Nuclear Beyond Base-load Electricity: Variable Electricity and Liquid Fuels

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Future Energy Scenarios Outline

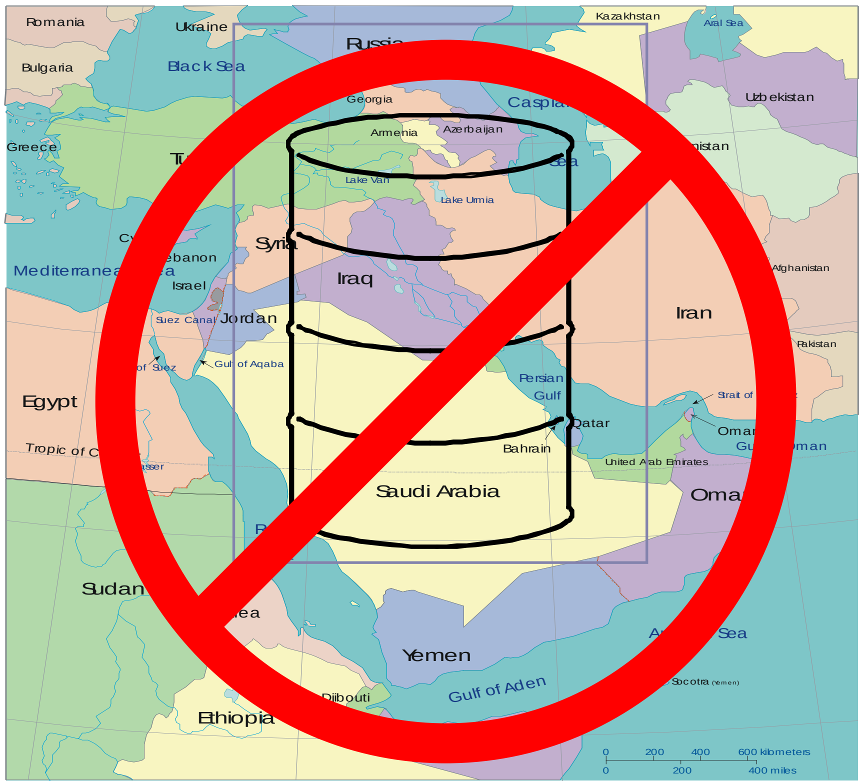
- The Energy Challenge
- Liquid Fuels
- Variable Electricity
- Conclusions

The Energy Challenge

Energy Futures May Be Determined By Two Sustainability Goals

No Imported Crude Oil

No Climate Change



Athabasca Glacier, Jasper National Park, Alberta, Canada
Photo provided by the National Snow and Ice Data Center

2050 Goal: Reduce Greenhouse Gases by 80%

Oil and Gas Reserves Are Concentrated in the Persian Gulf

Reserves of Leading Oil and Gas Companies

Rank	Company	Total Oil/Gas Reserves: Oil Equivalent (10^9 Barrels)
1	National Iranian Oil Company	316
2	Saudi Arabian Oil Company	305
3	Qatar General Petroleum Corp.	179
4	Iraq National Oil Company	136
	Non-Government Corporations	
14	ExxonMobil Corp.	15
18	BP Corp.	13

Price and Availability are Political Decisions

http://www.petrostrategies.org/Links/worlds_largest_oil_and_gas_companies.htm

Liquid Fuels

Oil Supplies 35% of World Energy

Transportation is the Key Issue

U.S. Options: Biofuels and Shale Oil

Three Inputs into Liquid Fuels

Carbon:
- Fossil fuel (CH_x)
- Biomass (CHOH)
- Atmosphere (CO_2)

Energy:
- Fossil fuel
- Biomass
- Nuclear

Hydrogen
- Fossil Fuel
- Biomass
- Water

Feedstock Conversion Process

Products:
- Ethanol
- Biofuels
- Diesel

Hydrogen Key Input for Lower Quality Feedstocks and Low CO_2
Biomass, Heavy oil, Oil Sands, Coal

We Will Not Run Out of Liquid Fuels

But the Less a Feedstock Resembles Gasoline, The More Energy it Takes in the Conversion Process

Liquid Fuel Feedstocks and Energy to Convert Feedstocks to Liquid Fuels

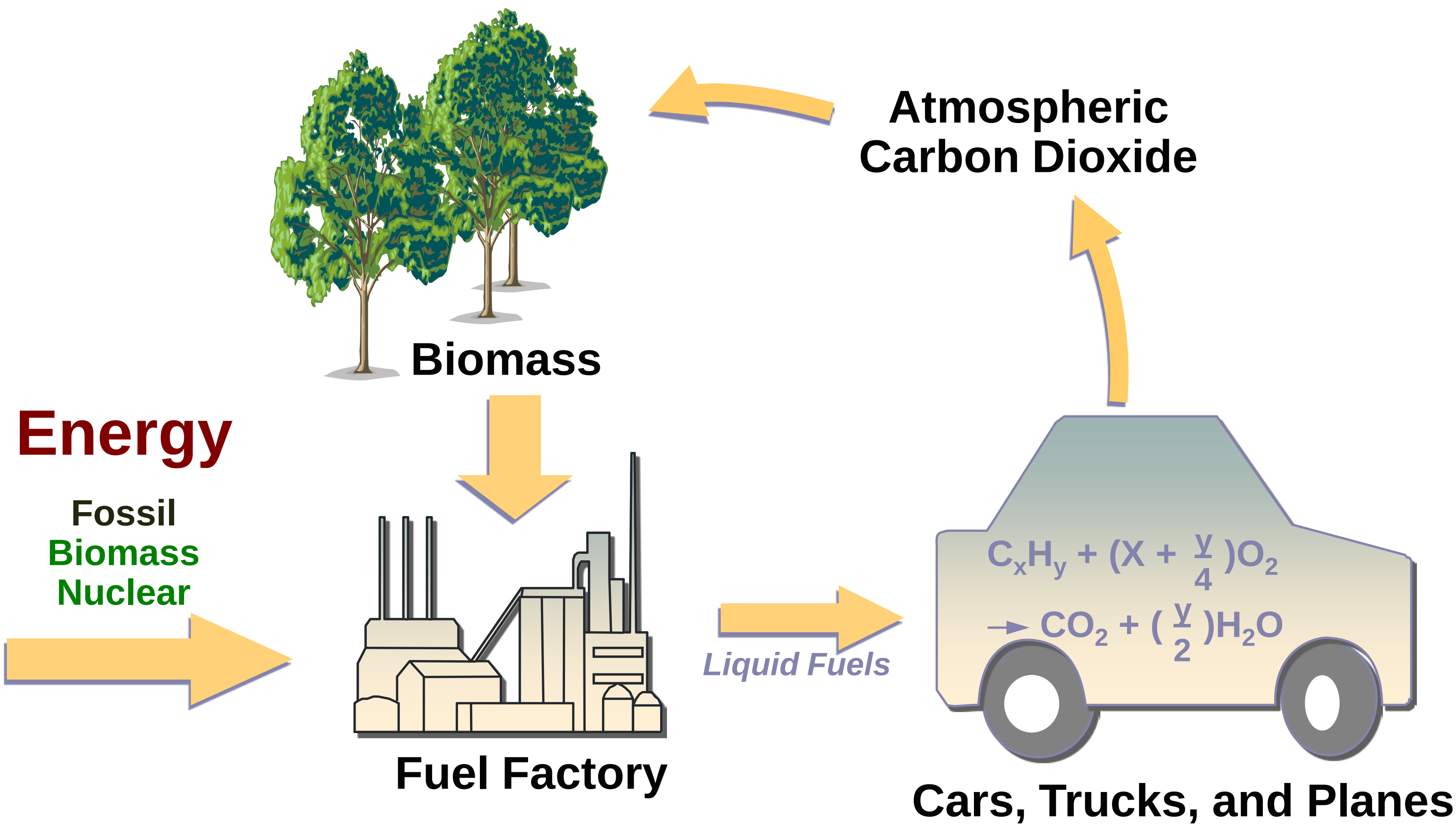
Feedstock	% World's Hydrocarbons	Heat Input As Fraction of Liquid Fuel Heating Value
Oil	2-3%	6-10%
Heavy Oil	5-7%	25-40%
Natural Gas	4-6%	~50%
Gas Hydrates	10-30%	
Oil Shales	**30-50%**	**>30%**
Coal/Lignite	20-30%	>100%
Biomass	**Annual**	**To 50%**

Observations on Resource Chart

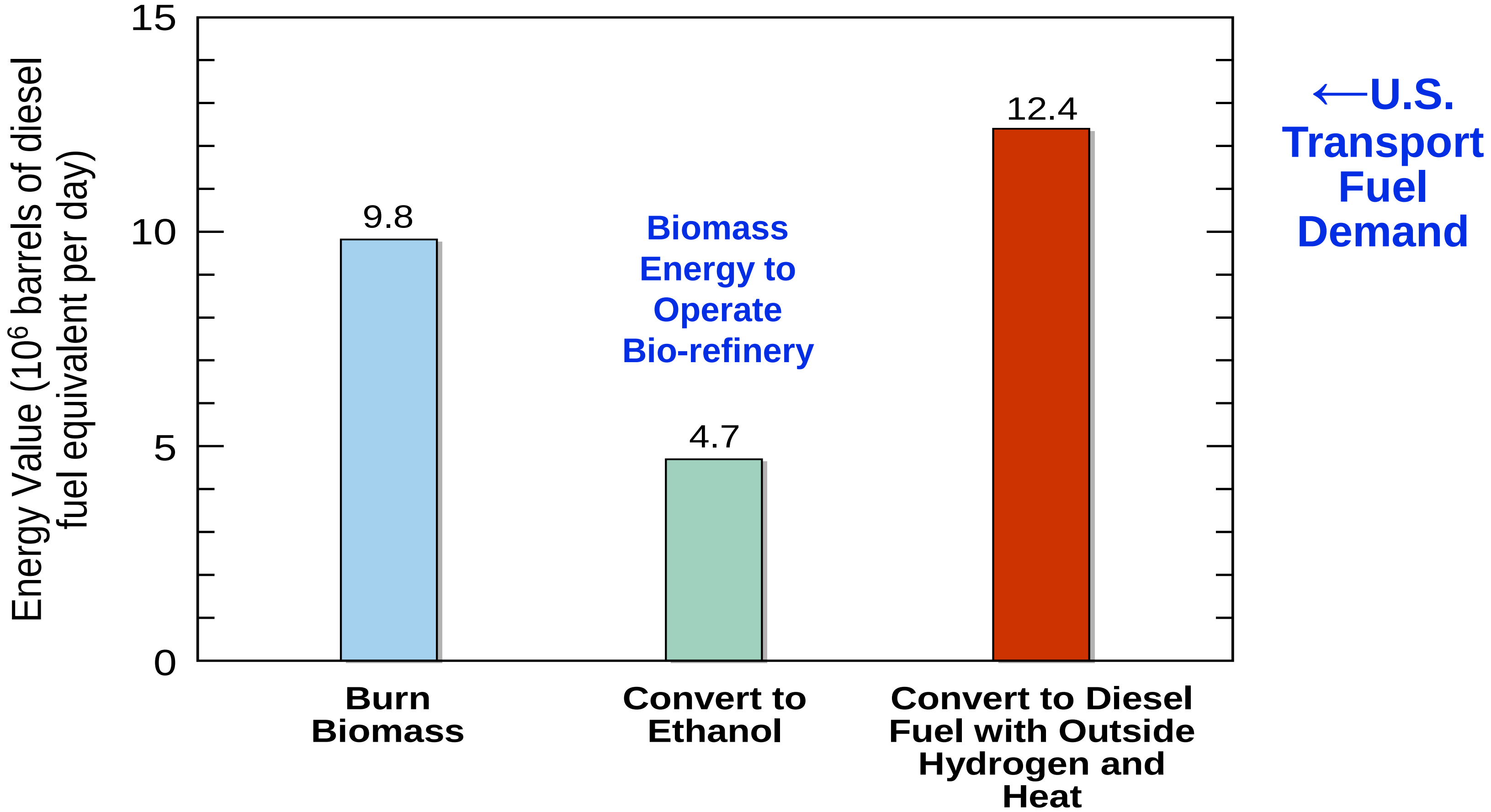
- Industrial world built on the least available fossil fuel—bad strategic policy
- Two interesting options
  - Shale oil: abundant and relatively low energy input to produce liquid fuels
  - Biomass: renewable and relatively low energy input to produce liquid fuels
- Look into future nuclear biomass and nuclear shale oil options

