NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Hydrogen Production: Fundamentals and Case Study Summaries

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World Hydrogen Energy Conference

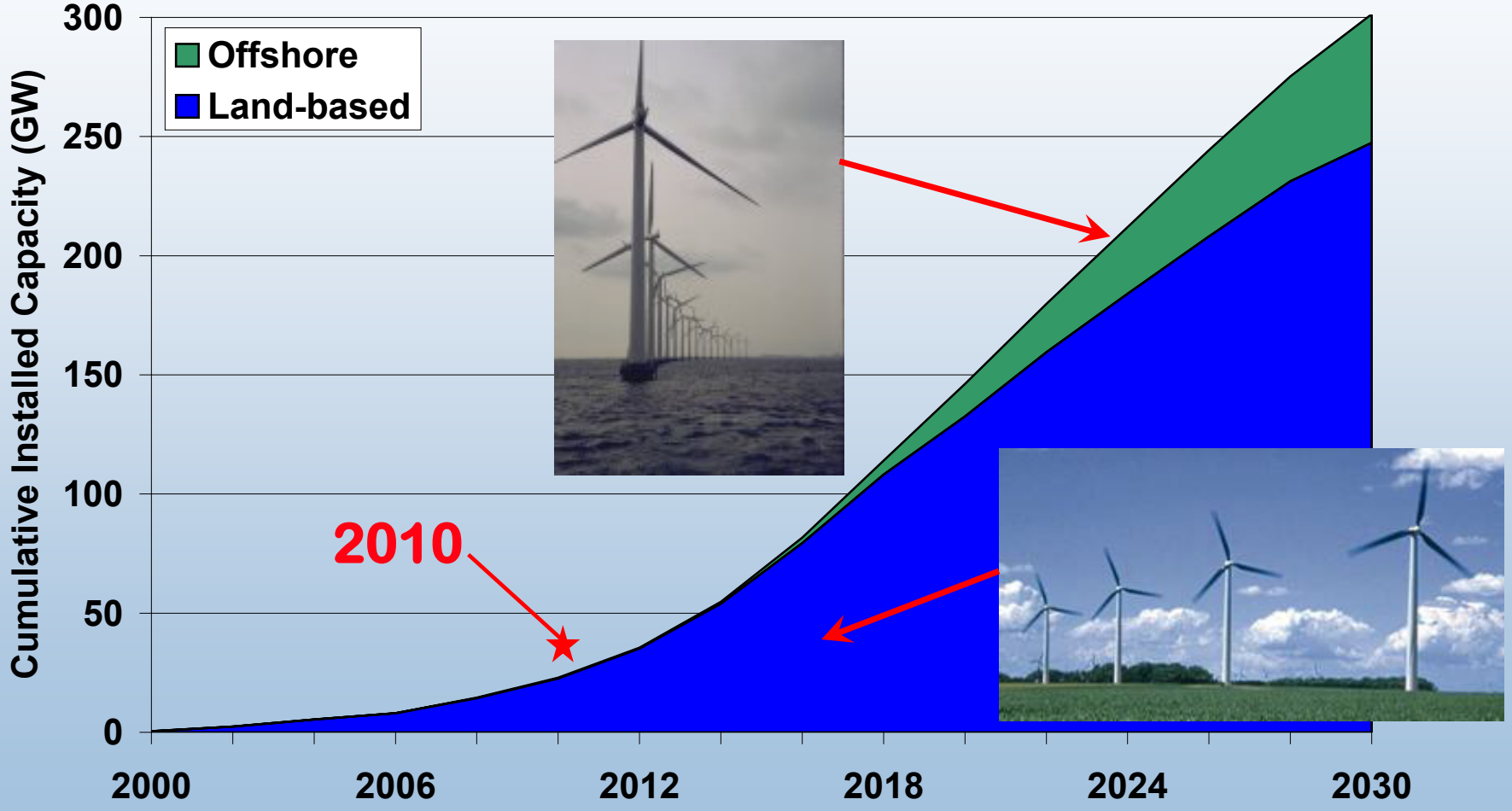
Essen, Germany

May 19, 2010

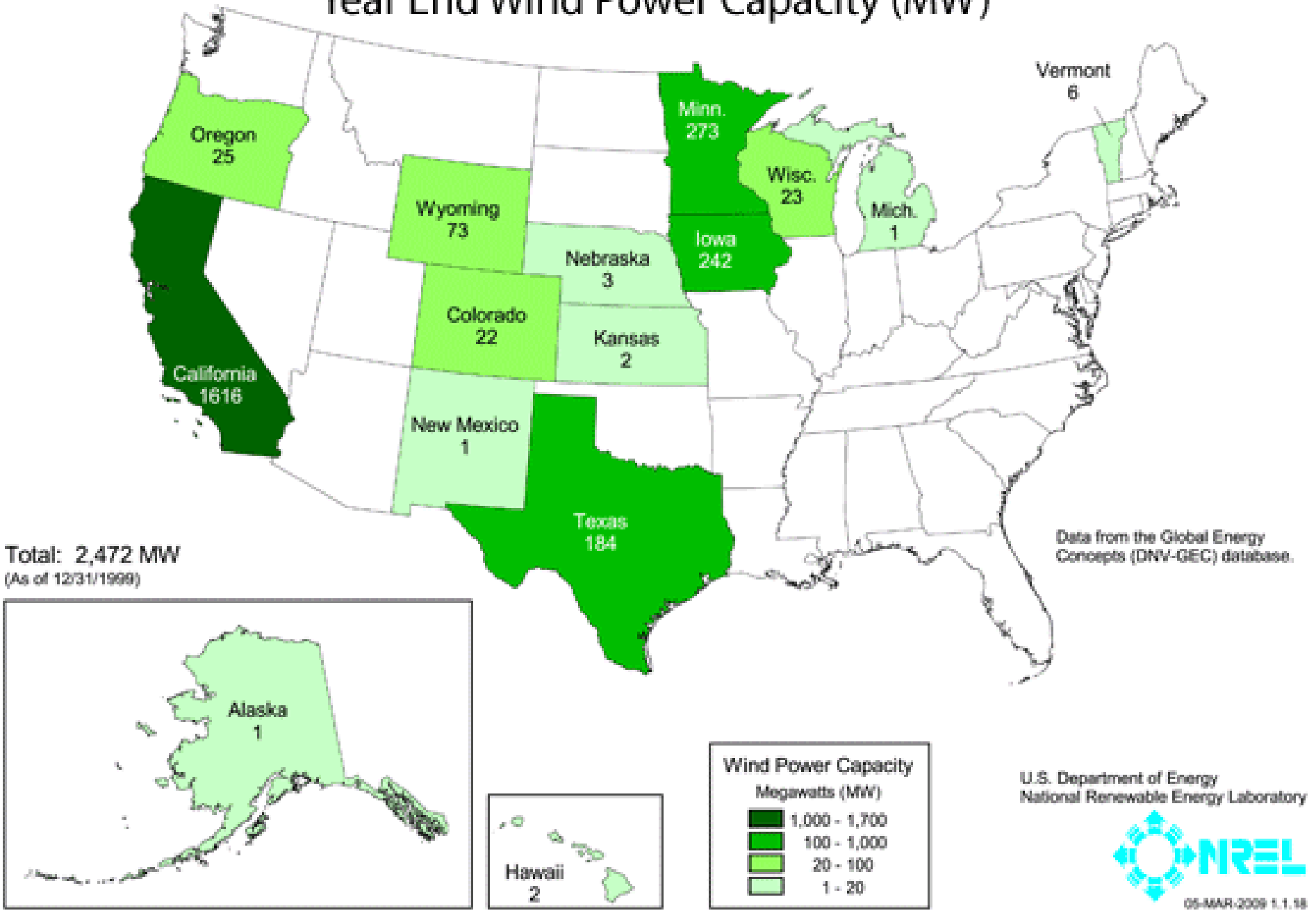
NREL/PR-560-48269

20% Wind by 2030 Scenario

As of December 31, 2009 - 34,863 MW of wind power have been installed across the United States.



1999
Year End Wind Power Capacity (MW)



Total: 2,472 MW
(As of 12/31/1999)

Data from the Global Energy Concepts (DNV-GEC) database.

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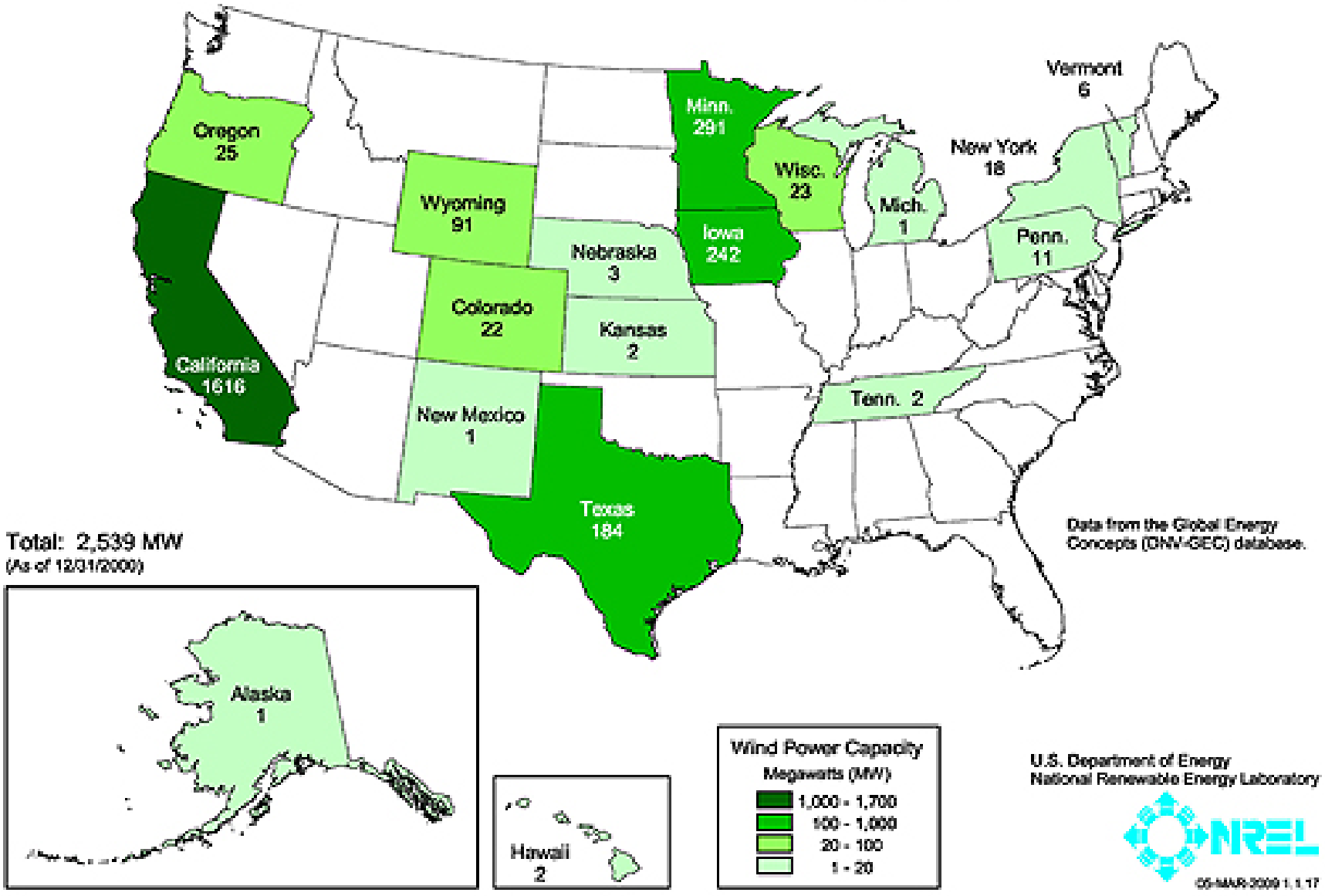
2000 Year End Wind Power Capacity (MW)



Total: 2,539 MW
(As of 12/31/2000)

Data from the Global Energy Concepts (DNV-GEC) database.

