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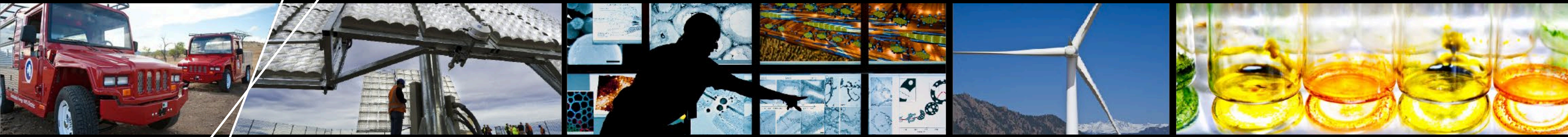
Analytic Methods for Benchmarking Hydrogen and Fuel Cell Technologies



227th ECS Meeting, Chicago, Illinois

Marc Melaina, Genevieve Saur, Todd Ramsden, Joshua Eichman

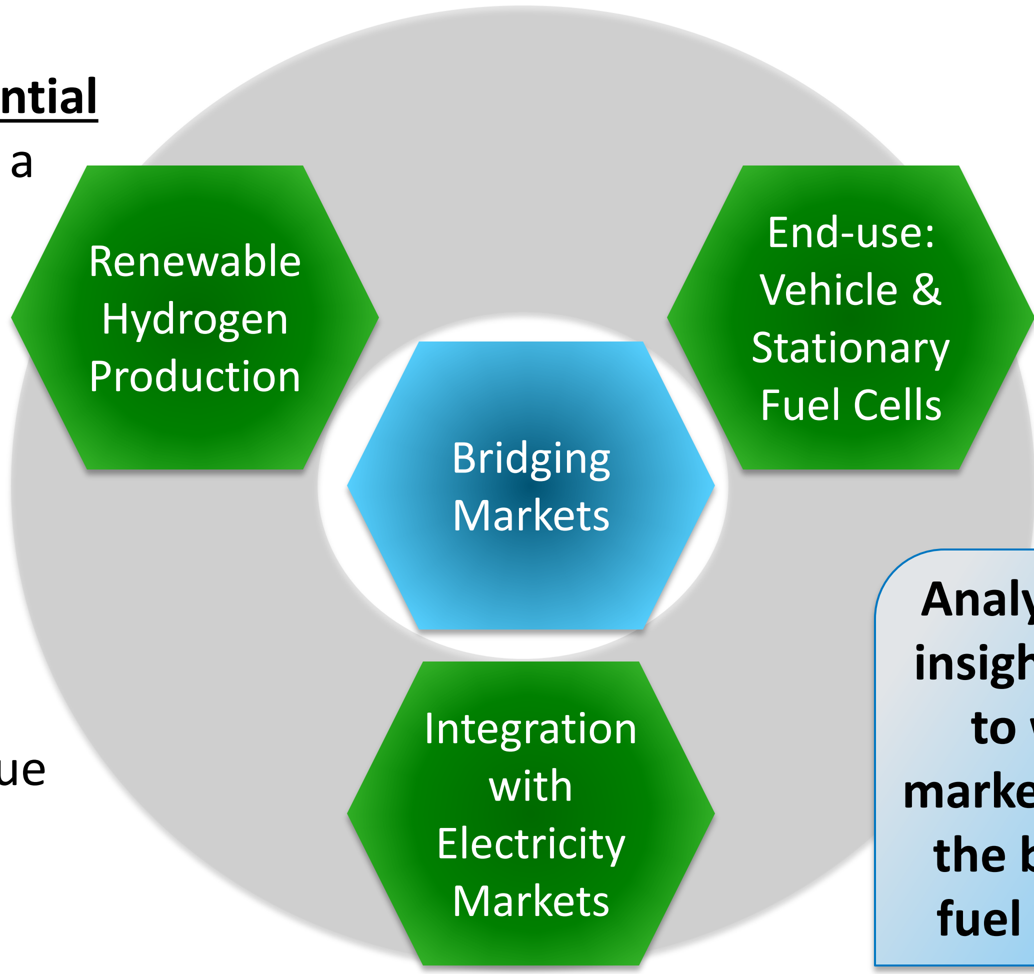
May 28, 2015

NREL/PR-5400-64420

Presentation Overview: Four Metrics

Analysis projects focus on low-carbon and economic transportation and stationary fuel cell applications

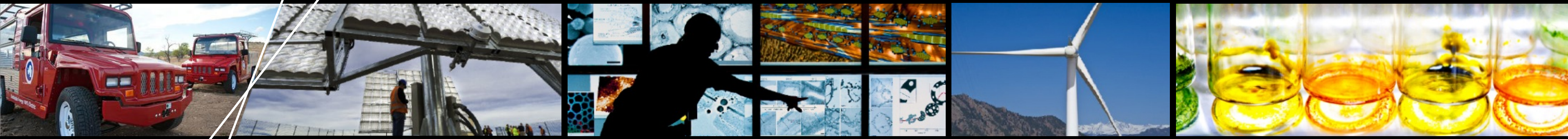
<u>1. Resource Potential</u>
Renewables, and a focus on biogas



<u>2-3: GHGs & Costs</u>
- Hydrogen for FCEVs
- Evaluation of stationary fuel cells

<u>4. Grid Services</u>
Estimating revenue streams for electrolysis units

Analysis tools provide insight into the degree to which bridging markets can strengthen the business case for fuel cell applications



Resource Potential

Resource Potential

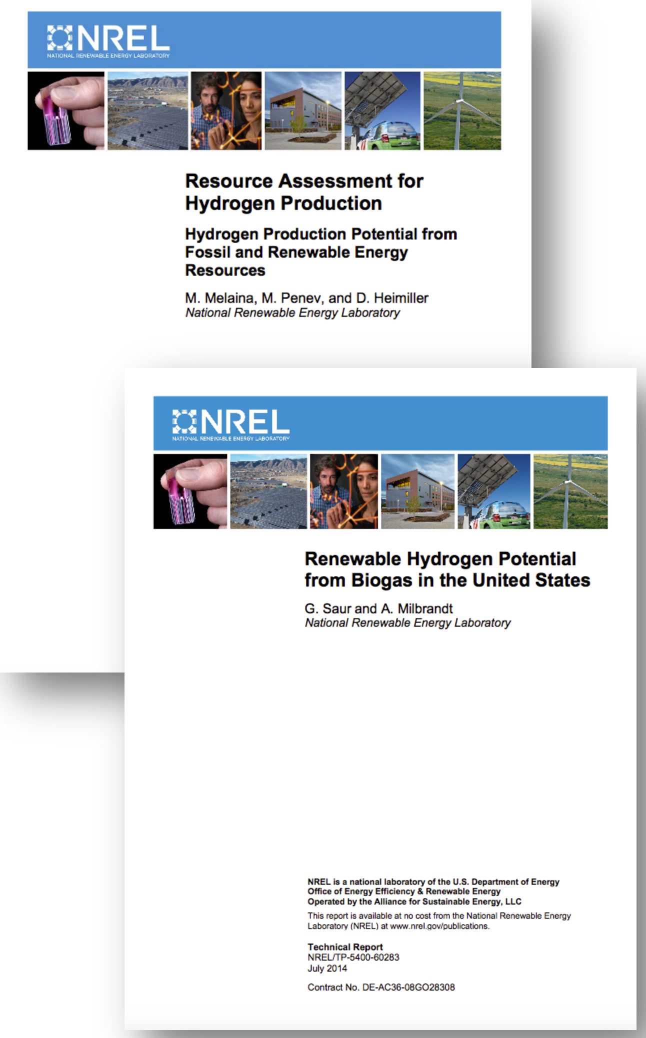
Objectives

Quantify energy resources for hydrogen production

- Alternatives to conventional sources of hydrogen (e.g., natural gas)
- Hedges again fluctuating costs and demand for fossil fuels
- Assist compliance with state policies for renewable fuels
- Shift to low-carbon energy resources

Technical Reports

- ➢ Melaina, M.; Penev, M.; Heimiller, D. (2013). Resource Assessment for Hydrogen Production: Hydrogen Production Potential from Fossil and Renewable Energy Resources. Golden, CO, NREL: NREL/TP-5400-55626.
- ➢ Saur, G.; Milbrandt, A. (2014). Renewable Hydrogen Potential from Biogas in the United States. Golden, CO, NREL: NREL/TP-5400-60283
- ➢ Milbrandt, A.; Bush, B; Melaina, M. (2015). Biogas and Hydrogen Systems Market Assessment. Forthcoming.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Resource Assessment for Hydrogen Production

Hydrogen Production Potential from Fossil and Renewable Energy Resources

M. Melaina, M. Penev, and D. Heimiller
National Renewable Energy Laboratory

NREL
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Renewable Hydrogen Potential from Biogas in the United States

G. Saur and A. Milbrandt
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5400-60283
July 2014

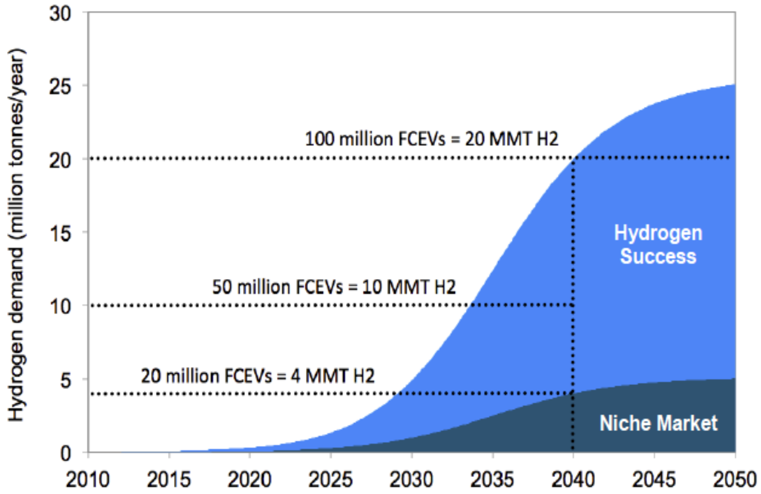
Contract No. DE-AC36-08GO28308

Pressure on resource use

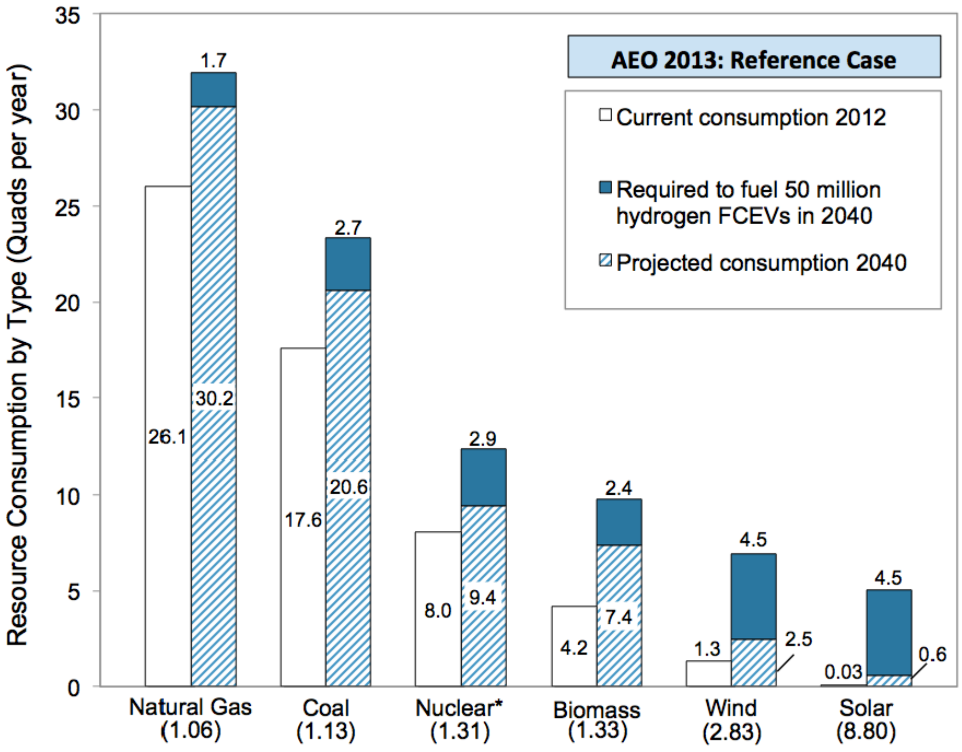
Assuming particular future market adoption of FCEVs, we estimating marginal pressure on energy resource use

