



# Nuclear Heat Integration

## Introduction and Industrial Applications



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# Mini Workshop Objectives



Foster collaboration and information exchange  
between industry sectors.



Learn from each other to facilitate integration.



What needs to be done for integration?



**Who is the Electric Power Research Institute (EPRI)?**

# EPRI Research & Development

## TECHNOLOGY INNOVATION

Driving thought leadership, advanced R&D, and technology scouting and incubation to sustain a full pipeline of solutions



Nuclear Power



Energy Supply and Low-Carbon Resources



Electrification and Sustainable Energy Strategy



Transmission and Distribution Infrastructure



Integrated Grid and Energy Services

## STRATEGIC RESEARCH



Low-Carbon Resources



End-Use/  
Economy-Wide Carbon Reduction



Electric System Reliability/Resilience



Electric System Flexibility



Market Transformation/  
Policy/Regulatory Education

# Advanced Nuclear Technology (ANT) Program Focus

**MISSION:** Accelerating the deployment of nuclear power around the world.

FROM PLANNING AND CONSTRUCTION...



Informing  
Resource  
Planning



Training



Supporting  
Plant Startup



Operational  
Readiness



Construction  
Optimization



Reducing  
Deployment  
Costs



Design and  
Engineering



Technology  
Development

...TO OPERATION AND MANAGEMENT

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90 companies



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Products



Dozens of  
Ongoing Projects



# EPRI's Nuclear Beyond Electricity



**Data  
Centers**



**Process  
Manufacturing**



**Low Carbon  
Fuels**



**Energy  
Storage**



**Maritime**



**Water &  
Wastewater**



**Medical  
Isotopes**



**District  
Energy**

## Purpose

Enable **existing** and **future** nuclear plants to **participate in energy markets beyond the practice of generating baseload electricity.**

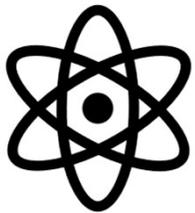


# Introduction to Nuclear Power

# Why Nuclear Power? – Reliable Energy

## ■ Dispatchable Generators

- Can be deployed as needed
- Usually ramp up and down to adapt to demand fluctuations
- Operating costs include fuel, maintenance, and staff



Nuclear Power



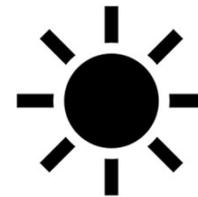
Natural Gas



Biomass Combustion



Wind Power



Solar Photovoltaic



Tidal Energy

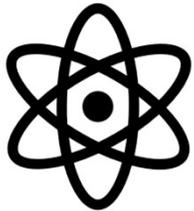
## ■ Non-Dispatchable Generators

- Can only be deployed effectively in some locations
- Generation is dependent on constantly changing environmental conditions
- Typically not carbon-emitting
- Operating costs are minimal compared to capital costs

# Why Nuclear Power? – Capacity Factors

- The capacity factor measures the **actual** energy output against **maximum** energy output
- Calculated capacity factors for baseload generators may be affected by fuel availability as well as the marginal cost of electricity production

$$\text{Capacity Deployed (MW)} * 8760 \frac{\text{hours}}{\text{year}} * \text{Capacity Factor (\%)} = \text{Expected Annual Generation (MWh)}$$



## Nuclear Power

Capacity Factor: 92.6%

Annual generation from 1 MW: **8103 MWh**



## Wind Power

Capacity Factor: 36.1%

Annual generation from 1 MW: **3162 MWh**



## Natural Gas Combined Cycle

Capacity Factor: 56.7%

Annual generation from 1 MW: **4967 MWh**

## Natural Gas Turbine

Capacity Factor: 13.7%

Annual generation from 1 MW: **1200 MWh**



## Solar Photovoltaic

Capacity Factor: 23.1%

Annual generation from 1 MW: **2024 MWh**

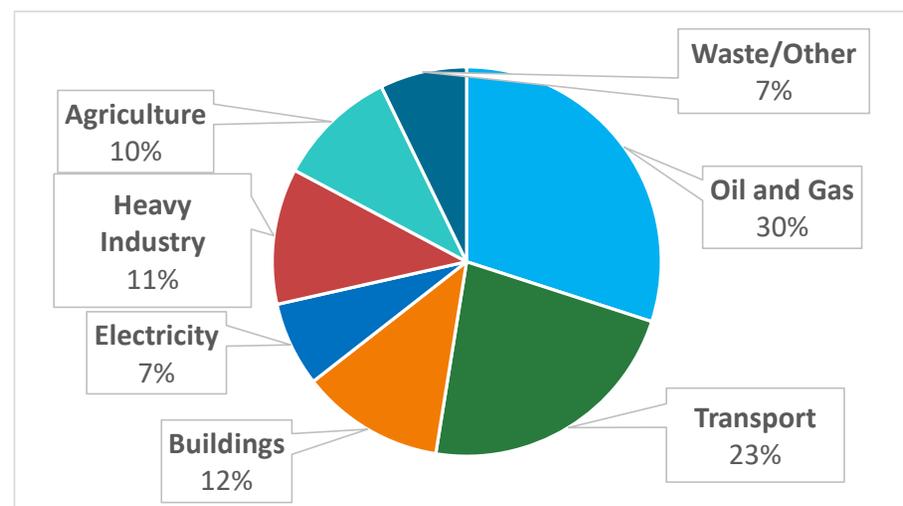
# Why Nuclear Power? – Comparing Generators

- The sources of costs for each generator affects its ideal operating strategy
- A reliable, cost-effective energy system typically requires a combination of generator technologies

	Traditional Nuclear Power 	Natural Gas Combined Cycle 	Wind 
<b>Capital Costs</b>	↑ Lifetime costs dominated by construction, financing	↓ Relatively faster and lower cost to deploy than traditional nuclear	↓ Benefits from mostly off-the-shelf construction
<b>Fixed Annual Costs</b>	↑ Significant staffing required (expected to decrease for advanced reactors)	↓ Requires minimal staffing and equipment	↓ Mostly self-sustaining, some upkeep required
<b>Marginal Costs</b>	↓ Fuel is extremely energy dense	↑ Fuel costs dominate lifetime costs	<b>None</b> Output based on environmental conditions
<b>Lifetime</b>	<b>60+ Years</b>	<b>20-30 years</b>	<b>20-30 years</b>
<b>Cost-Effective Operating Strategy</b>	Spread fixed costs over as much energy generation as possible	Deploy only when energy sale price is higher than marginal cost	Use all available energy and adapt to demand using other generators or storage

# Market Reality

- High penetration of renewables drives down electricity prices for other generators
- Market flexibility **increases revenue opportunities** for nuclear generators AND **ensures fast response** to grid demand changes
- Electricity only contributes to 7% of greenhouse gas emissions in Canada
- **Nuclear power is the only non-carbon-emitting option for industries requiring stable heat demand**



Greenhouse Gas Emissions By Economic Sector, 2023  
(Source: Government of Canada)

# Reactors Through the Generations

## GEN I & II

**Early demonstrations through GW-scale commercial fleets**

- Diversity of designs
- Diversity of vendors
- Limited standardization
- Evolving regulations

**Palo Verde's System 80 design is a Gen II plant**

## GEN III / III+

**Evolutionary designs, GW-scale +**

- Convergence on ALWRs
- Standardization
- Integration with licensing
- **EPRI and European utilities established LWR-centric requirements**

**Vogtle's AP1000 design is a Gen III+ plant**

## Advanced Reactors (ARs)

**Beyond large LWRs: non-LWRs, lwSMRs**

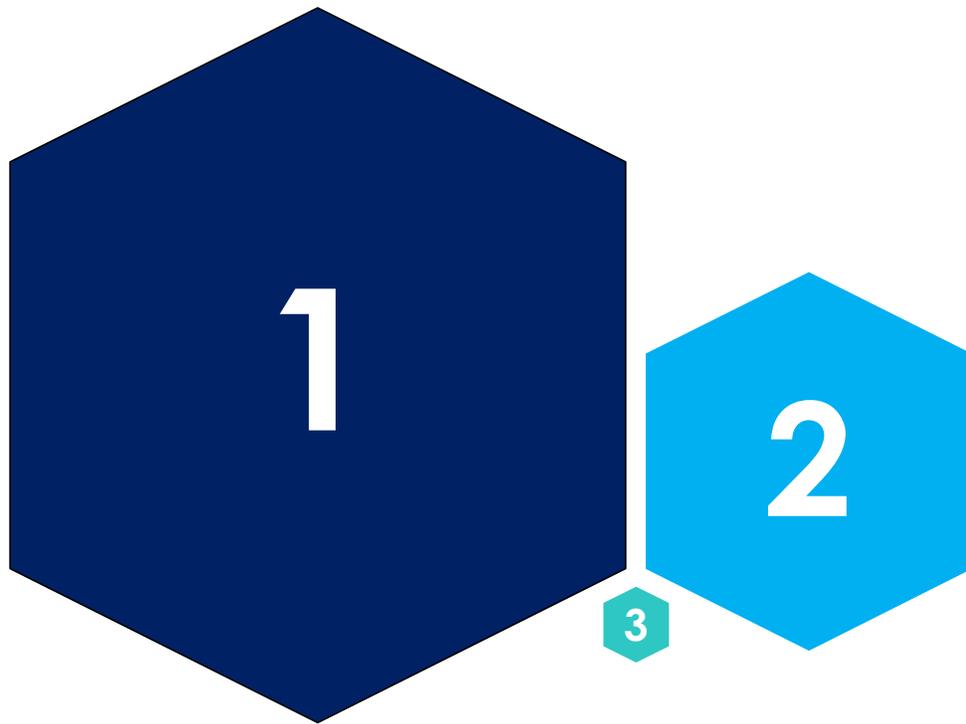
- Aggressive cost and schedule targets
- Competitiveness via new missions and customers
- Evolving regulatory frameworks
- **EPRI published AR Owner-Operator Requirements Guide**