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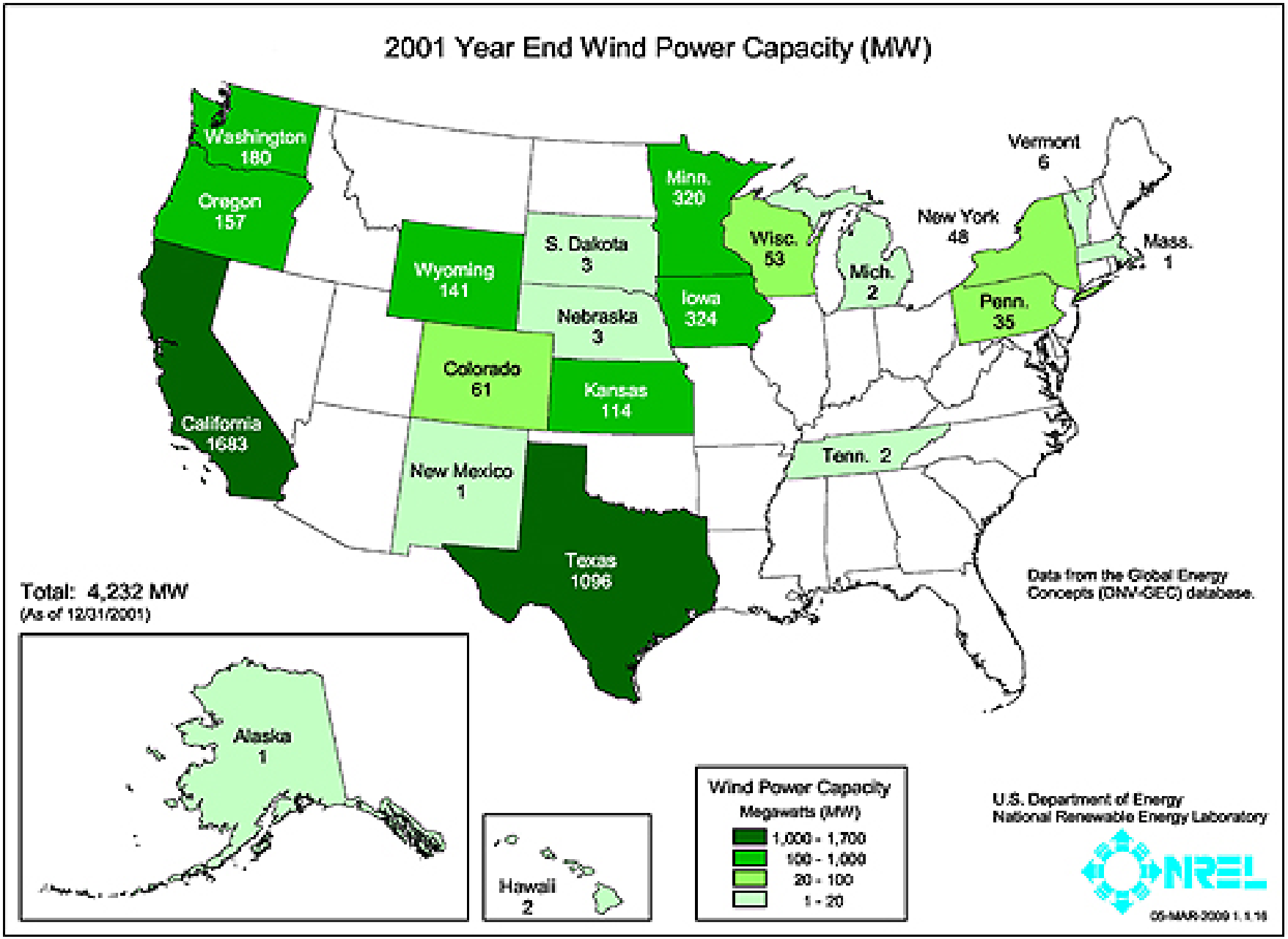
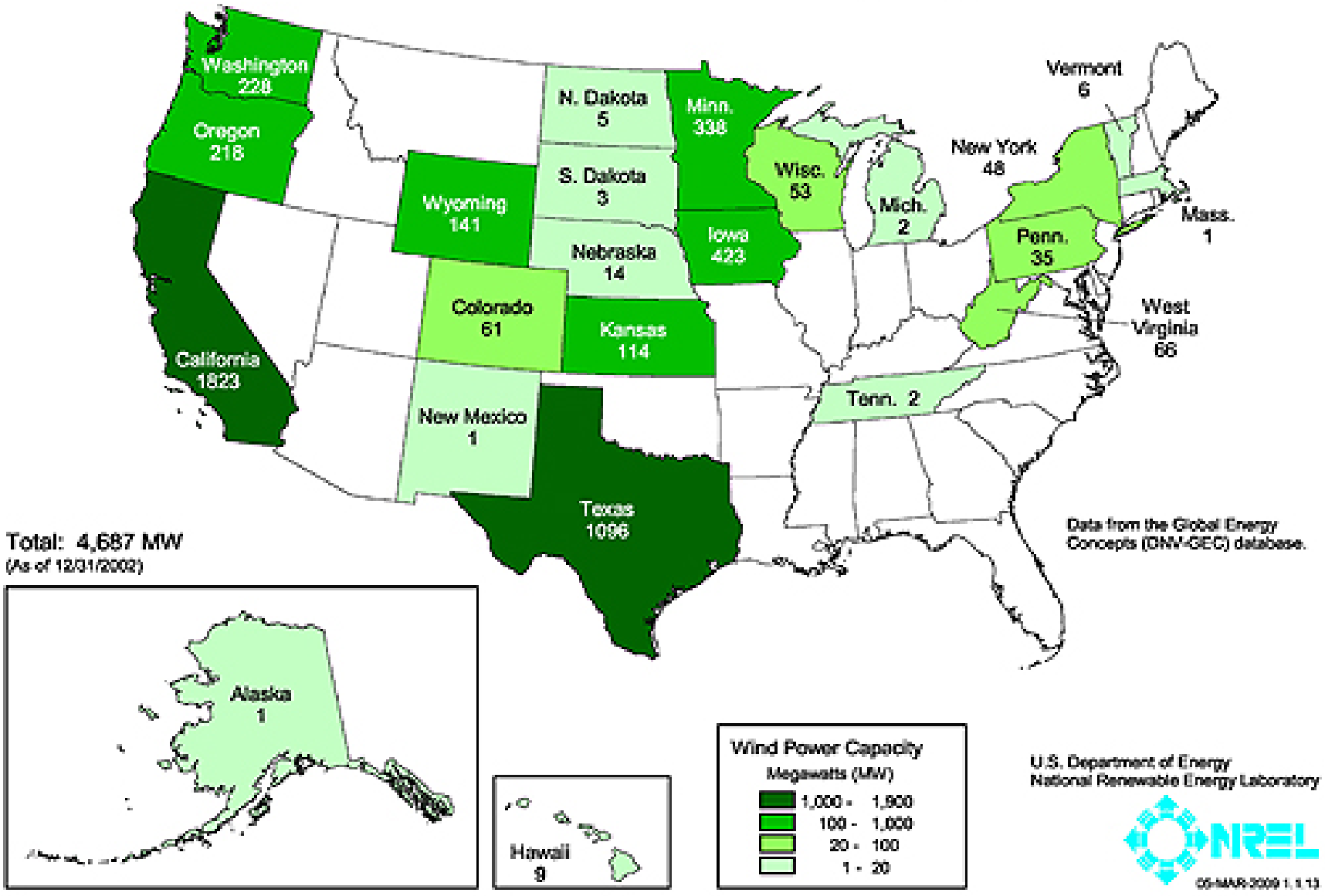

2001 Year End Wind Power Capacity (MW)
Washington 180
Oregon 157
California 1693
Wyoming 141
Colorado 61
New Mexico 1
Texas 1096
S. Dakota 3
Nebraska 3
Kansas 114
Minn. 320
Iowa 324
Wisc. 53
Mich. 2
Vermont 6
New York 48
Mass. 1
Penn. 35
Tenn. 2
Total: 4,232 MW
(As of 12/31/2001)
Alaska 1
Hawaii 2
Wind Power Capacity
Megawatts (MW)
1,000 - 1,700
100 - 1,000
20 - 100
1 - 20
Data from the Global Energy Concepts (DNV-GEC) database.
U.S. Department of Energy
National Renewable Energy Laboratory
NREL
05-MAR-2009 1.1.16

2002 Year End Wind Power Capacity (MW)



Total: 4,687 MW
(As of 12/31/2002)

Data from the Global Energy Concepts (DNV-GEC) database.

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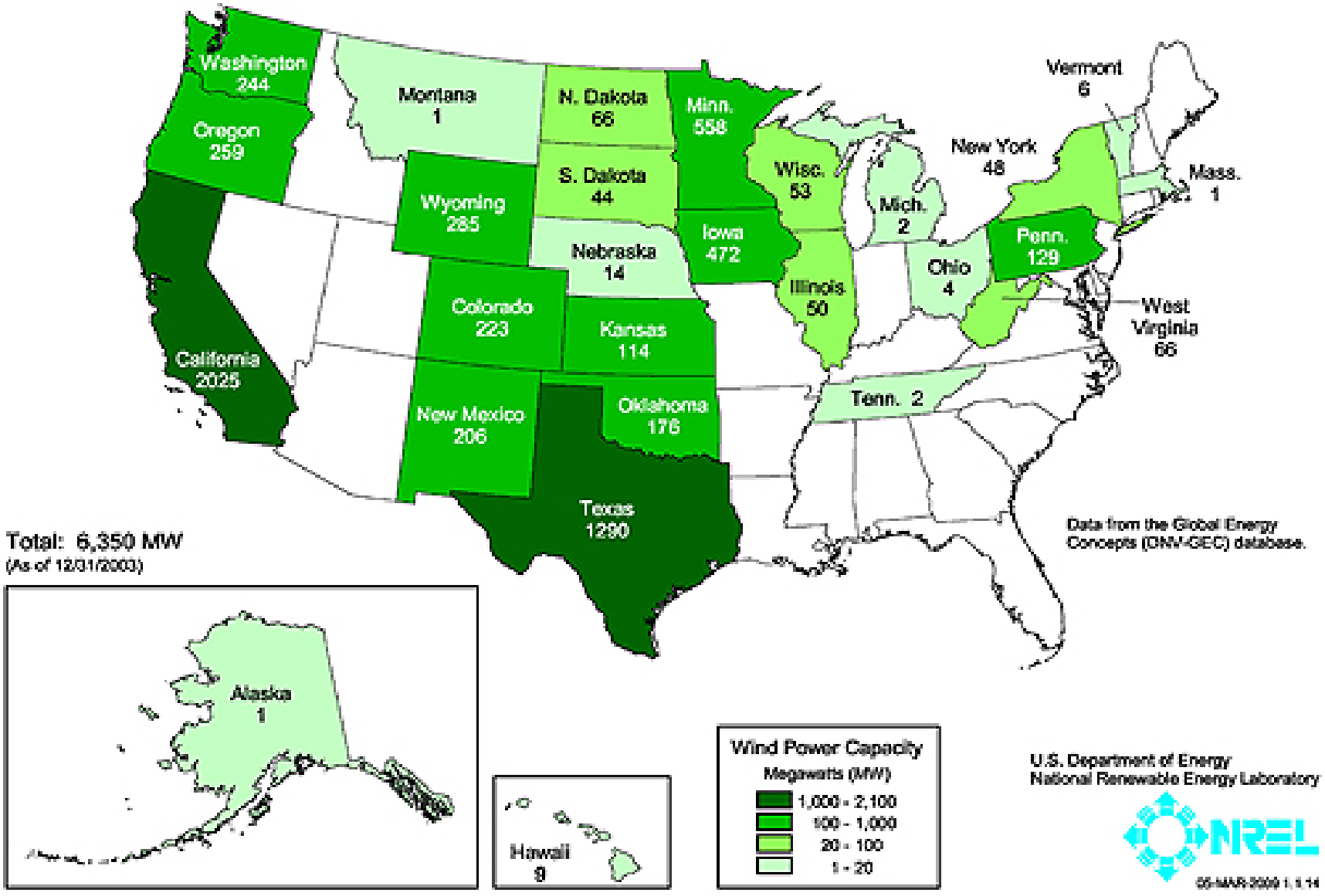
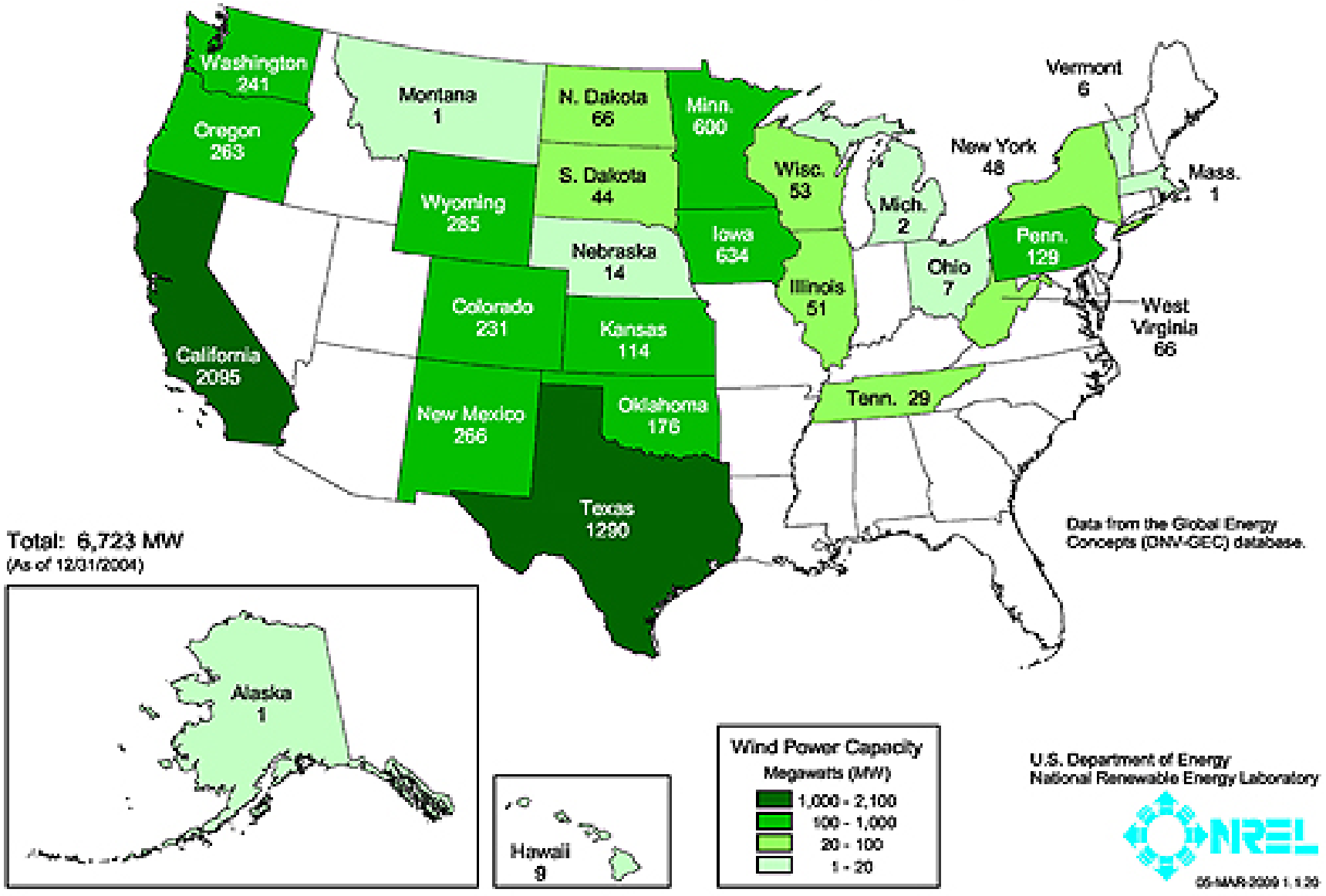
05-NAAR-2009 1.1.13

2003 Year End Wind Power Capacity (MW)



2004 Year End Wind Power Capacity (MW)



Total: 6,723 MW
(As of 12/31/2004)

Data from the Global Energy Concepts (DNV-GEC) database.

