NATIONAL RENEWABLE ENERGY LABORATORY
Innovation for Our Energy Future

Cost and GHG Implications of Hydrogen for Energy Storage

2010 Hydrogen Program Annual Merit Review

Darlene M Steward

National Renewable Energy Laboratory

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Project ID # AN006

Overview

Timeline

- Start: October 2008
- End: September 2010 (expected to continue in FY11)
- Complete: 75% (FY2010 work)

Barriers

- Stove-piped/Siloed Analytical Capability [4.5.B]
- Suite of Models and Tools [4.5.D]
- Unplanned Studies and Analysis [4.5.E]

Budget

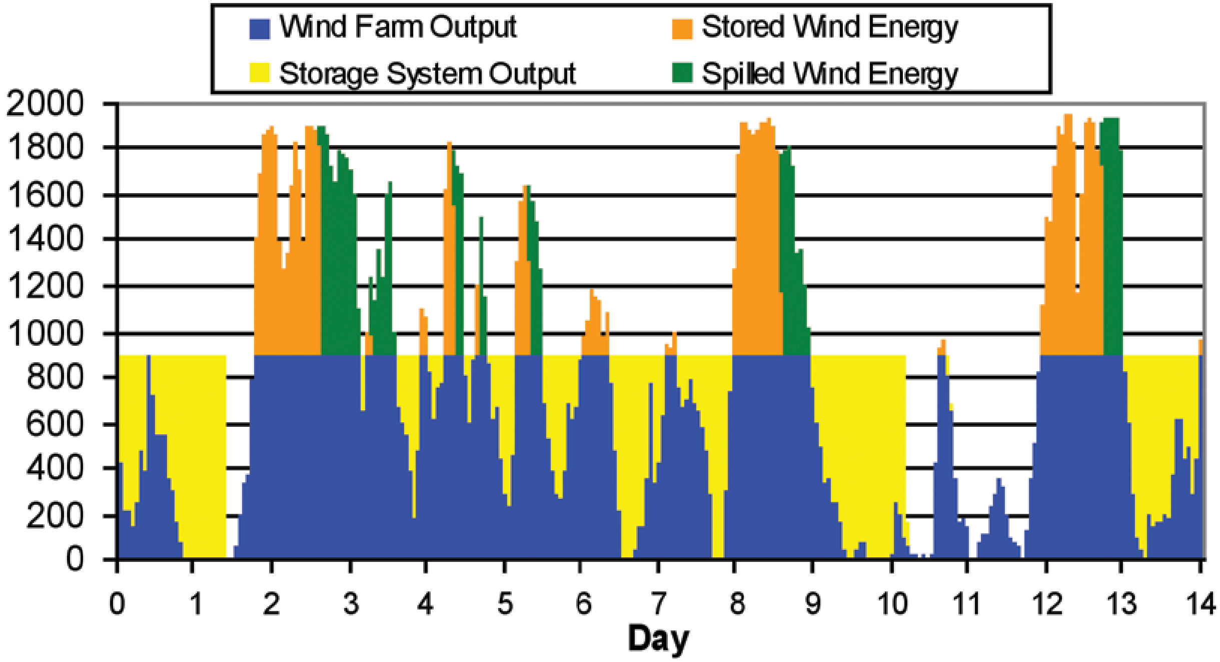
- Total Project Funding: $190k
  - 100% DOE-funded
- FY2009: $150k
- FY2010: $40k

Partners

- NREL H2 analysts
- NREL Strategic Energy Analysis Center analysts
- Pacific Northwest Laboratory
- Xcel Energy

Relevance: Hydrogen has Unique Attributes as an Energy Storage Medium

The Potential Value of Energy Storage - Make variable and unpredictable renewable resources dispatchable



Source: Denholm, Paul. (October 2006). “Creating Baseload Wind Power Systems Using Advanced Compressed Air Energy Storage Concepts.” Poster presented at the University of Colorado Energy Initiative/NREL Symposium. http://www.nrel.gov/docs/fy07osti/40674.pdf

Hydrogen could play duel role as a storage medium for electricity and as a fuel for vehicles.

Relevance: Lifecycle Cost Analysis Used to Evaluate Hydrogen Energy Storage

Facility lifecycle cost analysis used for both Task 1 and Task 2

Objective for Task 1

Evaluate the economic viability of using hydrogen for utility-scale energy storage applications in comparison with other electricity storage technologies

- Simple energy arbitrage scenario
- Analysis of potential for cost Improvements over time

Objective for Task 2

Explore the cost and GHG emissions impacts of interaction of hydrogen storage and variable renewable resources

- Specific locations and wind profiles
- Hourly energy analysis to capture detail

Relevance: Impact on Barriers

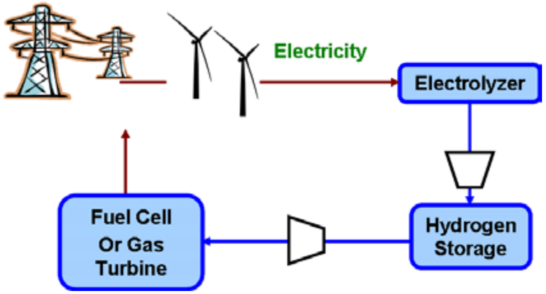
Barrier	***Impact***
Stove-piped/Siloed Analytical Capability [4.5.B]	•Competing hydrogen against other technologies in a lifecycle cost analysis provides context for results. •Analysis of production of excess hydrogen for vehicles integrates transportation and electricity sectors
Suite of Models and Tools [4.5.D]	• HOMER model provides a consistent, detailed platform for lifecycle cost analysis of varied suite of technologies •Fuel Cell Power model modified to evaluate storage integrates hourly energy analysis capability with H2A economic analysis capabilities •Results from storage studies can be evaluated geographically in the SERA model
Unplanned Studies and Analysis [4.5.E]	•Analysis integrating renewable resources (wind and solar) in specific locations with hydrogen storage

Approach: Milestones

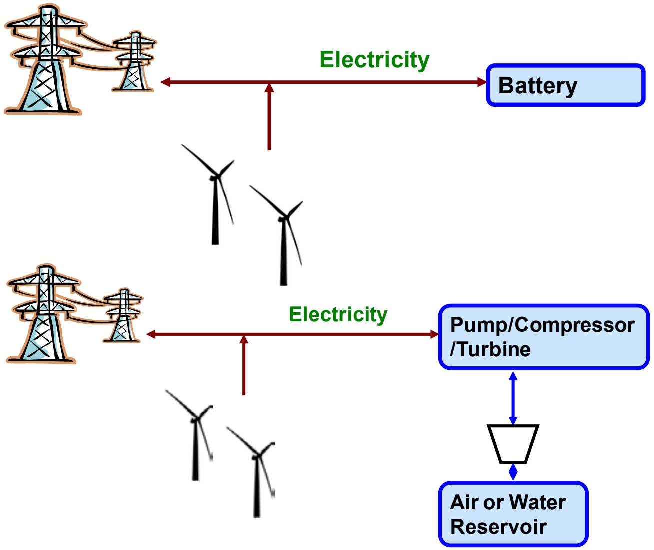
Milestone	***Title***	***Date***	***Status***
Task 1	Working draft energy storage scenario cost/ benefit analysis	Aug 2009	Complete
Task 1	Draft final energy storage scenario cost/ benefit analysis	Sept 2009	Complete
	Report published	Nov 2009	Complete
Task 2	Briefing on GHG avoided emissions and cost implications for carbon policy	Mar 2010	Complete

Approach: Task 2 Refines & Builds Upon the Results from Task 1

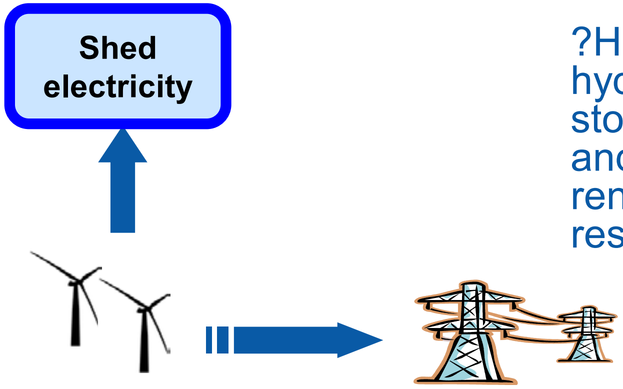
Task 1: Compare costs for hydrogen and competing technologies



