, rankings, and weightings.

- Household Income
  - Data origin: 2000 U.S. Census
  - Data representation: median household income
  - Rationale: Initial customers for hydrogen vehicles will be those with higher income levels.

Table 2. Household Income

Attribute	Values and Classification (median income, $U.S.)	Scoring of Classification	Weighting Score
Household Income	0–25,000	1	15% (High)
	25,001–50,000	2	
	50,001–75,000	3	
	75,001–100,000	4	
	> 100,000	5	

- Households with Two or More Vehicles
  - Data origin: 2000 U.S. Census
  - Data representation: number of households that have two or more vehicles
  - Rationale: Initial customers for hydrogen vehicles will be those in households that have at least two vehicles because of limited hydrogen range and refueling opportunities. (The NREL focus group considered this to be the most important factor in predicting hydrogen vehicle demand.)

Table 3. Households with Two or More Vehicles

Attribute	Values and Classification (number of households)	Scoring of Classification	Weighting Score
Two or More Vehicles per Household	0–100	1	15% (High)
	101–500	2	
	501–1,000	3	
	1,001–2,000	4	
	> 2,000	5	

- Air Quality
  - Data origin: U.S. Environmental Protection Agency, 2004
  - Data representation: non-attainment status of area (for one or more pollutants)
  - Rationale: Issues with local air pollution make consumers more aware of the impacts of vehicles on air pollution and can lead to additional funding or programs for consumers to purchase cleaner vehicles.

Table 4. Air Quality

Attribute	Values and Classification (level of non-attainment)	Scoring of Classification	Weighting Score
Air Quality	None	1	10% (Medium)
	Marginal	3	
	Moderate	4	
	Severe	5	

- Clean Cities Coalitions
  - Data origin: NREL/DOE Clean Cities Web site, October 2006
  - Data representation: existence of Clean Cities Coalition in area
  - Rationale: Having a local Clean Cities coordinator to assist in identifying funding, partnerships, and other positive factors in the area is critical to early adoption of hydrogen vehicles.

Table 5. Clean Cities Coalitions

Attribute	Values and Classification (Census tract falls within a Clean City)	Scoring of Classification	Weighting Score
Clean Cities Coalitions	No	1	10% (Medium)
	Yes	5	

- Commute Distance
  - Data origin: 2000 U.S. Census
  - Data representation: workers age 16+ who commute 20 or more minutes each way
  - Rationale: More time spent commuting in a vehicle might make consumers more interested in newer and more efficient vehicles.

Table 6. Commute Distance

Attribute	Values and Classification (number of people)	Scoring of Classification	Weighting Score
Commute Distance	0–100	1	10% (Medium)
	101–500	2	
	501–1,000	3	
	1,001–2,000	4	
	> 2,000	5	

- Education
  - Data origin: 2000 U.S. Census
  - Data representation: number of people age 25+ with a Bachelor's degree or higher
  - Rationale: Initial customers for hydrogen vehicles will be those with higher education levels.

Table 7. Education

Attribute	Values and Classification (number of people)	Scoring of Classification	Weighting Score
Education	0–100	1	10% (Medium)
	101–500	2	
	501–1,000	3	
	1,001–2,000	4	
	> 2,000	5	

- Hybrid Vehicle Registrations
  - Data origin: R.L. Polk, 2006
  - Data representation: number of registered hybrid vehicles
  - Rationale: Early adopters of new gasoline vehicle technologies could also be early adopters of new hydrogen vehicle technologies.

Table 8. Registered Hybrid Vehicles

Attribute	Values and Classification (number of vehicles)	Scoring of Classification	Weighting Score
Registered Hybrid Vehicles	0–5	1	10% (Medium)
	6–25	2	
	26–50	3	
	51–100	4	
	> 100	5	

- State Incentives
  - Data Origin: NREL/DOE Alternative Fuels Data Center (AFDC) Incentives and Laws Web site, January 2006
  - Data Representation: number of incentives per state
  - Rationale: States with current incentives promoting advanced transportation goals are likely to have such programs in place for hydrogen vehicles.

Table 9. State Incentives

Attribute	Values and Classification (number of incentives)	Scoring of Classification	Weighting Score
State Incentives	0	1	10% (Medium)
	1–4	3	
	5–9	4	
	10–18	5	

- ZEV Sales Mandate
  - Data origin: NREL/DOE AFDC Incentives and Laws Web site, June 2006
  - Data representation: existence of state ZEV mandate
  - Rationale: This regulation will increase the likelihood that hydrogen vehicles are offered by manufacturers in these states.

Table 10. ZEV Sales Mandate

Attribute	Values and Classification (existence of mandate)	Scoring of Classification	Weighting Score
ZEV Sales Mandate	No	1	10% (Medium)
	Yes	5	

Hydrogen Refueling Station Placement

Once hydrogen demand was calculated using the methodology described above, proposed hydrogen refueling stations were sited based on five factors:

Within 1 mile of major retail stores (Wal-Mart or Costco) or major retail shopping centers

In areas with "good" and higher hydrogen demand

Along major roads or road segments with high traffic volume (above the mean traffic volumes for the area)

In coordination with the previously proposed Interstate Highway stations[4] (Figure 2)

Providing balanced station coverage.

GIS was used to site stations near Wal-Mart, Costco, and major retail shopping center locations when the other criteria were met. When multiple locations were identified in the same area (e.g., Wal-Mart and Costco stores across the street from one another), only one station was proposed for that area. The goal was to keep the coverage of hydrogen stations balanced across the urban area.

No target number of stations was established; stations were sited in all locations that met the specified criteria while maintaining balanced coverage. The proposed stations represent an initial hydrogen infrastructure based on current demographics and characteristics of the areas analyzed. Figure 3 shows an example of the station siting criteria, mapped for the Denver subregion.

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[4] See Melendez, M.; Milbrandt, A. *Analysis of the Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles: Preprint*. NREL Report No. CP-540-37903. Golden, CO: National Renewable Energy Laboratory, 2005.

Hydrogen Refueling Station Coverage

After the proposed hydrogen stations were sited, the percentage of each subregion's population within 3, 5, and 10 miles of the stations was calculated. ArcGIS Network Analyst was used to create service areas—areas that encompass all accessible streets—within the specified distances. Service areas represent actual road distance away from stations and because of this are not perfectly circular. Once the service areas were defined, the number of people and proportion of the total subregion population residing within them were calculated.
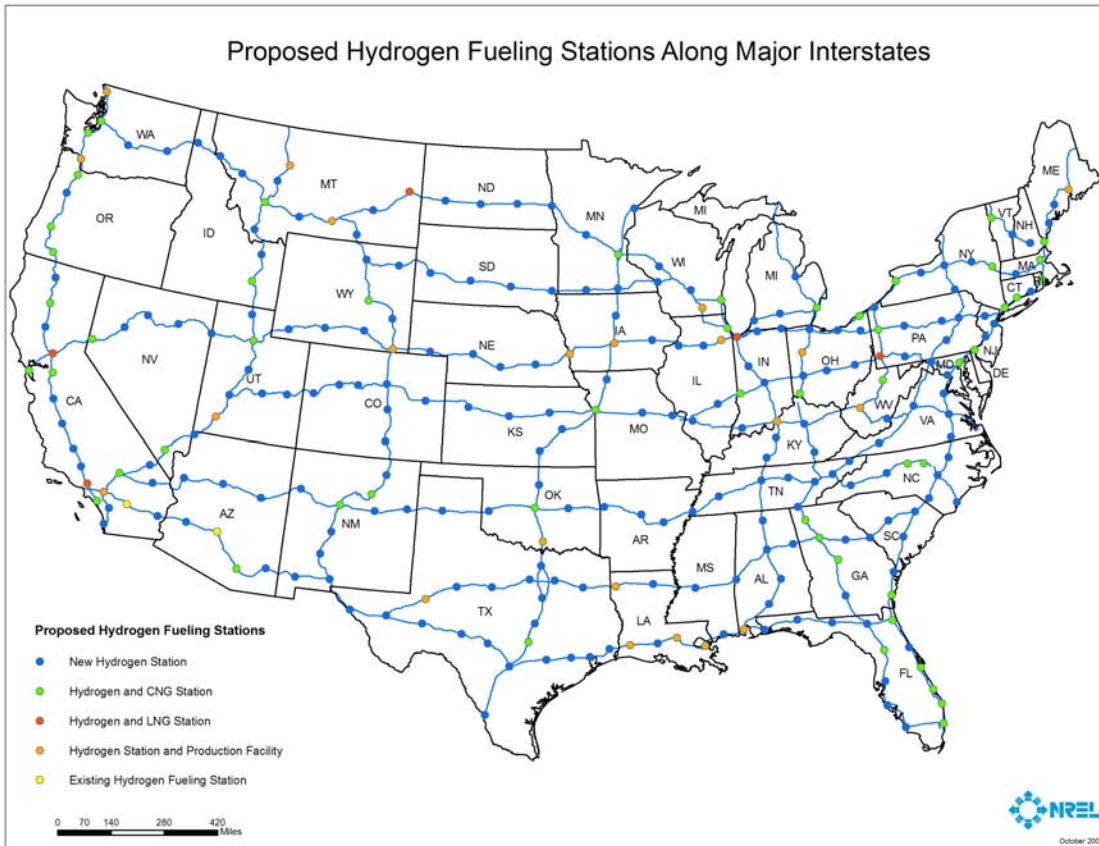
Figure 2. Interstate Highway Hydrogen Fueling Stations Proposed in FY 2005 Analysis
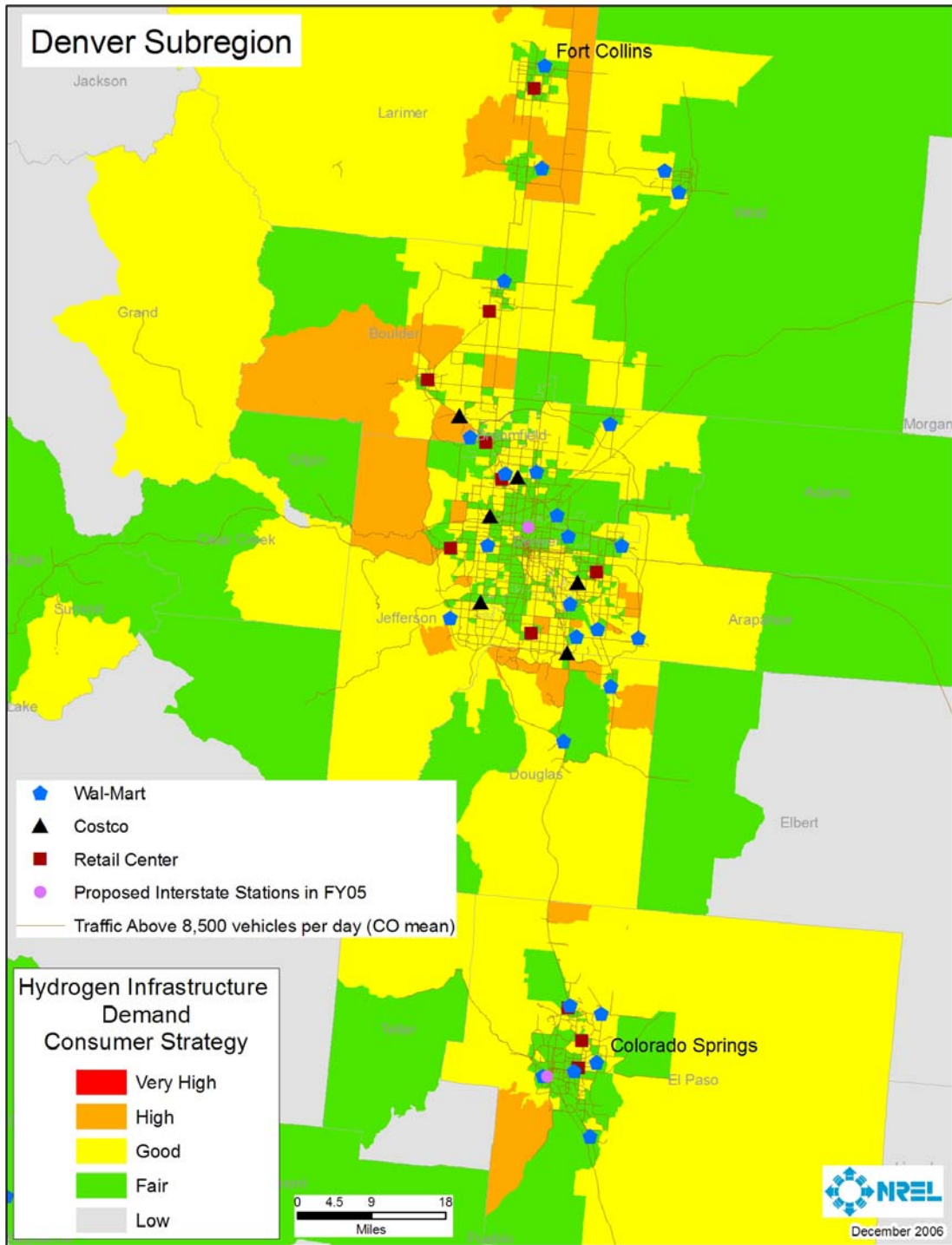
Figure 3. Example of Station Siting Criteria, Denver Subregion