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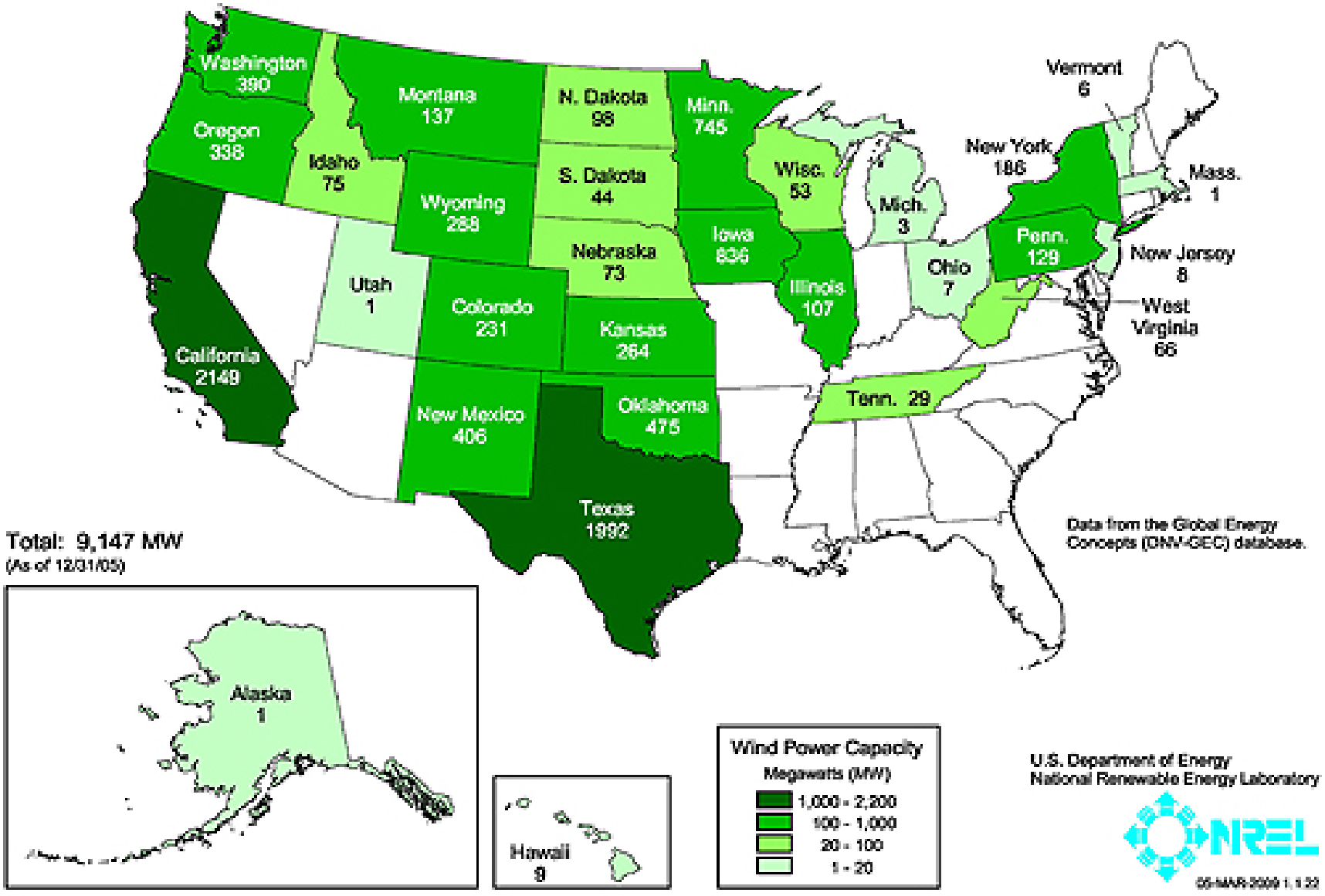
05-NAAR-2005 1.1.20

2005 Year End Wind Power Capacity (MW)



Total: 9,147 MW
(As of 12/31/05)

Data from the Global Energy Concepts (DNV-GEC) database.

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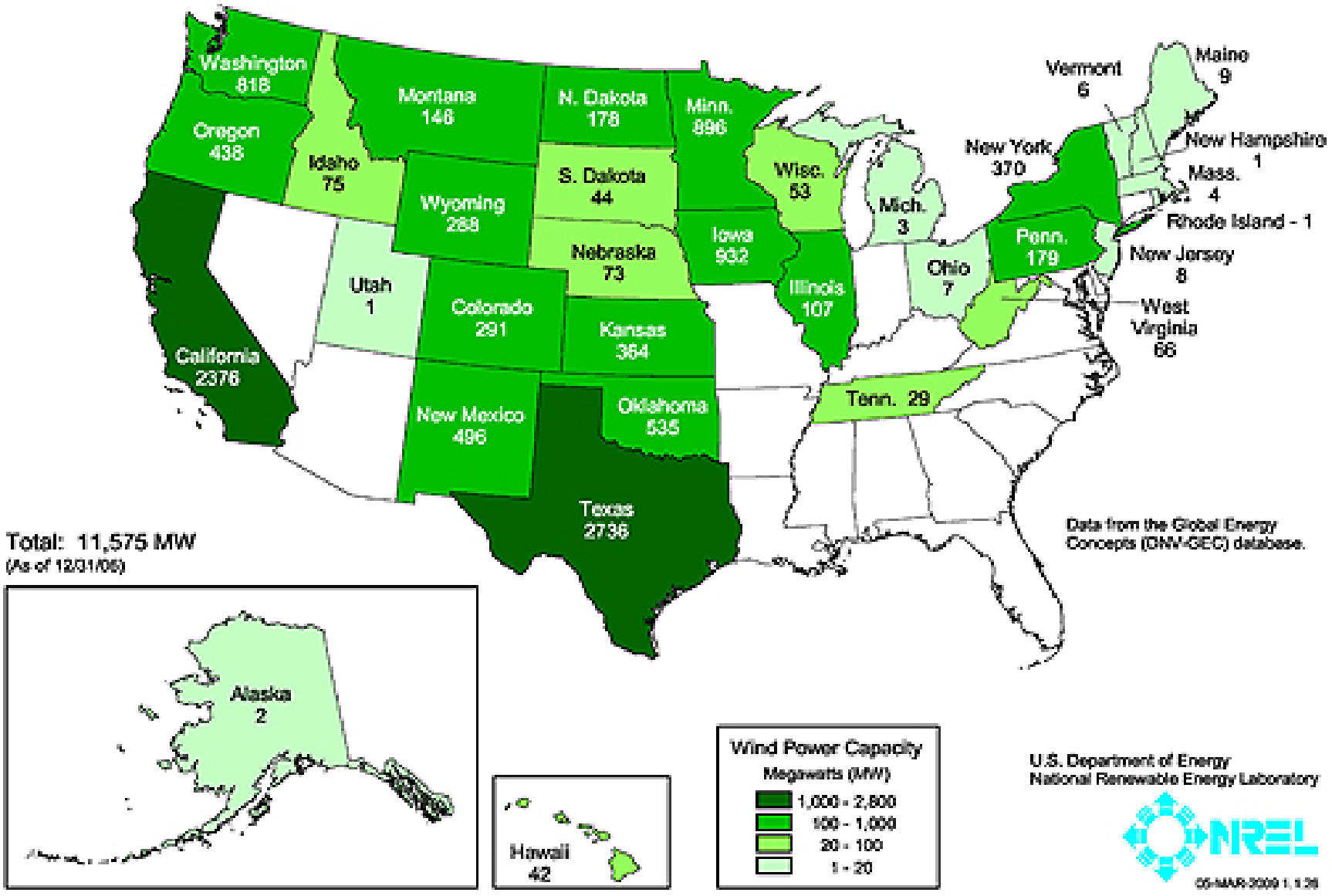
05-NWR-2006.1.1.22

2006 Year End Wind Power Capacity (MW)



Total: 11,575 MW
(As of 12/31/06)

Data from the Global Energy Concepts (DNV-GEC) database.

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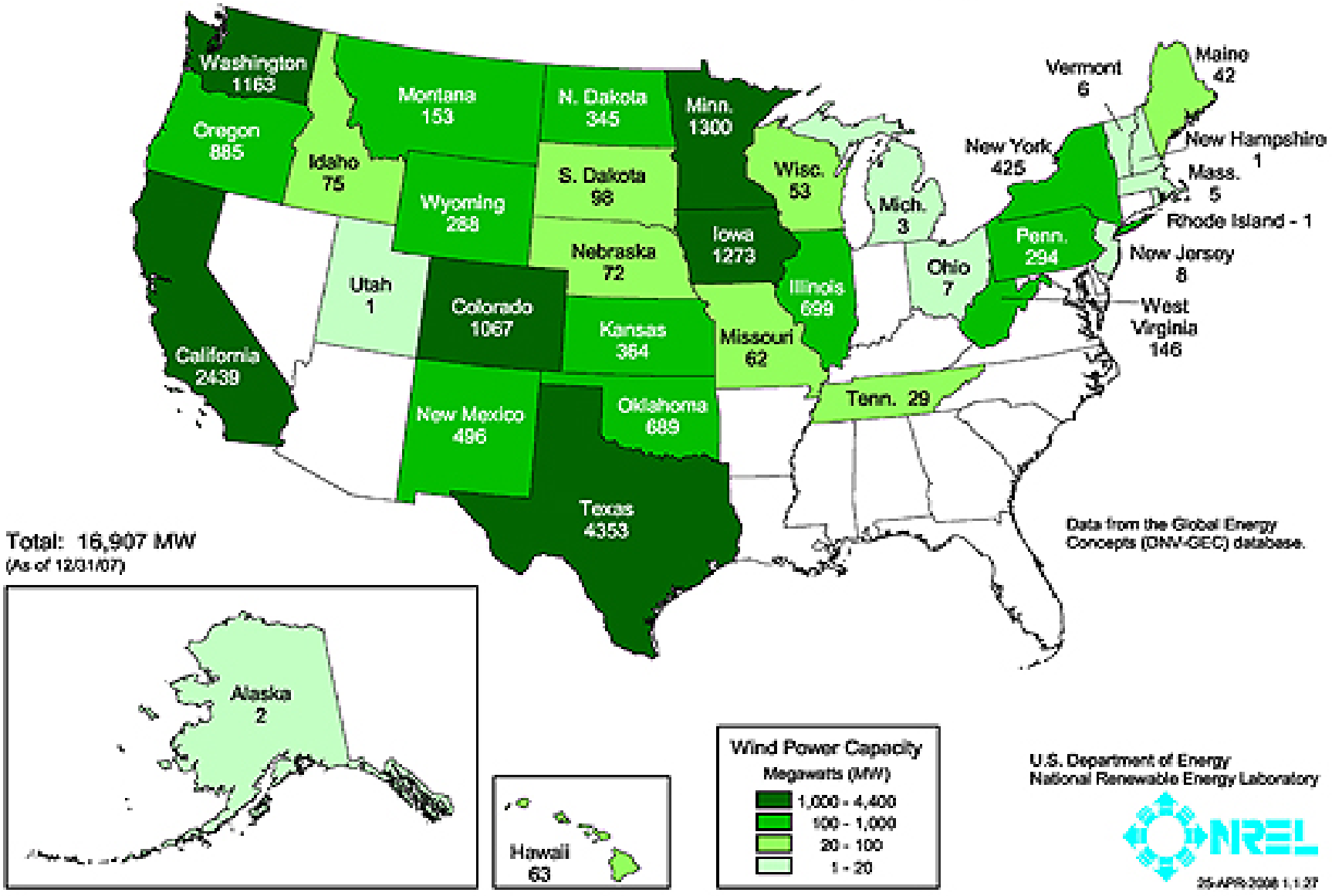
05-NAAR-2009 1.1.26

2007 Year End Wind Power Capacity (MW)



Total: 16,907 MW
(As of 12/31/07)

Data from the Global Energy Concepts (DNV-GEC) database.

