Grid-Based Renewable Electricity and Hydrogen Integration

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Goals for Electrolysis in Hydrogen Fuel Supply

- Goal is to supply hydrogen fuel for 20% of the light-duty vehicle fleet
  - 12 million short tons of hydrogen annually
  - 450 TWh per year
- Must be competitive
  - With gasoline, assuming FCV will have twice the efficiency of an ICE
  - With other hydrogen production methods
- Net zero impact or reduction in GHG emissions
  - Compared to Gasoline ICE - 31% reduction in carbon emissions from the current electricity mix
  - Compared to Natural Gas-Derived Hydrogen - 65% reduction in carbon emissions from the current electricity mix

Goals for Electrolysis (cont.)

- Need to cut the cost of hydrogen production via electrolysis in half
  – Lower feedstock cost (electricity)
  – Lower capital cost
- No net increase in carbon emissions
  – Improve efficiency of current generation mix
  – Increase market share for low- and no-carbon electricity sources
- But is this possible?

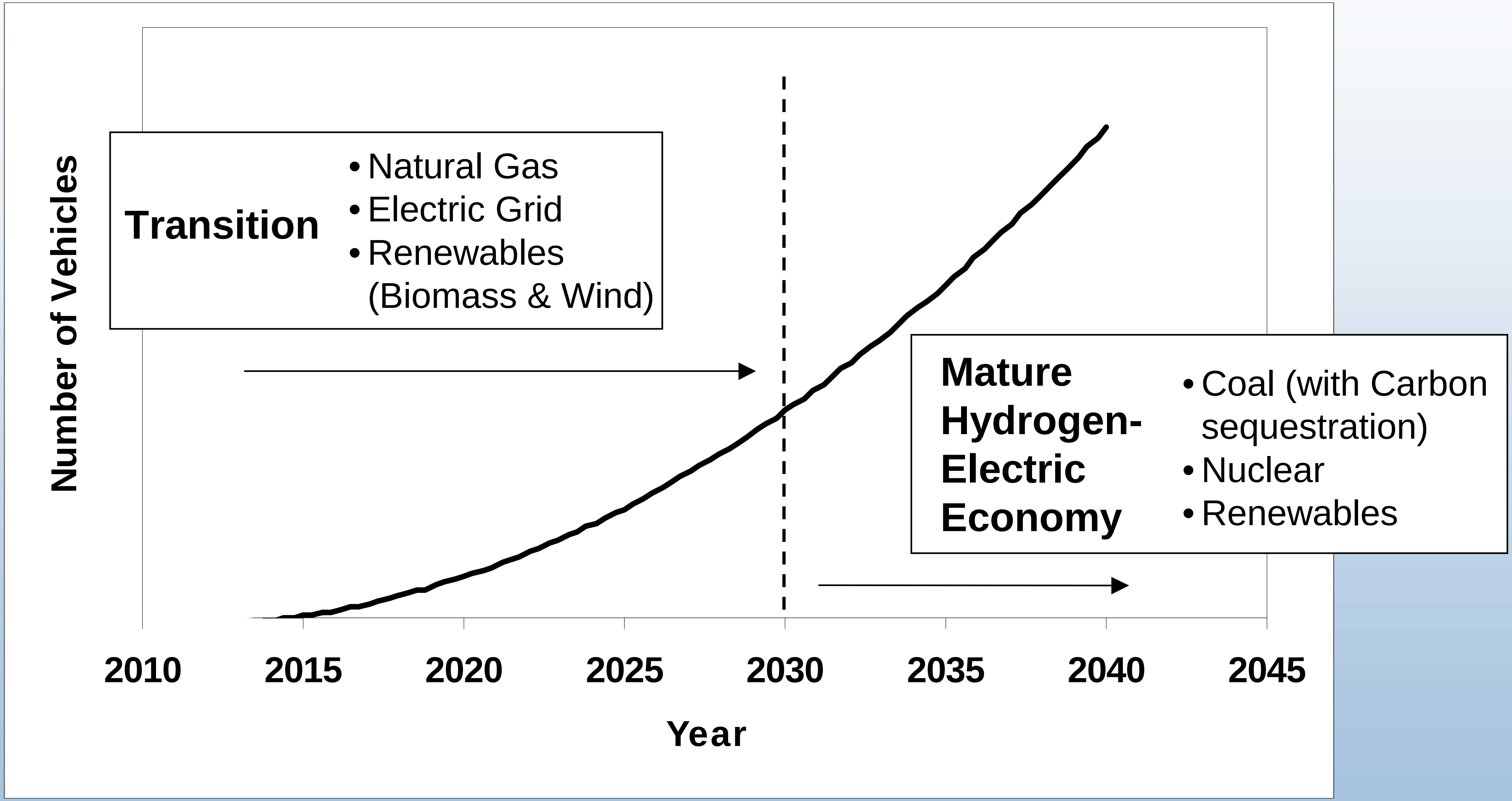
Figuring out the potential….

To answer this question we need to understand:

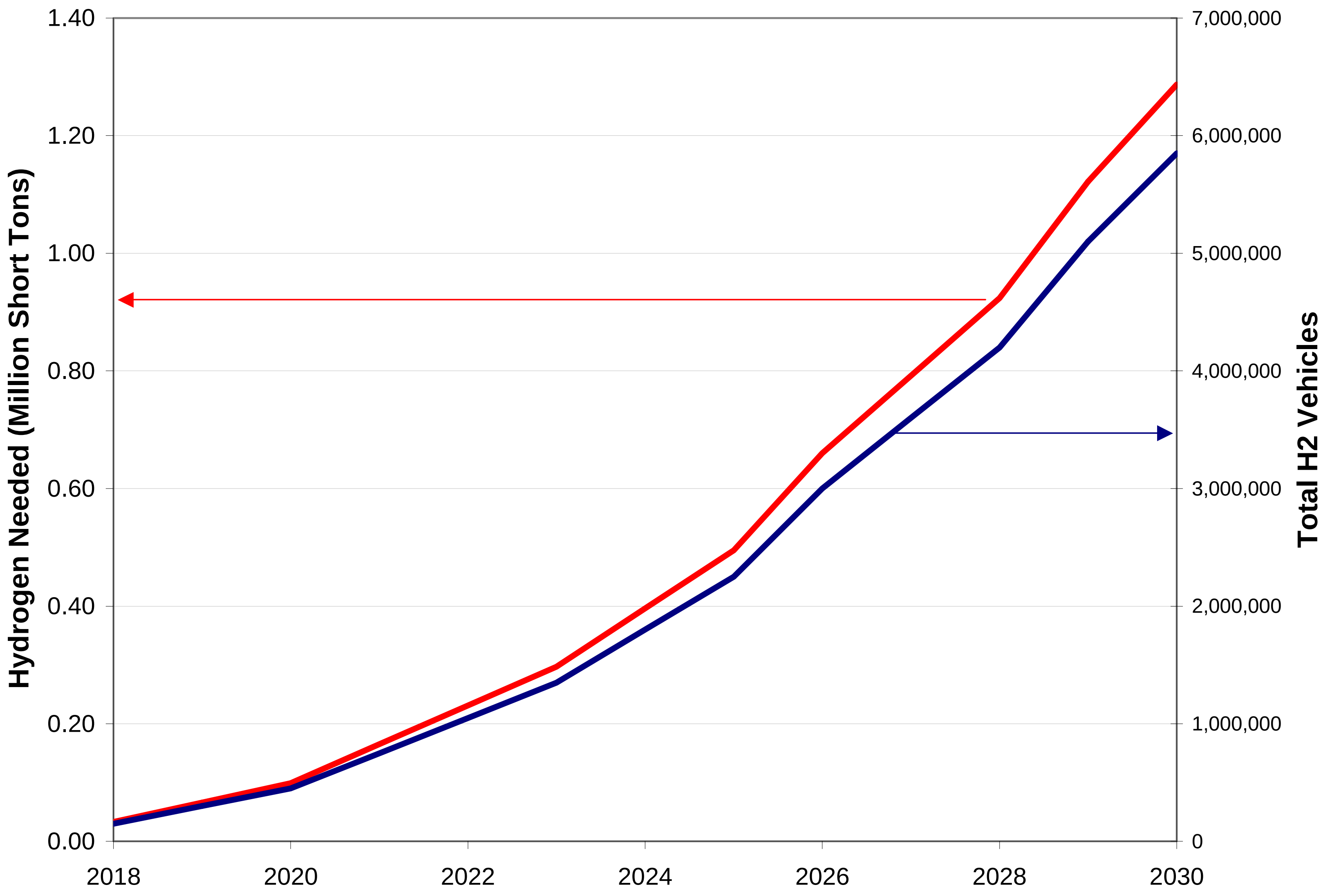
- Cost impacts, including requirements for capital, storage, and feedstock (electricity)
- How much hydrogen will be required, where, and when
  - Amount that could be produced by electrolysis
  - Competition
- Potential of non-carbon electricity sources
  - Resource availability
  - Cost
  - Impact on transmission and distribution

This represents a multi-level analysis issue.

Moving Toward a Hydrogen-Electric Future



How much hydrogen?



How much Hydrogen?

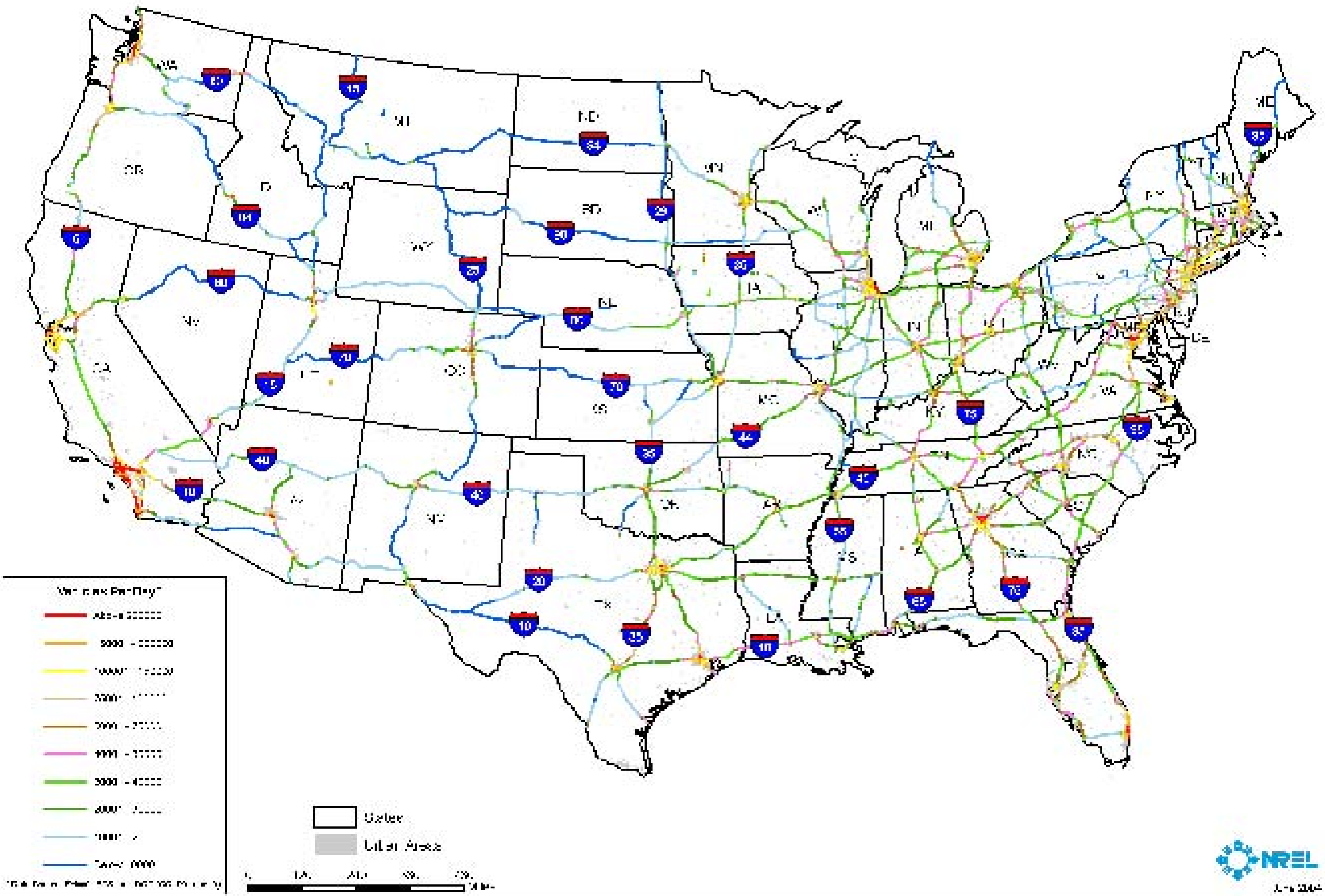
- Transition Period
  - Sufficient stations to enable interstate travel
  - Accessible in urban areas
- Major Market Share
  - ~120,000 hydrogen fuel stations
  - Convenient in urban areas
  - Accessible in rural areas

