Aug 5, 2025

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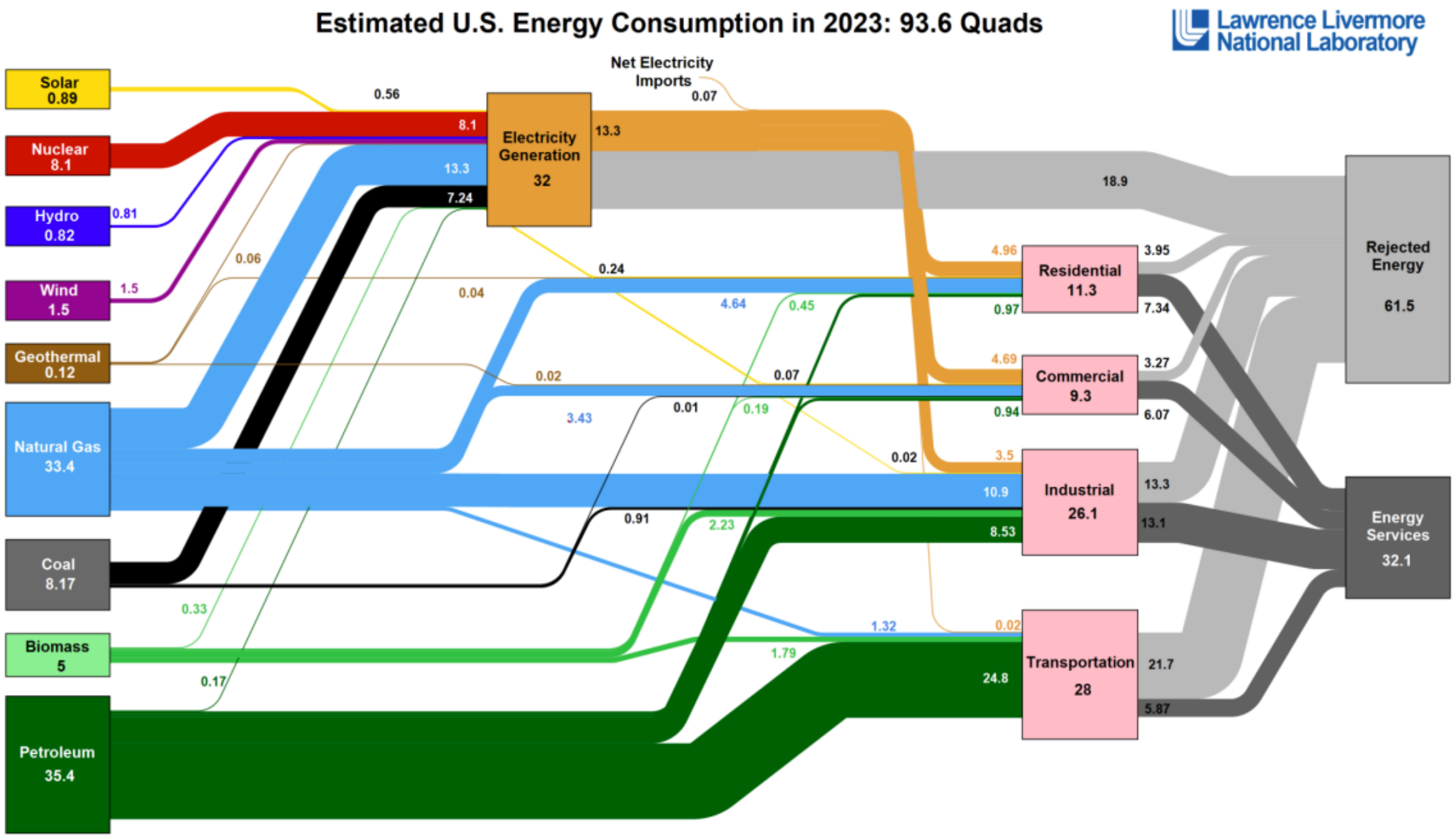
Group Load
Thermal Systems and Analysis

Integrated Energy Systems

Introduction
Energy Demand and Supply

Share of Nuclear Energy

- Nuclear energy accounts for 8-9% of the national energy supply (U.S. DOE/EIA 2023)



U.S. energy flow chart

Produced by Lawrence Livermore National Laboratory in Oct. 2024. Data is based on DOE/EIA SEDS (2024)

…and makes up just 3.4% of total industrial energy demand.

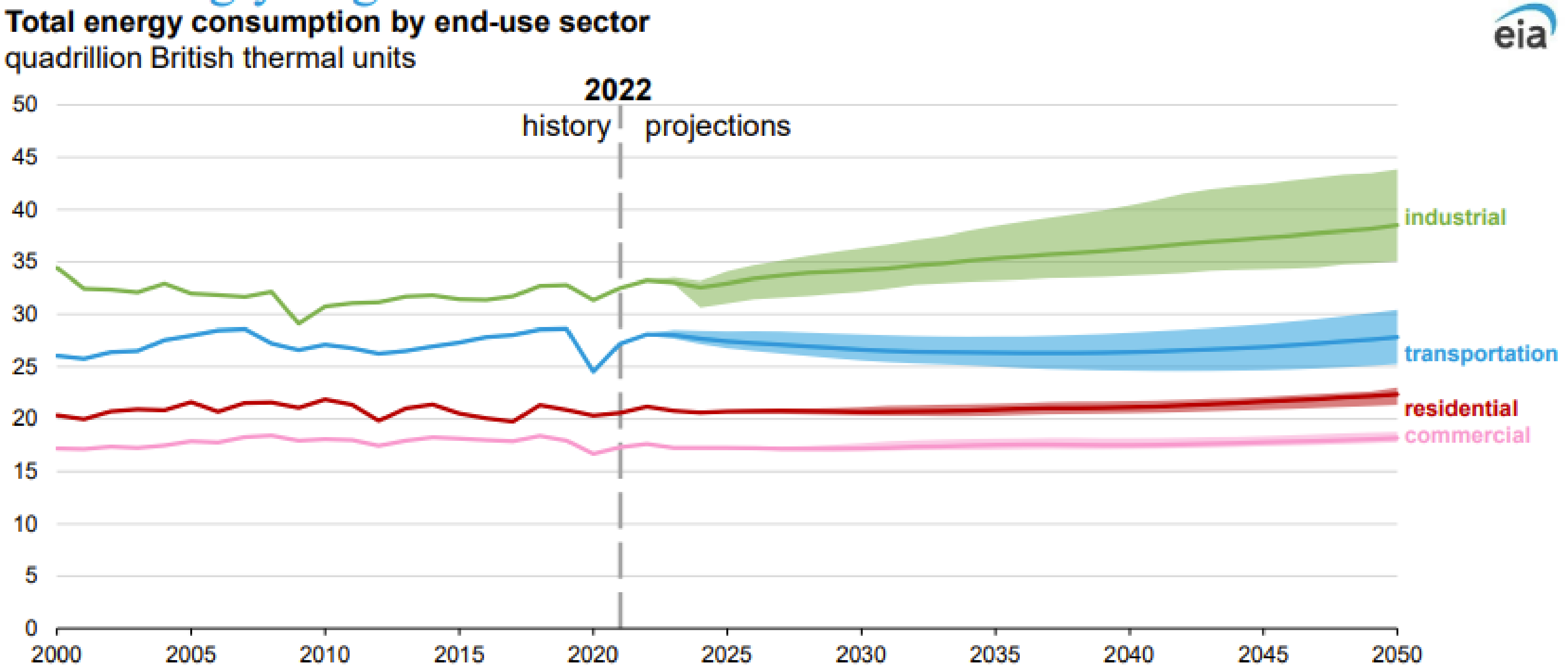
- **The industrial sector consumes 35% of the nation's total energy demand.**
- **The heat demand from the industrial sector relies mostly on fossil fuels.**

