Integrated Nuclear-Renewable Hybrid Energy Systems

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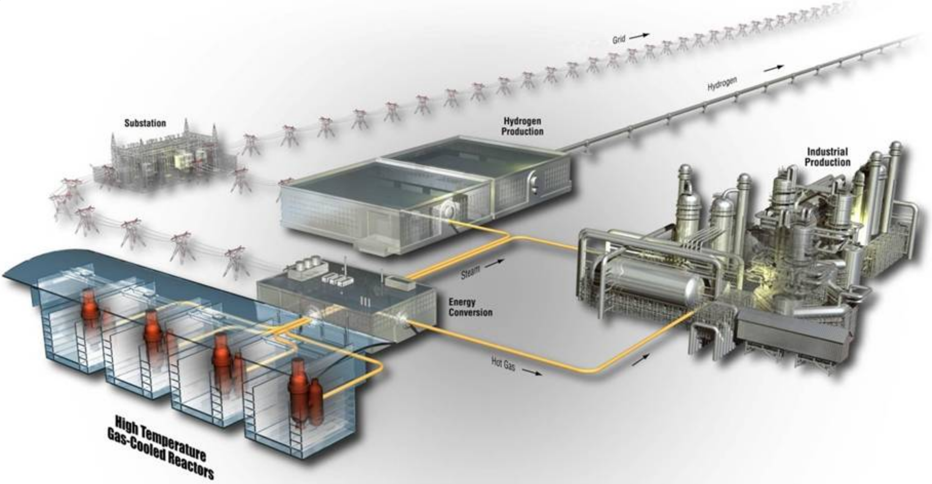
Nuclear Science & Technology

August 11, 2015



Curtiss-Wright Energy Symposium

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Idaho National Laboratory

Acknowledgements

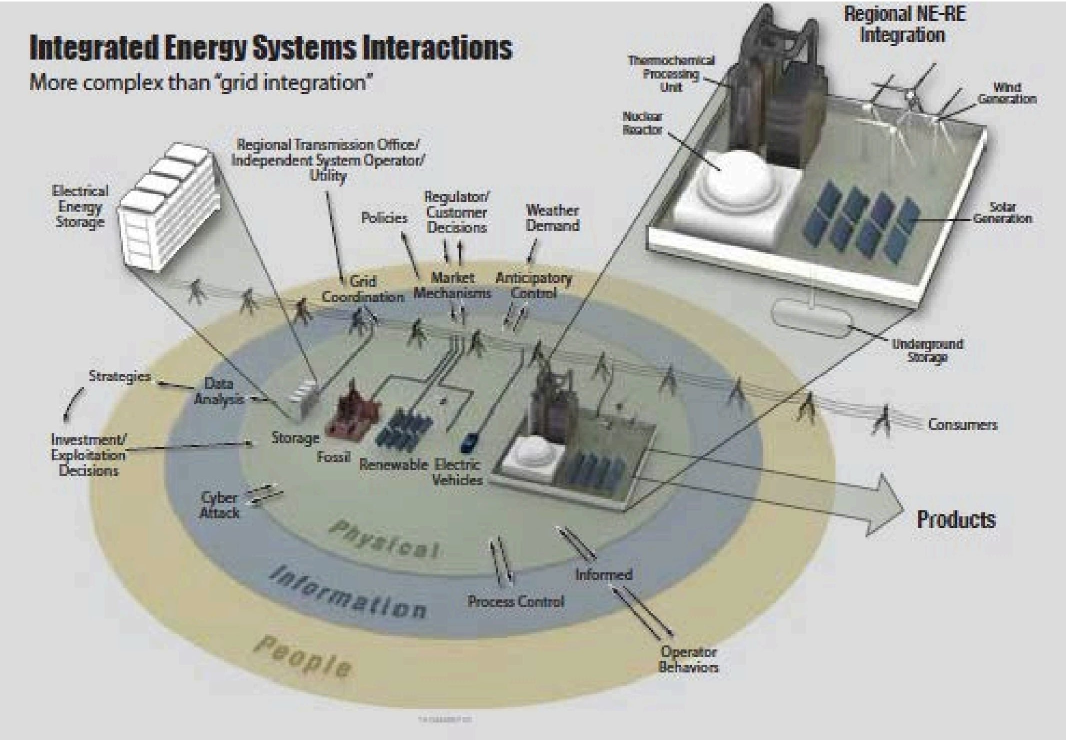
- Richard Boardman, NHES Co-Lead, INL Energy & Environment R&D
- Mark Ruth, NHES Lead for the National Renewable Energy Laboratory
- Charles Forsberg, NHES University Lead, MIT

- INL Technical Contributors:
  - Humberto Garcia
  - Cristian Rabiti
  - Michael McKellar
  - Wes Deason
  - Jong Suk Kim
  - Jun Chen

- This work is supported by the U.S. Department of Energy Office of Nuclear Energy Advanced Reactor Technologies Program.

Overview

- Brief definition of an integrated “hybrid” energy system
- The evolving grid:
  - Motivation for a new paradigm in energy generation and use
  - Options for grid flexibility
- Challenges to HES deployment
- Key research areas



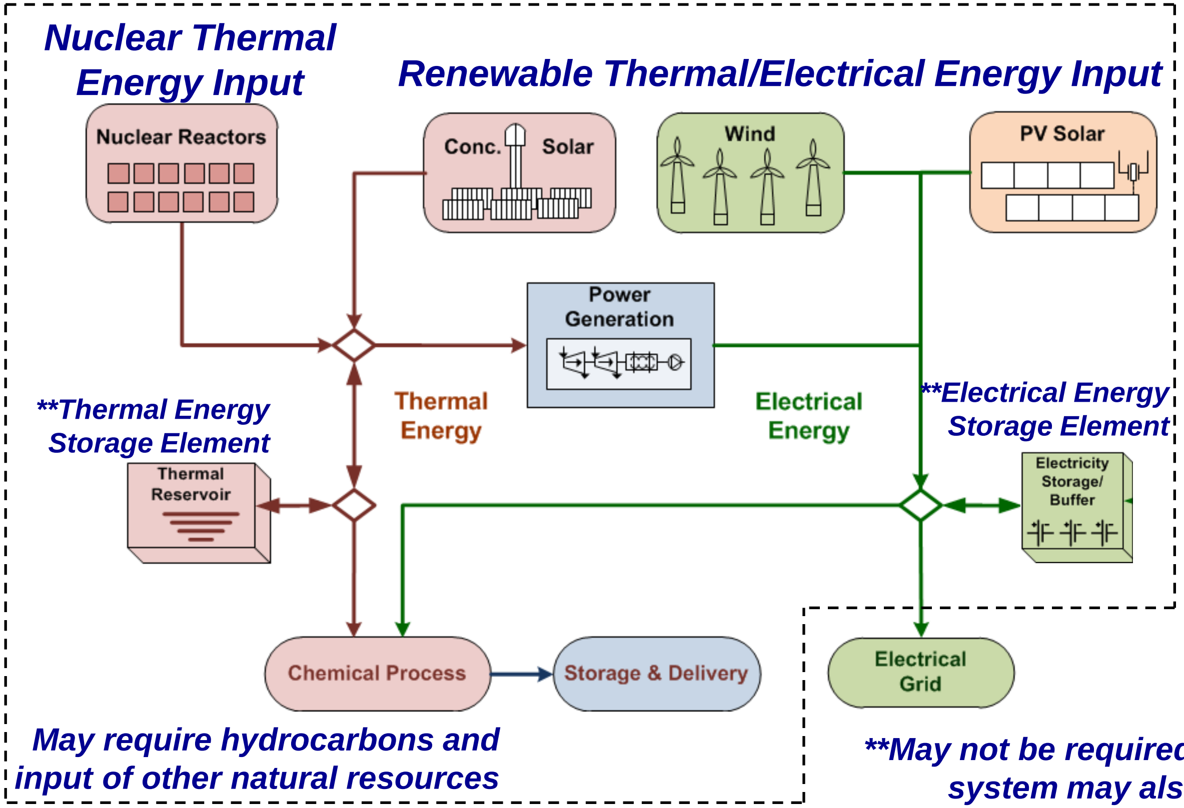
Integrated, Hybrid Energy Systems

Features of N-R HES:

- More than co-generation; dynamic operation of aggregated generation and industrial load
- Design based on zero-carbon emissions thermal and electrical power generation plants
- Co-optimization of grid operations with thermal energy dispatch

Goals of an Optimized N-R HES:

1. **Increased flexibility and reduced emissions for electricity generation,**
2. **Expanded use of low-carbon energy for industry,**
3. **Enhanced grid operation and generator profitability through production of non-electric commodities.**



Nuclear Thermal Energy Input

Renewable Thermal/Electrical Energy Input

Nuclear Reactors

Conc. Solar

Wind

PV Solar

Power Generation

Thermal Energy

Electrical Energy

***Thermal Energy Storage Element*

Thermal Reservoir

***Electrical Energy Storage Element*

Electricity Storage/ Buffer

Chemical Process

Storage & Delivery

Electrical Grid

May require hydrocarbons and input of other natural resources

***May not be required; system may also include chemical energy storage*

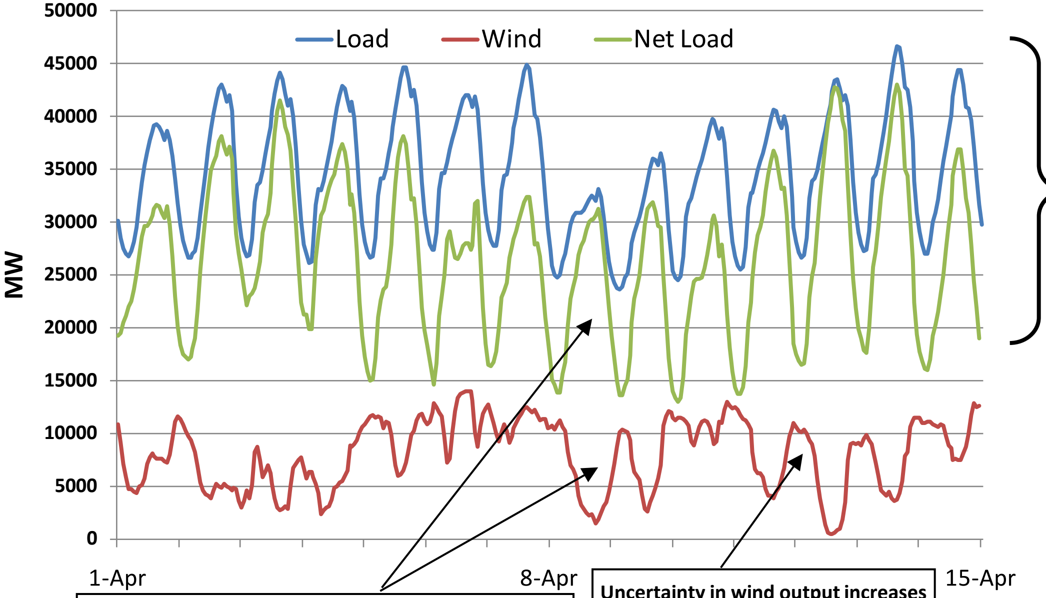
Key Take-Away:

Hybrid Energy Systems use thermal energy re-purposing and storage to respond to variability in net demand while operating the reactor at steady state – thus increasing profitability.