Results and Discussion

Figure 4 through Figure 8 show calculated hydrogen infrastructure demand by region and define subregions. Figure 9 through Figure 22 show proposed hydrogen station locations for each subregion.
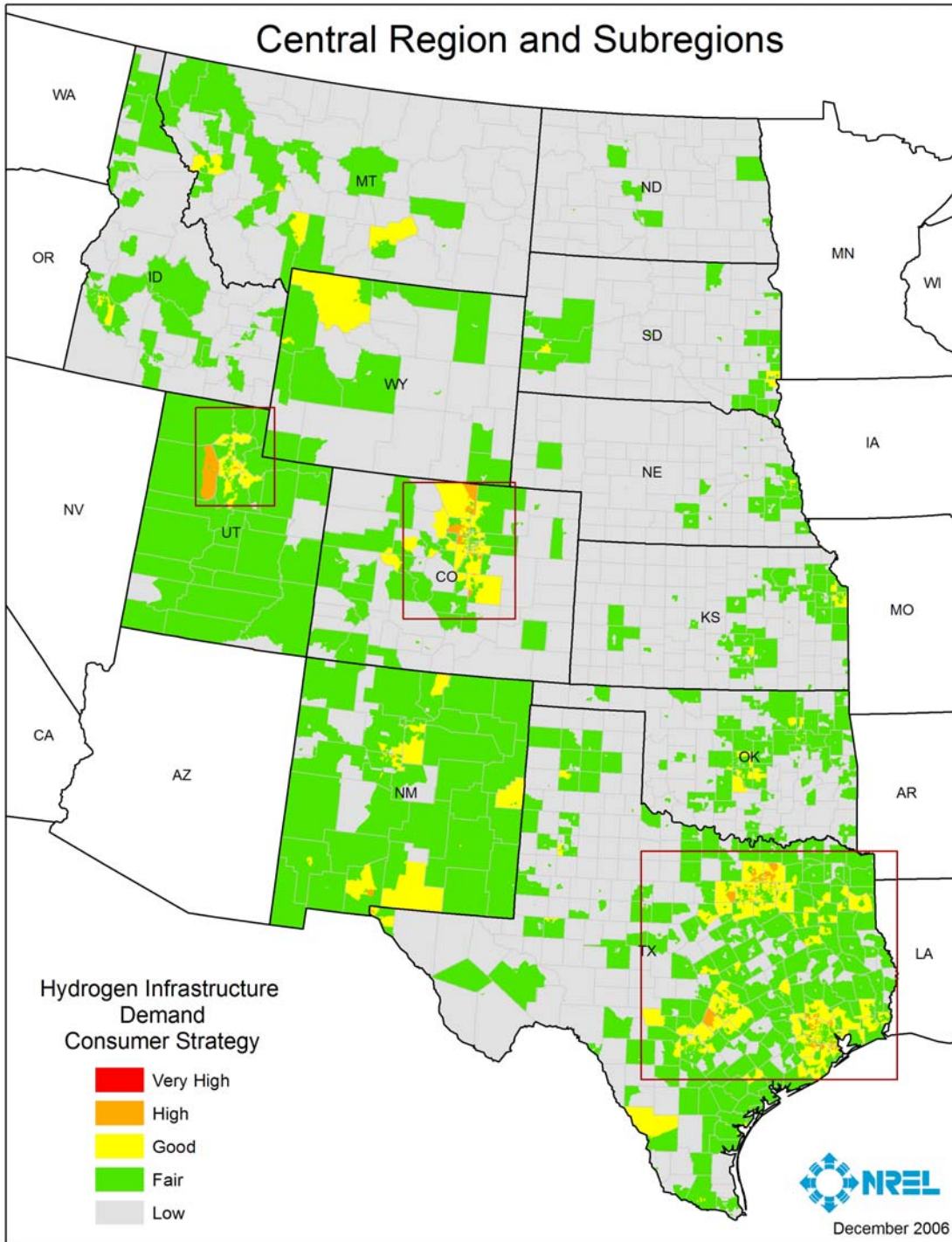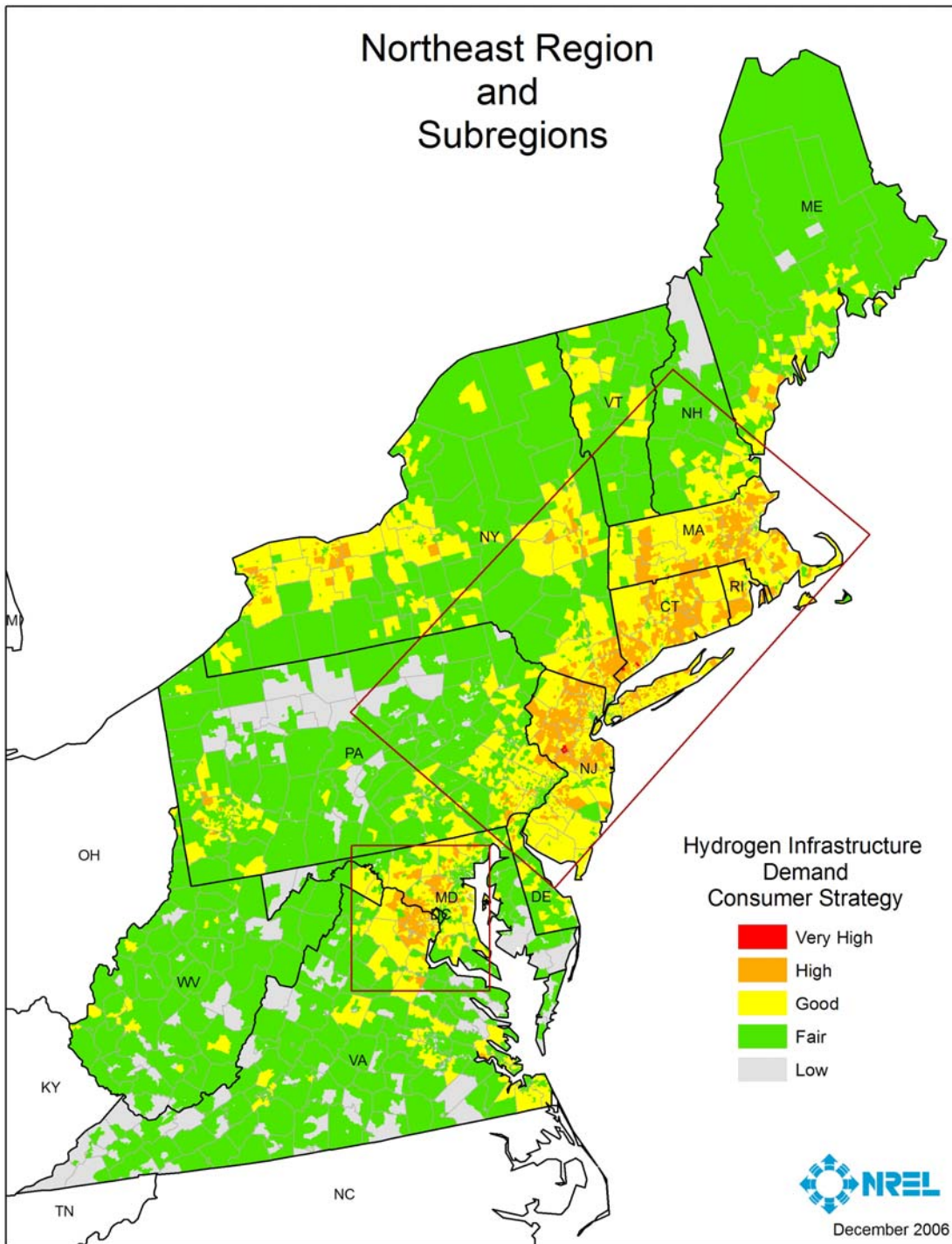