Nuclear Liquid Biofuels

Biomass Fuels: A Potentially Low-Greenhouse-Gas Liquid-Fuel Option



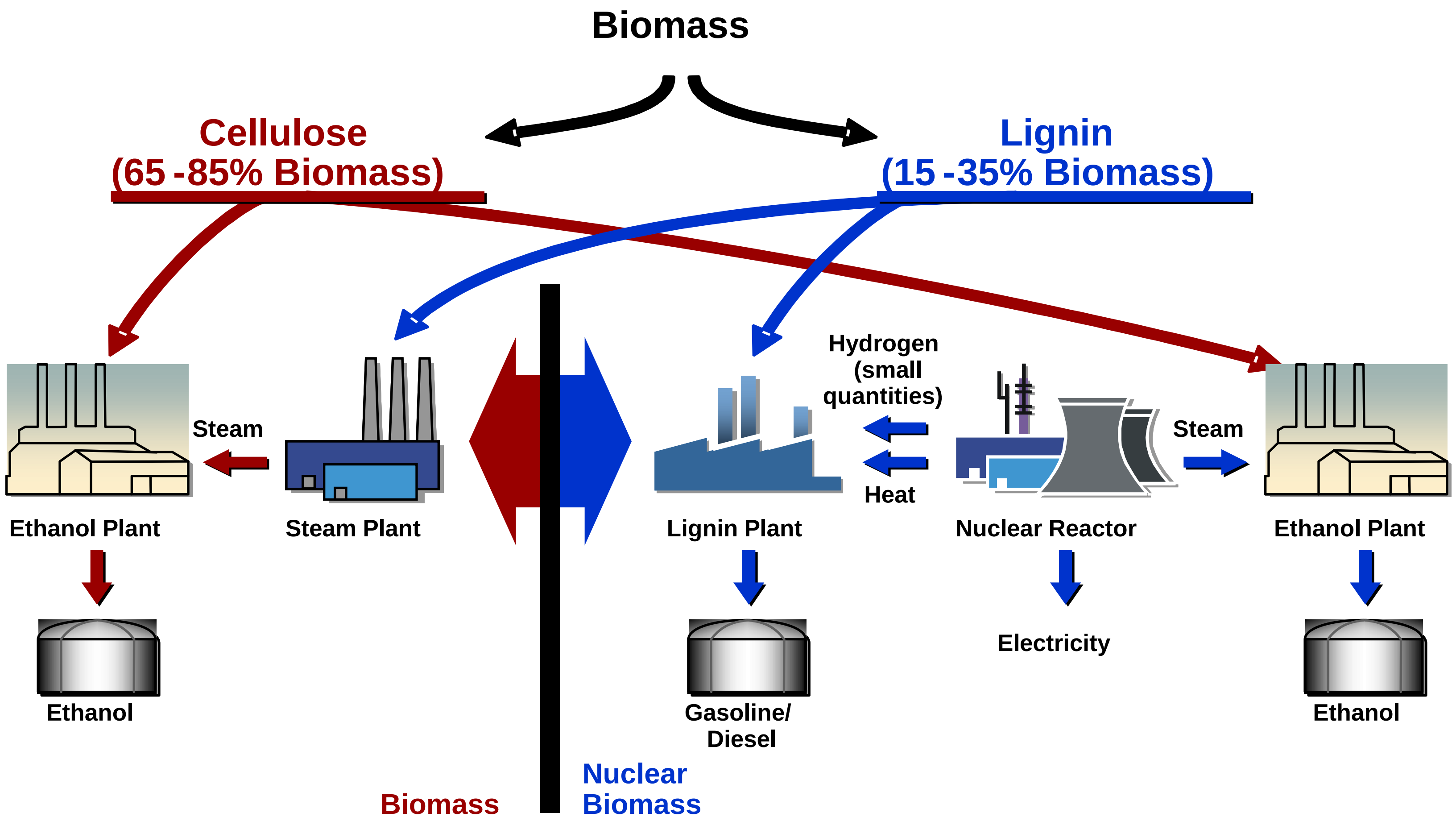
U.S. Biomass Fuels Yield Depends On the Bio-Refinery Energy Source



Without Impacting Food and Fiber Production

Future Cellulosic Liquid-Fuel Options

Biomass As Energy Source | Nuclear as Energy Source



50% Increase Liquid Fuel/Unit Biomass

Nuclear Energy Increases Liquid Fuels Per Ton of Biomass

Biomass As Feedstock and Boiler Fuel:

Useful But Not a Game Changer

Biomass Feedstock and Nuclear Energy

Replace Oil for Transport

Nuclear Shale Oil

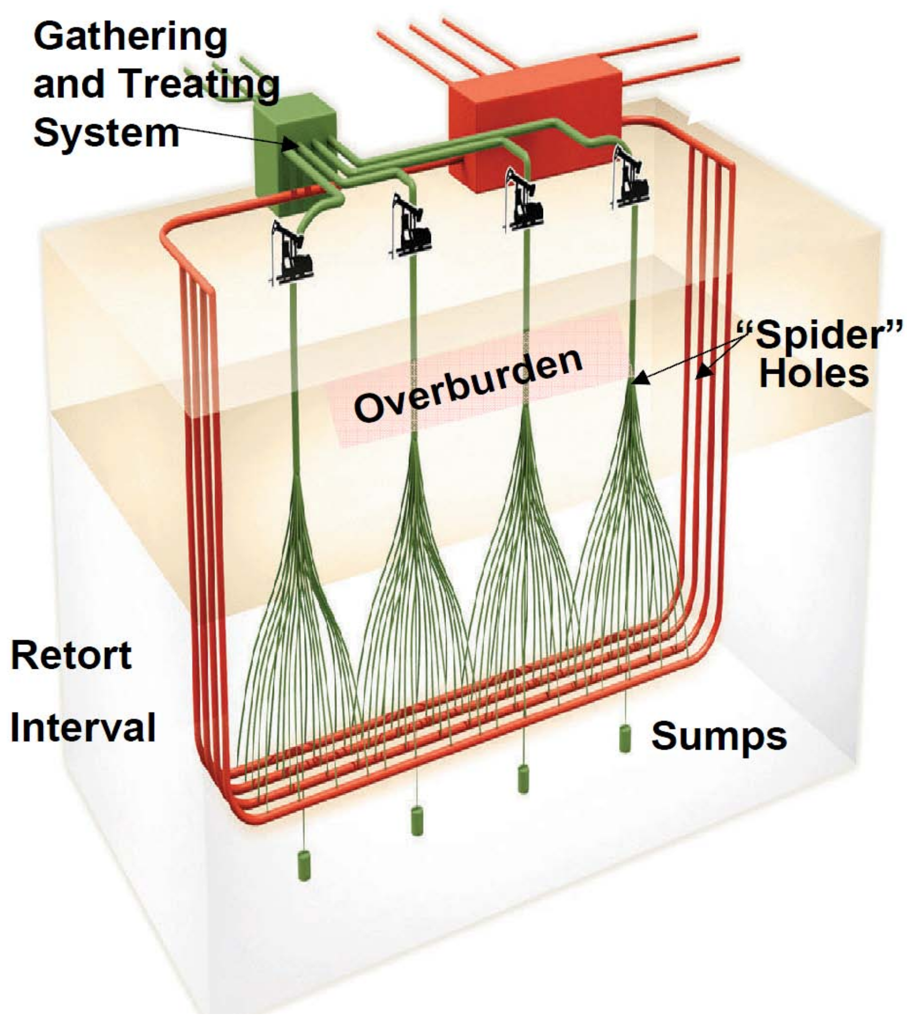
U.S. Oil Shale Could Replace Conventional Oil

- Green River recoverable reserves ~1.4 trillion barrels of oil
- Total world production of oil to date is 1.1 trillion barrels
- ~1 million barrels of oil per acre; Most concentrated fossil fuel on earth
- Pilot plants in operation

Conventional Shale Oil Production Implies Large Greenhouse Impacts

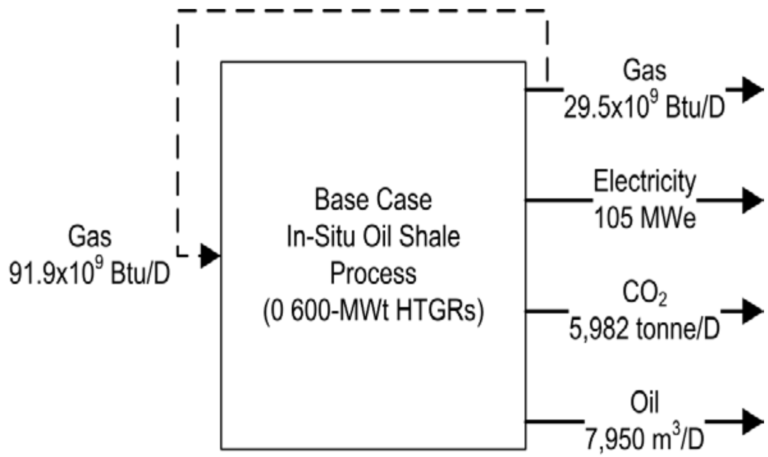
- Oil shale contains no oil but instead kerogen
- Heat kerogen underground to produce shale oil
- Current strategy—burn one third of oil and gas product to heat shale
- Large carbon dioxide release during production