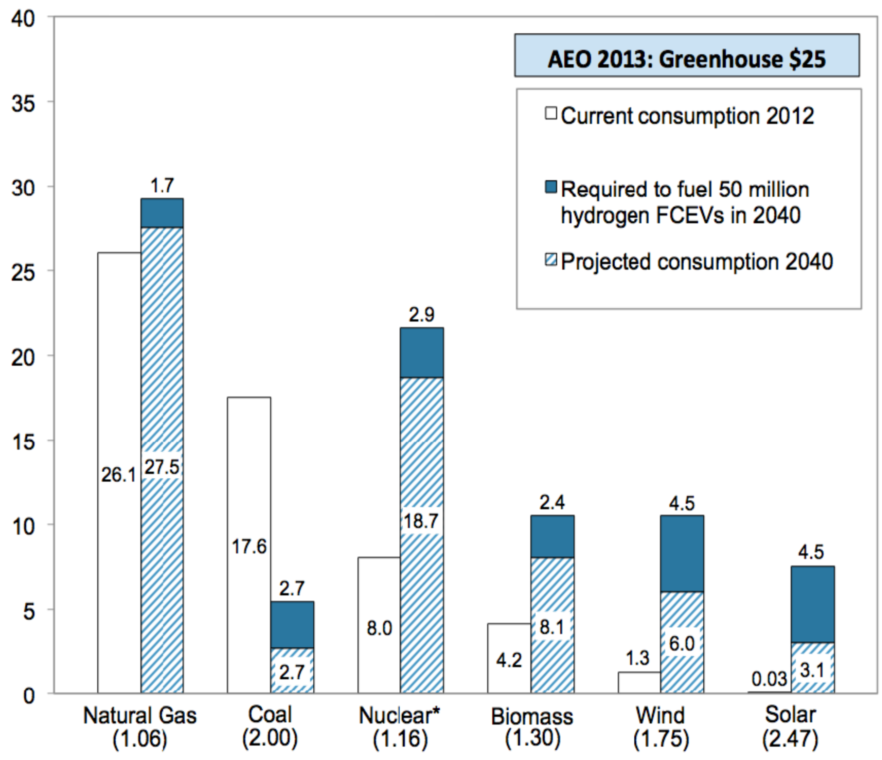
- Reference case (AEO 2013)
- “Low carbon” case (AEO 2013)

2040 Demand: 50 M FCEVs, 10 MMT H2



(Melaina et al. 2013)

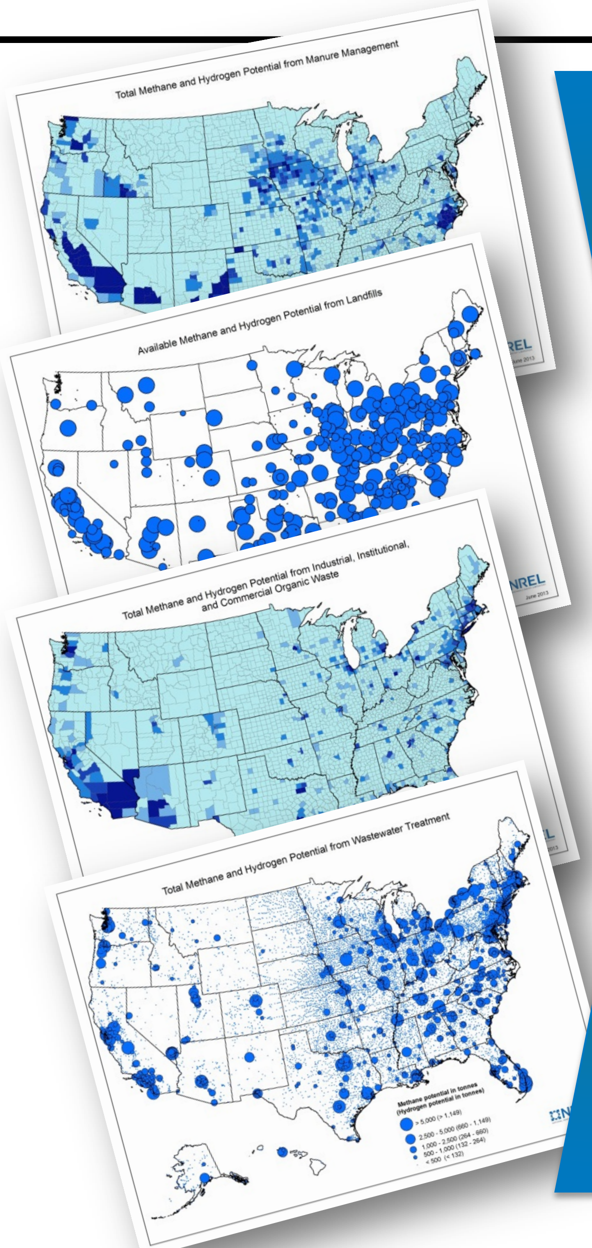




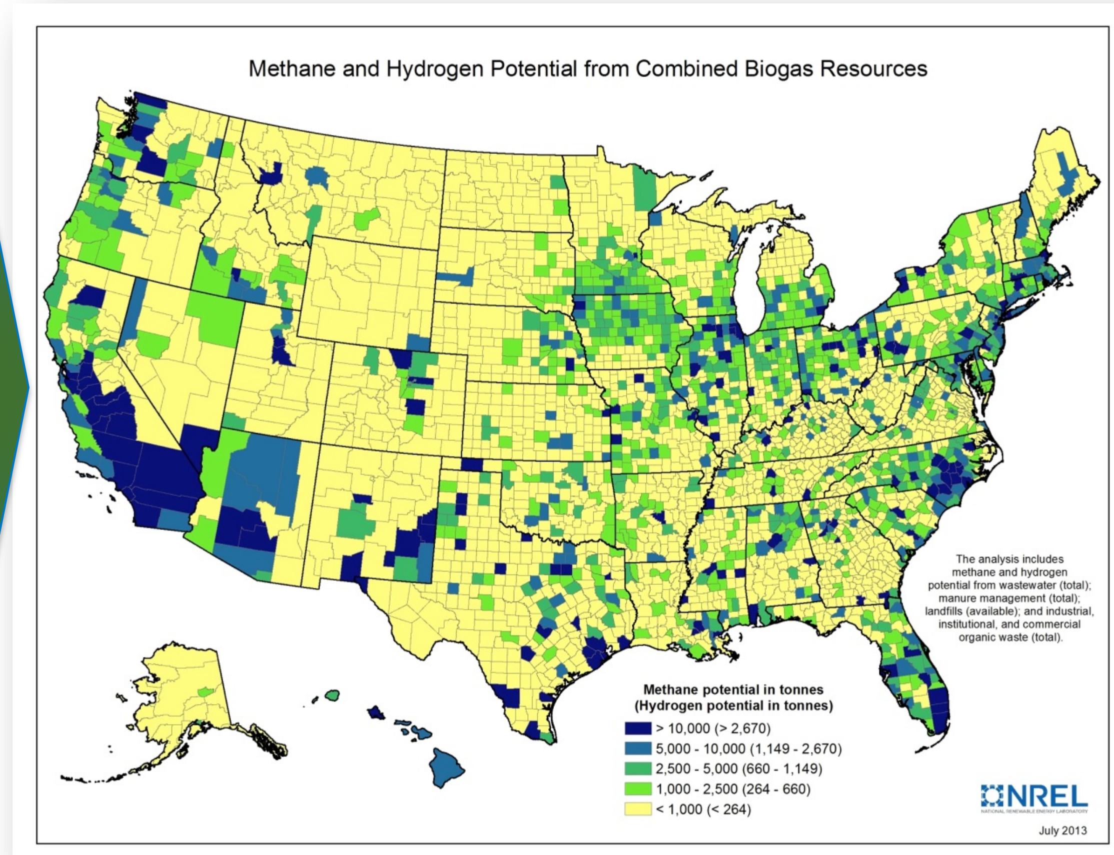
Resource Potential – Analysis Process

- **Biogas (methane) resource assessment**
  - Waste water treatment plants (WWTP)
  - Landfill gas (LFG)
  - Animal manure
  - Industrial sources and organic food waste
- **Net availability**
  - Estimated based on currently known applications
- **H_2 from biogas**
  - Conversion by steam methane reforming (SMR)
- **Vehicles Supported**
  - Use of 2020 medium case projection of fuel cell electric vehicles (FCEV) fuel efficiency
- **Final products**
  - US maps - national and regional
  - Tabular estimates – national, regional, top sources
  - FCEV supported
  - Final report

Resource Potential – Geographically Refined



Individual resource maps can be aggregated for total potential.

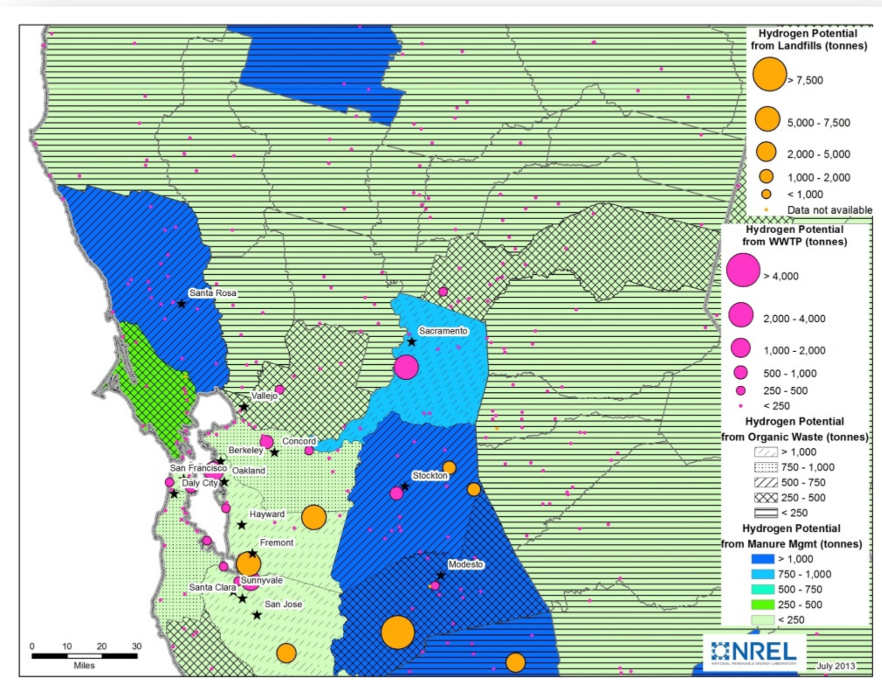


(Saur, Milbrandt 2014)

Resource Potential – Local level

Understanding the distribution of resources on a local level can help characterize challenges and opportunities for different communities.

Example – Sacramento, CA

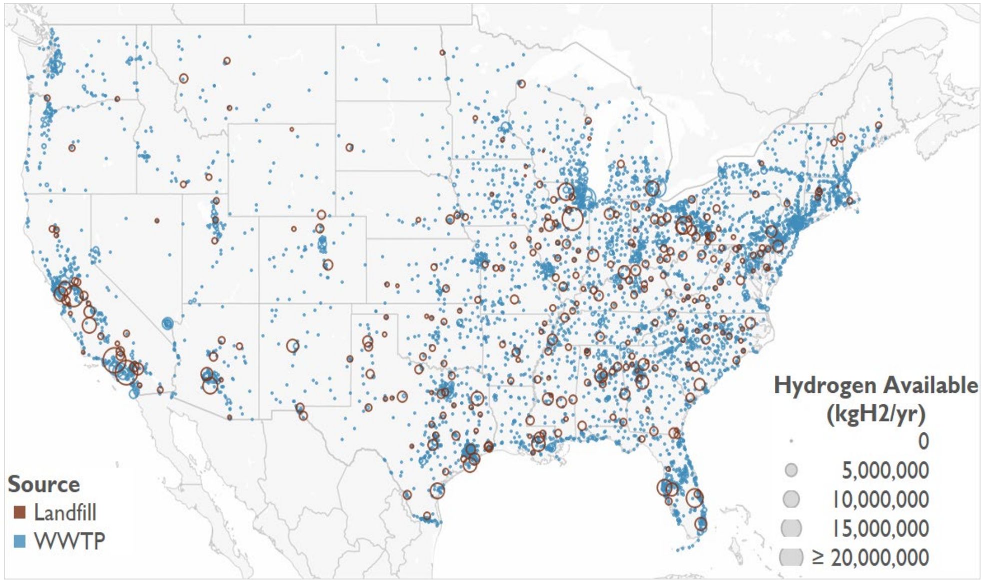


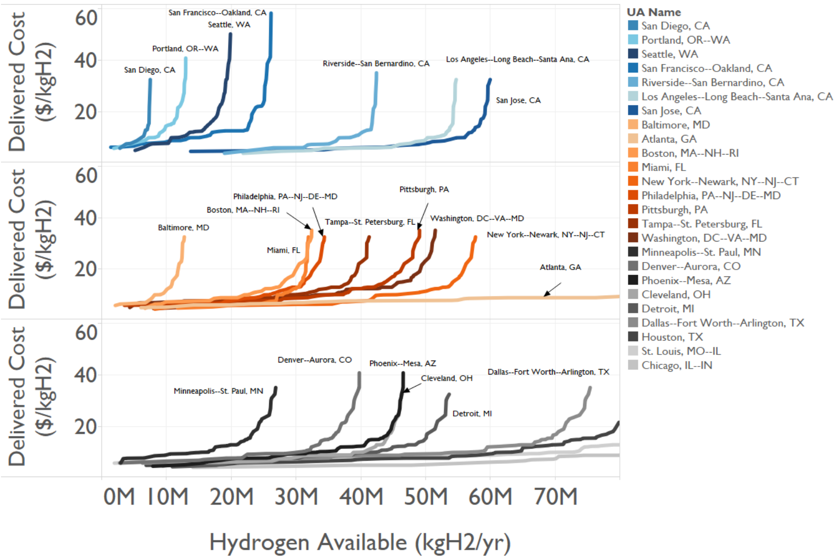
Source	H2 Potential (tonnes)	FCEVs Supported (thousands)	Counties
WWTP	11,800	66.8	39
Landfills	34,700	196.2	5
Animal Manure	34,500	194.9	29
Industrial Institutional Commercial	12,300	69.4	34
Total	*93,300*	*527.3*	*41*