Nuclear energy is solely used as an electricity provider for the industrial sector, but electrical energy accounts for only 13.4% of the total energy demand from industry.

Expected US Energy Demand Growth

- Source: U.S. Energy Information Administration "Annual Energy Outlook 2023"

U.S. energy consumption increases to 2050, and electricity plays an increasingly larger role

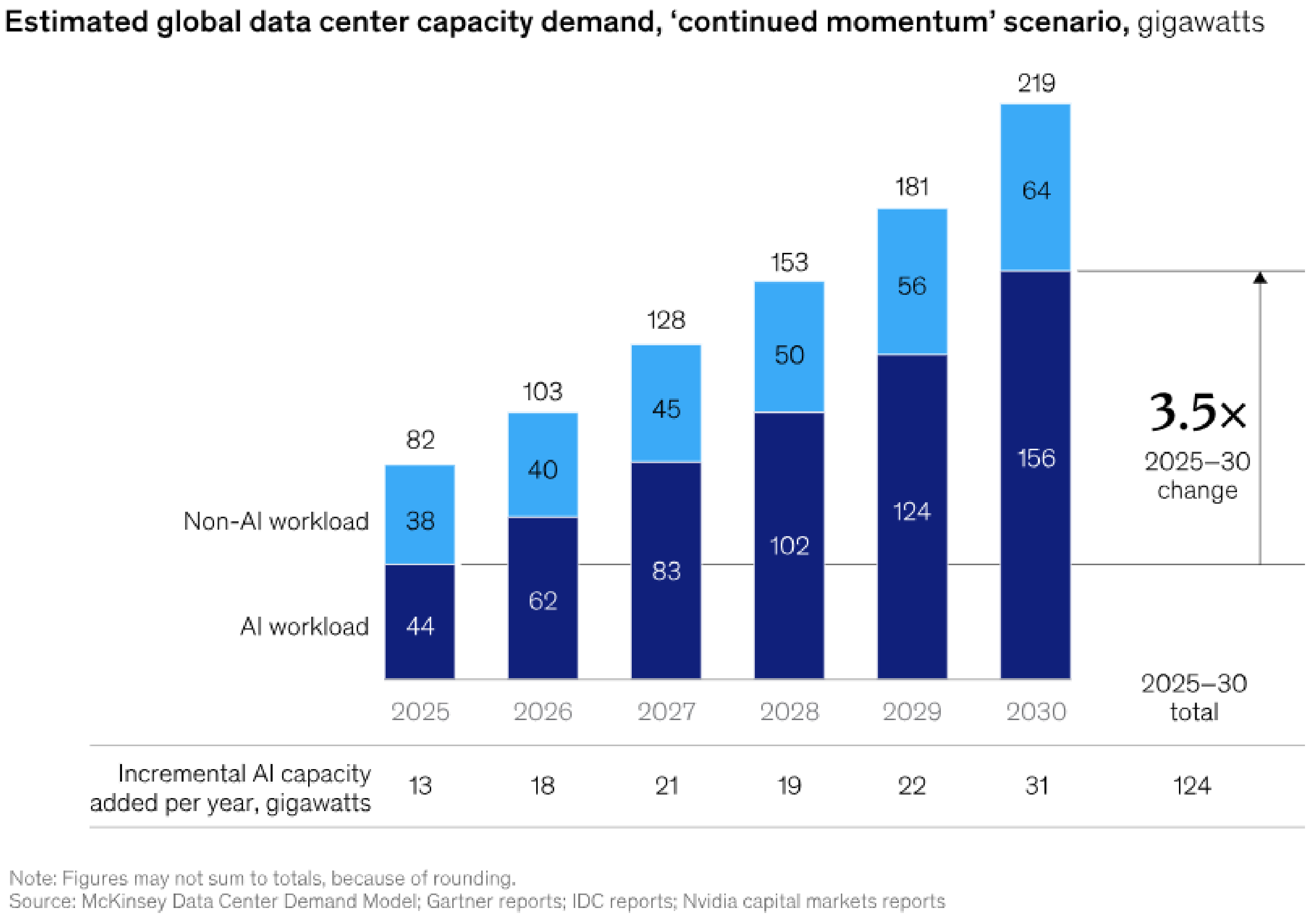


Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2023* (AEO2023)
Note: Total consumption in end-use sectors includes purchased electricity and electricity-related losses. Each line represents AEO2023 Reference case projections. Shaded regions represent maximum and minimum values for each projection year across the AEO2023 Reference case and side cases.

AEO2023 Release, RFF
March 16, 2023

Electric potential: Datacenter Power Hunger

Both, AI and non-AI workloads will be key drivers of global datacenter capacity demand growth through 2030.



Variable Renewable Generators in Electricity Markets

Need for grid stability and reliability, arbitrage potential

Example

Impact on demand of solar generation assets

- Peak generation ≠ peak demand
- Requires additional components and approaches to maintain stable, reliable grid
  - Energy storage
    - Within day, but also seasonal
  - Curtailment