Goal:

Increased flexibility and reduced emissions for electricity generation.

The Evolving Grid Will Require Additional Flexibility



Ramp Range (Increases in this two-week period from 19.3 GW/day to 26.2 GW/day)

Variation in wind output increases net load ramp rate (Increases in this period from 4,052 MW/hour to 4,560 MW/hour)

Uncertainty in wind output increases uncertainty in net load to be met with conventional generators

Lew, D., G. Brinkman, E. Ibanez, et al. (2013). *Western Wind and Solar Integration Study Phase 2*. NREL Report No. TP-5500-55588.

Four major impacts of variable generation on the grid:

1) Increased need for frequency regulation
2) Increased hourly ramp rate
3) Increased uncertainty in the net load
4) Increased ramp range

Currently electrical energy is not stored in bulk – electrical power systems require continual adjustment to match demand

Lessons Learned from Germany

- Rapid growth of renewable energy in Germany and other European countries in the 2000s due to proactive policies and generous subsidy programs
- Key lessons learned:
  - **Policymakers underestimated cost of renewable subsidies** [German program is estimated to reach costs of $884B by 2020]
  - **Retail prices for many electricity consumers have significantly increased** [subsidies paid by end users through cost-sharing procedure; household electricity prices in Germany have more than doubled from 2000 to 2013]
  - **Large-scale investments in the grid required to expand transmission grids** to connect onshore and offshore wind projects in north Germany to consumers in the south
  - **Fossil and nuclear plants facing stresses as they are now operating under less stable conditions and are required to cycle more often to help balance renewable variability**
  - **Large scale deployment of renewables does not displace thermal capacity** – variability requires redundant capacity to ensure reliability; grid interventions have increased as operator intervention is required to follow the market-based dispatching –
    - e.g. one German transmission operator saw interventions increase from 2 in 2008 to 1,213 in 2014

H. Poser, J. Altman, F. ab Egg, A. Granata, R. Board, *Development and Integration of Renewable Energy: Lessons Learned from Germany*, Finadvice, July 2014.

Solution Space for Increased Flexibility

System Operations

1) Decisions closer to real time and more frequently

2) Improved use of wind and solar forecasting

3) Increased collaboration with neighbors

Demand-Side Resources

1) Demand response

2) Storage

3) Responsive distributed generation

4) Enabling markets

Transmission

1) Reduce congestion

2) Connect balancing areas

3) Grid-scale electricity storage

Central Generation

1) Dispatchable intermittent generation

- reduced capital deployment efficiency / wasted thermal energy
- increased O&M / shortened plant life
- limited zero-carbon options

Solution Space for Increased Flexibility

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New Operational Paradigm

- Integrated industrial-scale energy systems with internally managed resources
- Reliably provide electricity to meet grid demand with less energy storage
- Provide thermal energy input to alternate applications (minimize cycling of base generators)

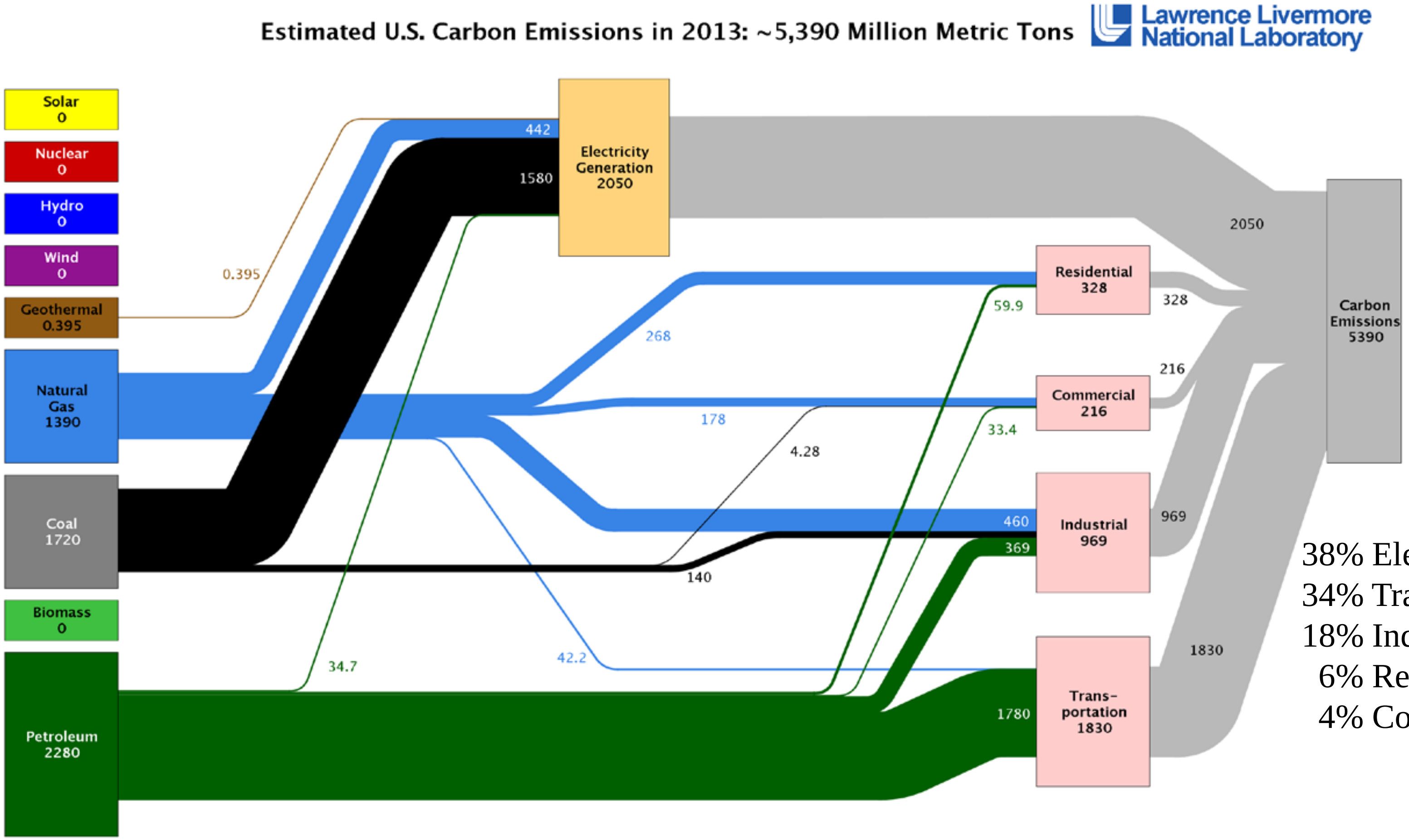
→ System operation in dynamic fashion.

Goal:

Expanded use of low-carbon energy for industry.

