INL/CON-24-76180-Revision-1

Decarbonizing Industrial Heat and Electricity Applications Using Advanced Nuclear Energy

January 2025

Changing the World's Energy Future

Elizabeth Kirkpatrick Worsham

Idaho National Laboratory

INL/CON-24-76180-Revision-1

Decarbonizing Industrial Heat and Electricity Applications Using Advanced Nuclear Energy

Elizabeth Kirkpatrick Worsham

January 2025

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

IES
Integrated Energy Systems

Decarbonizing Industrial Heat and Electricity Applications Using Advanced Nuclear Energy

POWERGEN International 2024

New Orleans, LA

January 24, 2024

Elizabeth Worsham
Systems Integration Engineer,
Idaho National Laboratory

Elizabeth.Worsham@inl.gov

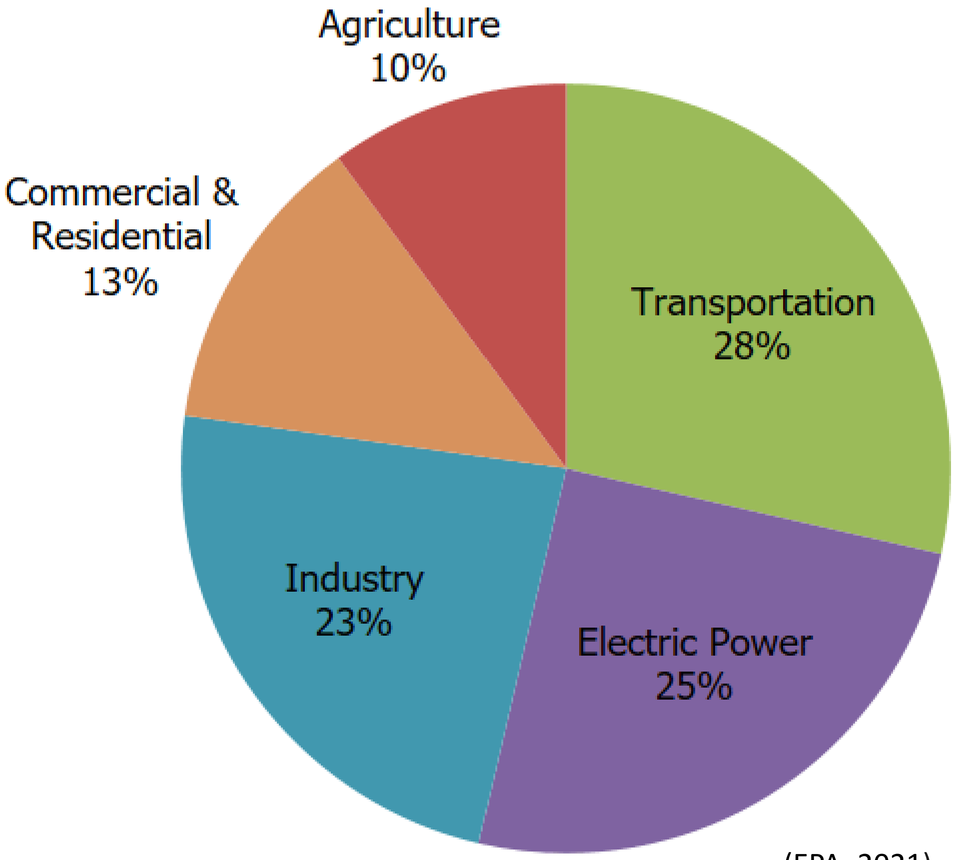
INL
Idaho National Laboratory

Overview

- The Decarbonization Problem
- A Solution: Nuclear and Integrated Energy Systems
- The Past: Process Heat and District Heating
- The Present: NPPs and Hydrogen
- The Future: Process Decarbonization
- How do we do it?
  - Siting and Safety
  - Regulatory
  - Operations
  - Examples

IES Integrated Energy Systems

The Decarbonization Problem



(EPA, 2021)

- Greenhouse gas (GHG) emissions from electricity generation only account for 25% of total U.S. Emissions
- 23% of GHG emissions come from industry
  - 50% is CO2 emissions from fossil fuel combustion
  - 20% is from natural gas and petroleum systems
- To effectively decarbonize, we must consider all sources of GHGs

