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Nuclear-Renewable-Storage Systems: Enhancing Planning and Operations of Integrated Energy Systems

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Changing the World's Energy Future

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Idaho National Laboratory

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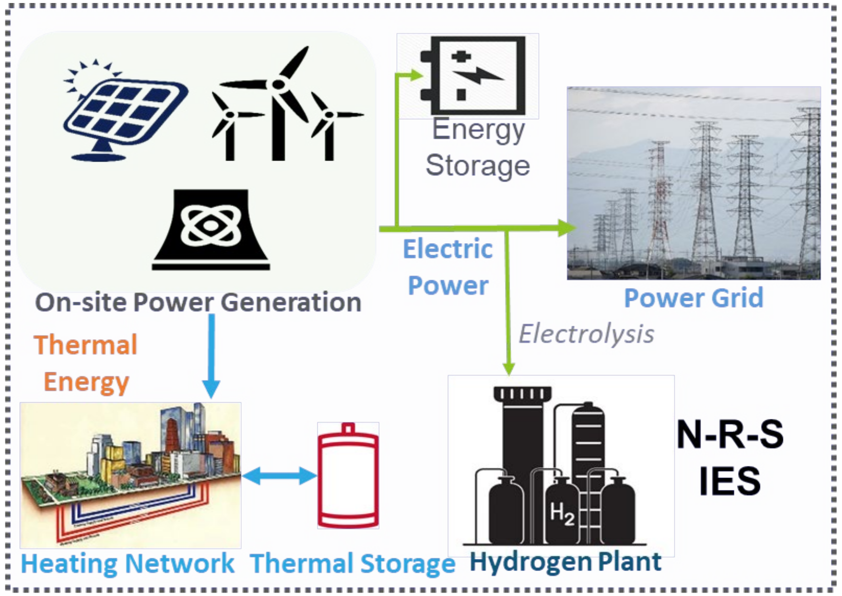
Background

- Goal: Improve system **economy**, **security**, and **reliability** of Nuclear-Renewable-Storage Integrated Energy Systems (N-R-S IES)
- Motivation
  - The U.S. is transiting to **carbon neutral**
  - Economy-wide decarbonization must consider **hard-to-decarbonize sectors** (e.g, industrial, transportation)
  - IES can provide low-carbon alternatives towards net-zero economy
- Innovation
  - Integrated **high-fidelity physics model** to inform the operation of IES
  - Develop **a multi-carrier IES operations model** to enable economic dispatch