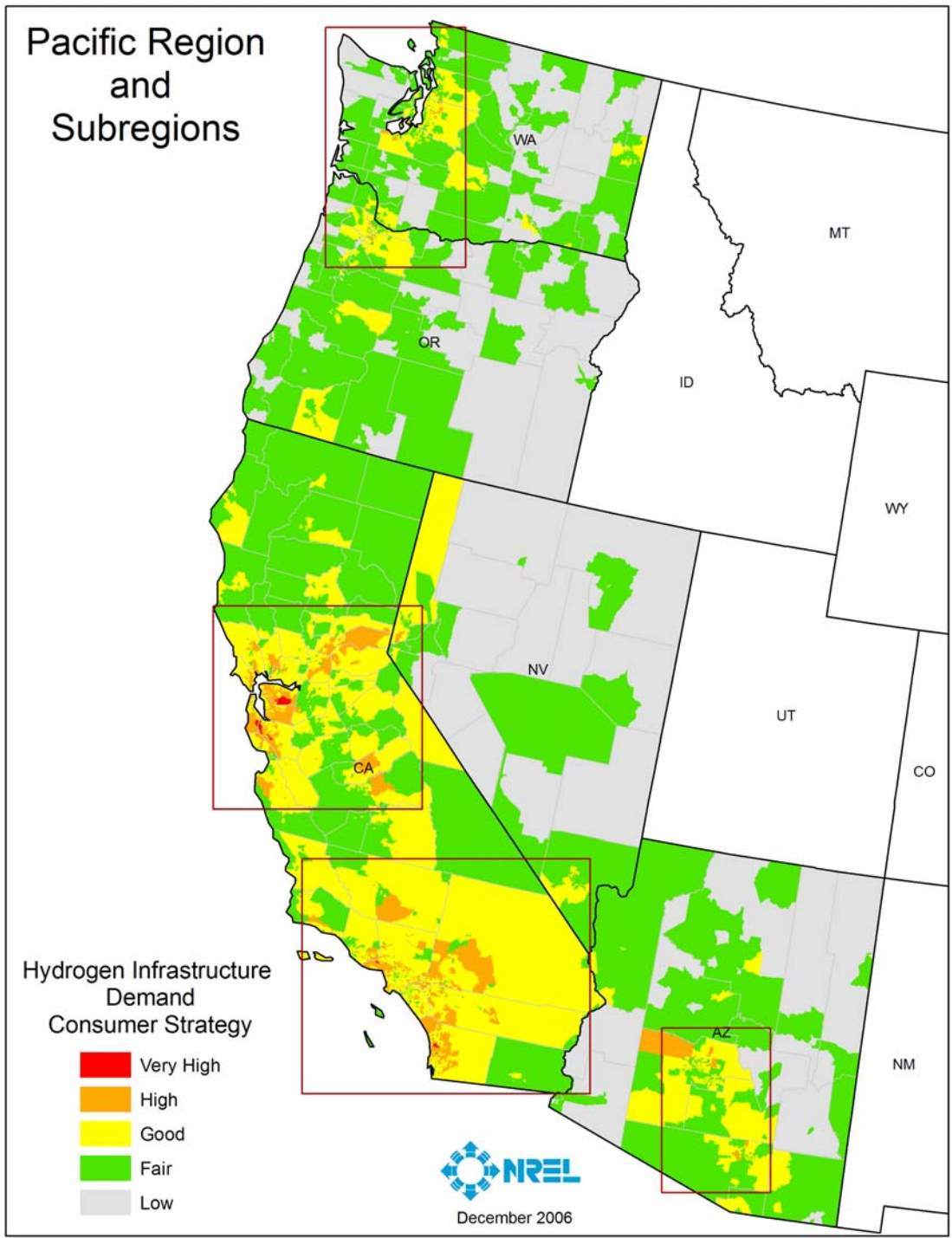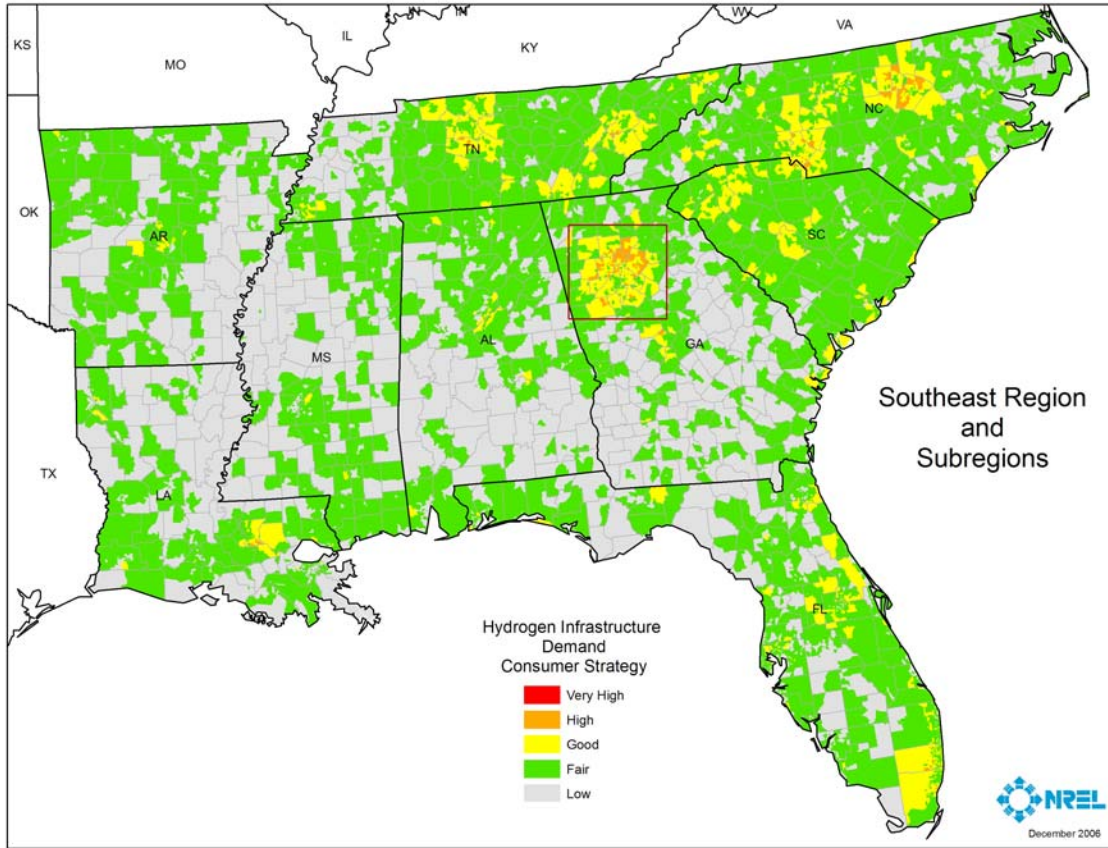**Figure 4. Central Region Hydrogen Infrastructure Demand and Subregions**
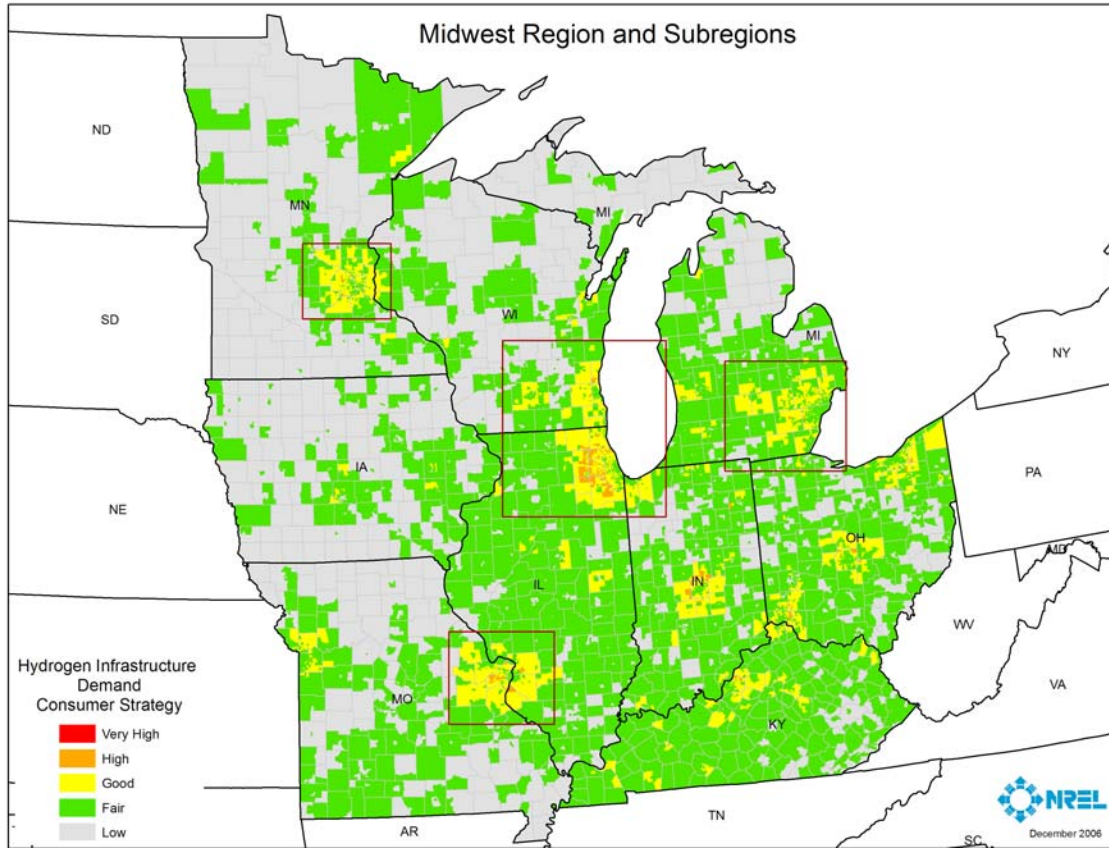
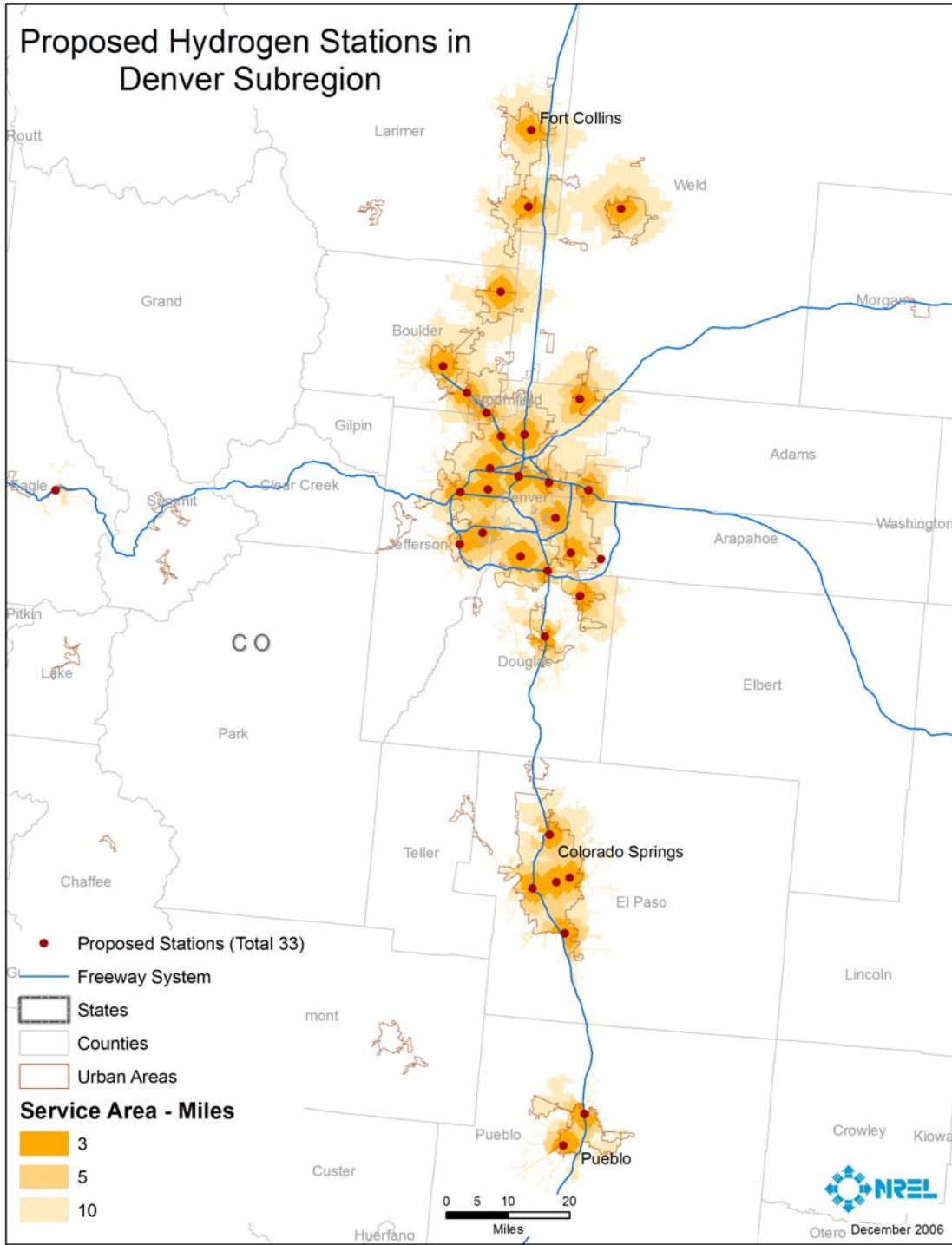**Figure 5. Midwest Region Hydrogen Infrastructure Demand and Subregions**