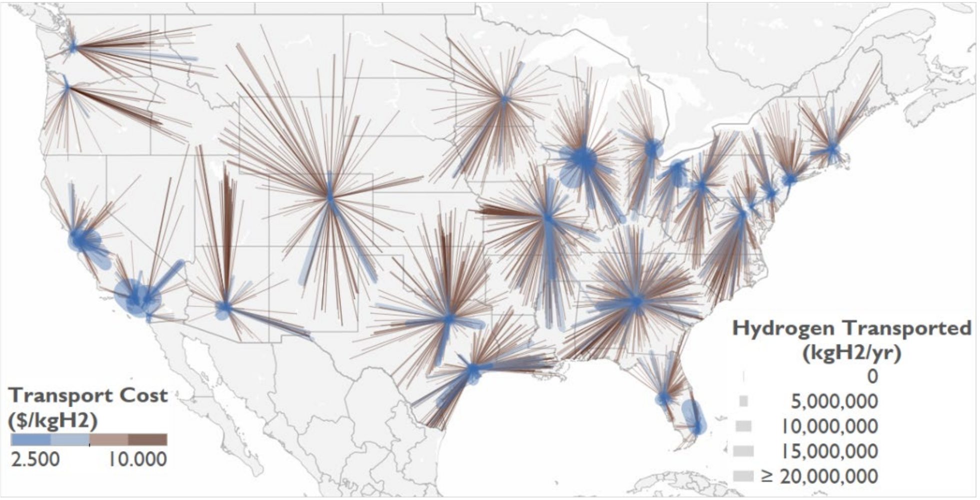
(Saur, Milbrandt 2014)

Supply curves for biogas to hydrogen

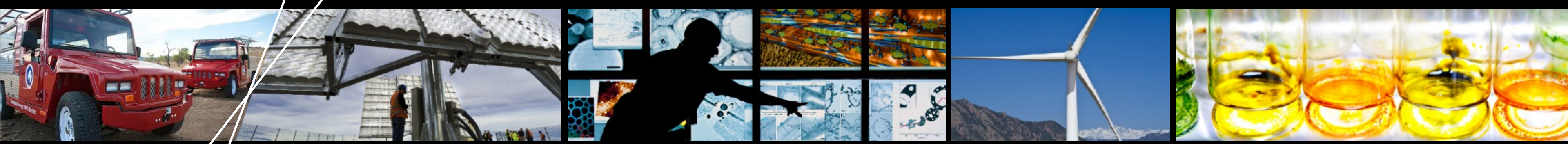
- Delivery cost included for major urban areas
- Total delivered cost by city & region shown in graph below
- Significant variability by region
- Potential to increase economies of scale by combining multiple sources or direct pipeline injection







PRELIMINARY RESULTS (Milbrandt et al. 2015)



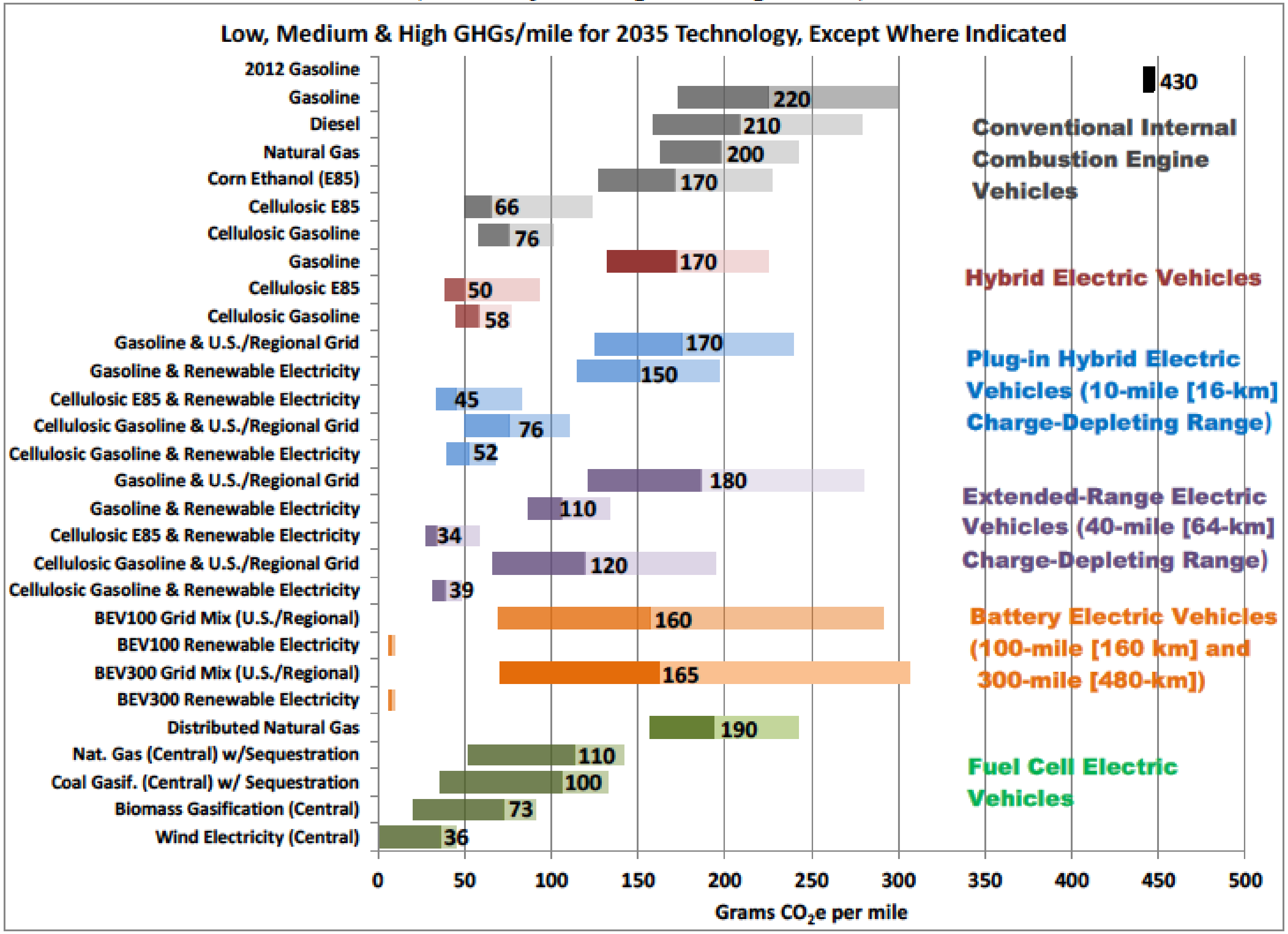
Greenhouse Gas Emissions and Cost of Delivered Energy

GREET lifecycle GHG emissions by vehicle-fuel

Low/medium/high: sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.

Potential for very low GHGs

Figure 1. Well-to-Wheels Greenhouse Gases Emissions for 2035 Mid-Size Car
(Grams of CO_2-equivalent per mile)



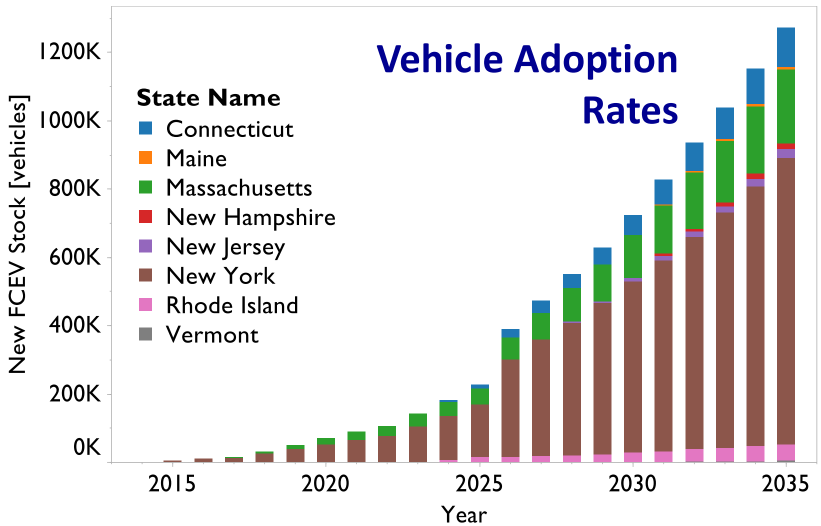
Nguyen, Ward, Johnson 2013. http://www.hydrogen.energy.gov/program_records.html

Detailed geo-temporal costs from the Scenario Evaluation and Regionalization Analysis (SERA) Model

- The SERA model can generate a large volume of scenario results
- Production sources can be networked over time to supply multiple end-use demand centers
- SERA can disaggregate national scenarios, such as from National Academies