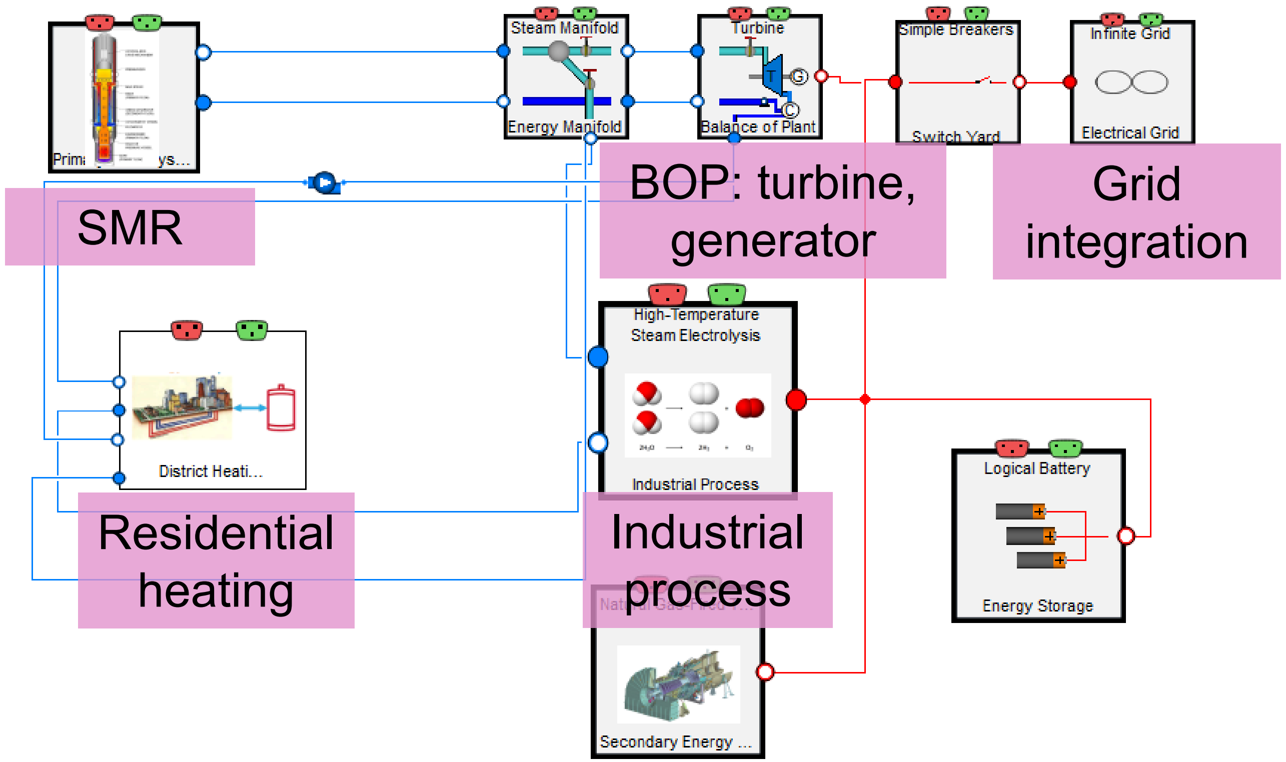


<u>Why N-R-S IES?</u>

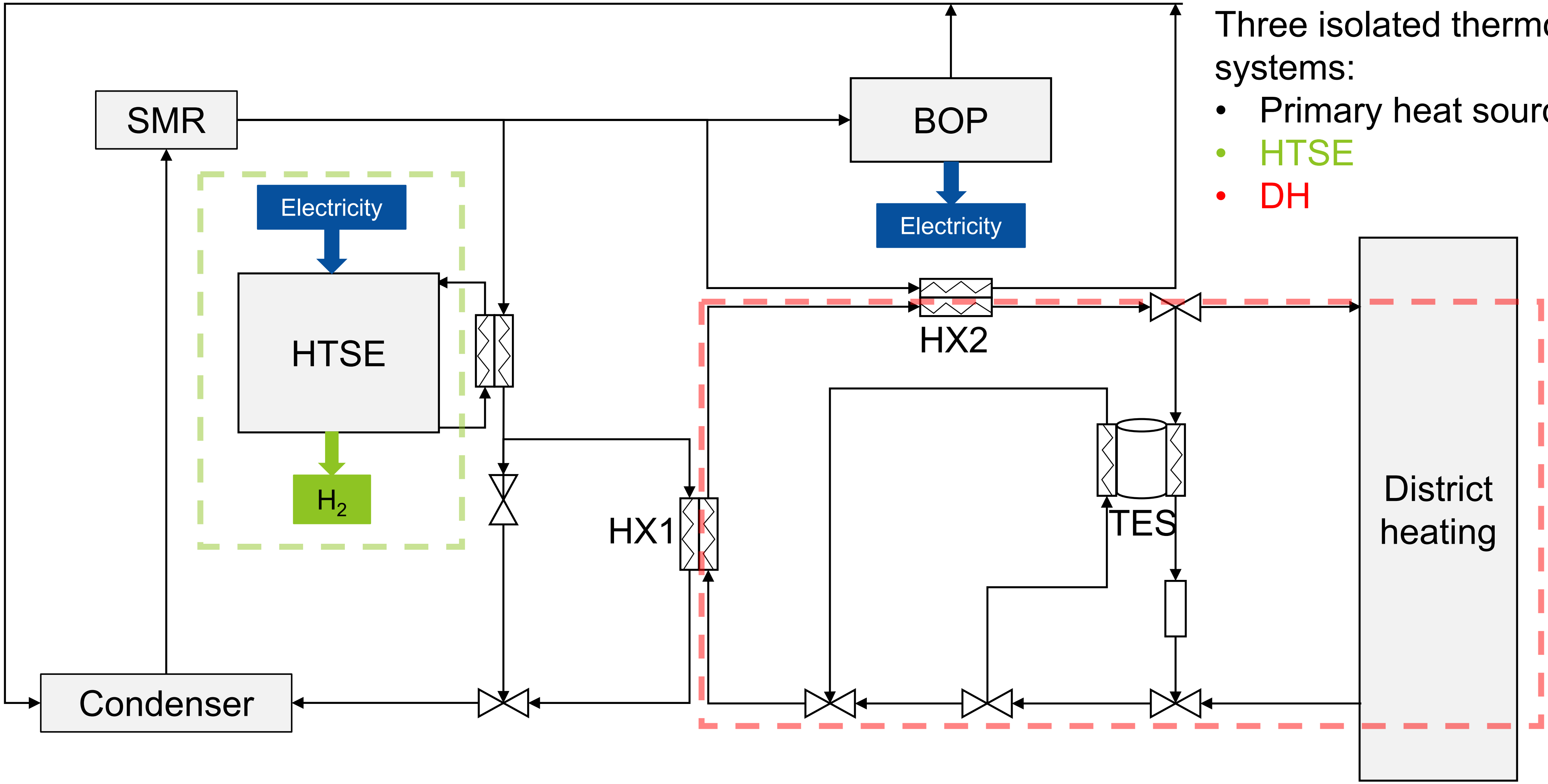
- Electricity and heat → **Multi-carrier** energy system
- Nuclear → Carbon-free **baseload**
- Renewable + short-term storage → flexible **peaking** capability

Overview: integrated energy systems (IES)

- Represented by high-fidelity physics model
- Based on an INL-developed repository, HYBRID
  - Developed in Dymola, a Modelica environment
  - Built on other open-source repositories, e.g., TRANSFORM