Where do we build hydrogen stations?

For the transition phase:

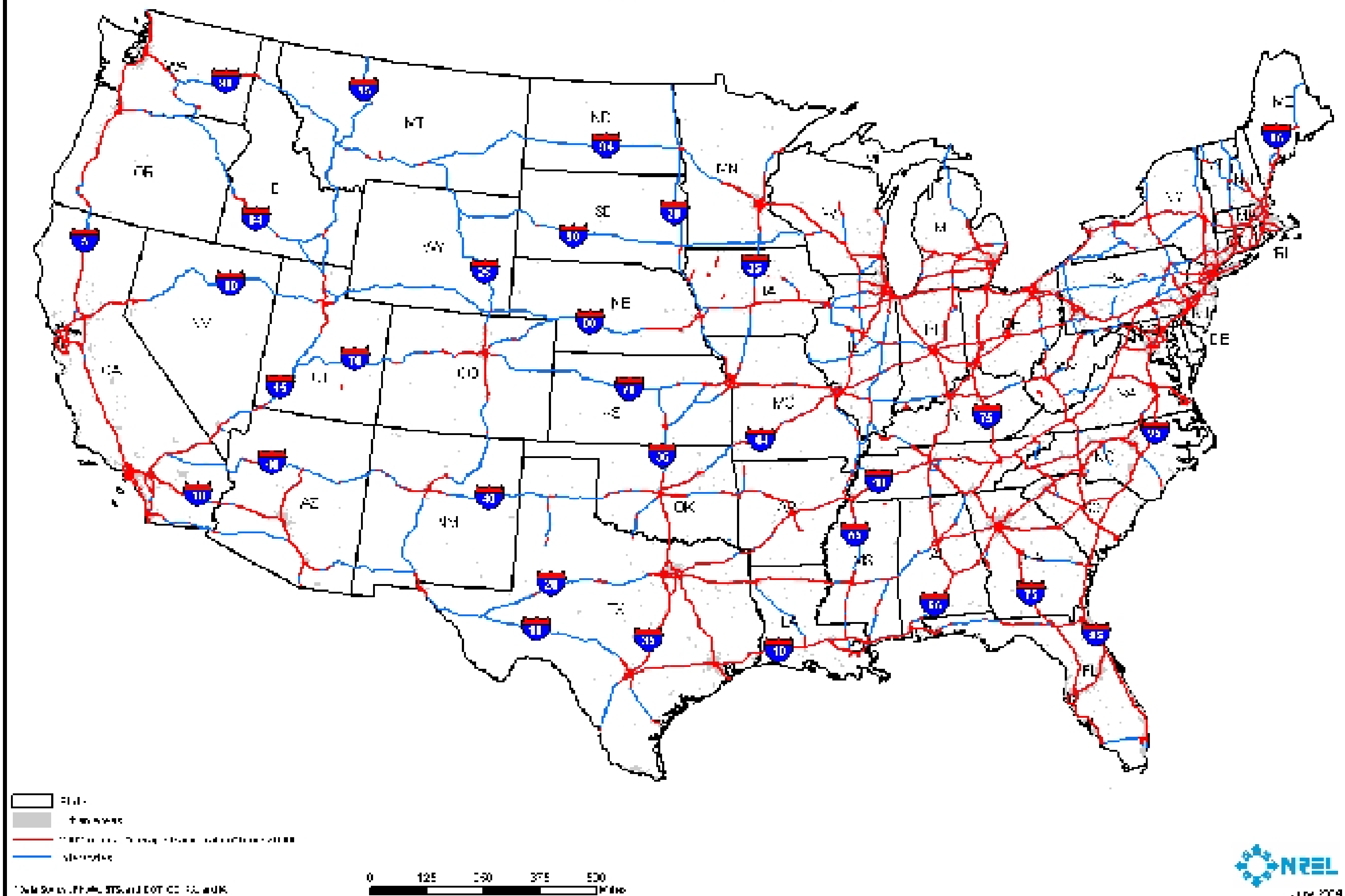
- Use existing hydrogen fueling stations
- Build near existing hydrogen production facilities
- Co-locate at existing alternative fuels stations