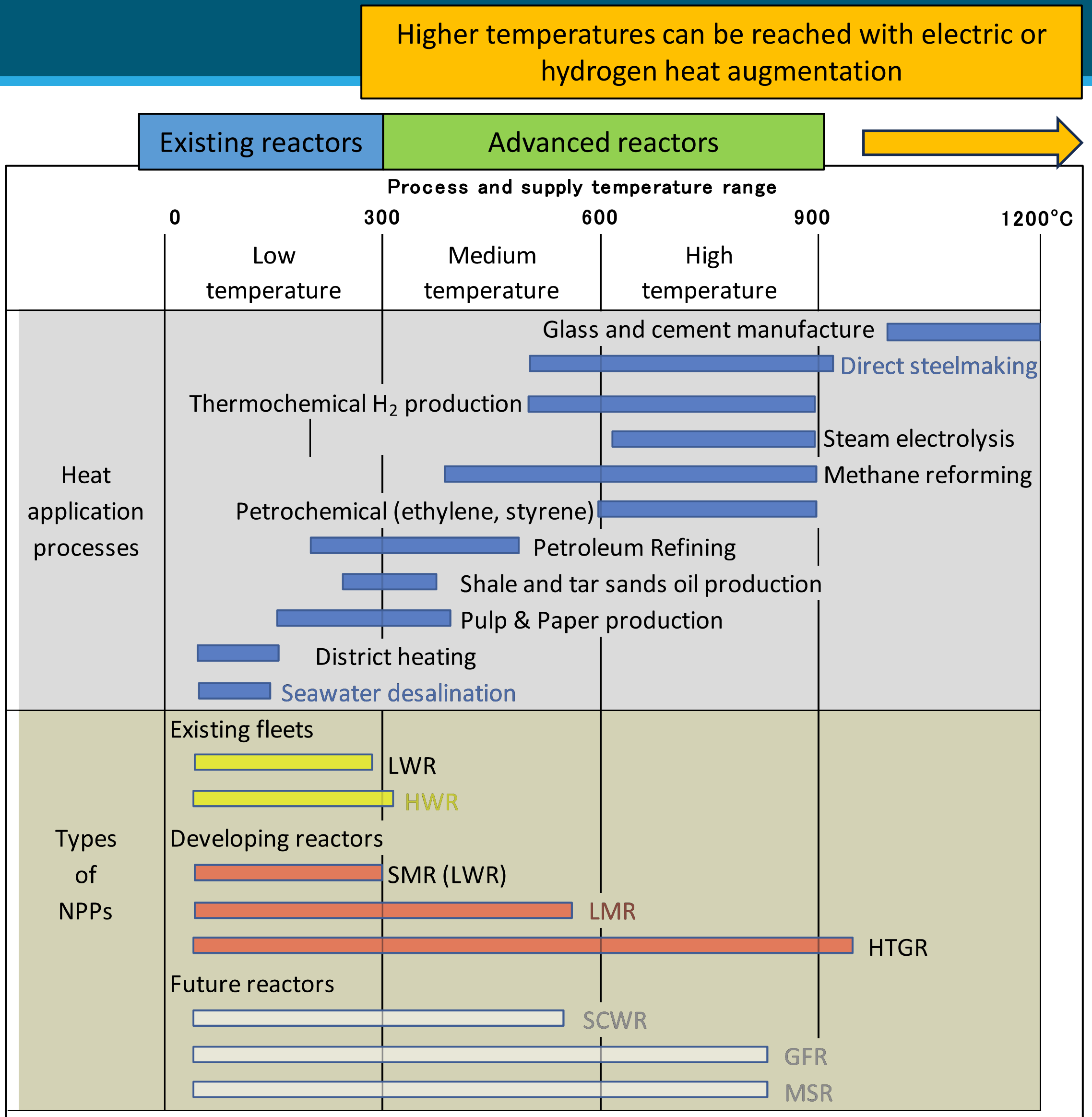
IES Integrated Energy Systems

The Decarbonization Problem

- Why is it so hard to decarbonize the industrial sector?
  - Combustion can supply high temperature air and steam
  - Processes are sensitive to temperature and pressure
  - Some GHG emissions result from chemical reactions
    - Example: Cement production $CaCO_3$ + Heat → CaO + CO_2
- Energy created and used in industrial processes is often intertwined with the process itself
  - Heat is recovered from CO_2 intensive processes
    - Example: Steam methane reforming converts natural gas and supplies heat
  - CO_2 is emitted from burning process byproducts as fuel
    - Example: Chemical recovery boilers at pulp mills

A Solution: Nuclear Power

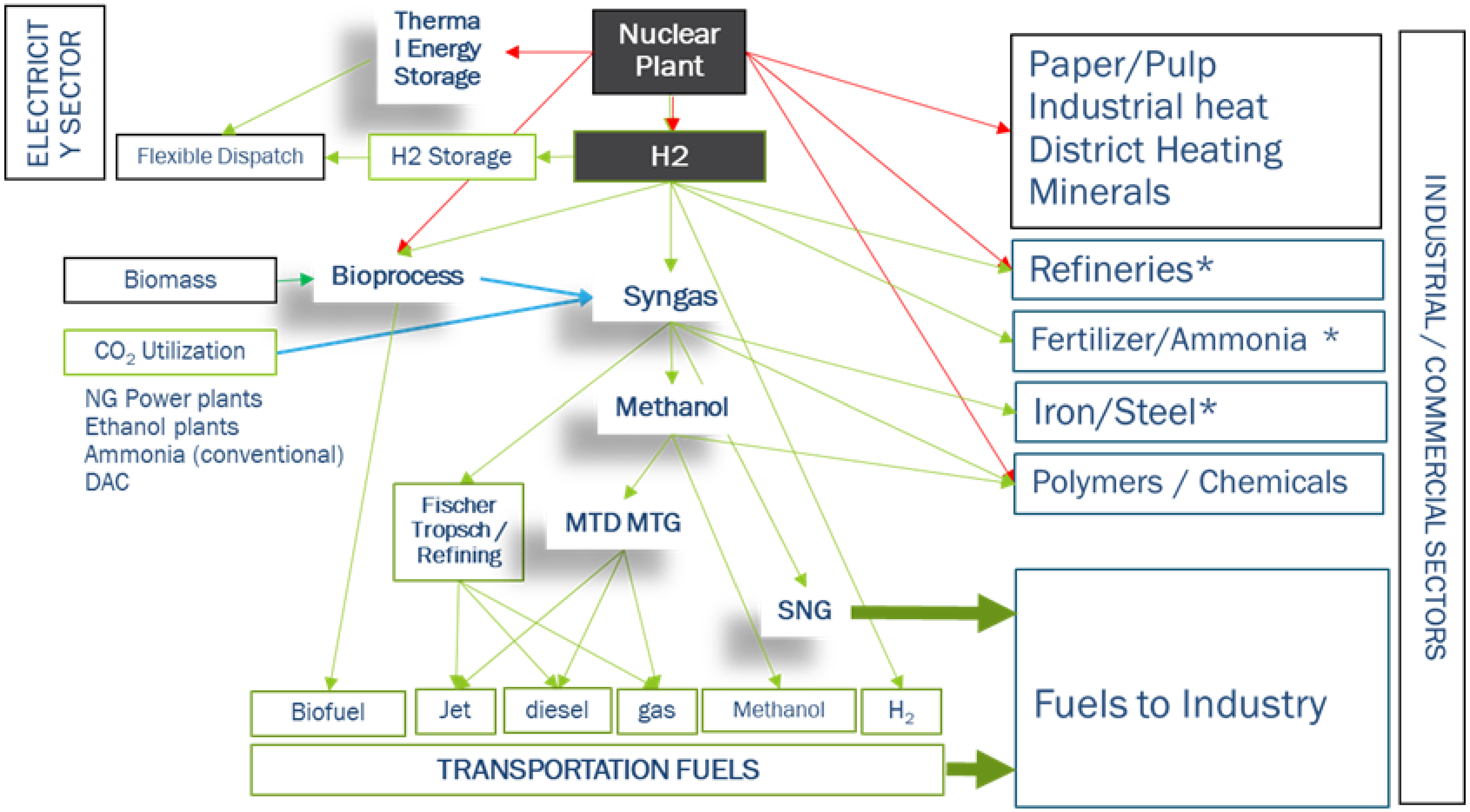
- Advantages
  - Low lifecycle carbon emissions
  - Cogenerate heat and electricity
- Advanced Nuclear
  - Smaller size, modular, passively safe, and easier to construct
  - Higher output temperatures
    - Liquid metal fast reactors (LMFRs): ~650°C
    - Molten salt reactors (MSRs): ~650°C
    - High temperature gas reactors (HTGRs): ~650°C to ~950°C for very high temperature reactor (VHTR)



Note: GFR — gas cooled fast reactor; HTGR — high temperature gas reactor; HWR — heavy water reactor; LMR — liquid metal reactor; LWR — light water reactor; MSR — molten salt reactor; NPP — nuclear power plant; SCWR — supercritical water reactor; SMR — small modular reactor.

