Applied Energy Symposium
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Nuclear Energy Drop-In Replacements for Gas Turbines, Natural Gas and Fossil Liquid Fuels

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icae
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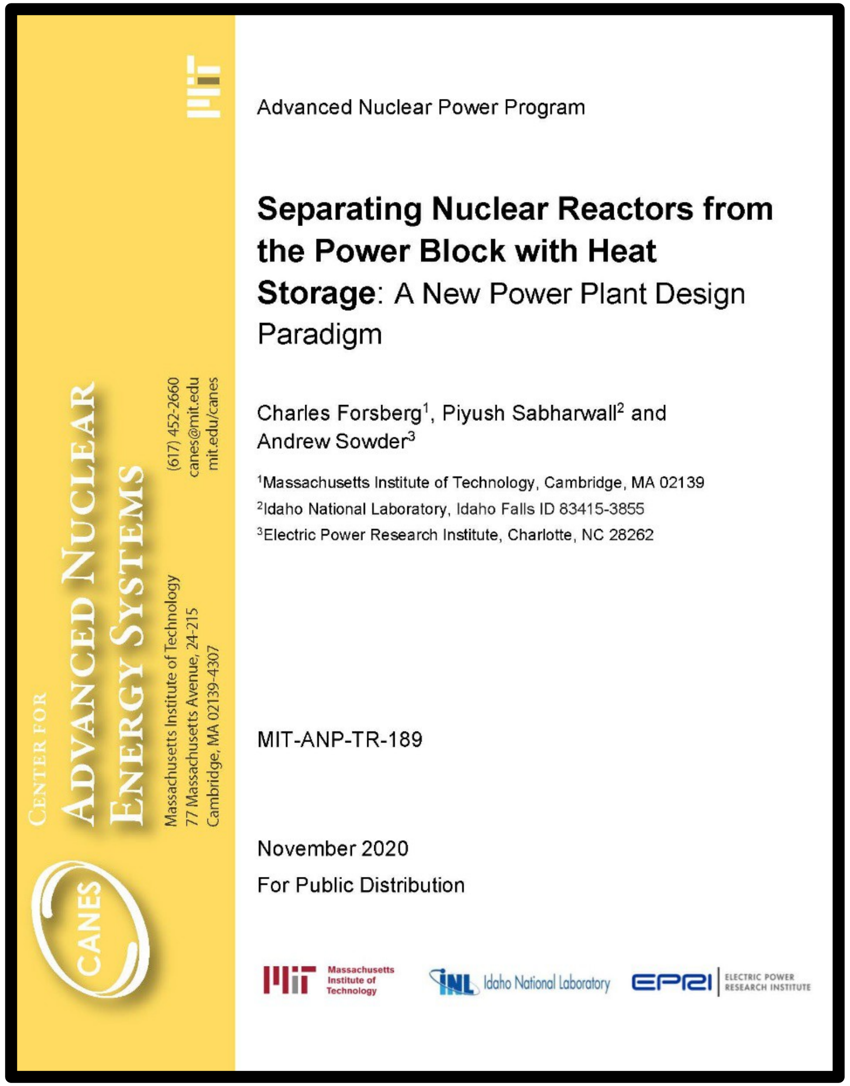
A SERIES OF STUDIES WERE UNDERTAKEN ON REPLACING FOSSIL FUELS WITH NUCLEAR ENERGY

1. Replacing the gas turbine using nuclear energy and heat storage to provide variable electricity to the grid
2. Replacing natural gas with nuclear hydrogen
3. Replacing fossil liquid fuels with nuclear biofuels

REPLACING THE GAS TURBINE: VARIABLE ELECTRICITY BY COUPLING HEAT STORGE TO NUCLEAR REACTORS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Advanced Nuclear Power Program

Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm

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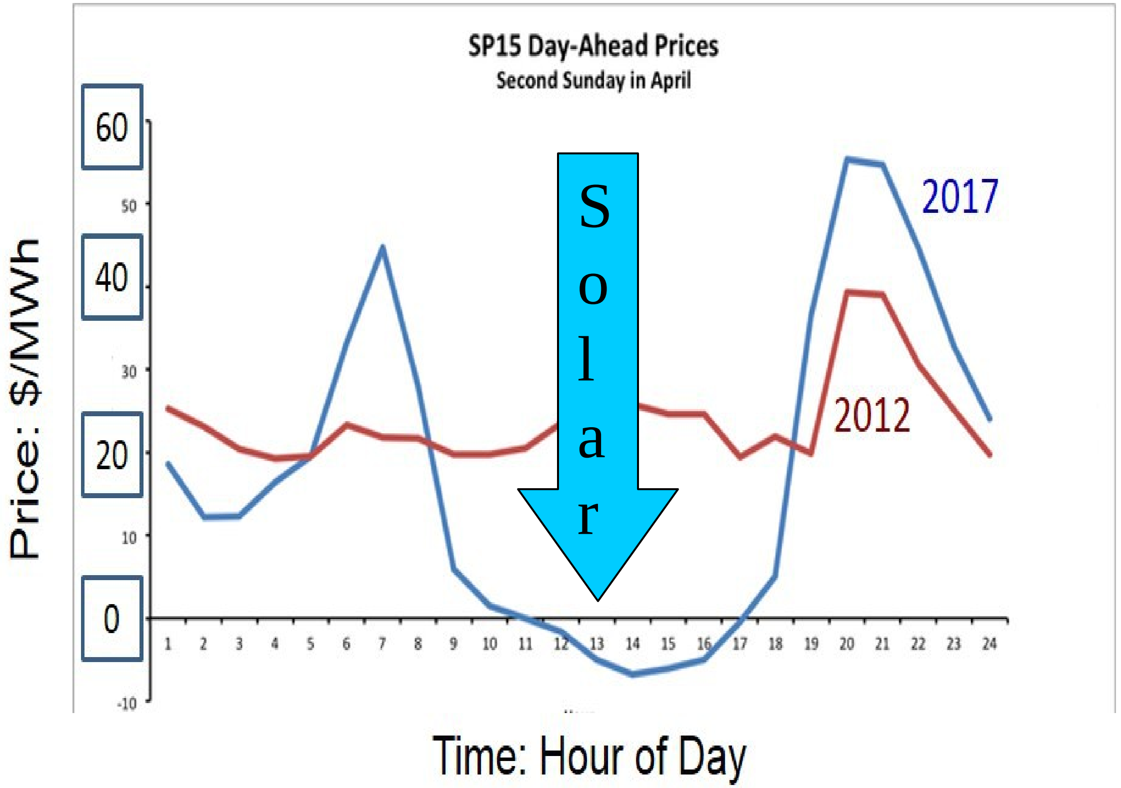
C. W. Forsberg, P. Sabharwall and A. Sowder, Separating Nuclear Reactors from the Power Block with Heat Storage: A New Power Plant Design Paradigm, Workshop Proceedings, ANP-TR-189, Massachusetts Institute of Technology, November 2020. https://www.osti.gov/biblio/1768046