2002 Annual Average Daily Traffic

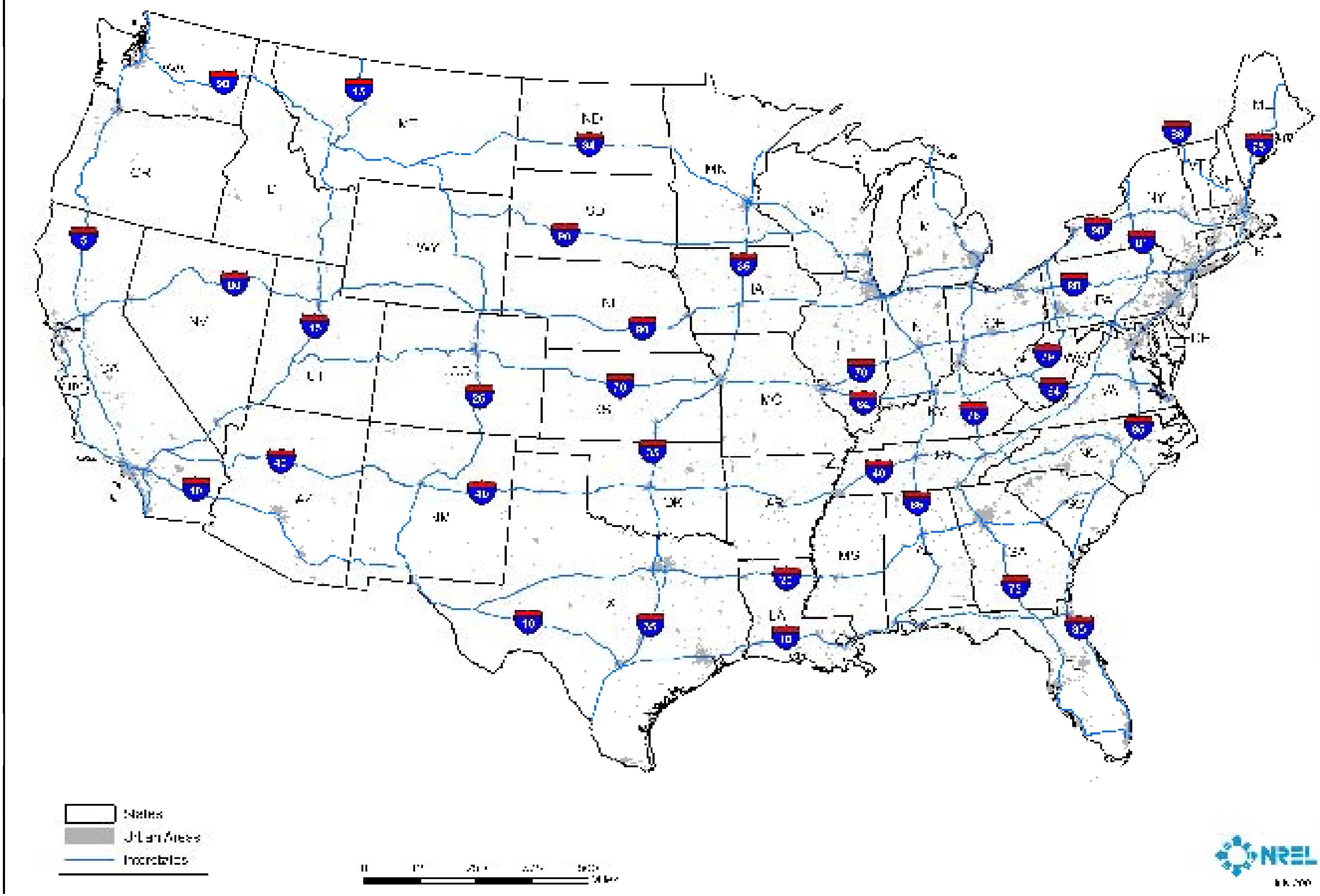


2002 Annual Average Daily Traffic

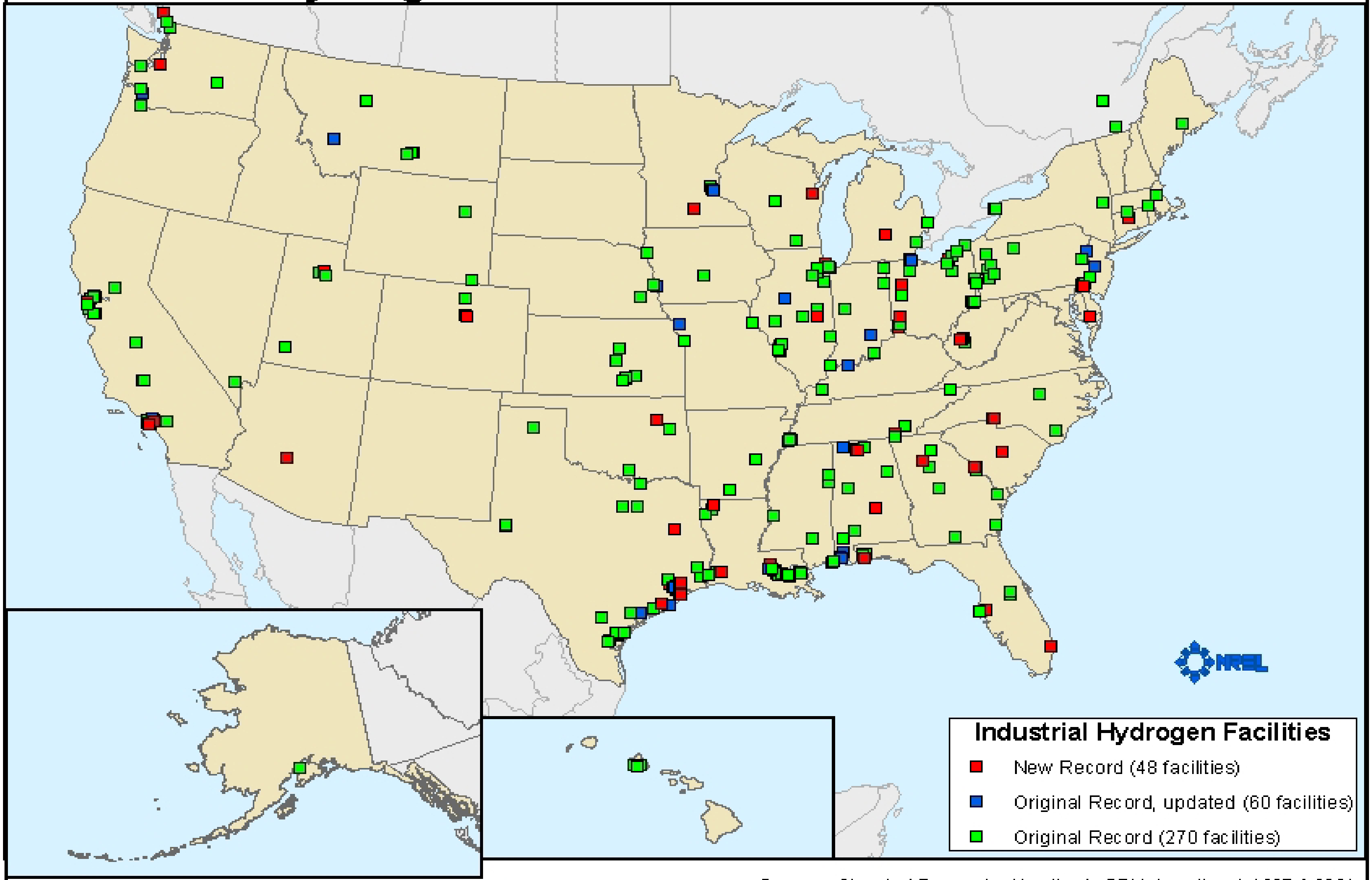
Above 20000 Vehicles Per Day



Proposed Interstate Routes for Hydrogen Refueling Infrastructure

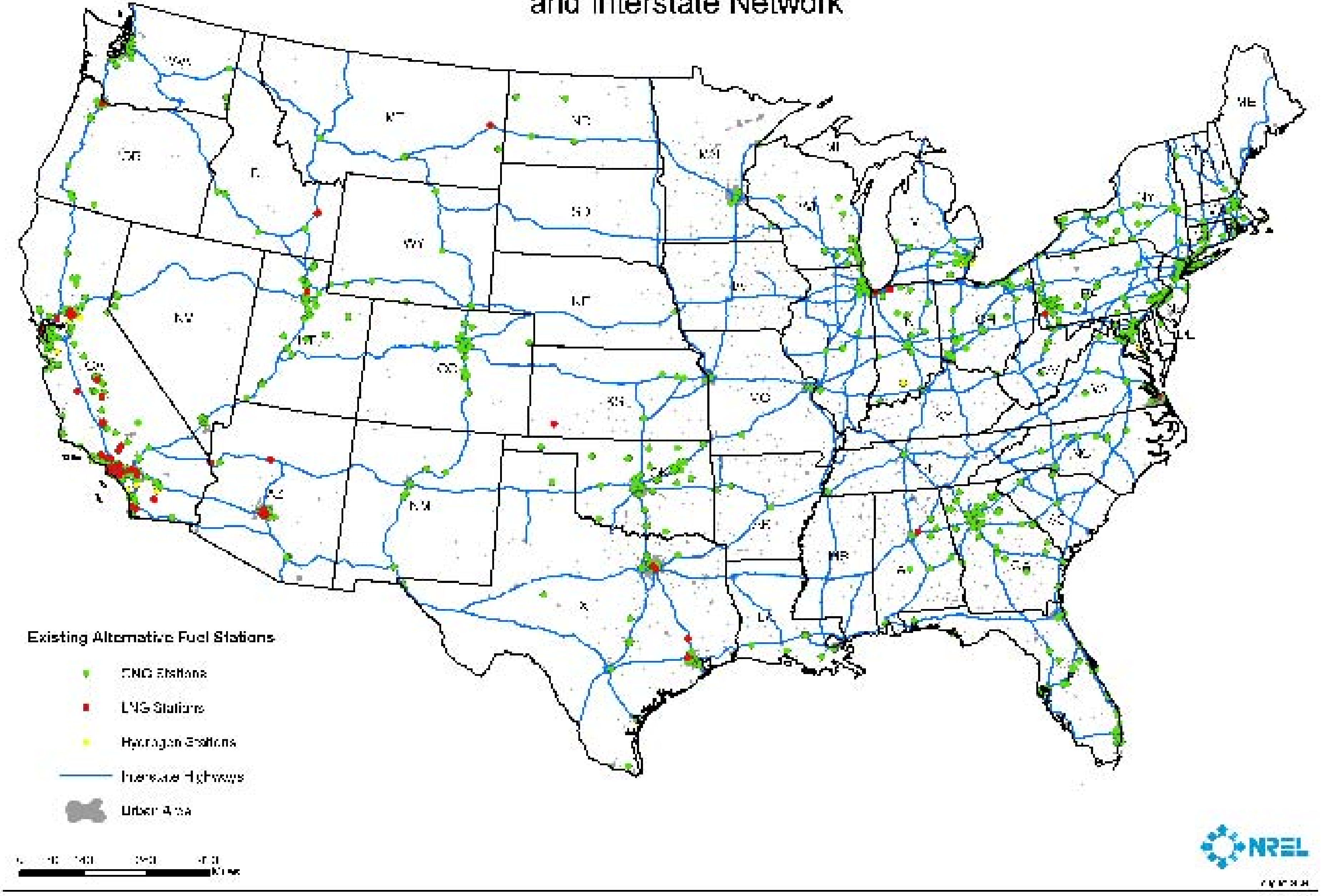


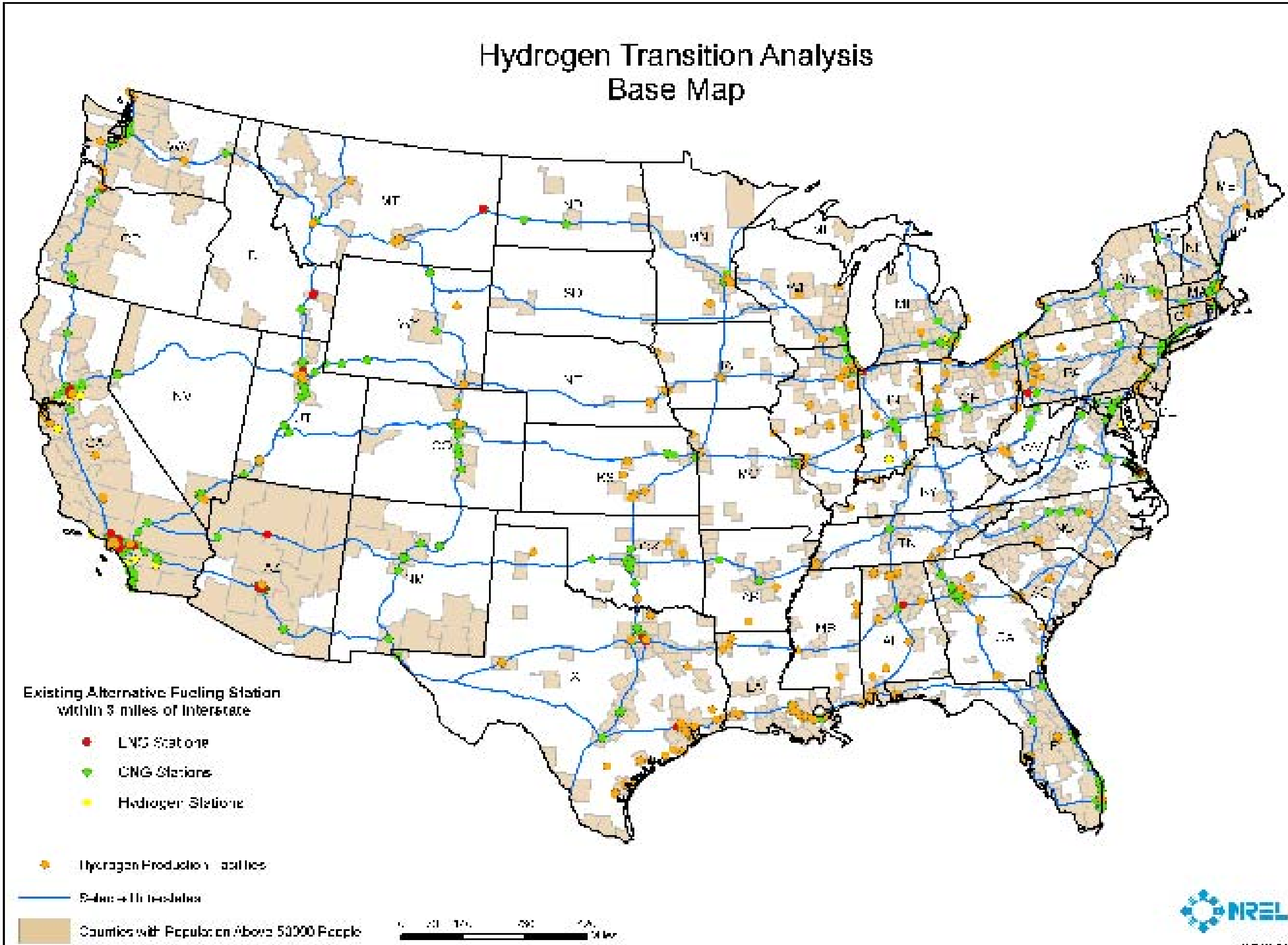
Hydrogen Facilities in the United States