## Microreactors

**MWe-scale expands AR options**

- Heat pipe cooling
- Remote deployment
- New markets
- Competition with diesel

# Benefits of ARs – Reduced Size, Expanded Siting Potential



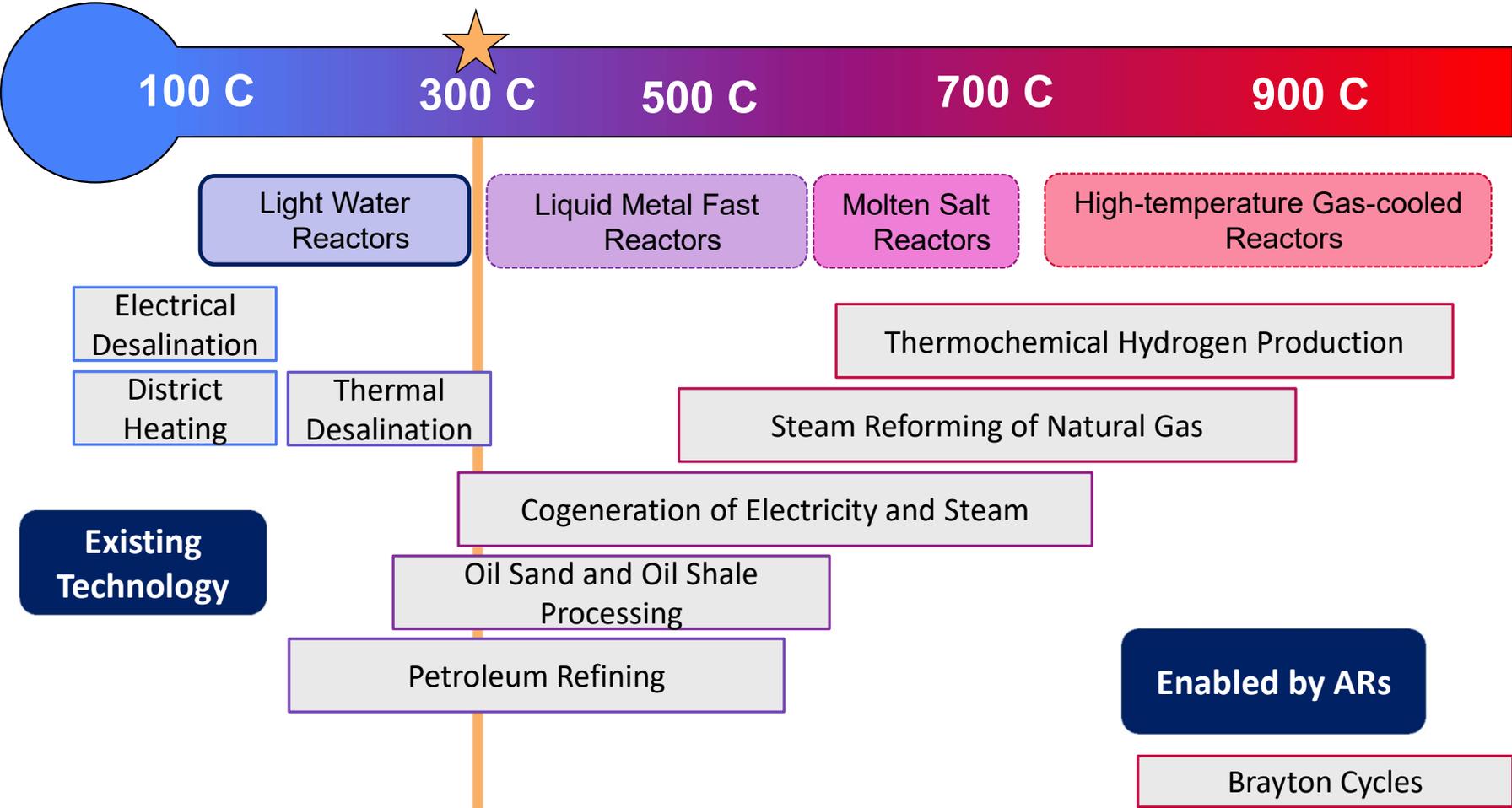
Commercial Power Reactor (~500 acres)

Small Reactor (~50 acres)

Microreactor (<1 acre)

Vogtle – 1.44 MWe/acre  
Palo Verde – 1.05 MWe/acre  
BWRx-300 – 44.77 MWe/acre

# Benefits of ARs – Higher Temperatures, New Markets



# How is energy generated?

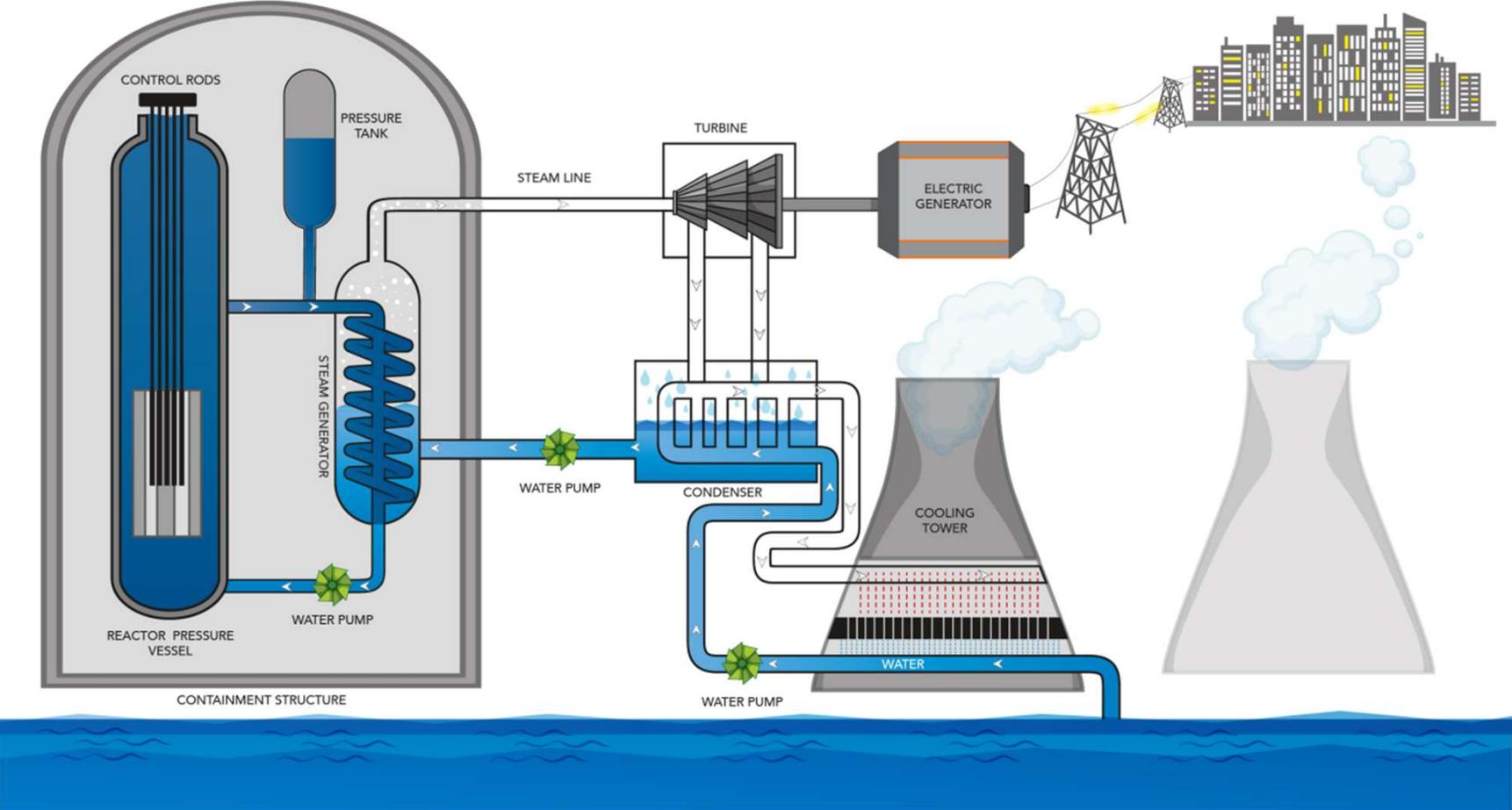
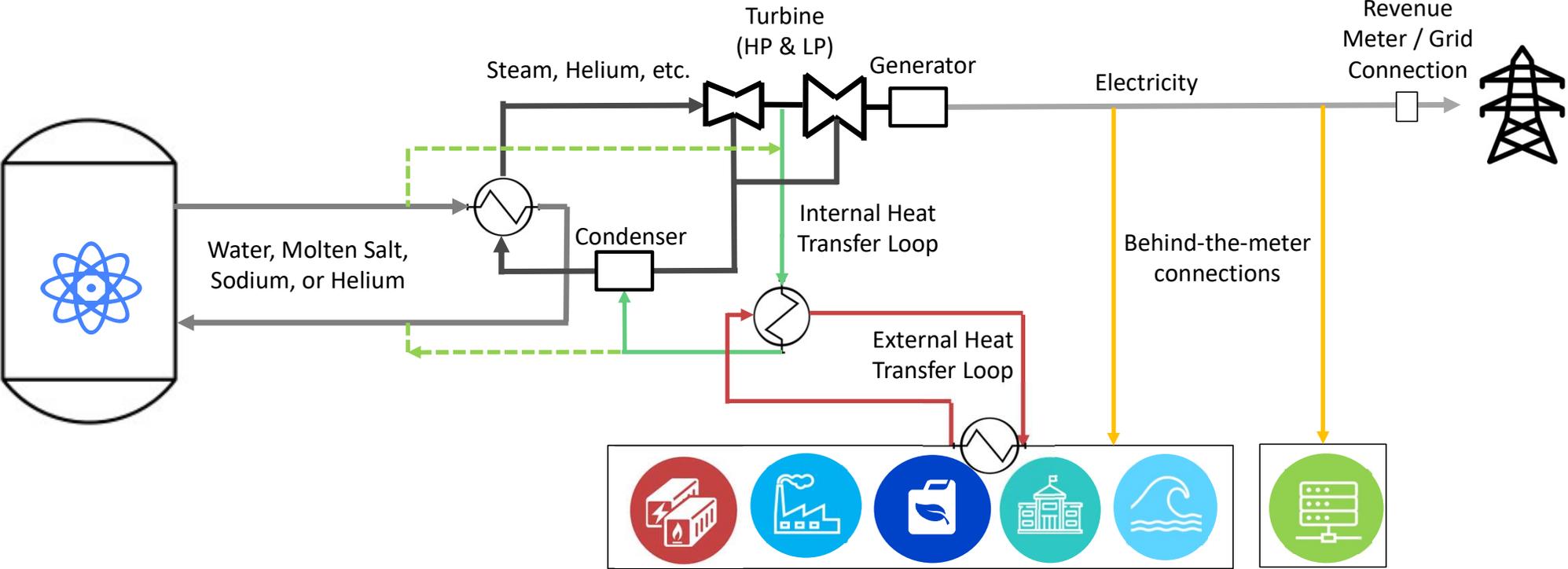


Image Credit: U.S. Department of Energy

# Nuclear-Industrial Integration

## Generic Example of Nuclear Cogeneration:



Note: The shown concept is for illustration purpose only. The specific integration depends on the reactor design, power conversion cycle (Rankine or Brayton) and application.