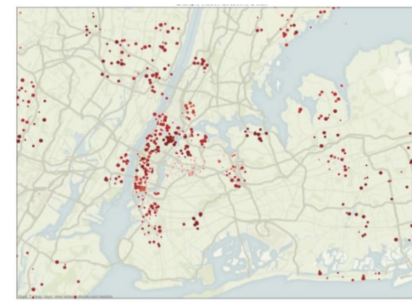
Demand and Delivery by City

Regional/State-level Subsets of Results

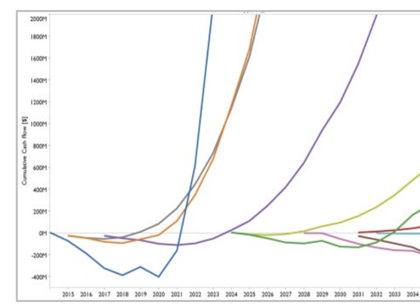


Stand-alone reports cannot capture the full range of possible outputs

Station Placement

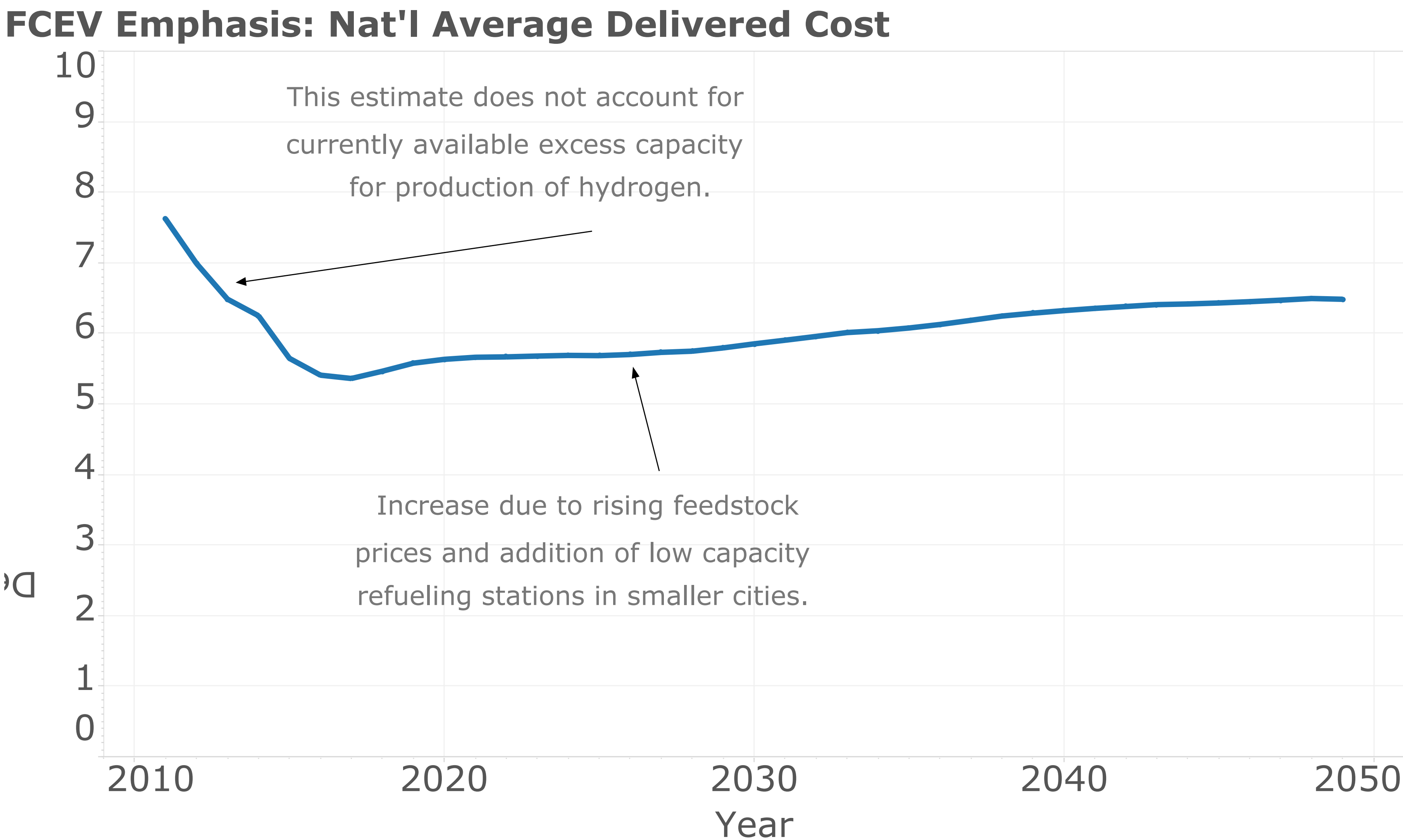


Cash Flows



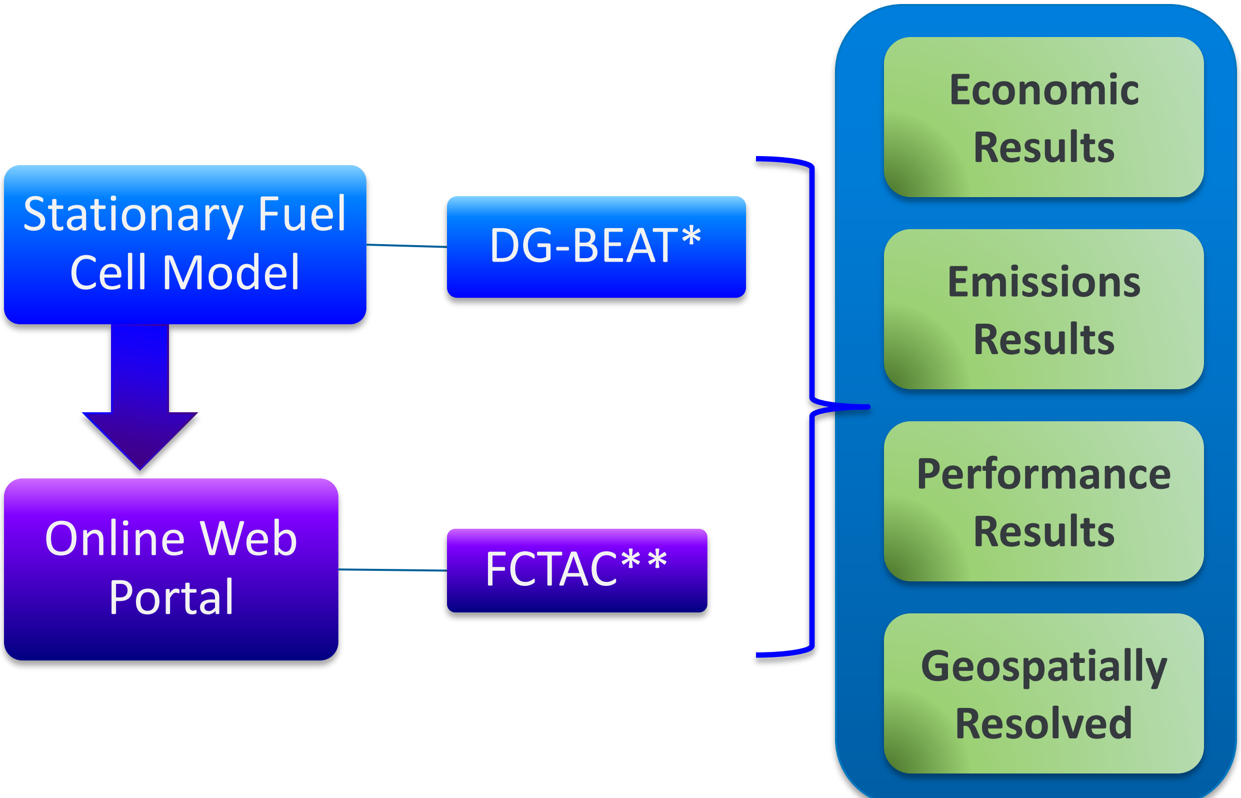
Internal consistency allows for examination of multiple physical and financial metrics across multiple markets and over time

Average national hydrogen Costs from SERA



Stationary Fuel Cell Integration and Control

Objective: Creation of tools that will enable research and advocacy of the benefits of stationary fuel cells as a component in a modernized energy infrastructure and aid early market growth for the industry.



The results can examine:

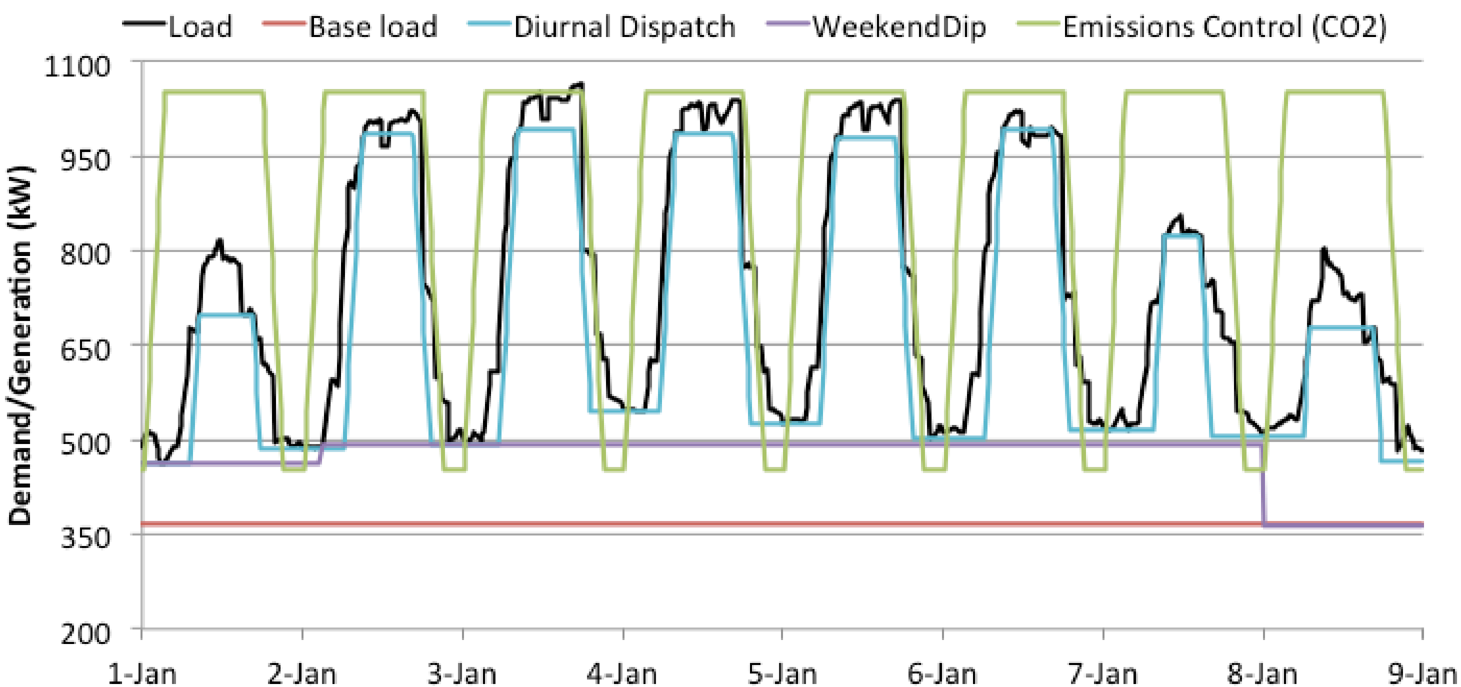
- FC sizing
- FC controls
- Regional cost implications
- Regional emissions
- Real or ideal building profiles
- Assess building or campus
- Inform market potential

* **D**istributed **G**eneration – **B**uild-out **E**conomic **A**ssessment **T**ool

** **F**uel **C**ell **T**ool for **A**ssessing **C**osts

DG-BEAT: Fuel Cell Dispatch and Sizing

- Currently 5 FC dispatch strategies and 4 FC sizing strategies
- Additional optimizations envisioned for both sizing and operations

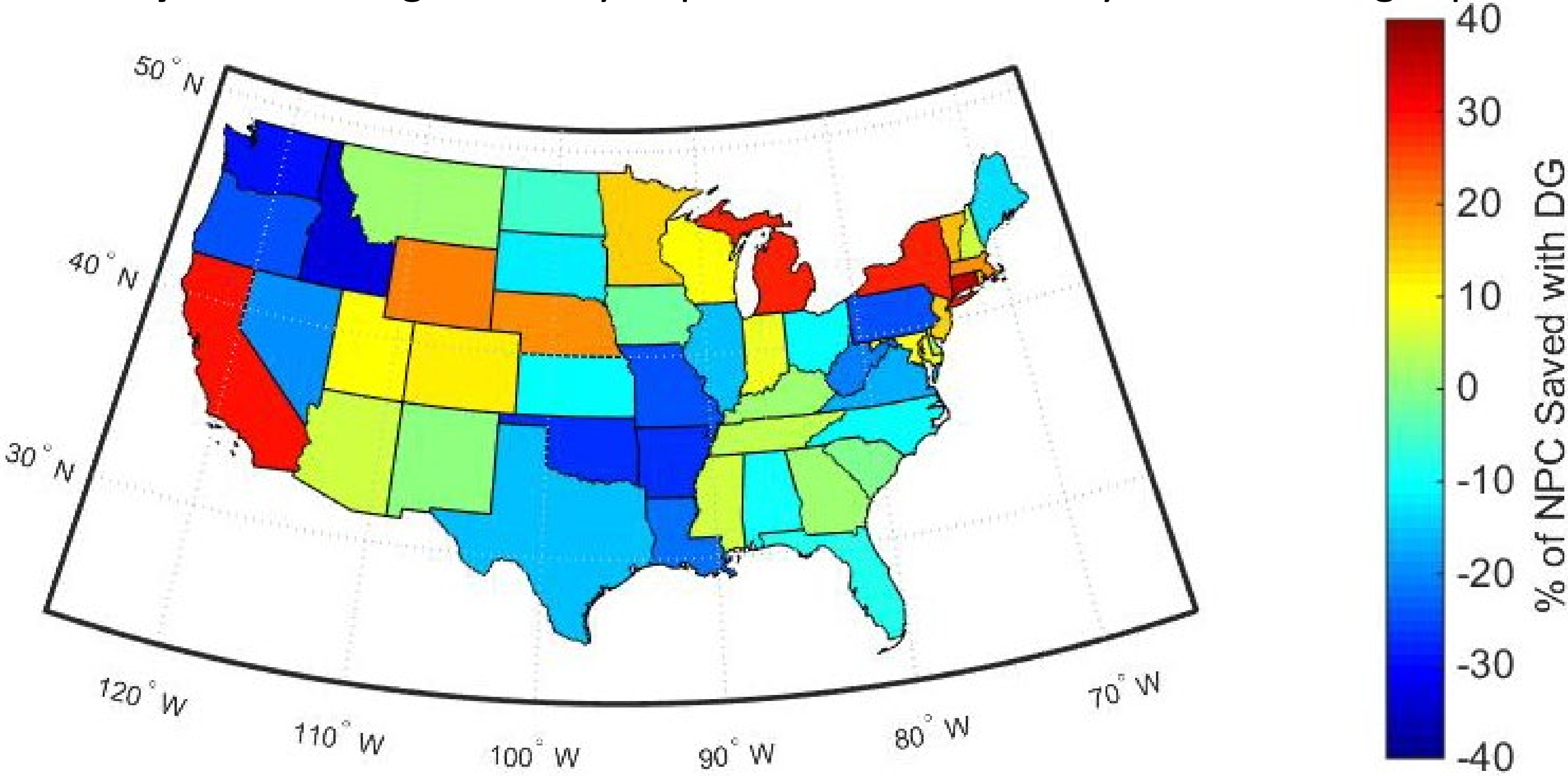


- **5 FC dispatch strategies**
- **4 FC sizing options**
  - Fixed size: User specified
  - 100% size: Sized to meet ≈ peak summer demand (ignores outliers 2% of points)
    - Dependent on FC dispatch strategy chosen
  - Cost optimal size: Iterates between base load size and 100% size to find the best NPV*
  - Emissions optimal size: Iterates to find the lowest net annual emissions