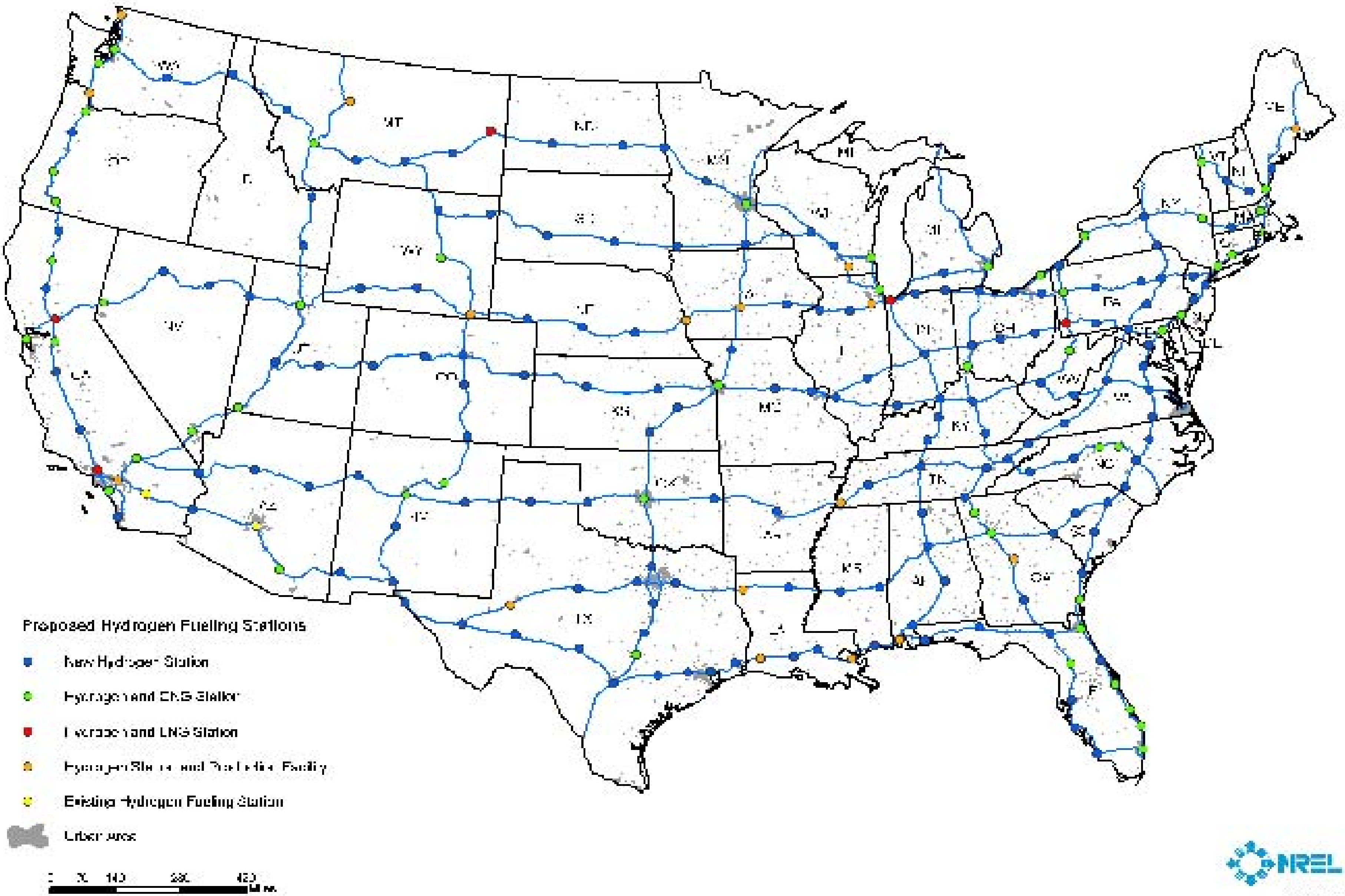
Source: Chemical Economics Handbook, SRI International, 1997 & 2001

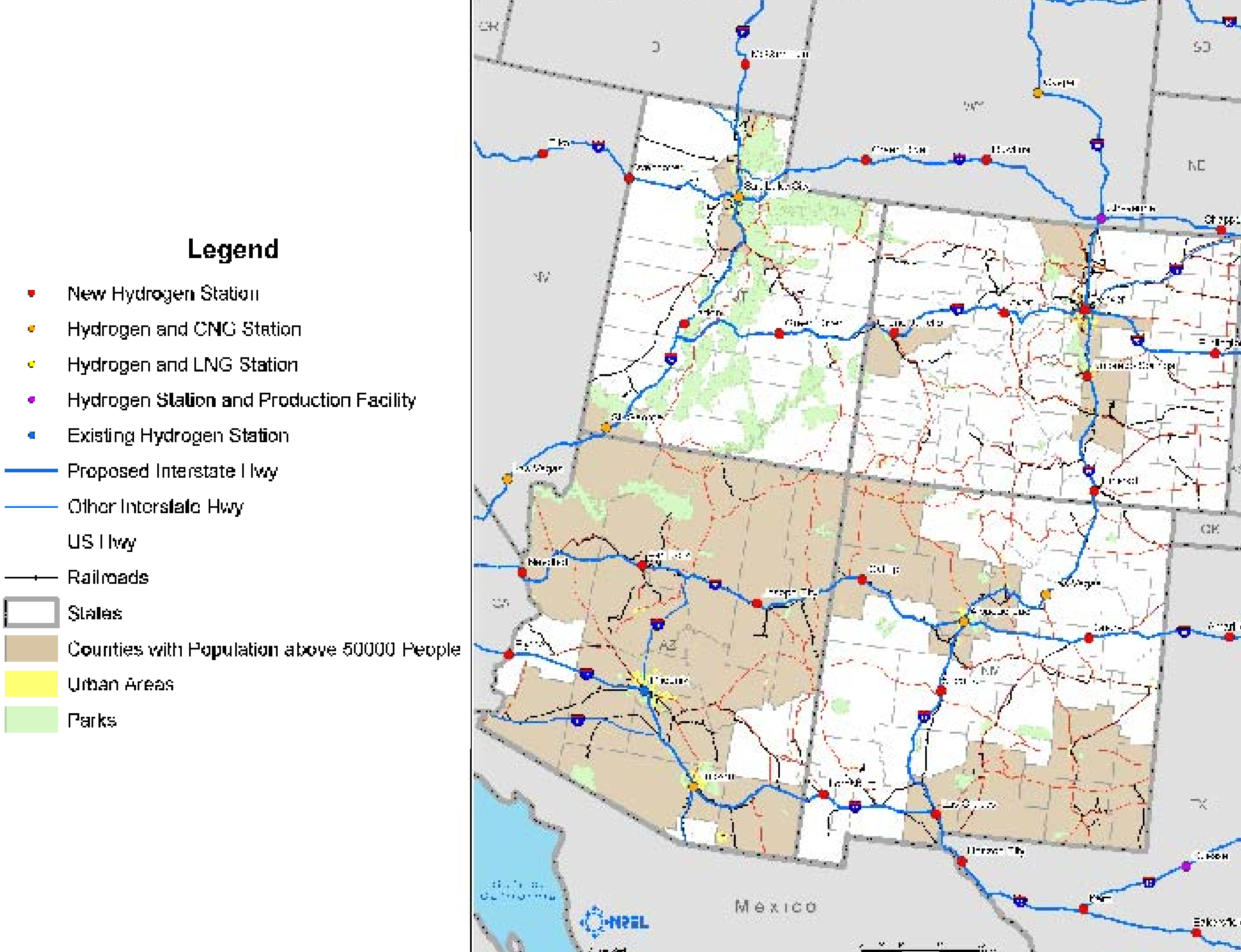
Existing CNG, LNG, Hydrogen Fuel Stations and Interstate Network

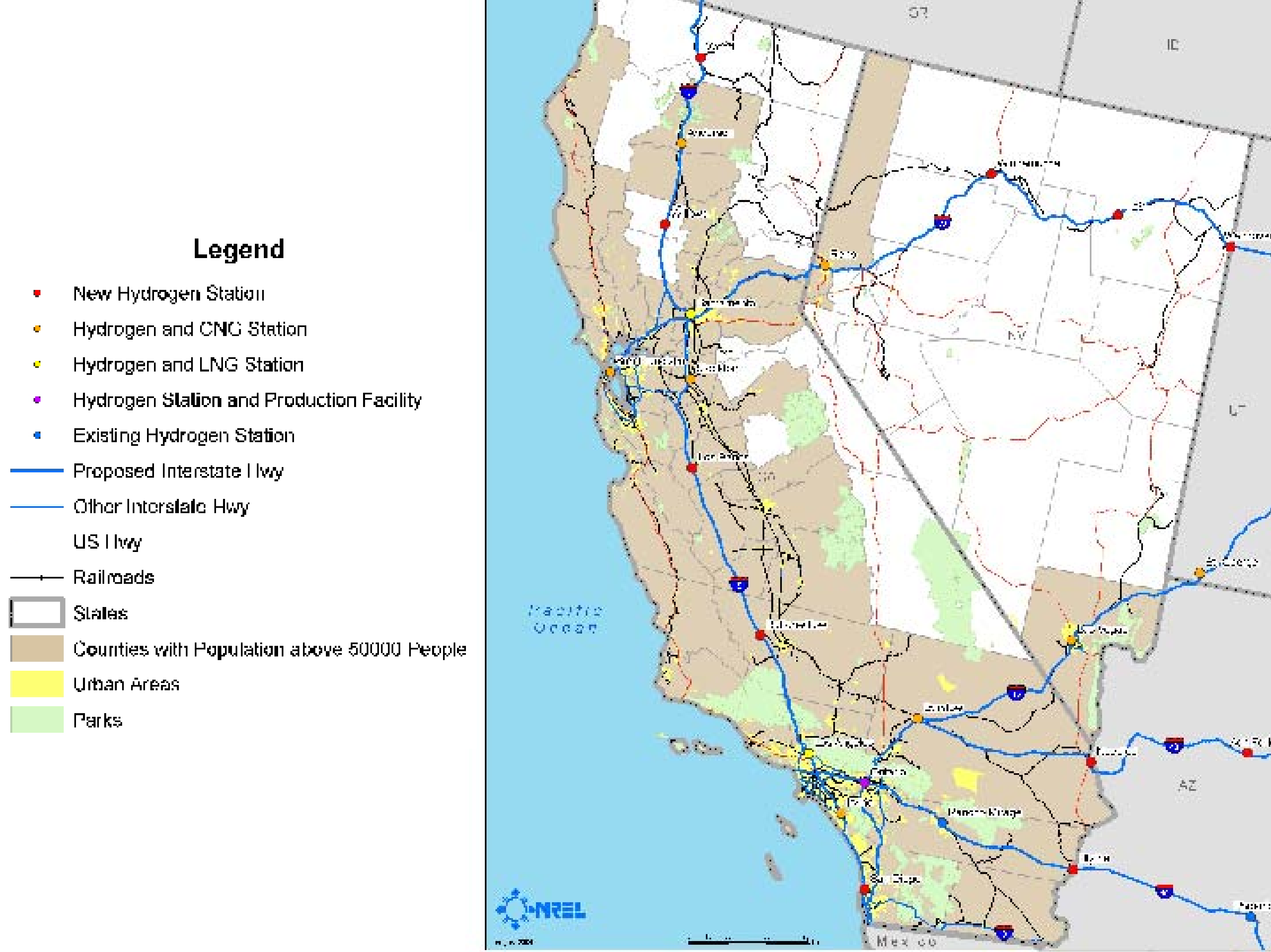



Hydrogen Transition Analysis
Base Map
Existing Alternative Fueling Station
within 3 miles of Interstate
LNG Stations
CNG Stations
Hydrogen Stations
Hydrogen Production Facilities
Counties with Population Above 50000 People
NREL