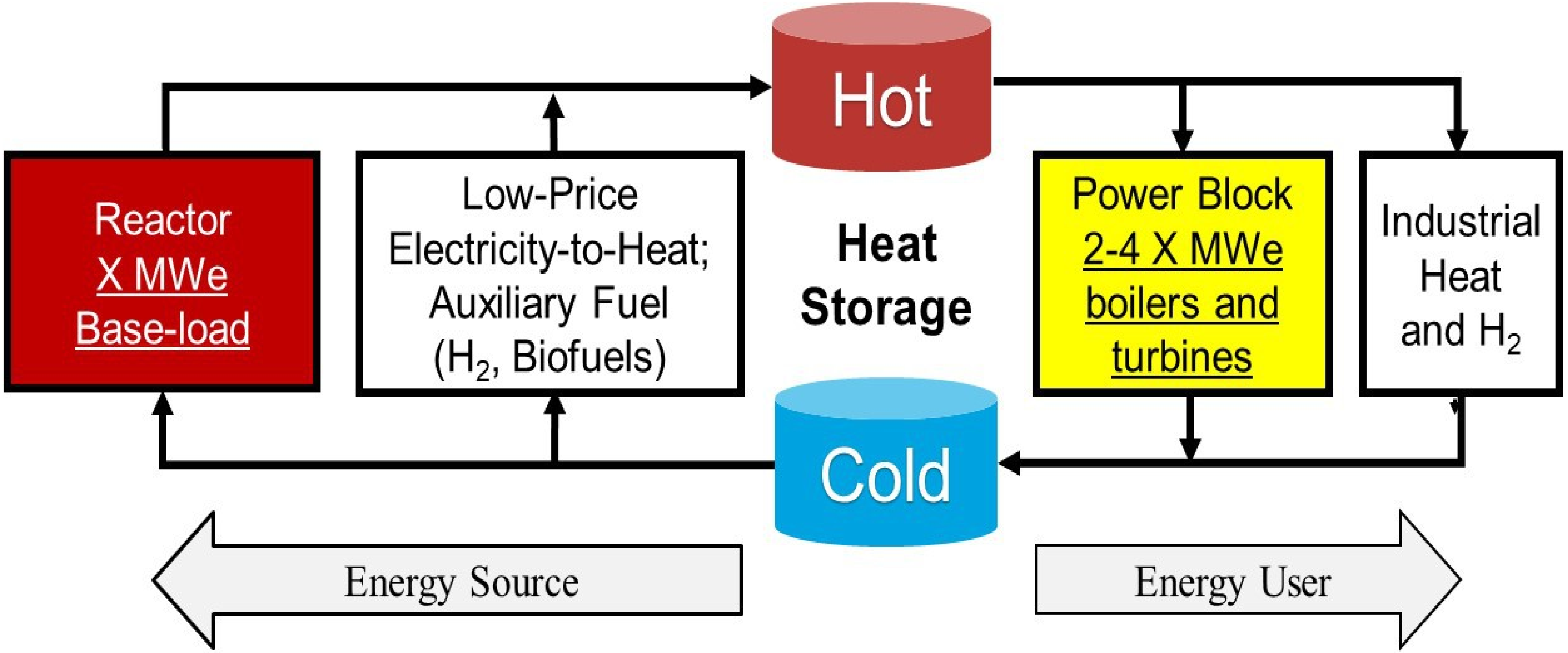
Electricity Markets are *Changing*

- **Electricity prices in fossil-fuel systems are relatively constant: most of the production cost is fuel (Red; California 2012).**
- **Large-scale wind or solar creates volatile electricity prices—including zero prices (Blue: California 2017).**
- ***Maximize revenue if sell when electricity prices are high*.**



Wholesale California electricity prices over 24 hours on a spring day

Requires Rethinking Nuclear Power with Heat Storage For Baseload Reactors with Variable Electricity to Grid