# NBE Roadmap (3002032210)

Addresses challenges identified during the 2024 Nuclear for Industrial Integration Workshop

Technical



01

Operational



02

Financial



03

Ownership



04

Policy / Regulatory



05

Permitting



06

Project Development & Execution



07

Security



08

Public Awareness

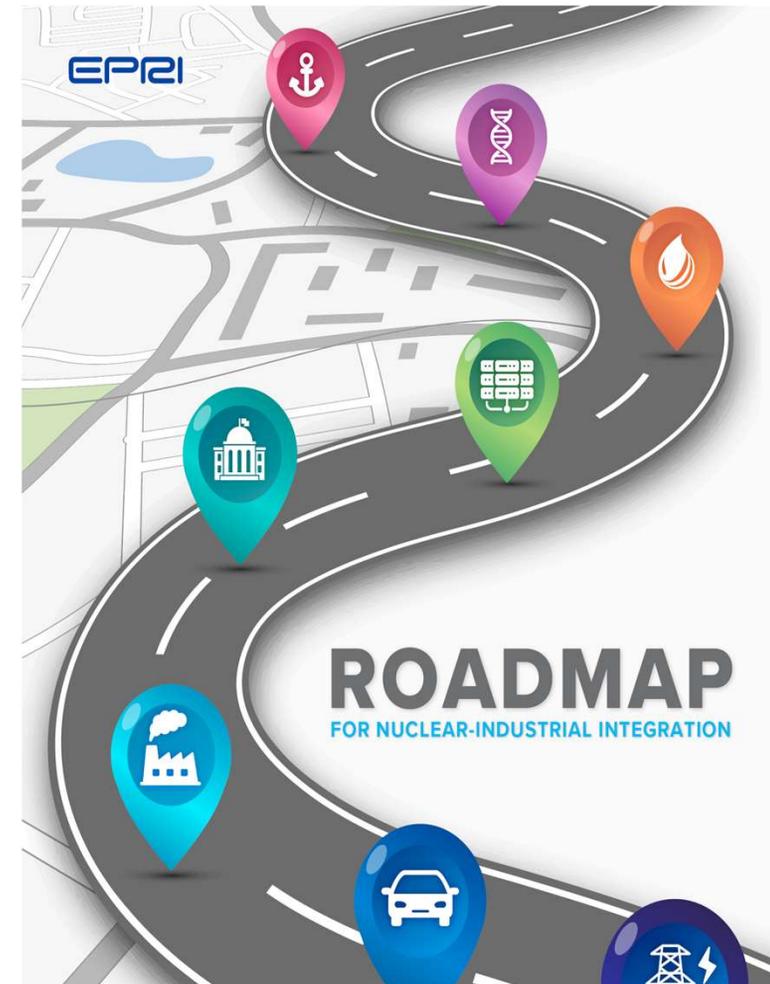


09

Insurance



10



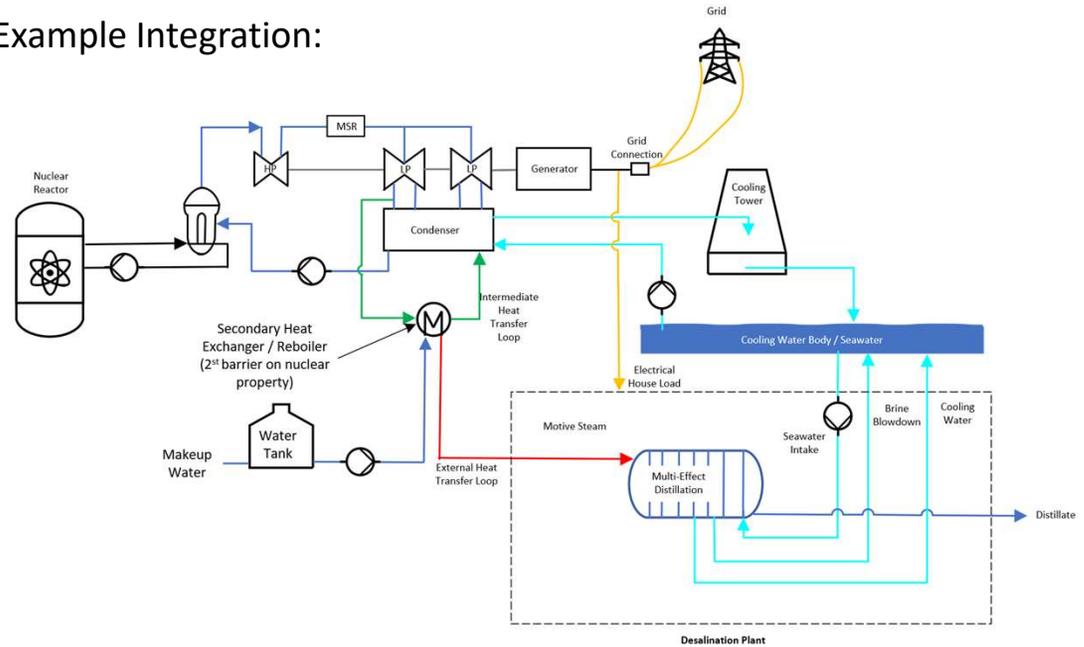


# Landscape for Nuclear Power Beyond Electricity

# Desalination

- Two main categories of desalination
  - Reverse Osmosis (RO): uses electricity to pump water through membrane filters
  - Thermal: heats water to evaporation to separate impurities
- RO is the most deployed and regarded as the most cost-effective option for nuclear integration
- Thermal desalination is best for high-grade purification or high salinity feeds
- RO can be flexibly deployed to provide an additional revenue stream for the power plant**

Example Integration:



## CURRENT

- Japan
  - 10 desalination plants linked to energy from pressurized water reactors
  - Mostly RO with some thermal

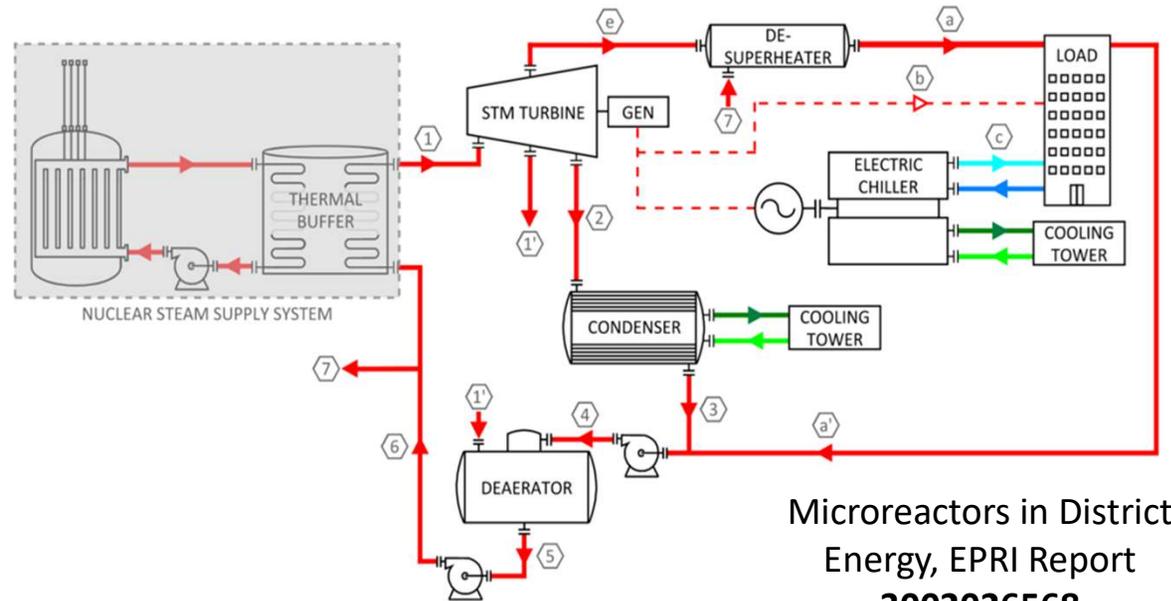


## FUTURE

- United States
  - Natura Resources and NGL Energy
  - Use reactor electricity and waste heat to purify wastewater from oil and gas operations

# District Heating

- Steam provides heating to a network of buildings
- Capital-intensive project best for small, dense, urban areas or clusters of industrial users
- Future nuclear power applications depend on how regulations are updated for reactors with smaller emergency planning zones
- **Cogeneration maximizes plant capacity factors by following seasonal demands for heat and electricity**



## CURRENT

- Bulgaria, China, Czech Republic, Hungary, Russia, Romania, Switzerland, Ukraine
- As of 2022, all have operating district heat networks linked to nuclear power plants
- Longest transport 64 km (Kalinin, Russia)

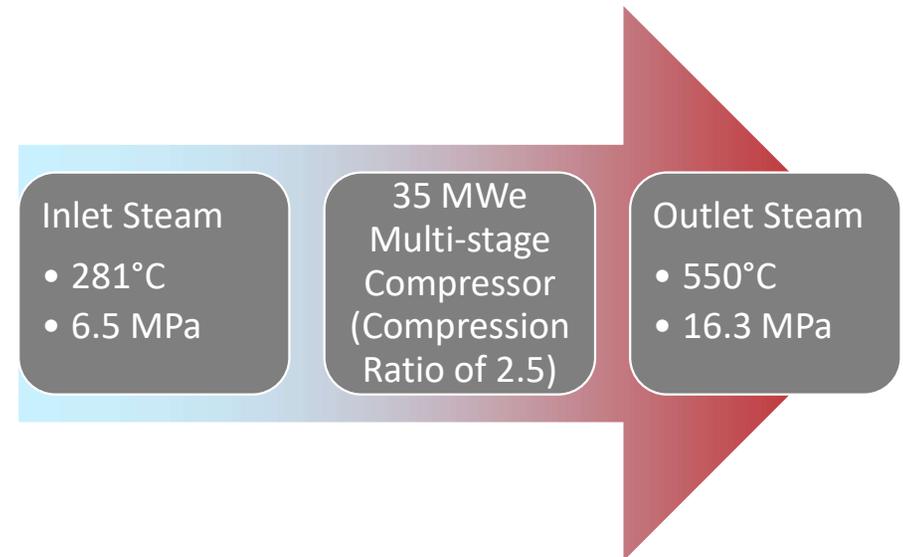


## FUTURE

- Helsinki, Finland
- Steady Energy and Helen to build pilot facility for a small modular reactor inside a former coal plant to supply a district heating network