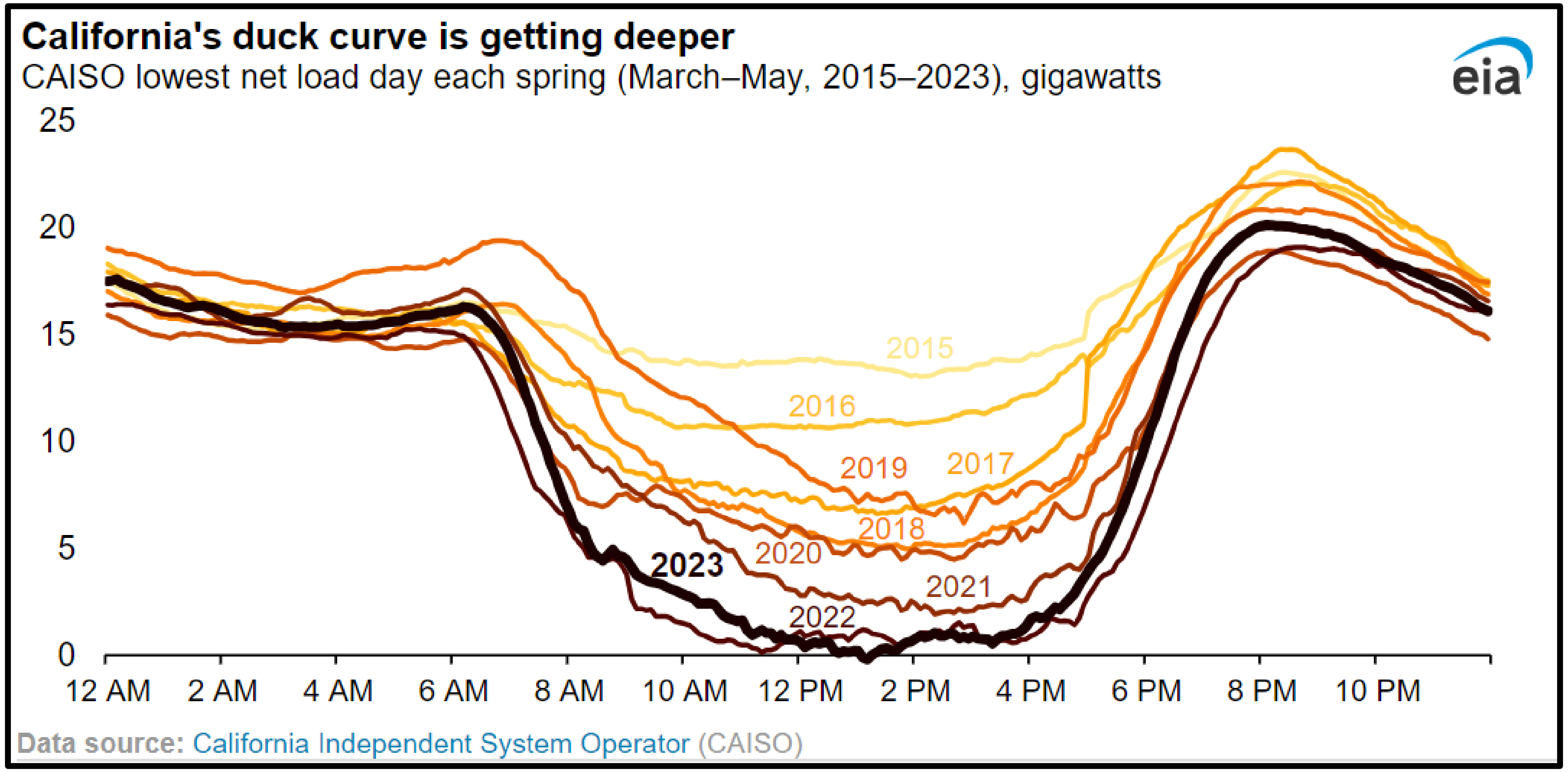
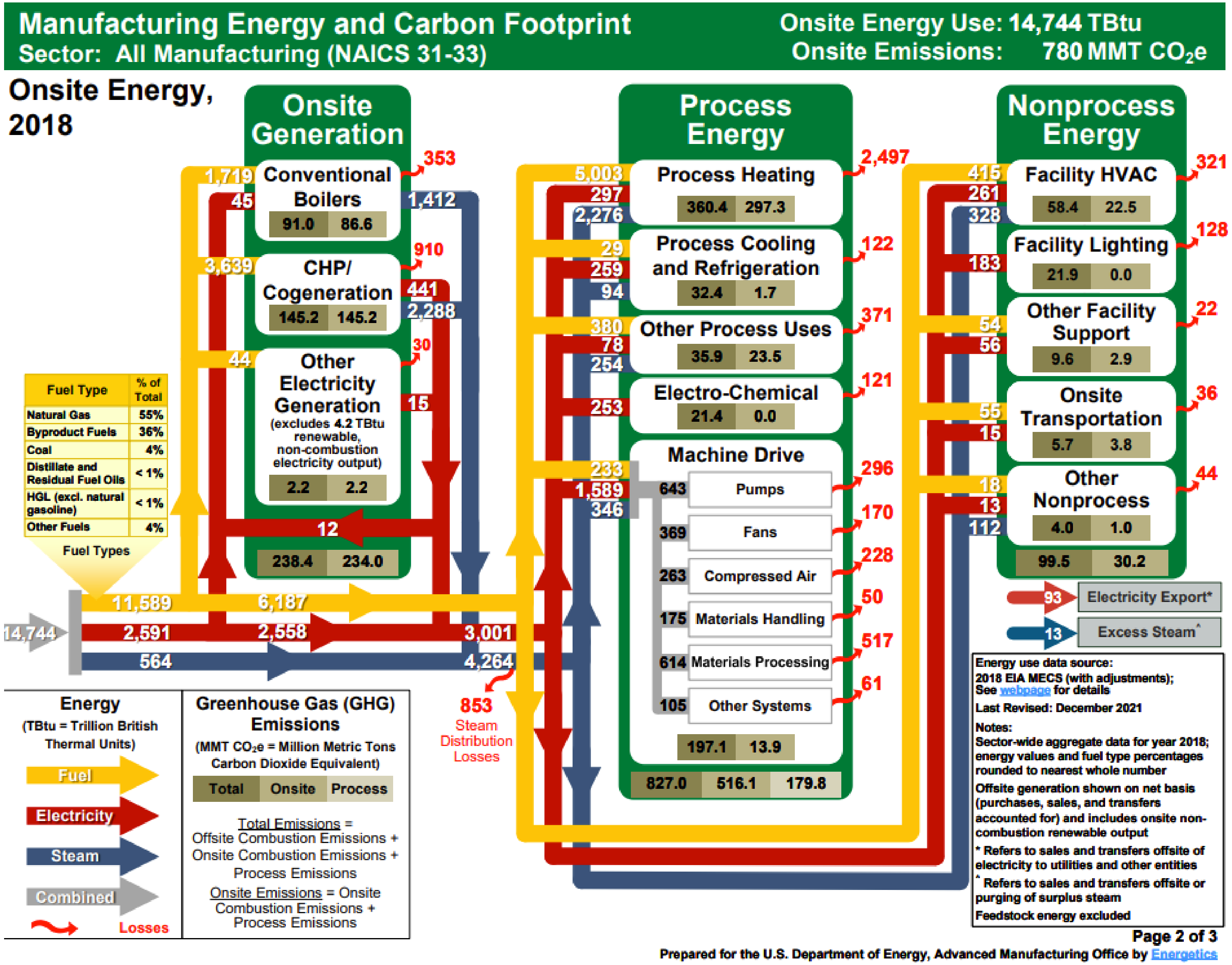


Figure developed by INL.