The modeled system: Overview

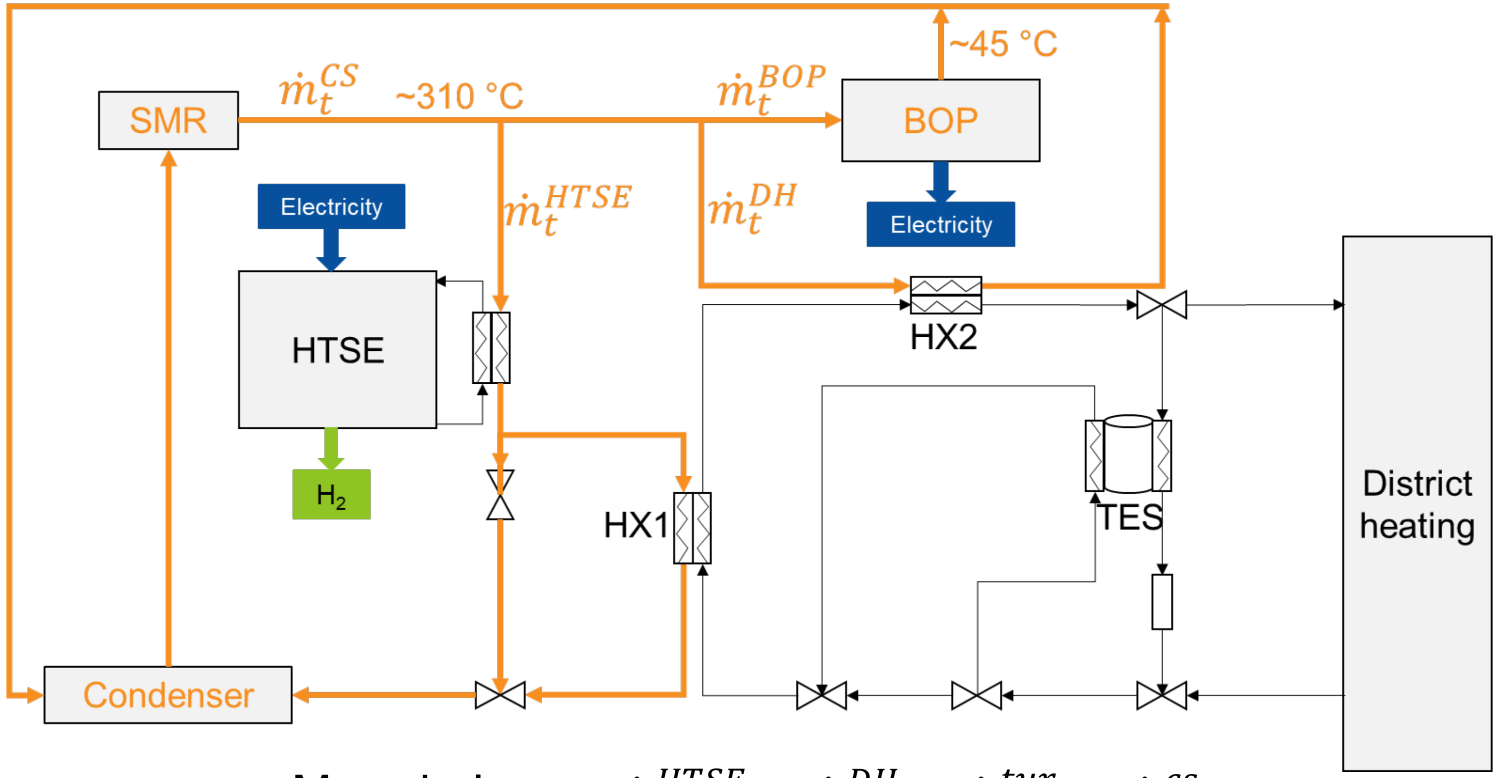


Three isolated thermodynamic systems:

- Primary heat source & BOP
- HTSE
- DH

The modeled system: Primary heat source and BOP

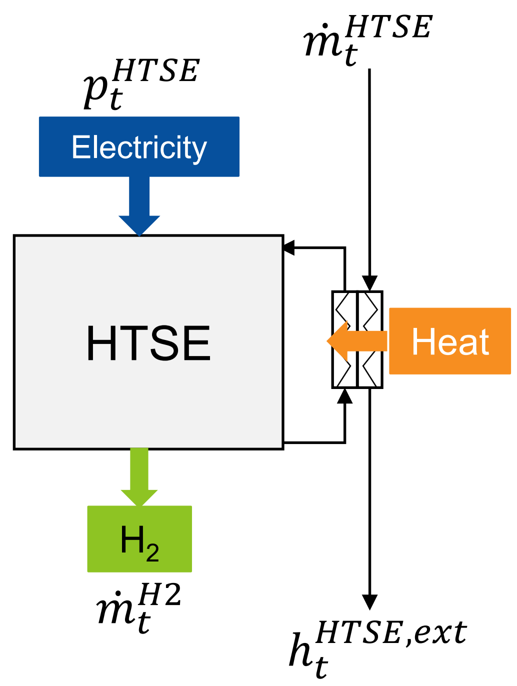
- Small modular reactor (SMR) provides heat to down stream processes:
  - Balance of plant (steam turbine)
  - Hydrogen production (HTSE)
  - District heating
- SMR operated constantly at rated capacity
  - Rated capacity: 200 MWth
  - Steam temperature: 310 °C
  - Steam rate: $\dot{m}^{cs} = 84$ kg/s
  - Enthalpy: $h^{cs} = 3011$ J/kg·K
- BOP: Rankine cycle steam turbine
  - Rated capacity: 60 MWe