Decarbonizing the Industrial Sector is Challenging

Estimated U.S. Carbon Emissions in 2013: ~5,390 Million Metric Tons

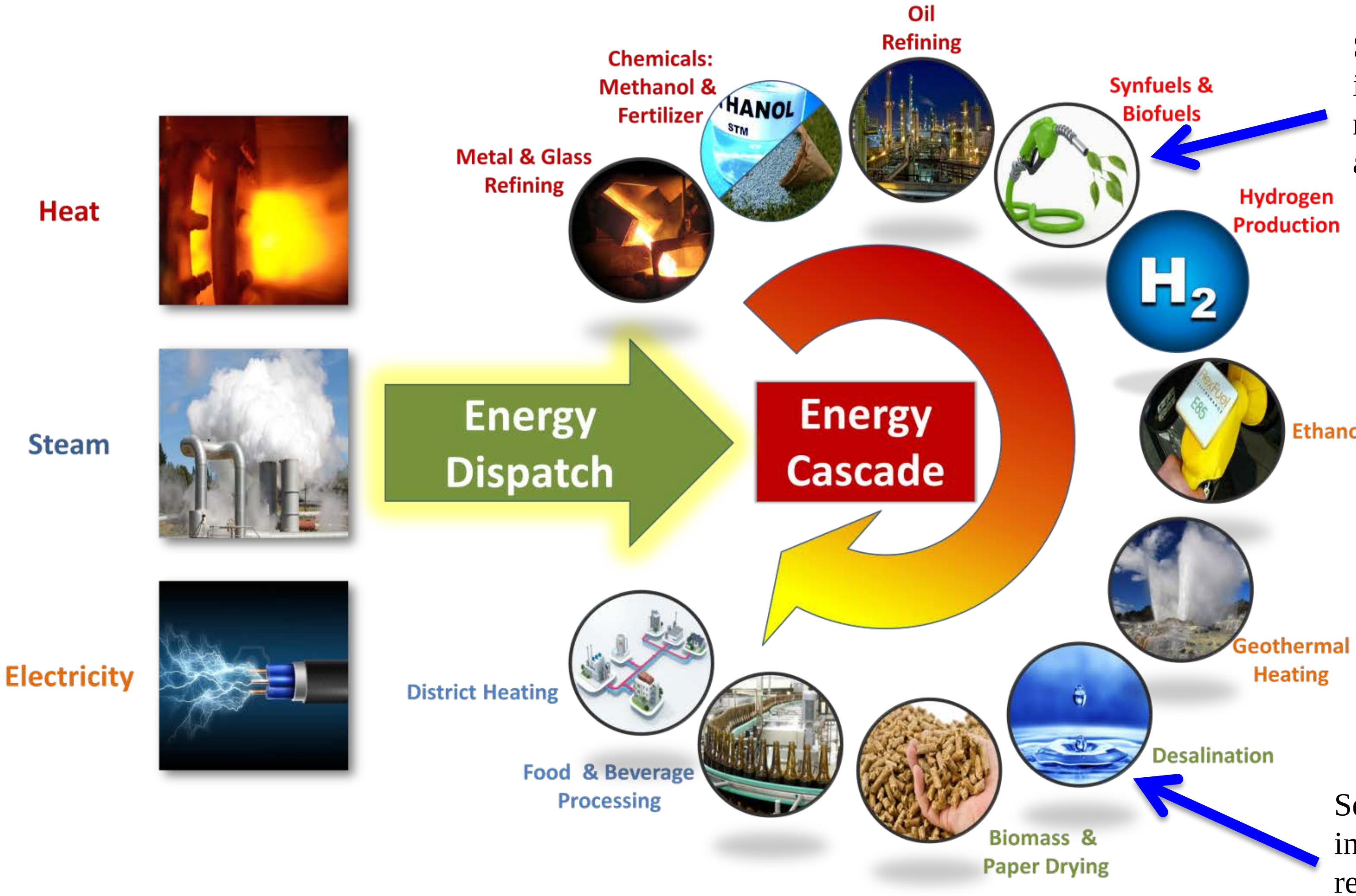


Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combusition of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-MI-410527

38% Electricity
34% Transportation
18% Industrial
6% Residential
4% Commercial

18% of the U.S.’s GHG emissions are direct emissions from the industrial sector. Alternative energy sources are limited due to heat delivery requirements.

Industrial Process Opportunities for HESs



Heat

Steam

Electricity

Energy Dispatch

Energy Cascade

Metal & Glass Refining

Chemicals: Methanol & Fertilizer

Oil Refining

Synfuels & Biofuels

Hydrogen Production

Ethanol

Geothermal Heating

Desalination

Biomass & Paper Drying

Food & Beverage Processing

District Heating

Selected for initial dynamic regional case analysis.

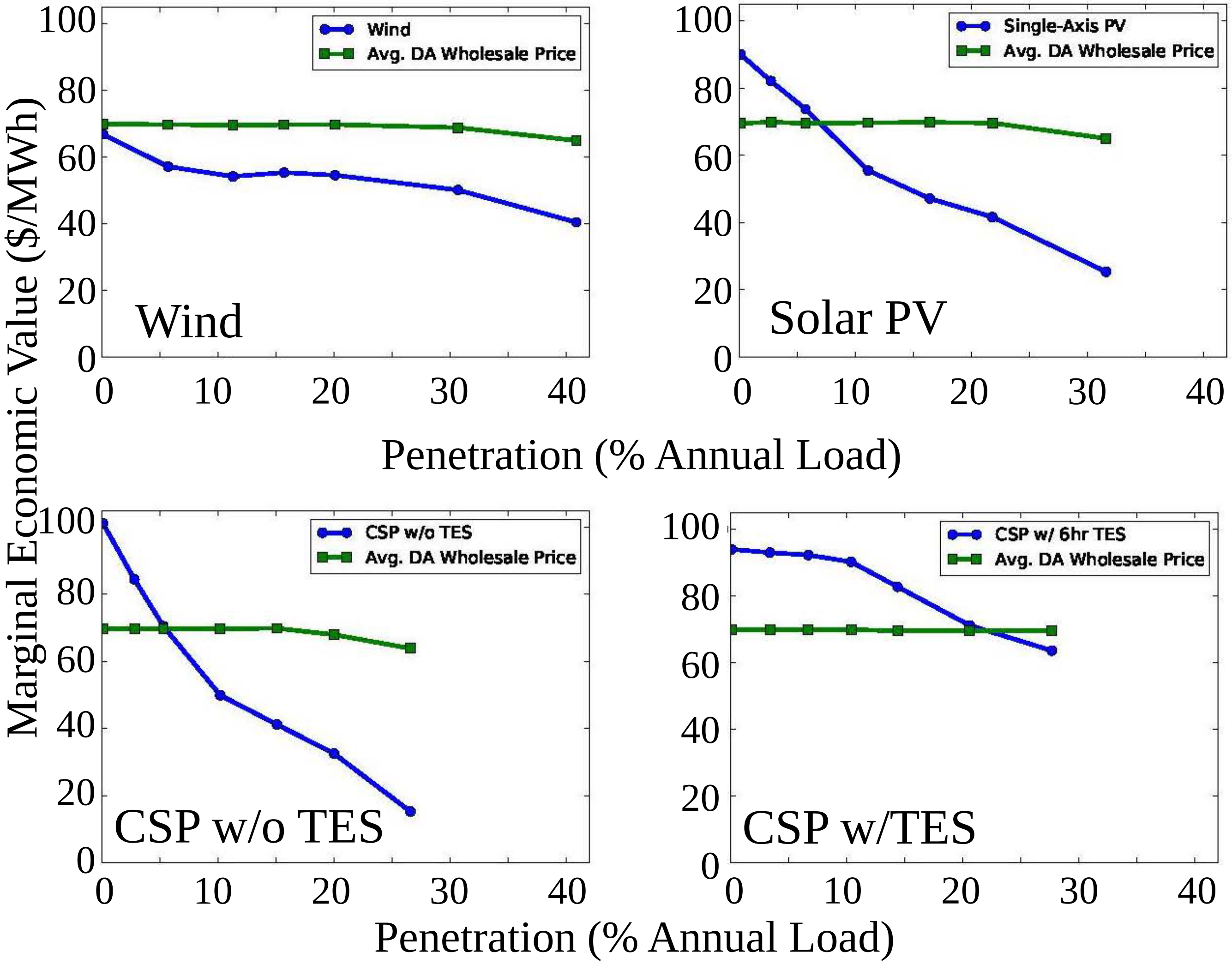
Selected for initial dynamic regional case analysis.

Goal:

Enhanced grid operation and generator profitability through production of non-electric commodities.

Price Suppression Limits Penetration

- Increasing penetration of variable generation reduces the marginal economic value – 80% drop in solar revenue with 30% PV penetration



Source:
A. Mills & R. Wiser (2012) “Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California” Technical Report: LBNL-5445E

TES = Thermal energy storage

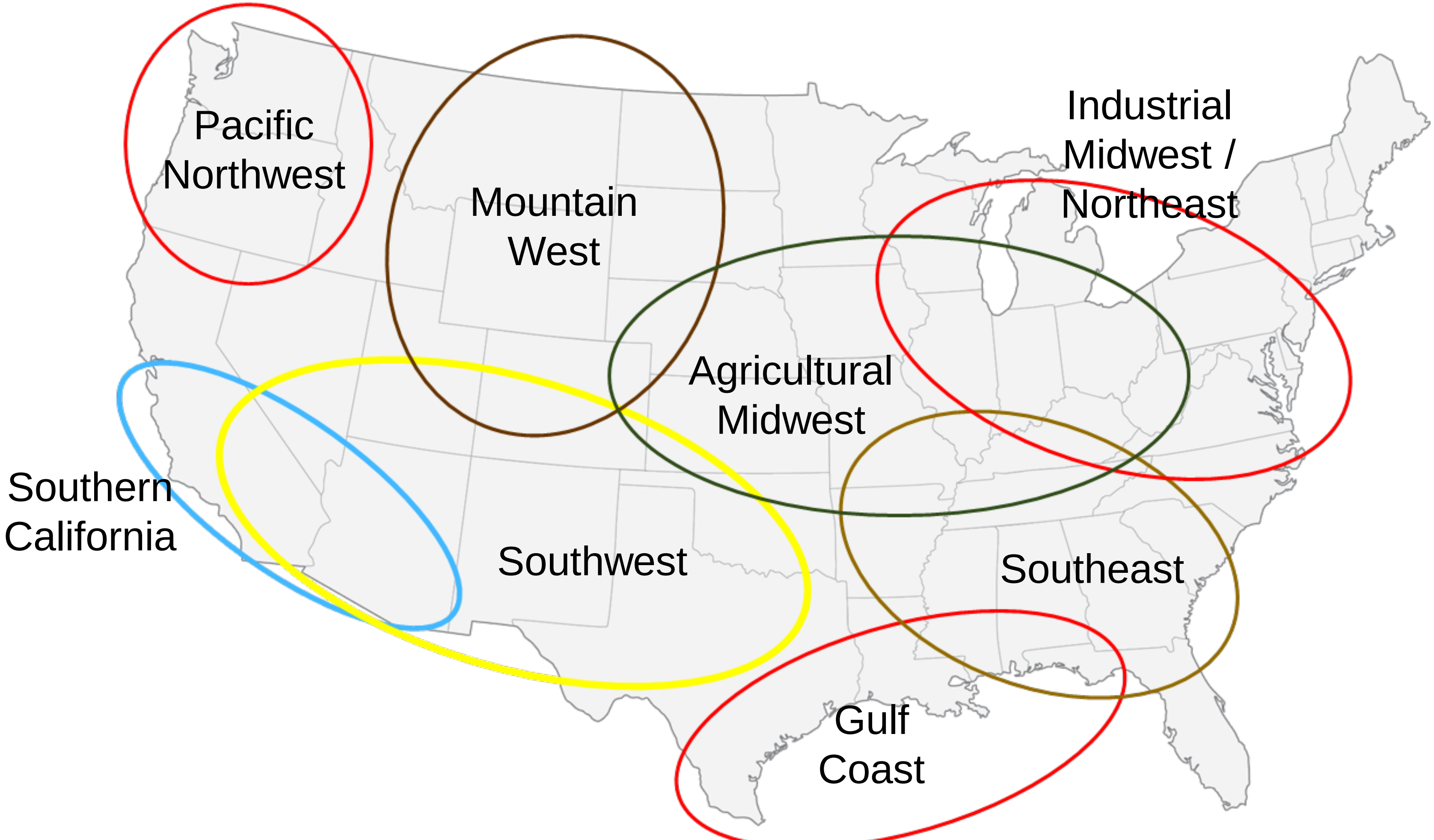
Hybrid Energy Systems Can Address the Revenue Suppression Challenge

- Switch heat from nuclear and solar thermal to industrial applications during times of electricity over-supply
  - Reduce electricity available to the grid
  - Reduce price suppression at times of high wind or solar output
- Hybrid systems can use heat storage to improve system economics – cheaper than electricity storage (may require both to some extent)
- Potential to provide seasonal storage capacity
- Net effects of N-R HES
  - Enable increased use of low-carbon renewables and nuclear
  - Provide low-carbon heat for industrial applications
  - Increase opportunities to produce higher value products from oil and gas (“carbon engineering”)
  - Additional revenue streams for nuclear and renewables

Moving Forward: Evaluation of regional nuclear-renewable HES opportunities.