Storage Separates Reactor from Power Block

Similar to Heat Storage at Concentrated Solar Power Plants

Oil to 400°C; Nitrate Salt to 600°C

Molten salt thermal energy storage

Crescent Dunes solar power station, Nevada

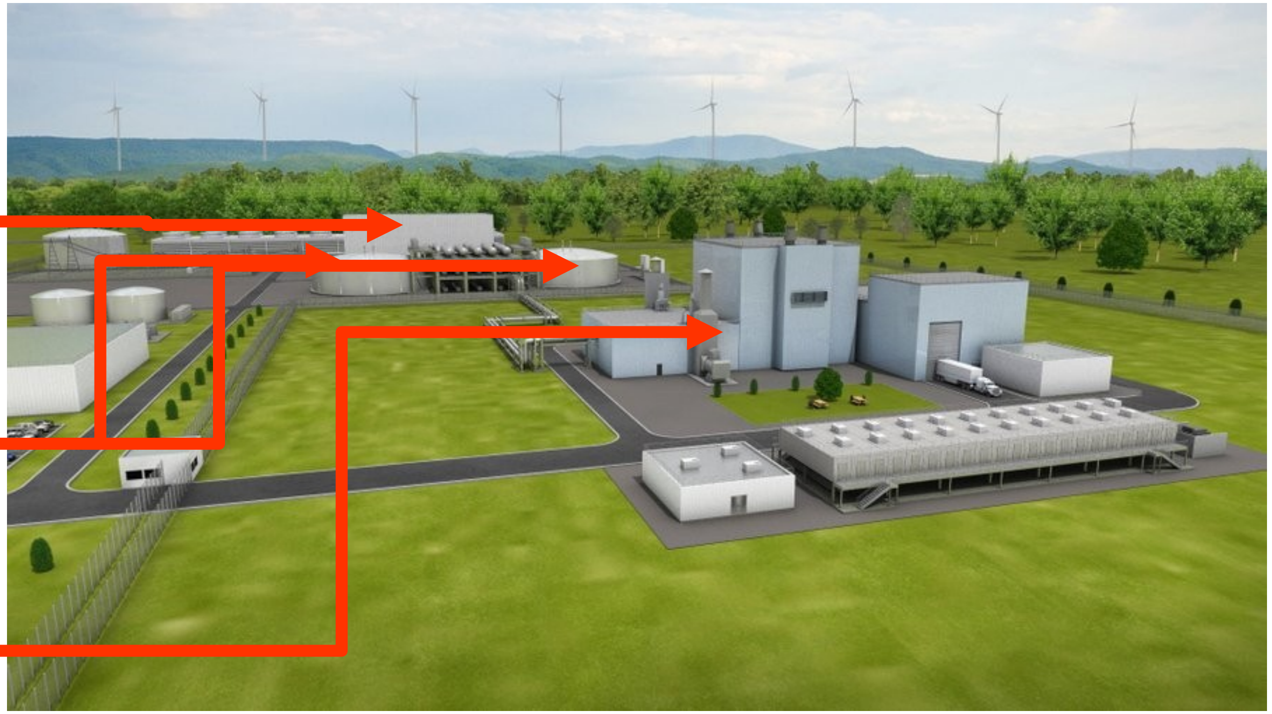
Solar System Heats Cold Nitrate Salt and Puts in Hot Storage Tank

Nuclear Energy With Large-Scale Heat Storage Is Competitive in a Low-Carbon Electricity Grid

- Base-load reactor operations minimize cost of heat production
- Heat storage enables variable electricity to maximize revenue and replace gas turbines. It is much less expensive than storing electricity
  - Capital Cost Heat Storage: $70/kWh(e)
  - Advanced heat-storage systems: <$10/KWh(e)
  - Battery capital cost >$200/kWh(e))

Advanced Reactors Including Heat Storage (GE/TerraPower, Moltex, Kairos Power) Nitrate Salt Intermediate Loop and Storage Media

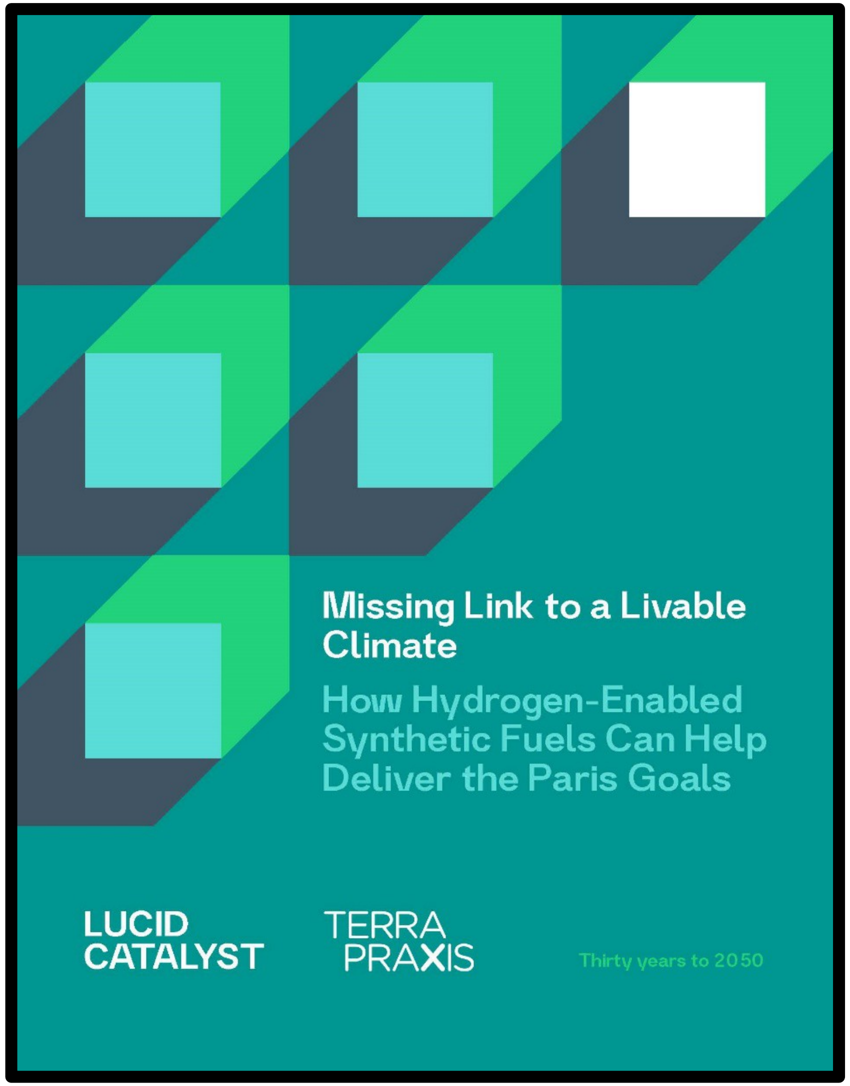
- Non-nuclear power block with peak power several times base-load output
- Non-nuclear nitrate-salt heat storage
- Base-load nuclear reactor