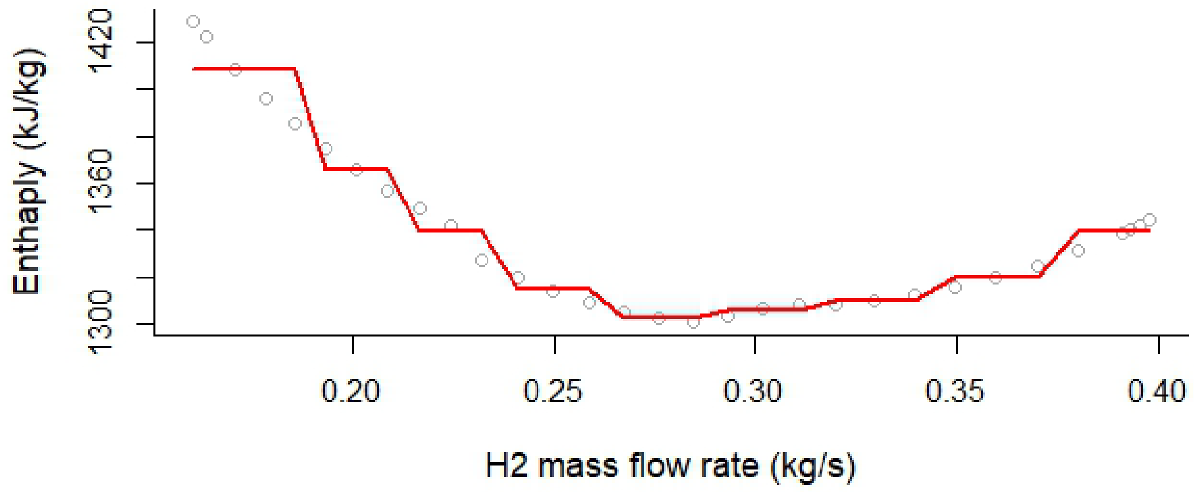


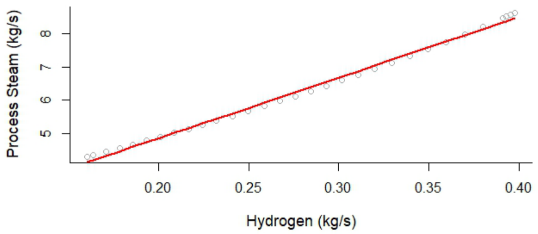
Mass balance: $\dot{m}_t^{HTSE} + \dot{m}_t^{DH} + \dot{m}_t^{tur} \leq \dot{m}^{cs}$

The modeled system: Hydrogen production (industrial)

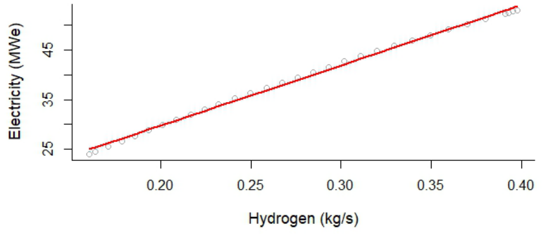
- High temperature steam electrolysis (HTSE)
  - Split high-temperature steam (~850 °C) into H_2 /O_2 via electrolyzing
  - SMR exhaust (~310 °C) to preheat, electric heater to provide additional heat
  - Rated capacity: 0.4 kg/s
- Linearization
  - Heat/electricity demand linearly related to H_2 flow rate ($\dot{m}_t^{H2}$)
  - Piecewise linear representation of exhaust enthalpy ($h_t^{HTSE,ext}$)