# Process Heat Applications

- Steam temperature output range 300-600°C depending on design
  - Can boost temperature or pressure using boilers, adiabatic compression, etc.
- Low pressure and temperature extraction has the smallest impact on electricity production in cogeneration mode
- Benefits to process heat integration
  - **Power plant:** Stable heat demand, guaranteed revenue through PPA
  - **End User:** Highly reliable steam source, price of energy less dependent on market fluctuations, no carbon emissions



Methods for Increasing Nuclear Steam Temperature, EPRI Report **3002032186**

## *PAST*

- Bruce Generating Station, Canada
- Provided heat for heavy water production, offsite industry, building heating



## *FUTURE*

- Dow Chemical, USA
- Partnering with X-Energy to supply heat for specialty materials production

# Hydrogen

- **Refining and industry currently consume almost ALL hydrogen produced, relying on steam methane reforming of natural gas**
- Hydrogen production technologies for nuclear power
  - Low-temperature electrolysis: highly flexible, powered with electricity
  - High-temperature electrolysis: requires thermal energy to vaporize feedwater and electric energy to complete electrolysis
  - Thermochemical hydrogen technologies: Low TRL
- Hydrogen and synfuels production can bridge nuclear power into hard to decarbonize industries



## ***CURRENT***

- **United States**
  - Constellation Energy 1 MW low-temperature electrolysis pilot at Nine-Mile Point



## ***FUTURE***

- **South Korea**
  - Korea Hydro and Nuclear Power partnering with FuelCell Energy to deploy solid oxide electrolyzers

# Canadian Applications - Mining



Overview of *existing* mines more than 20 kilometers from an electricity grid or self-generating with diesel as a fuel.

Reference: NEA (2024), SMRs for Mining: Opportunities and Challenges for Small Modular Reactors, OECD Publishing, Paris (Image reproduced with CC 4.0 [license](#))

## Energy Challenges

- **Often located in remote areas** without access to reliable grid supply
- Loss of power can have significant financial impacts on mining operations.
- **Power is typically a large portion of the operating costs, often surpassing 25%**
- The cost of electricity for remote mining operations can range from \$0.15/kWh to greater than \$0.80/kWh to self-generate electricity using diesel generators.
- The life of a mine varies depending on the type, quality, and abundance of the target ore – from a lifetime of only a few years up to decades.

**Canada has the second largest share of remote deposits**

# Nuclear Power Solutions

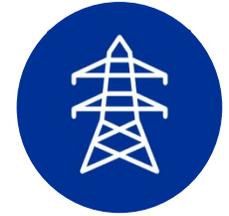
- **Energy infrastructure is a strategic asset** for the mining company (operations, public acceptance and financing).
- Nuclear integration to **provide reliable, zero carbon emitting, electricity and process heat**
  - Heating for buildings and mine shafts.
  - Hydrogen can be produced to locally fuel heavy equipment
  - Excess power can be provided to remote communities
- **Environmentally friendly and logistically simplified** alternative off-site diesel storage and transport
- **Potential to lower cost of electricity**

## *FUTURE*

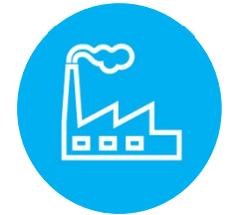
- **United States**
  - Tata Chemicals and BWXT Advanced Technologies to deploy microreactors for soda ash mining

## *FUTURE*

- **Canada**
  - Saskatchewan Industrial and Mining Suppliers Association signs agreement with GE-Hitachi



**Flexible  
Electric Power**

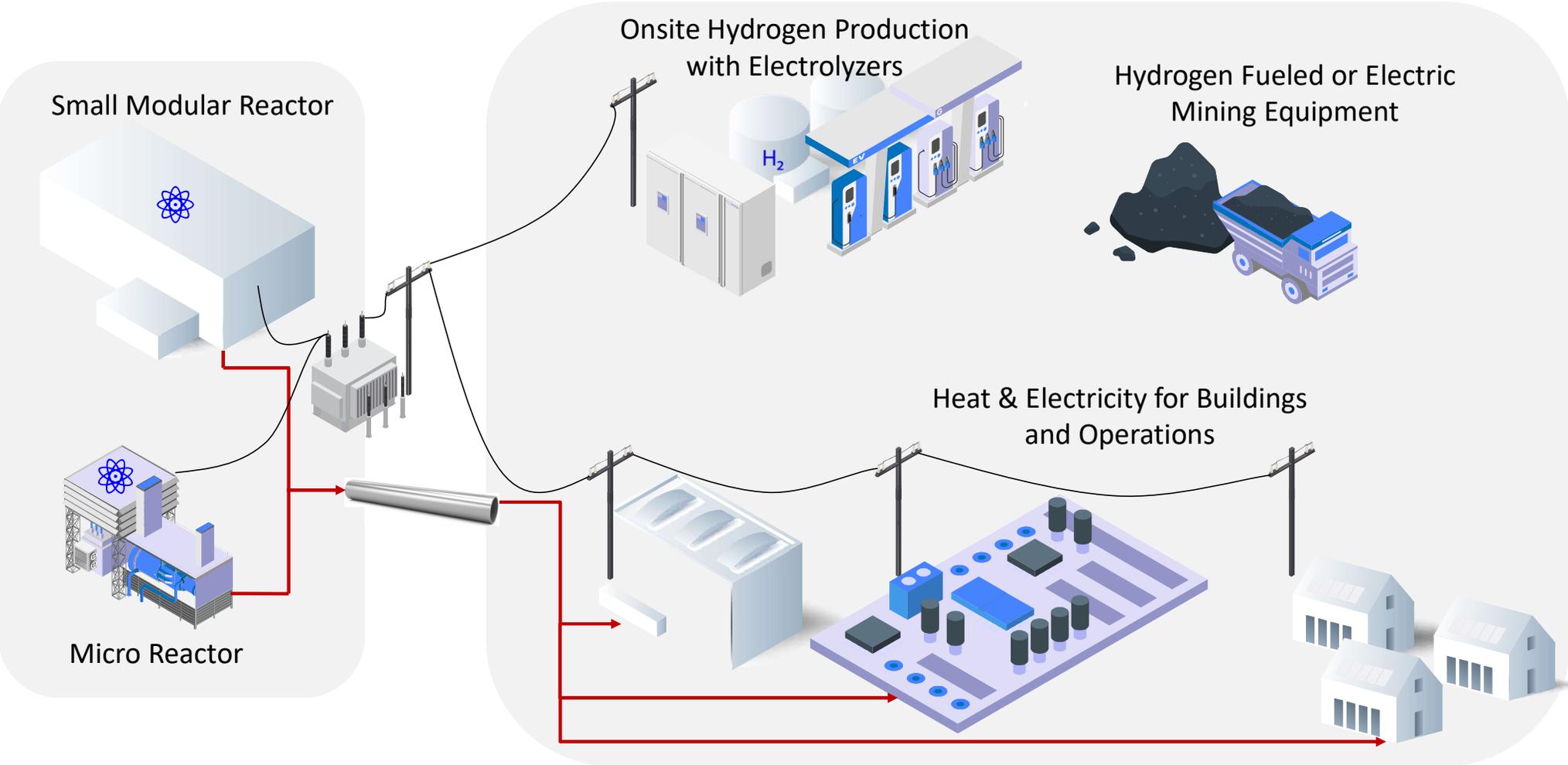


**Mining  
Operation**



**Heat for  
Structures**

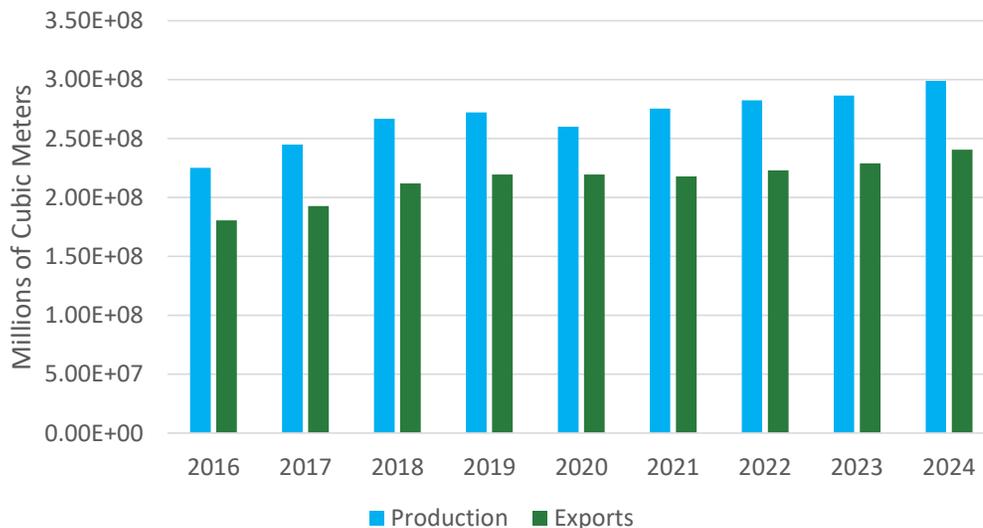
# Nuclear Integration Options for Mining Operations



