National Renewable Energy Laboratory

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Hydrogen Analysis Task Leader

DOE Hydrogen, Fuel Cells, and Infrastructure Technologies Program
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Charter

- NREL's mission: NREL develops renewable energy and energy efficiency technologies and practices, advances related science and engineering, and transfers knowledge and innovations to address the nation's energy and environmental goals.

- The NREL Hydrogen Analysis Group provides leadership in hydrogen production, delivery, transition, and market analysis, to increase the *efficiency* of hydrogen research and implementation.

- The NREL Hydrogen Analysis Group has received the majority of its funding from the DOE Hydrogen Program (now HFCIT), with some funding coming from PBA and OFCVT

History

- The NREL Hydrogen Analysis Group has done analysis work continually for DOE since 1993

- The NREL Hydrogen Analysis Group began by studying the technical and economic feasibility of hydrogen production. Other capabilities emerged naturally based on a broader understanding of hydrogen systems:
  - Resource analysis in 1995
  - NOMAHD delivery model in 1998
  - Life cycle assessment (environmental) in 1999
  - Market analysis in 2001
  - Infrastructure transition analysis in 2002
  - H2A in 2002

Skill Set - People

- Past analysts:
  - Wade Amos: Storage & Delivery (no longer at NREL)
  - Pam Spath: Production analysis, life cycle assessment (now in Biomass Program)
  - Keith Wipke: ADVISOR (now leading tech validation project)
- Current analysts (4.8 FTEs):
  - Nate Blair: ***Linear programming, energy market expert***
  - Lee Jay Fingersh: ***Wind analysis, electric grid/hydrogen interaction***
  - Johanna Ivy: ***Electrolysis, H2A, programming***
  - Maggie Mann: Project leader, ***H2A lead, production analysis, life cycle assessment***
  - Tony Markel: ***Vehicle analysis (ADVISOR)***
  - Bob McConnel: ***Solar energy analysis***
  - Margo Melendez: ***Infrastructure transition analysis, natural gas infrastructure and markets***
  - Matt Ringer: ***H_2 delivery, H2A, distributed H_2 production***
  - Walter Short: ***Transition analysis, energy market analysis, electric grid analysis***

Skill Set – Capabilities Summary

TYPE OF ANALYSIS	RESIDENT CAPABILITY?	STUDIES SPECIFIC TO H_2?	MODELS SPECIFIC TO H_2?
Resource Analysis	Yes	Yes	Yes
Technoeconomic Analysis	Yes	Yes	Yes
Environmental Analysis	Yes	Yes	Yes
Delivery Analysis	Yes	Yes	Yes
Infrastructure Development Analysis	Yes	Yes	Yes
Energy Market Analysis	Yes	Yes	Yes

Skill Set - Studies

- Technoeconomic Analysis
  - Hydrogen from **biomass** via gasification and pyrolysis: 1994, 1997, 2000, 2004
  - Hydrogen from **concentrated solar energy**: 2001
  - **Photobiological** hydrogen production: 1995, 2002, 2005
  - Hydrogen via bacterial water gas shift: 2002-2003
  - Enzymatic hydrogen production: 1997
  - Hydrogen **leak detection** technology: 1996
  - **Supercritical water** gasification: 2000
  - **Carbon nanotube** storage: 1996
  - **Electrolysis**: 1998 – present
  - Hydrogen from **PV and wind**, including **grid** interaction: 1998, 2001, 2004
  - Reversible fuel cells with wind: 2001
  - **Photoelectrochemical** hydrogen production: 1999, 2004
  - Membrane and adsorption reactor systems
  - Hydrogen from coal and natural gas: 1998, 2000
  - Gasoline-reformed **fuel cell** cold start analysis: 2001
  - **Fuel cell hybrid electric vehicles**: 1999 (in collaboration with VATech)
  - **H2A** formation and leadership : 2002-present

Skill Set - Studies

- Resource Analysis
  - **Mapping of renewable resource** potential for hydrogen production: 2003
  - Resource requirements for various **hydrogen penetration** levels: 2001
- Environmental Analysis
  - Life cycle assessment of **steam methane reforming**: 2000
  - Life cycle assessment of **wind/electrolysis**: 2001, 2004
  - Life cycle assessment of **biomass gasification/reforming**
  - Greenhouse gas benefits of **coal-bed methane** recovery: 1998
- Delivery Analysis
  - **Hydrogen storage and delivery**: 1997-present
  - Development of **NOMAHD** and the **Delivery Component Model**
  - **H2A** work on delivery
- Infrastructure Development Analysis
  - GIS study of **existing infrastructure**: 1998
  - Use of U.S. highway infrastructure for **hydrogen backbone**: 2003-2004s
- Energy Market Analysis
  - Comparative assessments of various **production and delivery pathways**: 1998-present
  - Resource and market opportunities for the production of electricity and hydrogen from **wind**: 2003-2004