Thermal potential: Energy use across all U.S. manufacturing



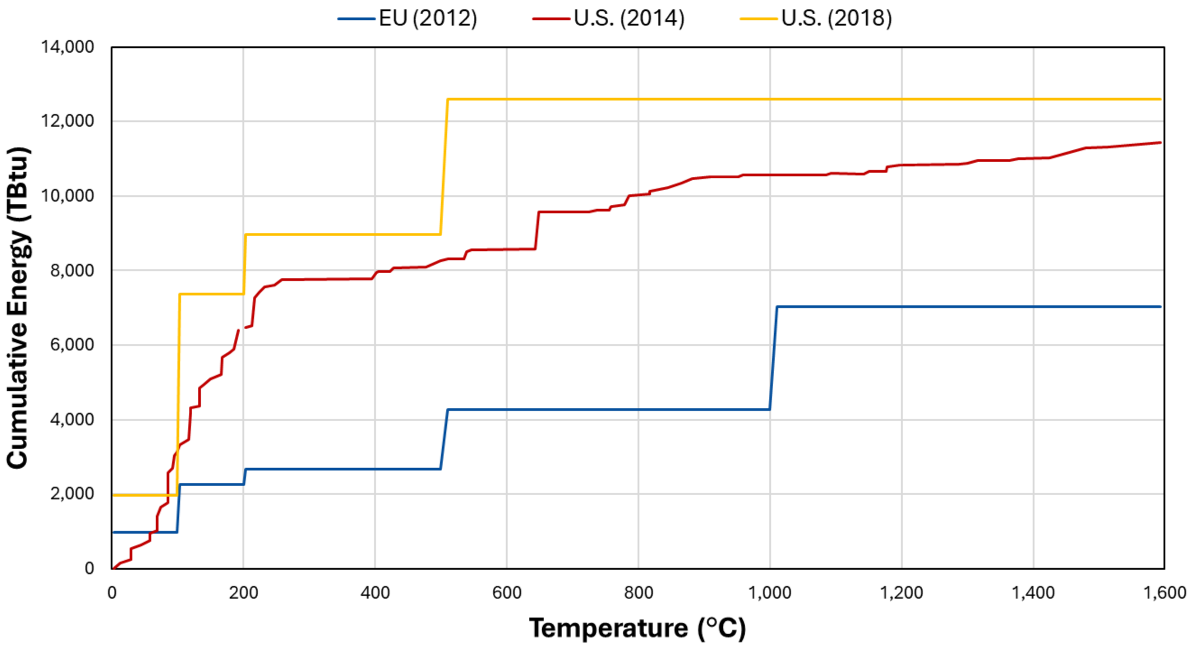
Total Energy = 432 GWh (Process and Non-process)

- 32 % steam
- 22% electrical power
- 46% combustion

Manufacturing Energy and Carbon Footprint - Sector: Petroleum Refining (NAICS 31-33), December 2021 (MECS2018)

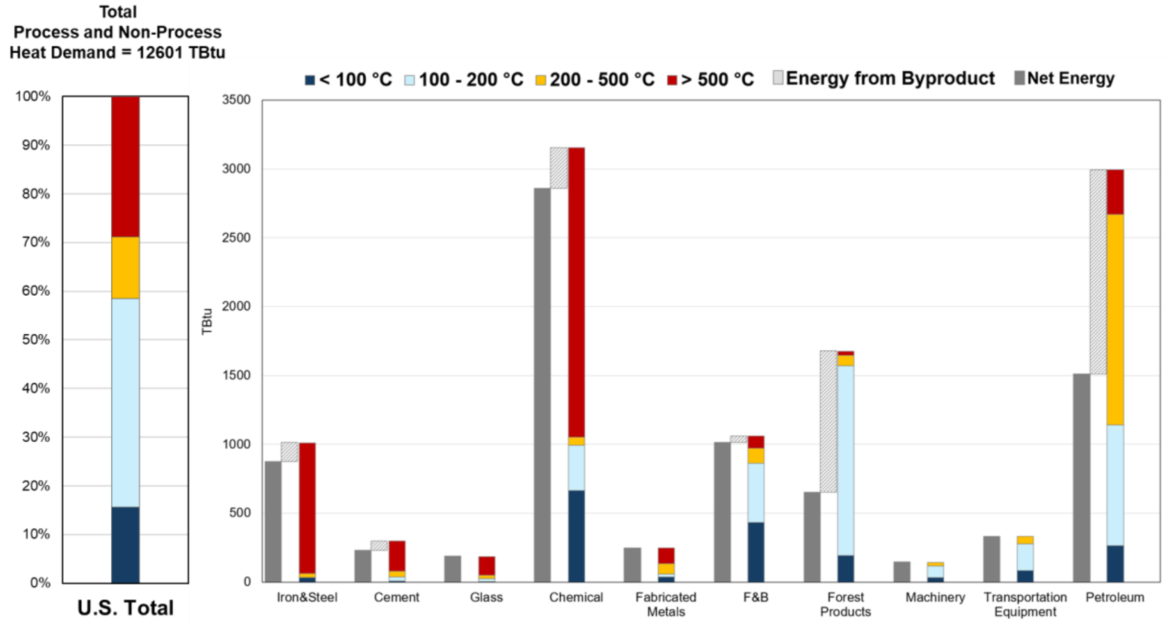
Industrial Heat Demand

- Across the entire U.S. industrial sector, 71% of heat requirements (8,965.8 TBtu) are for temperatures below 500°C.



Cumulative annual process heat demand by temperature

[3] Data compiled from *"Manufacturing Thermal Energy Use in 2014."* for U.S. 2014, from "Quantification of the European industrial heat demand by branch and temperature level" for the European Union (EU), and from *"Decarbonizing Low-Temperature Industrial Heat in the U.S."* and *"Manufacturing Energy and Carbon Footprints (2018 MECS)"* for U.S. 2018.