* Net present value

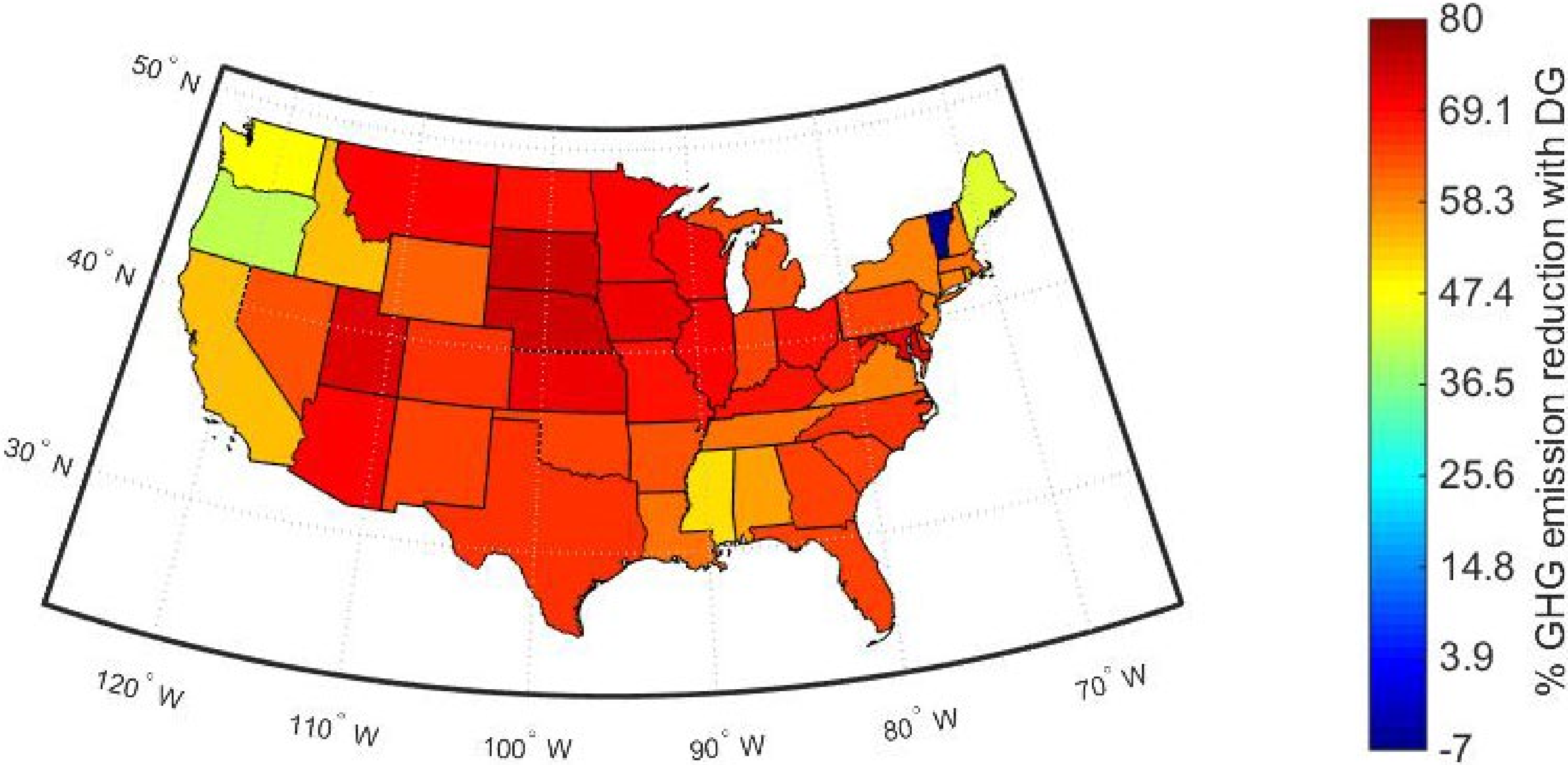
DG-BEAT: Example National Survey—Cost

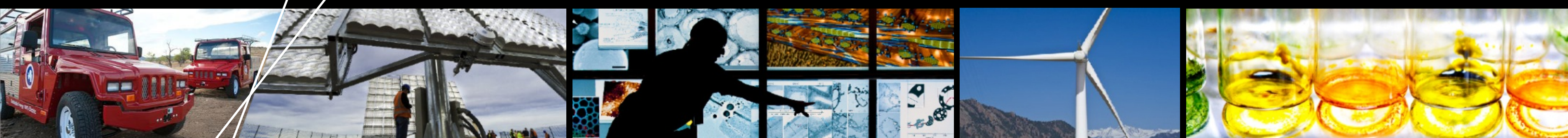
- **Hospital with FC only**
  - Load following with 100% component sizing
  - **Takeaway**: By region, only the South didn’t showed cost savings, but the state-by-state variation is greater.
  - **Takeaway**: Cost savings are very dependent on electricity and natural gas prices.



DG-BEAT: Example National Survey—Emissions

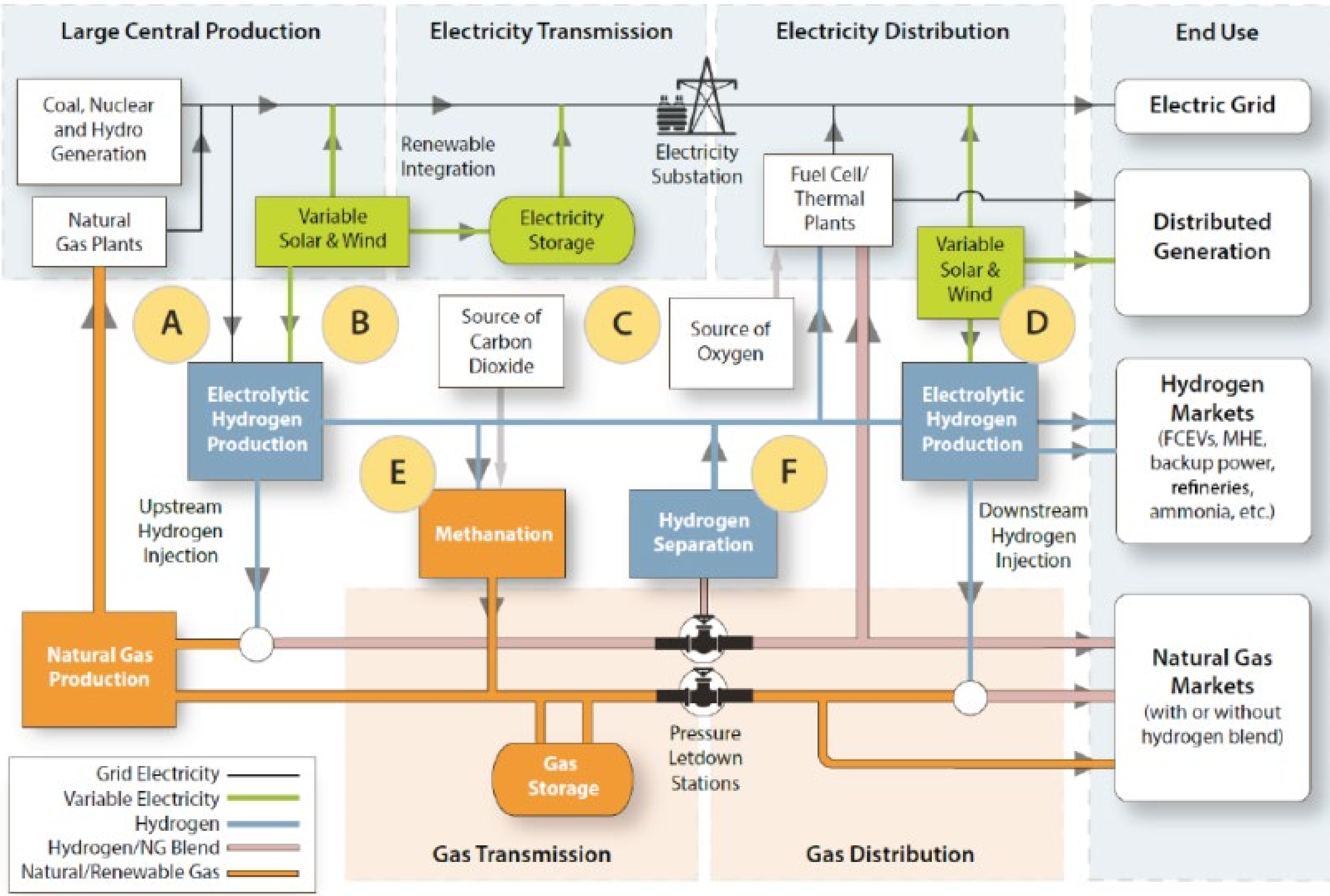
- **Hospital with FC only**
  - GHG emissions minimization control strategy and component sizing
  - **Takeaway**: Most regions have >50% emissions reductions from hospitals by adding an FC, but there is state-by-state variation.
  - **Takeaway**: Emissions savings are dependent on the state grid emissions.





Influence of auxiliary revenue streams

Hydrogen energy storage pathways



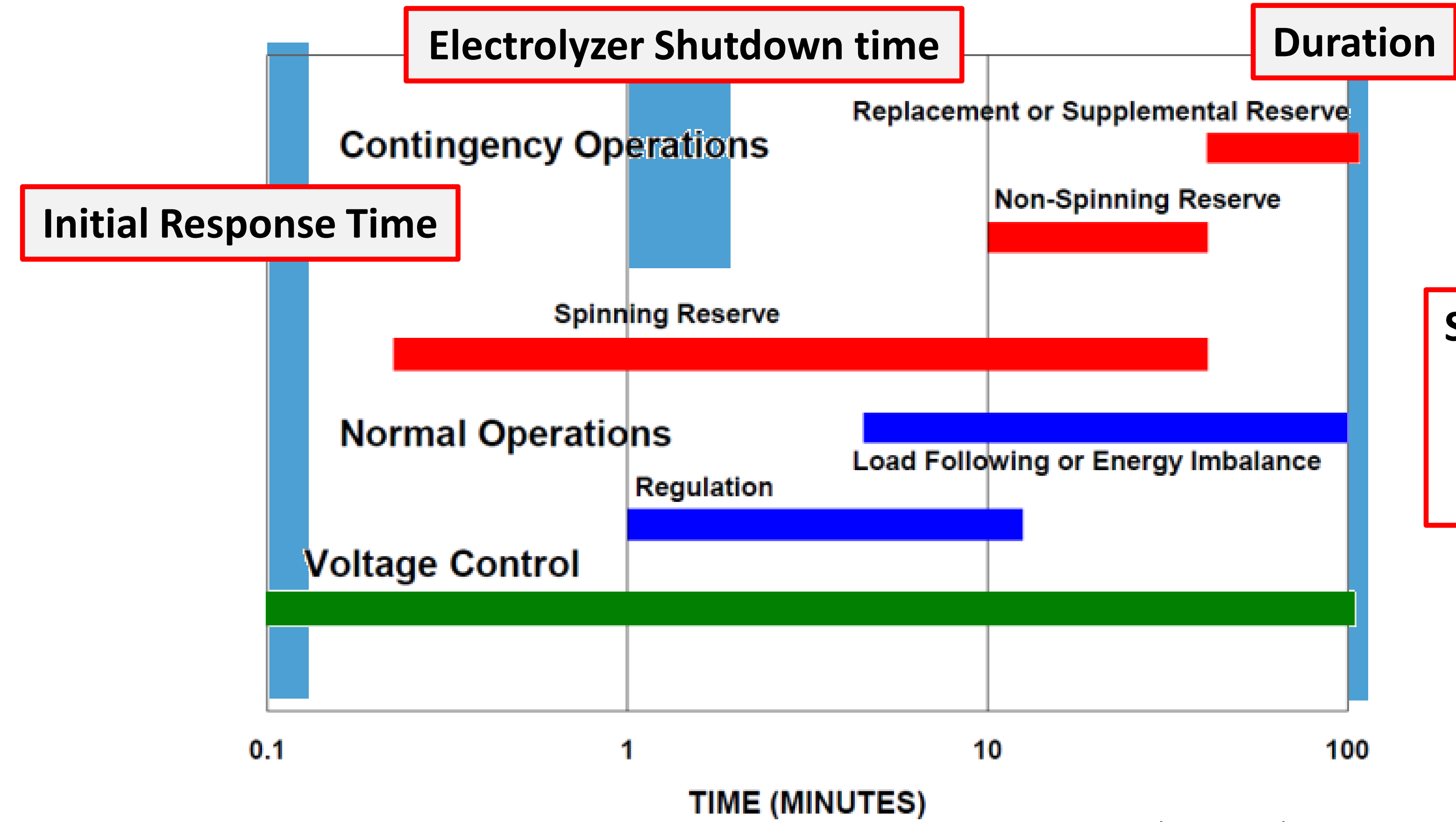
A. Electrolysis for Grid Support
B. Integration of large-scale central renewables
C. Conversion to grid electricity
D. Distributed production for variable resources
E. Methanation for renewable gas synthesis
F. Hydrogen Separation

Source: http://www.nrel.gov/docs/fy15osti/62518.pdf

Electrolyzer Flexibility Test Results

Electrolyzers can respond fast enough and for sufficient duration to participate in electricity markets (currently testing larger electrolyzers)