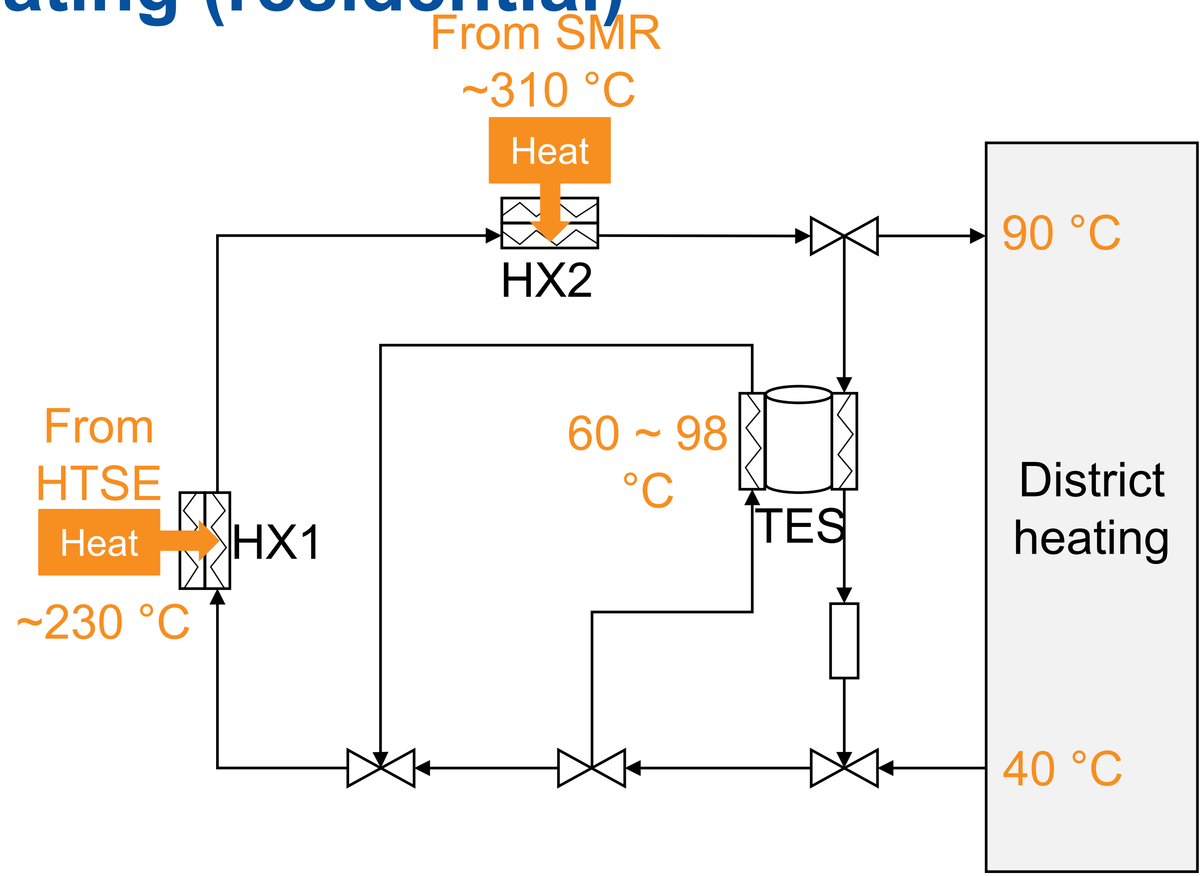
Heat demand vs. H_2 production rate



Electric demand vs. H_2 production rate

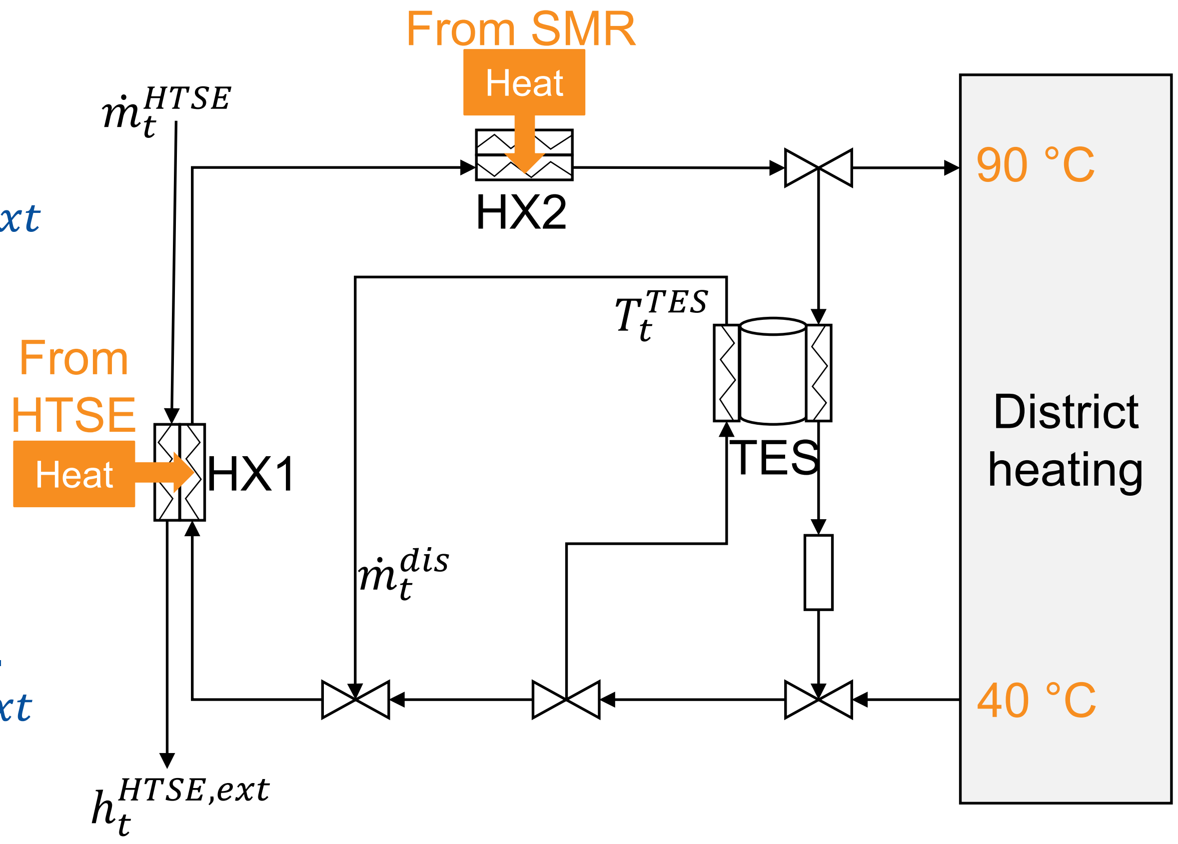
The modeled system: District heating (residential)

- Adopt a cascade heating design to maximize system efficiency
  - Heat from HTSE exhaust (via HX1)
  - Heat from SMR (via HX2)
- TES store excess heat and dispatch when in short



The modeled system: District heating (residential)

- Decision variables:
  - Specific enthalpy of HTSE exhaust: $h_t^{HTSE,ext}$
  - Mass flow of HTSE exhaust: $\dot{m}_t^{HTSE}$
  - Charge mass flow: $\dot{m}_t^{char}$
  - Discharge mass flow: $\dot{m}_t^{dis}$
  - TES temperature: T_t^{TES}
- Non-linear terms, product of two variables, e.g.
  - Enthalpy of HTSE exhaust: $\dot{m}_t^{HTSE} \cdot h_t^{HTSE,ext}$
  - Heat from TES discharge: $\dot{m}_t^{dis} \cdot T_t^{TES}$