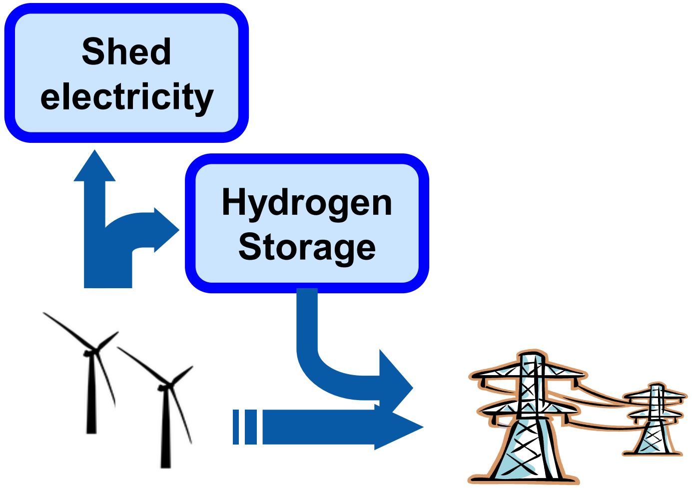
?Is hydrogen a potential solution for utility-scale energy storage



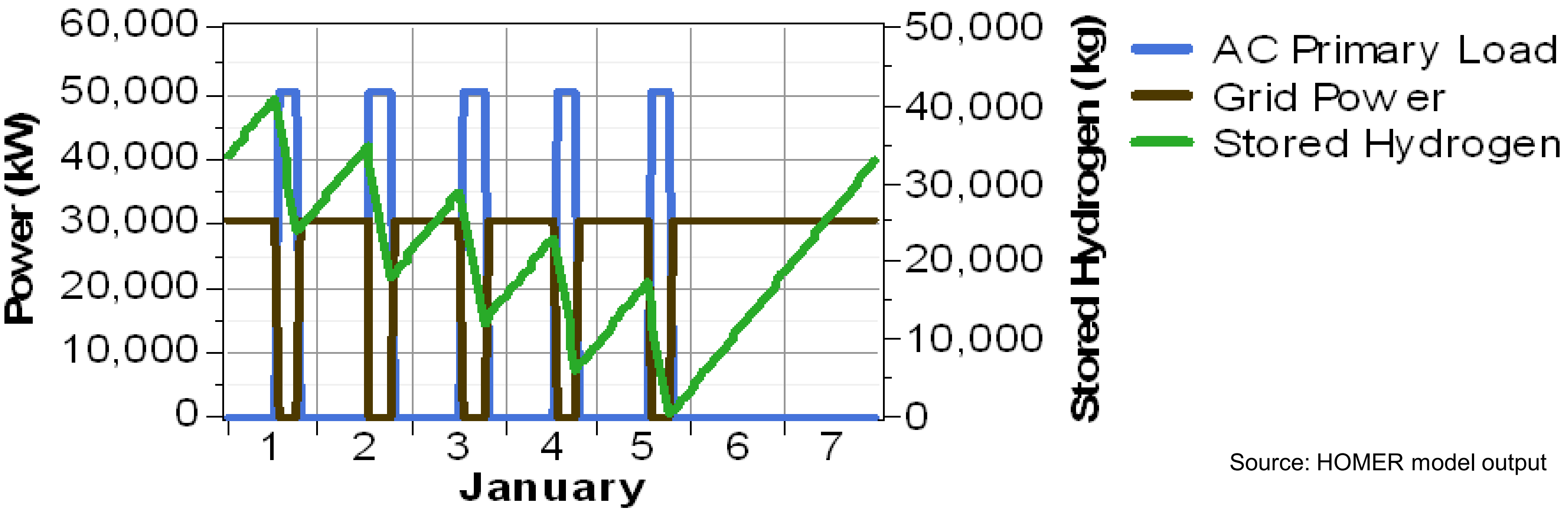
Task 2: Study of hydrogen energy storage for a specific renewable resource



?How would using hydrogen for storage impact cost and emissions for renewable resources



Task 1 Approach: Compete Hydrogen with Alternative Technologies for Simple Energy Arbitrage Scenario



Source: HOMER model output

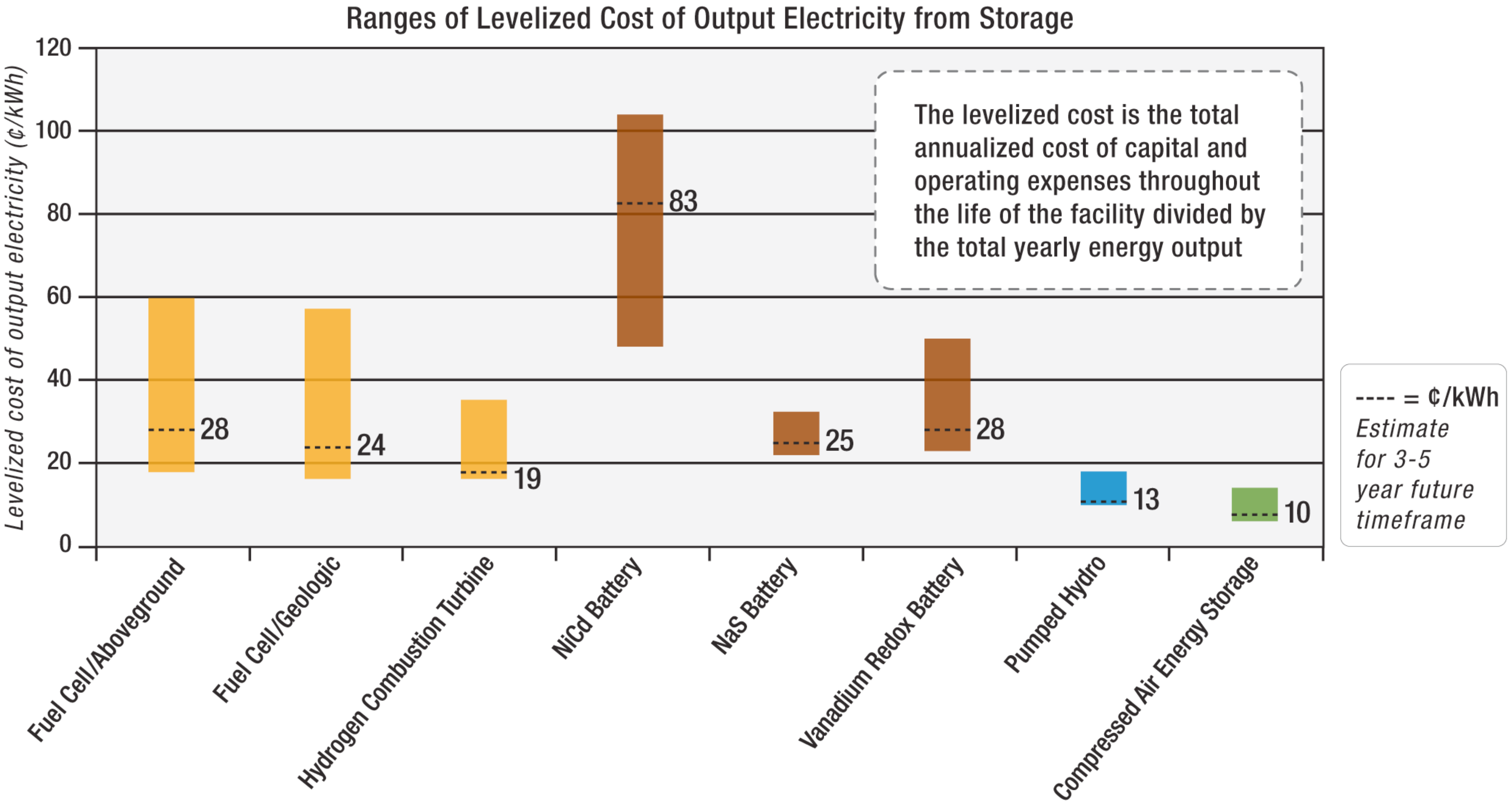
Nominal storage volume is 300 MWh (50 MW, 6 hours)

- Electricity is produced from the storage system during 6 peak hours (1 to 7 pm) on weekdays
- Electricity is purchased during off-peak hours to charge the system

Electricity source: excess wind/off-peak grid electricity

- Assumed steady and unlimited supply during off-peak hours (18 hours on weekdays and 24 hours on weekends)
- Assumed fixed purchase price of off-peak/renewable electricity