(IAEA, 2017)

A Solution: Integrated Energy Systems



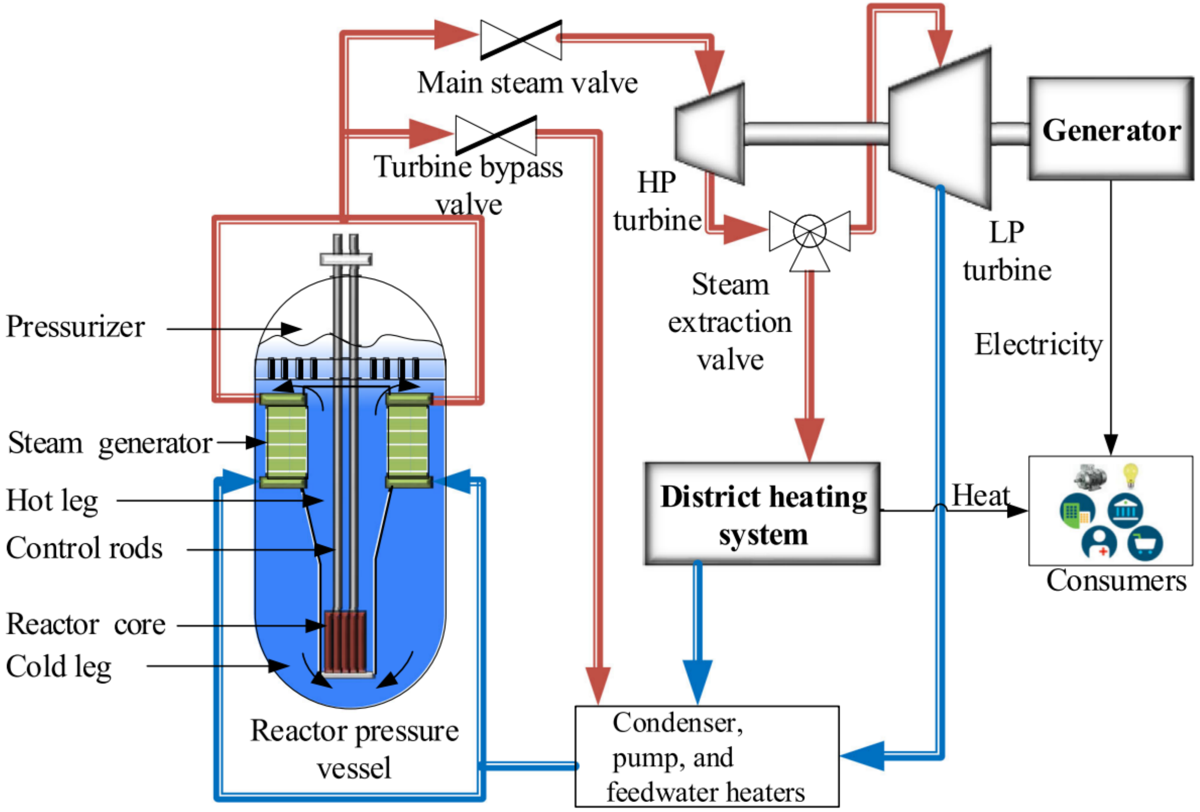
(Josek et al., 2024)

Attributes of IES

- Integration of thermal, electrical, and process intermediates
- More complex systems than co-generation, poly-generation, or combined heat and power
- May leverage the economics of grid-coordinated energy systems
- May provide grid services through demand response (import or export)
- Reactor sizes and temperatures align with the needs of each application

IES Integrated Energy Systems

The Past: Process Heat and District Heating



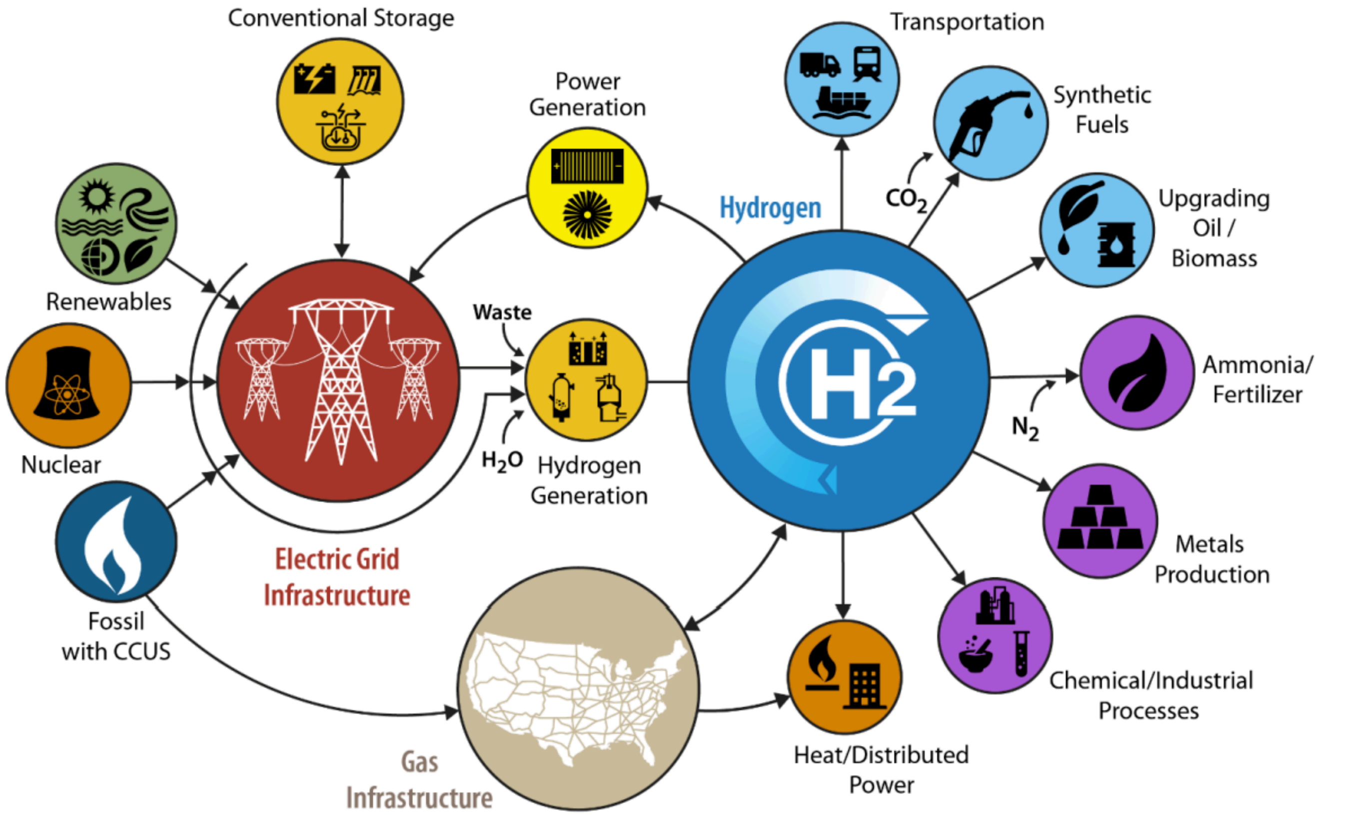
(Poudel and Gokaraju, 2021)