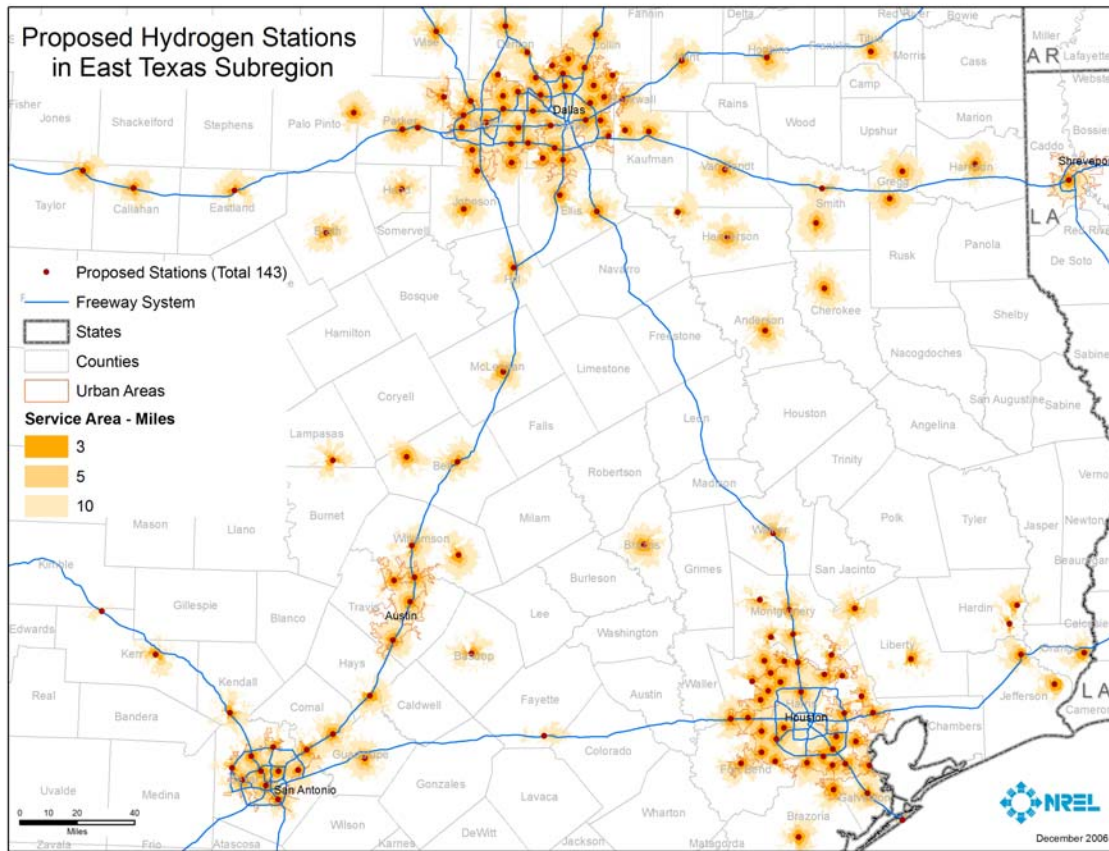**Figure 6. Northeast Region Hydrogen Infrastructure Demand and Subregions**