Skill Set - Models

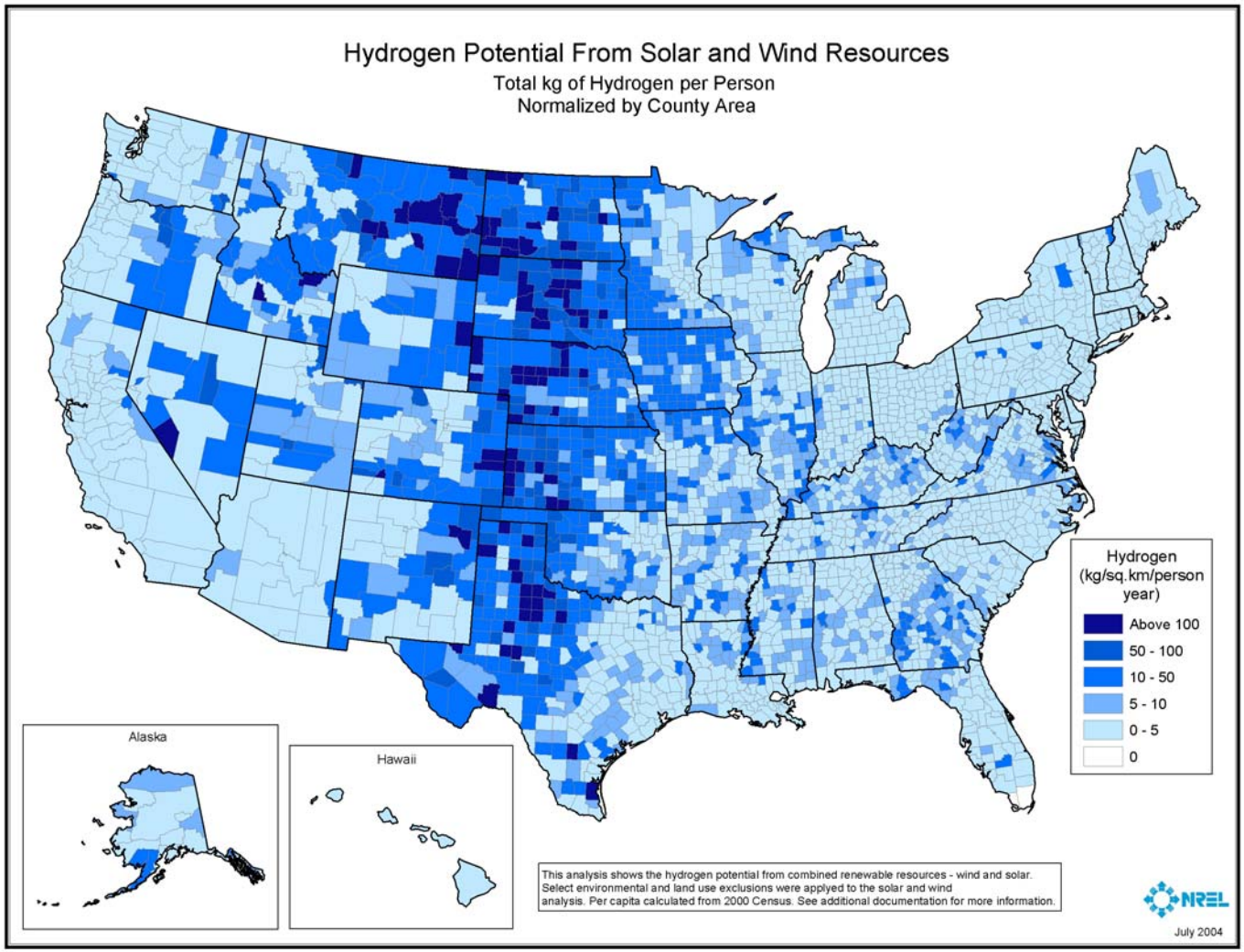
Resource Analysis

Hydrogen potential from renewable resources

- Methodology: geographic information systems analysis using wind, solar, and biomass data
- Platform: ArcView, outputs jpg & Excel
- Limitations: Currently does not represent cost of producing hydrogen from renewables (2005) or ideal modes of transport to demand centers (2005 infrastructure study)

Resource Analysis

Example Results



Skill Set - Models

Technoeconomic Analysis (hydrogen production)
Process analysis, (as shown on studies slide)

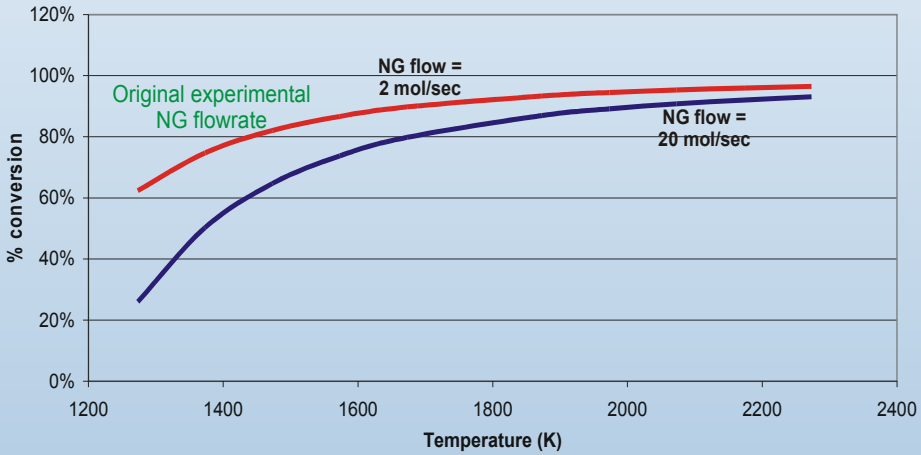
- Methodology and platforms:
  - ASPEN Plus for mass & energy balances, Icarus equipment costing and vendor quotes, discounted cash flow analysis in Excel H2A, Monte Carlo and parameter sensitivity analysis in Excel
  - Boundary analysis to determine opportunities for R&D improvements
- Limitations:
  - Does not predict absolute market costs
  - Cannot identify Eurekas
  - Most appropriately used to guide research toward areas which will have the greatest impact on costs