- Nuclear steam extraction is a decades-old practice
  - 1960s and 1970s: Nuclear district heating was popular in Eastern Europe and Russia
  - 1964: Halden reactor (Norway) sited specifically to provide process heat to a nearby paper mill
- Applications Today:
  - Gösgen PWR in Switzerland provides process steam to two nearby paper mills:
    - Steam is produced by separately built evaporator plants
  - 50 MW district heating project planned for Helsinki

IES Integrated Energy Systems

The Present: NPPs and Hydrogen

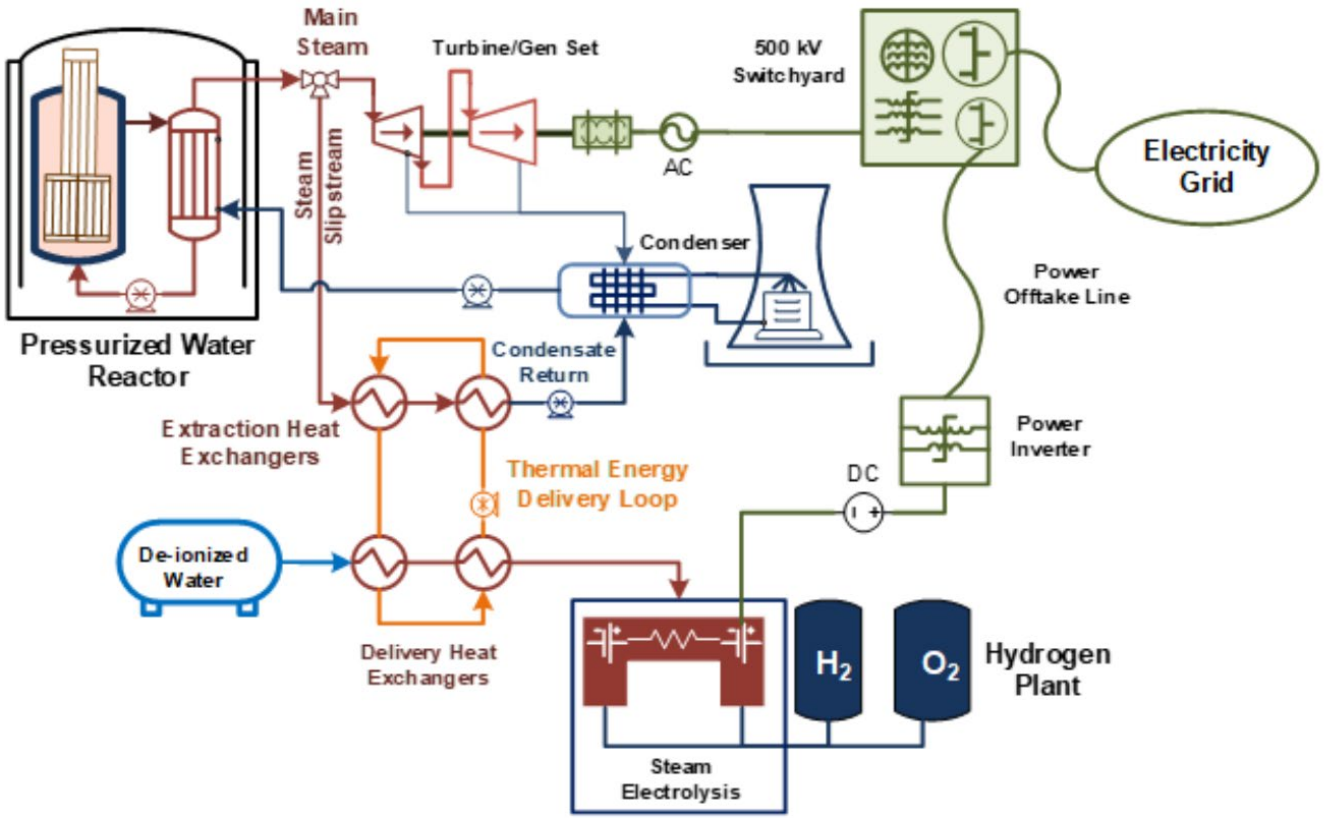
- Hydrogen generation can bridge the gap between heat and commodities
- Electrolysis enables cogeneration of hydrogen with electricity direct from the NPP
- Hydrogen generation can support many industries
- Hydrogen generated from nuclear supplied:
  - Electricity: Low Temperature Electrolysis (LTE)
  - Electricity and Steam: High-Temperature Steam Electrolysis (HTSE)



(U.S. Department of Energy, 2020)