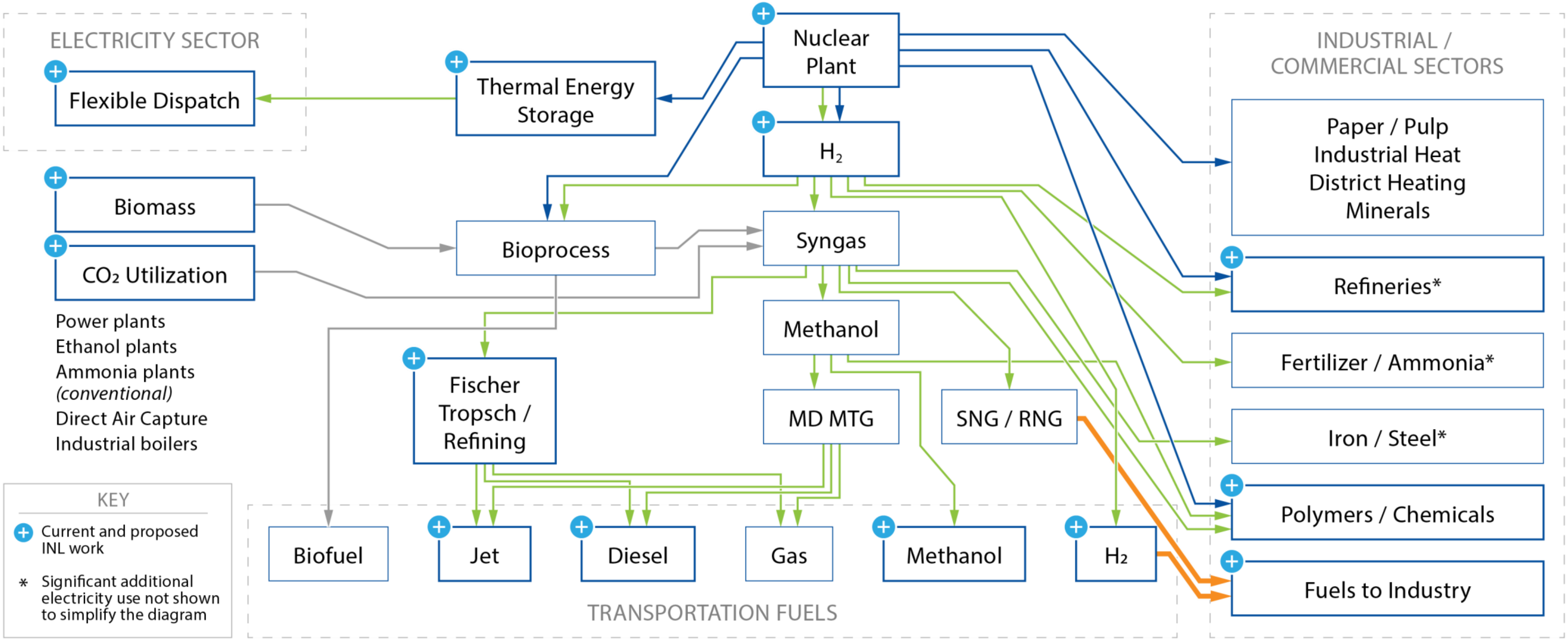


Annual heat demand by temperature range and industry

Data from Decarbonizing Low-Temperature Industrial Heat in the U.S. (Oct. 2022), Energy Innovation Policy & Technology LLC © and Manufacturing Energy and Carbon Footprints (2018 MECS) are combined. It is assumed that industrial heat demand by temperature ranges has not changed significantly between 2018 and 2021.

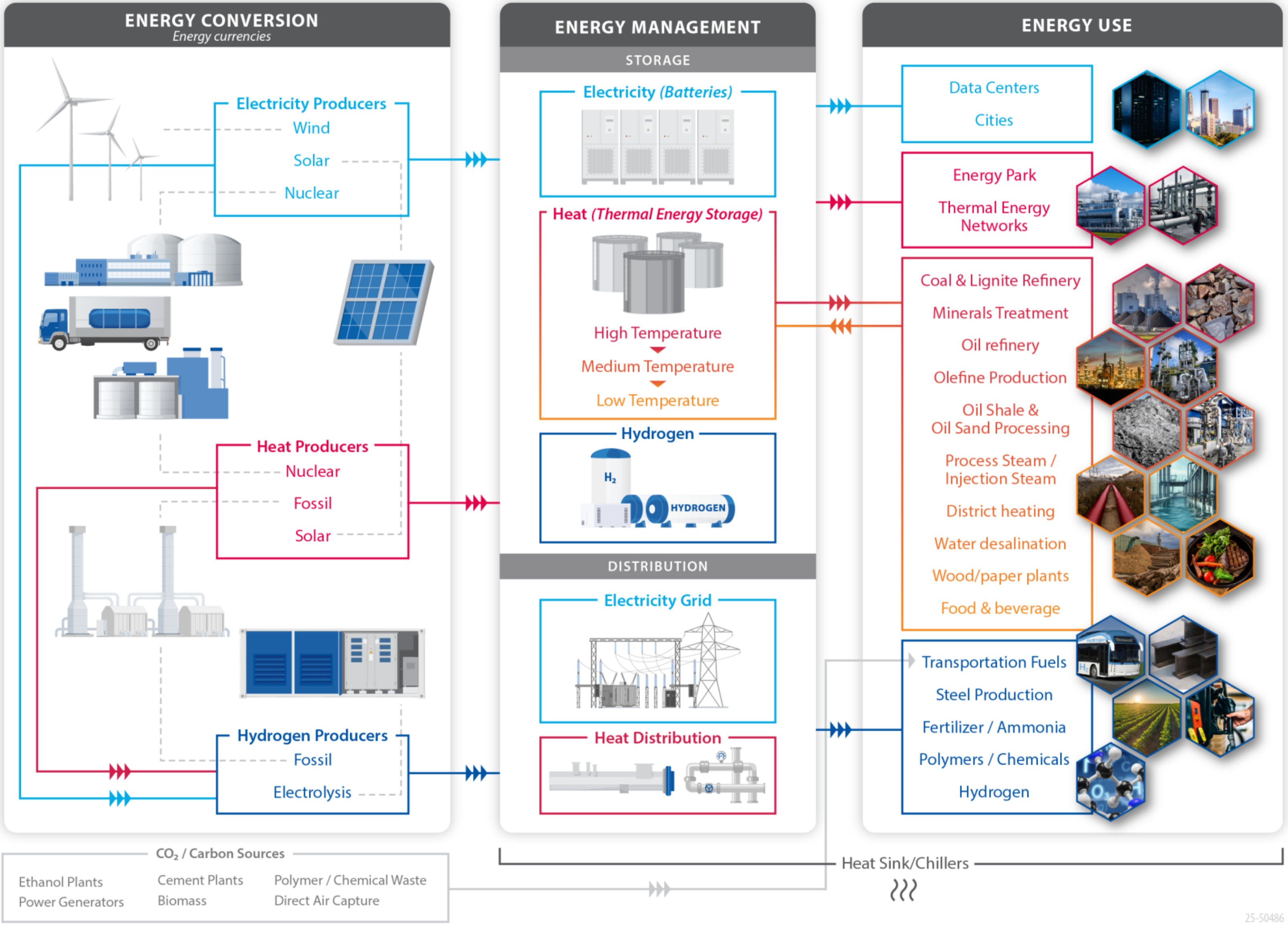
Advanced Nuclear Energy Pathways by Sector

Future Nuclear Energy Currencies are Chemical Feedstocks *(Syngas, FT liquids, Methanol, H_2)*