Proposed Hydrogen Fueling Stations Along Major Interstates




Legend
New Hydrogen Station
Hydrogen and CNG Station
Hydrogen and LNG Station
Hydrogen Station and Production Facility
Existing Hydrogen Station
Proposed Interstate Hwy
Other Interstate Hwy
US Hwy
Railroads
States
Counties with Population above 50000 People
Urban Areas
Parks
Salt Lake City
Denver
Phoenix
NM
AZ
Mexico
NREL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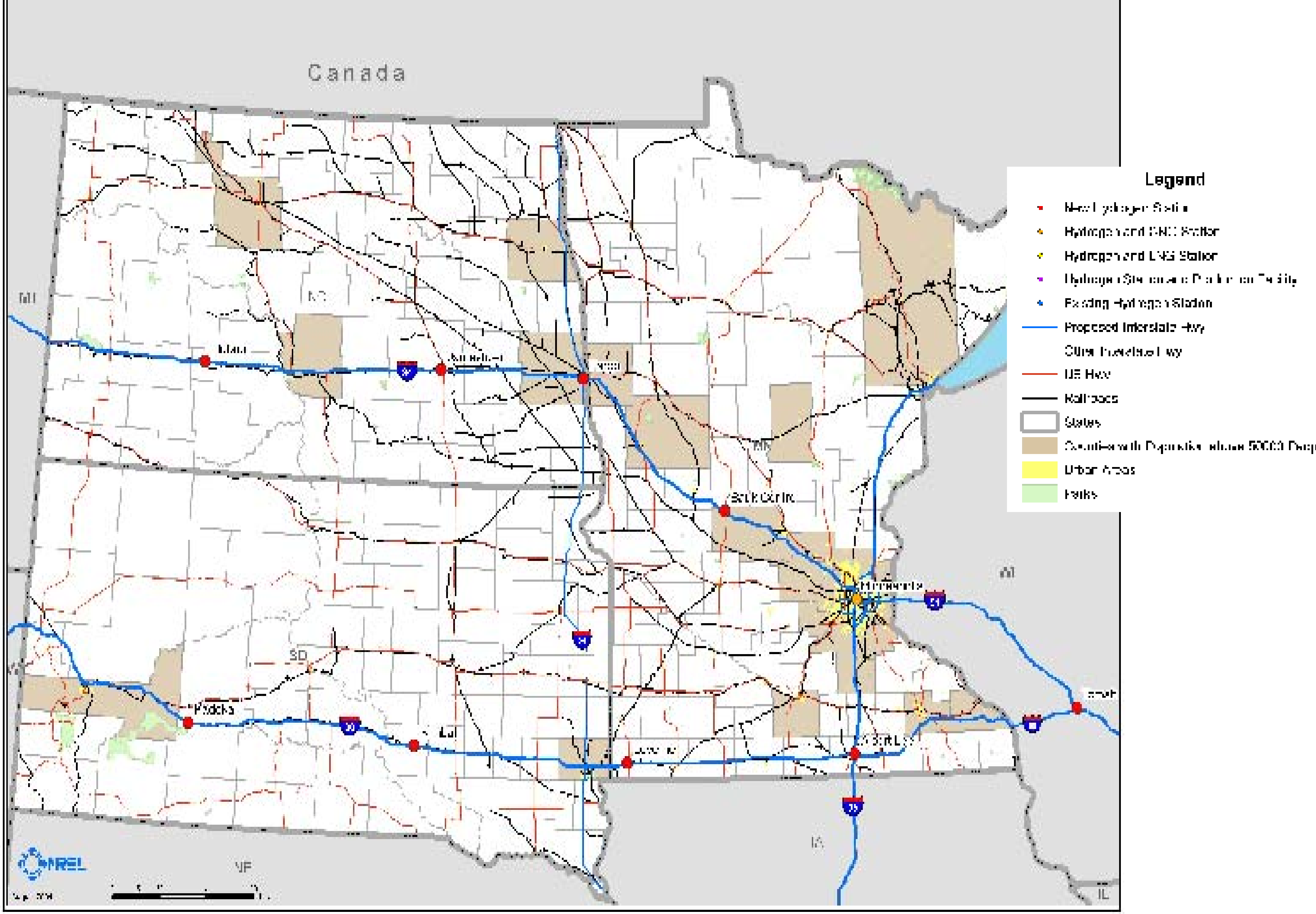
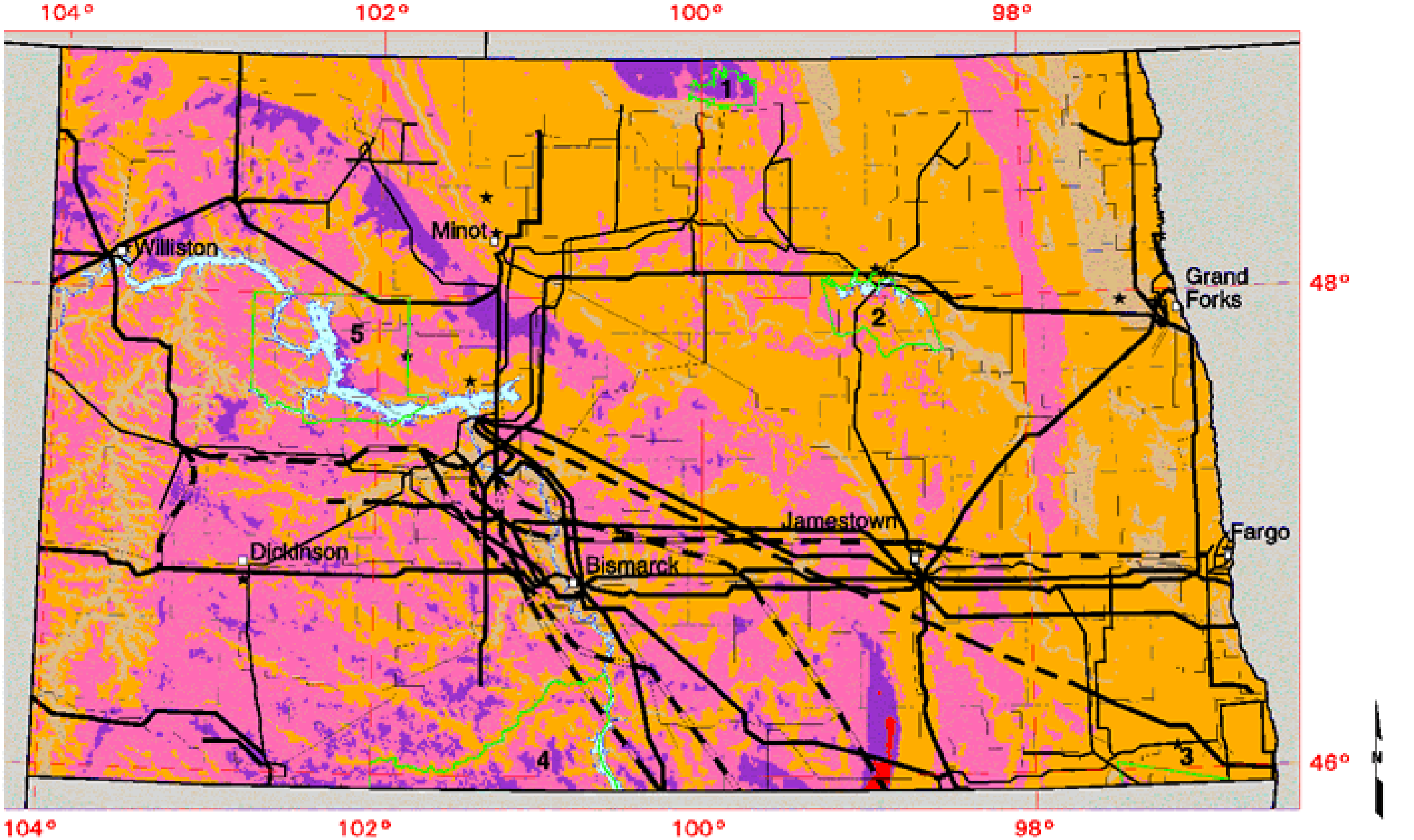

Canada
Legend
Hydrogen and LNG Station
Proposed Interstate Hwy
US Hwy
Railroads
States
Urban Areas
Parks
MT
ND
MN
SD
WI
IA
NE
IL

North Dakota - Wind Resource Map



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

★ Meteorological Station with Wind Data
□ City or Town

Transmission Line Voltage

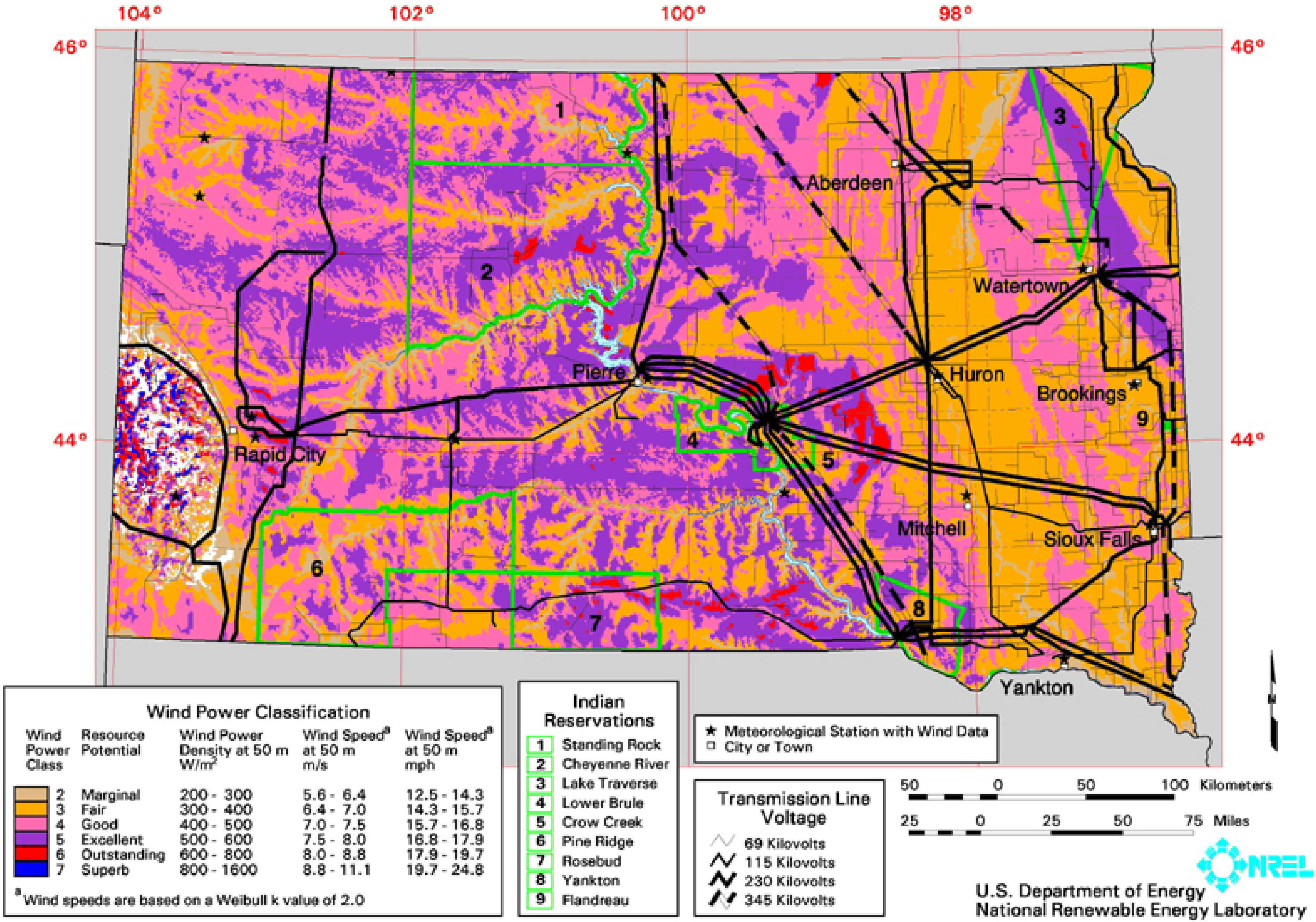
- 69 Kilovolts
- 115 Kilovolts
- 230 Kilovolts
- 345 Kilovolts
- Under Construction