IES Integrated Energy Systems

The Present: NPPs and Hydrogen



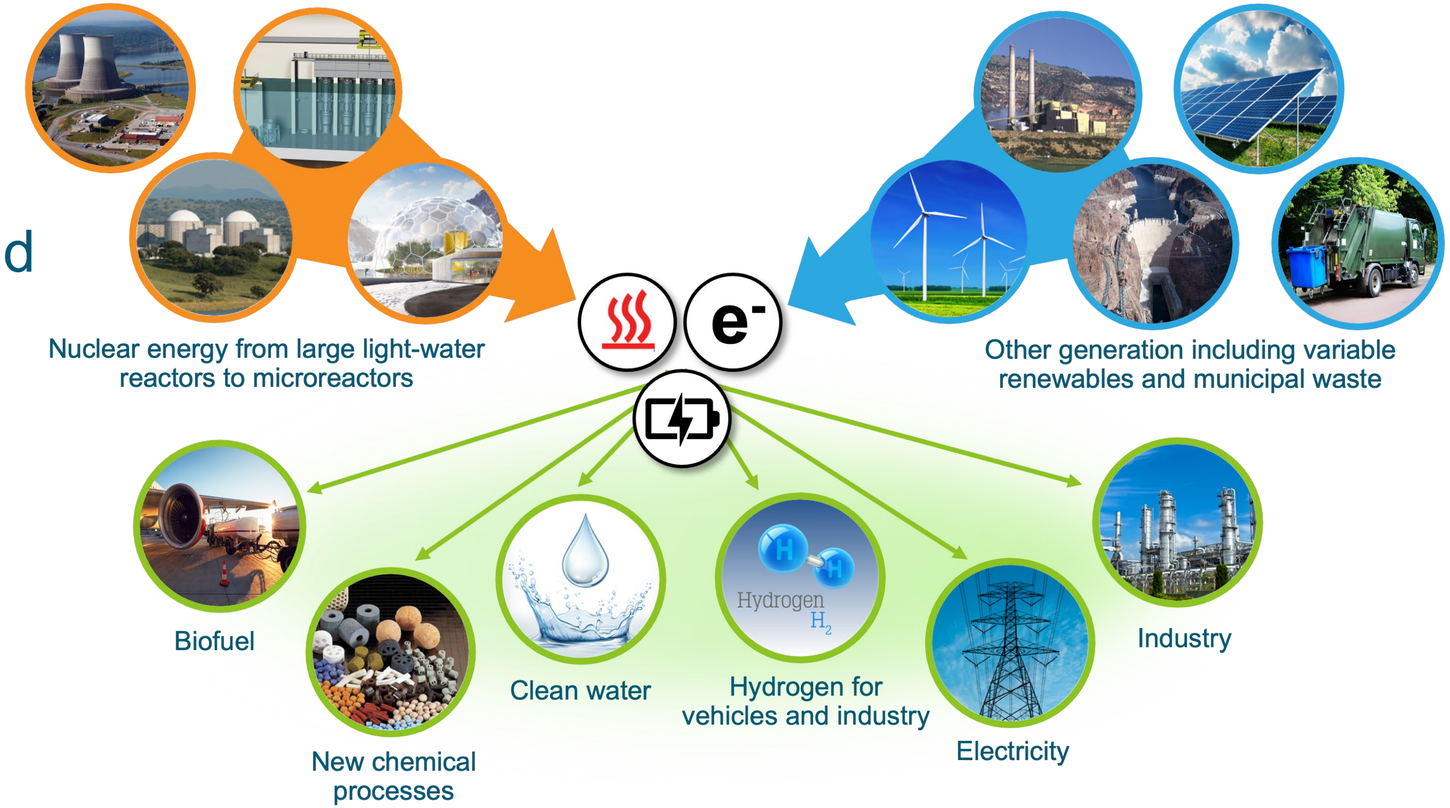
(Ruth et al., 2021)

- Hydrogen demonstration Projects
  - Constellation: Nine-Mile Point NPP (~1 MWe LTE)
  - Energy Harbor: Davis-Besse NPP (~1-2 MWe LTE)
  - Xcel Energy: Prairie Island NOO (~150 kWe HTSE)
  - FUelCell Energy: Demonstration at INL (250 kWe)

IES Integrated Energy Systems

The Future: Process Decarbonization

- Energy park configurations
  - NPP owner-operator (utility)
  - Heat and Electricity users (industry)
  - Integrate renewable electricity and waste products
  - Collocation of industries to share SMR resources (electrolytic hydrogen generation→ fertilizer production → biorefinery → wastewater treatment)
- Process improvements
  - Repurpose or eliminate waste products
  - Carbon capture and utilization



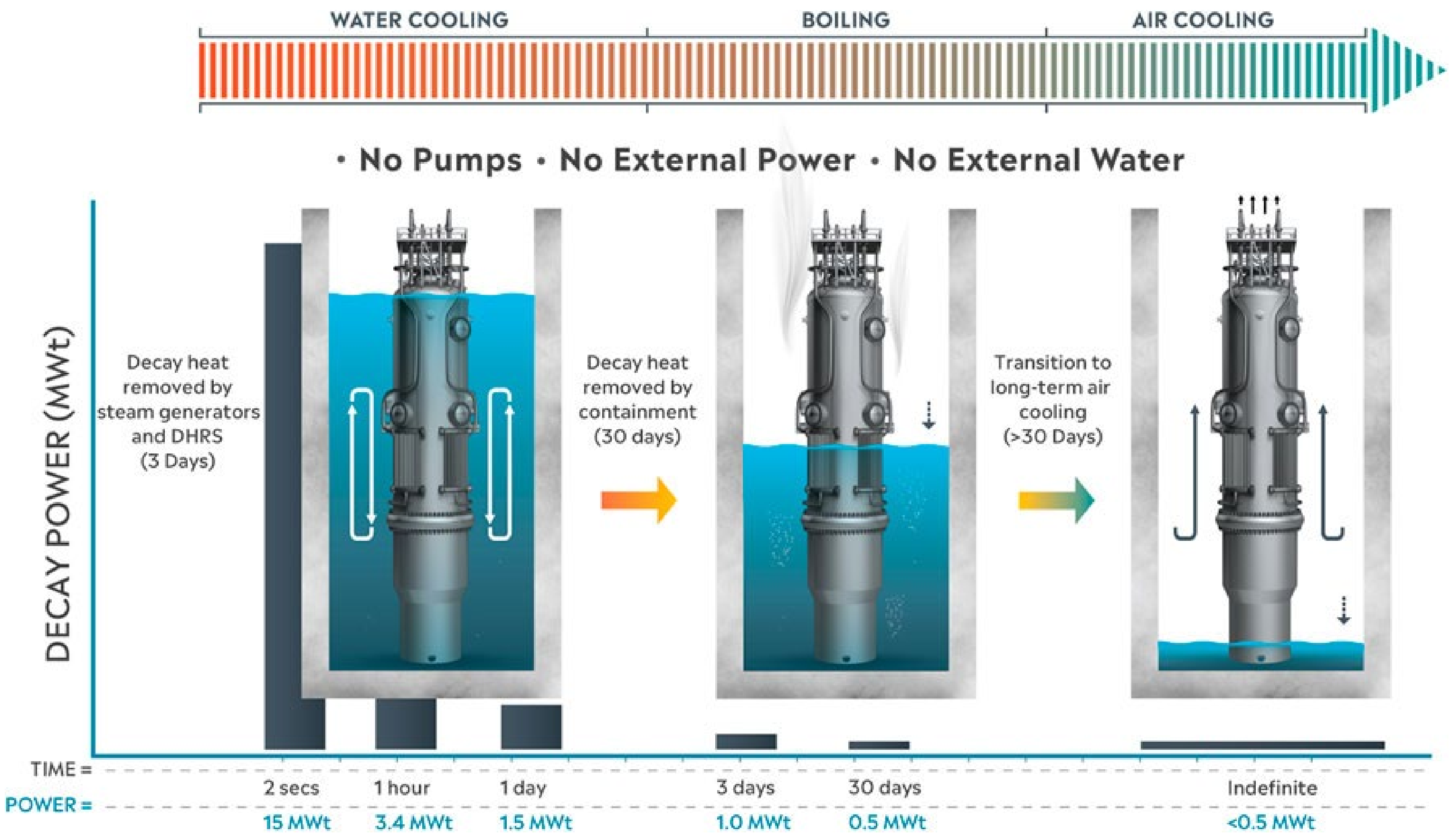
(U.S. DOE, 2022)