Technology Feasibility & Cost Analysis

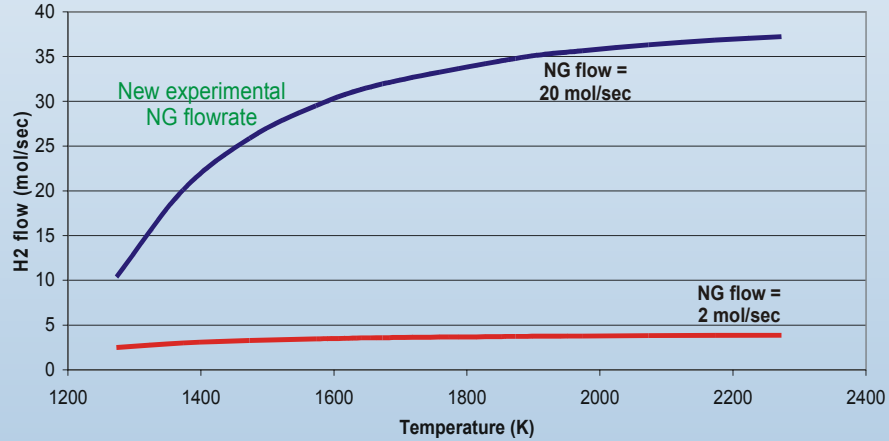
Example Results

Impacting Research Progress
Solar Thermal H_2 from Natural Gas

Natural Gas Conversion



Hydrogen Product Flow

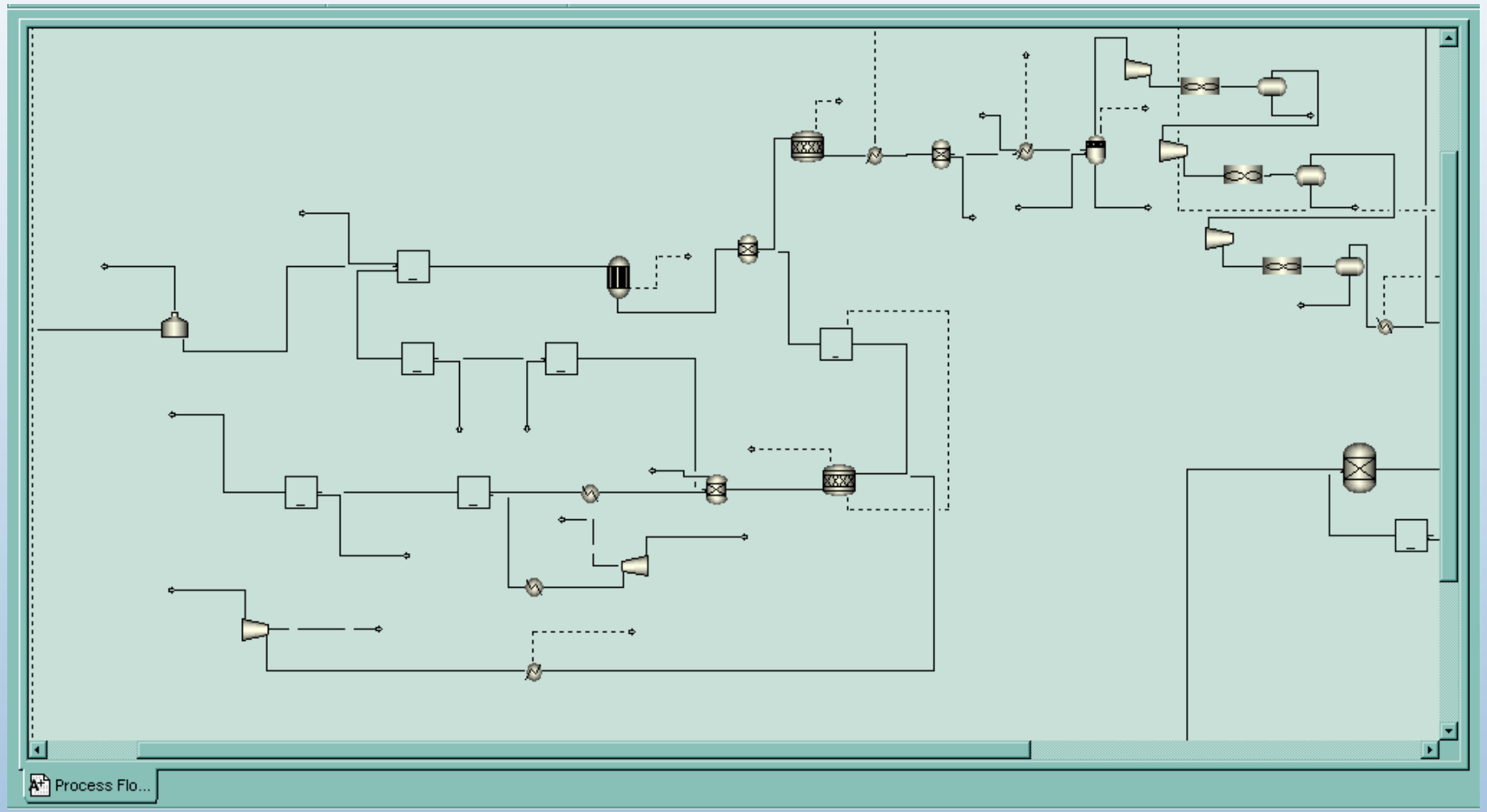


Increasing natural gas flowrate:

Reduces reactor temperature — Allows us to utilize more of the available solar energy — Reduces capital cost per unit of hydrogen produced