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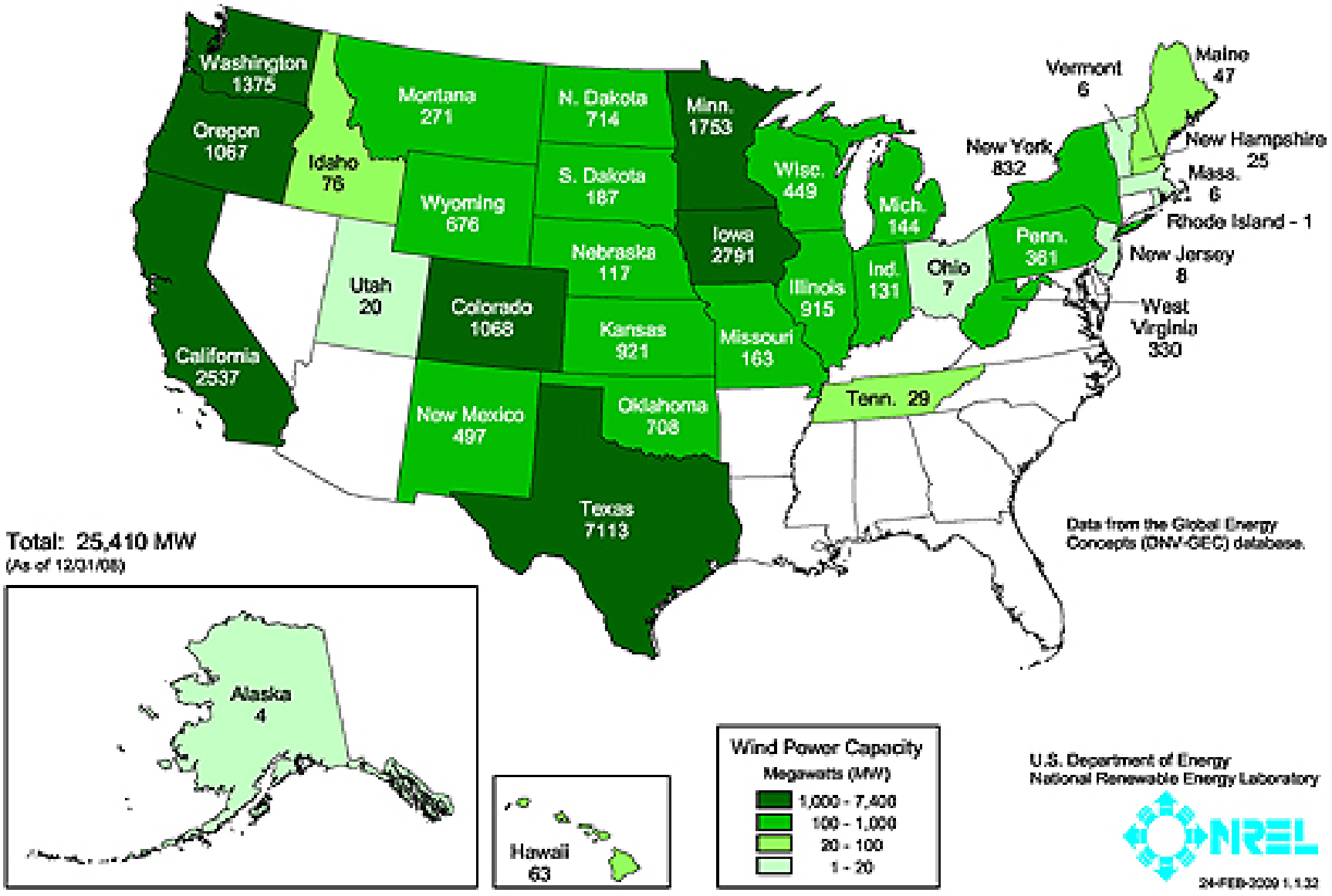
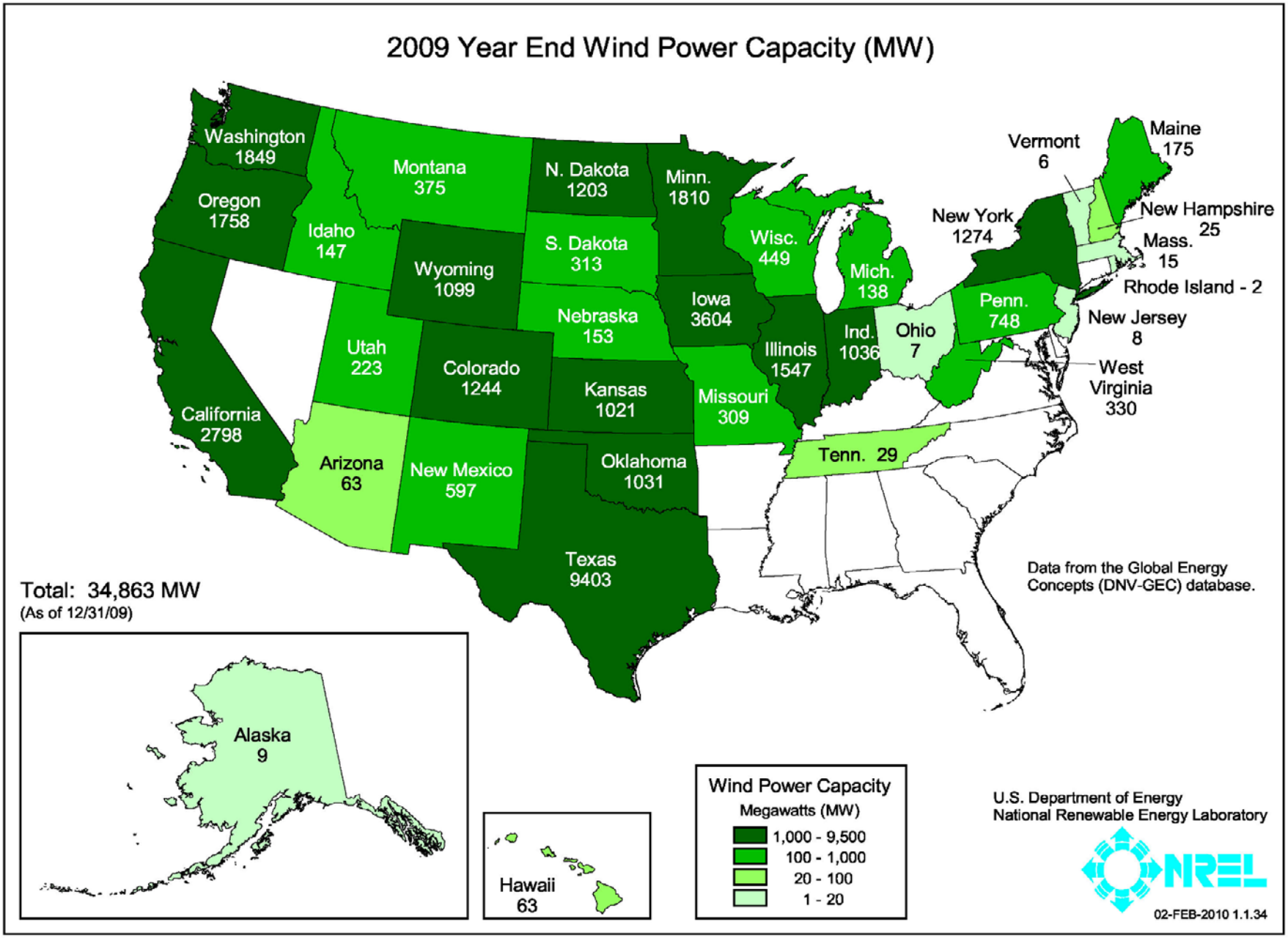
25-APR-2008 1.1.27

2008 Year End Wind Power Capacity (MW)




2009 Year End Wind Power Capacity (MW)
Washington 1849
Oregon 1758
California 2798
Idaho 147
Montana 375
Wyoming 1099
Utah 223
Colorado 1244
Arizona 63
New Mexico 597
N. Dakota 1203
S. Dakota 313
Nebraska 153
Kansas 1021
Oklahoma 1031
Texas 9403
Minn. 1810
Iowa 3604
Missouri 309
Arkansas
Louisiana
Wisc. 449
Illinois 1547
Mich. 138
Ind. 1036
Ohio 7
Tenn. 29
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
Virginia
West Virginia 330
Penn. 748
New York 1274
Vermont 6
Maine 175
New Hampshire 25
Mass. 15
Rhode Island - 2
New Jersey 8
Delaware
Maryland
Total: 34,863 MW
(As of 12/31/09)
Alaska 9
Hawaii 63
Wind Power Capacity
Megawatts (MW)
1,000 - 9,500
100 - 1,000
20 - 100
1 - 20
Data from the Global Energy Concepts (DNV-GEC) database.
U.S. Department of Energy
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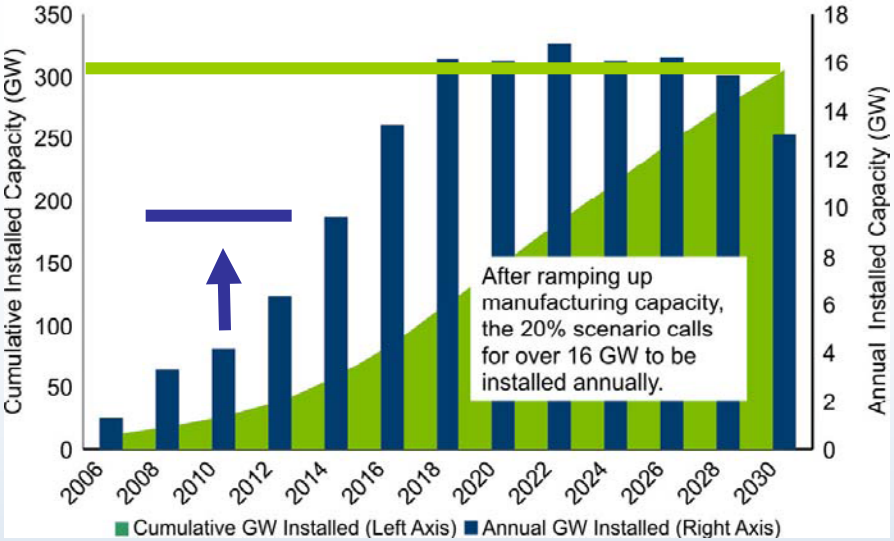
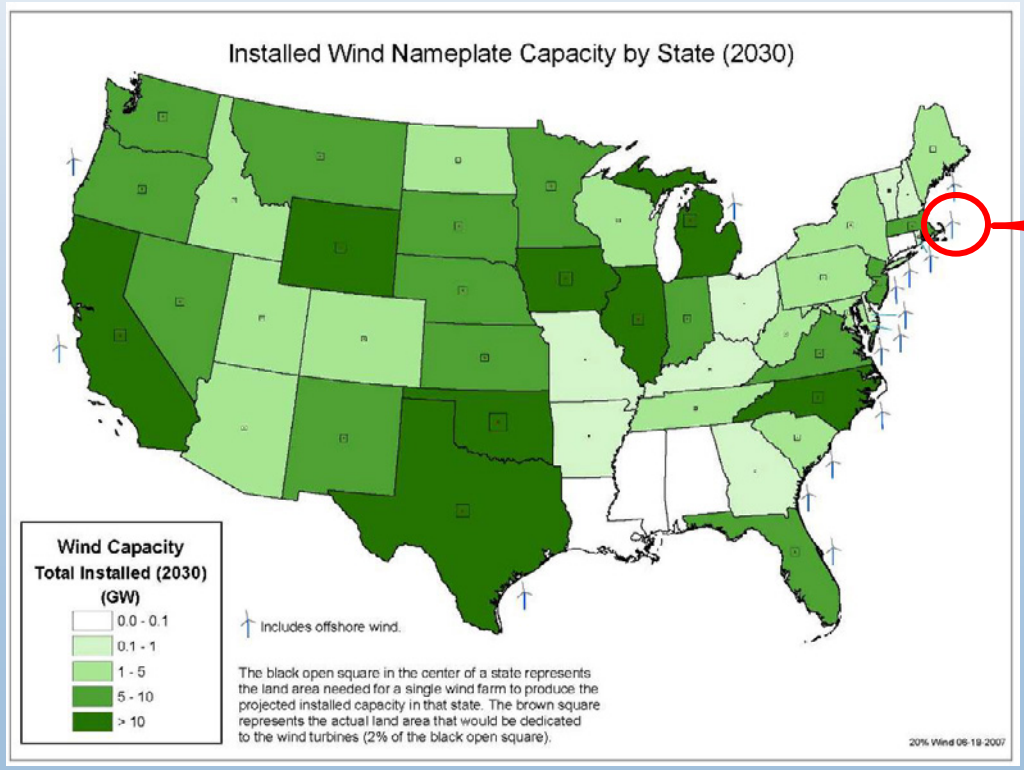
02-FEB-2010 1.1.34