Case Studies to Test the Potential Benefits – Definition of High Priority Regional Cases

- For initial discussion, the U.S. was divided into 8 regions based on **resources, traditional industrial processes, energy delivery infrastructure, and markets**



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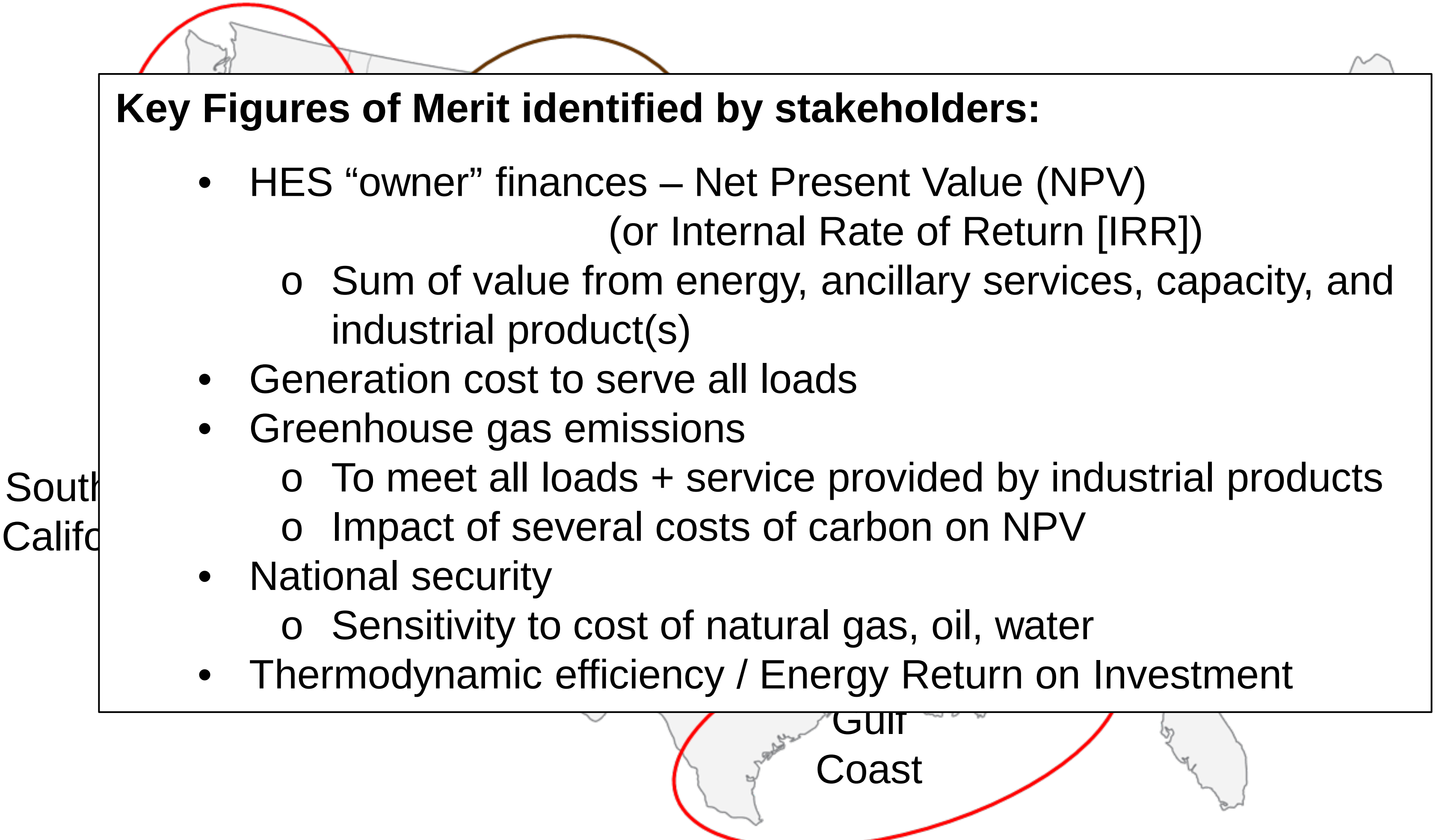


Key Figures of Merit identified by stakeholders:

- HES “owner” finances – Net Present Value (NPV) (or Internal Rate of Return [IRR])
  - Sum of value from energy, ancillary services, capacity, and industrial product(s)
- Generation cost to serve all loads
- Greenhouse gas emissions
  - To meet all loads + service provided by industrial products
  - Impact of several costs of carbon on NPV
- National security
  - Sensitivity to cost of natural gas, oil, water
- Thermodynamic efficiency / Energy Return on Investment

Scenario Definition & Core Assumptions

Scenario Definition

- Technology combination
- General location
- Penetrations of variable generation
- Hourly locational marginal costs / real-time costs and service prices
- Capacity value
- Business strategy
- Load to be served?

Core Assumptions

- Capital costs / scaling factors / size constraints
    - Minimum production of industrial process
    - Maximum RE resource availability
    - Maximum reactor size
    - Maximum HES generation
- Coal, oil, and natural gas costs
- Feedstock costs
- Fixed and variable operating cost estimates

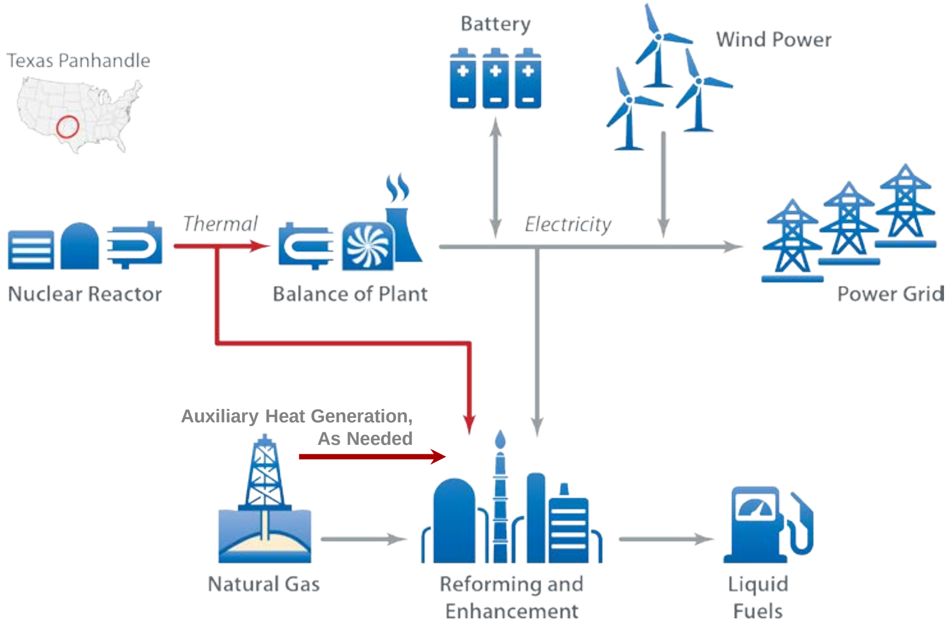
Challenges to Address

- **Integration Value:** Increased value of system components to both the owner of the hybrid system and to the grid as a whole; added risk of integration relative to improvement in efficiency and energy availability.
- **Technical:** Novel subsystem interfaces; ramping performance; advanced instrumentation and control for reliable system operation; integrated system safety; commercial readiness.
- **Financial:** Business model; cost and arrangement of financing and risk/profit taking agreements; risks of market and policy evolution; capacity factors (capital utilization).
- **Regulatory:** Projected environmental regulations; deregulated/regulated energy markets; licensing of a co-located, integrated system; involvement of various regulatory bodies for each subsystem and possible “interface” issues.
- **Timeframe:** Resolution of issues/challenges within the timeframe established based on external motivators (e.g. EPA recommendations).