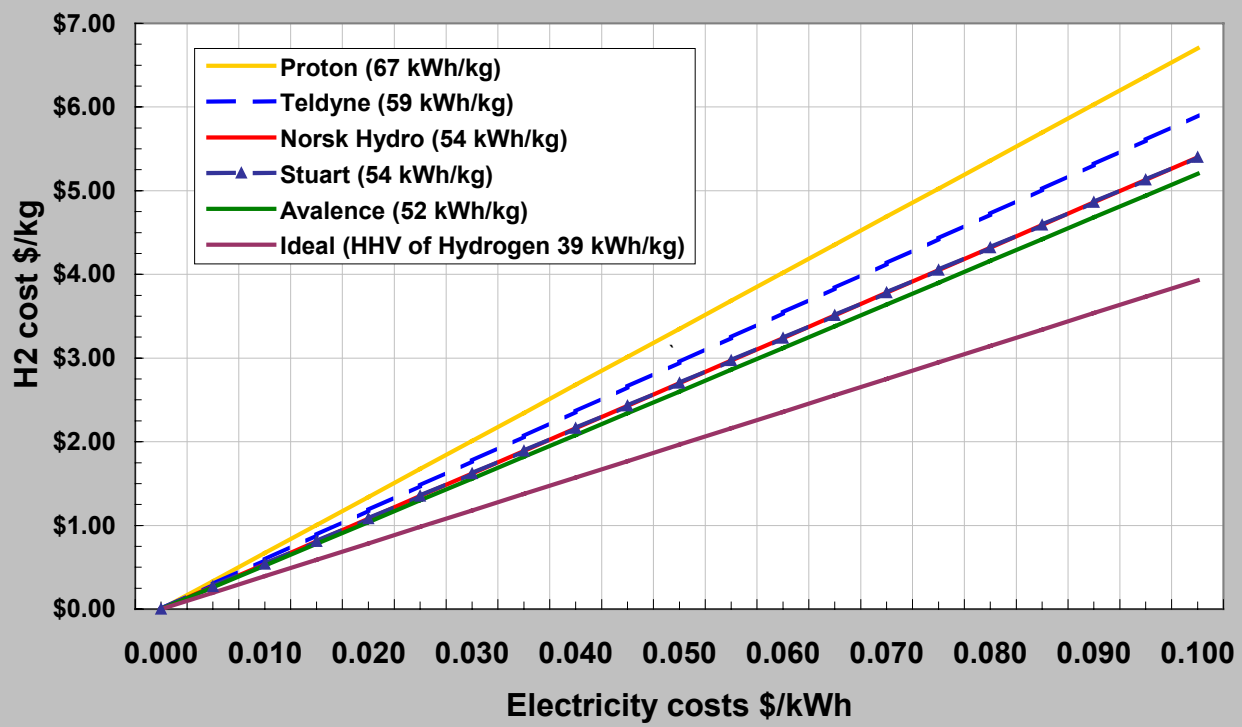
Technology Feasibility & Cost Analysis

Example Model Output



Technology Feasibility & Cost Analysis

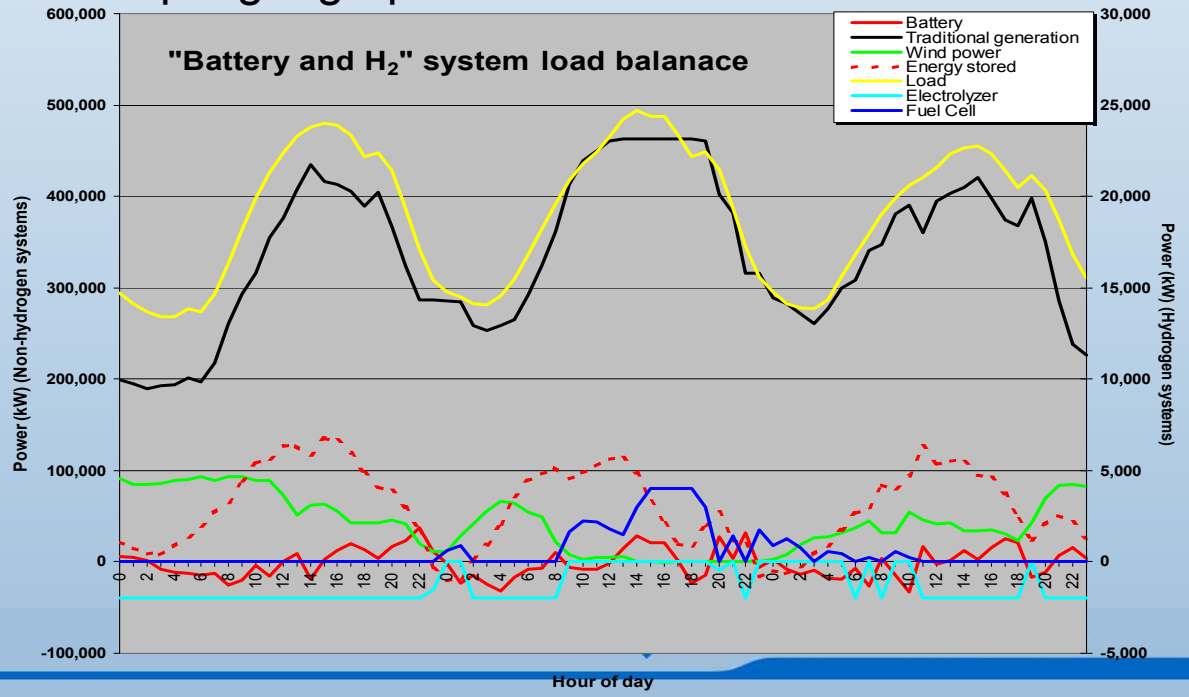
Example Model Output



Skill Set – Models

Technoeconomic Analysis

- WindSTORM, 2002 – current use; developed by Wind Program in partnership with H_2 Program
  - Methodology: Time-series power flow analysis. Includes wind, traditional electric generation, electrolyzers, fuel cells, batteries, hydrogen storage, hydrogen-for-fuel, and dispatchable load capability.
  - Platform: Excel with electric grid data
  - Limitations: Does not model multiple geographic sites
  - Results summary:
    - •Batteries are better than hydrogen for on-grid electricity storage
    - •Wind can economically produce hydrogen for fuel uses
    - •Capital costs can be reduced by integrating wind turbines and electrolyzers (eliminate duplicate power electronics)



Skill Set - Models

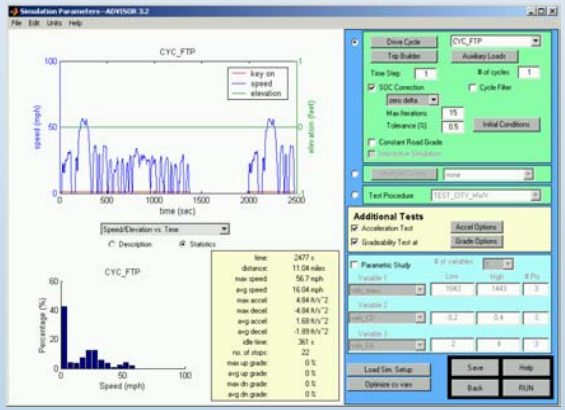
Technoeconomic Analysis (vehicles)

- ADVISOR, 1994-present
  - Downloaded by more than 8000 unique individuals
  - Licensed to a commercial partner (AVL) in 2003
  - Models hybrid electric (parallel, series), conventional and electric vehicle powertrains
    - Predicts vehicle fuel consumption and performance attributes
    - Primary role is to provide an understanding of energy management options and component interaction within the overall vehicle
  - Platform: MATLAB/Simulink environment
  - Limitations
    - Not intended for development of detailed dynamic component controls
    - Most sub-modules require empirical component data – not completely predictive

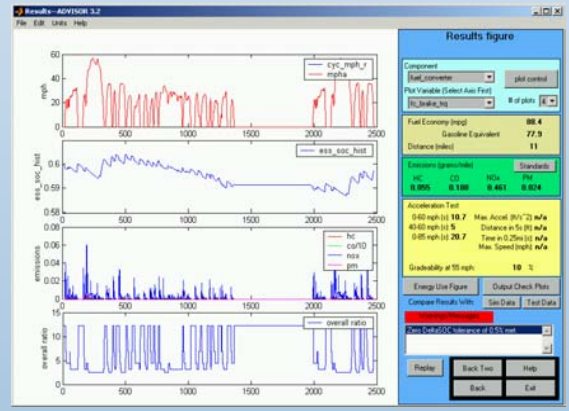
ADVISOR

Vehicle Input

Simulation Setup



Results



ADVISOR 2002
Advanced Vehicle Simulator

Skill Set - Models

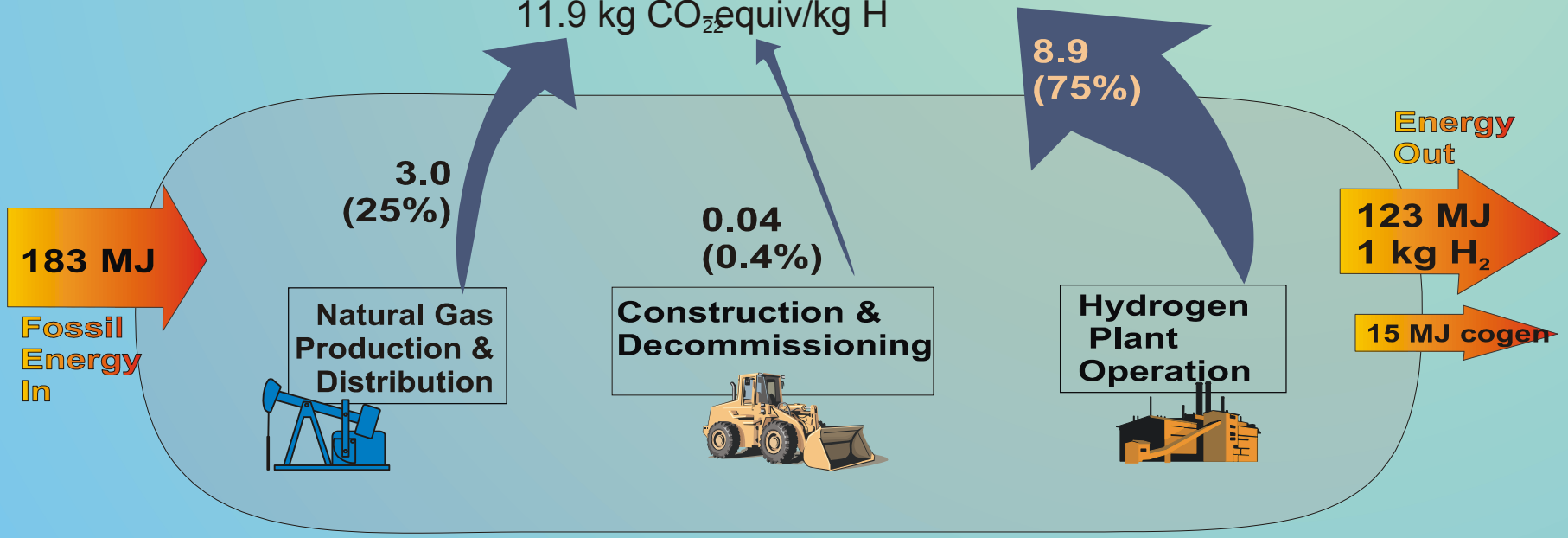
Environmental Analysis

Life cycle assessment models:

- Steam methane reforming (full LCA)
- Wind/electrolysis (full LCA)
- Concentrated solar splitting of natural gas (energy and greenhouse gases)
- Hydrogen from biomass (energy, GHG, criteria air pollutants)
- Hydrogen from coal with CO_2 sequestration

- Methodology: Quantify emissions, energy use, and resource consumption of all operations required to deliver hydrogen to consumer
- Platform: TEAM, U.S. Database
- Limitations: Cannot predict unknown environmental consequences

Life Cycle GWP and Energy Balance for Steam Methane Reforming



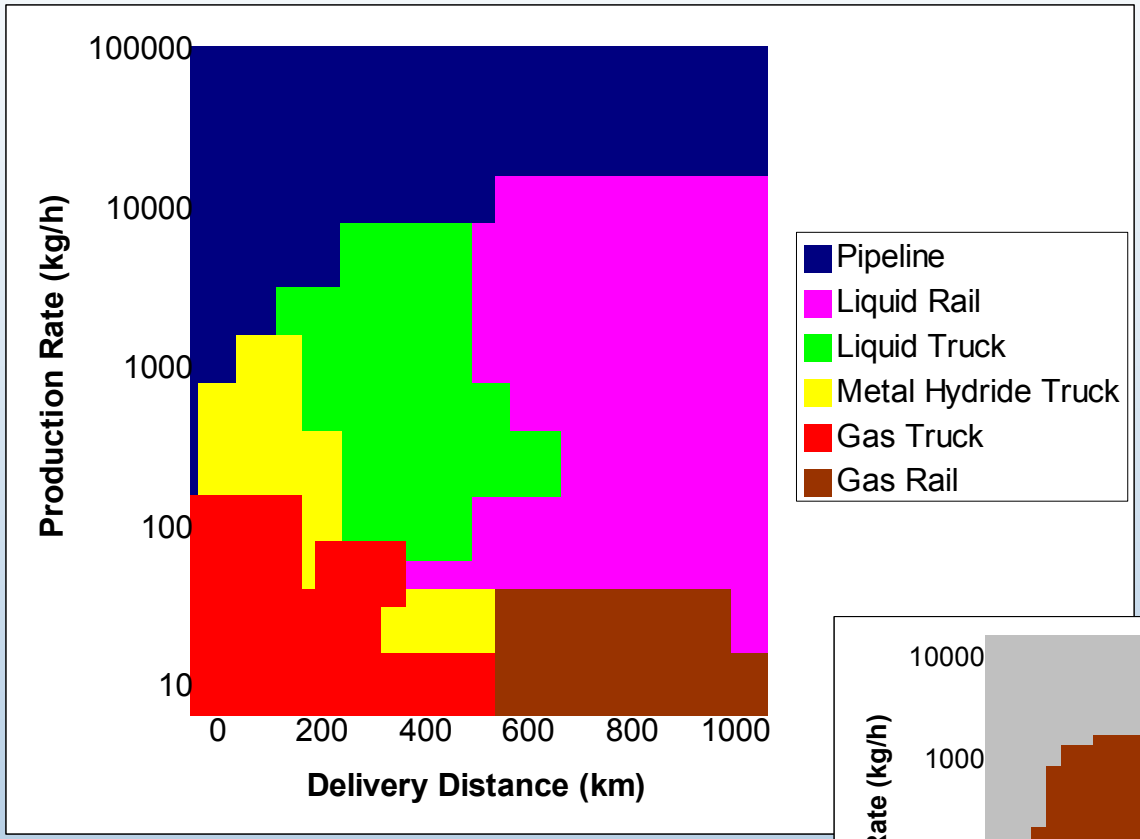
Net energy ratio = (123 MJ + 15 MJ) / 183 MJ = 0.75

Skill Set – Models

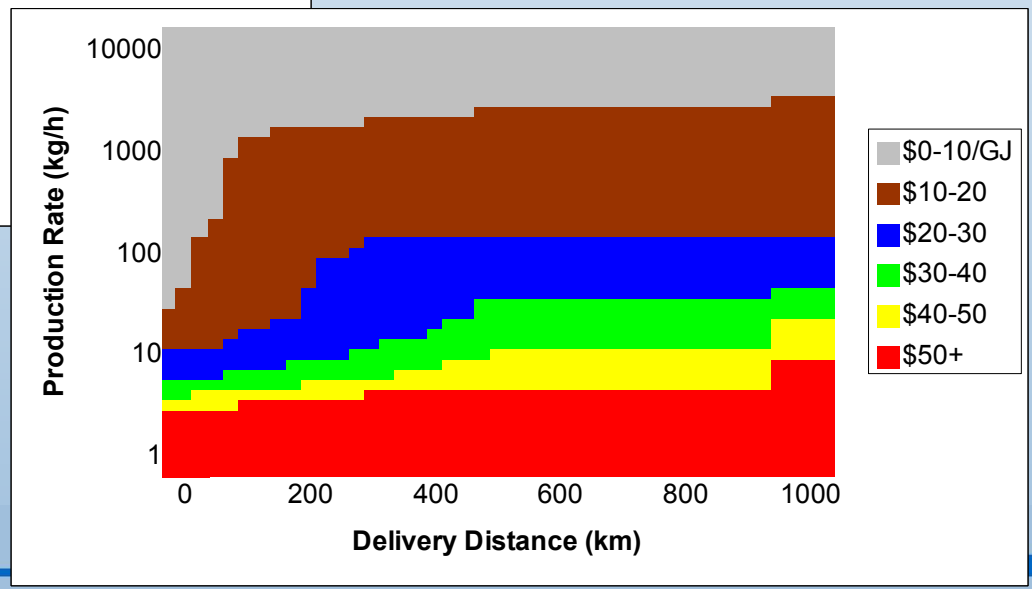
Delivery Analysis

- NREL Optimization Model for the Analysis of Hydrogen Delivery (NOMAHD), 1998 – current use
  - Methodology: Cost optimization - Uses database of component cost and design inputs, and weighted average cost of capital for financial analysis
  - Platform: Excel
  - Limitations: Accuracy of data in database (being addressed with with Monte Carlo analysis and H2A Key Industrial Collaborator input)
- Hydrogen Delivery Component Model – Companion to NOMAHD model, 2004, with H2A
  - Methodology: Costing Model – Determines delivery cost based on generalized scenarios and delivery hardware components. Capital, O&M -> fixed charge rate financial analysis
  - Platform: Excel
  - Model Limitations: Does not perform optimization calculations, but can work with NOMAHD