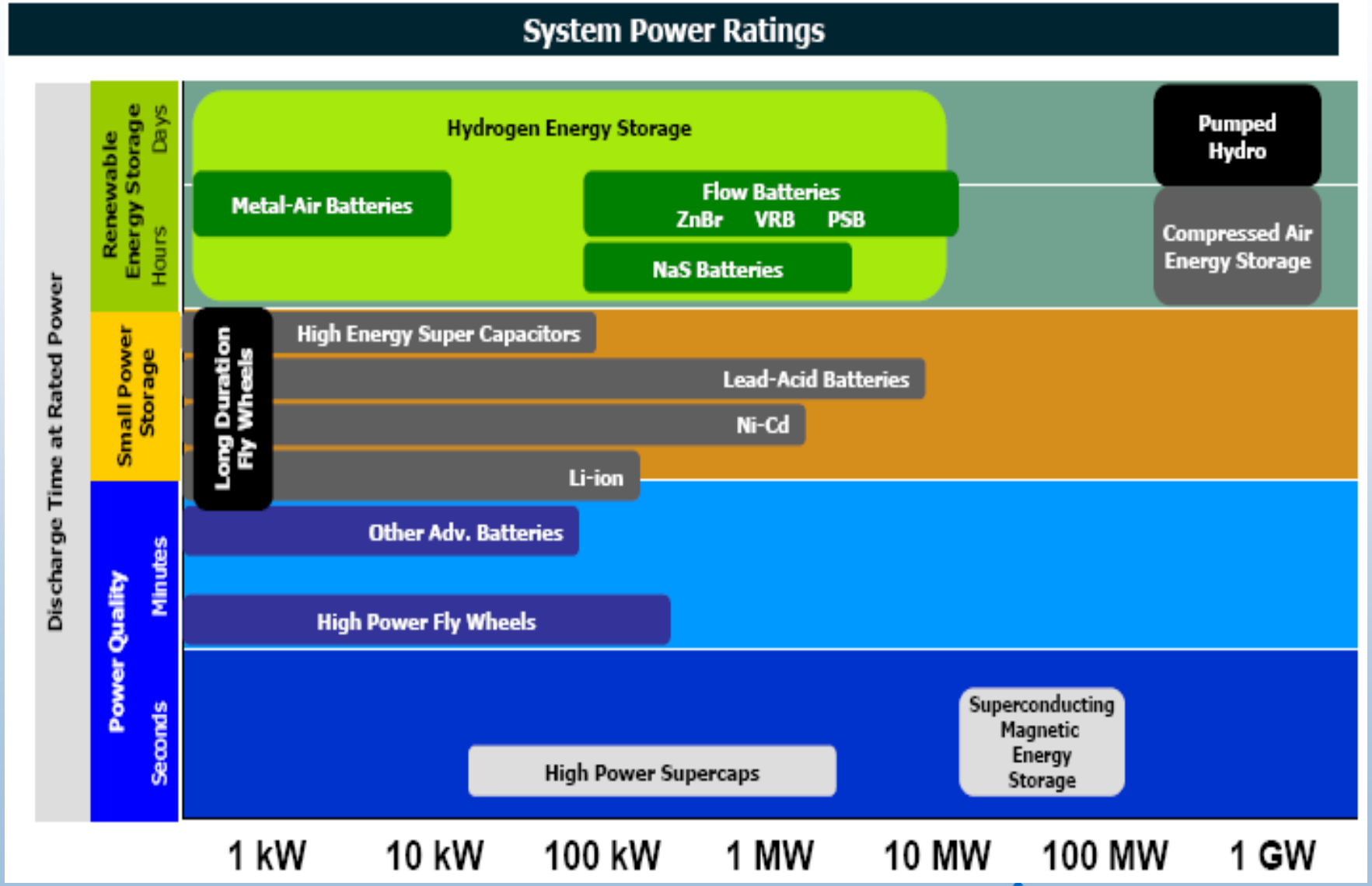




Challenges to 20%

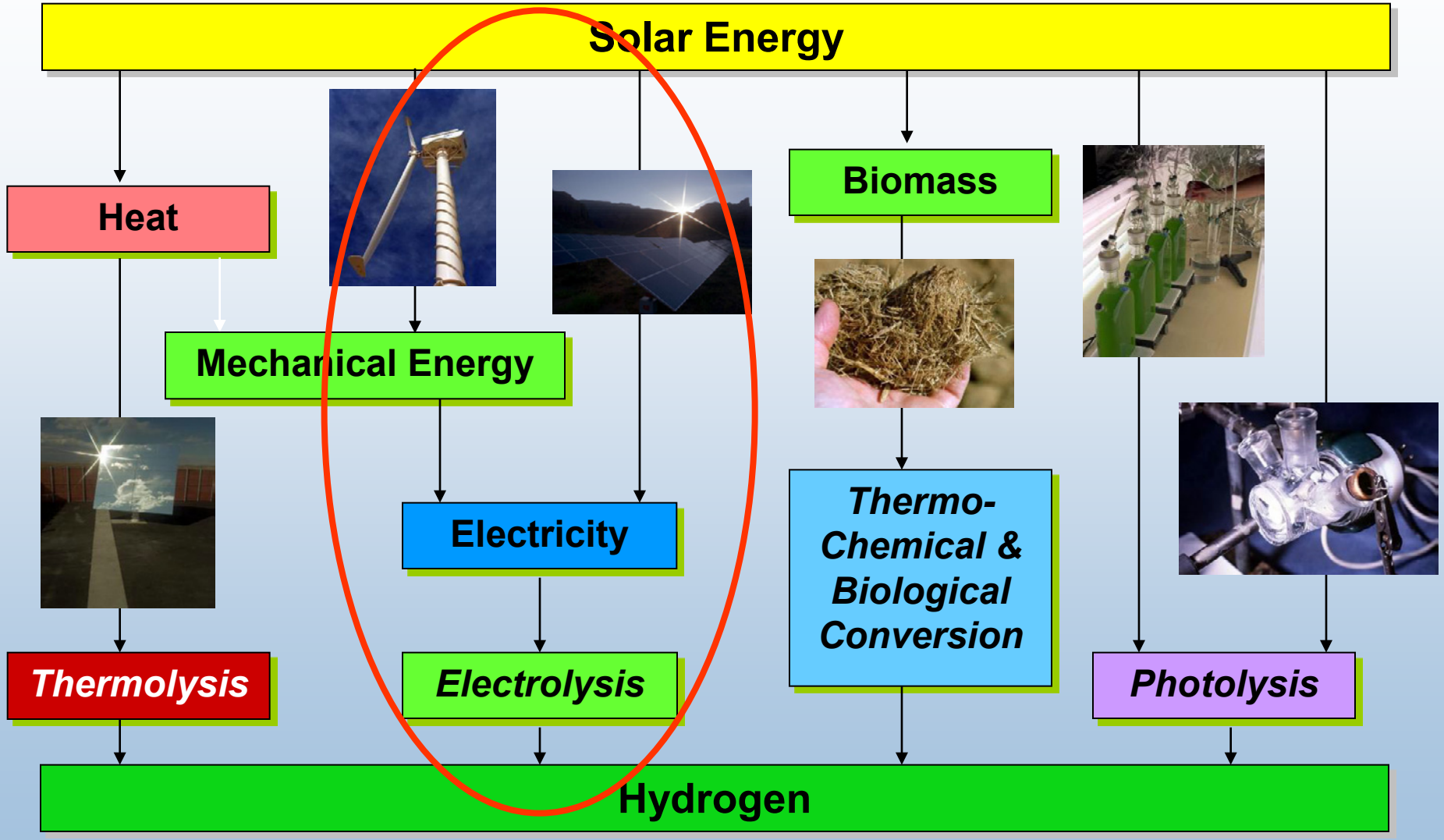
- **Growth in installations**
  - 8 GW installed in 2008
  - 9 GW installed in 2009
  - Total 34 GW 2009
- **50 GW offshore**
  - Cape Wind approved
  - 130 wind turbines
  - 420 MW
- **Performance is critical**
  - Gearbox reliability
  - Capital cost
  - Capacity Factor
  - O&M