- **Compared PEM and Alkaline Electrolyzer response to grid requirements**



Superimposed boxes show electrolyzer results

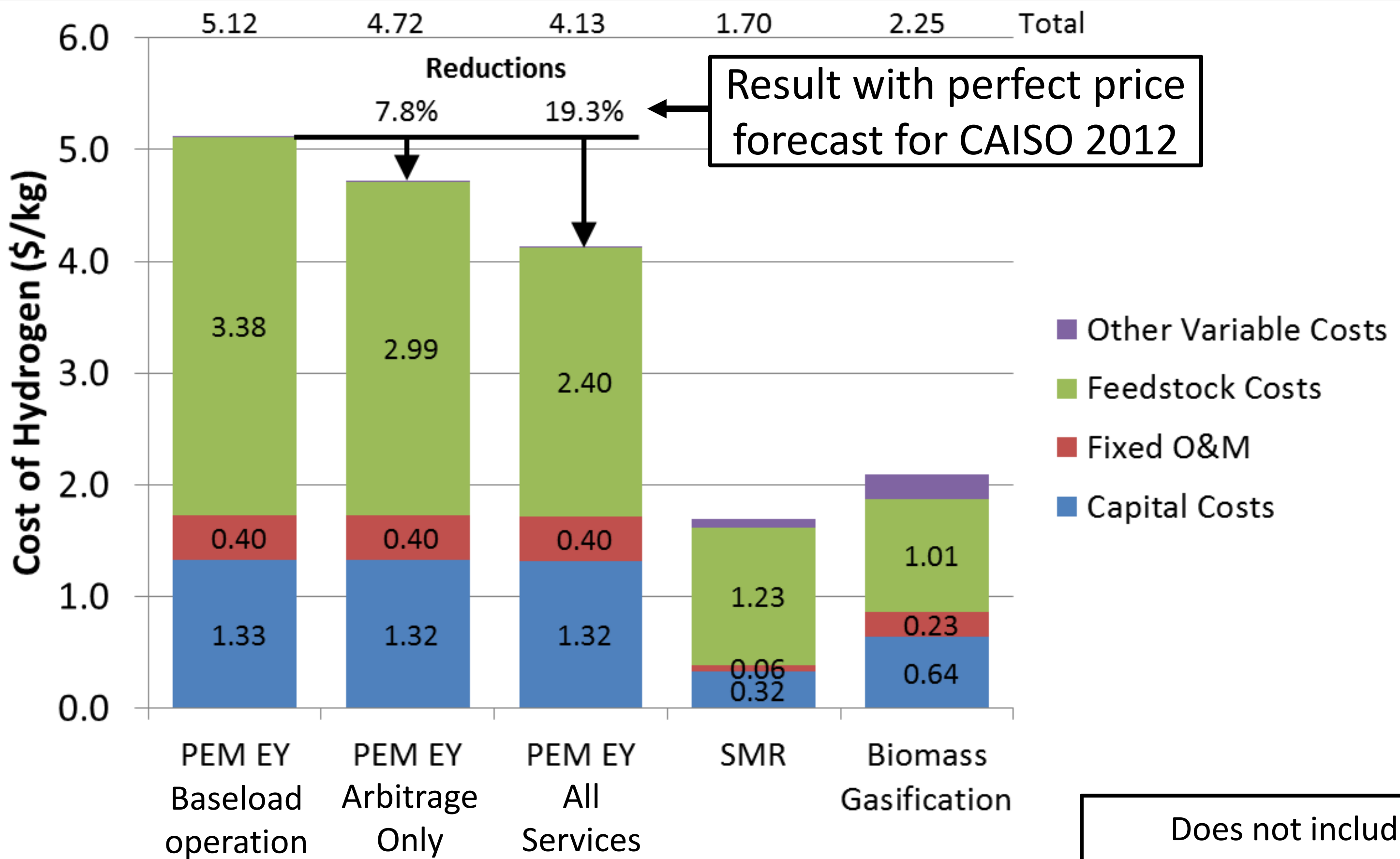
Source: Kirby, B.J. 2006. Demand Response for Power Systems Reliability: FAQ. ORNL/TM-2006/565

Source: Eichman, J.; Harrison, K.; Peters, M. (2014). Novel Electrolyzer Applications: Providing more than just hydrogen, NREL/TP-5400-61758, http://www.nrel.gov/docs/fy14osti/61758.pdf

Comparison to H2A

Integration with the grid can lower feedstock costs and increase revenue

- **H2A Current Central Hydrogen Production**



Name	Technology
EY	Electrolyzer
SMR	Steam Methane Reformer

Name	Services
Baseload	"Flat" operation
All	Energy and Ancillary Service Markets

Does not include gas compression and delivery cost

Source: http://www.hydrogen.energy.gov/h2a_prod_studies.html

Hydrogen energy storage analysis results

Flexibility Conclusions

1. Electrolyzers can respond sufficiently fast and for a long enough duration to participate in electricity markets.

Economic Viability Conclusions

1. Sell Hydrogen: Systems providing strictly storage are less competitive than systems that sell hydrogen
2. Revenue w/ ancillary service > energy only > baseload
3. More storage is not necessarily more competitive in current energy and ancillary service markets

Source: Eichman, J. (2014). "Analysis of fuel cell/electrolyzer cost of energy storage for California electrical grid", presented at the 2014 U.S. DOE Hydrogen and Fuel Cells Program Annual Merit Review, Washington, D.C., June 17, 2014. http://www.hydrogen.energy.gov/pdfs/review14/an049_eichman_2014_o.pdf

Summary and Suggestions for Future Research

Summary

- Analytic models can provide consistent comparisons across multiple metrics
- Bridging markets (e.g., multiple revenue streams) can improve business cases under certain market conditions

Future Research

- Useful tools must be tailored to particular end-users to improve decision making
- Higher degrees of model/market integration are needed to inform decisions for “business success”

Acknowledgements

- **These projects are supported by the U.S. Department of Energy's Fuel Cell Technologies Office**
  - DOE Project Manager, Fred Joseck
  - DOE Project Manager, Jason Marcinkoski
  - DOE Project Manager, Dimitrios Papageorgopoulos

- **Key analysis personnel (for materials presented)**
  - Stationary fuel cells:
    - Michael Penev, Genevieve Saur, Jen Kurtz, Chris Ainscough (NREL)
    - Jack Brouwer, Dustin McClarty (University of California – Irvine)
  - Biogas resources: Anelia Milbrandt (NREL)
  - Power-to-gas & ancillary markets: Joshua Eichman (NREL)
  - Systems analysis modeling:
    - Marc Melaina, Brian Bush, Michael Penev, Todd Ramsden (NREL)

Questions?

Contact: Marc.Melaina@nrel.gov

Backup slides

Resource Potential – Biogas Conversion

Wastewater Treatment (WWTP)

•1 ft^3 biogas/100 gal wastewater [4]

•65% CH_4*0.03 m^3 biogas/ft^3 biogas* .7 kg CH_4/m^3 CH_4 [5]

Landfill Gas (LFG)

•EPA Landfill Methane Outreach Program (LMOP): Candidate Landfills [6]

Animal Manure

•EPA State Workbook: Methodologies for Estimating Greenhouse Gas Emissions, Workbook 7 Methane Emissions from Manure Management. [7]

Industrial Process and Organic Food Waste

•US Census Bureau's County Business Patterns [8]

Methane to Hydrogen

•H2A Steam Methane Reforming (SMR) Central Case study : 3.3 kg CH_4/kg H_2 [9]

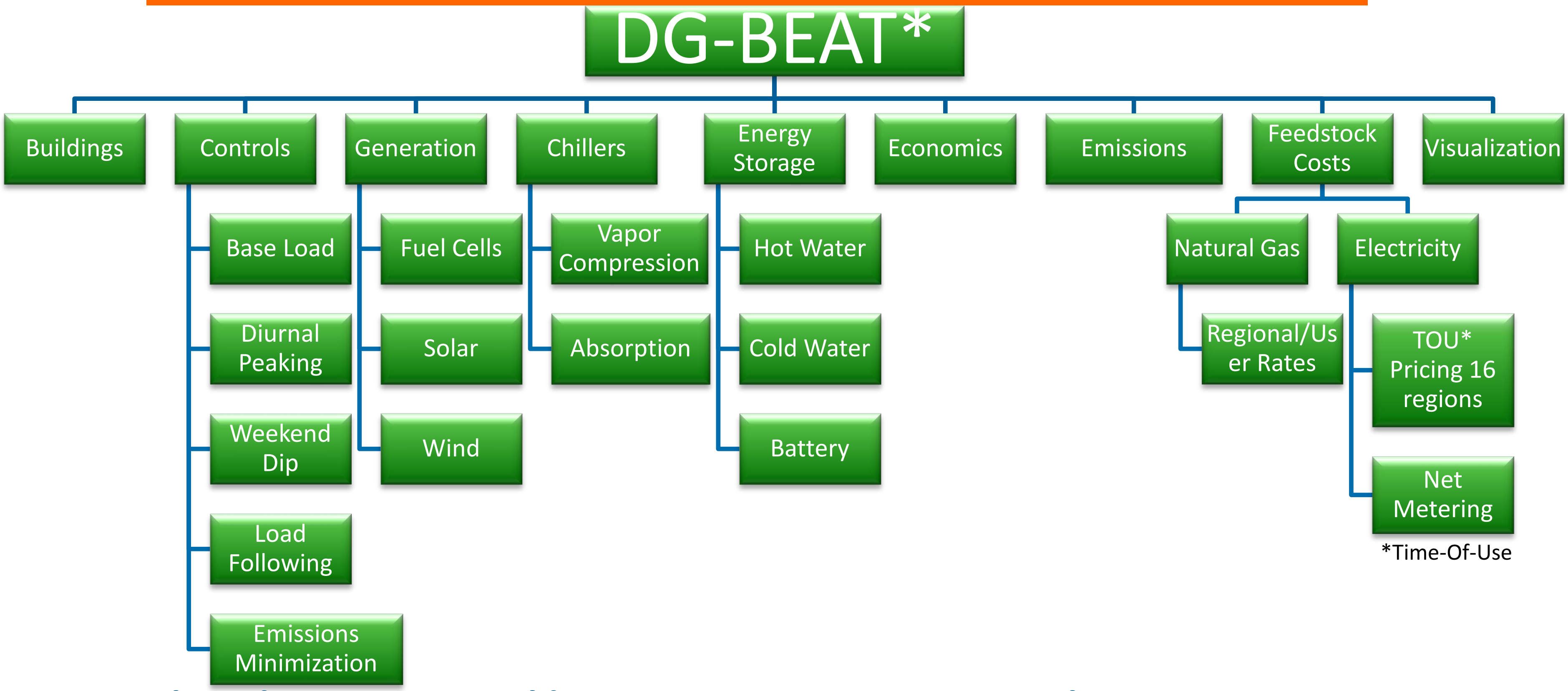
Vehicles Supported

•Total Costs of Ownership of Future Light-Duty Vehicles : Medium case 2020 : 57 miles/gge & 10,000 miles driven/yr [10]

•Transportation Energy Data Book [11] : 2010 car and two-axle, four-tire truck registrations : 230 million vehicles in 2011

DG-BEAT: Construction of Model

- ✧ **Modular Design**
- ✧ **Building Integrated Systems**
- ✧ **Controls Optimization**
- ✧ **Component Sizing**



- **Distributed Generation Build-out Economic Assessment Tool**

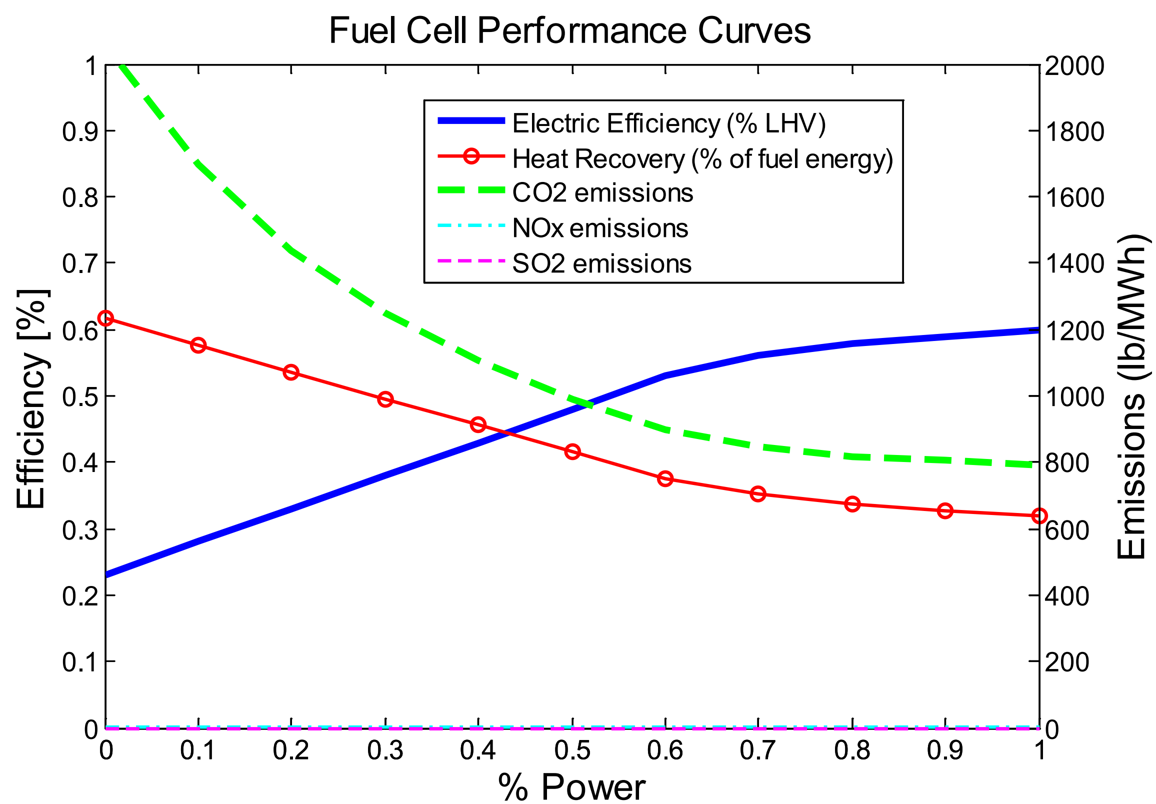
Codebase is hosted on GitHub (the largest code host in the world)