Delivery Analysis Results



NOMAHD identifies the most economical delivery option and cost



Skill Set - Models

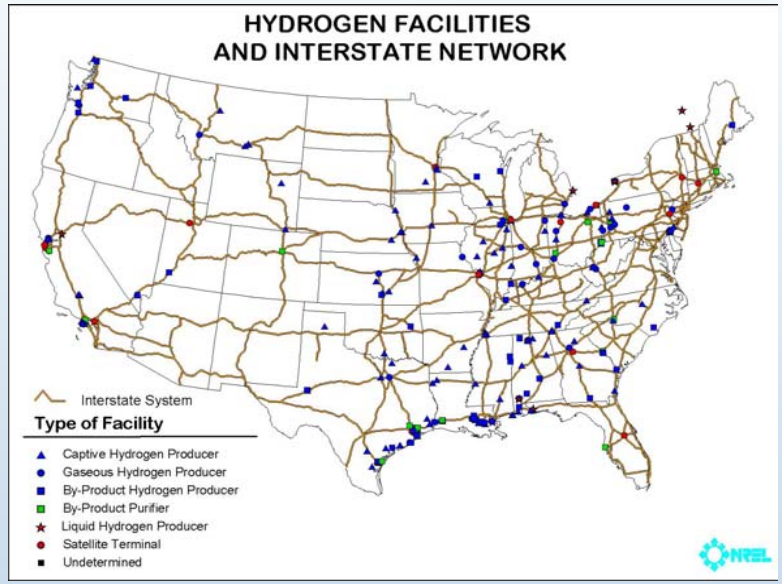
Infrastructure Development & Financial Analysis

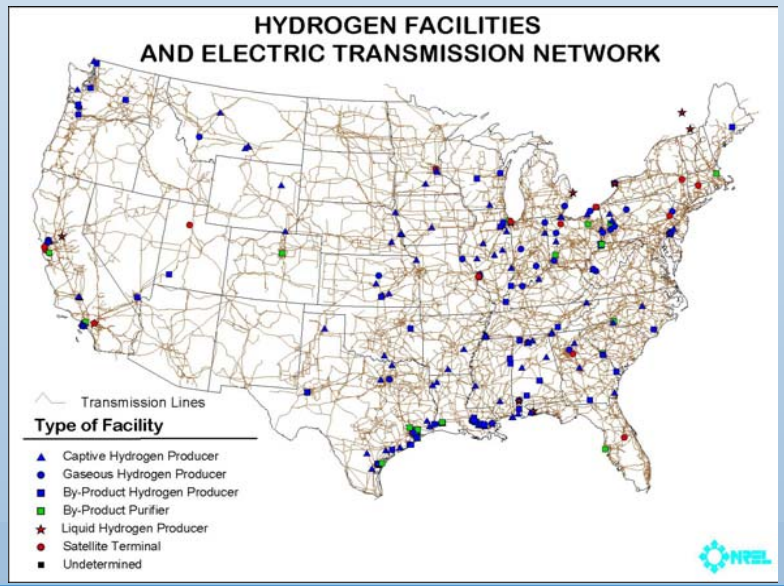
- Model of U.S. highway infrastructure for hydrogen backbone
  - Identifies areas for hydrogen production plants and stations along highways
  - Platform: Excel, GIS ArcView
  - Limitations: Geographical and cost optimization not yet linked (2005); does not prevent stranded investments with developing hydrogen markets

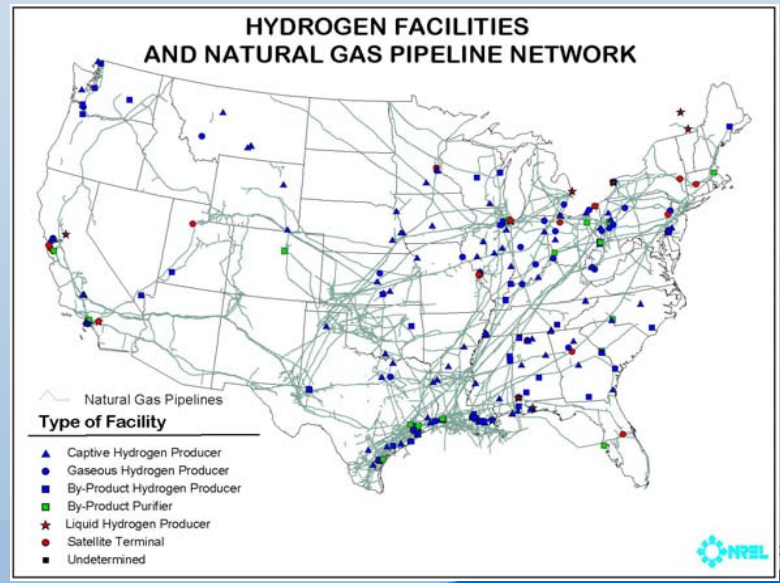
Infrastructure Analysis

Example Results

- Infrastructure exists today
- Is it enough for a while?
- How long before we need more?
- At what cost, and for what coverage?
- How do we avoid stranded investments?







Skill Set - Models

Energy Market Analysis (Vehicles)

Technical Targets Tool, 1998-current use

- Provide a high-level analysis of the potential benefits of the DOE research programs
  - Assess the sensitivity of fuel economy and national petroleum consumption to target values (cost, penetration, performance)
- Platform: MATLAB/Simulink environment, links to ADVISOR
- Predicts national fleet consumption over time for the light duty fleet
  - multiplatform focus
  - Includes competition among various technology options
- Limitations
  - Requires extensive computational resources
  - Does not include heavy vehicle sectors