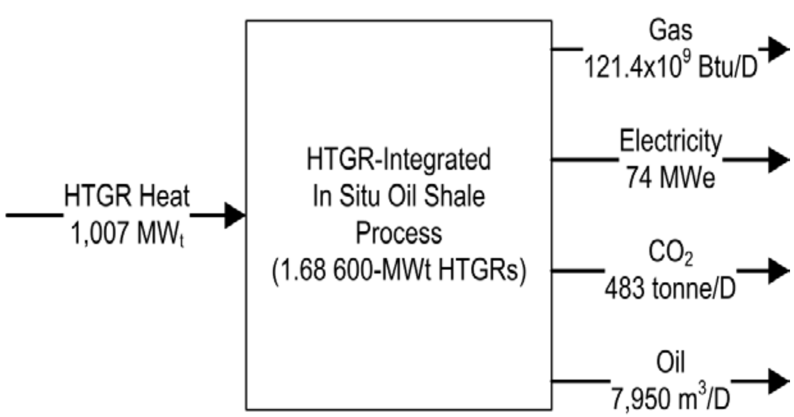
Nuclear Shale Oil Option



- Nuclear heating of oil shale (~370 C plus ΔT) to decompose into shale oil and char
- Carbon residue left underground
- Low production carbon footprint with sequestration that works

Nuclear Shale Oil: Low-Environmental-Impact Fossil Fuel Option





- Current strategy—burn one third of product to heat shale
- Nuclear heat avoids burning fossil fuels to make shale oil (1/3 of product)
- In effect, underground refinery thermal cracking and distillation to produce high-quality distillate oil
- Carbon sequestered as char, sequestration that works

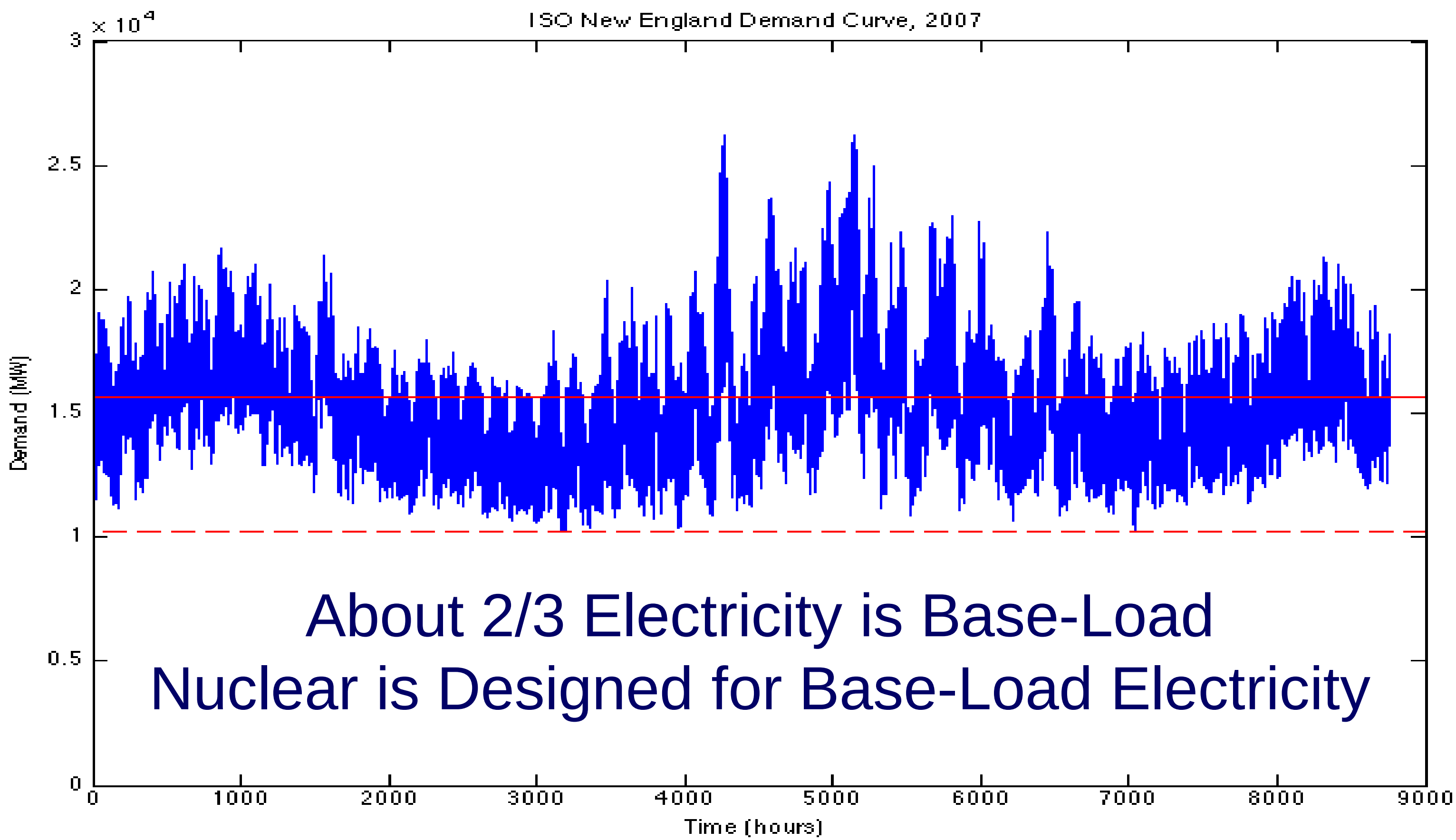
The Variable Electricity Challenge

The Challenge of Variable Electricity Production May Drive Energy Production Choices

Variable Electricity Demand

Hourly, Weekday/Weekend, and Seasonal

Demand (10^4 MW(e))



About 2/3 Electricity is Base-Load

Nuclear is Designed for Base-Load Electricity

Time (hours since beginning of year)

Variable Electricity Is the Challenge for a Low-Carbon World

- Variable electricity now produced by fossil fuel power plants because fossil fuels easy to store
- Expensive to capture and sequester carbon dioxide with variable electricity output
- Output from low-operating cost nuclear, wind, and solar plants do not match electricity demand
- If not use fossil fuels, two options to match production with demand
  - Store electricity when excess electricity production to meet later high electricity demand
  - Hybrid energy systems

Electricity Storage to Match Production and Demand

Storage Requirements

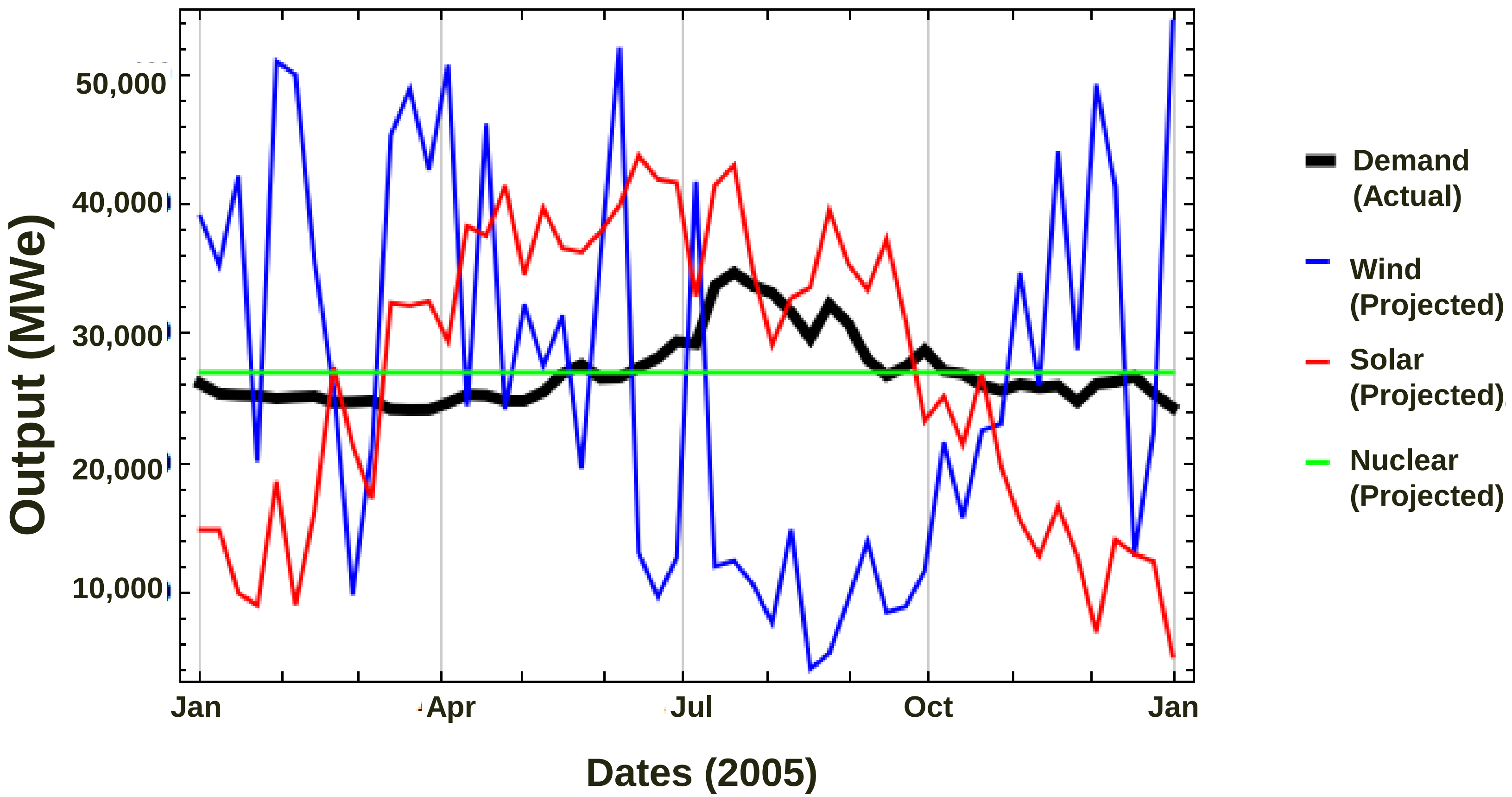
Nuclear-Geothermal Energy Storage

Analysis of Storage Requirements in a Low-Carbon World

- Nuclear, wind, and solar have high capital costs and low operating costs
- Best economics if operate at full capacity
- Analyzed three California cases assuming perfect electricity storage systems
  - All electricity from nuclear energy
  - All electricity from wind
  - All electricity from solar thermal—some storage