GE / TerraPower Natrium Reactor

REPLACING NATURAL GAS WITH NUCLEAR HYDROGEN (Gas Transition #2)

- Town gas (CO + H2)
  - 1800s to 1950s
- Natural gas (CH4)
  - 1950s to ?
- Hydrogen (H2)
  - 2030 forward?



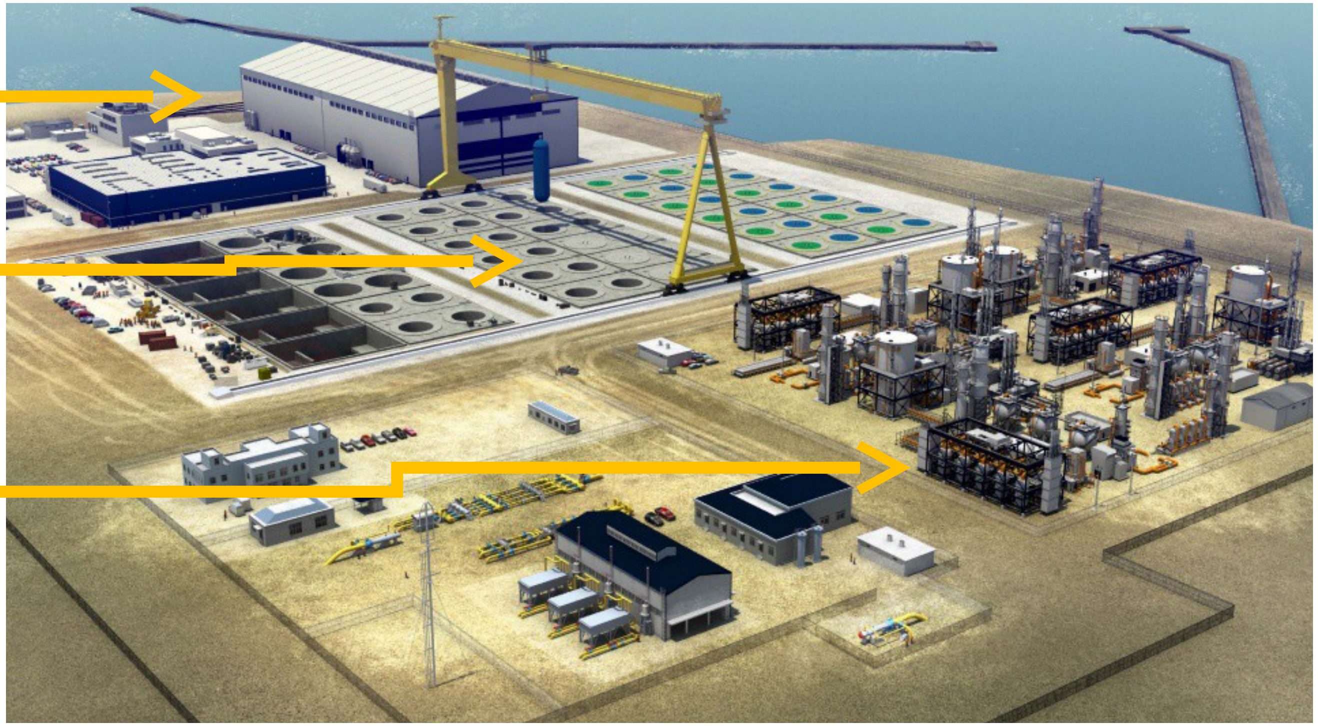
https://www.lucidcatalyst.com/hydrogen-report

HYDROGEN CAN REPLACE NATURAL GAS

- U.S. Consumes 10 million tons per year (fertilize, chemical industry and oil refining)
- Hydrogen shipped by pipeline and stored in underground facilities like natural gas
- **Can ship massive quantities of H2 by a single pipeline**
  - **Electric line capacity: 1-2 gigawatts**
  - **Large pipeline capacity is measured in 10s of gigawatts**

ABILITY TO TRANSPORT 10s OF GIGAWATTS OF H2 FROM A SITE ENABLES NUCLEAR GIGAFACTORIES

- Factory fabrication of modular nuclear reactors
- Reactors deployed next to the factory
- Hydrogen plant next to reactors
- **Economic hydrogen enabled by pipelines**