Indian Reservations

1. Turtle Mountain
2. Devil's Lake Sioux
3. Lake Traverse
4. Standing Rock
5. Fort Berthold

U.S. Department of Energy
National Renewable Energy Laboratory

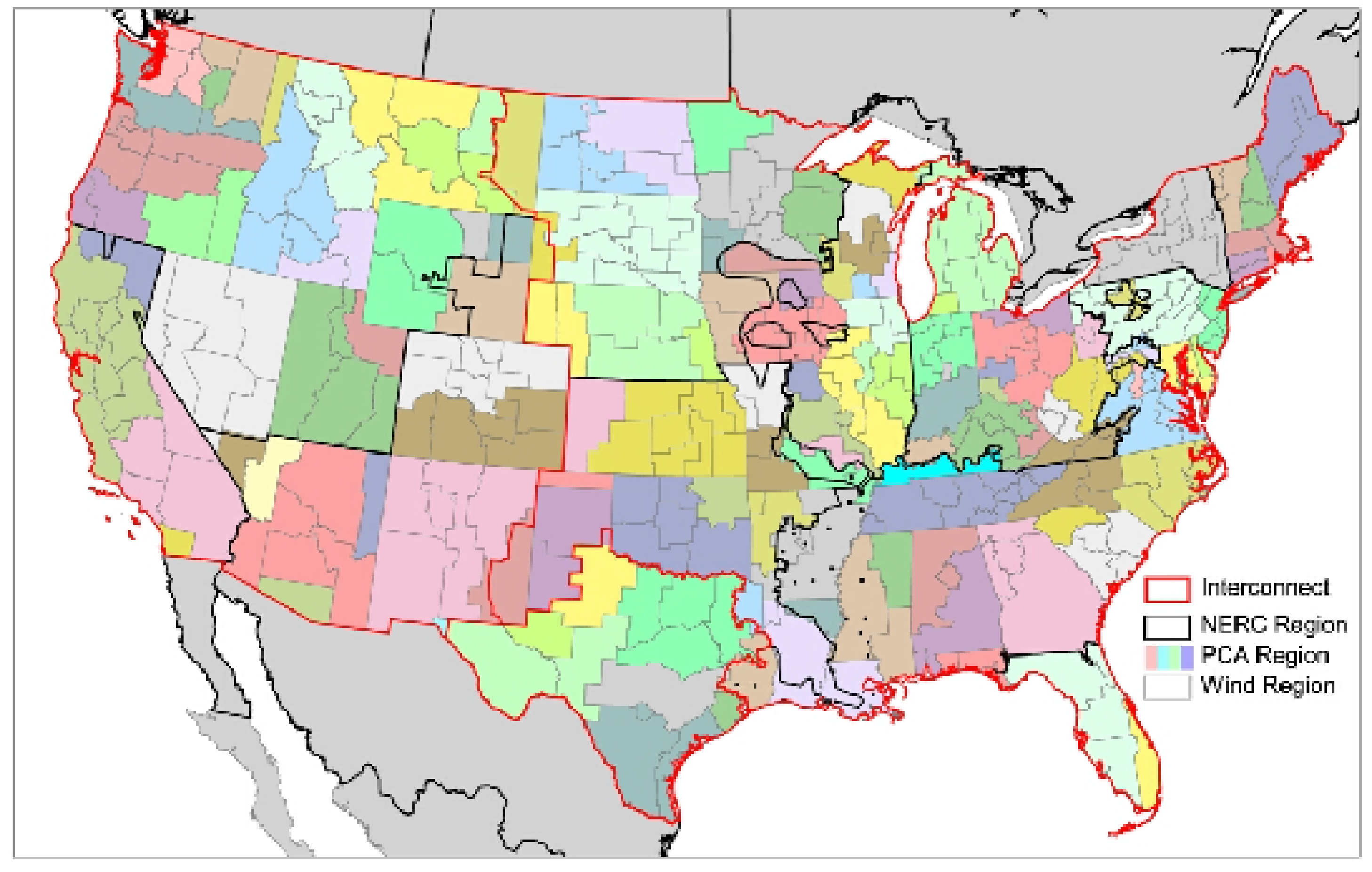
South Dakota - Wind Resource Map



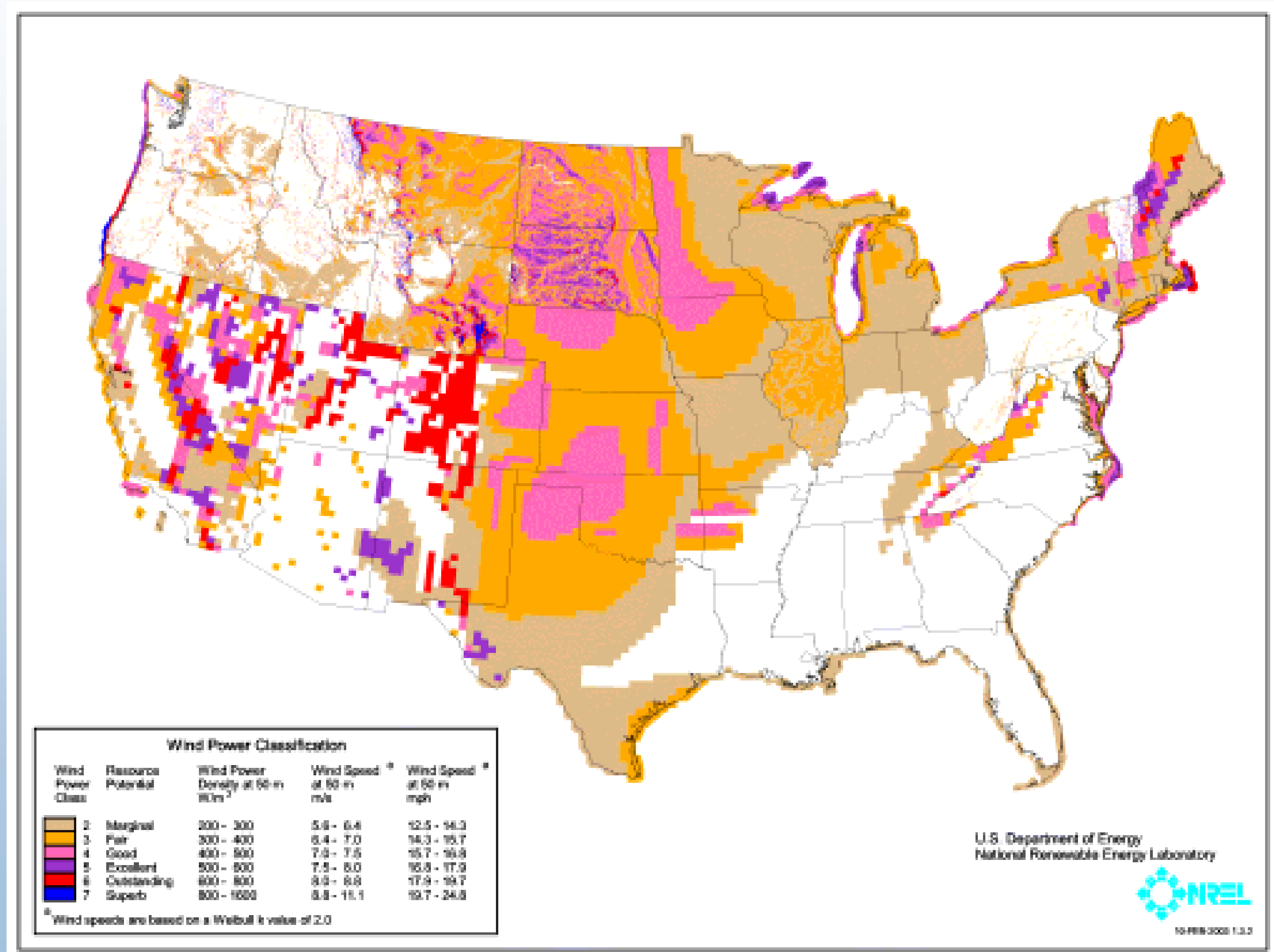
Market Analysis Using WinDS-H2

- A multi-regional, multi-time-period model of capacity expansion in the electric sector and hydrogen production in the U.S
- Designed to estimate market potential of wind energy and hydrogen from wind in the U.S. for the next 20 – 50 years under different technology development and policy scenarios