California Demand and Production with All-Nuclear, All-Wind, or All-Solar Systems

KWh Produced/Year By Each Technology = KWh Consumed/Year



California Weekly Averaged 2005 Data Assuming All Electricity Produced By Nuclear, or Wind, or Solar Trough (With Limited Storage)

California Electricity Storage Requirements As Fraction of Total Electricity Produced

Assuming Perfect No-Loss Storage Systems

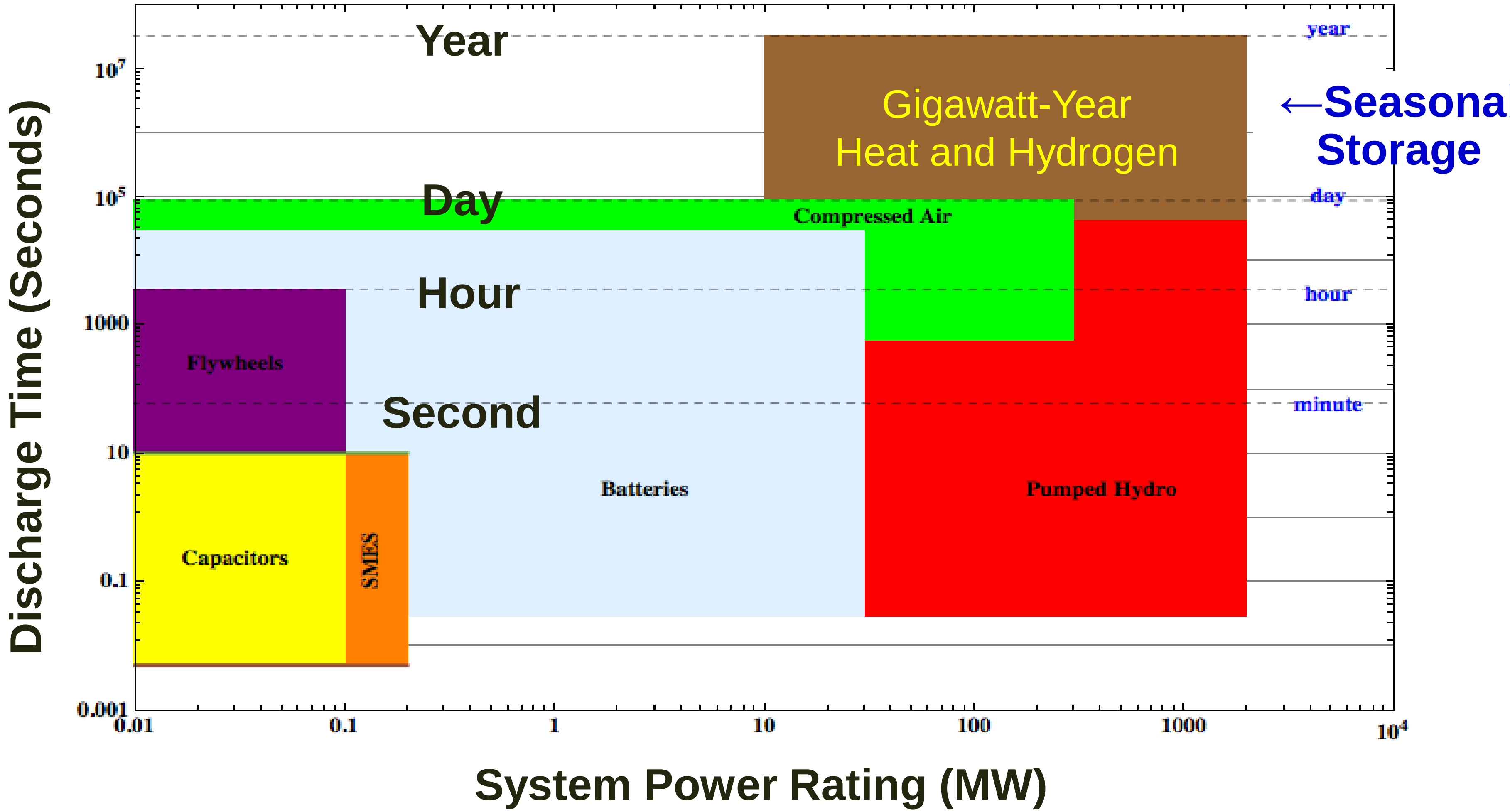
Electricity Production	Hourly Actual demand	Yearly Constant Demand Each Week[A]
All-Nuclear[1]	0.07	0.04
All-Wind[2]	0.45	0.25
All-Solar[2]	0.50	0.17

- Massive storage requirements for renewables
- Renewables must be cheaper than nuclear because of greater storage requirements

[A]Assume Smart Grid, Batteries, Hydro, etc for Daily Energy Storage

[1]Steady-state nuclear; [2]NREL wind and solar trough model (with limited storage) using CA wind / solar data

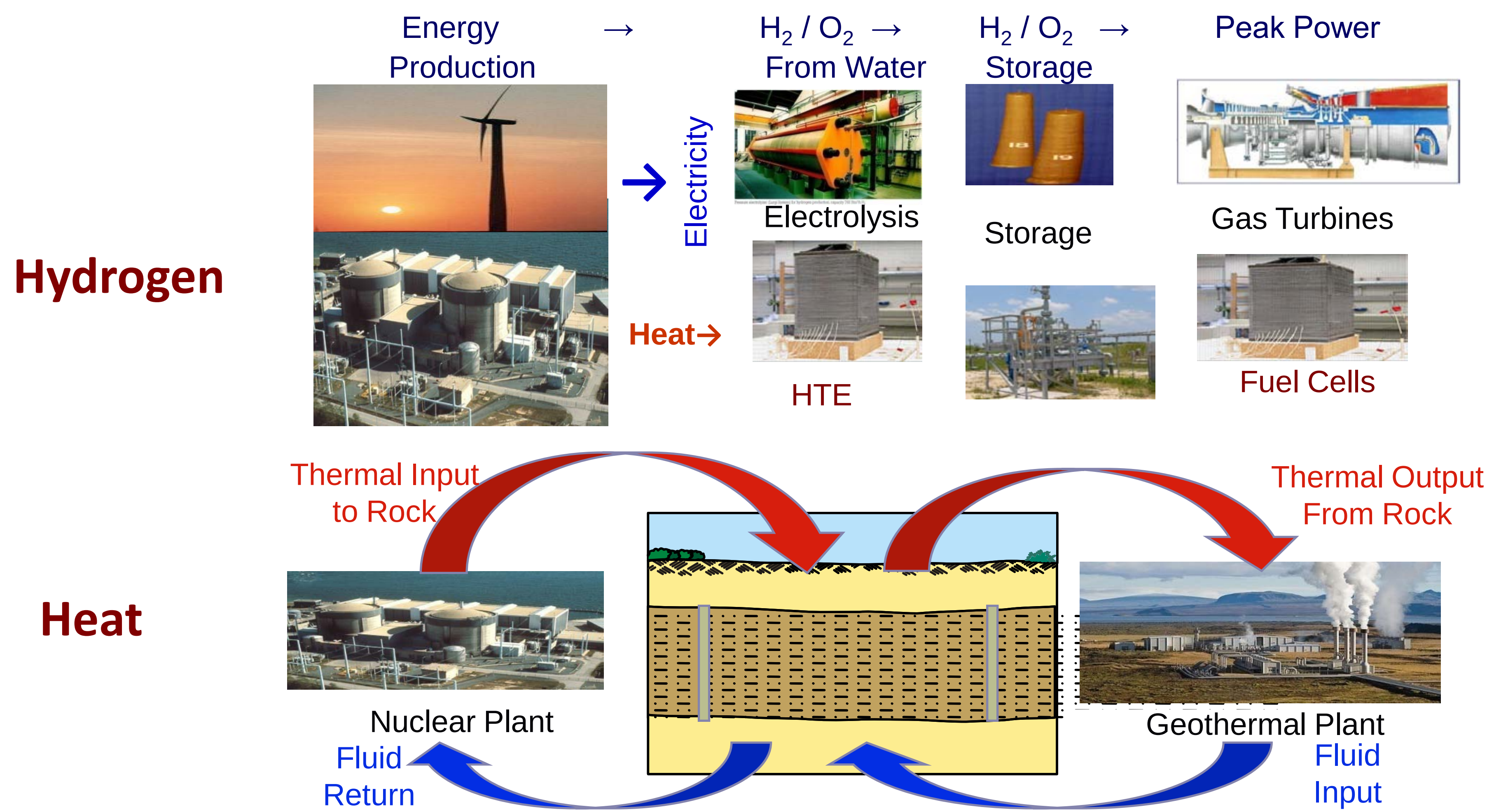
Energy Storage Expensive: Different Technologies for Different Times



Storage Costs can Exceed Energy Costs for All Renewable Systems

Seasonal Electricity Storage Options

Capital Cost and Roundtrip Inefficiencies: 50% for Several Options Today, 70% in Future