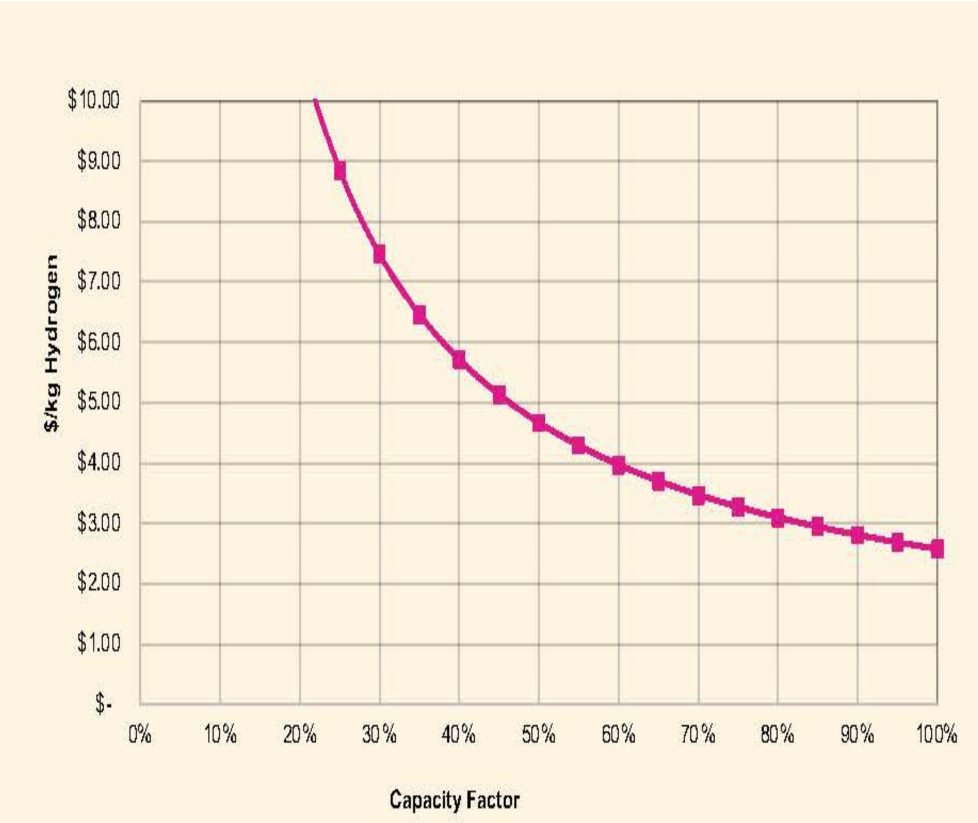


Different Building Model to Enable Very-Low-Cost Nuclear Hydrogen

HYDROGEN ELECTROLYSIS PLANTS HAVE HIGH CAPITAL COST THAT FAVORS NUCLEAR HYDROGEN PRODUCTION

- Need high-capacity factor heat and electricity inputs for affordable hydrogen
- Capacity factor of energy source drives H2 costs
  - Nuclear: 90%
  - Wind: 40%
  - Solar: 25% (Expensive)

Hydrogen Cost: $/Kg



Capacity Factor H2 Plant

REPLACING LIQUID FOSSIL FUELS WITH NUCLEAR BIOFUELS

Gasoline

Diesel

Jet Fuel

Chemical Feedstocks

($C_xH_{(2X+2)}$)

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Replacing liquid fossil fuels and hydrocarbon chemical feedstocks with liquid biofuels from large-scale nuclear biorefineries

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HIGHLIGHTS

- Biomass is a low-greenhouse-gas fuel and carbon source.
- Adding external heat and hydrogen during conversion of biomass to hydrocarbon fuels doubles liquid fuel per ton of biomass.
- Large-scale bio-refineries with nuclear heat and hydrogen enable economic biofuels.
- Local depotes are required to densify biomass for transport to biorefinery.
- Resource base with external heat and hydrogen for bio-refinery is sufficient to replace liquid fossil fuels.

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ABSTRACT

Liquid fossil fuels (1) enable transportation and (2) provide energy for mobile work platforms and (3) supply dispatchable energy to highly variable demand (seasonal heating and peak electricity). We describe a system to replace liquid fossil fuels with drop-in biofuels including gasoline, diesel and jet fuel. Because growing biomass removes carbon dioxide from the air, there is no net addition of carbon dioxide to the atmosphere from burning biofuels. In addition, with proper management, biofuel systems can sequester large quantities of carbon as soil organic matter, improving soil fertility and providing other environmental services. In the United States liquid biofuels can potentially replace all liquid fossil fuels. The required system has two key features. First, the heat and hydrogen for conversion of biomass into high-quality liquid fuels is provided by external low-carbon energy sources–nuclear energy or fossil fuels with carbon capture and sequestration. Using external energy inputs can almost double the energy content of the liquid fuel per unit of biomass feedstock by fully converting the carbon in biomass into a hydrocarbon fuel. Second, competing effectively with fossil fuels requires very large bio-refineries the equivalent of a 250,000 barrel per day oil refinery. This requires commercializing methods for converting local biomass into high-density storable feedstocks that can be economically shipped to large-scale biorefineries.

1. Introduction

About 37% of the total net energy used by the United States is for transportation [1], predominantly in the form of liquid fossil fuels such as gasoline, diesel and jet fuel [2]. Ninety four percent of transportation energy comes from fossil fuels whereas less than 1% is currently provided by electric power [1]. Liquid fossil fuels are also central to meeting other variable energy demands such as seasonal heating and peak electricity production. Last, fossil fuels are the primary feedstock for the chemical industry. Trillions of dollars of infrastructure have been created over many decades to produce, distribute, store and use liquid fossil fuels. For example, global investments in oil and gas supply alone

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The Existing Fossil Fuel System to Produce Liquid Hydrocarbon Fuels and Feedstocks