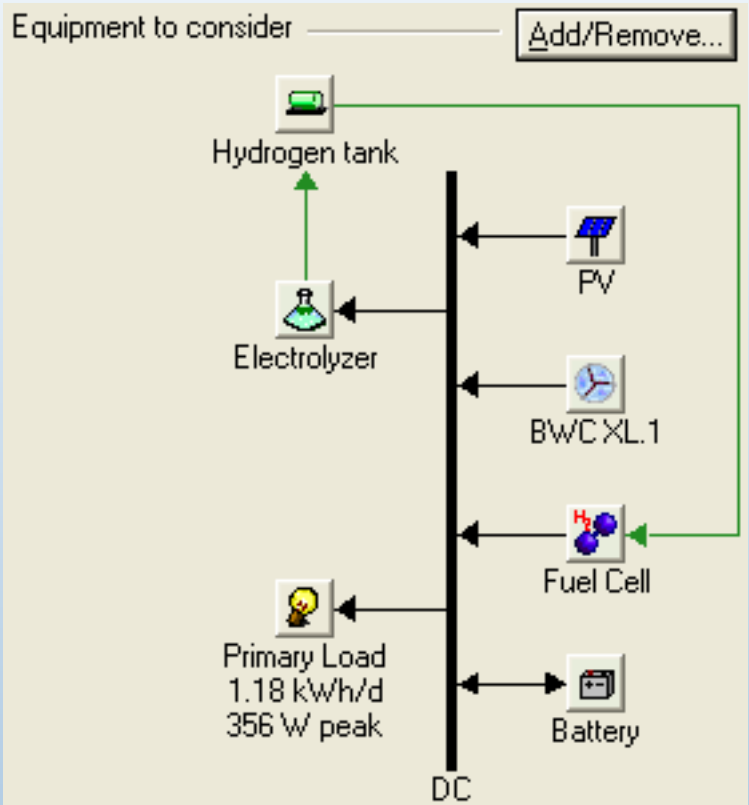
Skill Set - Models

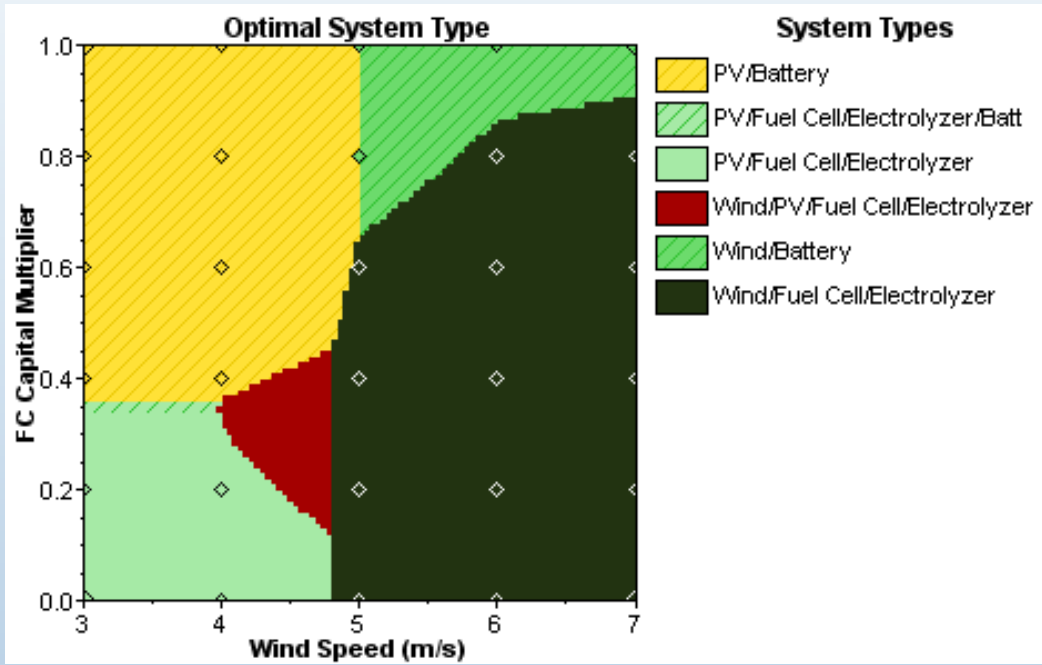
Energy Market Analysis

- HOMER, The Micropower Optimization Model, 1993-current use
  - Originally a linear program in GAMS, now a more flexible optimization model in Visual C++
  - 8760 hourly chronological optimization model with sensitivity analyses
  - Distributed generation project analysis
  - Instead of focusing strictly on H2, HOMER compares all DG technologies and determines the most economic mix of technologies to meet an electric and/or hydrogen demand.

NREL HOMER

Example Results





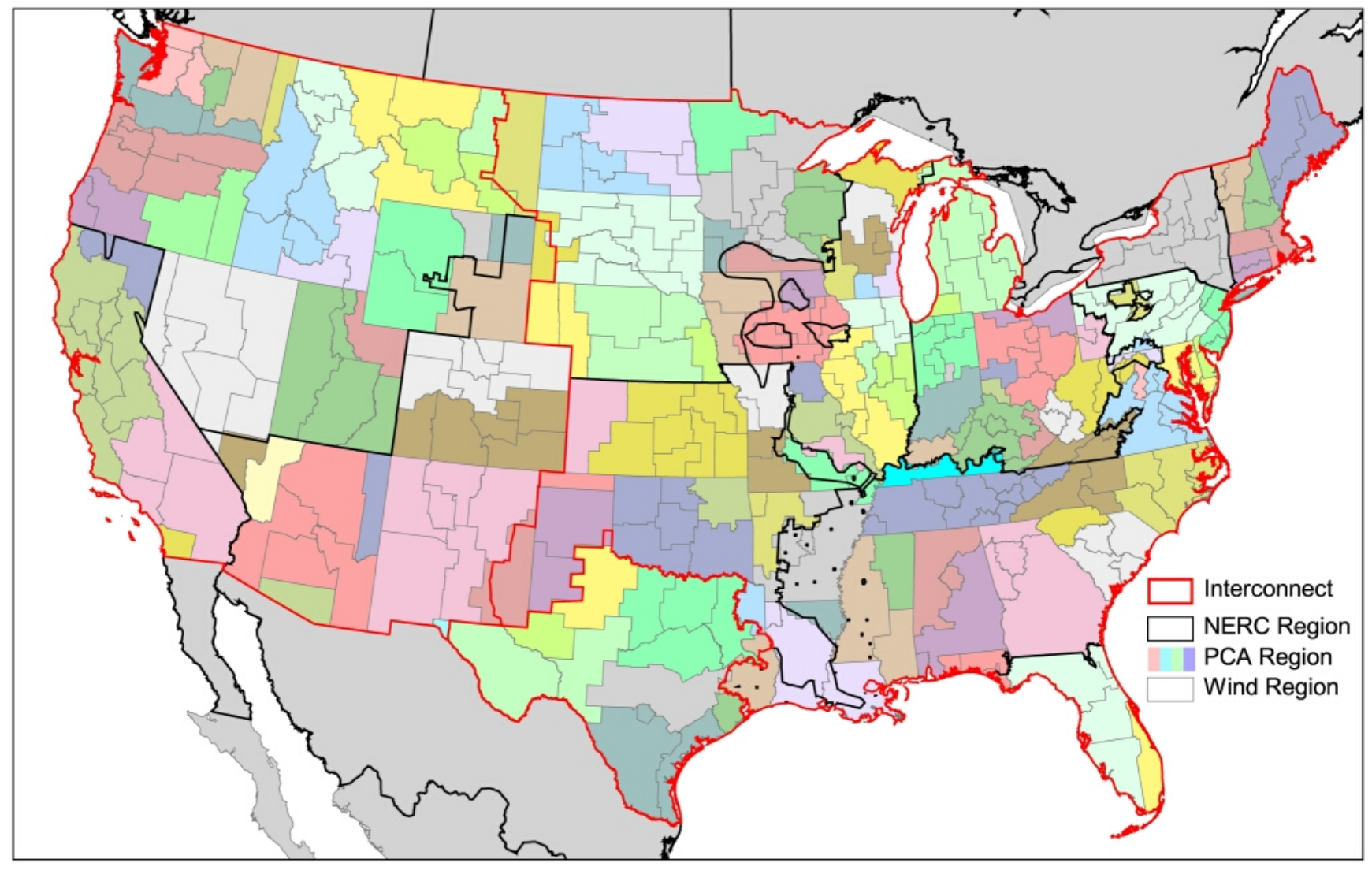
Skill Set - Models

Energy Market Analysis

- WinDS-H2 (**Win**d **D**eployment **S**ystems model with **H**ydrogen), 2003-current use
  - Projects U.S. market penetration of wind energy systems for electricity and hydrogen production through 2050 in competition with other sources of distributed hydrogen production and electricity generation
  - Platform: GIS (ArcInfo) and Linear Programming (GAMS) with Excel spreadsheet inputs and outputs
  - Limitations:
    - Assumes a market price for H2 (can vary over time); wind and other distributed systems contribute if they are competitive at that price
    - Cannot model discrete pipeline sizes (i.e., built at exactly the size needed with linear cost per unit capacity and length)
    - Cannot model economies of scale associated with distributed electrolysis and steam methane reforming plants.
    - Complex optimization model requiring experienced user.