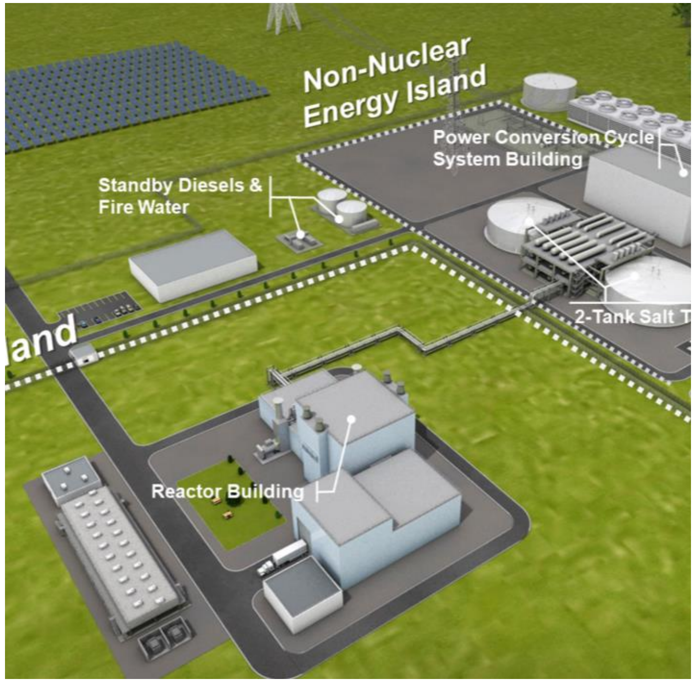
Based on a diagram courtesy of Office of Nuclear Energy

Ideal IES system is involved with all aspects of energy use



Thermal Energy Management

Thermal management solutions for better thermal efficiency and security



Based on Natrium TerraPower Rendering

Importance

- Thermal energy storage (TES) enables nuclear power plants to provide flexible power generation, meeting the variable demands.
- Decoupling the reactor from the power cycle and integrating TES allows for unrestricted heat diversion and higher efficiency.
- TES enhances operational reliability and adaptability to market conditions, ensuring minimal impact on reactor parameters during rapid power changes.

Recent work

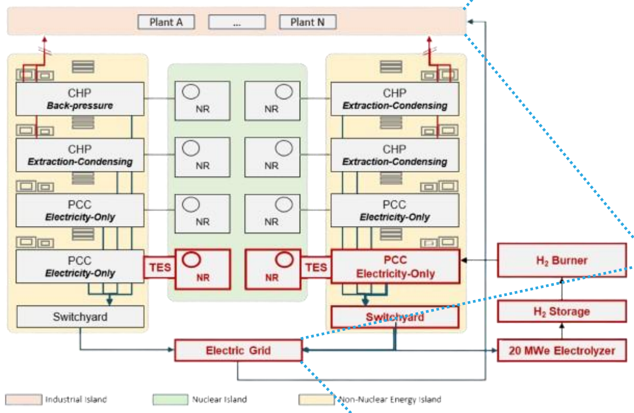
- Thermal energy storage technologies mapping with advanced nuclear reactors
  ECM: https://doi.org/10.1016/j.enconman.2022.115872
- Figure-of-Merit studies on thermal energy storage integrations with light water reactors
  NT: https://doi.org/10.1080/00295450.2021.1906473
- Concrete thermal energy storage system configurations for continuous power production
  JES: https://doi.org/10.1016/j.est.2022.104387
- Design and optimization of flexible decoupled HTGR with thermal energy storage
  ECM: https://doi.org/10.1016/j.enconman.2024.119098

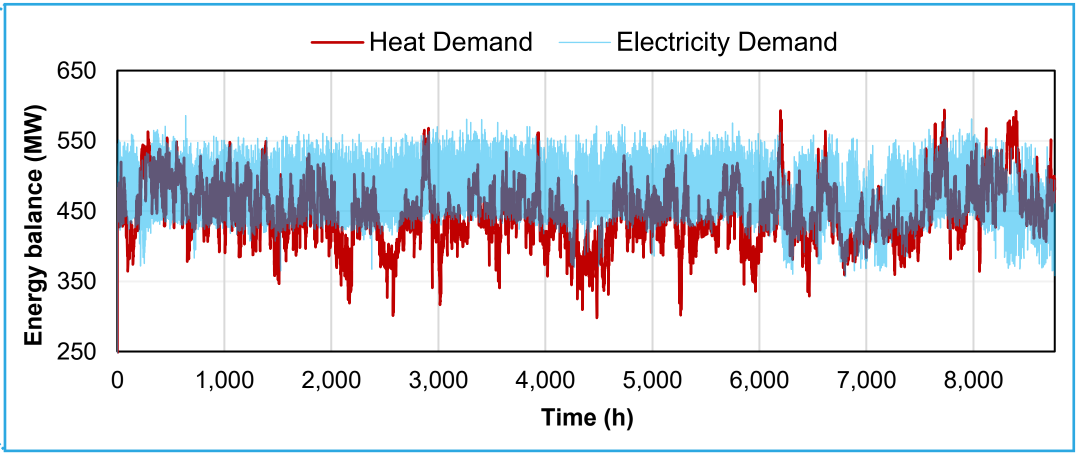
Thermal Energy Management

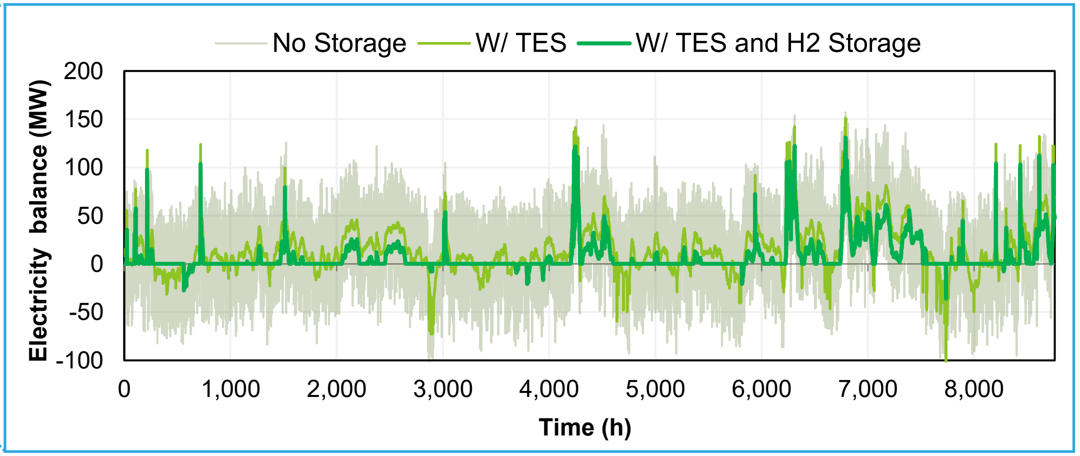
Thermal management solutions for better thermal efficiency and security

Proposed nuclear-based system configuration for the energy park (Left) and Electricity balance after integrating thermal energy storage (TES) and additional H_2 storage (Right).

- Highly fluctuating heat and electricity demand from industrial park – demand from Chemical / Iron and steel / petroleum combined
- TES and H_2 generated by 20 MWe electrolyzer have used to flatten the fluctuating energy demand.
- The energy storage systems decreased natural gas usage by up to 77%.