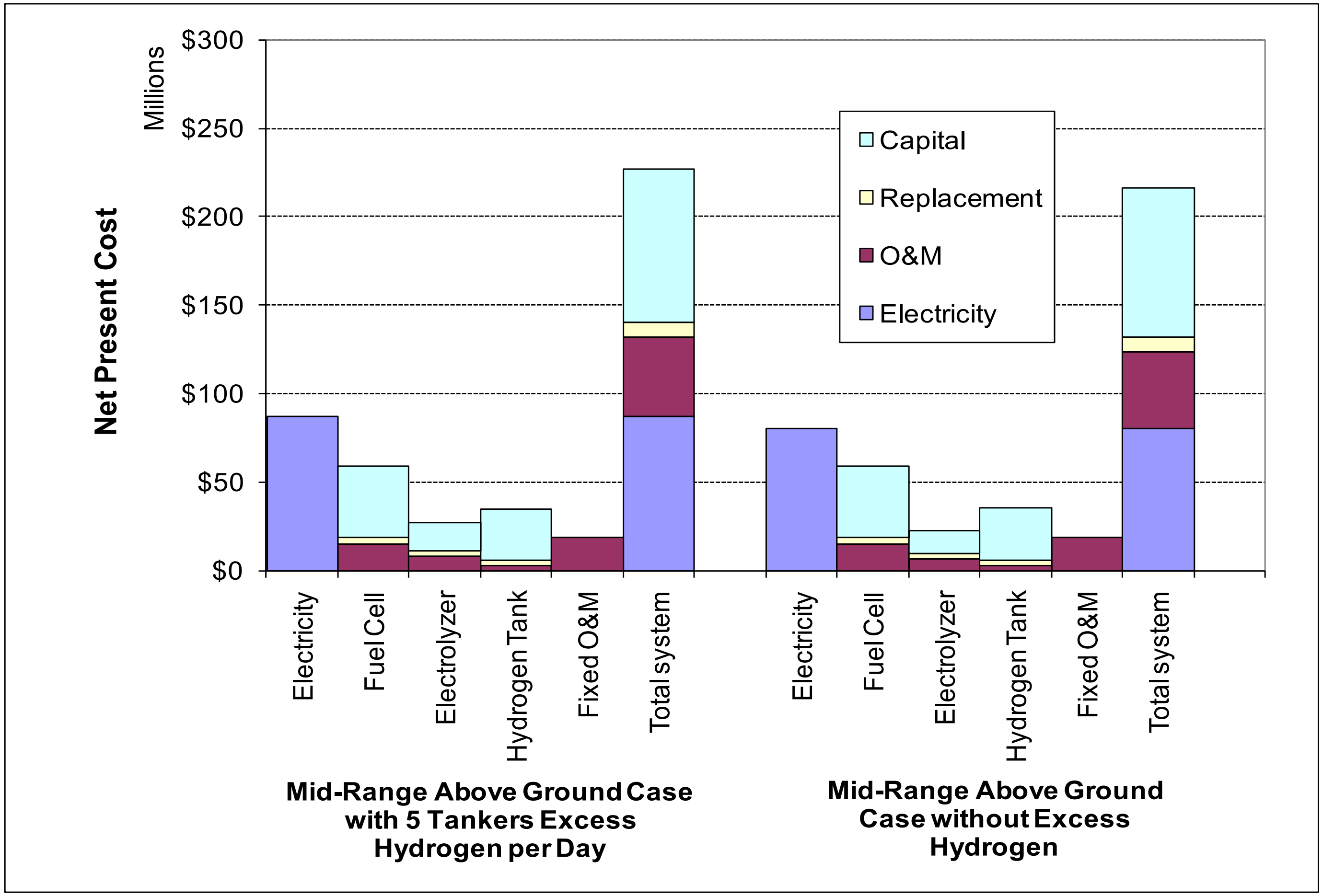
Task 1 Accomplishments: Levelized Cost Comparison of Hydrogen and Competing Technologies



The levelized cost is the total annualized cost of capital and operating expenses throughout the life of the facility divided by the total yearly energy output

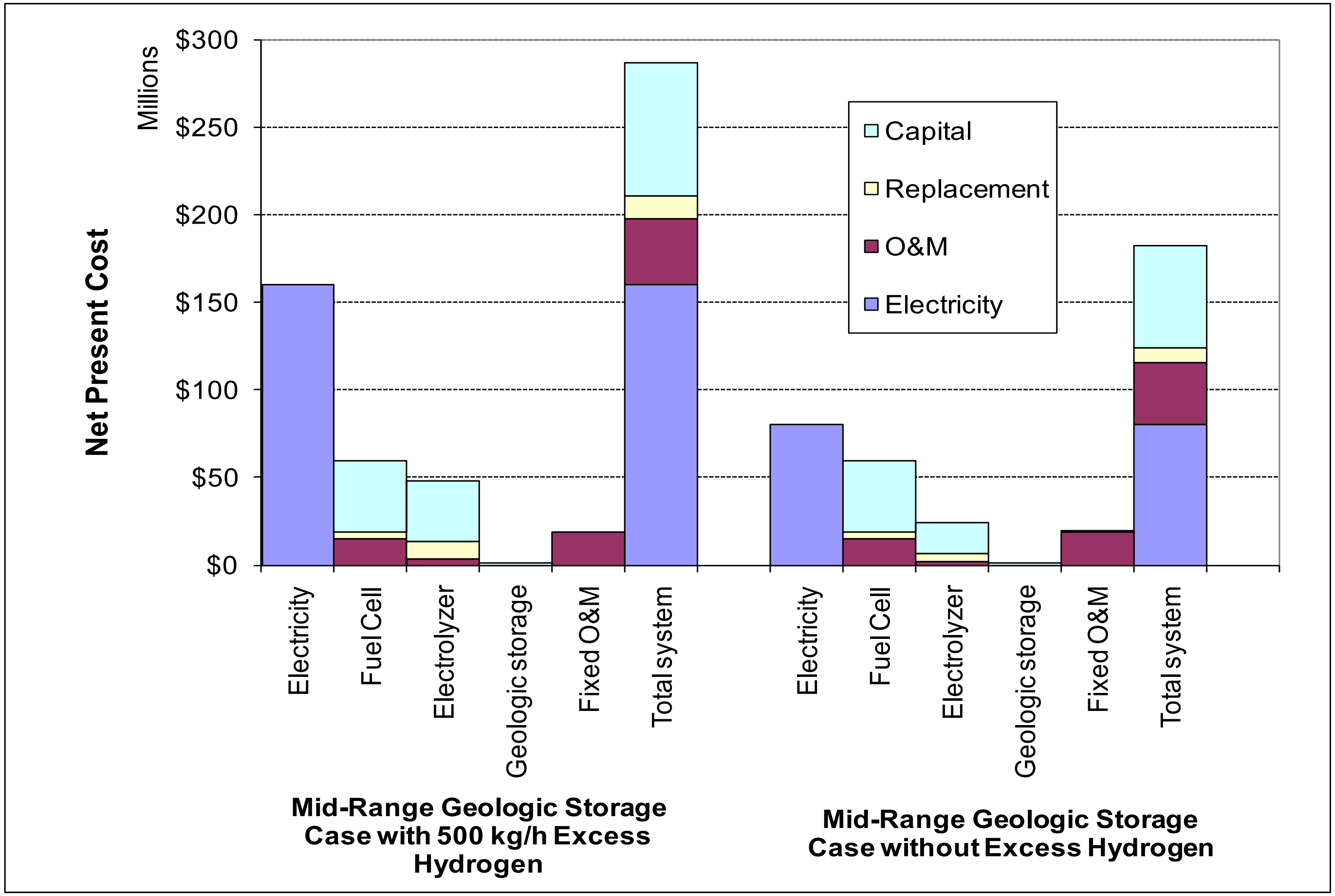
Hydrogen is competitive with batteries and could be competitive with CAES and pumped hydro in locations that are not favorable for these technologies.

Task 1 Accomplishments: Hydrogen Energy Storage System with 1,400 kg Excess Hydrogen per Day—NPC



- **Five tankers of excess hydrogen per day (1,400 kg/day)**
  - Electrolyzer and hydrogen tank slightly larger for the excess hydrogen case than for the case without excess hydrogen
  - Hydrogen LCOE of $4.69/kg (not including tanker truck transport and dispensing)
  - Compares to ~$4 for production portion of electrolysis forecourt station