How do we do it?: Siting

- Industrial Hazards: Use and transport of hazardous materials around an industrial facility
- Industrial Site Characteristics: Distance from population centers, proximity to undeveloped land, proximity to rail and water transport
- The use of certain materials in thermal transfer or storage could introduce additional hazards
- Long distances between facilities may reduce efficiency/feasibility for heat use

How do we do it?: Safety

- Advantages of advanced Reactor Designs
  - Passive operation – “inherently safe”
  - Reduced Emergency Protective Zone (usually site boundary)
  - Reduced inventory of fission products
  - More effective heat removal

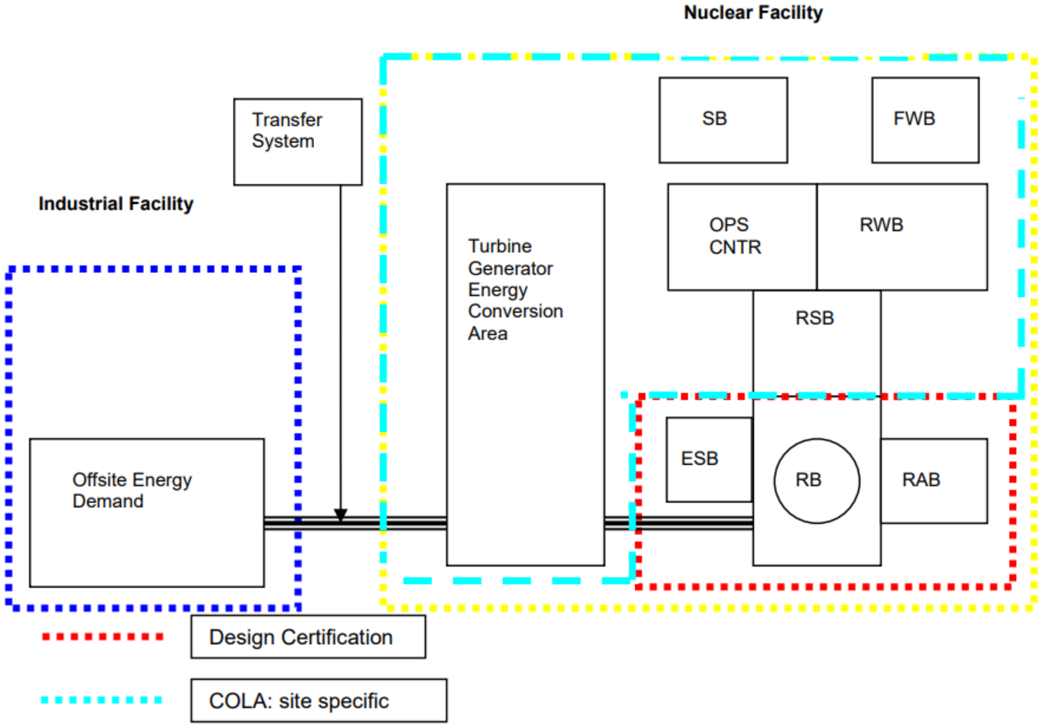


(Welter, Reyes, and Brigantic, 2023)

IES Integrated Energy Systems

How do we do it?: Regulatory

- Establish two sets of regulatory boundaries based on current licensing process
  - Design Certification (DC): Provides conceptual level information about the physical reactor plant and operations (could apply to many sites)
  - Combined Operating License Application (COLA): Site-specific design information addressing interfaces between reactor, energy conversion, and use.
- DC and COLA contain a complete description of the nuclear energy plant, including non-safety and safety related systems.
  - The certified portion of the reactor plant design would bound all worst-case operating and accident scenarios for potential site-specific energy conversion systems and operating configurations
  - Essentially, within the boundary, show that the reactor is designed so that it can operate safely independent from changes in out-of-boundary operation

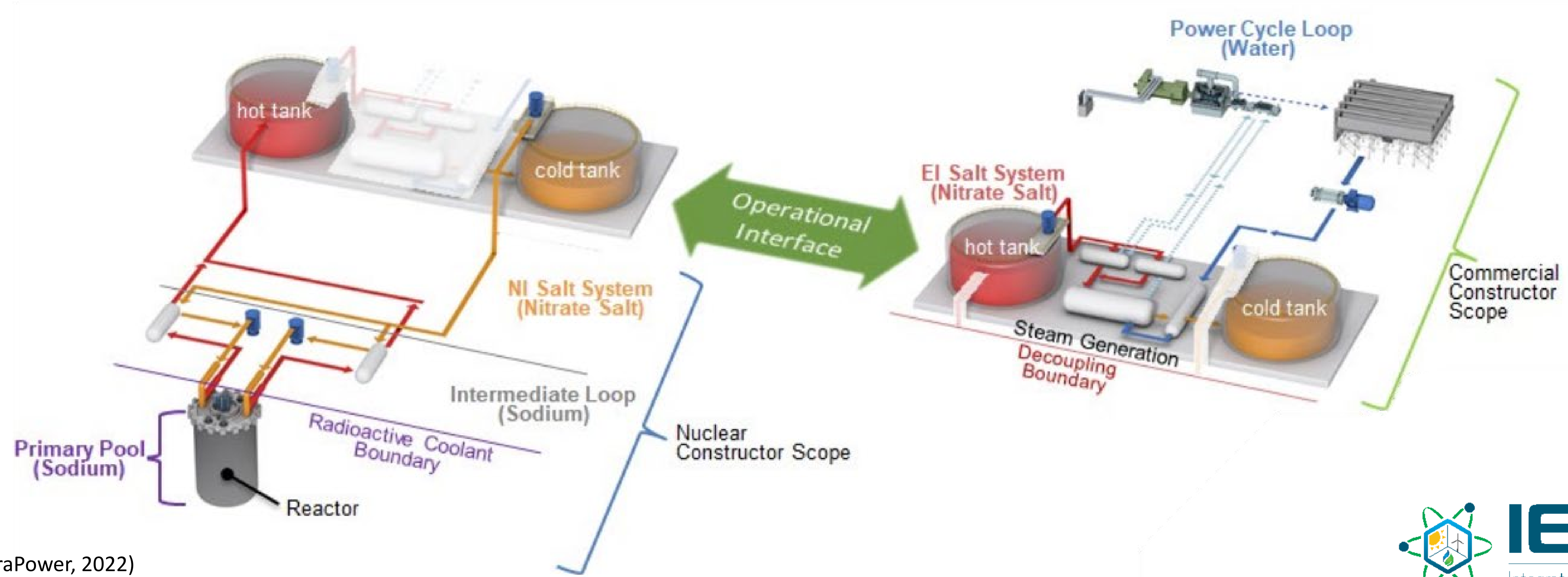


RB: Reactor Building including reactor vessel, primary circuit, cross vessel, secondary circuit pressure vessel, piping connecting the primary helium circuit to support systems, (e.g., shutdown cooling system, primary helium service and purification system)
RAB: Reactor Auxiliary Building
ESB: Electrical Service Building
RSB: Reactor Support Building
OPS CNTR: Operations Center and Control Room
RWB: Radwaste Building
SB: Security Building
FWB: Fire Water Building and Fire Pump House