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Figure 7. Pacific Region Hydrogen Infrastructure Demand and Subregions
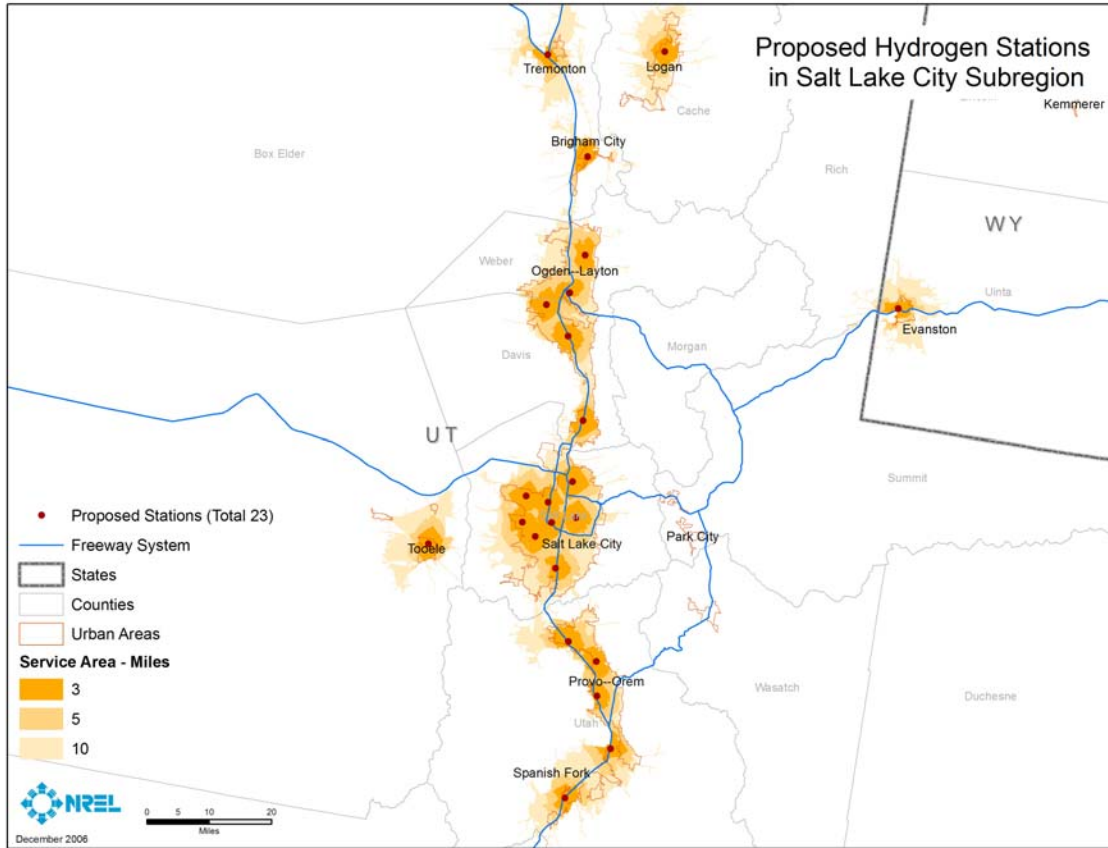
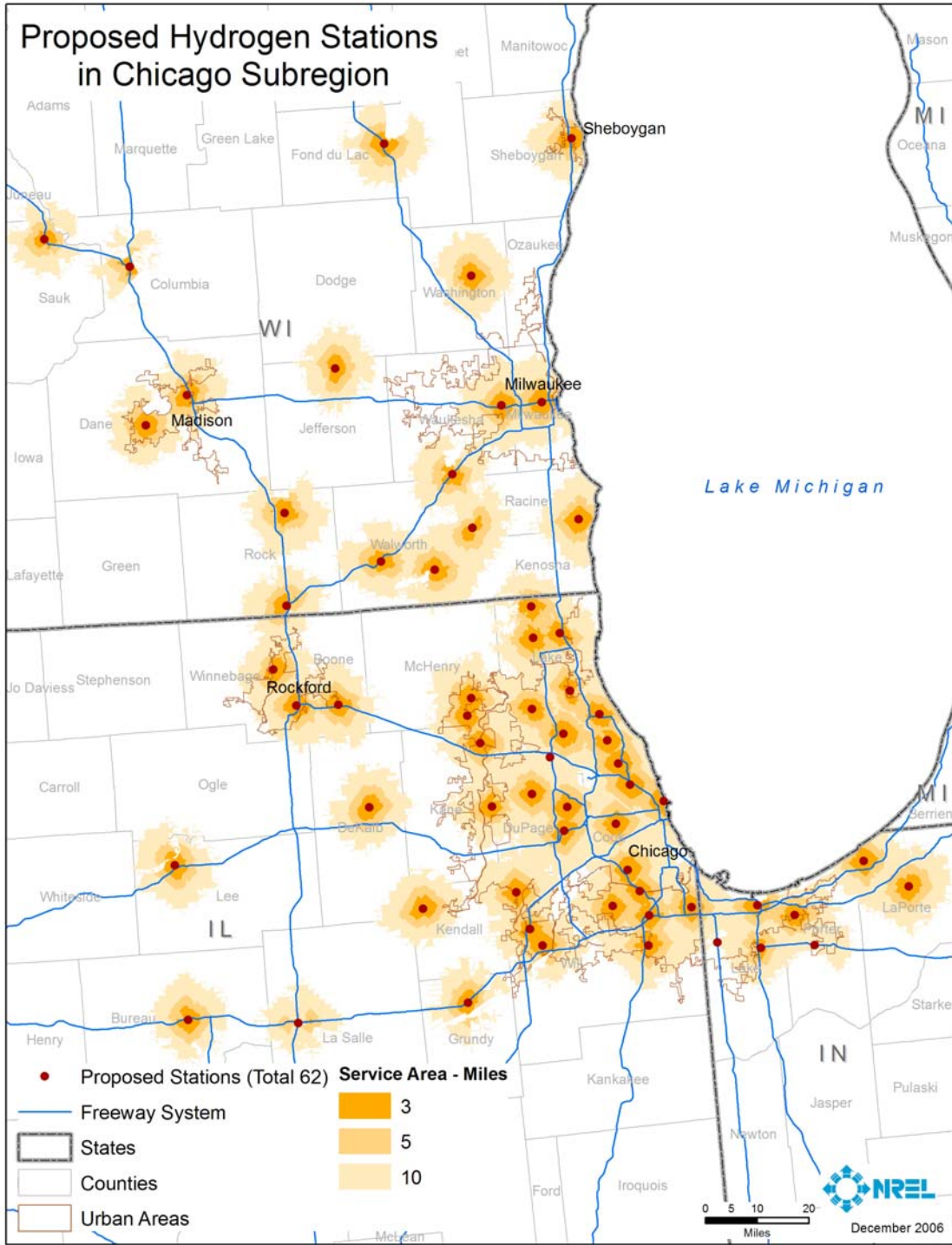**Figure 8. Southeast Region Hydrogen Infrastructure Demand and Subregions**

Figure 9. Proposed Hydrogen Stations in Denver Subregion

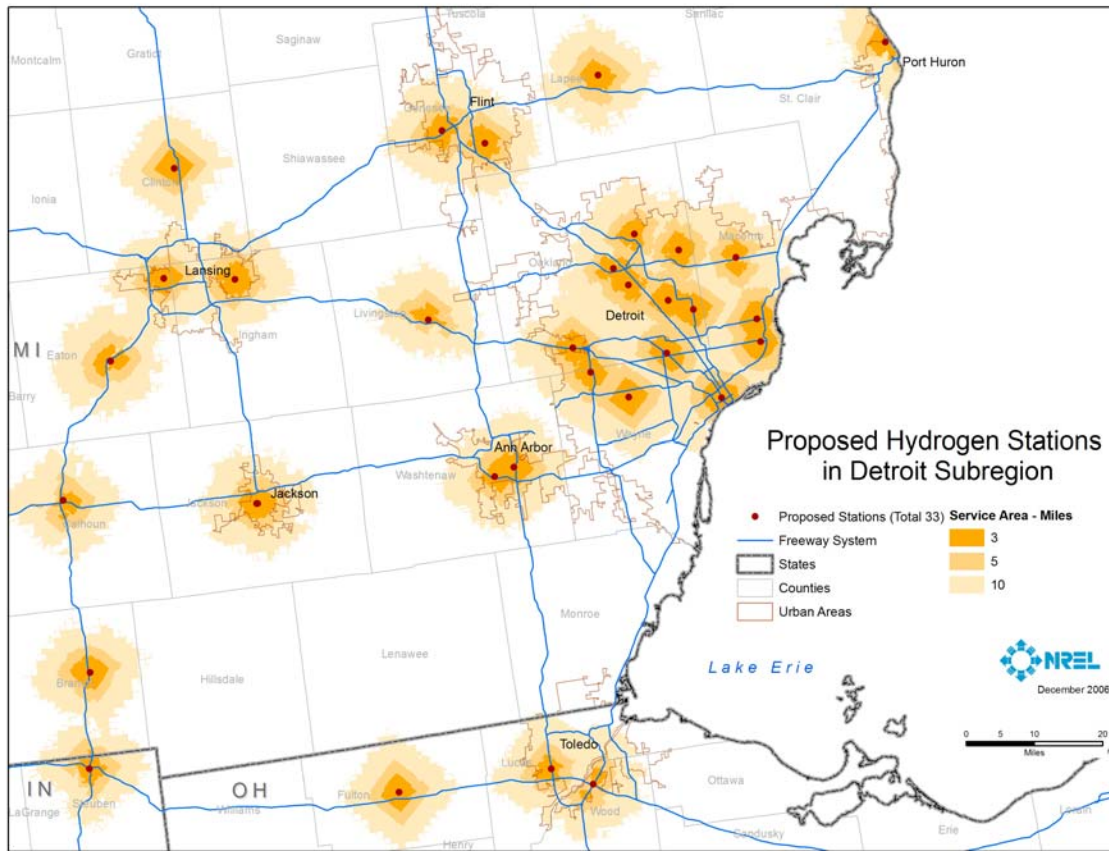**Figure 10. Proposed Hydrogen Stations in East Texas Subregion**

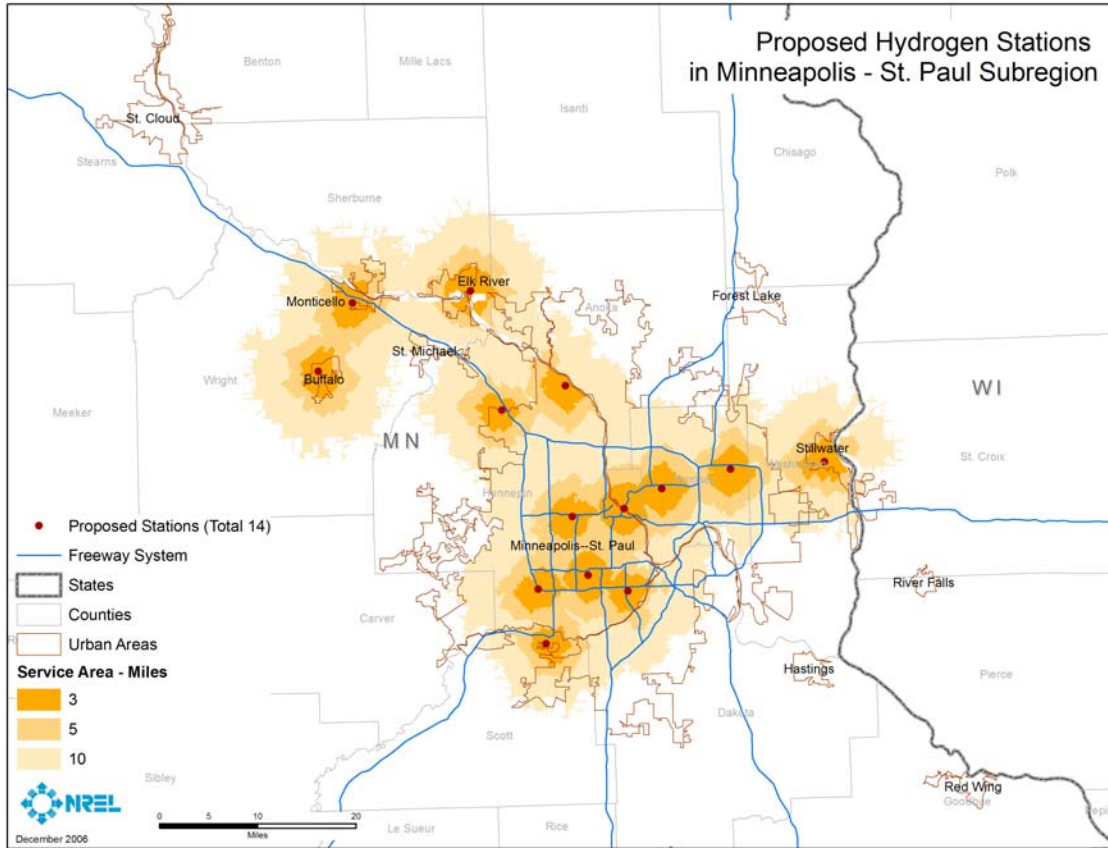**Figure 11. Proposed Hydrogen Stations in Salt Lake City Subregion**