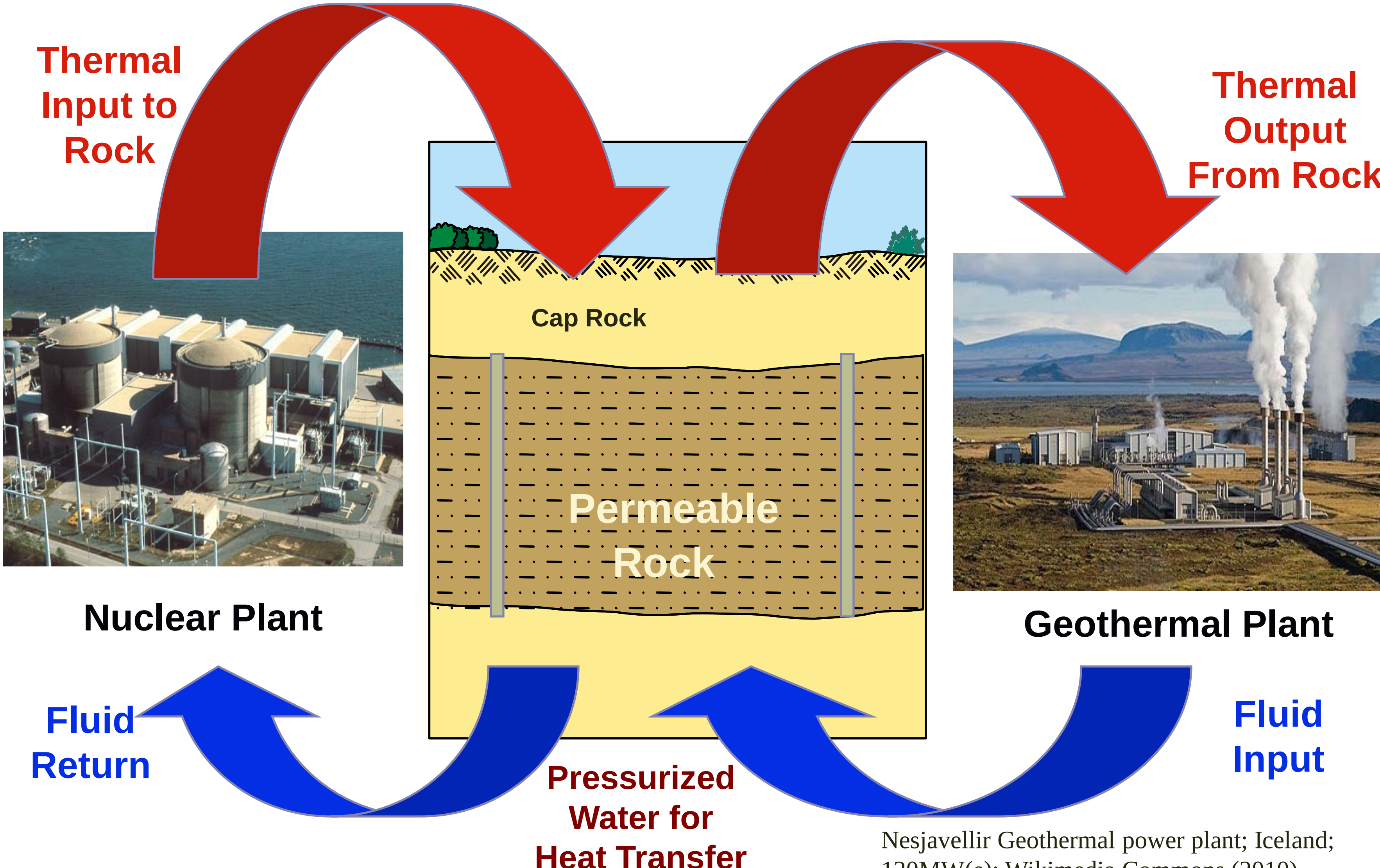
Gigawatt-Year Nuclear-Geothermal Heat Storage

Seasonal Energy Storage

Status: Early R&D

Initial Assessment: Commercially Viable

Nuclear-Geothermal System

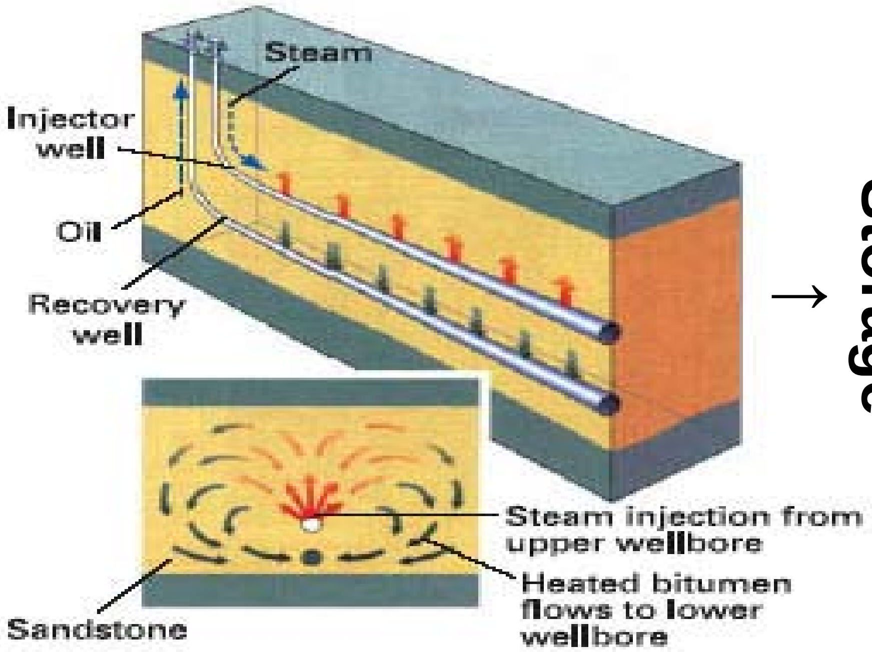


Nesjavellir Geothermal power plant; Iceland; 120MW(e); Wikimedia Commons (2010)

Nuclear-Geothermal Storage Is Based On Two Technologies

Recovery of Heavy Oil By Reservoir Heating

California and Canada



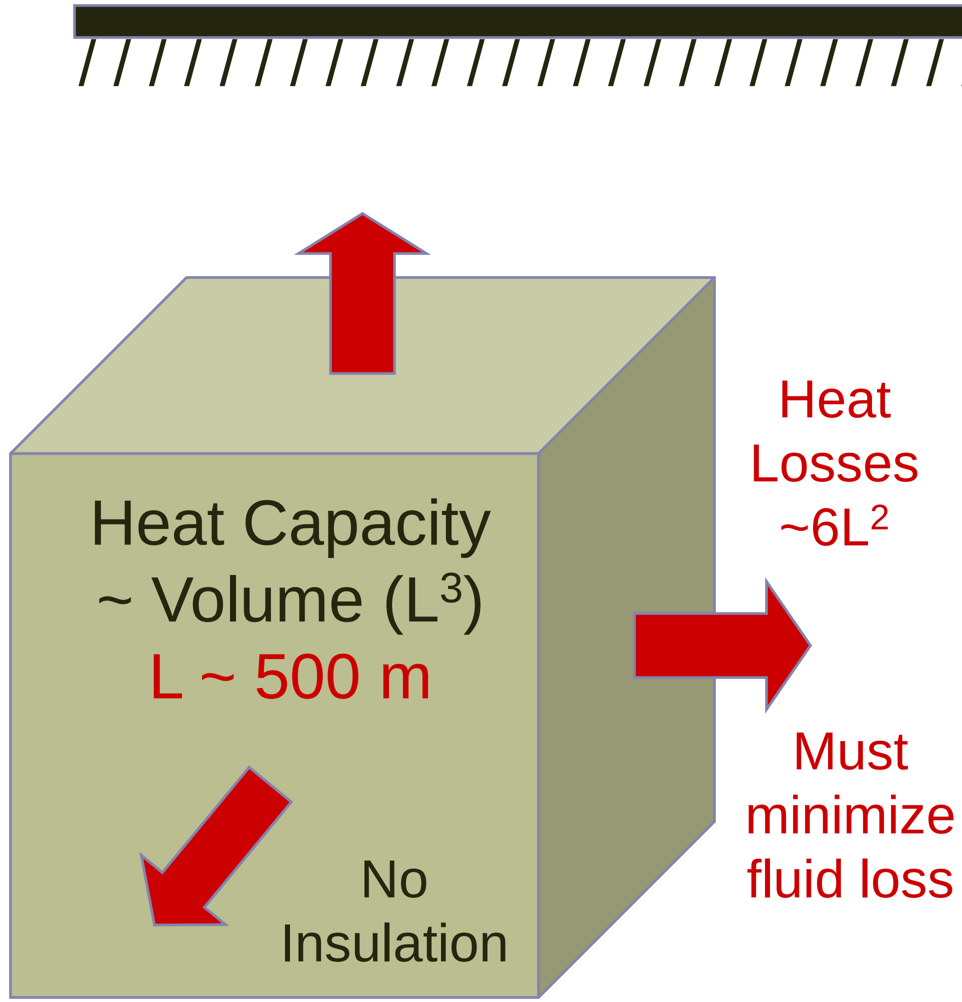
→ **Storage** →

Geothermal Power Plant Heat Extraction

Figure courtesy of Schlumberger; Nesjavellir Geothermal power plant, Iceland: 120MW(e); Wikimedia Commons (2010)

Heat Storage Must Be Large to Avoid Excessive Heat Losses

Intrinsic Large-Scale Nuclear Storage System

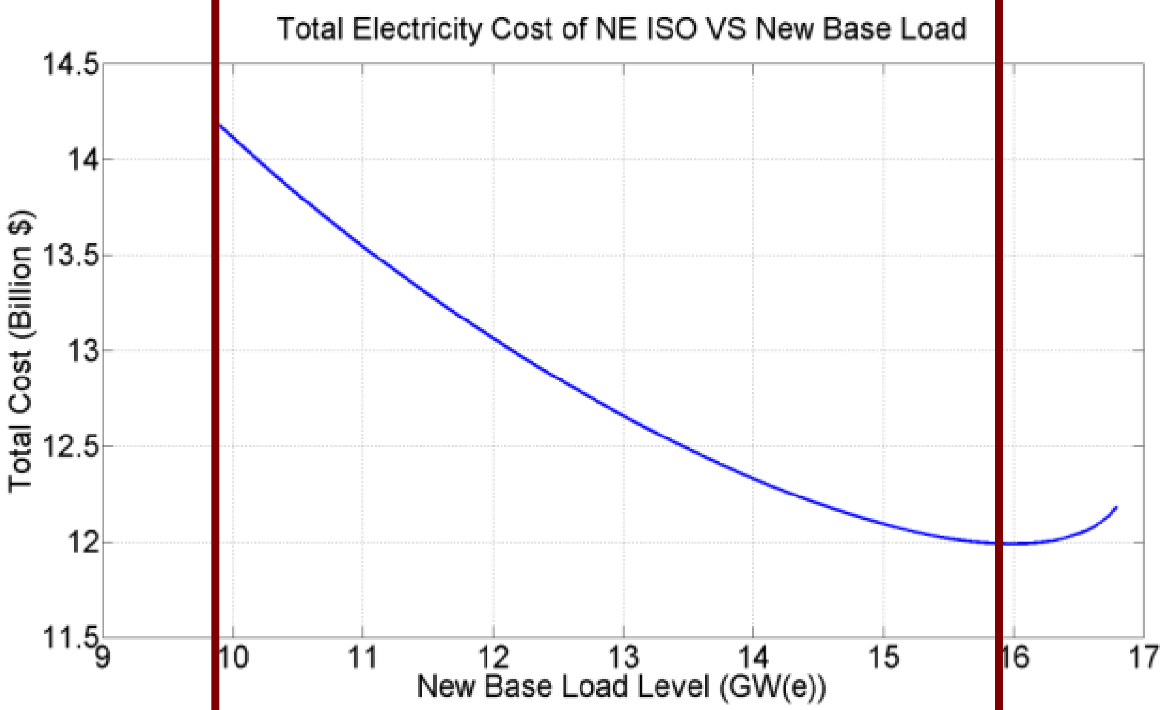


- Can not insulate rock
  - Heat loses ~ surface area
  - Heat capacity ~ volume
- Large storage has smaller fractional heat loses