Competitive Energy Storage Technologies



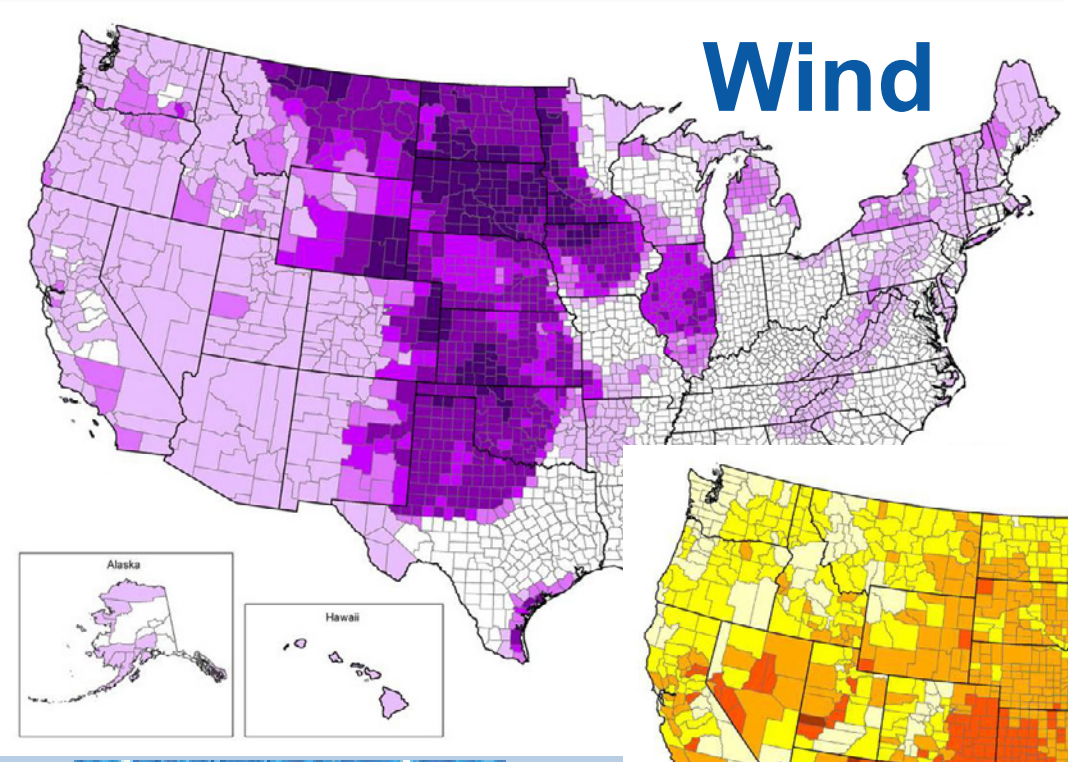
Source: Energy Storage Association

Sustainable Paths to Hydrogen

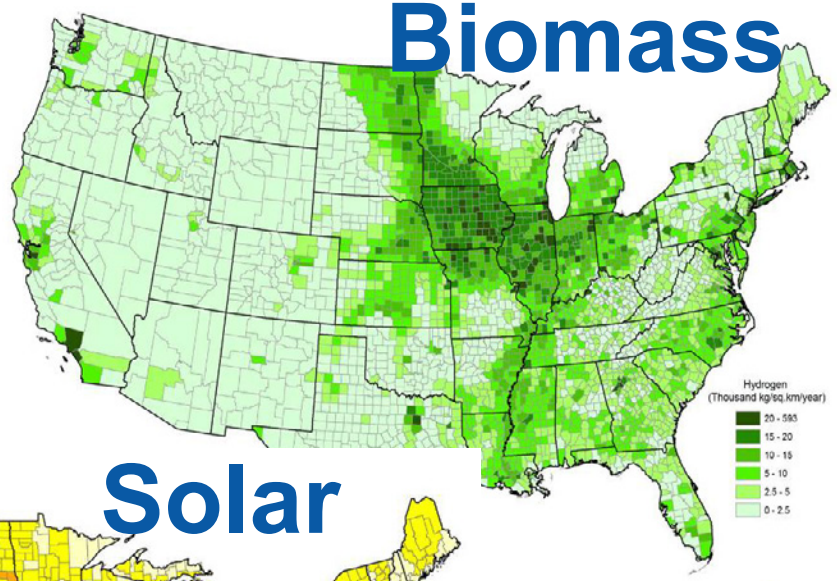


Sustainable Hydrogen Potential

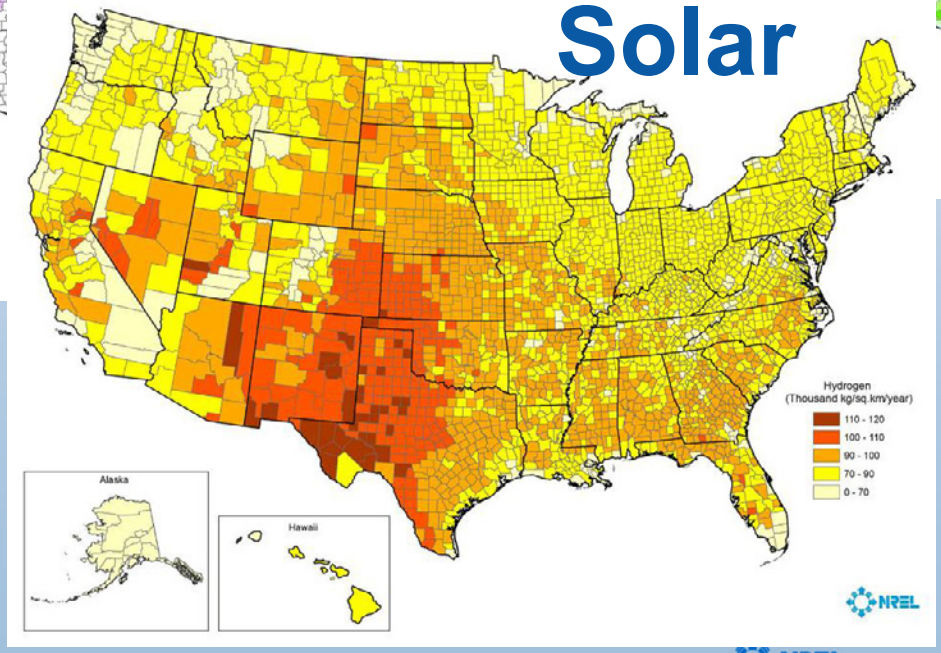
Wind



Biomass



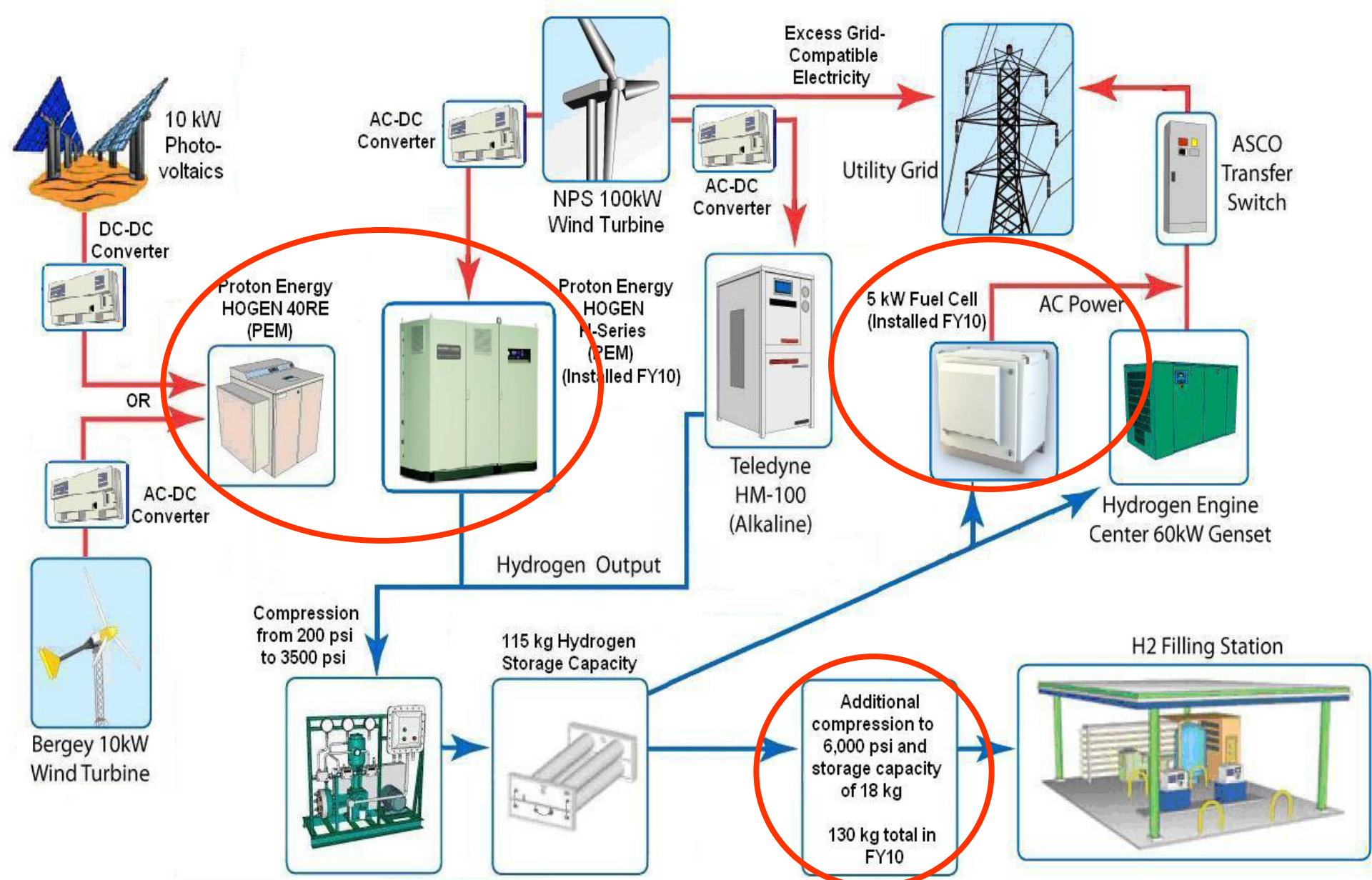
Solar



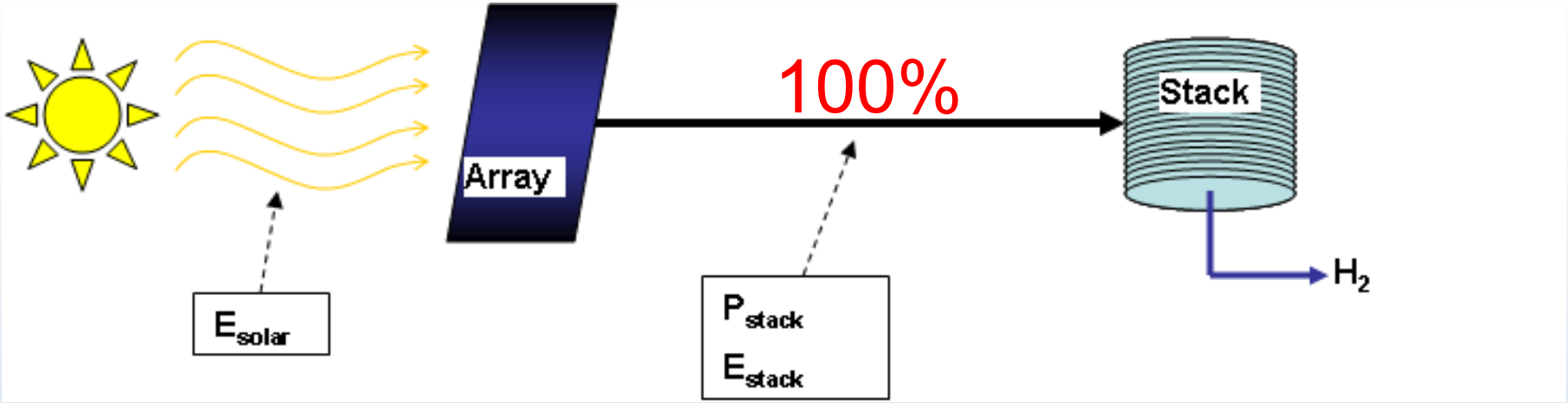
NREL/Xcel Energy
Wind to Hydrogen - Objectives

- Examine benefit to utility by time shifting wind and PV energy with hydrogen production
- Research optimal wind/hydrogen through systems engineering and power electronics integration
- Characterize and control wind turbine/PV and H2-producing stack
- Evaluate synergies from co-production of electricity and hydrogen

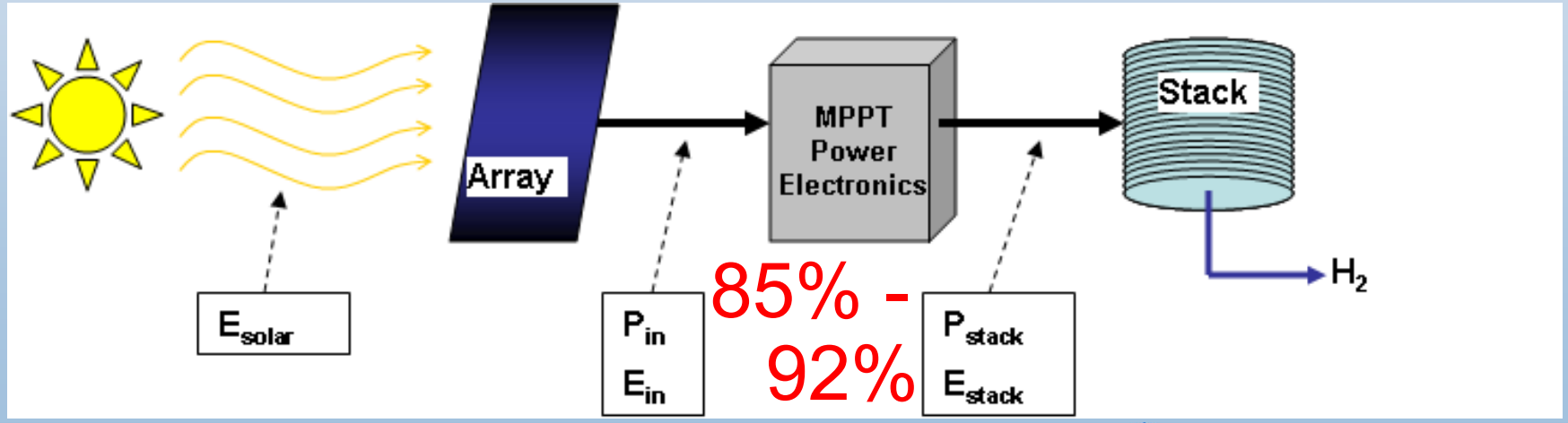
New Wind2H2 Configuration



PV Configuration Testing

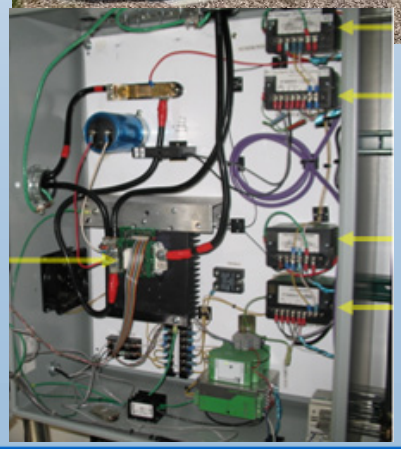


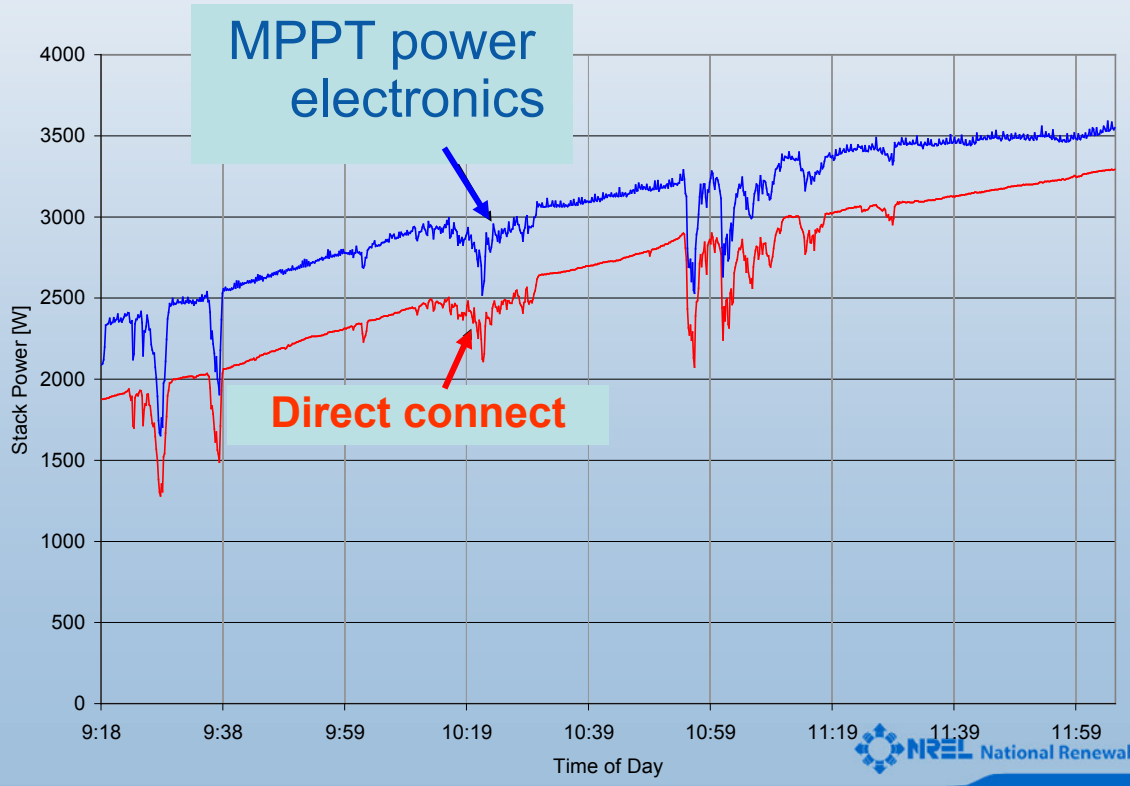
Direct connect versus various input voltages (E_{in}) through power controller



Round I - PV Powered Electrolysis

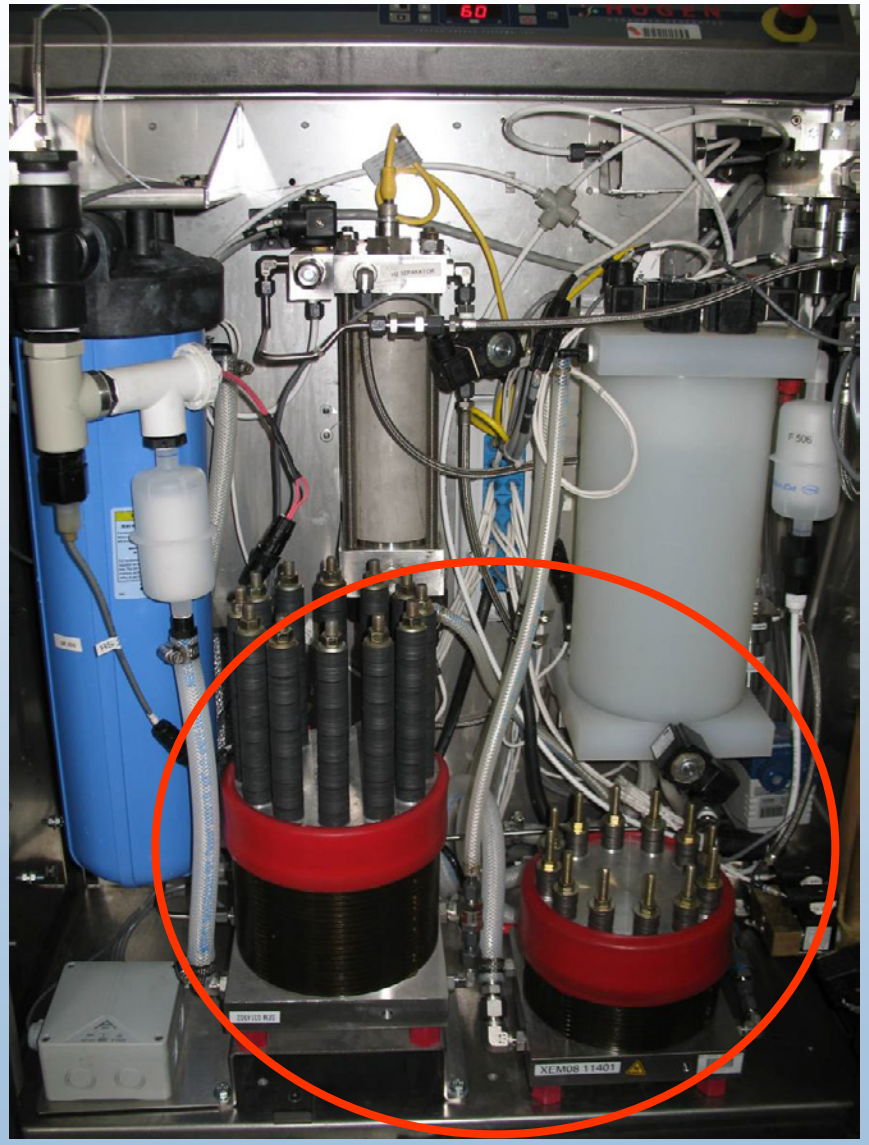
- Onboard power electronics account for 15 – 30% of the overall electrolyzer system cost
- The data illustrates improvement in energy capture to stack when using MPPT power electronics
- Testing showed a 10% – 20% increase in energy capture depending on input voltage to power electronics