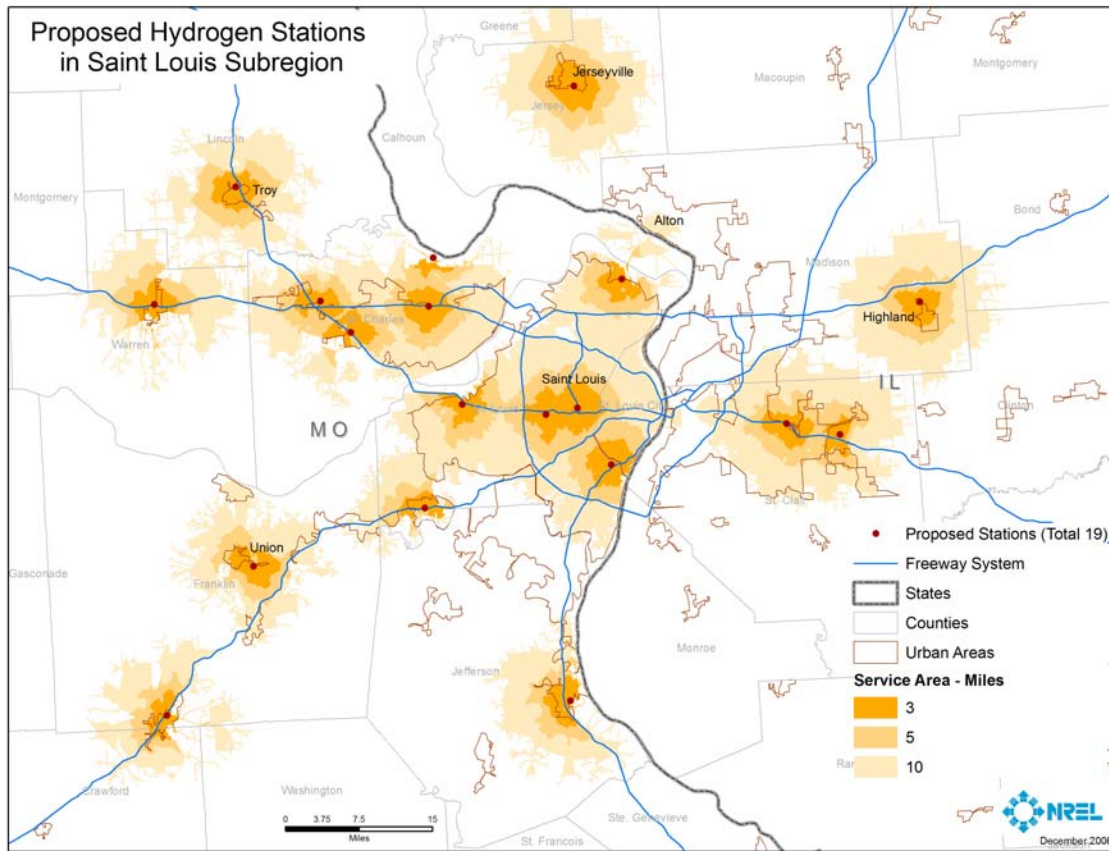**Figure 12. Proposed Hydrogen Stations in Chicago Subregion**

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Figure 15. Proposed Hydrogen Stations in St. Louis Subregion

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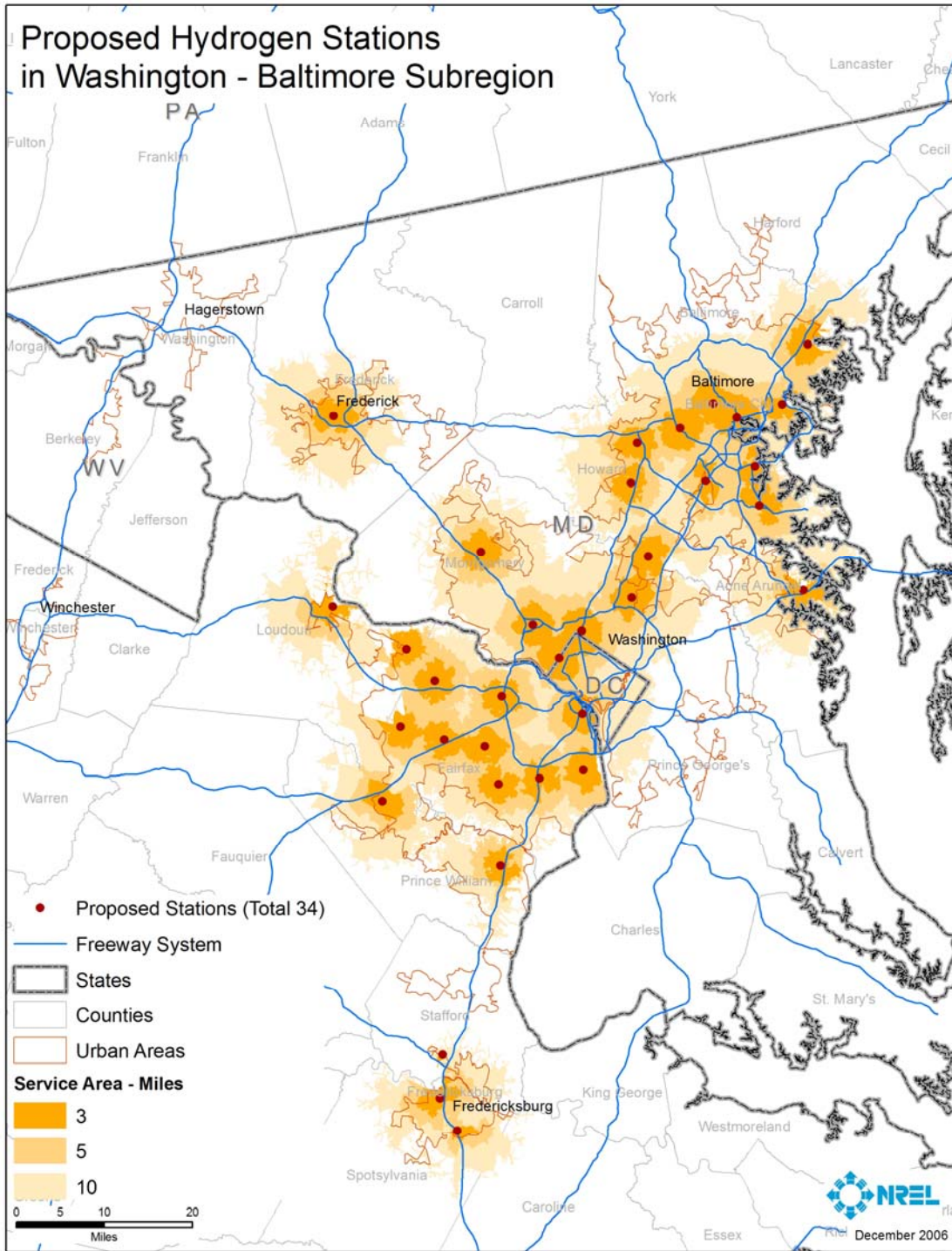
Figure 17. Proposed Hydrogen Stations in Washington - Baltimore Subregion