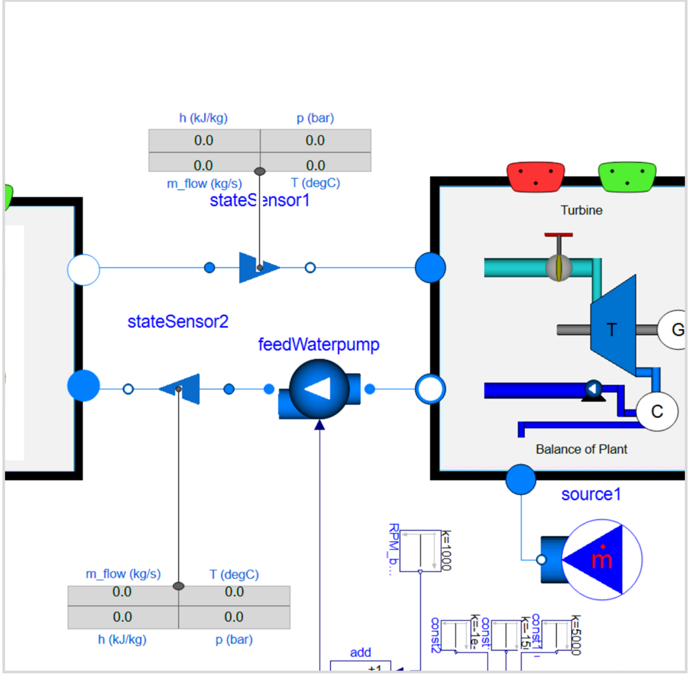




[5] *Václav Novotný, Junyung Kim, So-Bin Cho, Aidan Rigby, Rami M. Saeed. "Nuclear-based Combined Heat and Power Industrial Energy Parks - Application of High Temperature Small Modular Reactors." Energy Conversion and Management: X.*

Dynamic System Modeling and Control (HYBRID on Github)

Real-time system analysis with digital twin of system



Importance

- Dynamic modeling and control enable seamless integration of various energy sources and systems, ensuring coordinated and efficient operation.
- Real-time analysis and control help identify and mitigate potential disruptions, enhancing the reliability and resilience of energy systems against unforeseen events and fluctuations.

Capabilities

- Dynamic modeling of nuclear reactor and power conversion cycle system
- Rule-based control logics
- Multiple system model integration and coupling

Recent work:

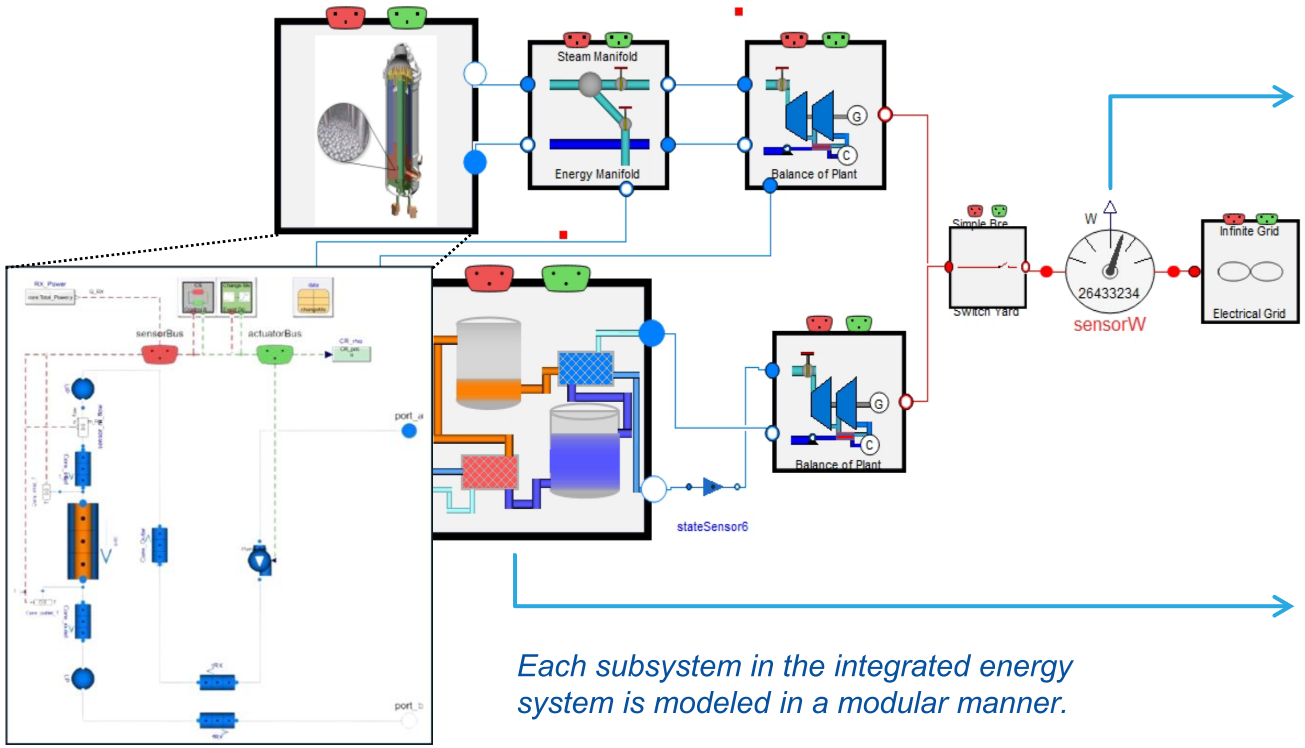
- Development of NuScale reactor module in Modelica
  NT: https://doi.org/10.1080/00295450.2020.1781497
- Development of Thermal-Energy Distribution System (TEDS) in Modelica
  Energies: https://doi.org/10.3390/en13236353
- Controls for integrated energy storage system in energy arbitrage configuration
  Applied Energy: https://doi.org/10.1016/j.apenergy.2022.118800
- Nuclear-integrated energy system modeling for the remote microgrid
  Energies: https://doi.org/10.3390/en17235826

Dynamic System Modeling and Control (HYBRID on Github)