# Canadian Applications – Oil Sands

## Energy Challenges

Canadian crude oil production increased in 2024 for the fourth consecutive year



Production and Exports of crude oil and equivalent products

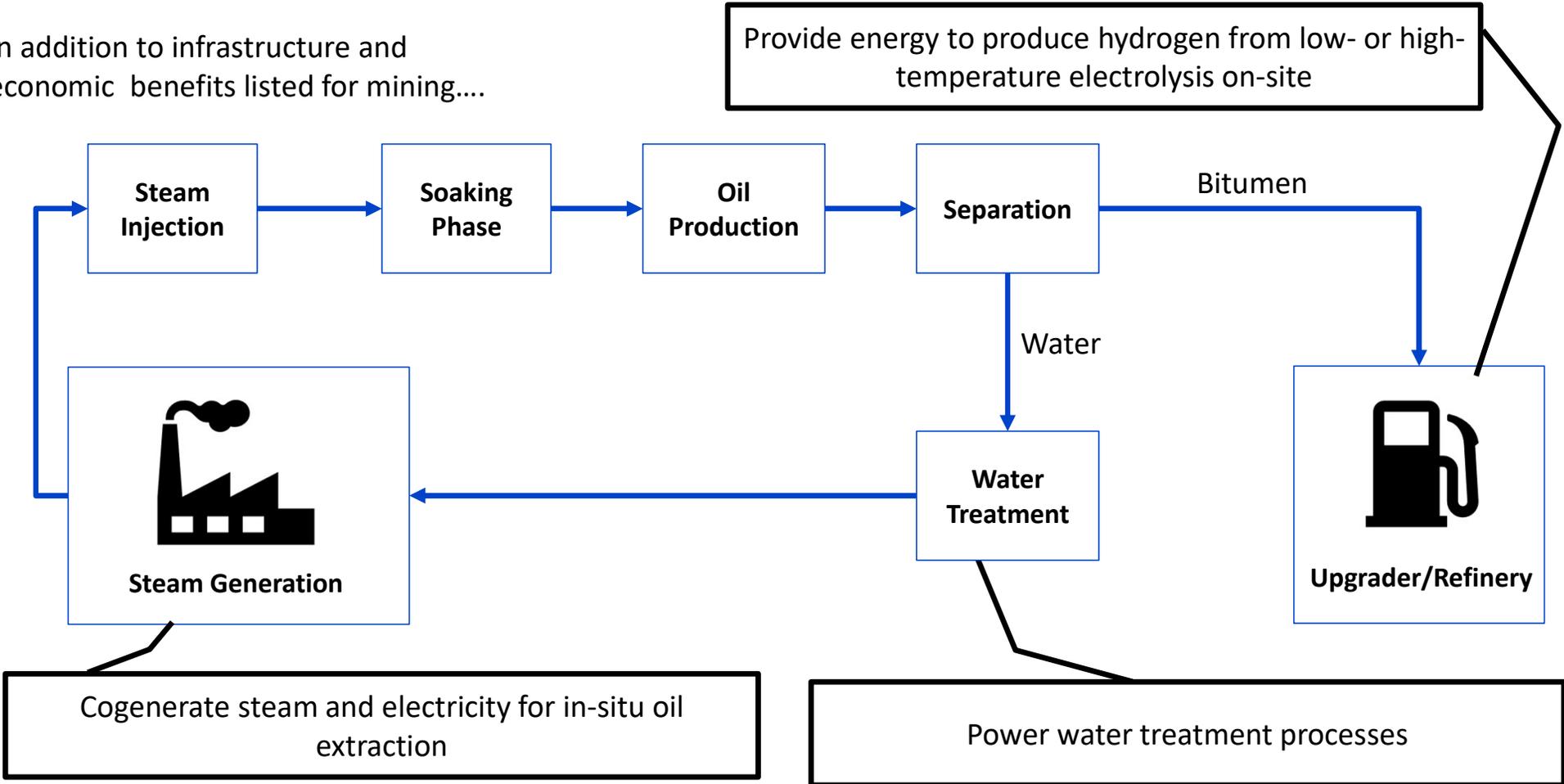
Data Source: Statistics Canada

- **Steam, electricity and hydrogen used on site for in-situ extraction (80% of reserves)**
- **Reliant on natural gas for steam and power, impacted by price fluctuation**
- Often located away from the main electric grid
- Sites are small and widely distributed
- Sites have high startup costs but long lifetimes at low operating costs, keeping the oil products cost competitive
- The oil and gas industry in Canada employs 446,000 people and **contributes billions of dollars to the federal government in taxes and royalties**

**Balance economic importance with environmental regulation**

# Nuclear Power Solutions

In addition to infrastructure and economic benefits listed for mining...





# Integration Example: Nuclear Hydrogen Production

# Reports on Nuclear Integrated Hydrogen Production

## ■ **Methods of Nuclear Integrated Hydrogen Production ([3002027703](#))**

The following nuclear integrated hydrogen production methods are addressed:

- Steam Methane Reforming
- Autothermal Reforming
- Biomass-Derived Liquid Reforming
- Partial Oxidation
- Coal & Biomass Gasification
- Methane Pyrolysis
- Chemical Looping Reforming
- Thermochemical Water-Splitting (S-I and Cu-Cl)

## ■ **Conceptual Design Guide for Developing a Nuclear-Integrated Hydrogen Facility ([3002026514](#))**

This guide provides general input and considerations for electrolyzer technology selection:

- PEM, Alkaline, SOEC
- Hydrogen plant design
- Nuclear plant integration design
- Overall project planning