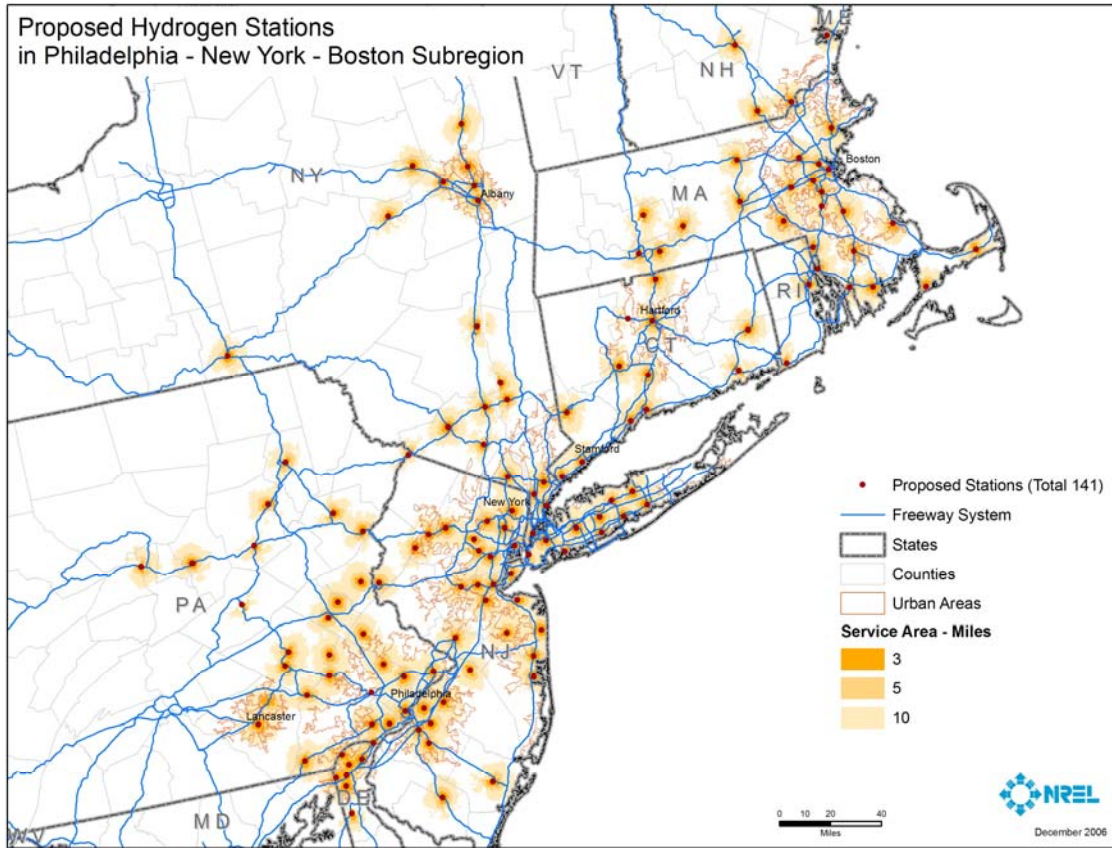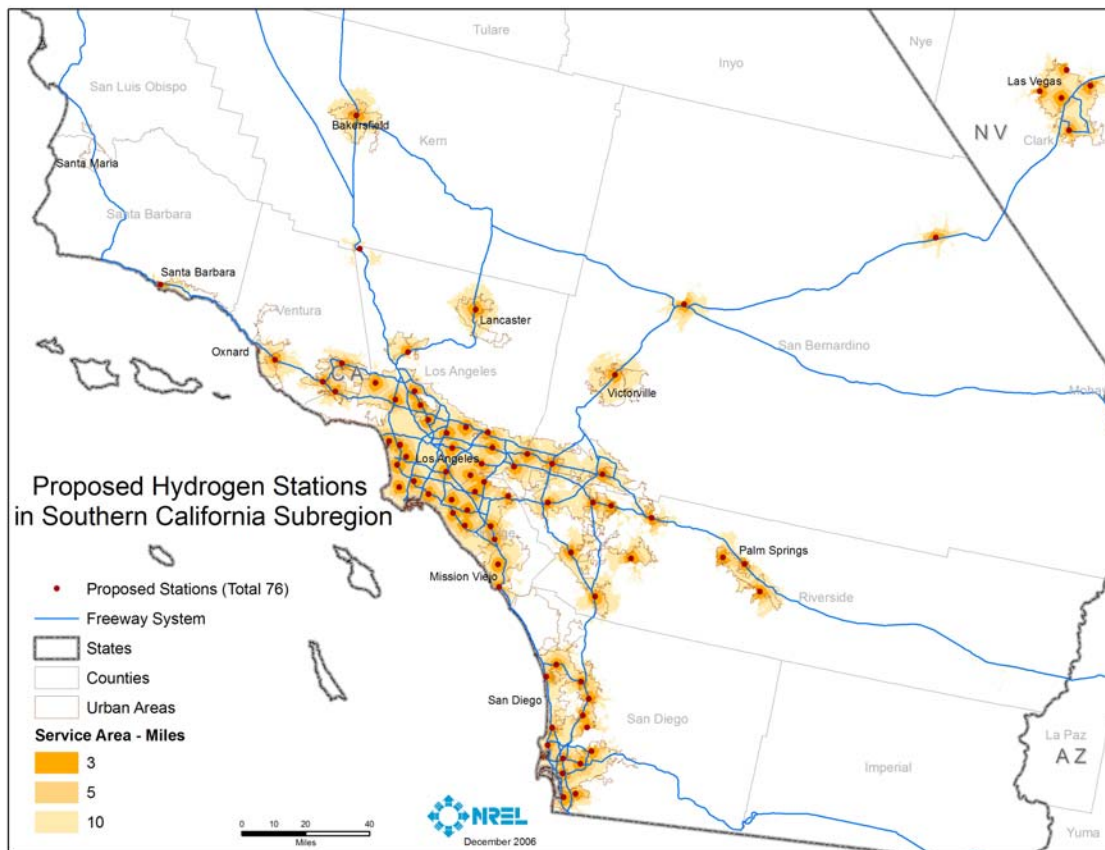**Figure 18. Proposed Hydrogen Stations in Southern California Subregion**
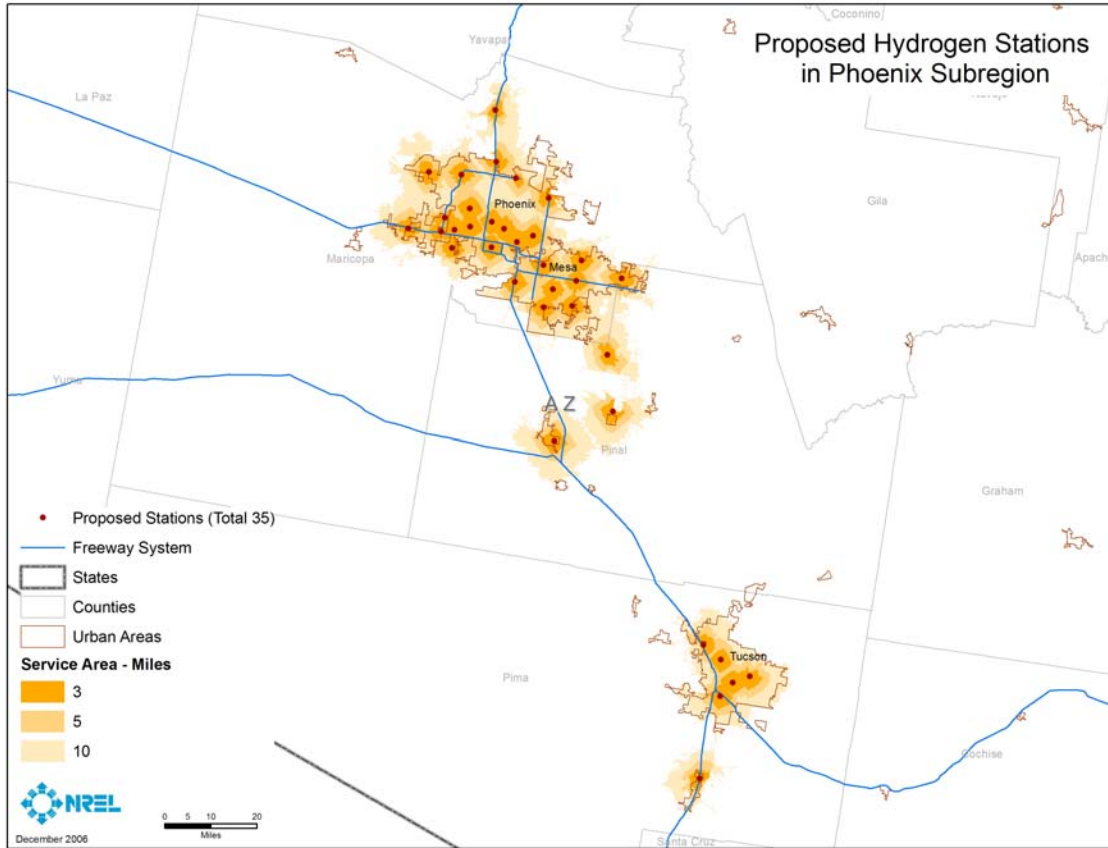
Figure 19. Proposed Hydrogen Stations in Phoenix Subregion