Real-time system analysis with digital twin of system

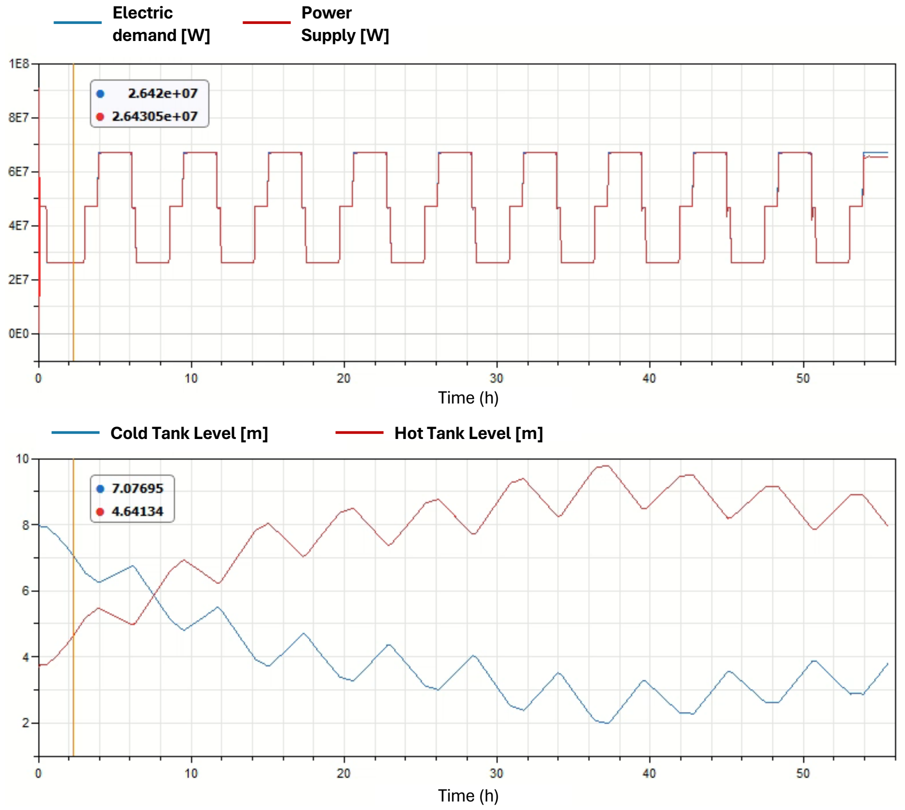
Fully-integrated microgrid system model

Prismatic high temperature gas-cooled reactor, thermal energy storage, power conversion cycle, and heat application system



Each subsystem in the integrated energy system is modeled in a modular manner.

Integrated system control to follow electric demand

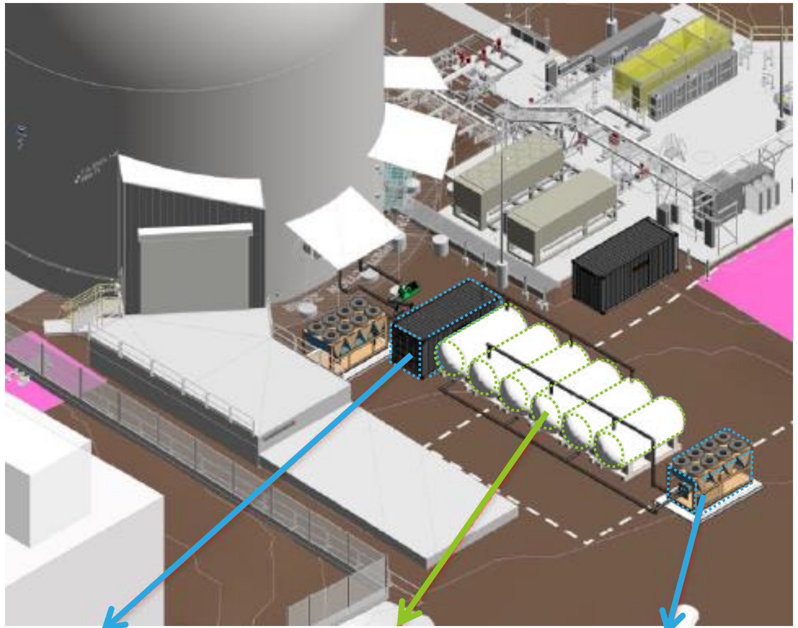


[6] *Saeed, Rami M., et al. Multilevel analysis, design, and modeling of coupling advanced nuclear reactors and thermal energy storage in an integrated energy system. No. INL/RPT-22-69214-Rev000. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2022.*

IES Experimental System Design

Improving the design, scaling, and model validation and verification of thermal-hydraulic loops

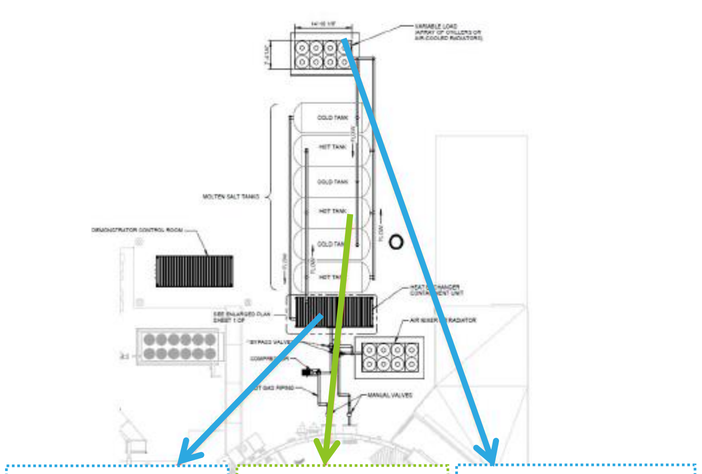
Schematic of the Nuclear-TES Energy Island 2-D sketch of the system



Charge System
Gas-to-molten-salt heat exchanger (reactor heat)

Storage System
TES loop (hot and cold tanks and molten-salt loop)

Discharge System
(i.e., Controllable Load)
Heat rejection (air-cooled radiator)



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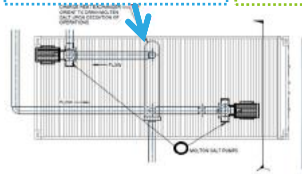
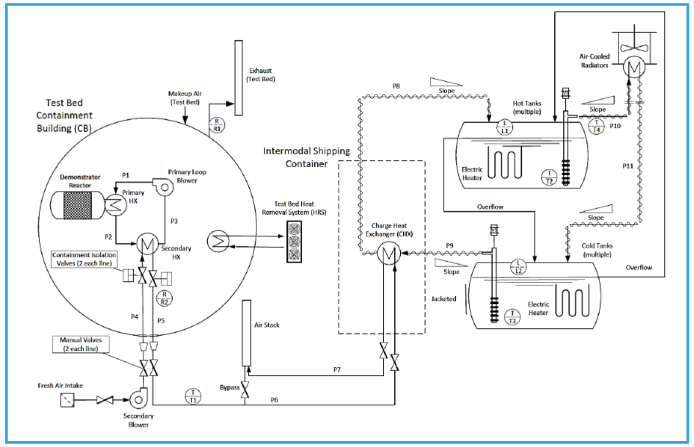


Operational concept of the Nuclear-TES Energy Island



Condition	Nominal Value
Hot molten salt temp.	420°C
Hot molten salt pres.	120–400 kPa
Cold molten salt temp.	267°C
Cold molten salt pres.	120–400 kPa
Compressed hot gas maximum temp.	750°C
Compressed hot gas maximum pres.	7000 kPa

[8] *Saeed, Rami M., and Terry James Morton. Advanced Reactors Integrated Energy System-Thermal Energy Storage Island Design. No. INL/RPT-23-74798-Rev000. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2023.*

Thank you!

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