- Allows for distributed collaboration
- Open source, controlled access to fuel cell developers, NREL, UCI, and other stakeholders

DG-BEAT: Component Performance

➢Pre-loaded or user defined component performance characteristics

- **Fuel Cell**
  - Efficiency, heat recovery, emissions
  - Heat recovery by temperature
  - Max/min power, response rate, turndown ratio
- **Chiller (Absorption and Electric)**
  - COP by % output
  - Size (kW and Tons)
  - Heat/cold available
- **Thermal Storage (Cold and Hot)**
  - Tank Size (kWh and gal)
  - Reservoir Temperatures
  - Losses
  - Fill and discharge rates
- **Battery**
  - Type and size
  - Charge/discharge characteristics
  - Cell characteristics
- **Wind and Solar also available**

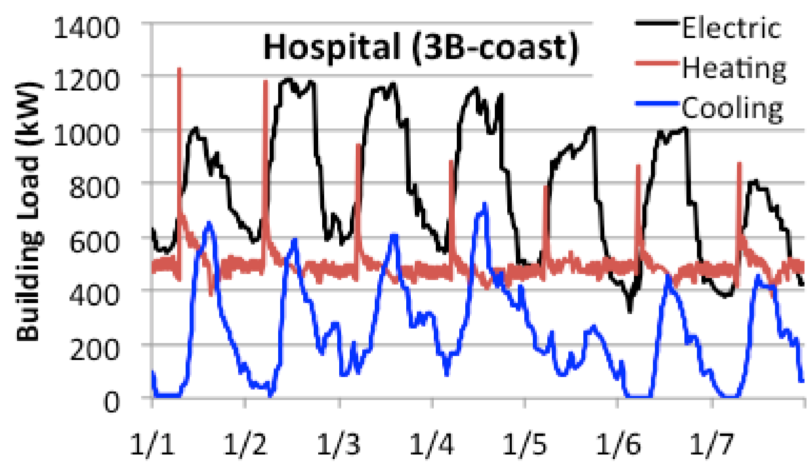


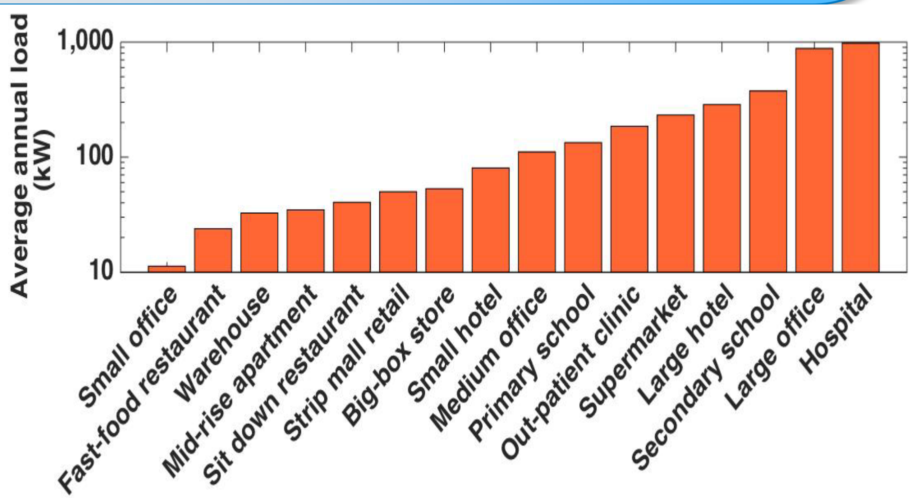
DG-BEAT: Regional Building Profiles

NREL's Electricity, Resources, and Building Systems Integration Center has provided energy use profiles* .

- 1280 total building profiles
- Load profiles include electricity, heating, cooling (thermal kW & electric kW), electric refrigeration, and exterior lighting
- 15 min time interval data for a year

✧ Can also use real building data if available





Building types	Locations
Restaurant: full-service (sit down) Restaurant: quick-service (fast food) School: primary school School: secondary school Office: large office Office: medium office Office: small office Hospitality: large hotel Hospitality: small hotel/motel Health care: large hospital Health care: outpatient facility Retail: big-box, standalone retail store Retail: retail strip mall Retail: supermarket Mid-rise apartment building Unrefrigerated warehouse	Miami (ASHRAE 1A) Houston (ASHRAE 2A) Phoenix (ASHRAE 2B) Atlanta (ASHRAE 3A) Los Angeles (ASHRAE 3B-Coast) Las Vegas (ASHRAE 3B-Inland) San Francisco (ASHRAE 3C) Baltimore (ASHRAE 4A) Albuquerque (ASHRAE 4B) Seattle (ASHRAE 4C) Chicago (ASHRAE 5A) Boulder (ASHRAE 5B) Minneapolis (ASHRAE 6A) Helena, MT (ASHRAE 6B) Duluth, MN (ASHRAE 7) Fairbanks, AK (ASHRAE 8)
Vintages	2010, 2007, 2004, Post-1980, Pre-1980

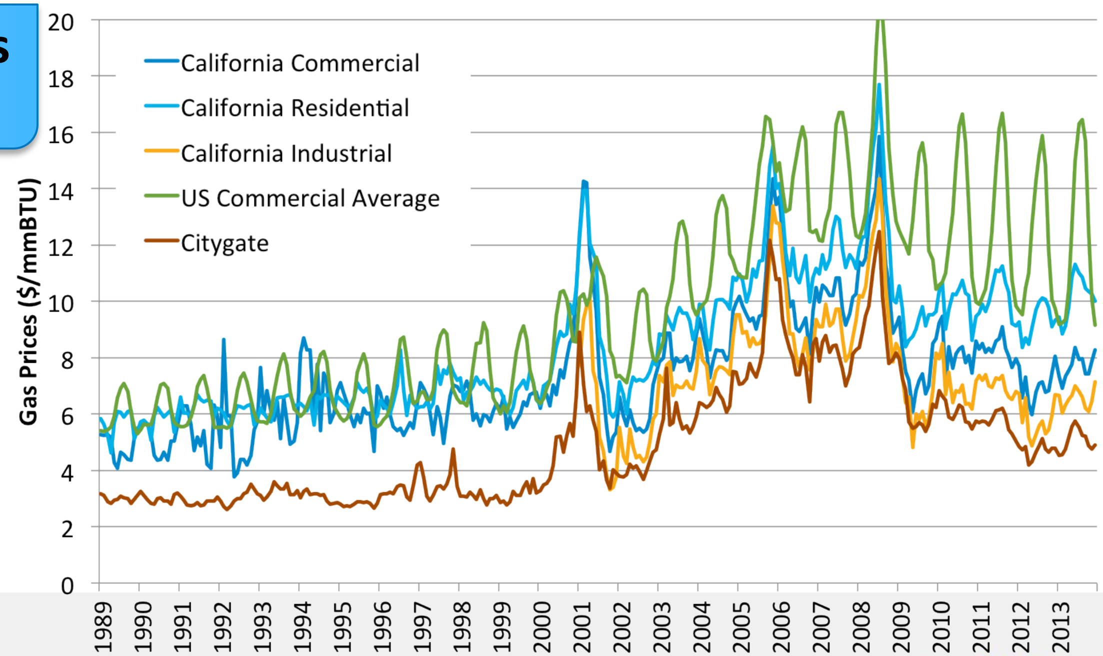
* Using data from the Commercial Buildings Energy Consumption Survey (CBECS)

DG-BEAT: Regional Utility Costs

- **Preloaded regional utility profiles**
- **Input your own**

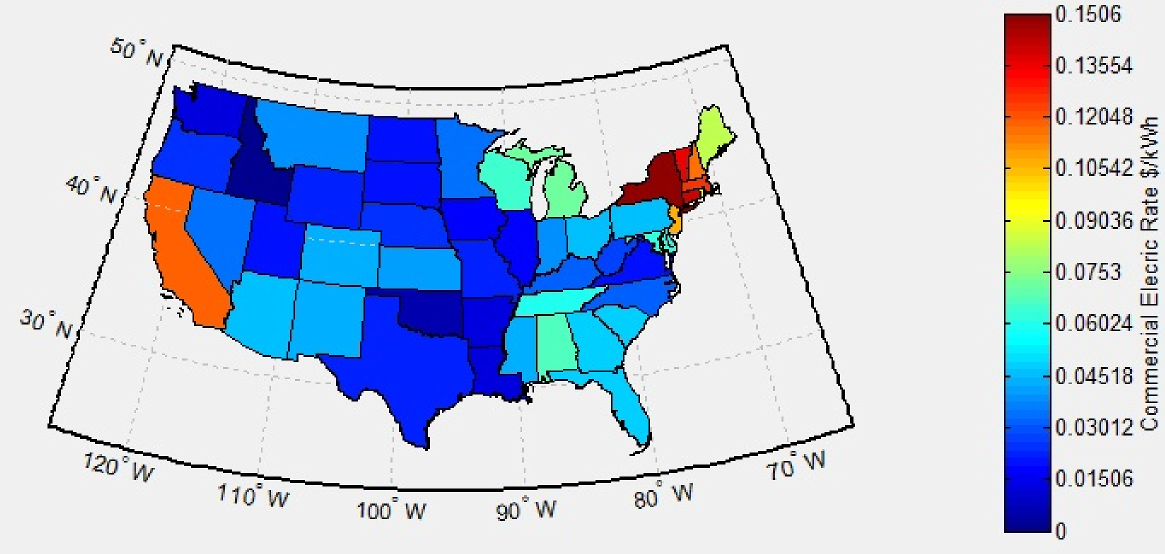
Natural gas cost

- EIA forecasted by state with seasonal variation
- Historical and forecasted rates



Electricity

- TOU electricity rates
  - 20+ preloaded rate structures
  - State average energy costs
- Net-metering
  - No net metering
  - Fixed rate sellback
  - TOU sellback (% of incoming charge)

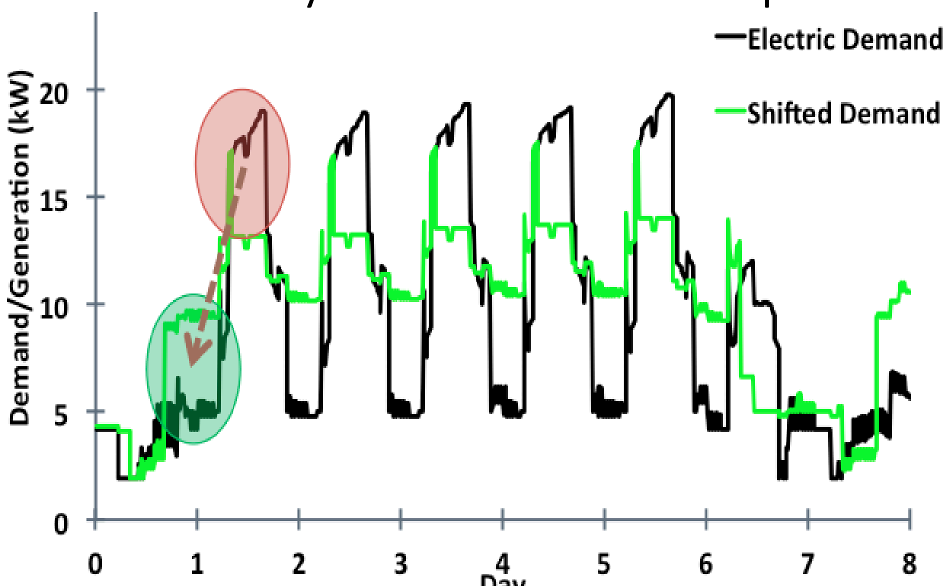


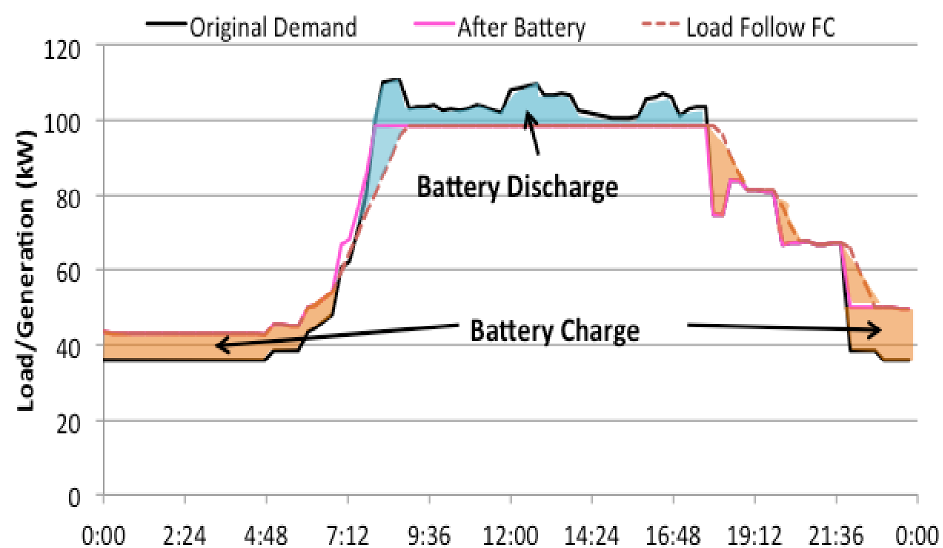
DG-BEAT: Component Sizing

- ➢ **Foundations for additional component sizing are implemented**
- ➢ **Modular designs allows additional component creation**

- **Electric and Absorption Chillers**
  - Absorption Chiller sized based on heat available or demand whatever lowest
  - Electric chiller required to meet 100% of remaining peak summer demand
- **Thermal Energy Storage (TES)**
  - Sized to shift 100% of cooling from peak hours to off-peak
  - Sized for hottest day during summer on-peak months
- **Battery**
  - Primary purpose is to reduce demand charges during on-peak hours
  - Set by total kWh or hours of peak demand

Wind and Solar components also available!