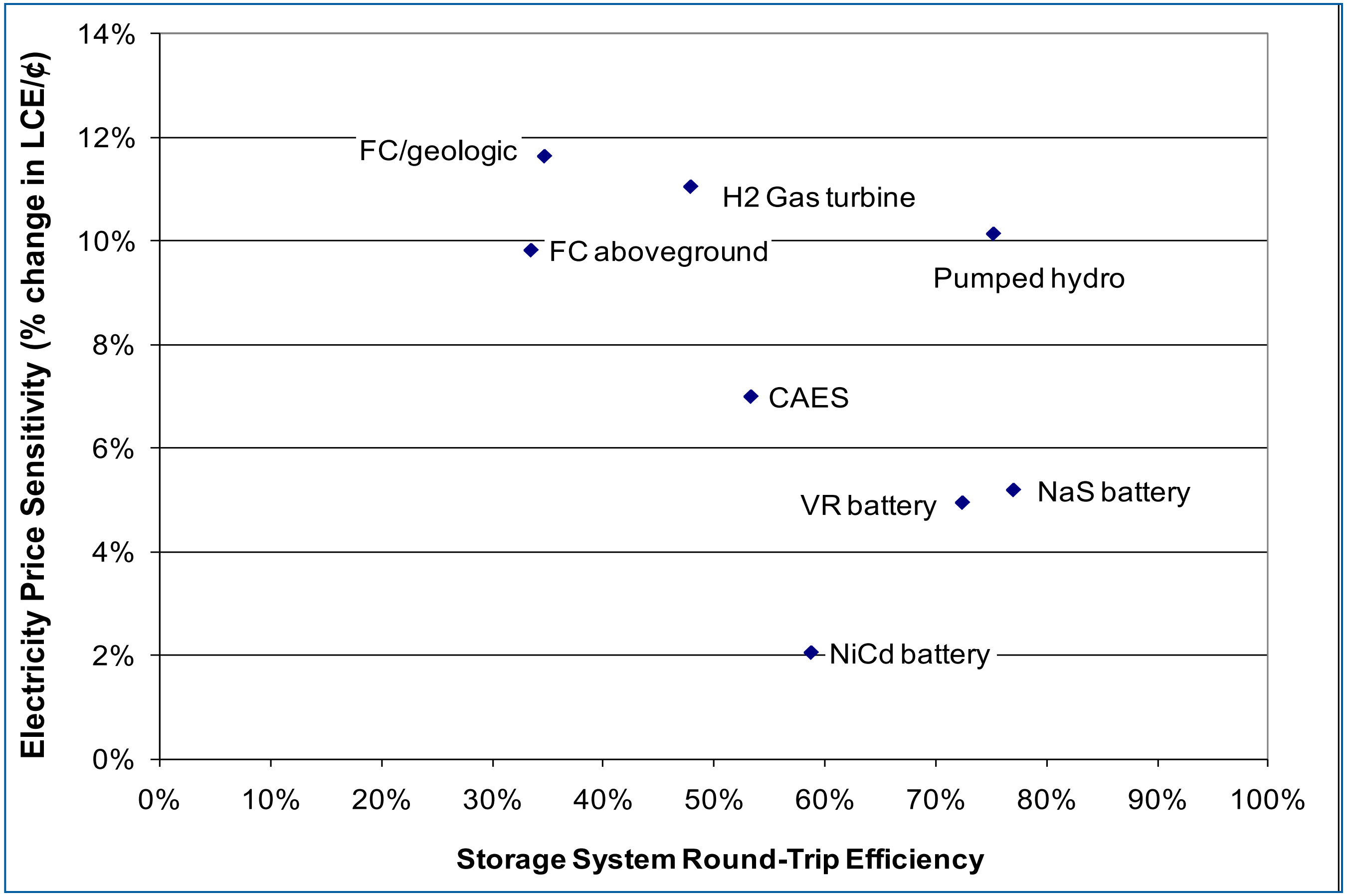
Task 1 Accomplishments: Hydrogen Energy Storage System with 12,000 kg Excess Hydrogen per Day—NPC



- **500 kg/h of excess hydrogen (12,000 kg/day)**
  - Electrolyzer approximately doubled in size in comparison to the case without excess hydrogen
  - Hydrogen LCOE of $3.33/kg (not including tanker truck transport and dispensing)
  - Compares to ~$7 for electrolysis at a central production facility of the same size

Task 1 Accomplishments: Round-Trip Efficiency and Electricity Price Sensitivity

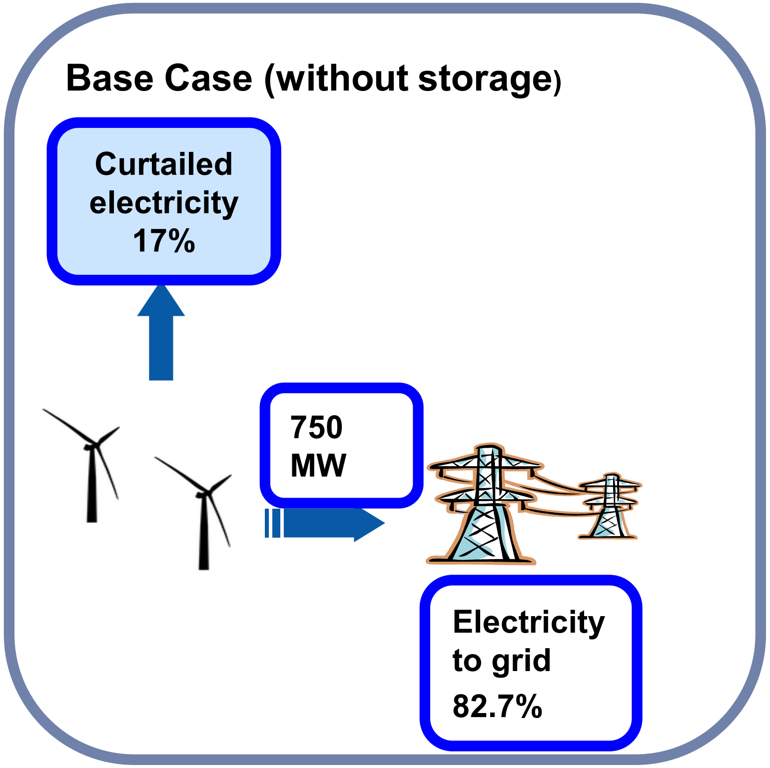
Sensitivity to electricity price is roughly inversely proportional to round-trip efficiency



- Low-capital-cost, high-efficiency pumped hydro system is sensitive to electricity price
- High-capital-cost NiCd system is insensitive to electricity price

Task 2 Approach: Study Framework - Add Hydrogen Storage to a Base Case Without Storage

Analysis of the base case provides LCOE and avoided emissions for comparison

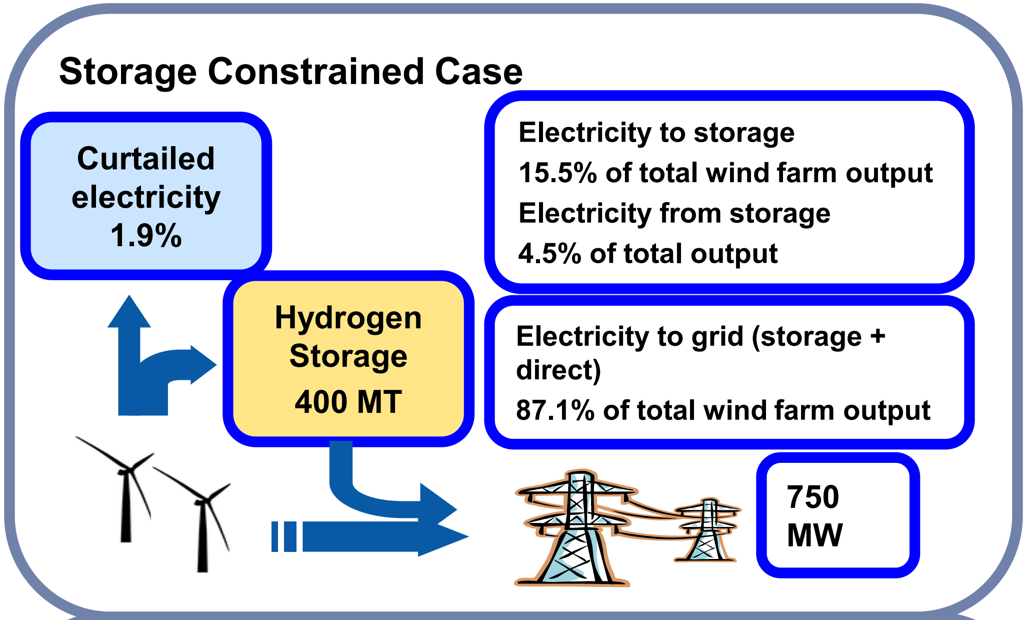


Base Case (without storage)