Crude Oil

Carbon: 83-87%

Hydrogen: 10-14%

Nitrogen: 0.1-2%

Oxygen: 0.05-1.5%

Sulfur: 0.05 to 6%

https://www.thoughtco.com/chemical-composition-of-petroleum-607575

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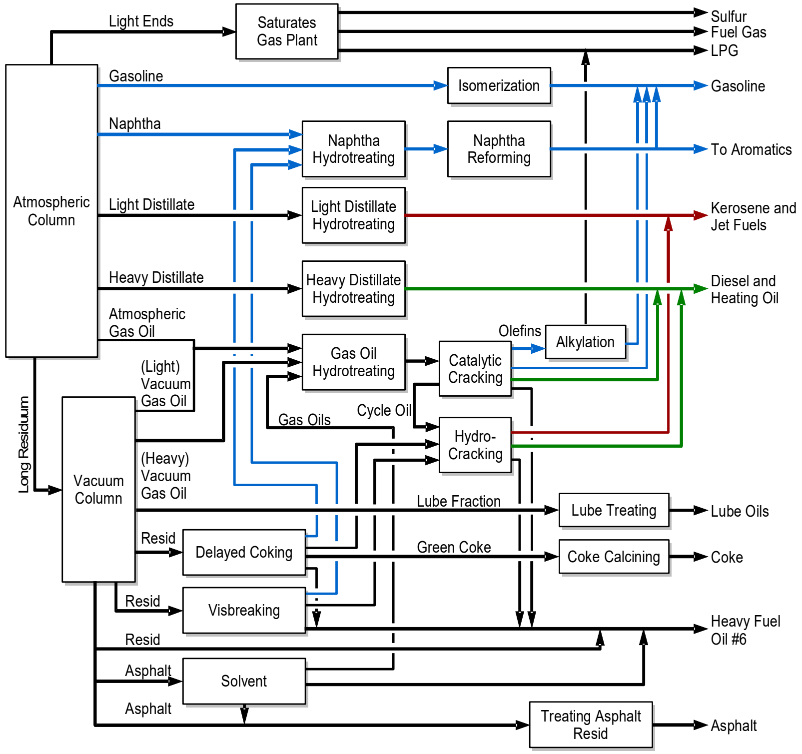
Oil Refinery



Hydrocarbons

Gasoline

Diesel

Jet Fuel

Chemical

Feedstocks

$(C_xH_{(2X+2)})$

Switching Feedstocks From Crude Oil to Biomass Carbon Eliminates Adding CO2 to the Atmosphere

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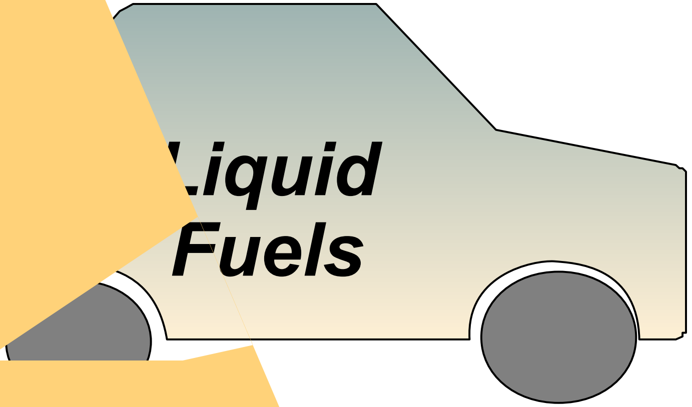

Biomass (CH1.44O0.66)

He

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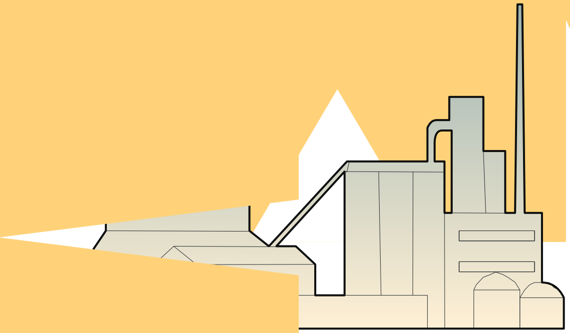


Biorefinery

Optional Low-Cost Carbon Sequestration

High-Level Biomass Processing Choices

Biomass + Oxygen → Hydrocarbons + Carbon Dioxide

CH1.44O0.66 + O2 → (CH2)xH2 + CO2

- Carbon used to make hydrocarbon fuels (gasoline, diesel and jet fuel)
- Carbon oxidation (1) removes oxygen and (2) provides energy for the process

Biomass + Hydrogen + Nuclear → Hydrocarbons + Water

CH1.44O0.66 + H2 + Heat → (CH2)xH2 + H2O

- **External H2 and heat doubles energy of hydrocarbon fuel per unit feedstock**
- **Enables use of low-energy-value high-carbon-content biomass feedstocks**
- **Not using carbon as an energy source or to remove oxygen**

Nuclear Biofuels can Replace Oil Without Major Impacts on Food and Fiber Prices

- Most biomass studies view biomass as an *energy source; that is, bioenergy*
- Nuclear biofuels views biomass as a *carbon source*, including low-energy biomass (kelp, double crops, sewage sludge, garbage, etc.)
- **External heat and H2 inputs multiply the energy value of hydrocarbon fuel per ton of biomass input**