(Moe and Hicks, 2020)

How do we do it?: Operation

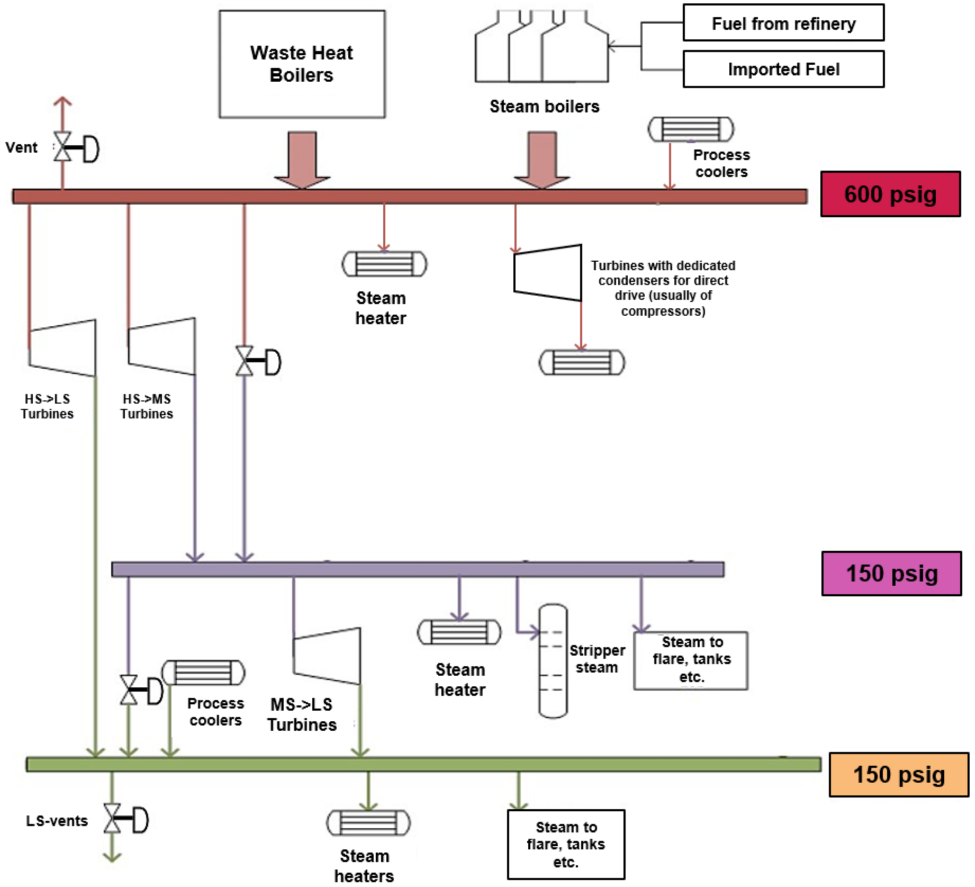
- TerraPower has proposed an “Energy Island Decoupling Strategy” to the NRC for review
  - A molten salt energy storage system connects the nuclear reactor and its systems
  - The “nuclear island” and “energy island” can be operated as separate power plants if the salt tank conditions remain in controlled bands



(TerraPower, 2022)

How do we do it?: Petroleum Refining

- Hydrogen
  - 25% of hydrogen supply in the United States is utilized to process petroleum
  - Replace steam methane reforming with electrolysis



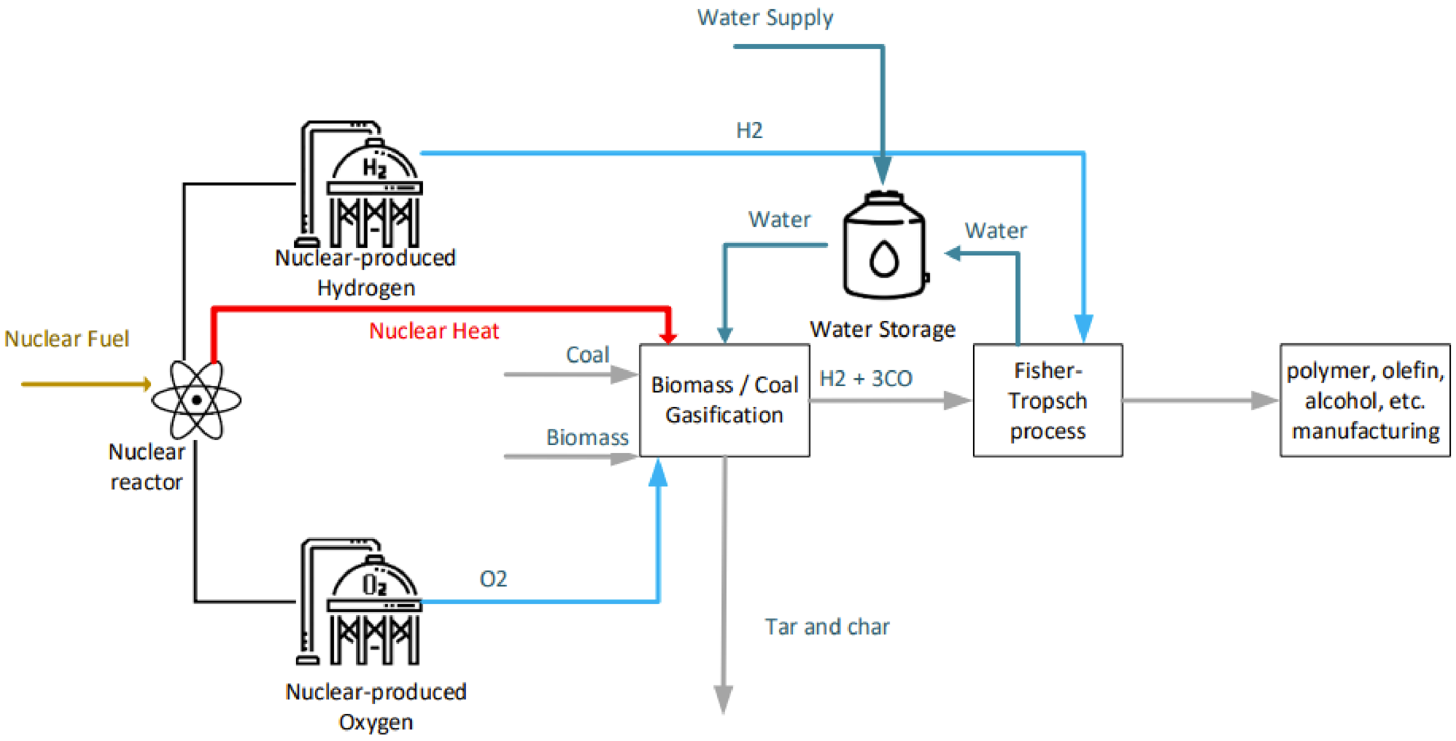
(Josek et al., 2024)