Curtailed electricity 17%

750 MW

Electricity to grid 82.7%



Storage Constrained Case

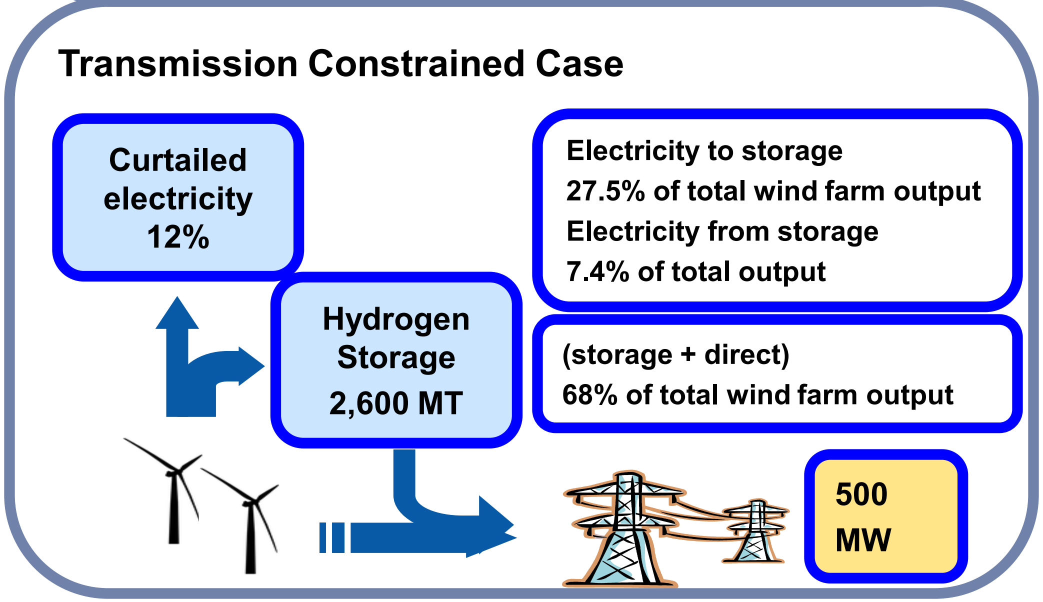
Curtailed electricity 1.9%

Hydrogen Storage 400 MT

Electricity to storage
15.5% of total wind farm output
Electricity from storage
4.5% of total output

Electricity to grid (storage + direct)
87.1% of total wind farm output

750 MW



Transmission Constrained Case

Curtailed electricity 12%

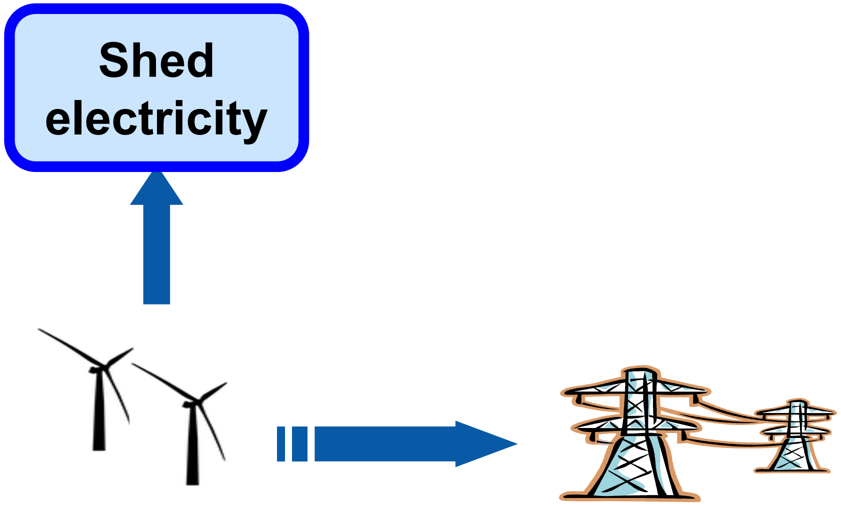
Hydrogen Storage 2,600 MT

Electricity to storage
27.5% of total wind farm output
Electricity from storage
7.4% of total output

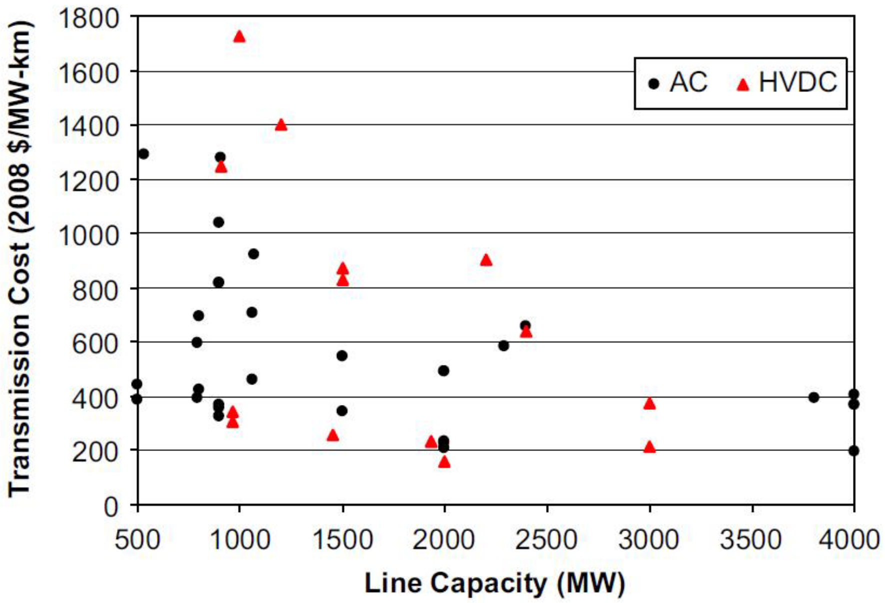
(storage + direct)
68% of total wind farm output

500 MW

Task 2 Approach: Configure a Base Case Without Storage



Shed electricity

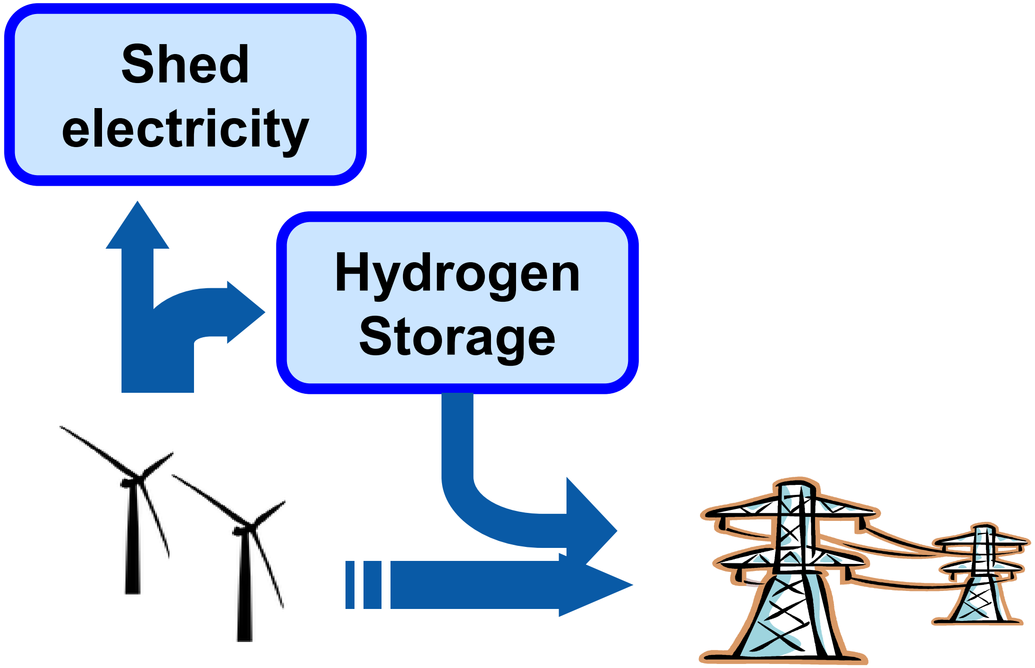


*Source: P. Denholm, R. Sioshansi, Energy Policy 37 (2009) 3149-3158

Base Case Configuration

- Power from the wind farm is routed to the transmission line up to the maximum capacity of the line (MW)
- Power from the wind farm will be curtailed (shed) if it exceeds the maximum capacity of the transmission line
- Transmission line cost per MW capacity trend decreases with increasing capacity.