Total Annual Electricity System Cost Vs Nuclear Geothermal System Size

Economic Assessments Indicates Market Is Intermediate Load

Higher Capital But Lower Operating Cost Than Natural Gas



←10 GWe Base Load Electricity

6 GWe Nuclear Geothermal: Electricity and/or Heat to Storage

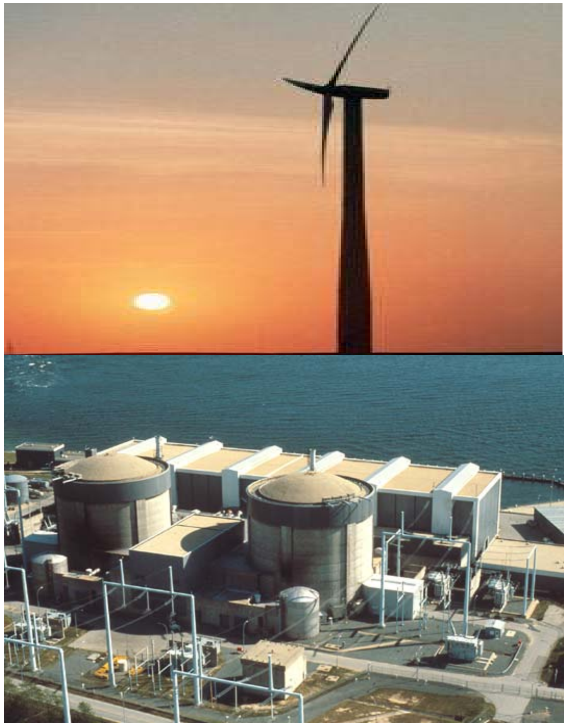
Natural Gas→

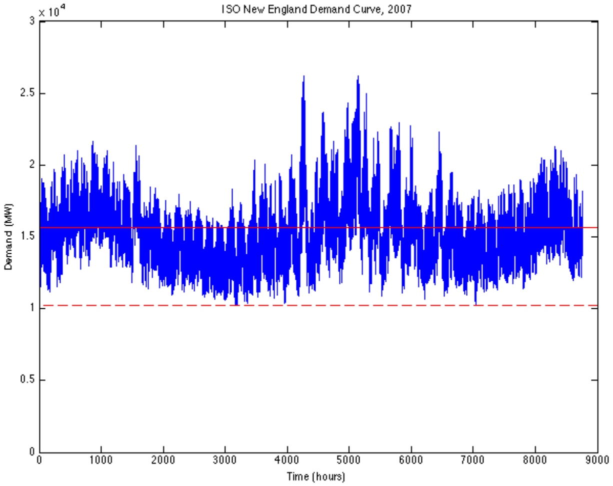
Hybrid Energy Systems

Combining Energy Sources and Uses

Hybrid Nuclear-Renewable Systems to Minimize Expensive Electricity Storage

Maximize Capacity Factors of Capital Intensive Power Systems = Meet Electricity Demand + Efficient Use of "Excess" Energy for Fuels Sector



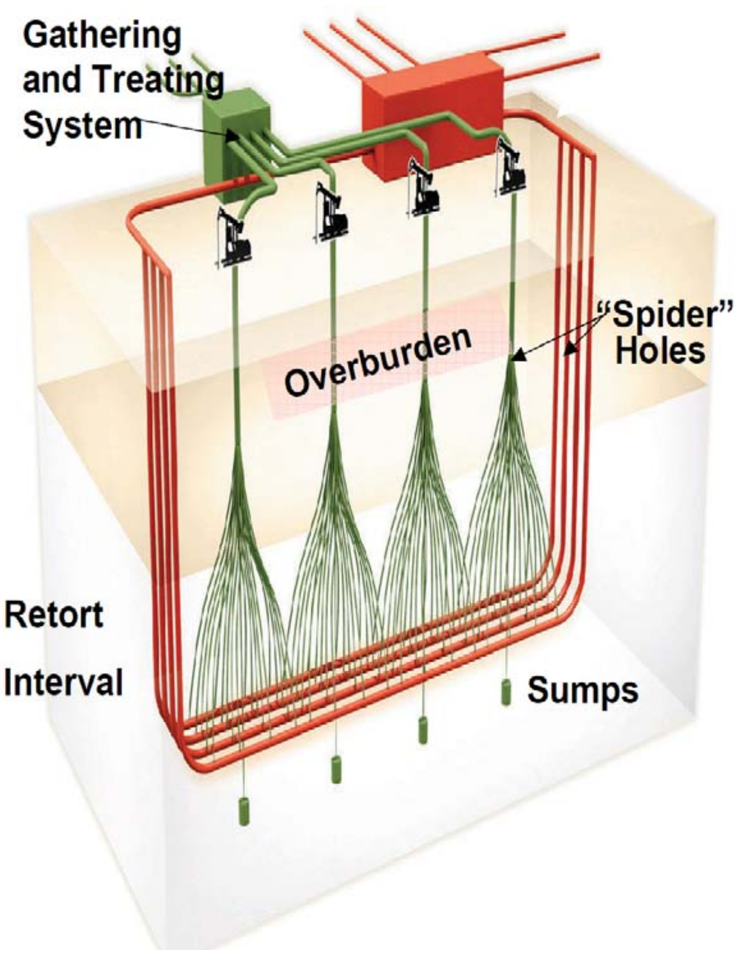


- Biofuels
- Oil shale
- Refineries
- Hydrogen

Option for a Low-Carbon World

Shale Oil and Variable Electricity

Nuclear Shale Oil and Variable Electricity Production



- Heating shale oil takes months because of low thermal conductivity rock
- Cogeneration option
  - Variable electricity when high prices
  - Heat oil shale with low-cost night time heat
- Enable wind and solar without natural-gas turbine backup

Shale Oil Production Is Unusual Industrial Operation That Allows Variable Heat Input

- Low thermal conductivity rock so variable heat impact will not cause large changes in oil output
  - Months to years of heating
- Reactors, not wells, are the primary expense so not heating at full rate has limited economic impact
- The key economic requirement is for base-load operation of the nuclear plant

Nuclear Shale-Oil With Variable Electricity: the Cleanest Fossil Fuel?

- Example analysis: assumptions
  - 2-GWY nuclear: ½ variable electricity, ½ shale oil
  - 1-GWY nuclear heat yields 2 GWY shale oil
  - Nuclear and fossil electricity efficiencies identical
- Results
  - 1-GWY no-fossil fuel variable electricity
  - 2-GWY shale oil
  - CO_2 saved from nuclear variable electricity equal to not burning 1-GWY shale oil: Can be credited to shale oil

Net Greenhouse Gas Release per Liter Half That of Gasoline From Crude Oil

Conventional Shale Oil Production:

Large Environmental Impacts

Nuclear Shale Oil with Variable Electricity Production

Enable Large-Scale Renewables

Lowest Environmental Impact Fossil Liquid Fuel

Transfers Half-Trillion Dollars per year Spent on Foreign Oil Back to the U.S. Economy

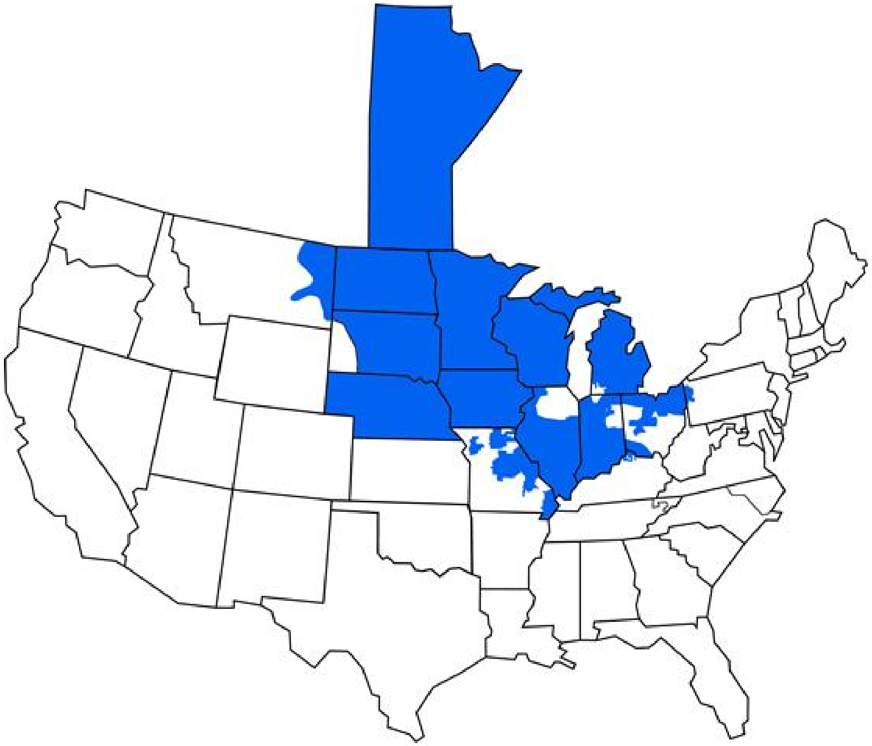
Nuclear and Wind for Variable Electricity and Hydrogen

Nuclear-Renewable Hydrogen-Electric Systems

- Nuclear, wind, and solar are capital intensive—maximize production to minimize cost.
- Wind and solar constraints
  - Can not match electricity demand
  - Energy storage is expensive
- If wind or solar economics improve, is there a way to create an economic reliable power systems?