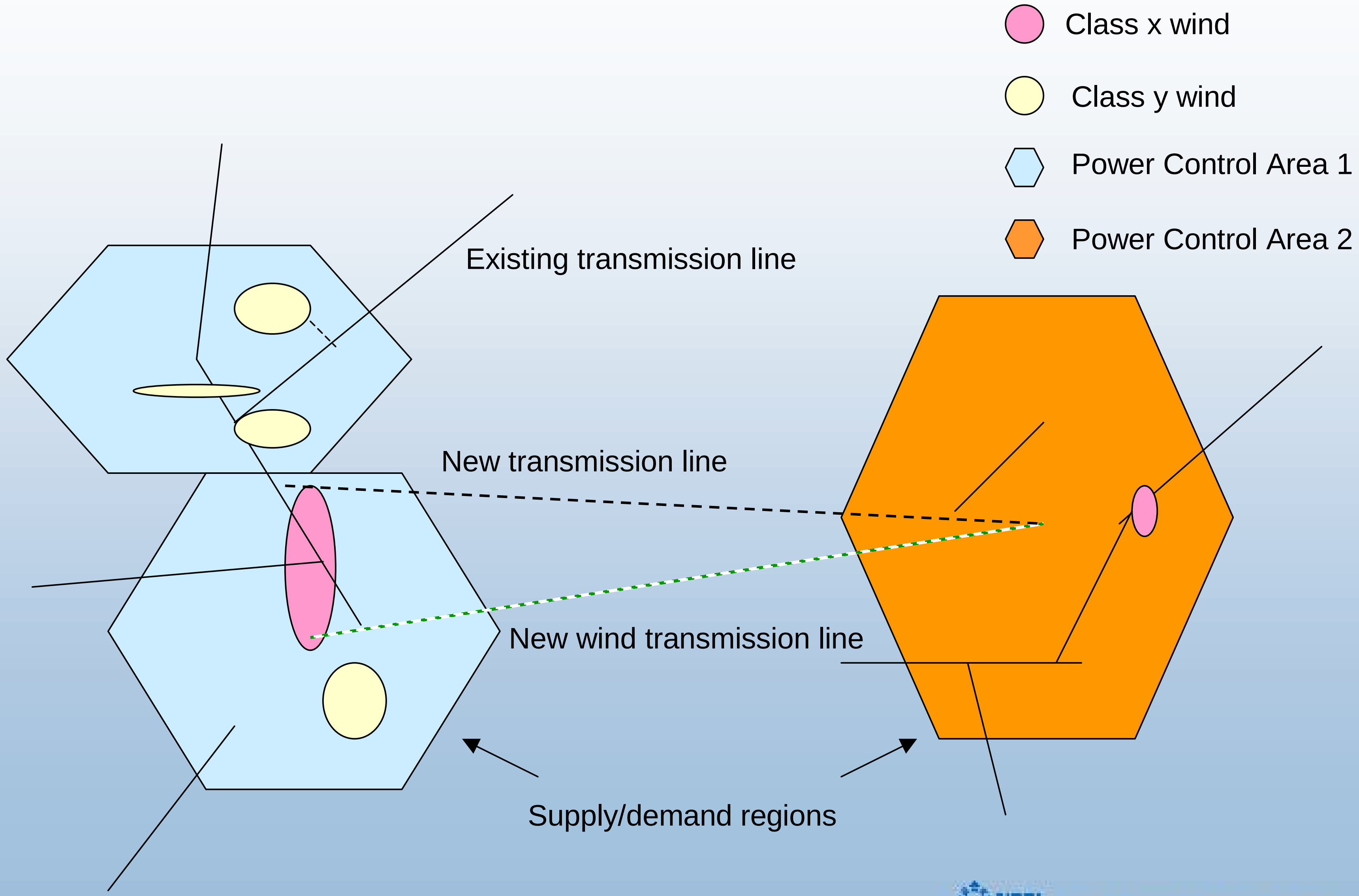
Market Analysis Using WinDS



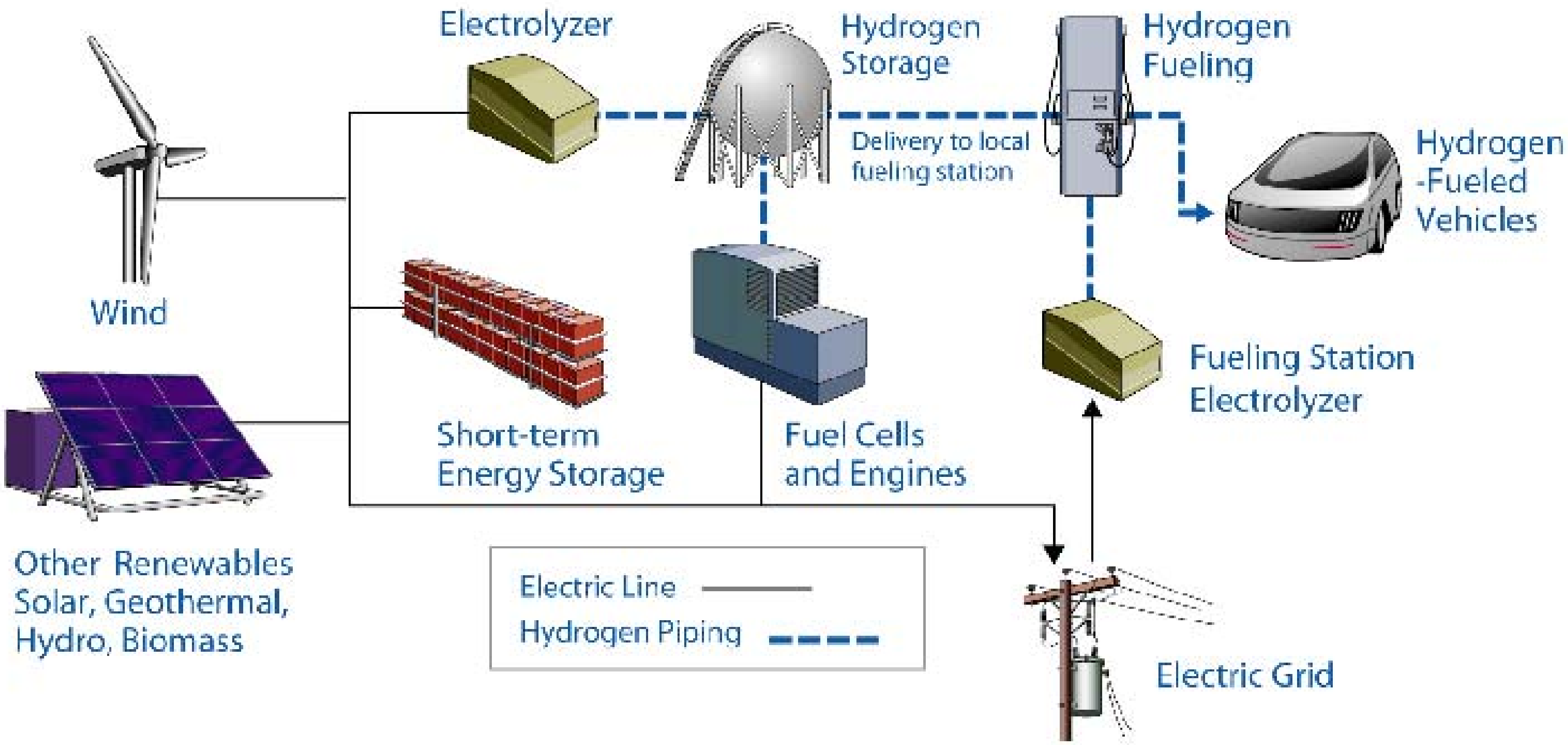
Wind Resources



Constraints on Wind Transmission



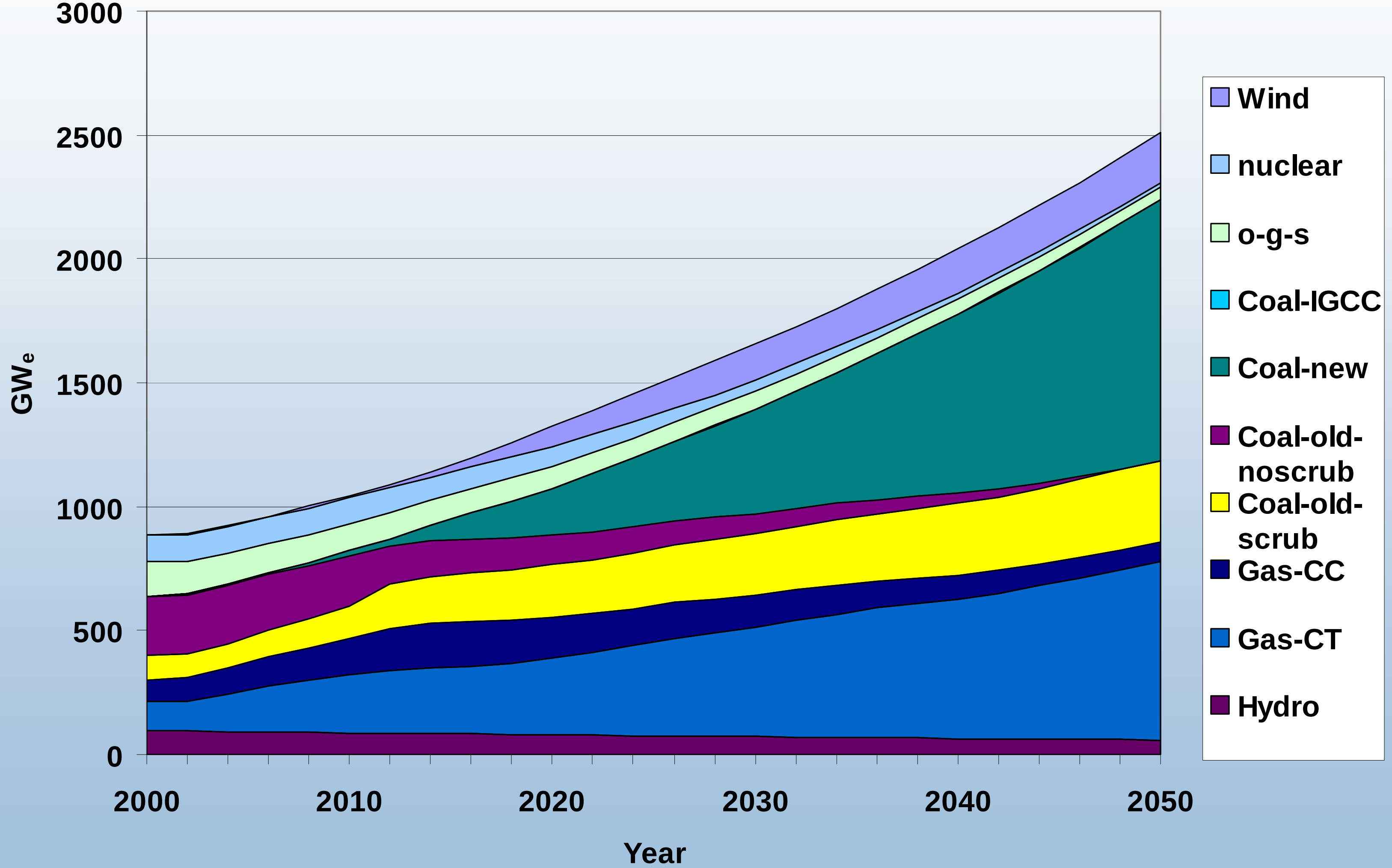
Electrolysis Options



Cost/Performance for Class 6 Wind Resources

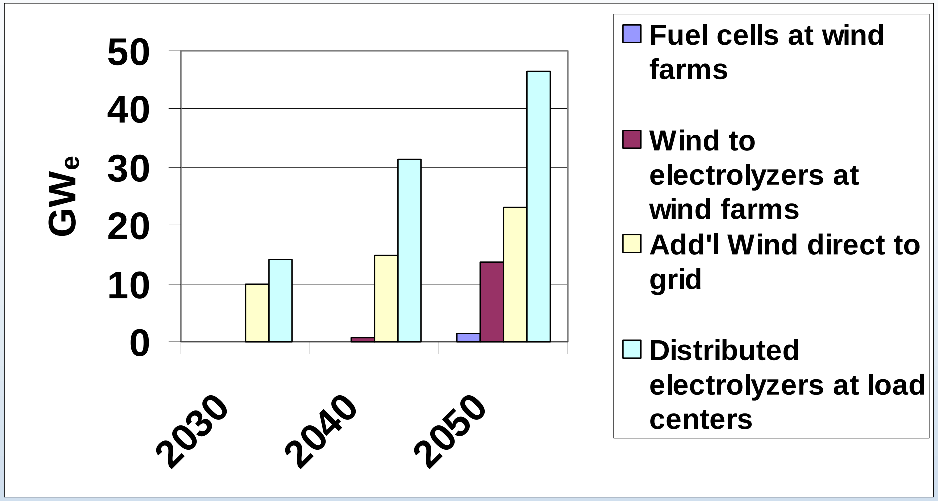
Year	Capital Cost ($/kW)	Capacity Factor
2000	942	0.4
2010	754	0.5
2020	706	0.54