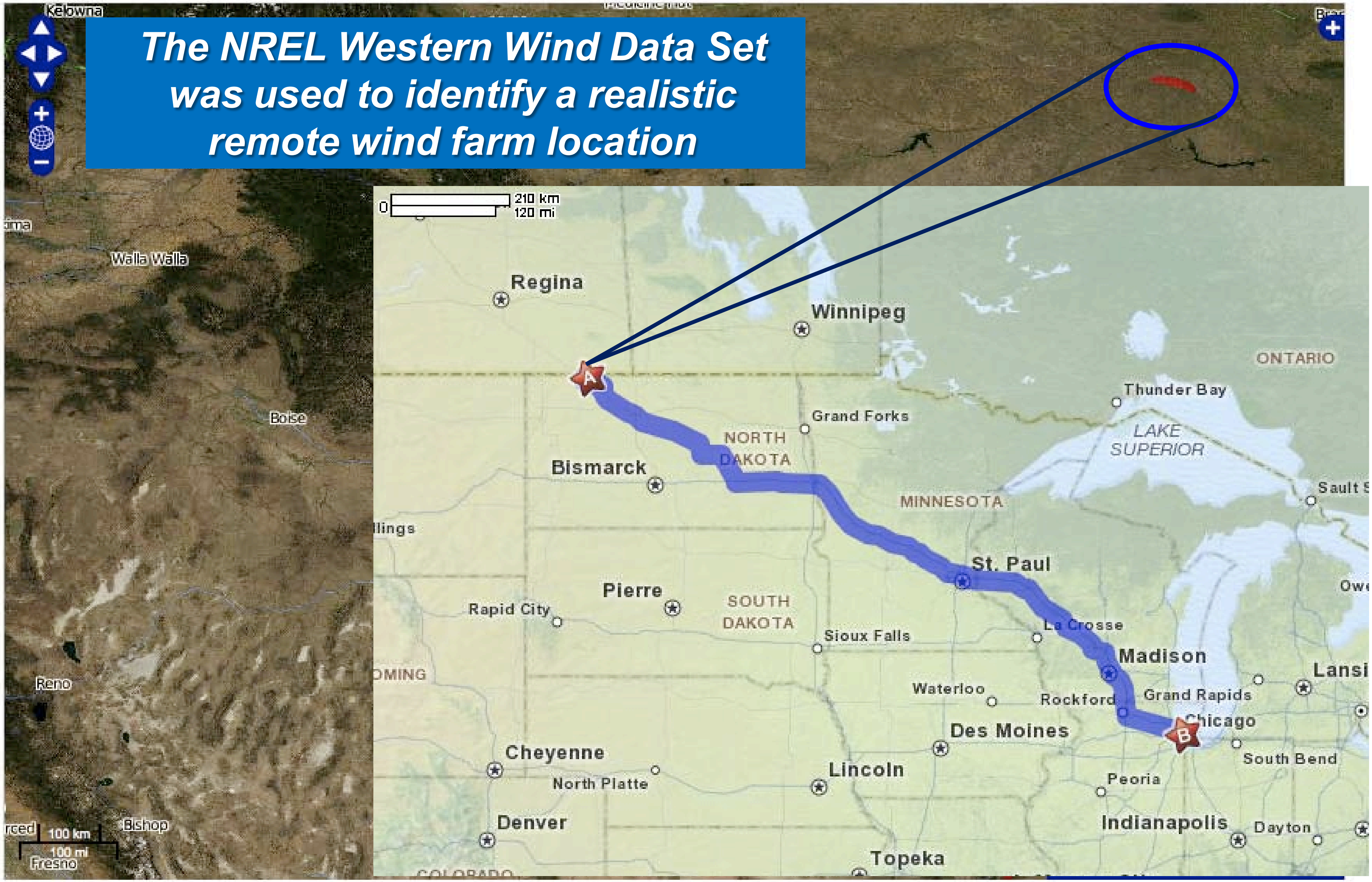
Task 2 Approach: Add Hydrogen Storage to the Base Case



Major Assumptions

- Electrolyzer and PEM fuel cell performance and cost values derived from mid-cost case of lifecycle cost analysis
- Hydrogen storage in geologic storage
- The storage system is located at the wind farm & all electricity charged to the storage system is derived from the wind farm
- A dedicated transmission line carries electricity from the wind farm/storage system to the grid near demand centers.
- Power from the wind farm will be curtailed (shed) if:
  - It exceeds the maximum charging rate of the storage system + maximum capacity of the transmission line
  - The storage system is full

Task 2 Approach: Wind Farm Location



The NREL Western Wind Data Set was used to identify a realistic remote wind farm location

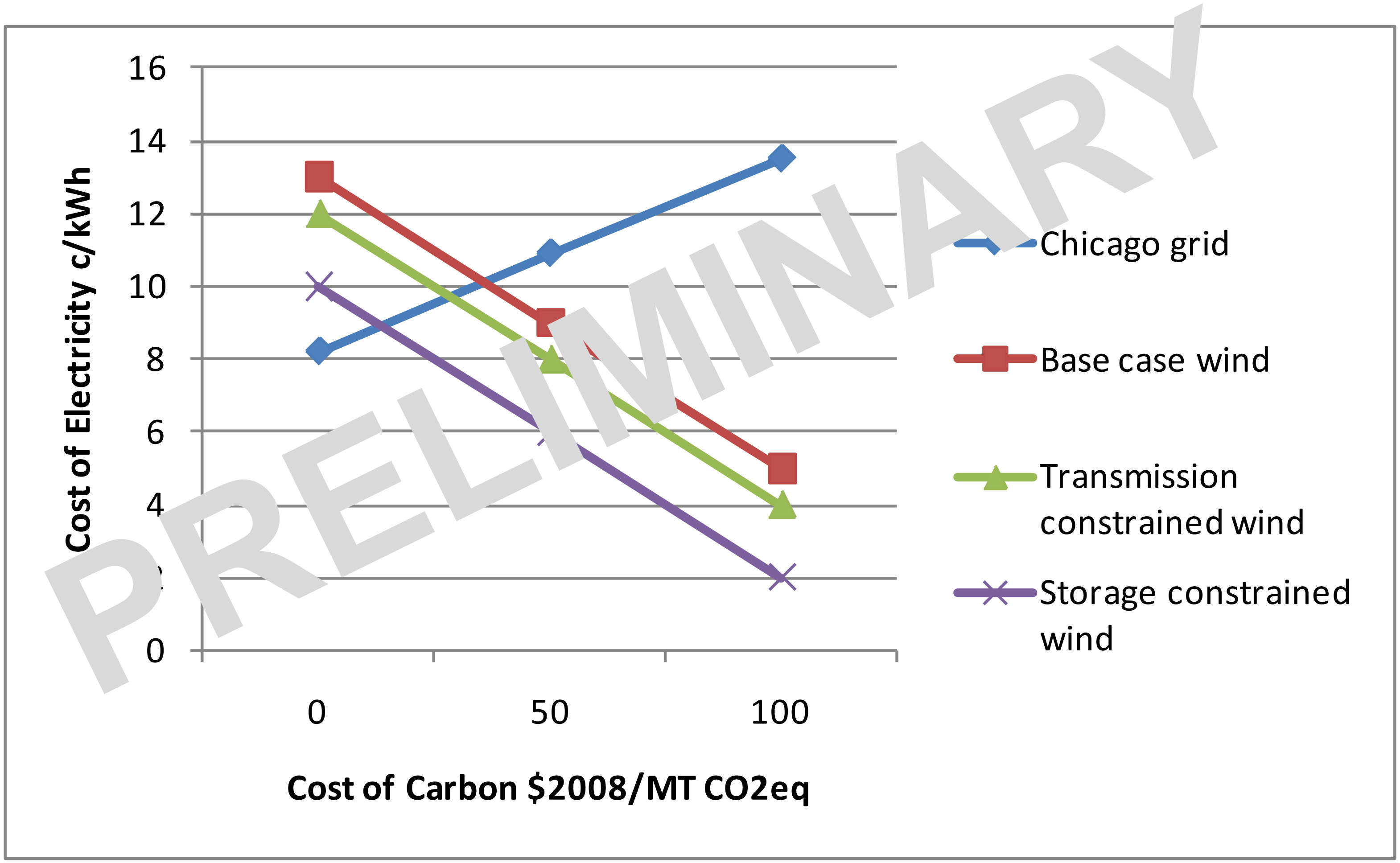
Task 2 Accomplishments: Preliminary Results

Storage reduces the amount of electricity that must be curtailed and reduces the LCOE

	Base Case	Storage Constrained	Transmission Constrained
	(% of Total Wind Farm Output)		
Electricity Direct from Wind Farm to Transmission Line	82.7	82.7	60.8
Electricity from Storage	N/A	4.5	7.4
Electricity Shed	17.3	1.9	11.7
Net Electricity to Transmission Line	82.7	87.2	68.2
	(% of Total Transmission Line Capacity)		
Transmission Line Utilization	56.0	59.0	69.0
	(LCOE ¢/kWh)		
Without cost of carbon	13	10	12
@ cost of carbon $50/MT CO2eq	9	6	8
@ cost of carbon $100/MT CO2eq	5	2	4

Task 2 Accomplishments: Preliminary Results – Cost of Carbon

Credit for avoided emissions reduces LCOE for wind electricity below grid price



Cost comparison for Chicago Grid Electricity v Wind Electricity for Various Storage Configurations

Summary

Relevance	• Comparison of hydrogen and other technologies for energy storage forms a basis for future research and analysis work. • Hydrogen could bridge power and transportation sectors • Hydrogen storage could provide an advantage for large scale isolated renewables
Approach	• Comparison of hydrogen to alternative technologies in a facility lifecycle cost analysis for a simple scenario • Extension of results to analysis of hydrogen storage for a realistic case study for an isolated wind farm.
Accomplishments	• Hydrogen is competitive with batteries and could be competitive with CAES and pumped hydro in locations that are not favorable for these technologies. • Hydrogen storage could reduce the amount of electricity that must be curtailed and reduce the LCOE for an isolated wind farm.
Collaborations & Reviewers	• Xcel Energy • NREL H2 analysis team, NREL Strategic Energy Analysis team • Pacific Northwest National Laboratory
Proposed Future Work	• Optimization of electrolyzer, storage capacity, fuel cell and transmission • Analysis of solar installations and additional wind sites

Proposed Future Work

- Develop a methodology for optimizing the size of the storage system components and transmission to minimize costs for an isolated wind farm or solar installation
- Perform an analysis for an isolated solar installation
- Compare greenhouse gas emissions/carbon tax implications for hydrogen storage and compressed air energy storage.