	Power demand	Steam process heat	Combustion heat	Feedstock H2
HTGR	Yes	Yes	Theoretically, but demand is met with refinery fuel gas	Yes (HTSE viable)
LWR	Yes	Conditionally (requires steam compression)	No	Yes (HTSE viable)

IES Integrated Energy Systems

How do we do it?: Methanol

- Heat requirements are too high to be met by HTGR or LWR
  - There may not be opportunities for integration with conventional methanol plants
- Syngas
  - Produce via co-electrolysis: $CO_2 + H_2O \rightarrow CO + H_2 + 1/2\ O_2$
  - Produce from biomass or coal gasification with carbon capture
- Hydrogen
  - Supplement hydrogen supply through electrolysis
  - Adding pure hydrogen to shift syngas to the proper ratio and eliminates water gas shift reactor



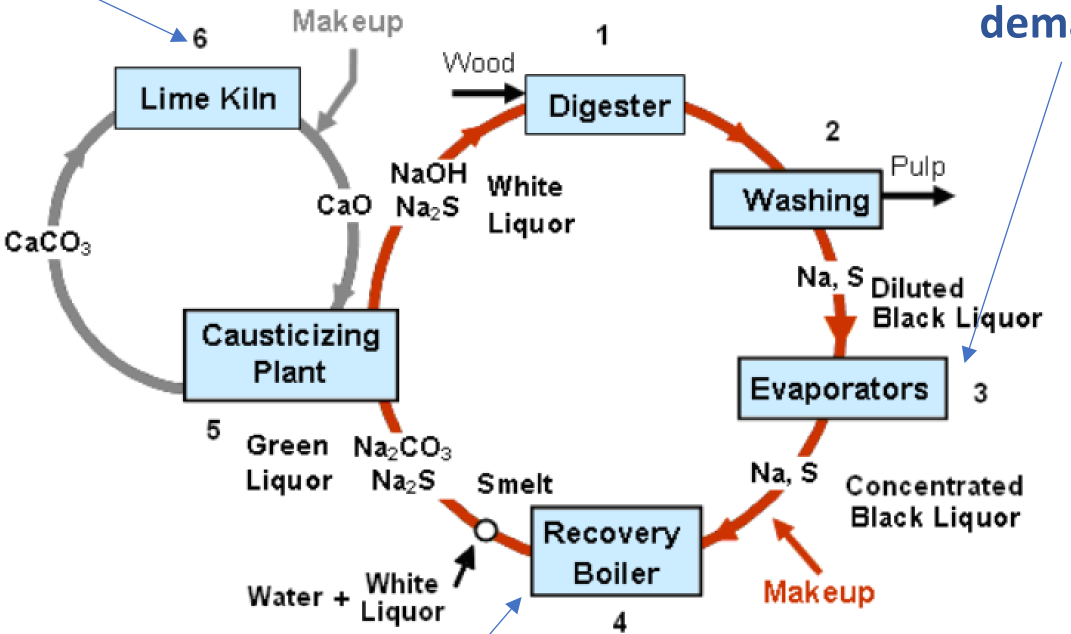
(Foss et al., 2021)

How do we do it?: Pulp and Paper

- Steam from LWR or HTGR
  - Pulp mills already have a turbine system for cogenerating steam and electricity
  - The largest demand is for low pressure steam: evaporators and paper pressing
- Black liquor and wood waste
  - The largest challenge for decarbonization – chemical recovery hinges on black liquor combustion
  - Shift from fuel to products
- Lime kiln
  - Alternative firing methods: oxy-firing, electric heating
  - Carbon capture for process generated CO2

Typically heated with fuel oil or natural gas

Largest steam demand



~50% steam generated for int. mill

(Tran and Vakkilainen, 2007)

IES Integrated Energy Systems

Summary

- We need nuclear to reach net-zero, but electricity generation is only a part of the picture (about 33%)
- Nuclear can support industrial decarbonization with heat, steam, electricity, and hydrogen
- Historical technical experience and the current regulatory infrastructure support the feasibility of nuclear and industrial pairings
- Next steps:
  - Siting analysis and characterization of different industry sites
  - Modeling plant systems with nuclear integration
  - Additional decarbonization options: hydrogen, biorefining, etc.

Contacts: Rami.Saeed@inl.gov
Elizabeth.Worsham@inl.gov

IES Integrated Energy Systems

References

- EPA 2021 : Inventory of U.S. Greenhouse Gas Emissions and Sinks | US EPA
- IAEA *2017: Opportunities for Cogeneration with Nuclear Energy*
- Welter, Reyes, and Brigantic 2023: Unique safety features and licensing requirements of the NuScale small modular reactor
- Tran and Vakkilainnen 2007: The Kraft Chemical Recovery Process
- Moe and Hicks 2020: Establishing Jurisdictional Boundaries at Collocated Advanced-Reactor Facilities
- Foss et al. 2021: NRIC Integrated Energy Systems Demonstration Pre-Conceptual Designs
- Josek et al. 2024: Thermal Integration of Advanced Nuclear Reactors with a Reference Refinery, Methanol Synthesis, and Wood Pulp Plant (Pending Publication)
- TerraPower 2022: "Energy Island Decoupling Strategy",
- Vedros, Christian, Otani 2022: Probabilistic Risk Assessment of a Light-Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant
- U.S. DOE 2020: Department of Energy Hydrogen Program Plan
- U.S. DOE 2022: Nuclear Energy Supply Chain Deep Dive Assessment
- Ruth et al. 2021: Case Study: Hybridizing Nuclear Energy Systems in the U.S.
- Poudel and Gokaraju 2021: Small Modular Reactor (SMR) Based Hybrid Energy System for Electricity & District Heating

IES Integrated Energy Systems

Idaho National Laboratory