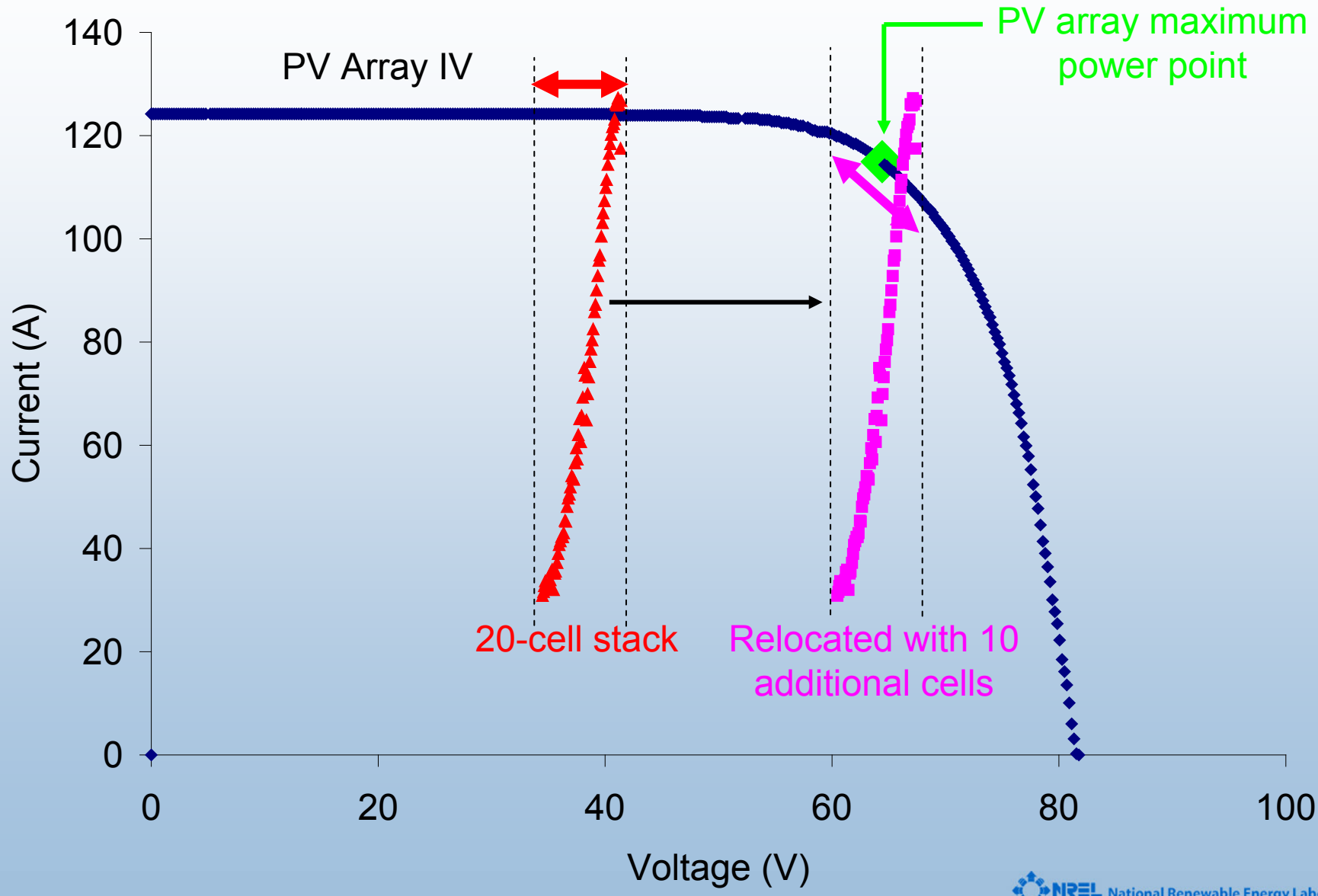


PV-to-Stack Optimization

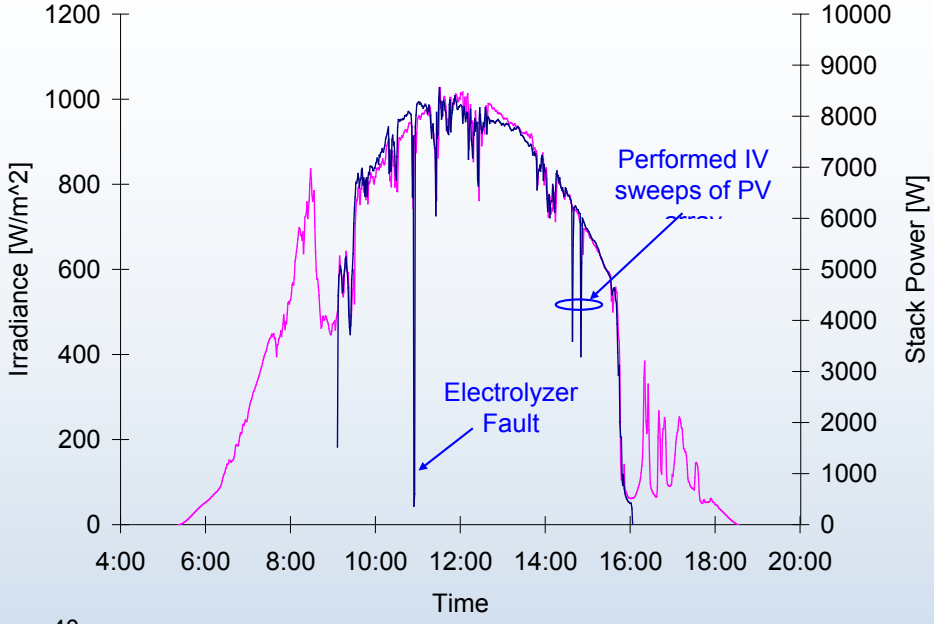
- Installed 10-cell stack in series with existing 20-cell stack to better align PV and stack operating points
- Improved PV-to-stack sizing enabled 2nd phase direct coupling versus MPPT power electronics