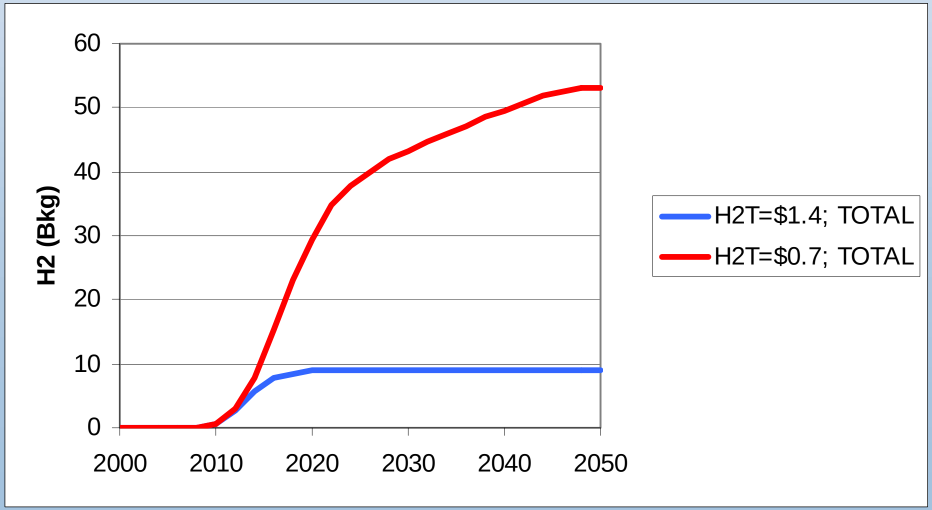
Base Case Results



Cases Considered (so far)

- Low-cost high-efficiency electrolyzers
  - Electrolyzers show up at both the wind farm and the load center
  - More wind to grid
- Sensitivity to hydrogen delivery cost
  - Hydrogen delivery distance/cost will have significant impact
- Increased wind penetration depends heavily on hydrogen conversion device (i.e. fuel cell) cost and efficiency





Integration with Renewables: Research Opportunities

- Co-producing electricity and hydrogen can address issues that currently face intermittent and season renewable technologies
- Wind/electrolysis could be the first economical renewable system
- R&D: hybrid system optimization, power electronics, system design

Component Development

Grid Electricity

Dedicated Test Bay for Electrolytic Hydrogen Production

On-Site Wind- and PV-Generated Electricity

Shared Power Electronics Package

Component Development

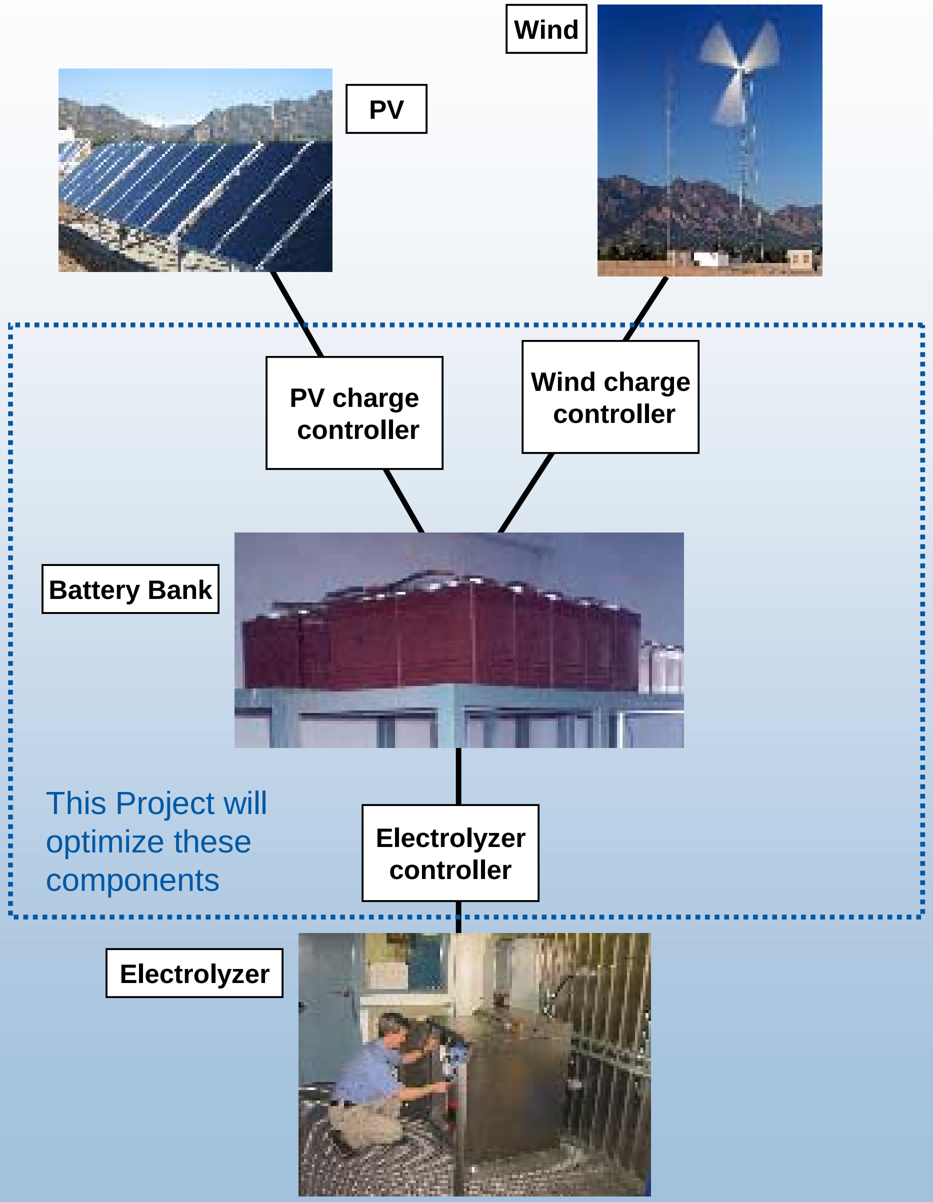
Past research on integrating electrolyzers with renewables has focused on integrating commercially available electrolyzers and renewables, both complete with their own dedicated power electronics and controller.

Designing a single power electronics package and controller will:

- Eliminate this redundancy
- Allow matching of renewable power output to electrolyzer power requirements leading to gains in system efficiency.

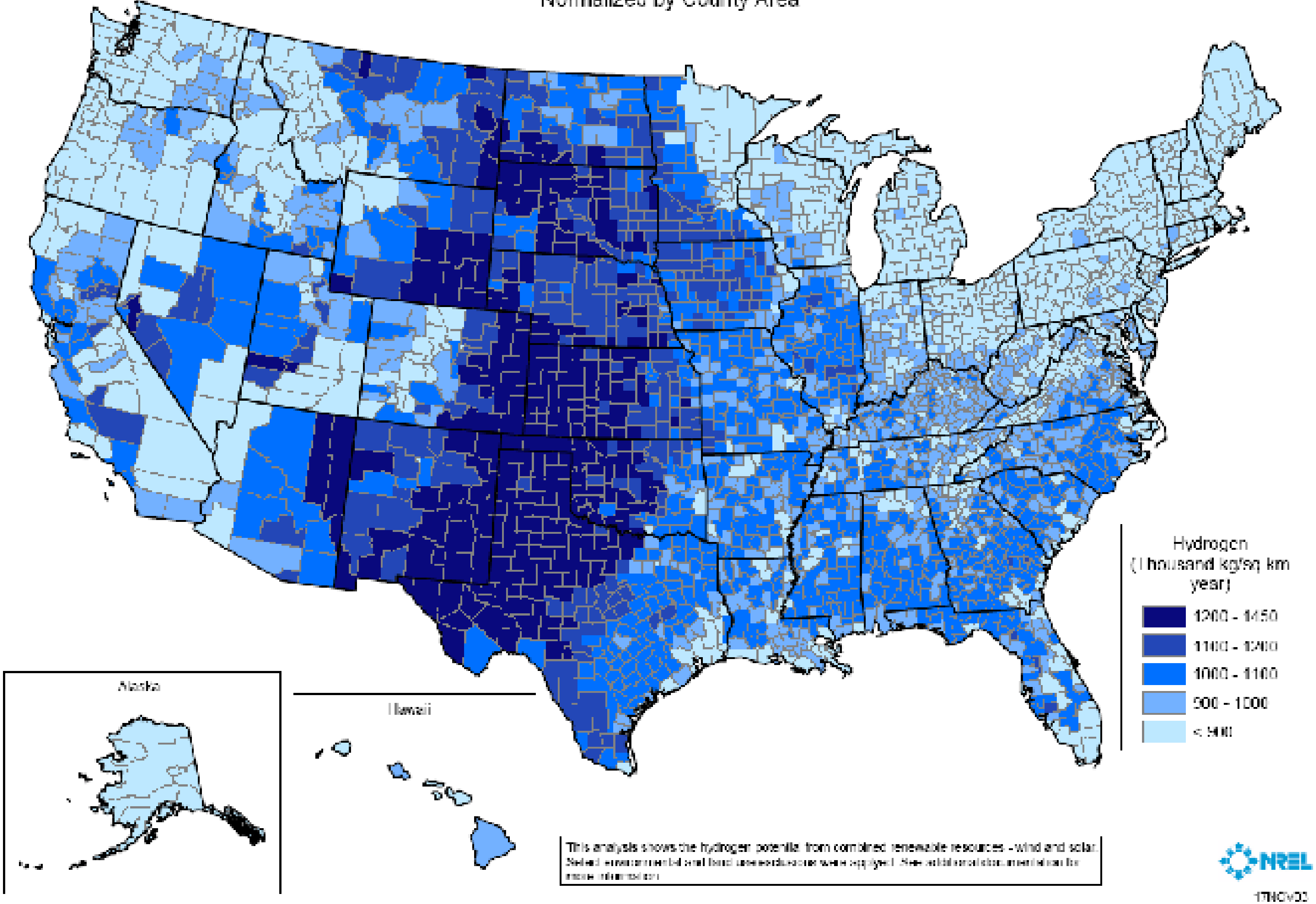
This new design will eliminate the need for a constant voltage DC bus and associated battery bank present in all systems previously studied.

Typically power electronics can be up to 30% of each system's cost.



Hydrogen Potential From Renewable Resources

Total kg of Hydrogen per County
Normalized by County Area



Opportunities

- Wind could play a substantial role in hydrogen production at competitive prices, while reducing carbon from the generation mix
- Wind is essentially a fuel-free hydrogen generation source
  - Removes most uncertainty related to energy cost projection
  - Directly tied to capital cost of components

What might be practical?

- Levelize wind generation profile
  - Reduce risk
  - Downsize transmission
- Hydrogen fuel production at the wind site near hydrogen demand
- Electrolyzers at fueling stations creating new, controllable demand
  - Levelize load
  - Intelligent grid control
- Electrolyzers at fueling station create constant load
  - Long-term purchase agreements