Economics Requires Massive Biorefineries

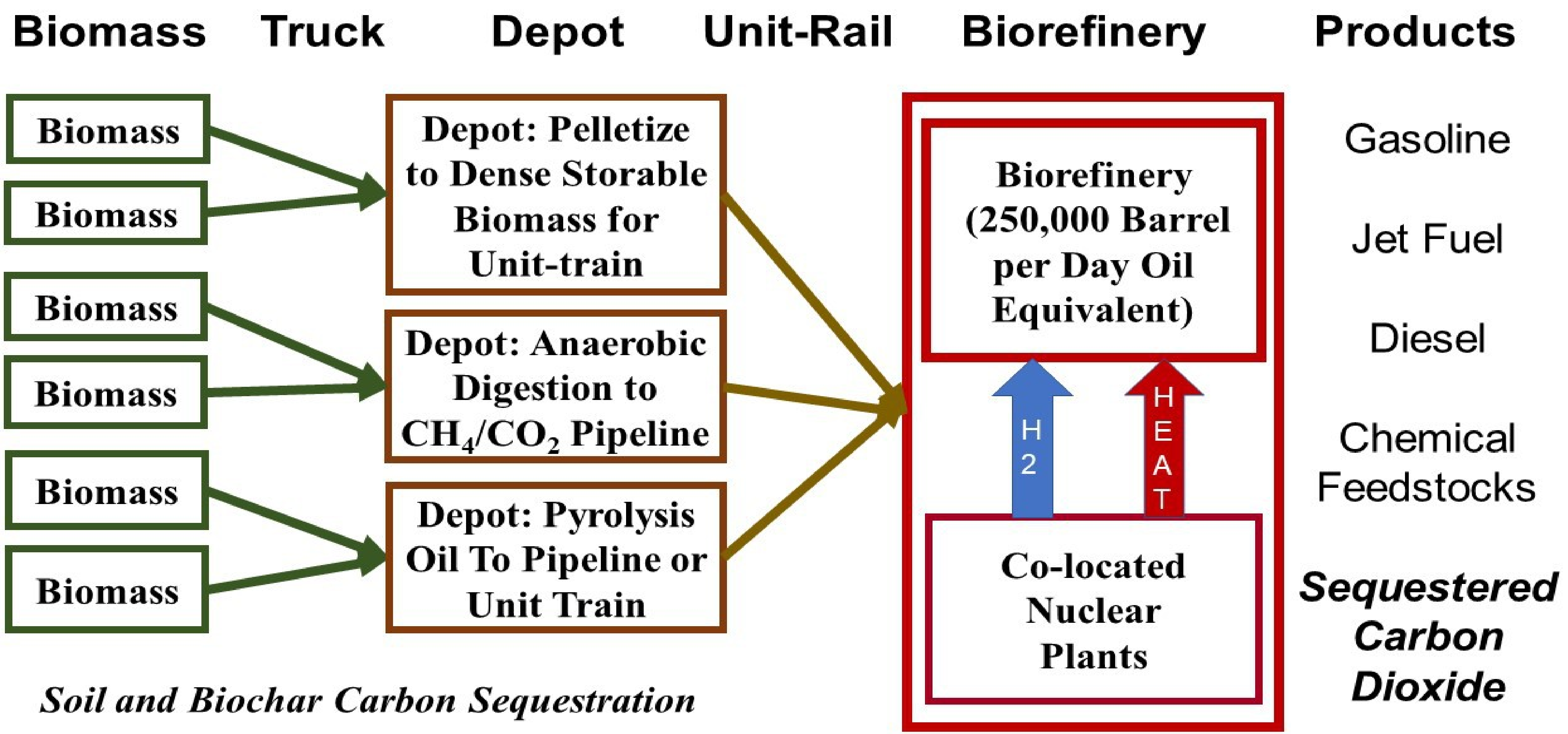
- Example: Fischer Tropsch
  - Converts natural gas (Shell, right) and coal (Sasol) into synthetic crude oil
  - Can convert biomass to synthetic crude oil (pilot plants)
- Couples to an oil refinery
- **All options require massive scale: 250,000 barrels / day**

Shell Natural Gas-to-Liquids Fischer-Tropsch Plant, Qatar: 260,000 Barrels/day

Implications of Large Biorefineries

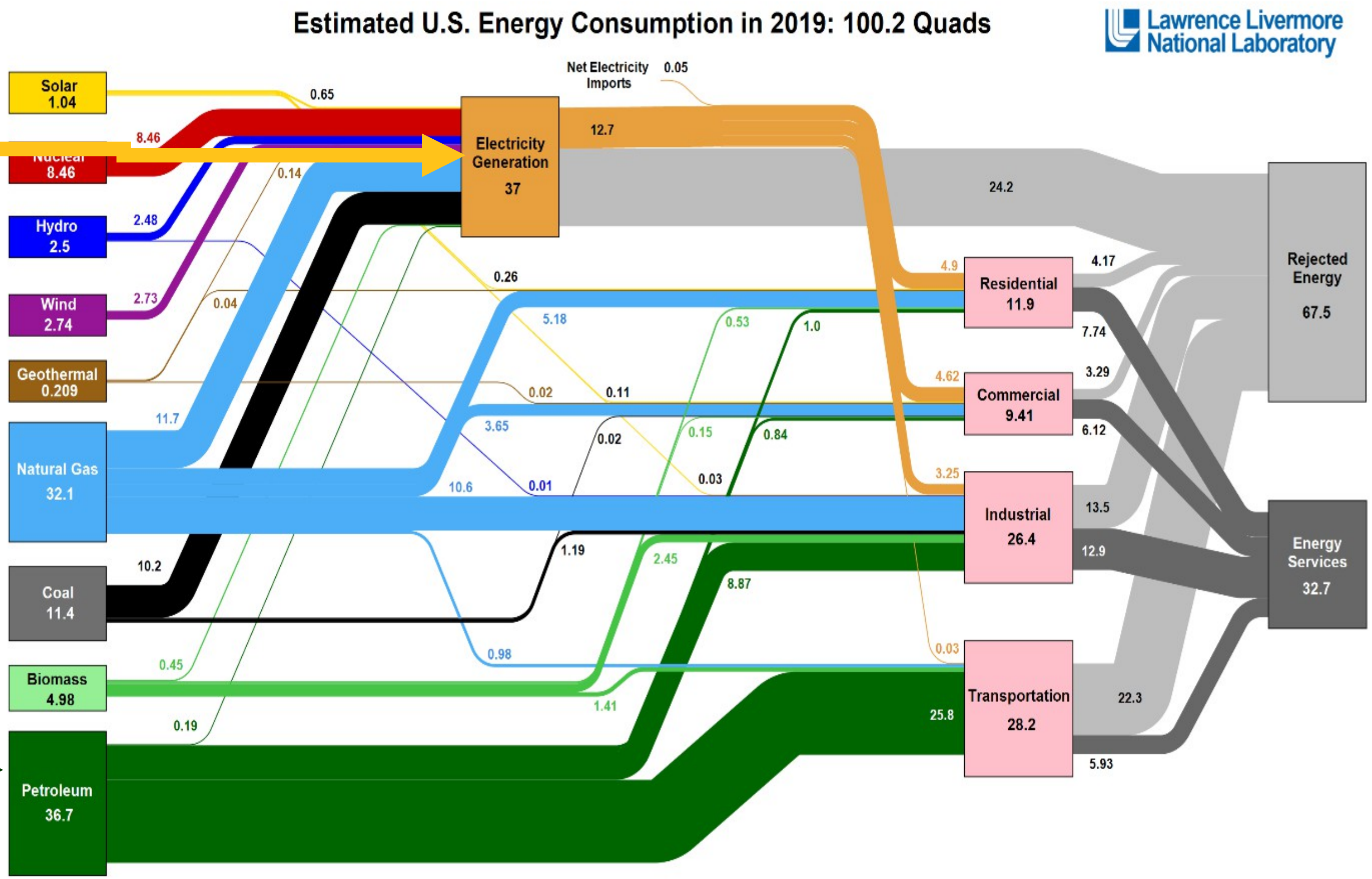
- Require gigawatt heat sources that can only be provided by nuclear or fossil fuels with carbon capture and sequestration
- Require massive amounts of biomass feedstocks
  - ~60,000 tons per day per biorefinery (250,000 barrel/day)
  - Low-density biomass can be economically shipped 30 to 50 miles. Insufficient biomass to support a nuclear biorefinery
  - **Require depots to consolidate biomass near the farm or forest into economically-shippable biomass products**