Figure 20. Proposed Hydrogen Stations in Seattle - Portland Subregion

Figure 21. Proposed Hydrogen Stations in Northern California Subregion

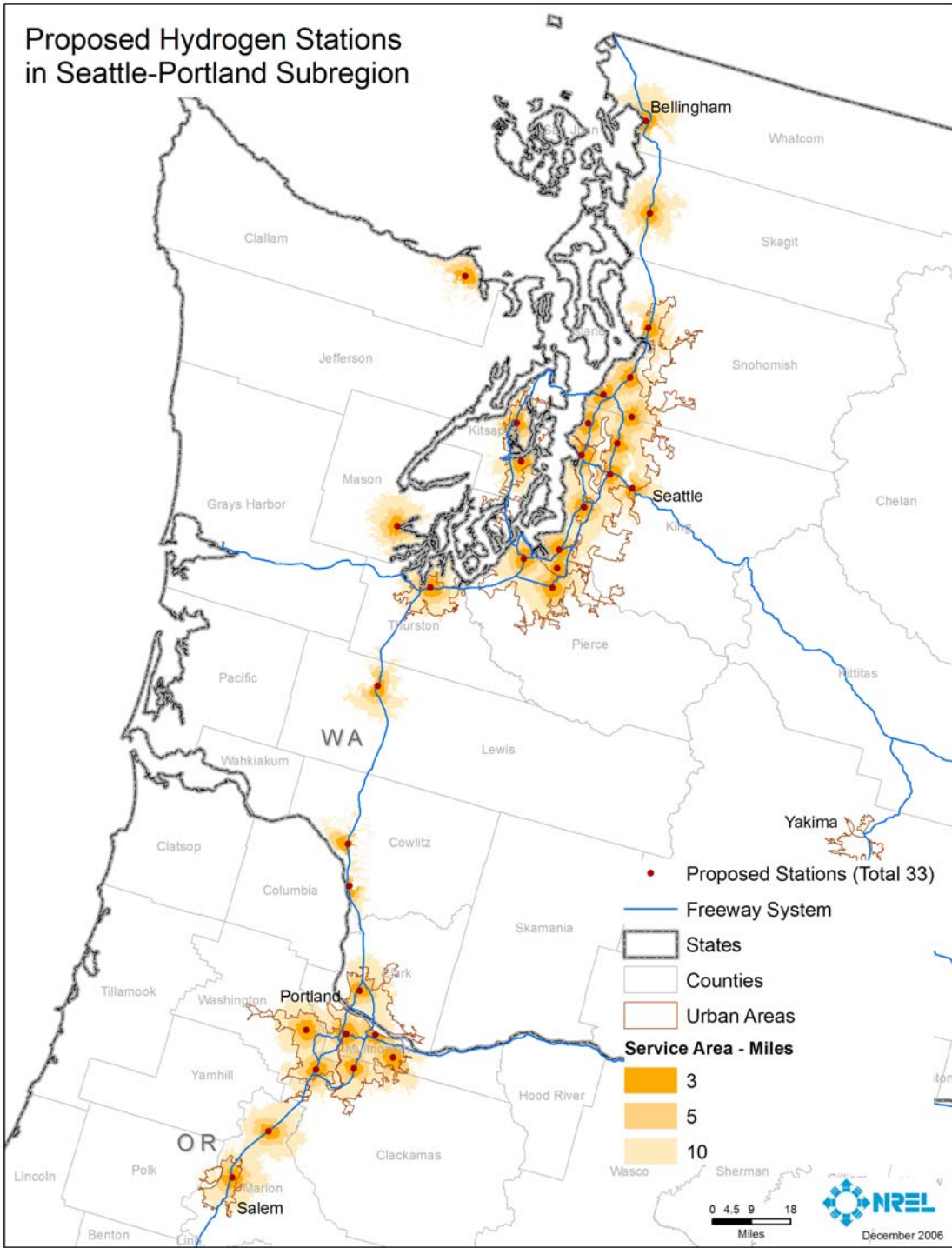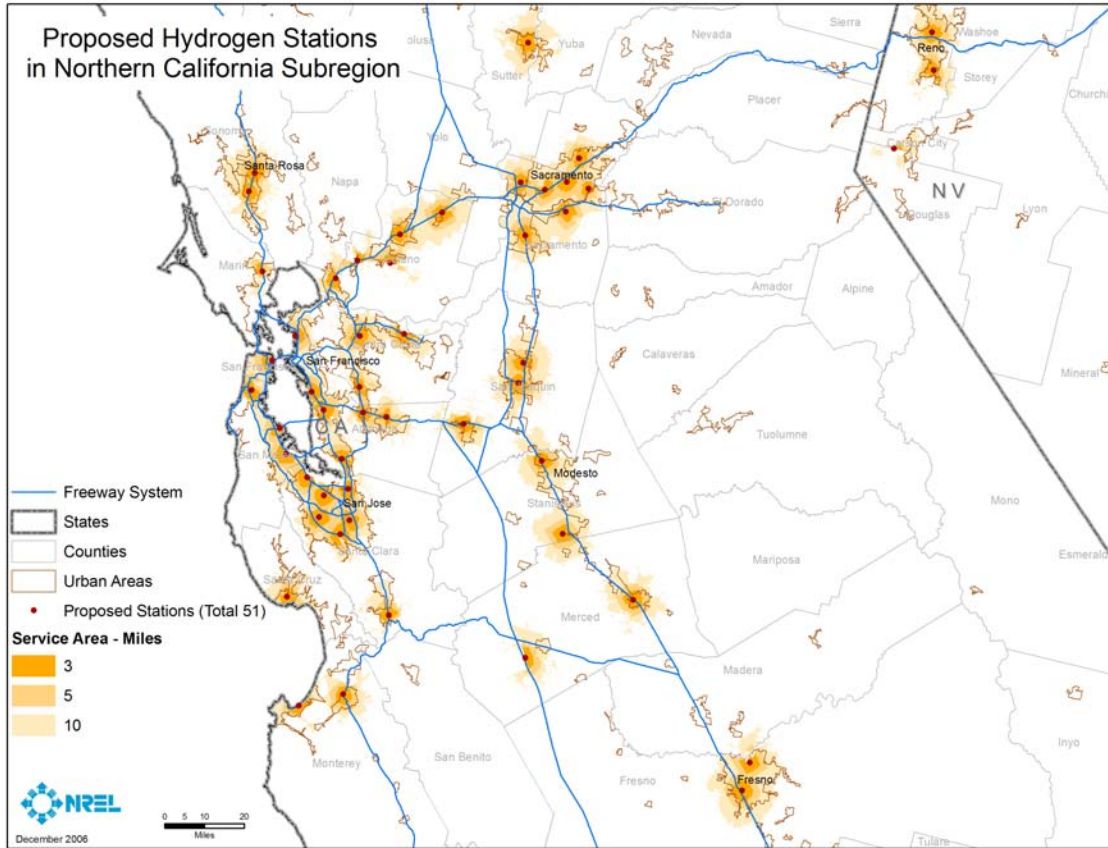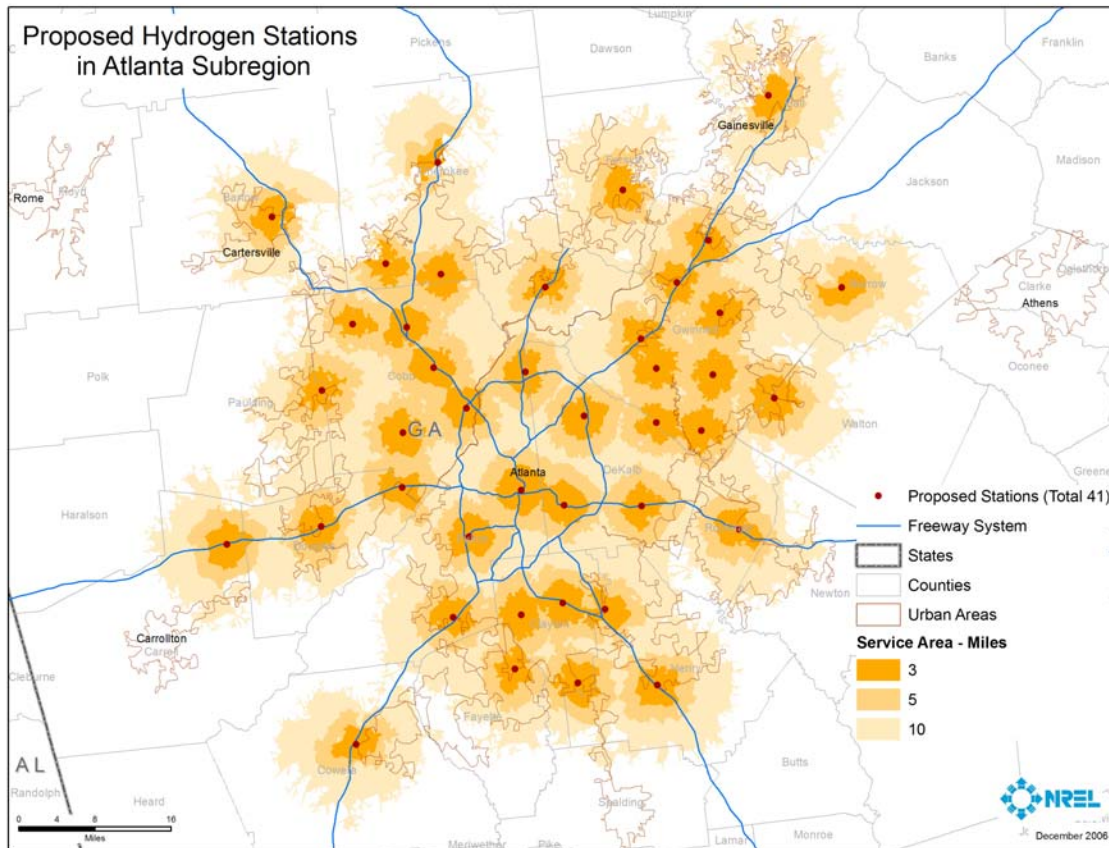**Figure 22. Proposed Hydrogen Stations in Atlanta Subregion**

These figures show the customized station placements required to match the unique hydrogen demand characteristics of each urban area. Some subregions are strongly aligned with geographic features, such as Denver (Figure 9) and Salt Lake City's (Figure 11) alignment with adjacent mountains (and Great Salt Lake in Utah), giving them an asymmetrical, almost linear demand distribution. Some subregions have multiple distinct demand centers, such as East Texas (Figure 10, with centers in Houston, Dallas - Fort Worth, and San Antonio) and Seattle - Portland (Figure 20). Atlanta (Figure 22) and St. Louis (Figure 15) are examples of symmetrical demand distributions.

Table 11 lists hydrogen station coverage by subregion. There is considerable variability among subregions with respect to the proportion of their populations located within 3 and 5 miles of a proposed station, indicating how closely the population distribution of the subregions matches the hydrogen demand and station placement criteria used in this study. All the subregions have 90%–99% (average 95%) of their populations within 10 miles of a proposed station. In areas that are more densely populated, the total number of people per station is greater than in the subregions less densely populated. As vehicles deploy, in areas where there are many people per station, additional stations may be necessary in the immediate area. Although the proportion of a subregion's population with access to a station is an interesting metric, the methods and criteria used in this study

to site stations are the most valuable aspect of the project because it gives a good picture
of where the greatest hydrogen demand is likely to be.

Table 11. Proposed Subregional Hydrogen Station Coverage

Subregion	Population	Number of Stations	Stations per Million People	Population within Distance of a Station		
				3 mi	5 mi	10 mi
Denver	3,463,445	33	9.5	49%	84%	96%
East Texas	15,512,273	143	9.2	36%	65%	90%
Salt Lake City	1,903,127	23	12.1	57%	87%	97%
Chicago	11,714,972	62	5.3	26%	56%	96%
Detroit	5,919,388	33	5.6	23%	53%	91%
Minneapolis - St. Paul	2,547,509	14	5.5	23%	54%	92%
St. Louis	2,288,078	19	8.3	21%	46%	94%
Phil - New York - Boston	37,451,570	141	3.8	25%	56%	93%
Washington-Baltimore	6,389,207	34	5.3	38%	70%	96%
Southern California	20,730,299	76	3.7	36%	72%	98%
Phoenix	3,915,528	35	8.9	53%	87%	99%
Seattle - Portland	5,457,743	33	6.0	31%	66%	97%
Northern California	11,131,278	51	4.6	36%	67%	93%
Atlanta	4,095,659	41	10.0	37%	74%	97%

Conclusions

Using a GIS approach to spatially analyze key attributes affecting hydrogen market
transformation, this study proposes hypothetical hydrogen refueling station locations in
select subregions to demonstrate a method for determining station locations based on
geographic criteria. These stations represent the locations that provide access within 10
miles for at least 90% of the population in the sub-regions. This represents a minimum
hydrogen infrastructure needed to provide consumers access to fueling and make
purchasing hydrogen vehicles a possibility.

The maps of estimated hydrogen demand and proposed hydrogen station locations show
unique patterns among U.S. urban areas. There is no one-size-fits-all solution. Each area's
unique demand characteristics should be considered to maximize the effectiveness of a
limited initial hydrogen infrastructure Optimizing the match between emerging hydrogen
demand and emerging infrastructure is critical to a successful transition to hydrogen-
powered transportation. The methods used in this study represent a good process for
identifying and capturing these unique geographic characteristics regarding market
transformation.

Future Work

The station locations identified in this project demonstrate a scenario that provides access
to a majority of potential early adopters of hydrogen vehicle technology, but does not
explore the actual volume of hydrogen demand at each location nor the feasibility of

siting a station in these locations. Issues such as the land availability, zoning and permitting requirements, natural gas or other feedstock availability and distribution should be explored as a next step analysis in support of hydrogen transition.

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Using a GIS approach to spatially analyze key attributes affecting hydrogen market transformation, this study proposes hypothetical hydrogen refueling station locations in select subregions to demonstrate a method for determining station locations based on geographic criteria.

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