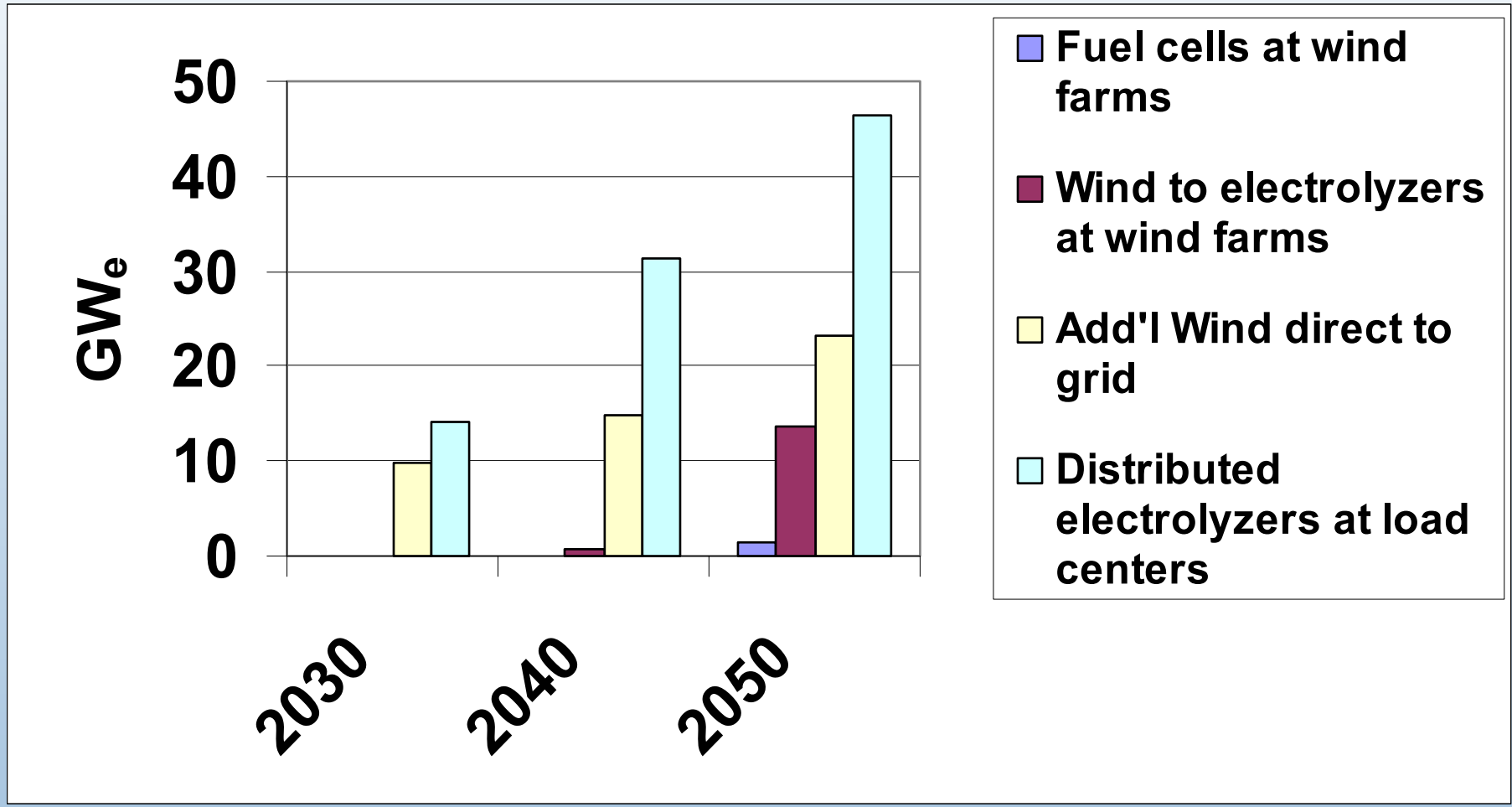
WinDS-H2 Regions

(358 regions, with electric transmission detail and cross-regional supply/demand)



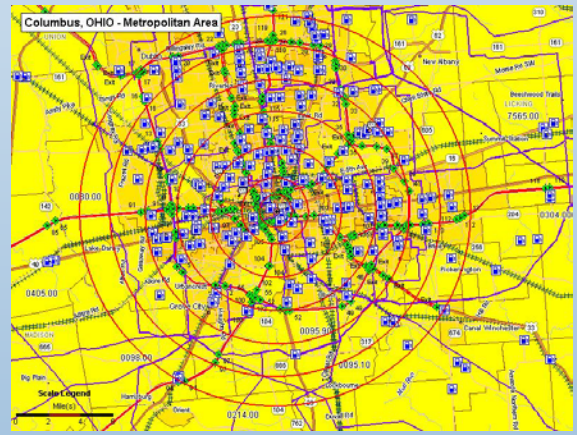
WinDS-H2 Results

Capacities in the Base Case



Skill Set – NREL Subcontracts

- Tellus Institute
  - Hydrogen production in a greenhouse gas constrained situation
- University of California, Davis – Joan Ogden
  - Technical and economic studies of regional transition strategies toward widespread use of hydrogen



Future

- No great development effort is planned:
  - The NREL Hydrogen Analysis Group plans to add to its portfolio of studies and models by building on its existing capabilities and knowledge of hydrogen systems.
- Specific areas of growth:
  - General energy market model that explicitly addresses market uncertainties (e.g., carbon taxes, fuel prices, etc.).
  - Pathway analysis, which will link existing models and previous studies

Analysis Issues

- **Desperately need:**
  - **Coordination**
  - **Cooperation**
  - **Interaction**
  - **Peer-review**
- Specific areas that analysis should shed light on:
  - Future policy relating to renewable and hydrogen (e.g., tax credits, tax structure, carbon emissions)
  - Under what scenarios and market conditions will a hydrogen economy be necessary and flourish?
  - Future deployment cost of hydrogen components
  - Fuel cell vehicle system design
  - Technology choice
  - Transition vs end-point analysis