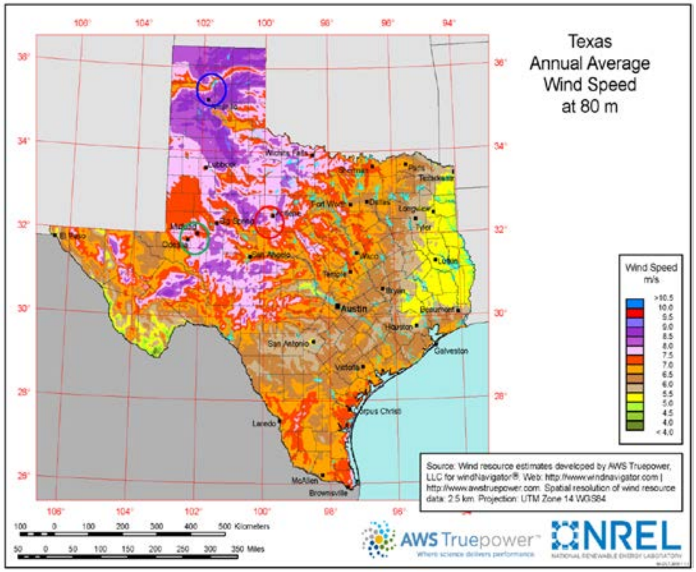
High Priority Regional Cases

- Two initial cases selected for dynamic analysis:
  - **Texas Panhandle:** Nuclear (LWR) + Wind → Electricity + Natural Gas to Liquid Fuel
  - **Arizona:** Nuclear (LWR) + Solar PV → Electricity + Desalination (Reverse Osmosis)
- Additional development of component models for interface and storage technologies
  - Hydrogen production
  - Batteries
- Steady-state analysis for preliminary system design (Aspen)
- Initial dynamic analysis (technical and economic performance) (Modelica)
- Analysis goals include initial performance evaluation, identification of technical development needs, and preliminary financial assessment
- Results will be considered preliminary and will provide guidance for further modeling, simulation, and controls tool enhancements and economic assessment tool development

Example: Texas Panhandle



- Proximity of natural gas wells can provide the needed carbon source for liquid fuel
- Wind speeds sufficient to use existing or to build additional wind farms
- Electricity sold to the Southwest Power Pool of Eastern Interconnection vs. ERCOT
- 600 MWth / 180 MWe + up to 45 MWe wind (can divert up to the equivalent of 45 MWe /150 MWt to chemical plant complex)



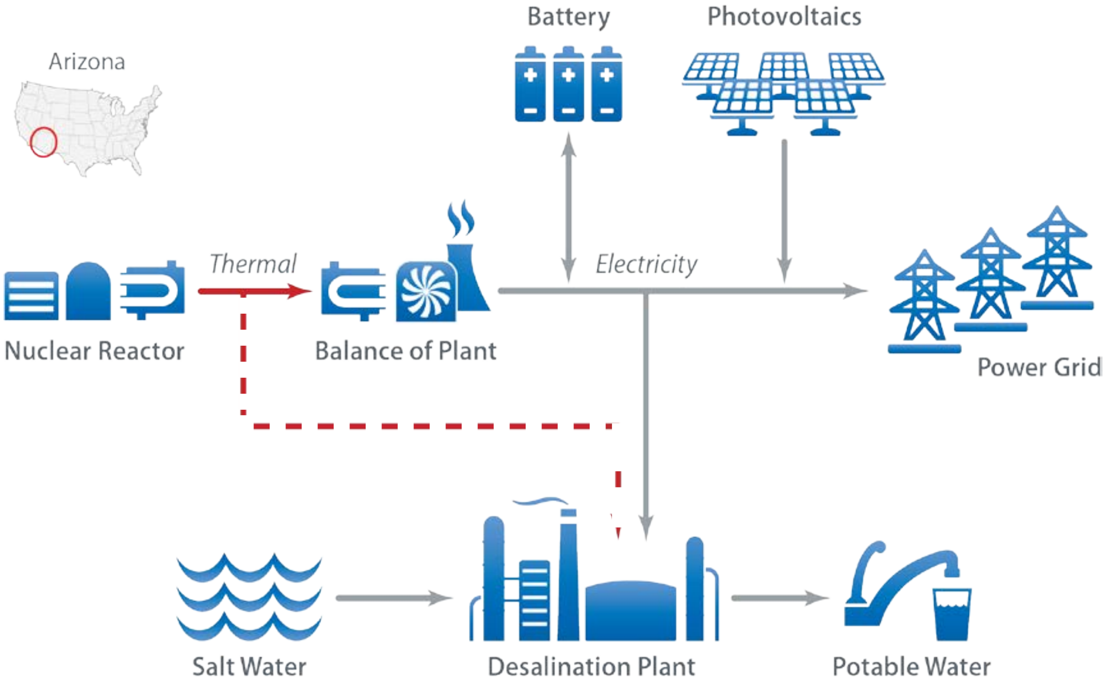
Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: UTM Zone 14 WGS84

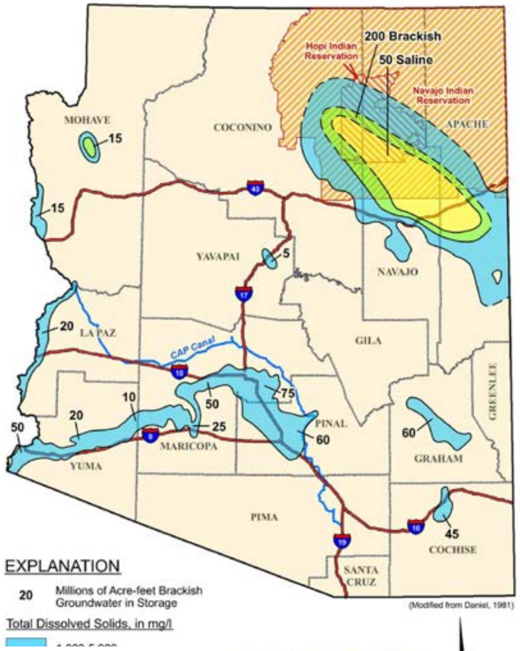
Additional options / considerations:

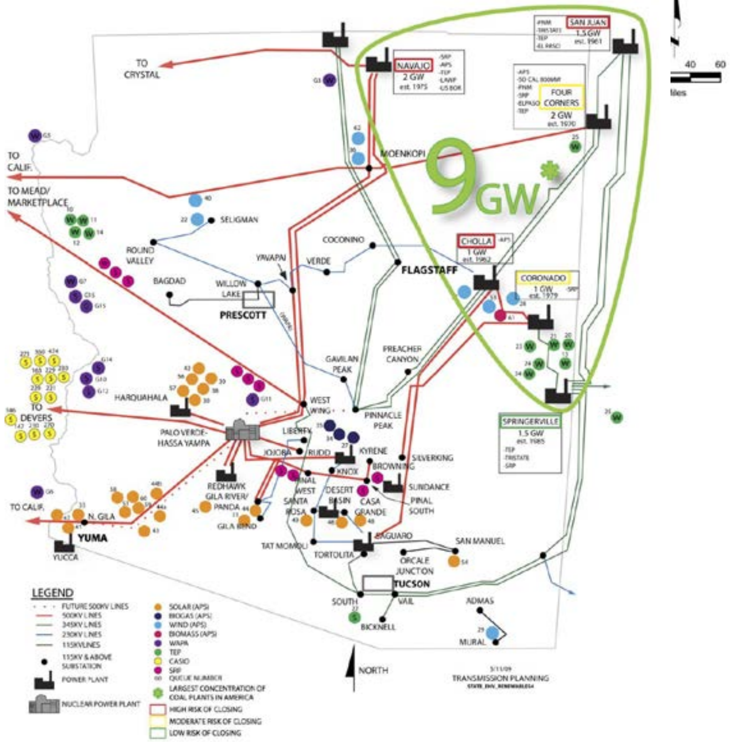
- Coal-to-synfuels industrial process
- Hydrogen production as an interface; provides chemical feedstock to upgrade fossil fuels

Example: Arizona

- 600 MWt / 180 MWe + up to 45 MWe solar PV to drive a 45 MWe reverse osmosis plant + electricity generation
- Produce 14,970 to 44,900 m^3/hr of water to provide daily water needs for 950,000 to 2.85 million people







Additional options / considerations:

- Concentrated Solar
- Land-based wind

Path Forward

The FY2015 effort is continuing to evaluate hypotheses and will develop a *Roadmap* that addresses the development challenges and identifies necessary resources.

Key FY15 Objectives:

1. Quantify the value proposition of two nuclear-renewable hybrid energy systems (HESs) identified for specific regional implementations, as compared to loosely-coupled systems.

2. Compose a Roadmap for N-R HES development.
   - Develop a detailed modeling and simulation strategy
   - Identify dynamic analysis, technology development, testing, and validation needs
   - Identify market options per detailed market analysis
   - Obtain stakeholder input and review

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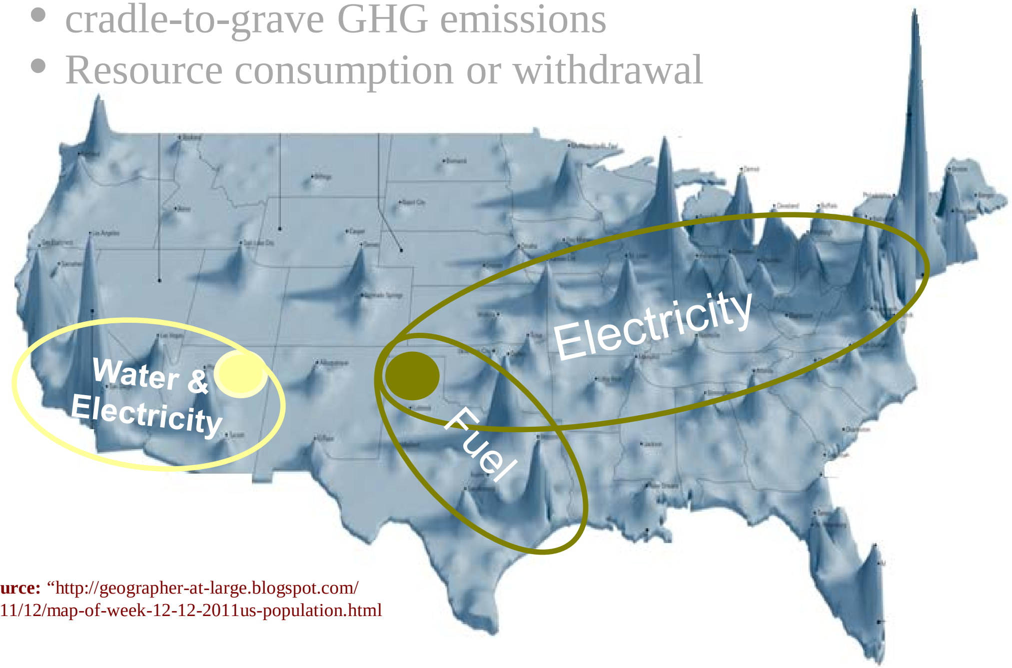
Preliminary Dynamic Analysis: Texas Panhandle and Northeast Arizona

Objectives:

- Economic Assessment
  - Total capital investment
  - NPV / IRR
  - Investment payback period
  - Actual cost of energy
  - Employment (jobs)
- Environmental Benefits
  - CO_2 avoided
  - Air quality / regional haze
  - Water resource
  - Resource stewardship
- Technical Assessment
  - Controllability
  - Reserve / peak power supply
  - Load managing response
  - Power regulation response
  - Energy storage potential

Tools & Approach:

- Static and Dynamic (time dependent) Processes and Systems Operation/Control, and Optimization Models
- Time Dependent Financial Pro-Forma
  - Day-Ahead electricity price
  - Seasonally adjusted for other commodities
- Life-Cycle Analysis
  - cradle-to-grave GHG emissions
  - Resource consumption or withdrawal



Source: “http://geographer-at-large.blogspot.com/2011/12/map-of-week-12-12-2011us-population.html

Case Study: Arizona

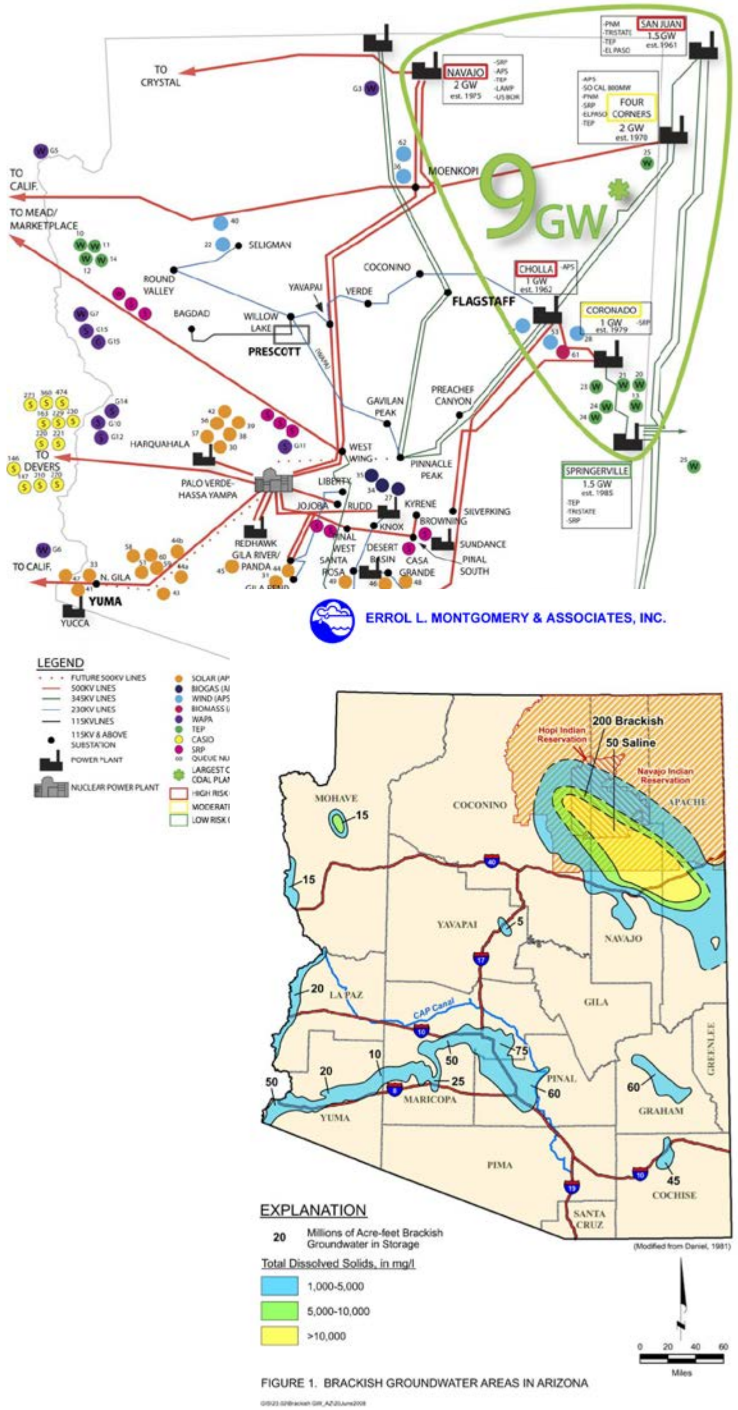
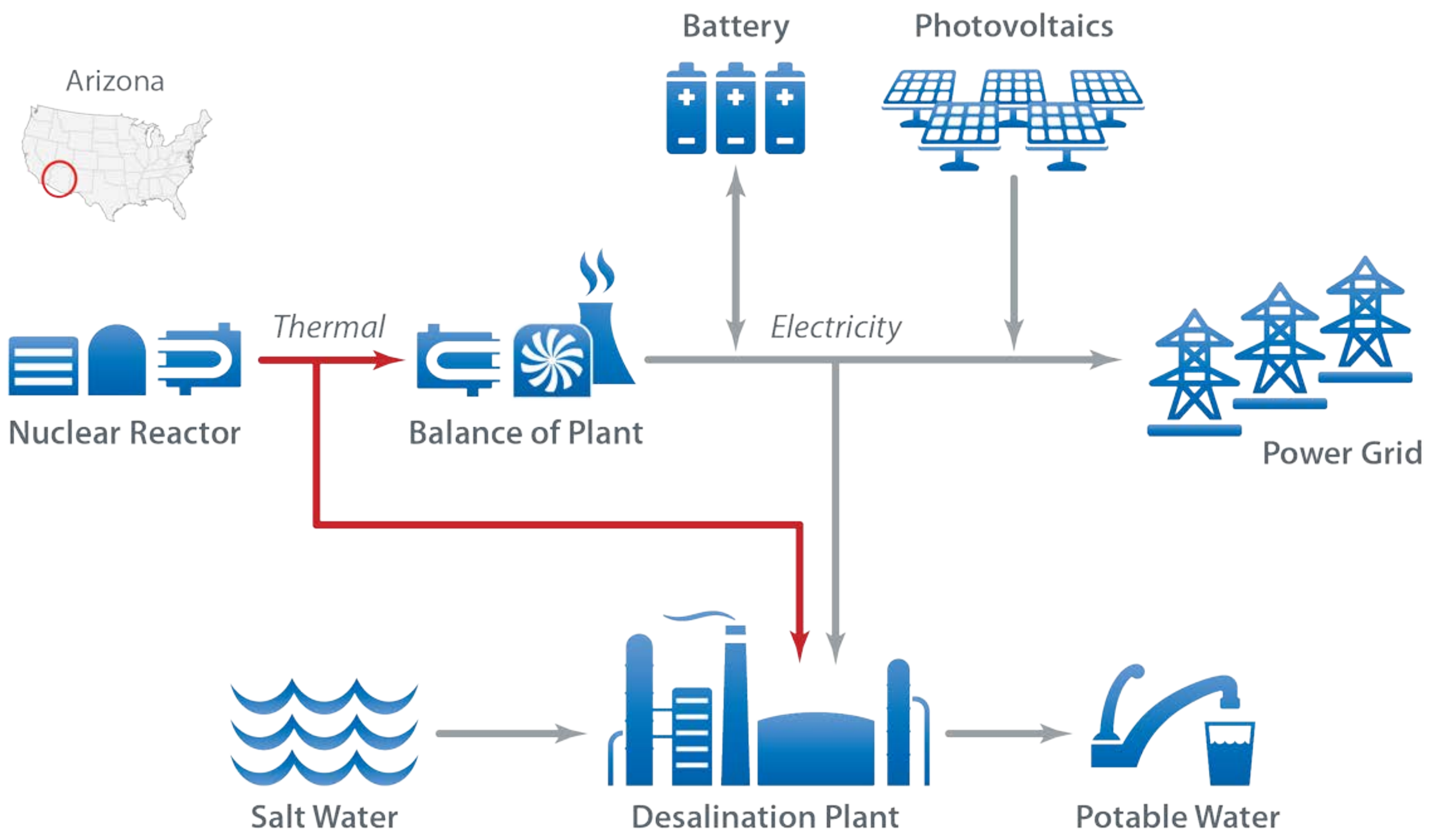


FIGURE 1. BRACKISH GROUNDWATER AREAS IN ARIZONA

- Expecting increased power and water needs over the next 15 to 20 years
  - Electricity demand predicted to grow from 8,124 MWe to 12,982 MWe by 2029
  - Renewables projected to grow from 3,182 GW-hr to 6,944 GW-hr by 2029
  - Water demands projected to grow from 6.9 million acre-feet to ~8.2 to 8.6 million acre-feet in 2035
  - Coal plants:
    - 9 GWe in NE corner of the state
    - 50% predicted to be closed by 2020 due to EPA emission regulations
  - Vertically integrated utility
- Current generation could be replaced by nuclear baseload and be located over an aquifer with a large amount of brackish water
  - 600 MWt / 180 MWe + up to 45 MWe solar PV to drive a 45 MWe reverse osmosis plant + electricity generation
  - Produce 14,970 to 44,900 m^3/hr of water to provide daily water needs for 950,000 to 2.85 million people

Example: Arizona



Additional options / considerations:

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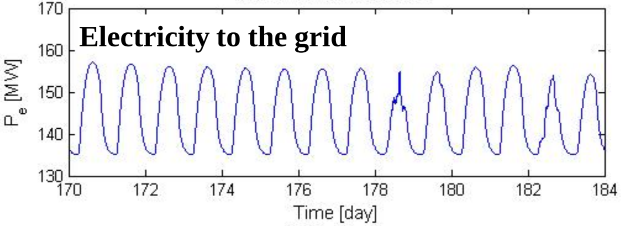
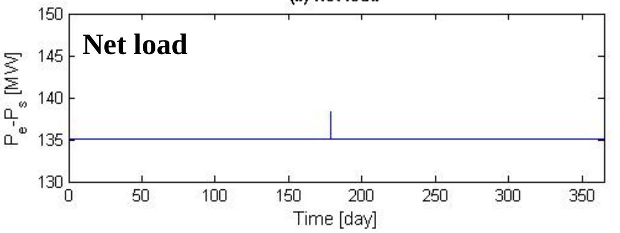
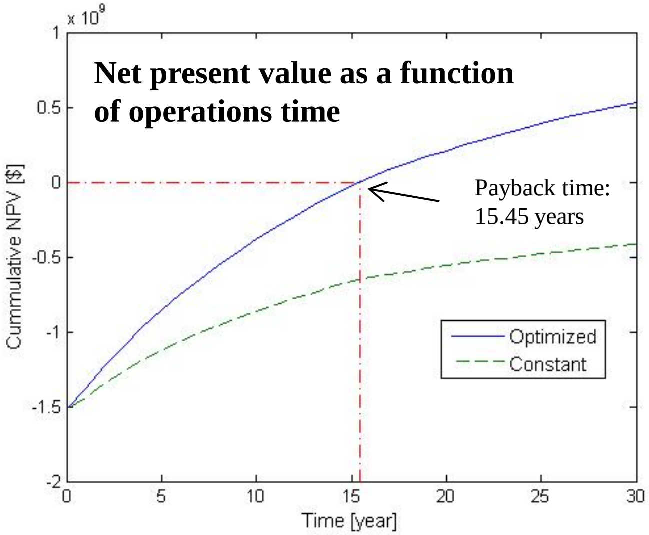
Arizona: Economic Takeaway

(a) Electricity production



(b) Net load

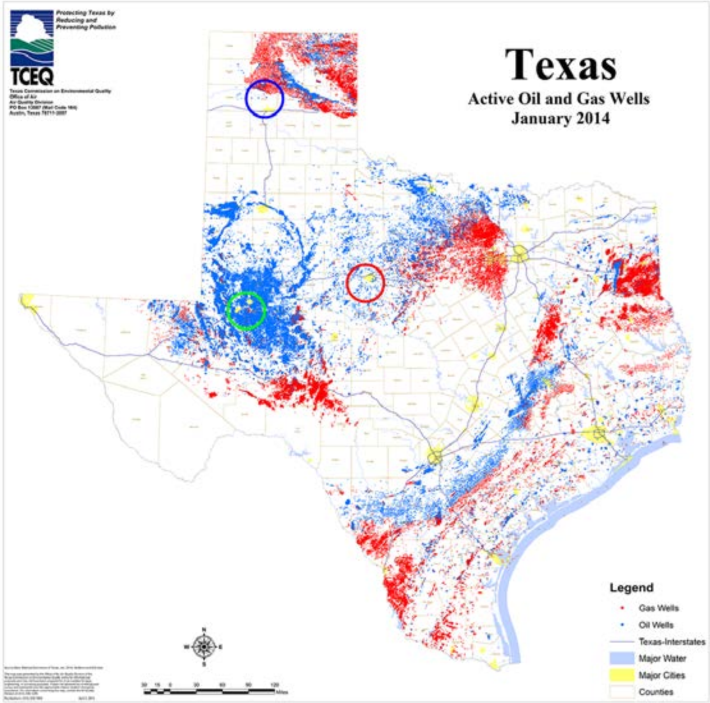


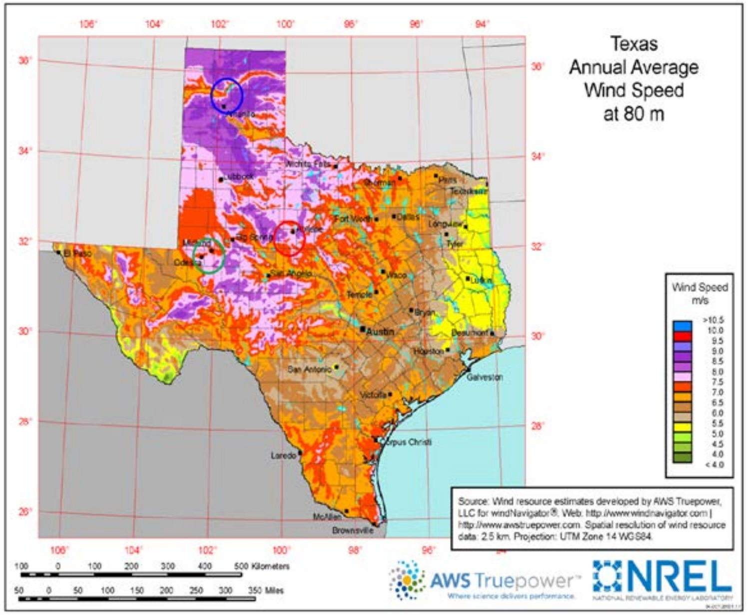


- Combination of alternative products (fresh water and brine) and electricity production deliver superior economics
- Payback time: 15.45 years; IRR: 8.2% (30 years operations)
- Supply a reserve capacity of 30 MW (maximizes economic value and supports grid stabilization)
- Electricity sales in both day-ahead and real-time market
- Electric demand variability (e.g., from 135 to 165 Mwe)
- 60.6 billion gallons/year of fresh water; 88% of water consumption in Phoenix and Tucson, AZ).
- Reduced CO_2 emission (e.g., 1.4 million metric tons per year) by using nuclear reactor
- Fast ramping rate to allow renewable penetration

Case Study: Texas

- >12 GW wind energy -- ~1/5th of the total U.S. wind generation
- Largest crude oil producer in the U.S. (>1/3rd total U.S. production)
- Largest natural gas producing state (just <1/3rd total U.S. production)
- Electricity grid: Eastern Interconnection or Electricity Reliability Council of Texas Interconnection
- Locations considered: Permian Basin of West Texas, the area near the city of Abilene, and the panhandle
- Selected: Texas Panhandle
  - Close proximity of natural gas wells can provide the needed carbon source for liquid fuel
  - Wind speeds are sufficient to use existing or to build additional wind farms
  - Note: electricity must be sold to the Southwest Power Pool of Eastern Interconnection, rather than the ERCOT Interconnection
  - 600 MWth / 180 MWe + up to 45 MWe wind (can divert up to the equivalent of 45 MWe /150 MWt to chemical plant complex)





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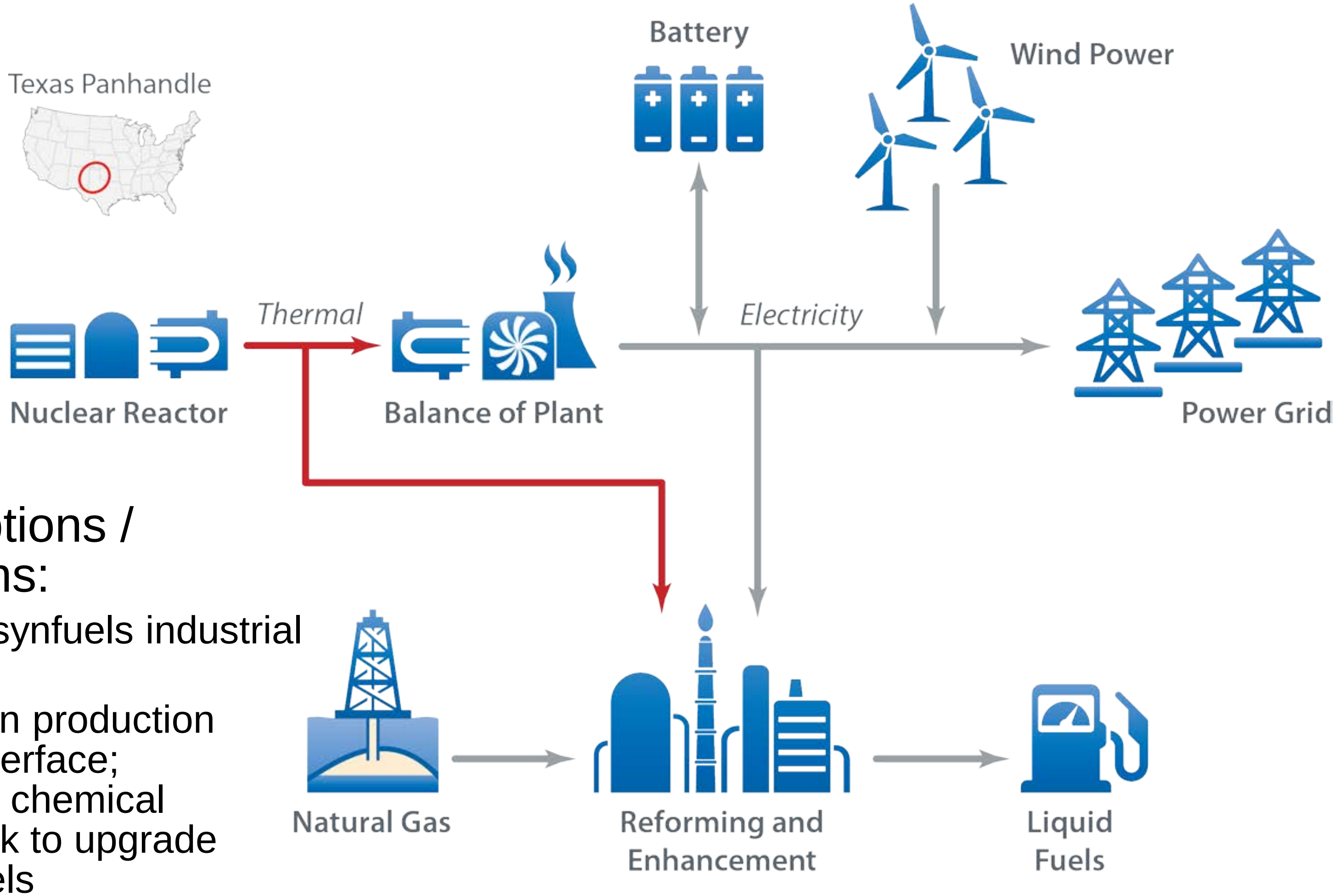
Example: Texas Panhandle



Additional options / considerations:

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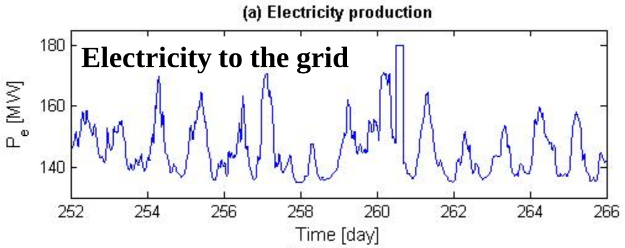
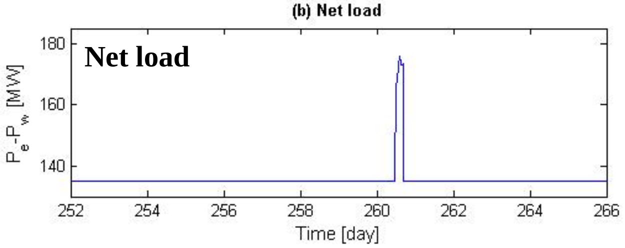
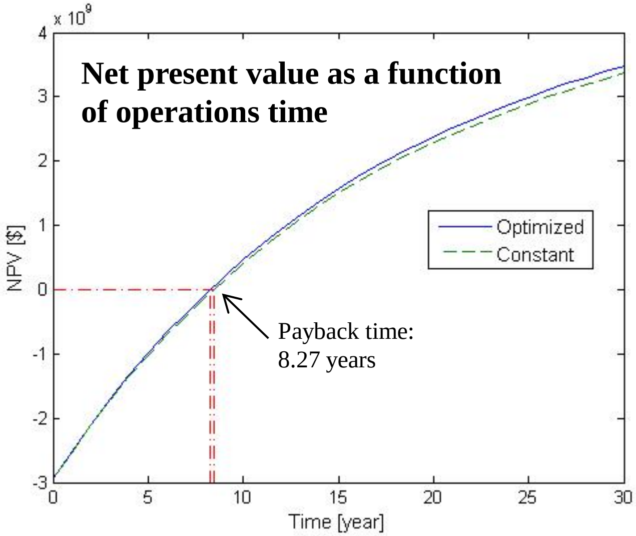
- Hydrogen production as an interface; provides chemical feedstock to upgrade fossil fuels

Texas Panhandle: Economic Takeaway

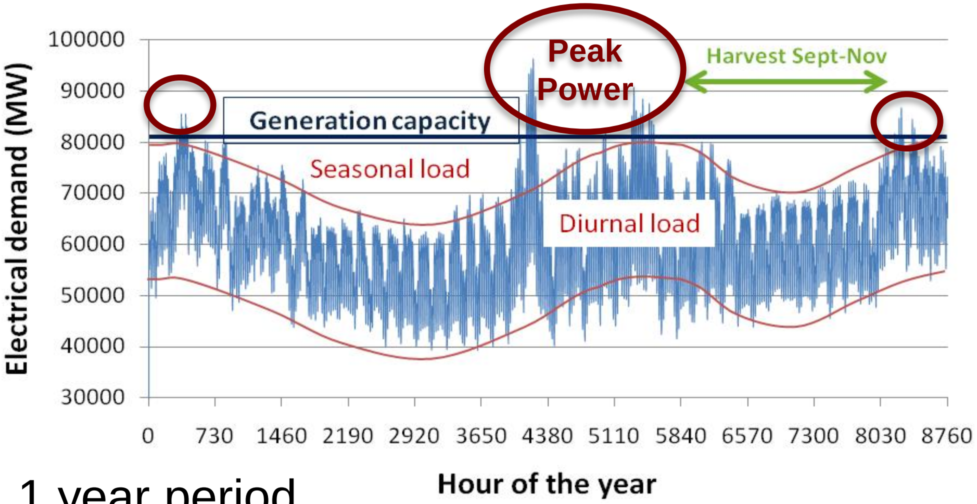




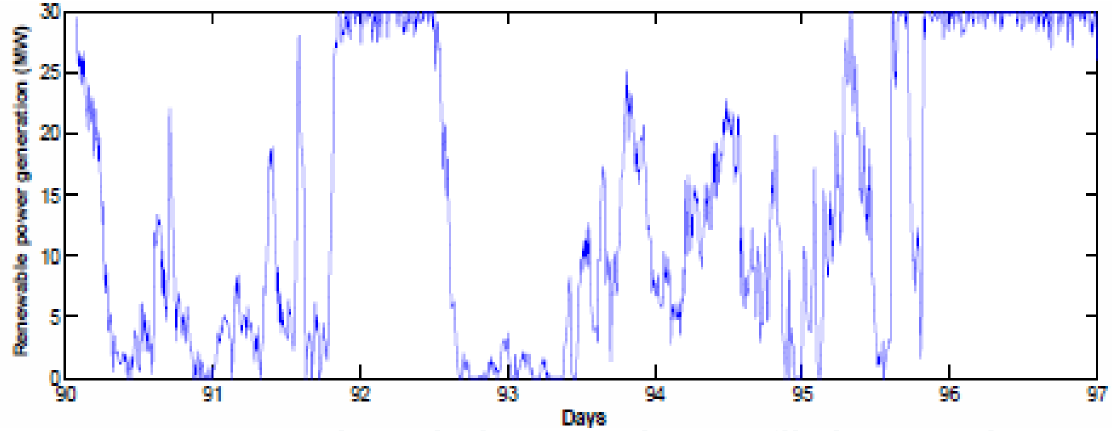


- Combination of alternative products (e.g. gasoline, LPG) and electricity production deliver superior economics
- Payback time: 8.27 years; IRR: 14.5% (30 years operations)
- Supply a reserve capacity of 45 MW (maximizes economic value and supports grid stabilization)
- Electricity sales in both day-ahead and real-time market
- Electric demand variability (e.g., from 135 to 180 MWe)
- Reduced CO_2 emission (e.g., 1.4 million metric tons per year) by using nuclear reactor
- Fast ramping rate to allow renewable penetration

The Evolving Grid Will Require Additional Flexibility



1 year period



Representative Wind Generation Profile in Wyoming

1 week

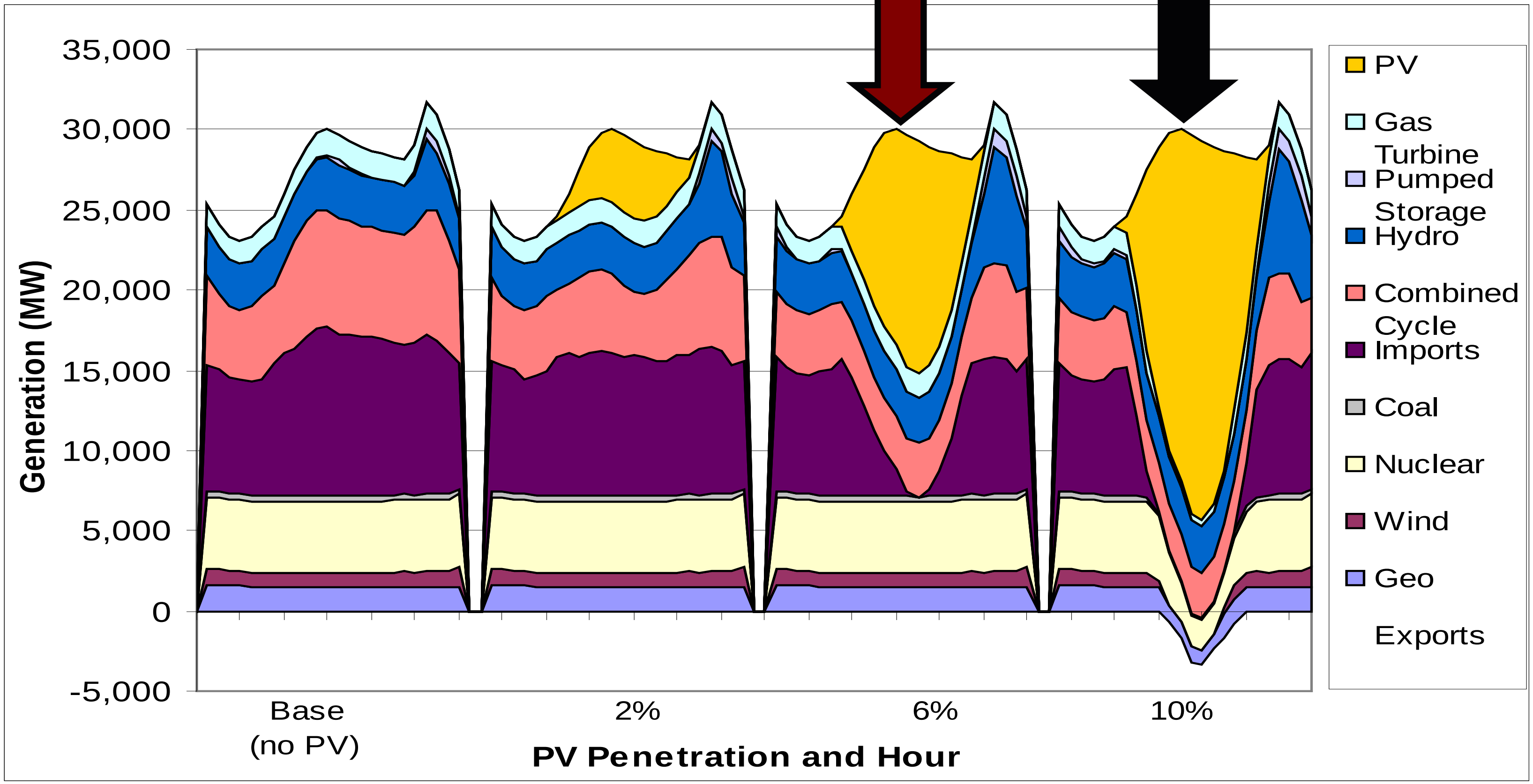
Load Following for Nuclear?

- US experience in flexible nuclear power (NPP) plant operation is currently limited to pre-planned power changes
- Example:
  Columbia NPP (WA) frequently communicates with the independent system operator to plan power based on forecasted weather, river flow, load demand

Adding Solar and Wind Changes Electricity Grid and Price Structure

Expensive Reserves

Excess Electricity with Price Suppression



California Daily Spring Electricity Demand and Production with Different Levels of Annual Photovoltaic Electricity Generation

Denholm, P., R. M. Margolis and J. Milford. (2008) “Production Cost Modeling for High Levels of Photovoltaics Penetration” NREL/TP-581-42305.