# Technical Considerations for H2 production

## General Planning

### Technology Selection

Electrolytic

Gasification / Pyrolysis

Thermochemical

Footprint and Configuration

Stack / Component Degradation

Startup and Shutdown

Ramping Ability

Design Parameters

Performance Characteristics

### Site Selection Considerations

### Separation / Security Considerations

### Operational Concepts

## Hydrogen Plant Design

Hydrogen Systems

Cooling Systems

Water Systems

Building Requirements

Utility Gas Systems

Electrical Systems

Structural Requirements

## Nuclear Plant Integration

Thermal Extraction

Electrical Integration

Cooling Water Integration

Controls Integration

Safety Evaluations

## Project Planning

Schedule Development

Training

Codes and Standards

Maintenance

Construction

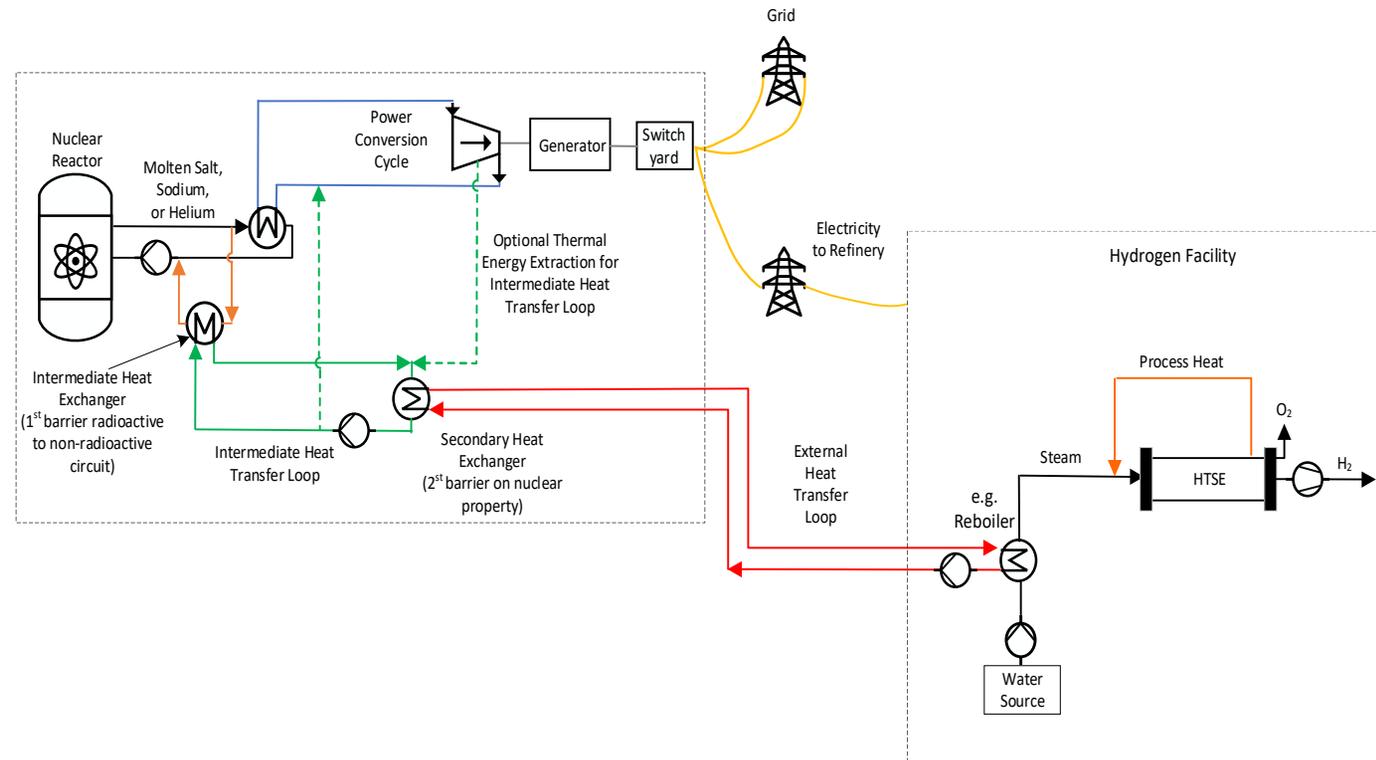
Licensing and Permitting

Procurement

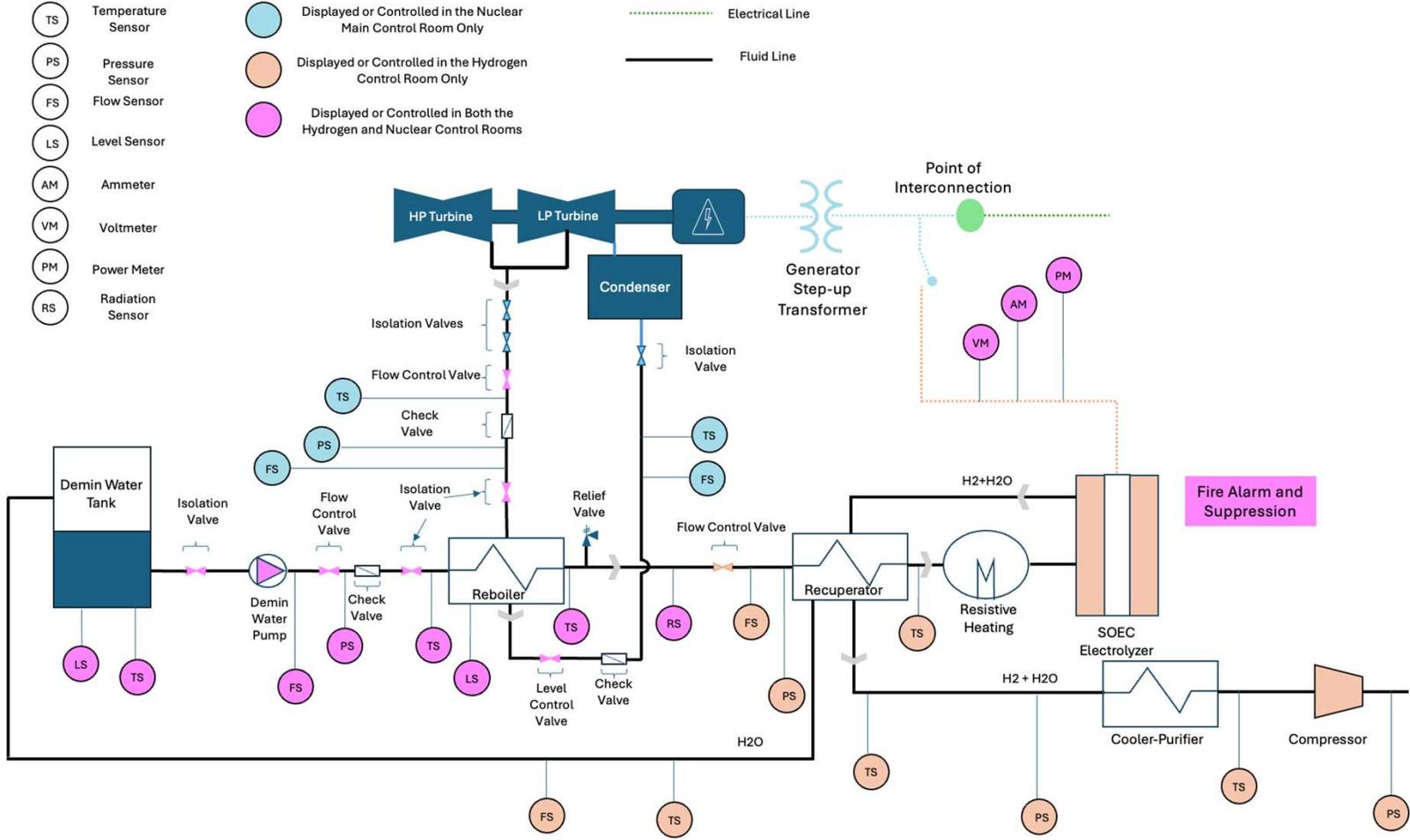
Engineering and Design

# Example SOEC Integration

- Solid Oxide Electrolyzer Cell (SOEC)** is a fuel cell that runs in regenerative mode to **separate water by using a solid oxide, electrolyte** to produce hydrogen and oxygen.
- Compared to Alkaline or PEM, SOEC uses steam as input.** The heat of vaporization increases efficiency by ~5 kWh/kg.
- 40-60% of the thermal demand can be provided by heat recovery from stack.**



# Example - SOEC Control Integration



Level of  
Integration.

# Safety Considerations – Accident Transients

## ■ Hydrogen Ignition Transients

- The Sandia National Laboratory created the software HyRAM+ (<https://hynam.sandia.gov/>) to access the hydrogen and other alternative fuels (e.g. methane and propane) leak risk and ignition consequences.
- The U.S. NRC Regulatory Guide 1.91 Rev 3, “*Evaluations of Explosions Postulated to occur at Nearby Facilities and on Transportation Routes Near Nuclear Power Plants,*” provides an acceptable method for establishing a safe distance where overpressures from explosions should not exceed 6.9 kPa (1 psi) on plant structures.

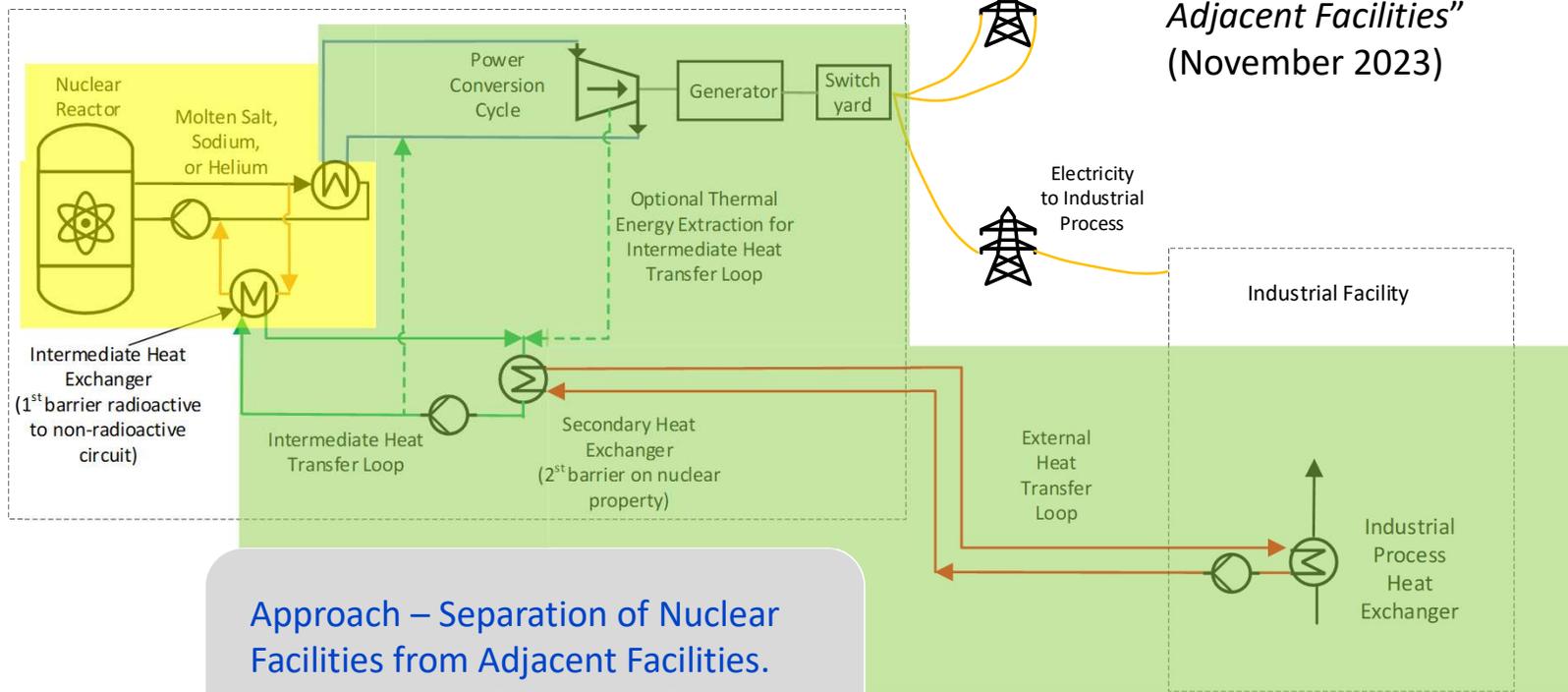


On January 8, 2007, a hydrogen explosion at the Muskingum River Power Plant’s 585-MW coal-fired supercritical Unit 5 caused one fatality, injuries to 10 other people, and significant damage to several buildings. *The explosion occurred during a routine delivery of hydrogen when a hydrogen relief device failed, which allowed the contents of the hydrogen tank to escape and be ignited by an unknown source.*

# Approach: Separation Nuclear from Adjacent Facilities

Key approach – separation of nuclear safety related and non-safety related equipment.

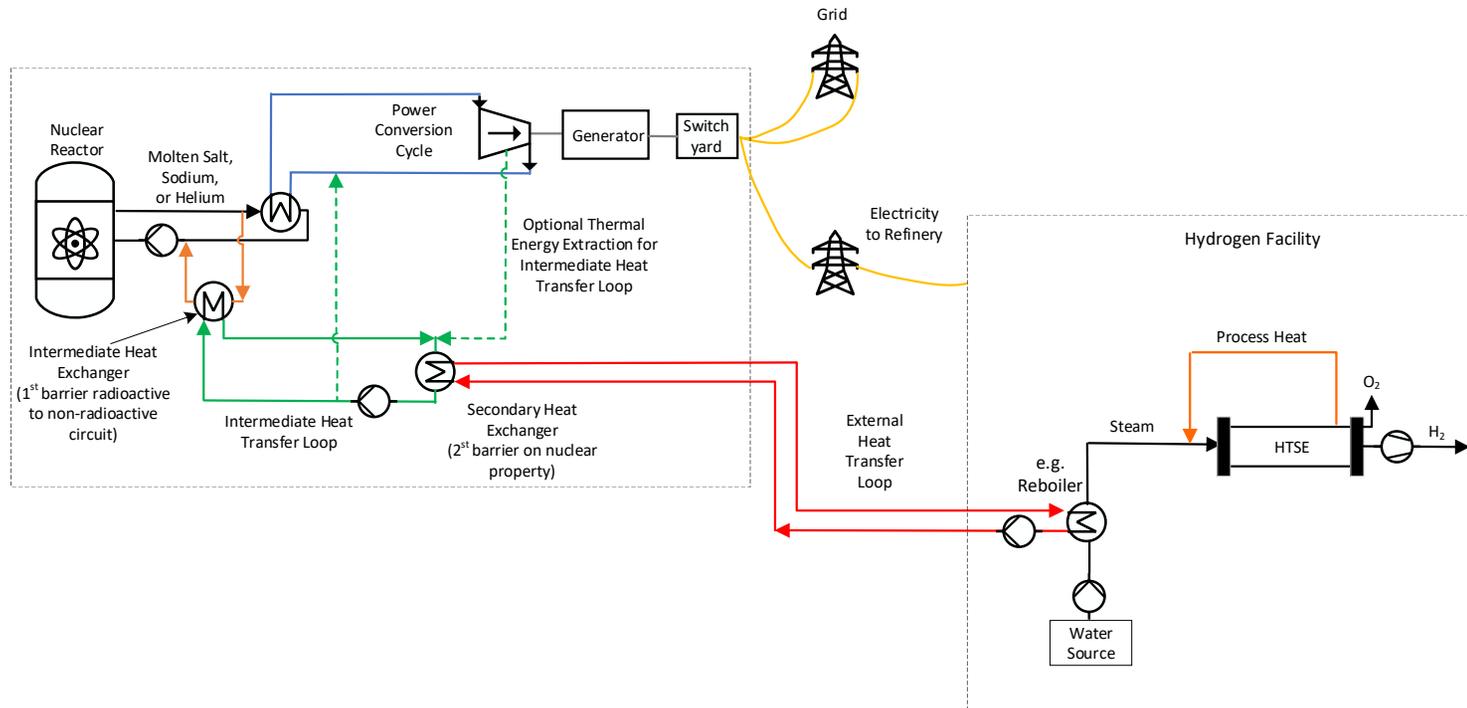
EPRI Report 3002026499  
“Technical Methodology to Demonstrate the Separation of Nuclear Facilities from Adjacent Facilities”  
(November 2023)