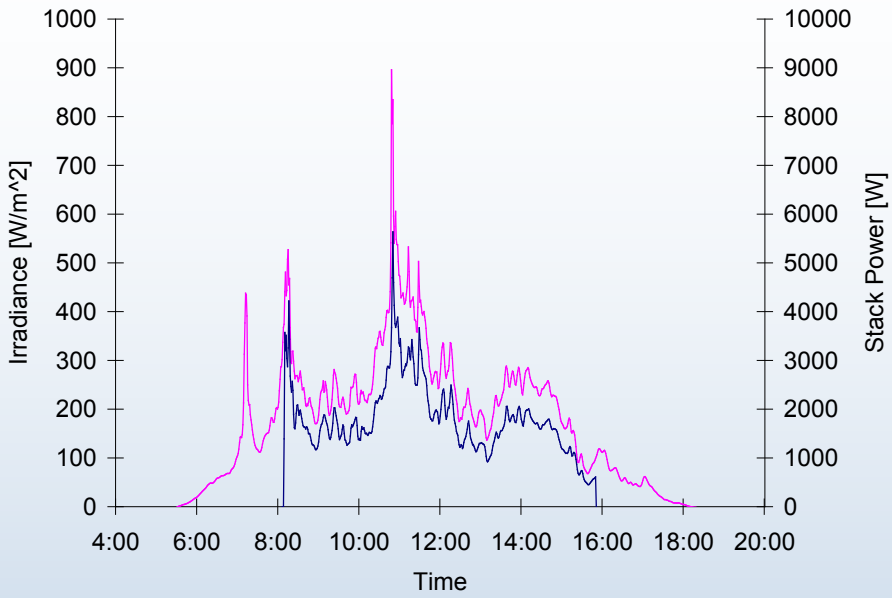


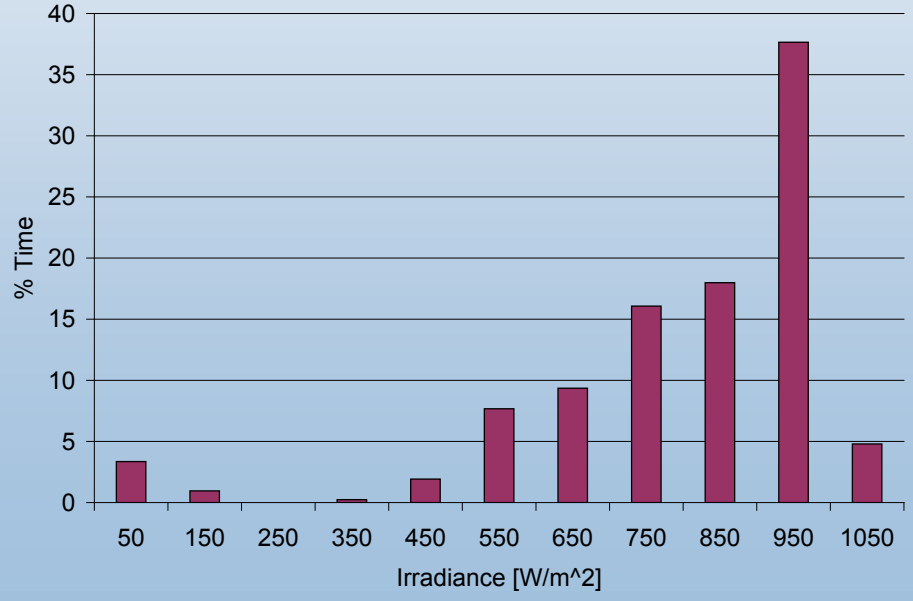
Impact of Shifting Operating Point

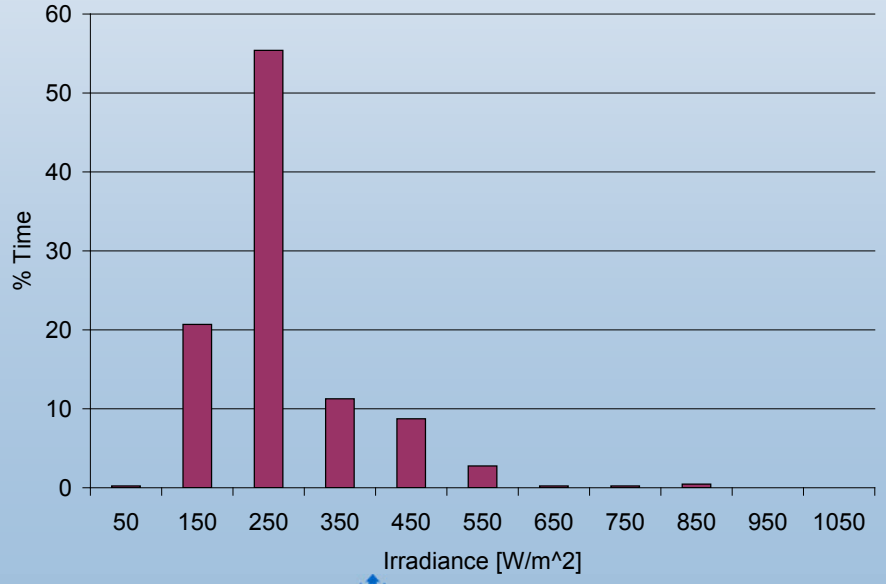


Solar Irradiance

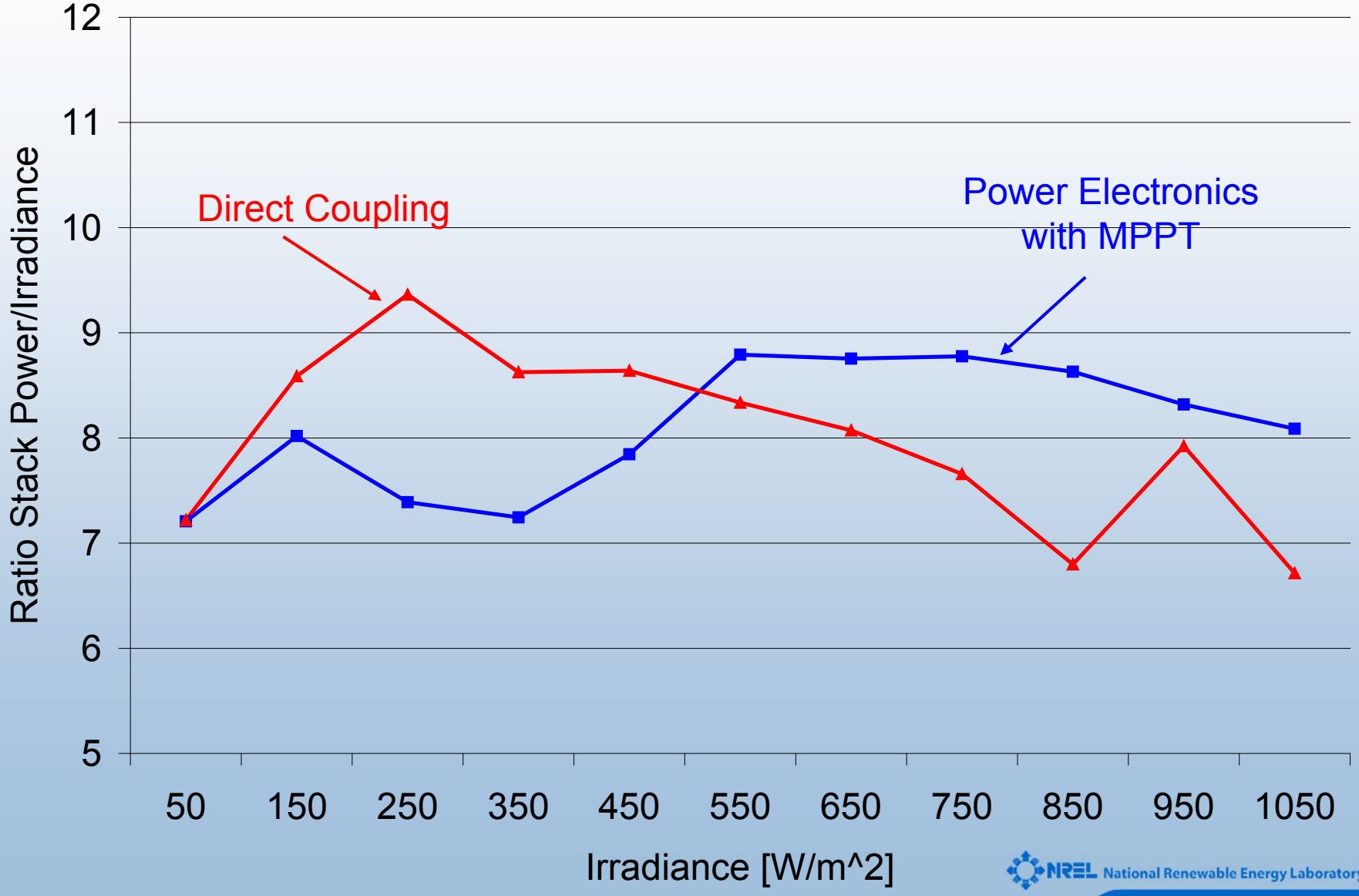




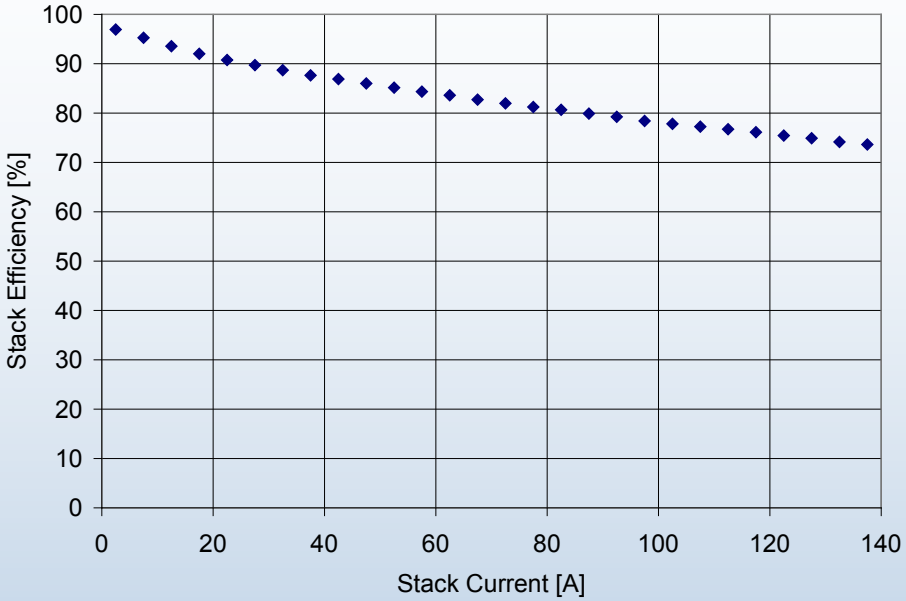




Direct Coupling v. Power Electronics



General Electrolyzer System Data

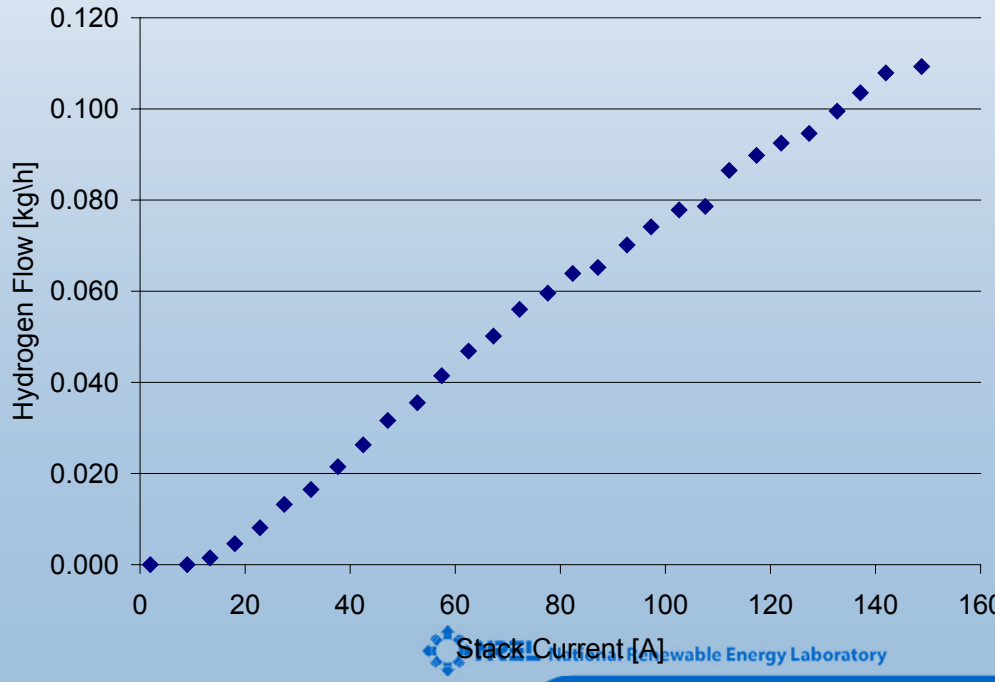


Although stack efficiency is higher at lower current the hydrogen flow (thus system efficiency) is zero at currents below 15 A

Electrolyzer consumes hydrogen to maintain the desiccant drying system

New techniques and incremental improvements in drying systems will improve system efficiency

Higher pressure electrolyzers will dissolve more hydrogen that is also wasted



350 bar Vehicle Fueling System

New System Components

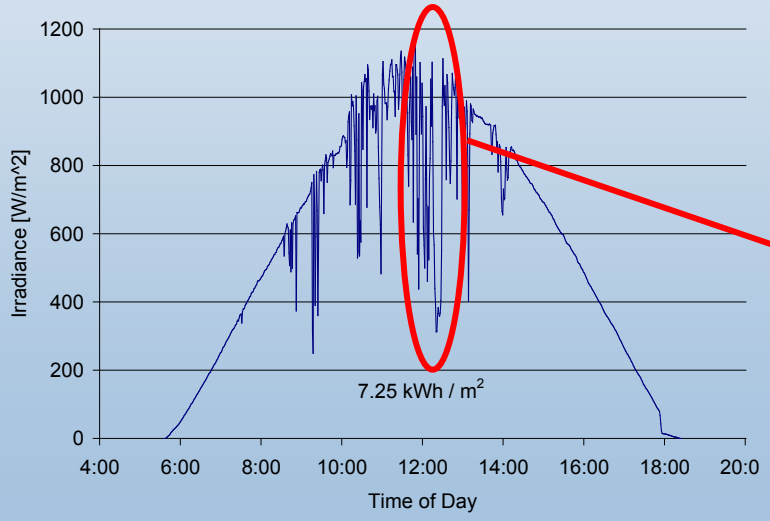
- Storage tank, compressor and dispenser
  - 18 kg @ 6000 psi
  - 120 kg @ 3500 psi
- June 2010
  - Additional 6000 psi storage
  - Cascade filling
  - Total 250 kg (including 3500 psi tanks)
- 9 months of refueling A-Class Mercedes (~2 kg, 110 miles)
- Proterra Fuel Cell Bus
  - March 2010, 20 kg
- Yesterday, Ford H2 ICE shuttle leased by NREL

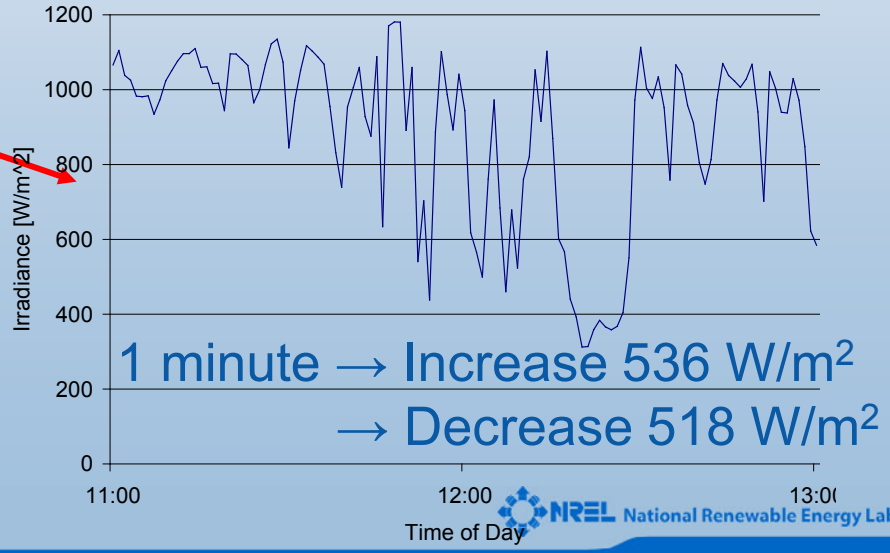
Integrated Renewable Energy System

Integrated Systems

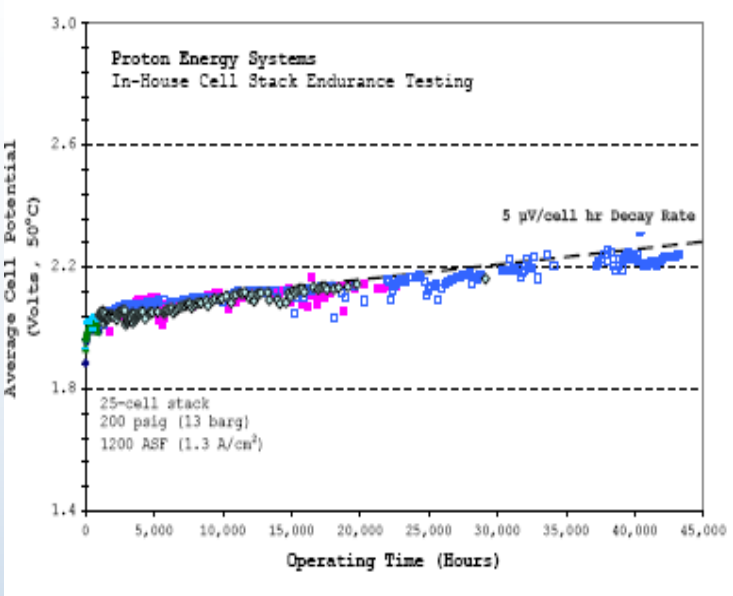
- 5 kW fuel cell (PEM)
- 5 kW to 10 kW PV array
- 10 kW wind turbine

TEST: Dynamic response (both DC and AC) of fuel cell with both PV and wind systems





Variable Stack Current Testing



Comparison Testing

PEM: 3-stack design with Individual power supplies

Alkaline: New stack installation

Test: Long duration testing of stacks with highly variable (wind profile) current

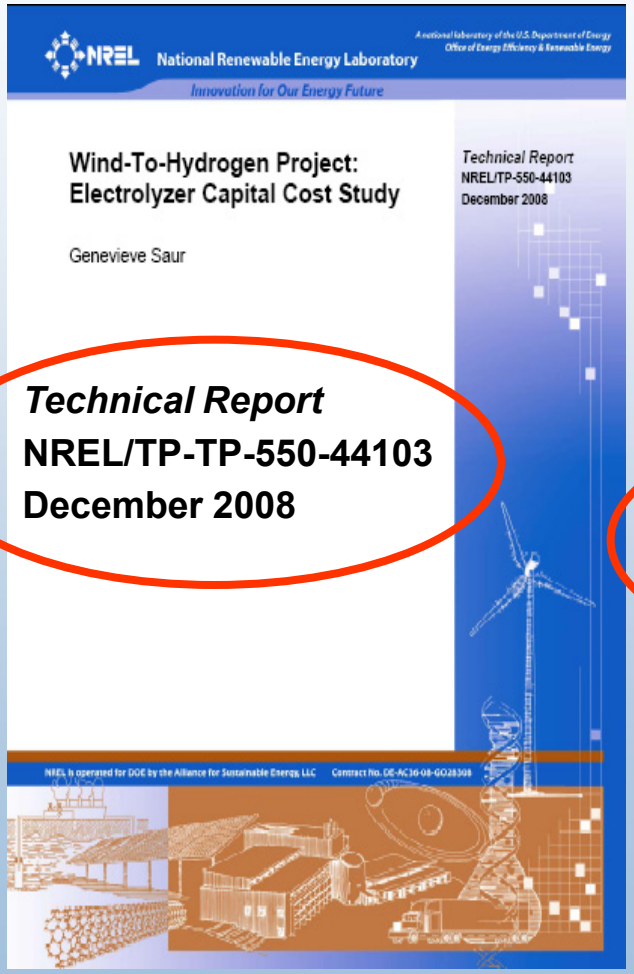
WIND ENERGY & HYDROGEN INTEGRATION

International Energy Agency, Hydrogen Implementing Agreement, Annex 24

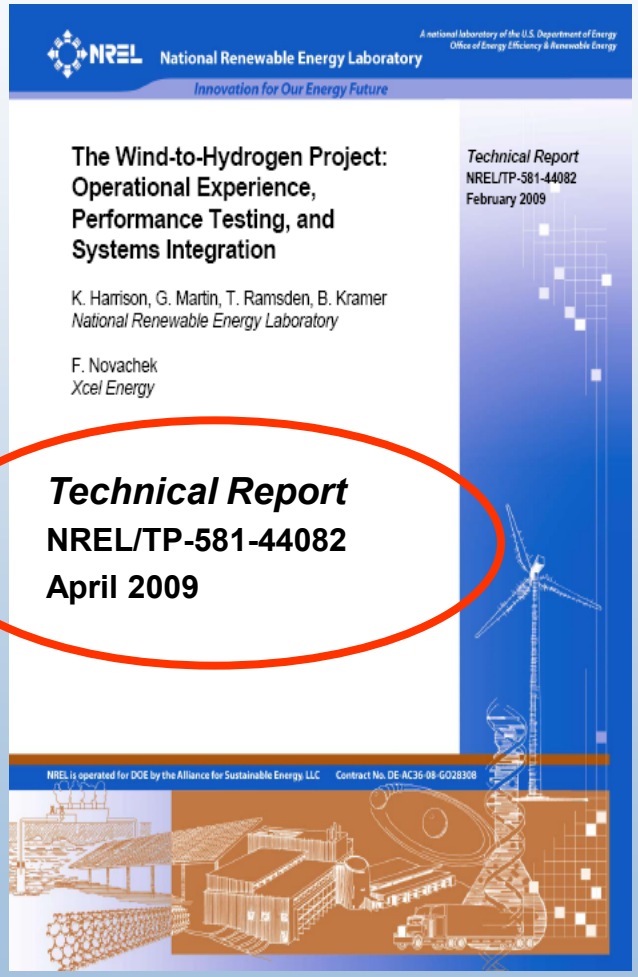
To explore in detail all possible issues (technical, economical, social, environmental, market and legal) related to hydrogen production using electrolysis with wind energy.

Recent Publications

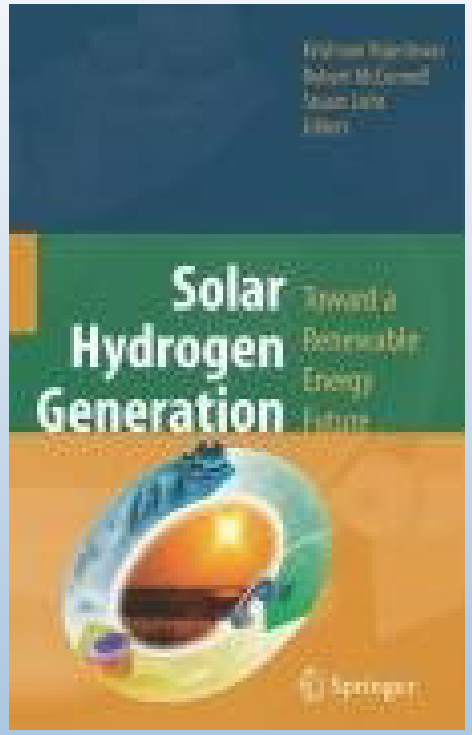
http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html



Technical Report
NREL/TP-TP-550-44103
December 2008



Technical Report
NREL/TP-581-44082
April 2009



Thank you for your attention!

Questions?