Nuclear Biofuels System: Biomass, Depot and Refinery



Conclusions: We are Developing a Low-Carbon Nuclear Energy Strategy

- **Electricity: Nuclear with Heat Storage**
- **Natural Gas: Replace with Nuclear Hydrogen**
- **Oil: Replace with Nuclear Biofuels**



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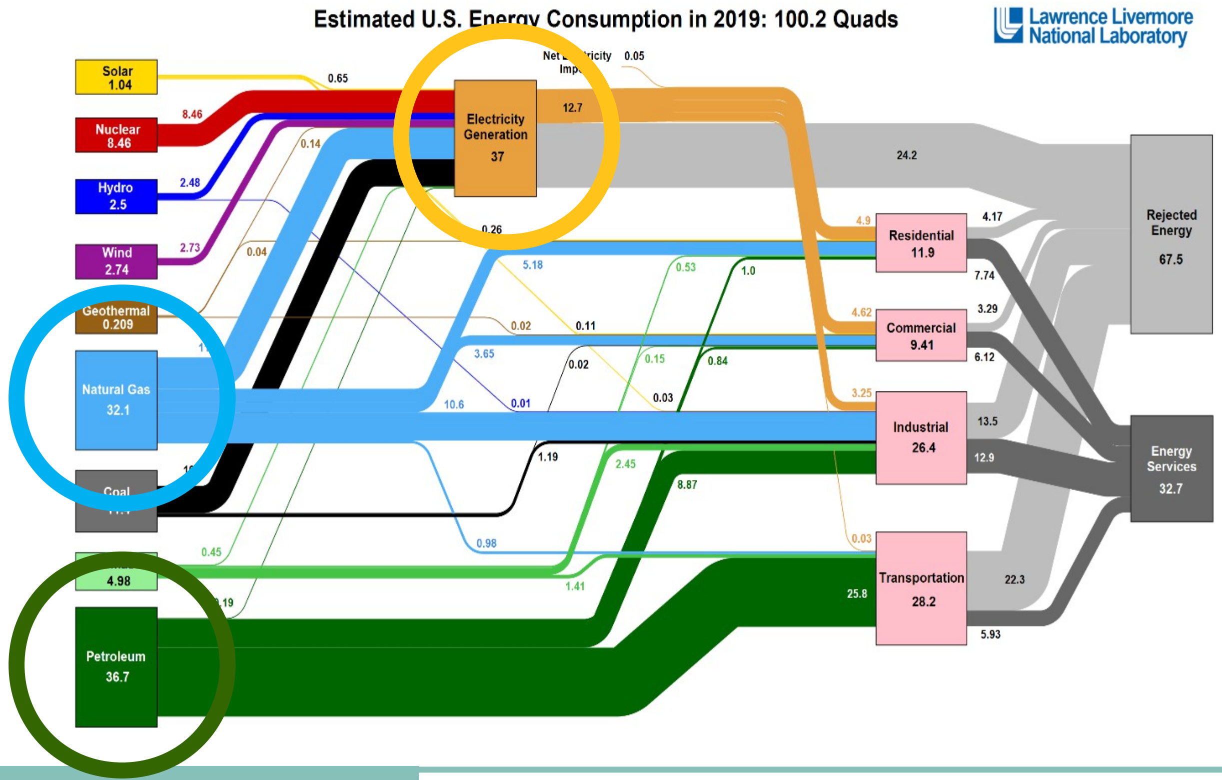
Questions



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Thank You / Questions

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Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His research areas include (1) Fluoride-salt-cooled High-Temperature Reactors (FHRs), (2) utility-scale heat storage including Firebrick Resistance-Heated Energy Storage (FIRES) and 100 GWh Crushed Rock Ultra-Large Stored Heat (CRUSH) systems and (3) nuclear hybrid systems including nuclear biofuels. He teaches the fuel cycle and nuclear chemical engineering classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory.

He is a Fellow of the American Nuclear Society (ANS), 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 waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a Director of the ANS. 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 12 patents and published over 300 papers.

http://web.mit.edu/nse/people/research/forsberg.html