Supplemental Slides

Approach Task 1: Compete Hydrogen with Alternative Technologies for Simple Energy Arbitrage Scenario

Study Framework

- Basic energy arbitrage economic analysis
  - Lifecycle costs including initial investment, operating costs, and future replacement costs
  - Results presented as levelized cost of delivered energy ($/kWh)
- Benchmark against competing technologies on an “apples to apples” basis
  - Batteries
  - Pumped hydro
  - Compressed air energy storage
- Cost Analysis Performed Using the HOMER Model (HOMER Energy, www.homerenergy.com)

Timeframes

High cost or “current” technology

Mid-range cost

Some installations exist

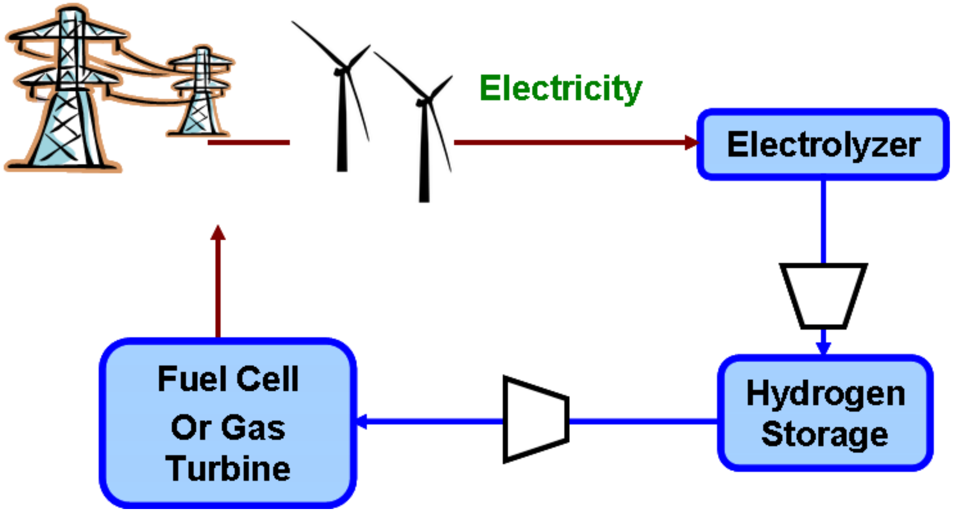
Some cost reductions for bulk manufacturing and system integration have been realized

Installations are assumed in the near future: 3 to 5 years

Low-range cost

Estimates for fully mature technologies and facility experience

Approach Task 1: Hydrogen Scenarios—Major Assumptions

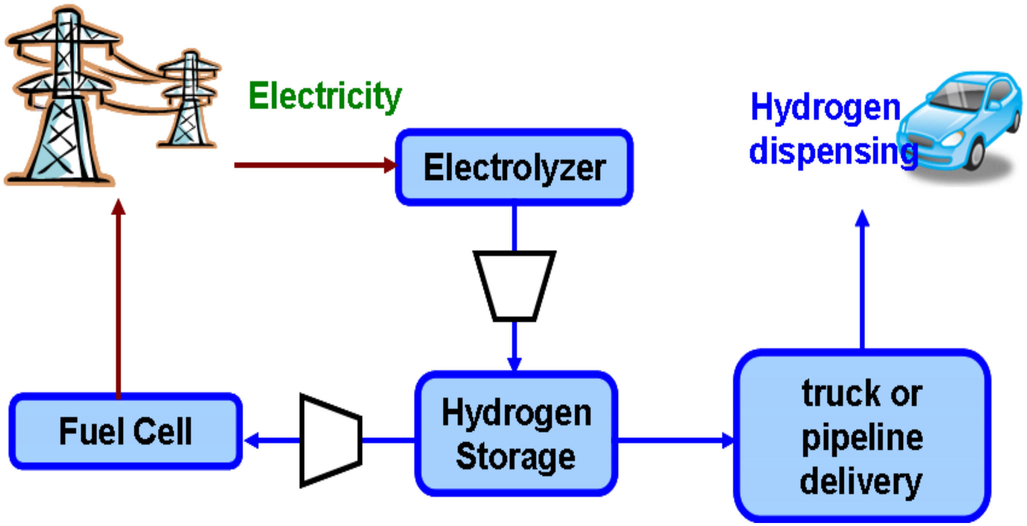


Electricity

Electrolyzer

Hydrogen Storage

Fuel Cell Or Gas Turbine



Electricity

Electrolyzer

Hydrogen dispensing

Fuel Cell

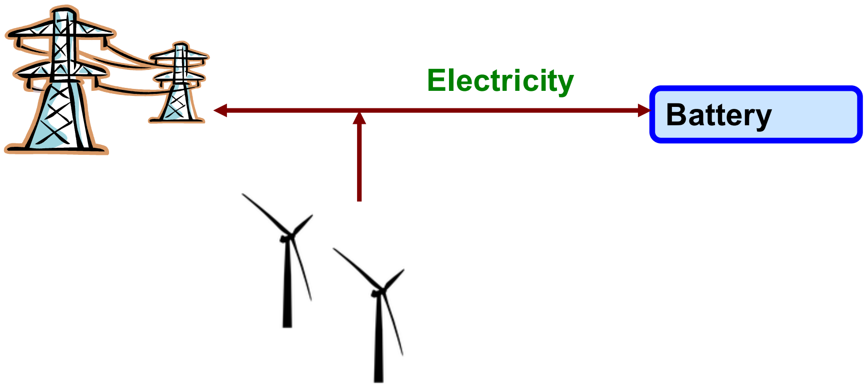
Hydrogen Storage

truck or pipeline delivery

Major Assumptions

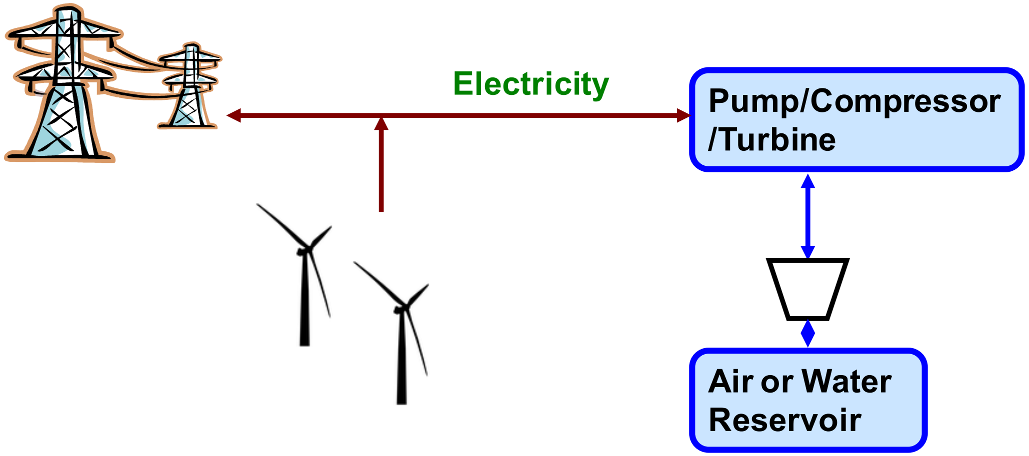
- Electrolyzer performance and cost based on alkaline electrolyzers operated at 435 psi, 80°C
- Polymer electrolyte membrane (PEM) air cooled fuel cell operated at ~ 30 psi
- Hydrogen storage in aboveground steel tanks or geologic storage
  - Hydrogen storage losses assumed minimal
  - Compression energy not recovered
- Hydrogen delivery and dispensing not included in the analysis of excess hydrogen for vehicles

Approach Task 1: Batteries, Pumped Hydro, & CAES—Major Assumptions



Electricity

Battery



Electricity

Pump/Compressor /Turbine

Air or Water Reservoir

Major Assumptions

- Power conversion system for battery round-trip efficiency is 90%.
- Pumped hydro and CAES systems do not require separate power conversion system.
- For compressed air storage systems, compression heat is not stored. Air from the storage system is heated with turbine exhaust gas.