Nuclear-Wind-H_2-Natural Gas System: Test Case

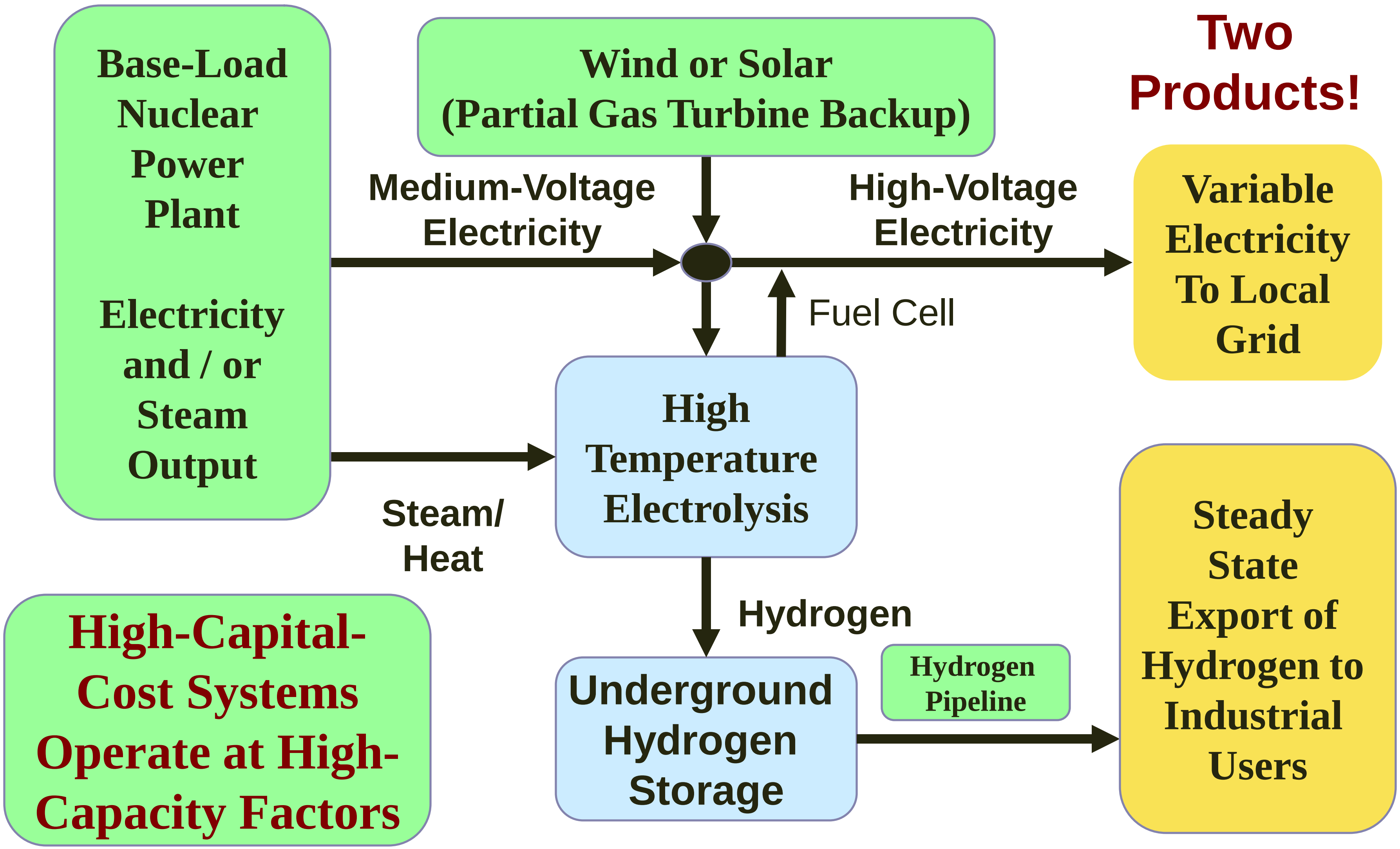
- North Dakota wind
- Products
  - Electricity for Midwest grid
    - Average: 61.8 GWe
    - Peak: 96.5 GWe
    - Minimum: 39.5 GWe
  - Hydrogen export
    - Chicago refineries
    - Alberta tar sands



Midwest ISO Regional Reliability Area

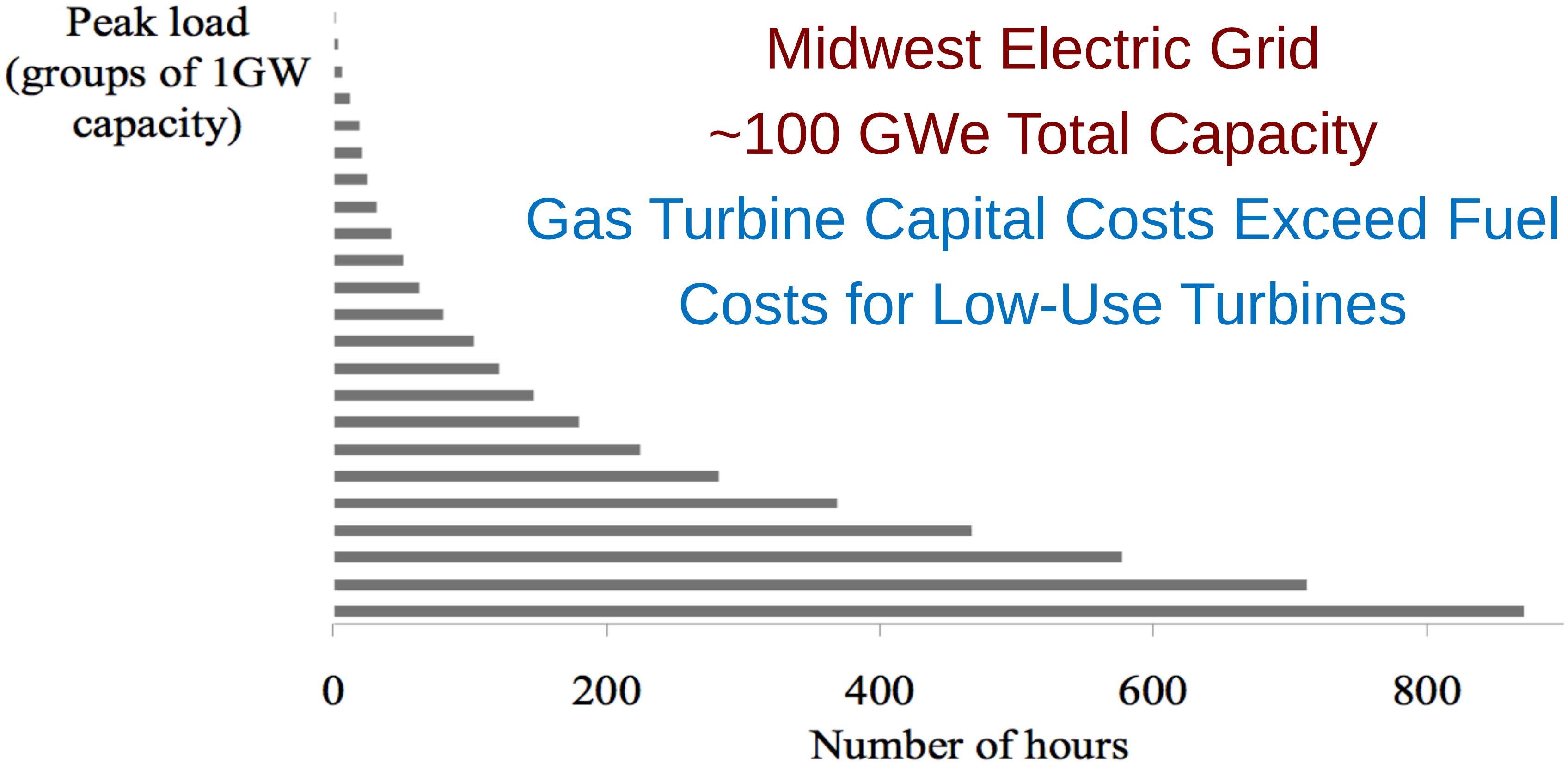
Competitive if reduce wind and HTE cost with higher price natural gas

Structure of Nuclear-Renewable Electric-Hydrogen System



About 20% of Generating Capacity is to Meet Peak Power Demand

Many Gas Turbines Have Very Low Capacity Factors



Midwest Electric Grid

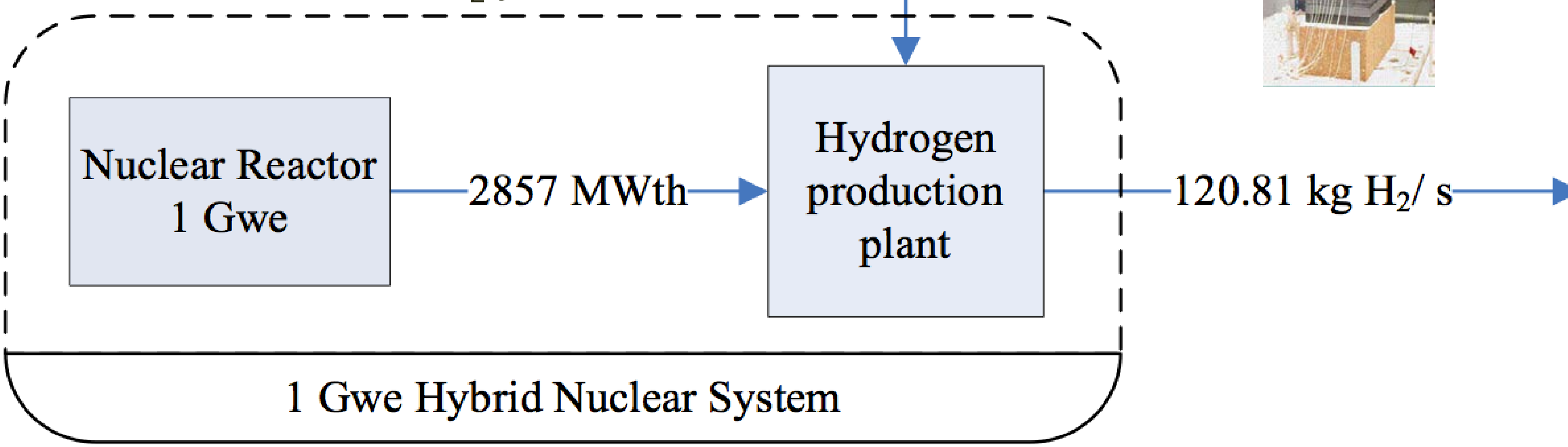
~100 GWe Total Capacity

Gas Turbine Capital Costs Exceed Fuel Costs for Low-Use Turbines

Light Water Reactor
High-Temperature Electrolysis

Water + Electricity + Heat → Hydrogen and Oxygen

- Products: Variable electricity and H_2 outputs
- Optimized case in analysis
  - 2.5 GWe nuclear
  - 1.3 million tons H_2/year