Hydrogen storage and Power-to-gas (PtG) projects

- **Germany has 22 green hydrogen and PtG projects as of 2012 (see figure)**

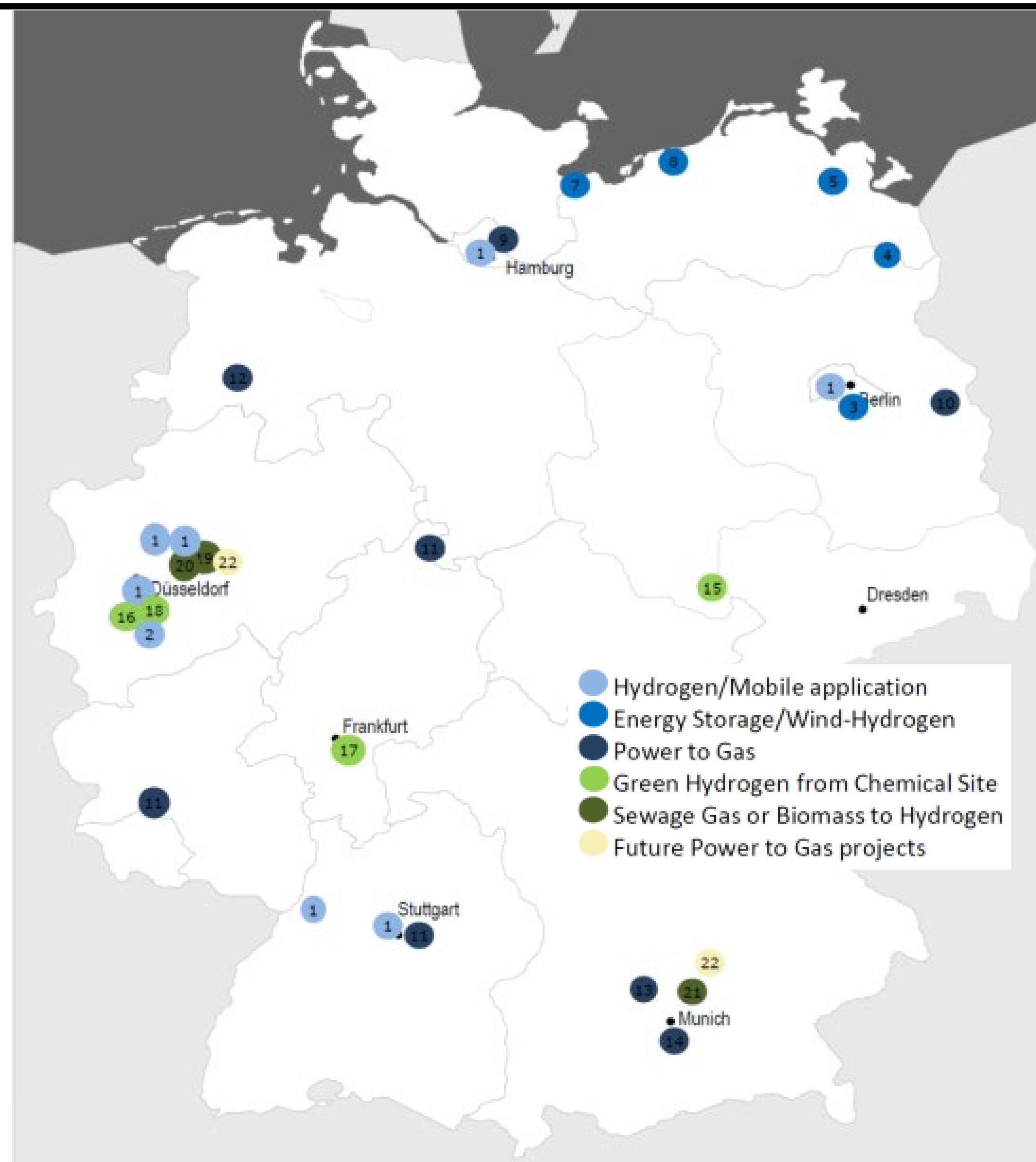
Source: www.gtai.de/GTAI/Content/EN/Invest/SharedDocs/Downloads/GTAI/Info-sheets/Energy-environmental/info-sheet-green-hydrogen-power-to-gas-demonstrational%2520projects-en.pdf

- **2 MW Power-to-Gas project planned for Ontario, Canada**
  - Acts as energy storage for grid management and regulation

Source: www.hydrogenics.com/about-the-company/news-updates/2014/07/25/hydrogenics-selected-for-2-megawatt-energy-storage-facility-in-ontario

- **Two Power-to-Gas pilot projects In California (SoCalGas, NREL, UC Irvine)**
  - Reduce variability of renewable generation

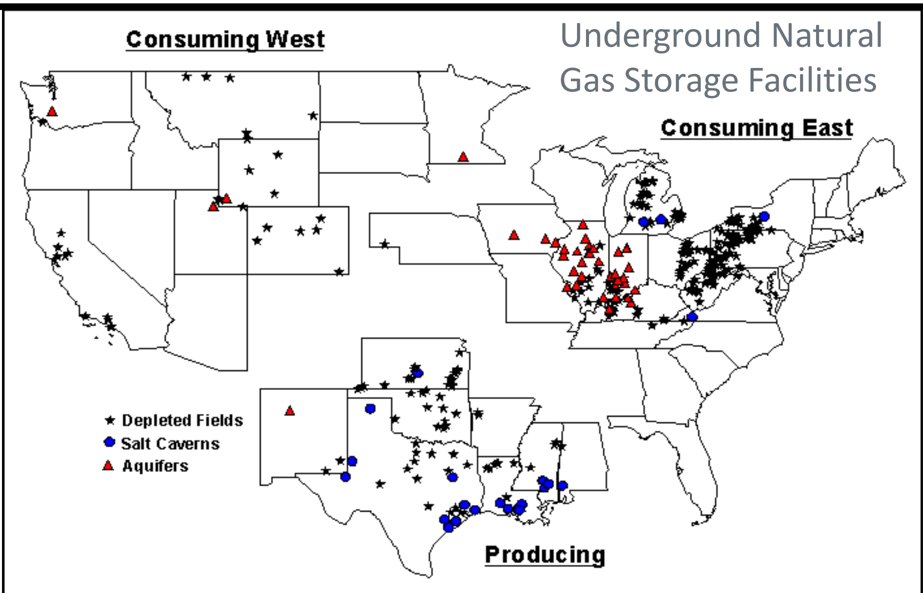
Source: www.bloomberg.com/news/articles/2015-04-13/california-utility-to-make-gas-from-solar-for-pipeline-storage



Opportunities for Power-to-gas

- **Natural Gas System**
  - 305,000 miles of transmission pipelines
  - 400 underground natural gas storage facilities
  - 3.9 Bcf underground storage working gas capacity

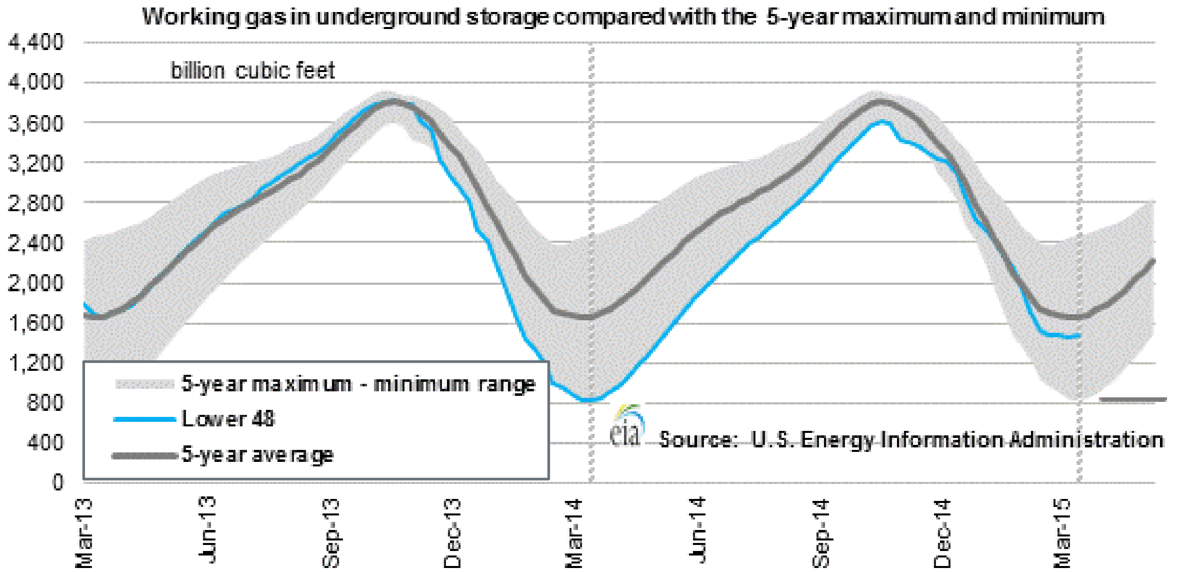
Source: www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html



Source: Energy Information Administration (EIA), EIA GasTran Geographic Information System Underground Storage Data Base.

- **Storage equates to…**
  - ~60 days of NG use across the U.S.
  - 38 billion kg of H_2 used to produce CH_4 from CO_2 methanation for one fill

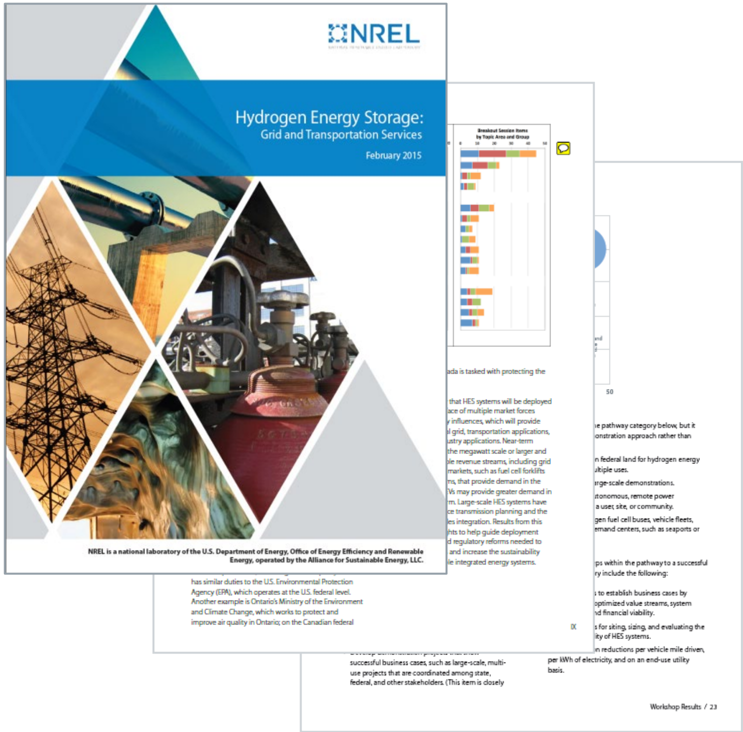
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
(Sabatier process)



Clean Energy Dialogue – US/Canada

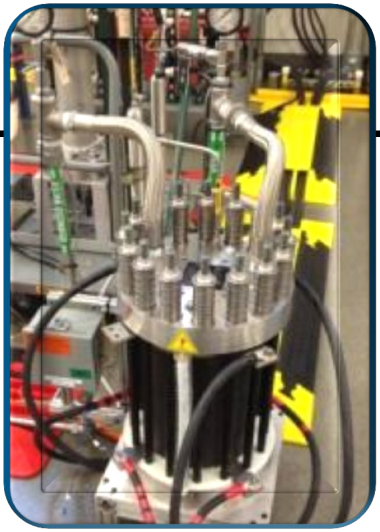
- **Hydrogen Energy Storage (HES) Workshop**
  - Held May, 2014 in Sacramento, CA and included a diversity of stakeholders
  - Explored barriers, policy and next steps for encouraging HES
  - Workshop proceedings are available

- **Example Findings**
  - Criteria and Barriers
    - Technical and Economic Viability
    - Multiple end uses
  - Policy
    - Equal treatment and credit in markets
  - Next Steps
    - Demonstration and pilot projects



Source: http://www.nrel.gov/docs/fy15osti/62518.pdf

Electrolyzer Flexibility Tests



- **Testing explored several parameters**
  - Startup and Shutdown
  - Minimum Turndown
  - Response Time
  - Ramp Rate
  - Frequency Response