Accomplishments Task 1: Cost Implications for Hydrogen Systems

- Costs could be reduced by increasing the round-trip efficiency.
    - Fuel cell efficiency has a bigger impact on LCOE than electrolyzer efficiency.
        - ~ 0.5% change in LCOE per percent change in fuel cell efficiency
        - ~ 0.2% change in LCOE per percent change in electrolyzer efficiency

- Cost could be reduced if a reversible fuel cell with higher round-trip efficiency were developed.
- Hydrogen is competitive with battery technologies for this application and could be competitive with CAES and pumped hydro in locations that are not favorable for these technologies

- Excess hydrogen could be produced for the transportation market.

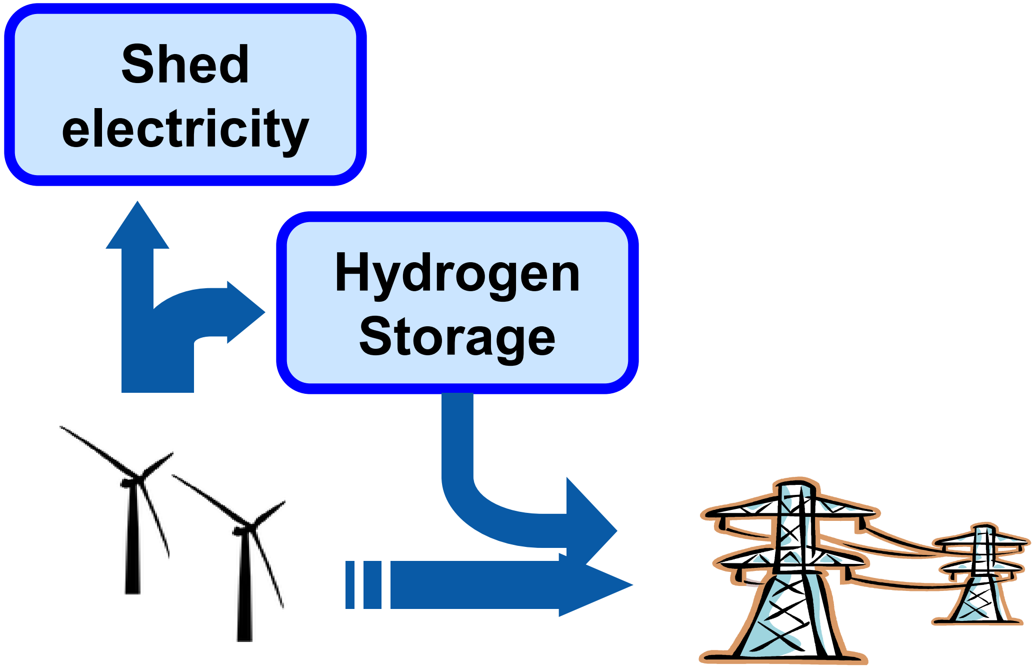
- Hydrogen has several important advantages over competing technologies, including:
- Hydrogen has very high storage energy density (170 kWh/m3 vs. 2.4 for CAES and 0.7 for pumped hydro).
- Allows for potential economic viability of aboveground storage
- Hydrogen could be co-fired in a combustion turbine with natural gas to provide additional flexibility for the storage system.

- The major disadvantage of hydrogen energy storage is cost.
- Research and deployment of electrolyzers and fuel cells may reduce cost significantly.

Accomplishments Task 1: Conclusions

- Hydrogen is competitive with battery technologies for this application and could be competitive with CAES and pumped hydro in locations that are not favorable for these technologies
- Excess hydrogen could be produced for the transportation market.
- Hydrogen has several important advantages over competing technologies, including:
  - Hydrogen has very high storage energy density (170 kWh/m3 vs. 2.4 for CAES and 0.7 for pumped hydro).
    - Allows for potential economic viability of aboveground storage
  - Hydrogen could be co-fired in a combustion turbine with natural gas to provide additional flexibility for the storage system.
- The major disadvantage of hydrogen energy storage is cost.
  - Research and deployment of electrolyzers and fuel cells may reduce cost significantly.

Approach Task 2: Study Framework – Storage Model



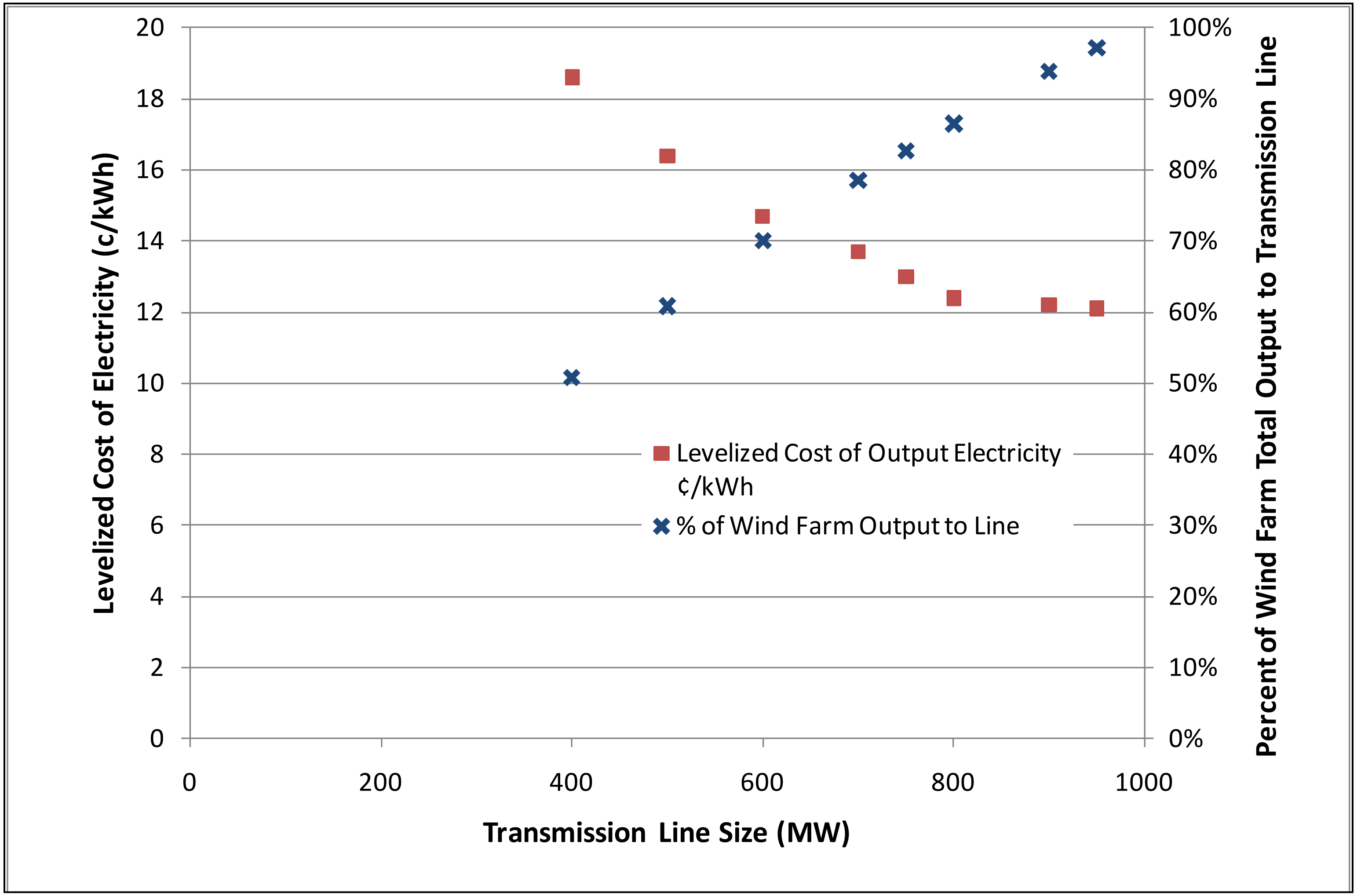
Shed electricity

Hydrogen Storage

Modeling constraints

- Modified FCPower model used for energy and cost modeling
- Power from the wind farm is first routed to the transmission line up to the maximum capacity of the line (MW)
- Electricity charging and discharge rates from the storage system are constrained by the size of the electrolyzer and fuel cell respectively
- Power from the wind farm will be curtailed (shed) if:
    - It exceeds the maximum charging rate of the storage system + maximum capacity of the transmission line
    - The storage system is full

Accomplishments Task 2: Base Case (wind farm without storage)



- ○ The benefit of increasing the transmission line size decreases as the transmission line size approaches 100% of the nameplate capacity of the wind farm (1,000 MW)