Approach – Separation of Nuclear Facilities from Adjacent Facilities.  
E.g. Commercial piping code

# Safety Considerations – Accident Transients

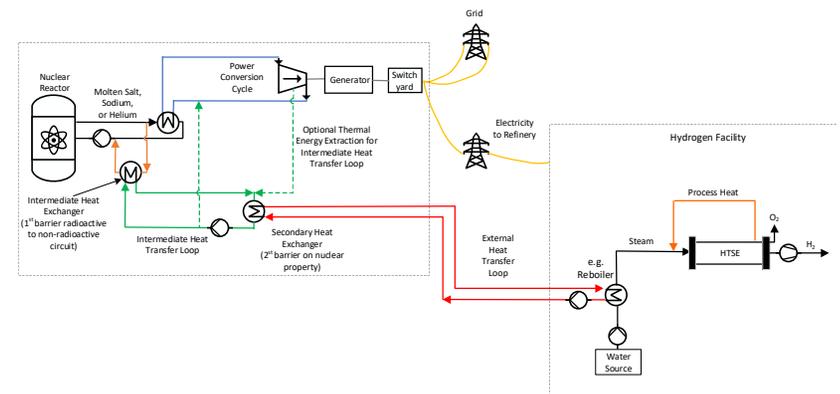
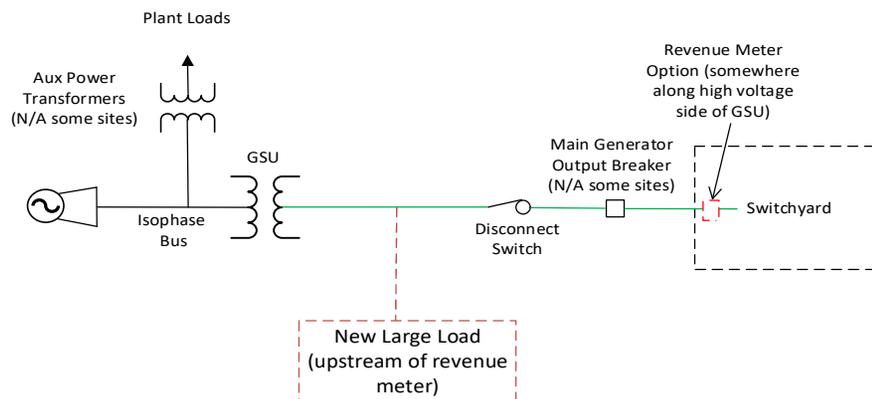
- **Process Heat Transfer Transients (for heat integration, e.g. SOEC)**
  - A **heat rejection** from the hydrogen facility might impact the **power conversation cycle** that can lead to a **cascading effect**.



# Safety Considerations – Accident Transients

## ■ Electrical Transients

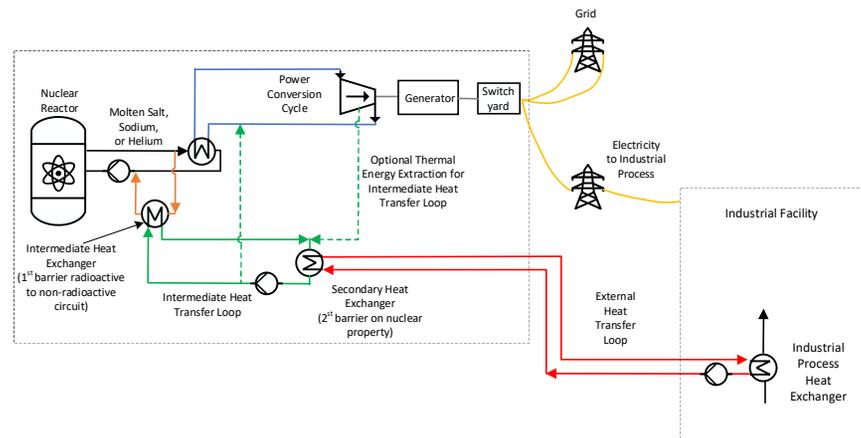
- **Load rejection** from the hydrogen facility (e.g. electrolyzer stacks) when directly connected behind plant generator (behind the revenue meter).
- A rejection of a large electrical load must be evaluated to **assess the impact on the plant generator and other electrical transmission systems** and components regarding **stability, short circuit, load flow, harmonics, and protective devices**.
- The **design** of the electrical system **must account for these transients to prevent a trip of the NPP**.



# Safety Considerations – Accident Transients

## ■ Cross Contamination Transients

- **Radioactive cross-contamination** is considered a transient where radioactivity (e.g. **Tritium**) is unintentionally transferred from a radioactive system to a non-radioactive system (e.g. heat exchanger tube leakage).
- **Multiple barriers of isolation reduce the risk of cross-contamination**, such as **multiple heat exchanger barriers**. Additionally **online radiation detectors** can be used to provide monitoring for radiation to limit any potential nuclear cross-contamination to the protected or owner-controlled area.





# Nuclear Beyond Electricity Research Projects

# Options for Delivery of High Temperature Heat from Nuclear Power Plants (300203224)

## Background:

- Nuclear power plant siting requirements may **restrict colocation** with an existing industrial facility, requiring **high temperature fluids to be transported over long distances**
- High temperature **heat requirements of industrial facilities** may be difficult to meet depending on the transport distance

## Objective:

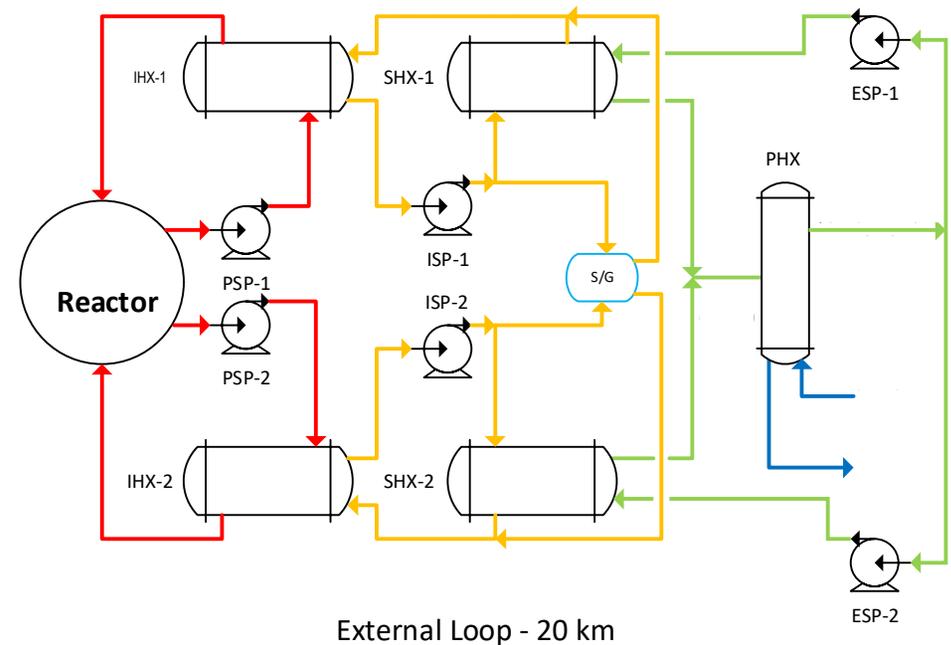
- Determine the heat delivery conditions from various nuclear reactor types and plant arrangements for distances of **2.5 km, 5 km, 10 km, and 20 km between the NPP and industrial facility**
- Investigate the **impact of different heat transfer fluids** in the primary, secondary, and external loop.
- Calculate rough order of magnitude equipment costs (pumps, heat exchangers) for the various arrangements and fluid combinations

## Value:

- Quantifying the impact of distance on cost and heat quality will **inform siting assessments**
- **Demonstrates the feasibility** of transporting high temperature heat over up to 20 km distance
- Informs future **levelized cost of heat** calculations

# Options for Delivery of High Temperature Heat from Nuclear Power Plants (3002032244)

- **Temperature drops are approx. 25-100°C over 20 km piping distance.**
- Lowest temperature loss with molten salt
- Highest temperatures can be delivered with HTGR and MS reactors
- **Steam can be delivered at 386 °C over 20 km (with initial steam lift to 500°C )**
- Cost of pumping power and specialized equipment are barriers to molten salt and helium use



# Methods for Increasing Nuclear Steam Temperature (3002032186)

## Background:

- Technology selection or distance may **impact the temperature of steam delivery**
- A single reactor may provide heat to **multiple facilities with different requirements**