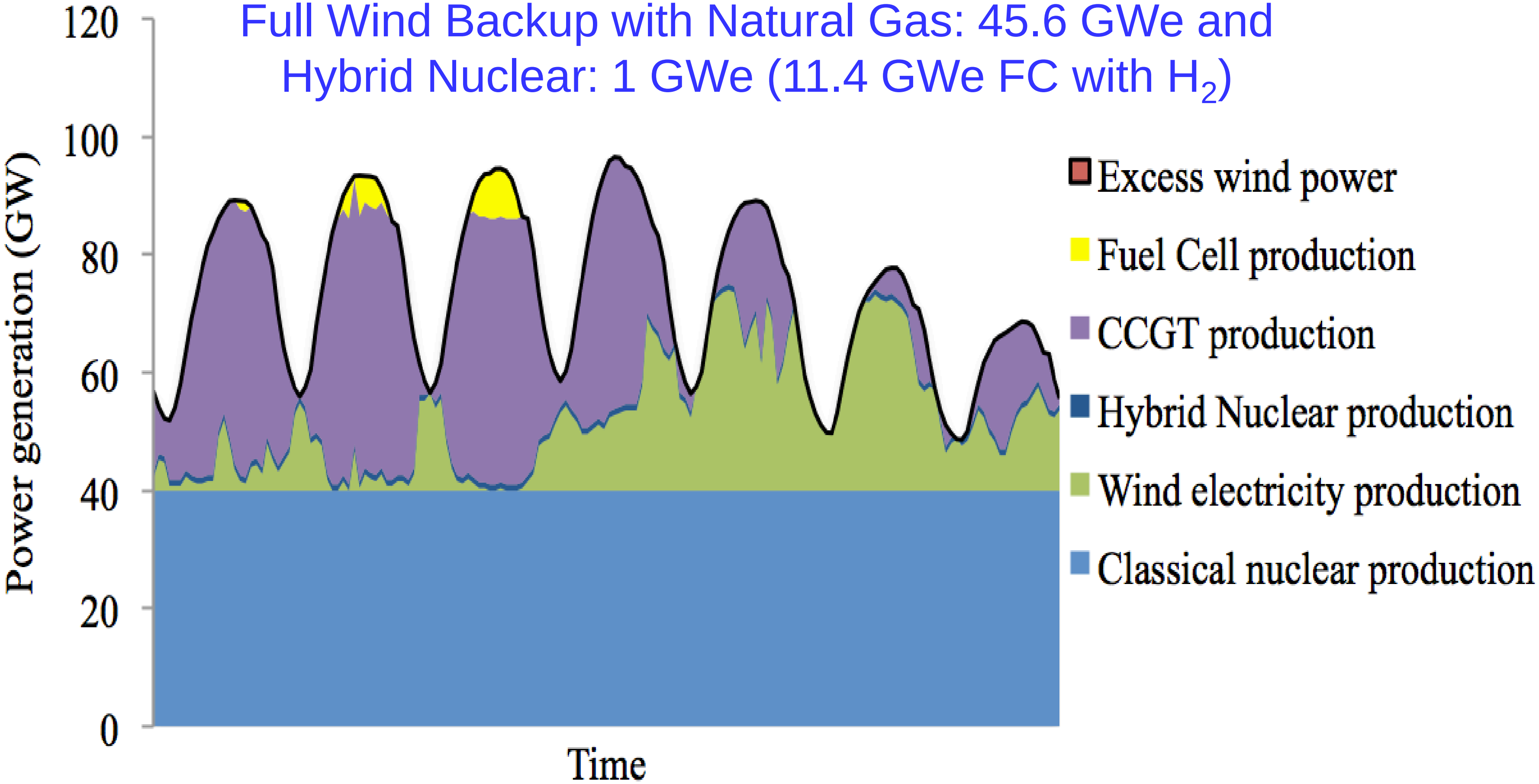


Reversible as Fuel Cell to Produce Electricity: Inefficient Electricity to H_2 to Electricity But Avoid Expensive Low Capacity Gas Turbines

Meeting Electricity Demand With Nuclear Wind Natural-Gas H_2

Capacity: Nuclear Base-load: 40 GWe; Wind: 50 GWe

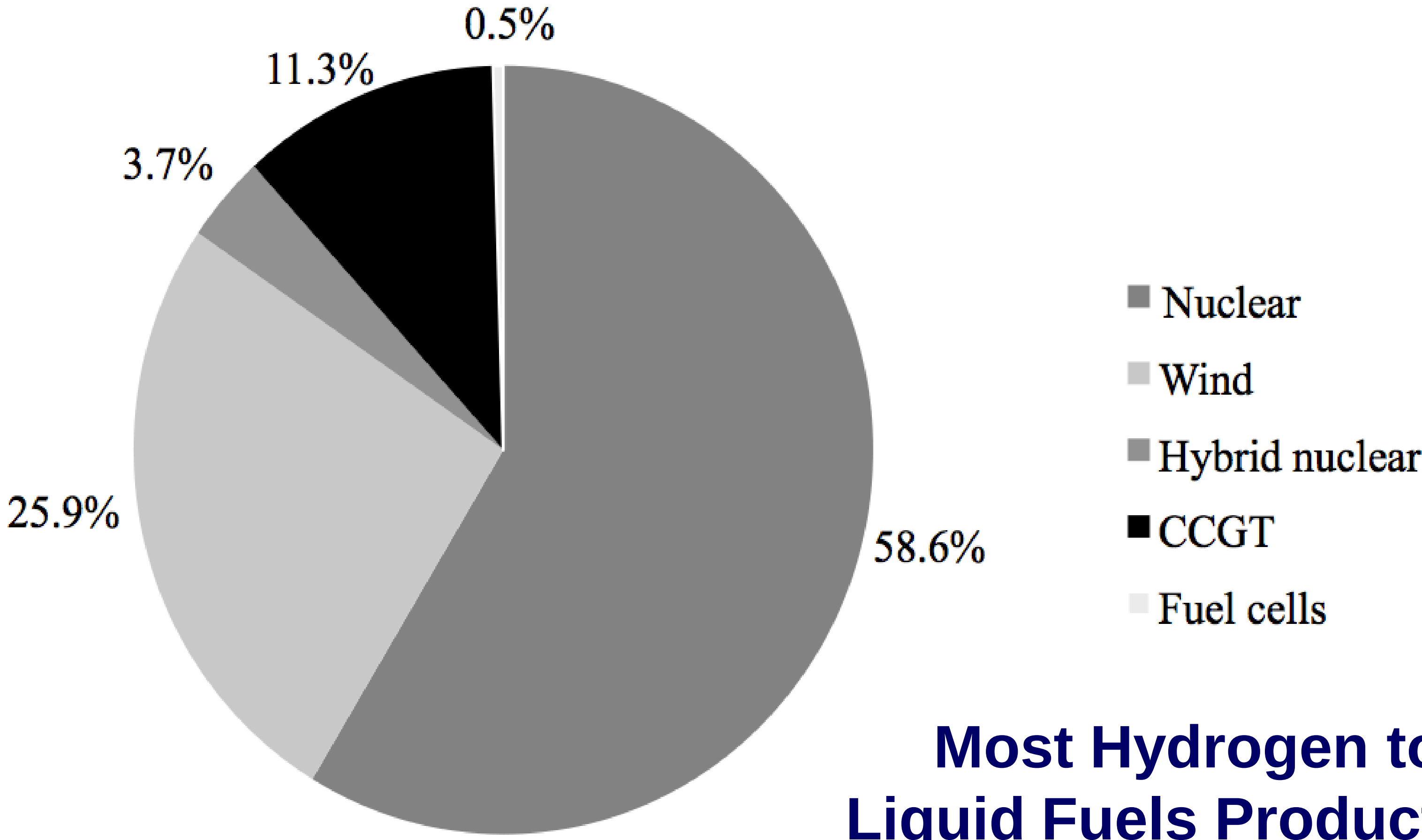
Full Wind Backup with Natural Gas: 45.6 GWe and Hybrid Nuclear: 1 GWe (11.4 GWe FC with H_2)



1 GW(e) Nuclear-HTE Implies 11.4 GW(e) Fuel Cell Capacity (Yellow) that Replaces 11.4 GW(e) Low-Capacity Gas Turbines

Electricity Generation Breakdown

H_2 Fuel Cells (HTE Units in Reverse) Provide Large Peak Capacity But Small Fraction of the Electricity (0.5%); Help Pay for H_2 Production System



Most Hydrogen to Liquid Fuels Production

System Design to Minimize Total Cost

- Nuclear base-load to minimize expensive storage
- Hydrogen energy sink
  - Absorb excess energy when high wind and low demand
  - Provide H_2 for liquid fuels and other uses
- **Hydrogen primarily to industrial markets**
- When high electricity demand, HTE operates in reverse as a fuel cell to produce electricity
  - Inefficient electricity to storage to electricity mode
  - Use only small amount of H_2 in this expensive mode
  - However, replacing low capacity gas turbines helps pay for electolyzers

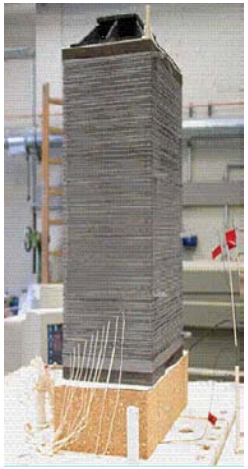
Many Design Variants--Unexplored

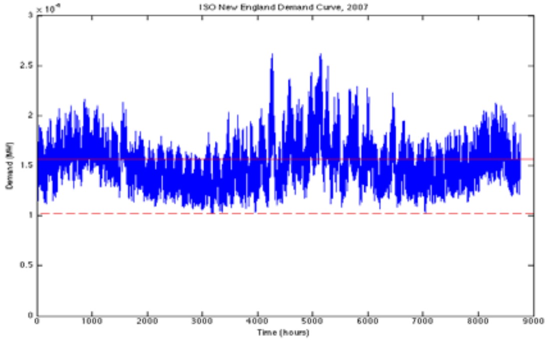
- Solar rather than wind
- Nuclear geothermal heat storage rather than natural gas
- All cases include
  - Base-load high-capital cost nuclear, wind, and solar
  - Secondary market for "excess" energy to avoid energy storage penalties
- Solid system architecture—relative use of nuclear, wind, and solar dependent upon relative costs

Conclusions

- Hybrid Nuclear Energy Systems Can Meet Variable Electricity and Liquid Fuels Markets
- Major Technical Challenges and Uncertainties but multiple Low-Carbon, No-Imported-Oil Paths Forward Exist
- All nuclear or all renewable likely to be much more expensive (Particularly all renewables)
- Potentially economic

Questions





Full Report

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Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

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