## Objective:

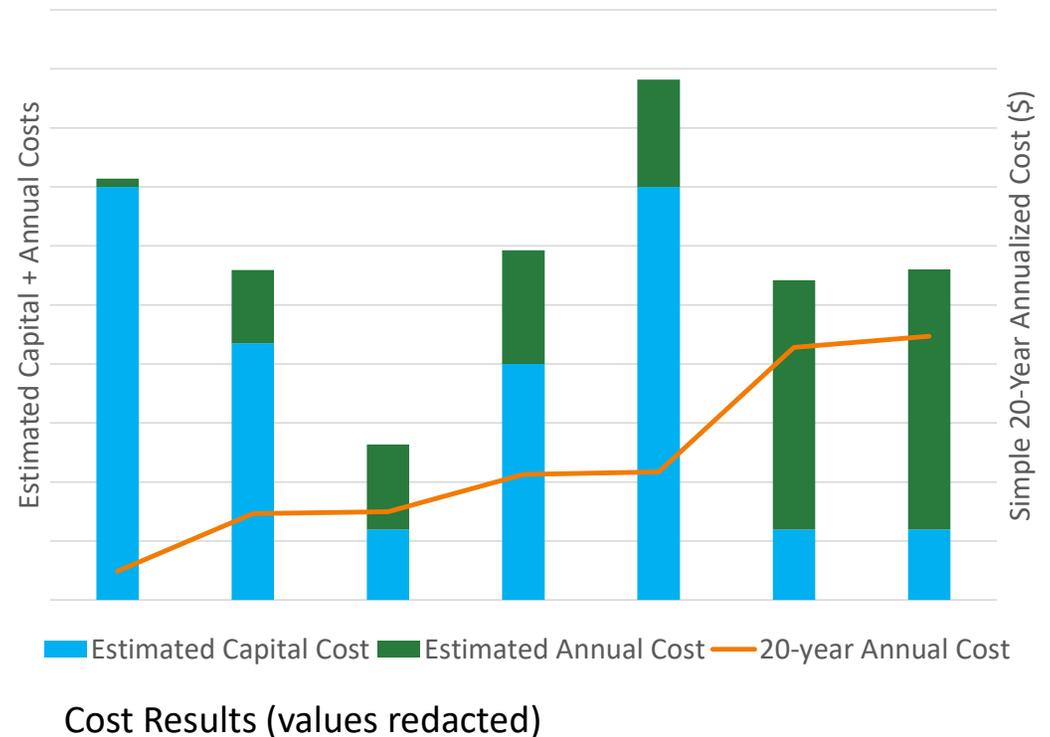
- Evaluate **existing and novel pathways to lift steam temperature** for industrial applications.
- Evaluate Industrial Boilers, Electric Heating, (Very) High Temperature Heat Pumps, Adiabatic Compression
- Consider technology TRL, floorspace, integration effort, and cost.

## Value:

- Provide industrial stakeholders with **flexibility to utilize nuclear power**
- Identify opportunities for technology development

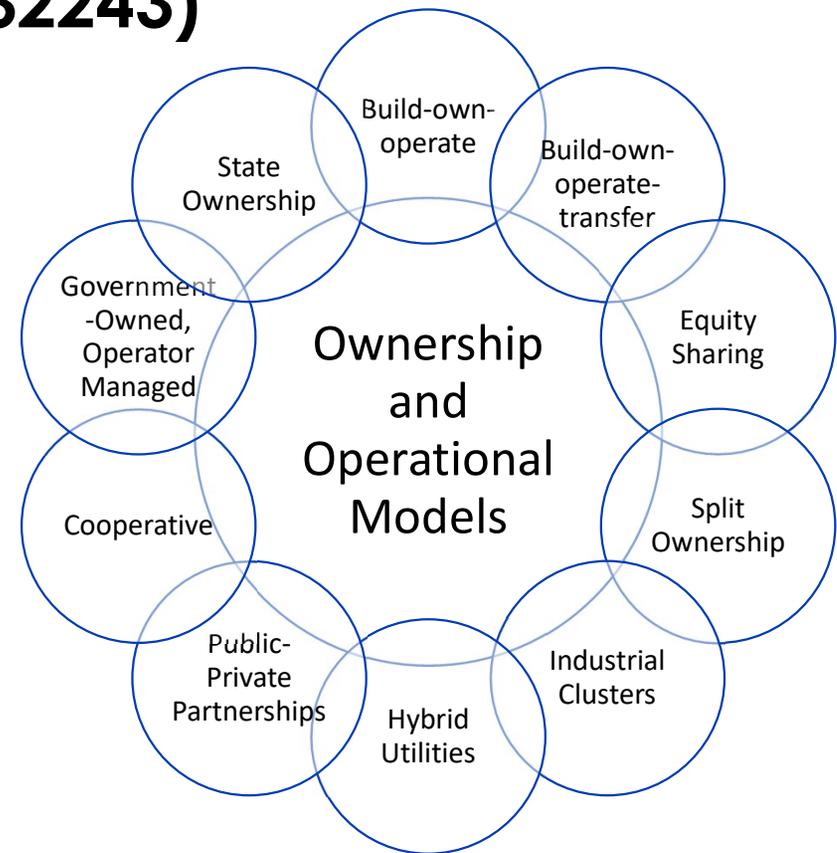
# Methods for Increasing Nuclear Steam Temperature (3002032186)

- Industrial boilers are the most readily available technology
- Adiabatic compression (steam-powered) and very high temperature heat pumps are cost effective options, but require further development
- Combinations of technologies may be more suitable



# Ownership and Operational Models for Nuclear Beyond Electricity Applications (3002032243)

- Describes financing models and ownership models for NPPs
  - Types of models and examples
  - Key contract elements and participants
  - Division of responsibilities
- Includes decision tree to select models
- NBE ownership and operational models continue to evolve, and we need to track the success of innovative models



## Examples of Upcoming Projects

### Probabilistic Risk Assessment of Colocated Nuclear Power Plants with Industrial Facilities

#### Purpose and Scope:

- **Assess new events or hazards that are introduced by collocating NPPs with industrial facilities** (e.g., petrochemical or large electrical consumers)
- Build off existing reports, **add unaccounted transients and expand to larger industries.**
- Determine if **new events change the magnitude, frequency, or consequences of accident scenarios.**
- **Recommend technical and operational solutions to properly model and mitigate potential changes** in accident frequencies and consequences.
- Results can **provide a framework for regulators to make decisions based on realistic risks to a nuclear plant.**

### Conceptual Guide for Nuclear Integration with a Chemical Plant

#### Purpose and Scope:

- Explore the integration of a nuclear reactor with a chemical plant to **provide carbon free heat and electricity.**
- Leverage **Aspen process modeling for component sizing.**
- Provide considerations for **nuclear site selection, physical separation between the NPP and the chemical plant, electrical integration, I&C integration, accident transients, physical and cyber security, licensing & regulatory, and project planning**
- Perform **technoeconomic analysis to support business case.**

## Examples of Upcoming Projects

### Siting Tool for Energy System Integration

#### Purpose and Scope:

- Develop a **state-of-art, user friendly tool, for site screening to support nuclear colocation and deployments.**
- Accessible **interactive siting tools and data visualization tools will become increasingly important as non-nuclear industry players enter the market.**
- **Tool will include EPRI research data, results, and methodologies in combination with public geographic information system (GIS) data, plus industry specific data layers.**
- **Incorporate an AI framework.**

### Develop Industry Standard for Levelized Cost of Heat

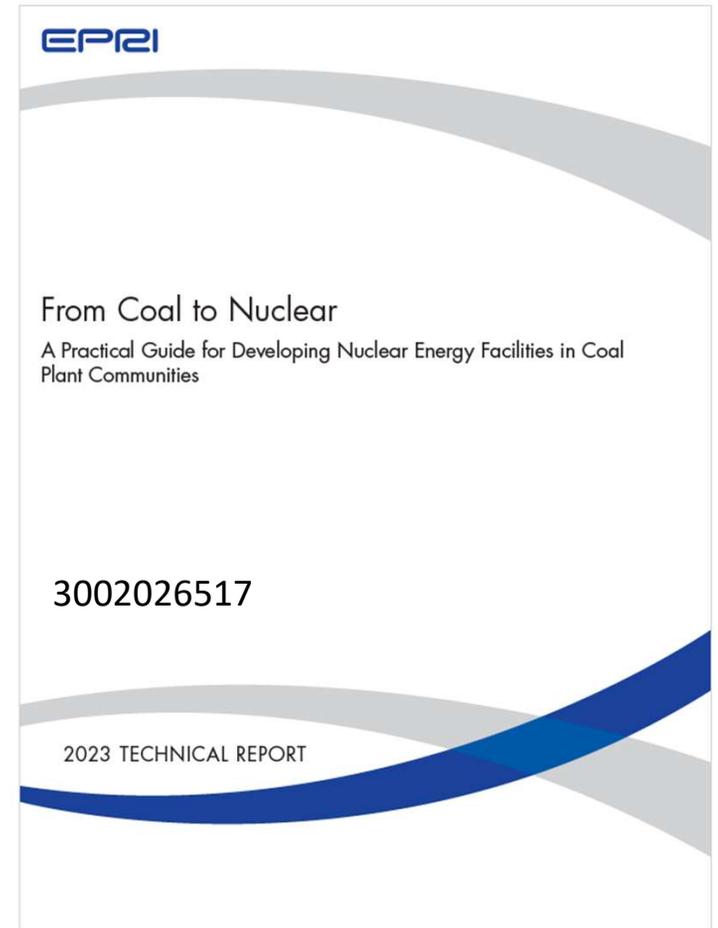
#### Purpose and Scope:

- There is **no standardized way to calculate the value of the heat produced by the power plant and the cost to transport it to the end user.**
- **Difficult to compare the cost of nuclear energy to other conventional heat generating technologies** (such as other fossil fuel boilers).
- **Develop a methodology for calculating the levelized cost of heat including considerations such as distance between the plant and the end user, heat quality, and heat quantity.**
- Perform a **sensitivity analysis to estimate the impacts of each variable** on the final cost.

**We are leveraging the depths of EPRI and our Collaboration Partners**

# From Coal to Nuclear

- The report provides a practical guidance **for the future deployment of a nuclear energy facility on or near an existing coal plant site.**
- Benefits:
  - **Reuse of water use and environmental permits, land, transportation and transmission infrastructure systems.**
  - **Reuse of existing buildings, e.g. warehouse and administrative buildings**
  - **Repurposing of available workforce (leverage existing skilled labor, e.g. technicians)**



**Results in potentially lower cost and faster deployment**

# What do you think is missing?

What Research Gaps and Roadblocks can you think of regarding Nuclear Heat Integration under the following areas?



## Upcoming Event...

### EPRI's Annual Nuclear Energy for Industrial Applications Workshop

**Target: Early October in Texas, USA**



This event will again bring **leading companies from the oil and gas, petrochemicals, and manufacturing sectors together with nuclear designers, utilities, regulators, architectural engineering firms, government representatives, and EPRI subject matter experts** to exchange insights and advance collaboration on nuclear integration with data center.



**Thank you for your  
participation**

**Any questions?**

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The EPRI logo is displayed in a bold, blue, sans-serif font. The letters 'E', 'P', and 'R' are connected, and the 'I' is separate. The background of the slide is a dense grid of small, semi-transparent portraits of diverse people, with a dark blue gradient at the top and bottom.

**TOGETHER...SHAPING THE FUTURE OF ENERGY®**

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