Linearization of product of two variables

- Linearize non-linear products by discretization
- To linearize $x \cdot y$

$$x \cdot y = \left(\sum_i x_i \cdot \lambda_i\right) \cdot y = \sum_i x_i \cdot z_i$$

$$x = \sum_i x_i$$

$$\sum_i \lambda_i = 1, \lambda \in \{0,1\}$$

$$y^{min} \cdot \lambda_i \leq z_i \leq y^{max} \cdot \lambda_i$$

- Apply this method to all product terms

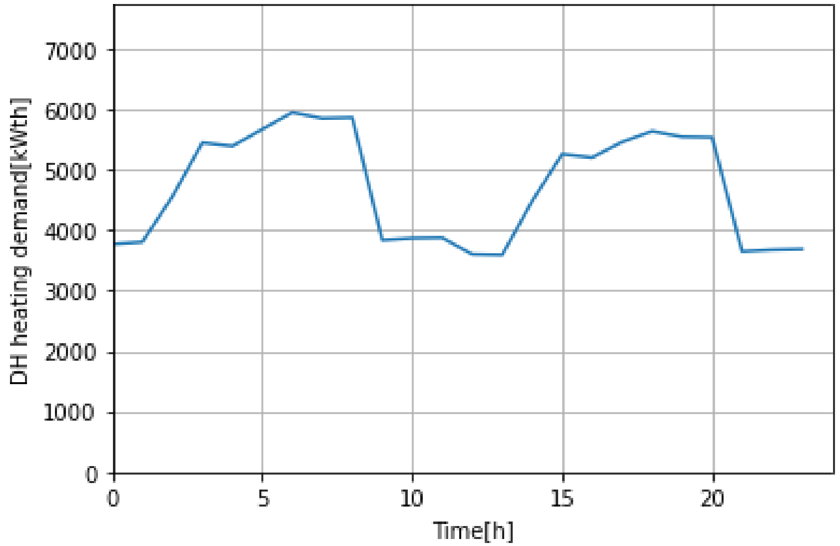
Model formulation: The complete form

- Objective function

$$\max: \sum_t \left(\underbrace{\pi_{1,t} p_{s,t}}_{\text{Electricity sales}} - \underbrace{\pi_{2,t} p_{b,t}}_{\text{Electricity purchase}} + \underbrace{\pi_{3,t}\, \dot{m}_t^{H2}}_{H_2 \text{ sales}}\right)$$

$$s.t. \text{ (operations constraints)}$$

- Parameters
  - Simulate a 24-h heat demand profile
  - Constant prices
    - H_2 ($\pi_{3,t}$): \$6/kg
    - Electricity sales ($\pi_{1,t}$): \$0.039/kWh
    - Electricity purchase ($\pi_{2,t}$): \$0.08/kWh
- Implemented in Pyomo and solved with CPLEX.

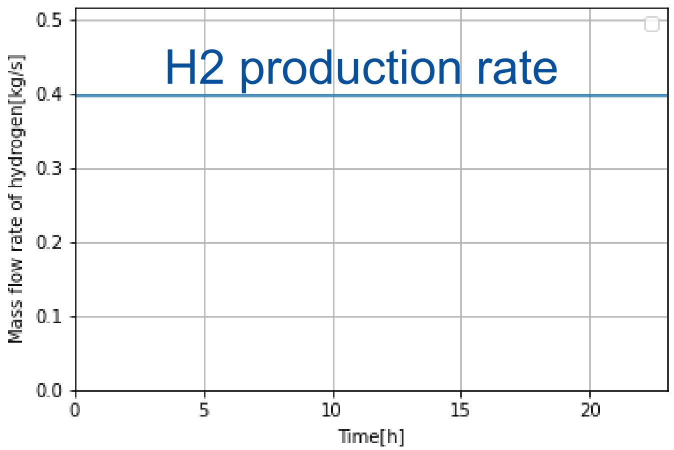


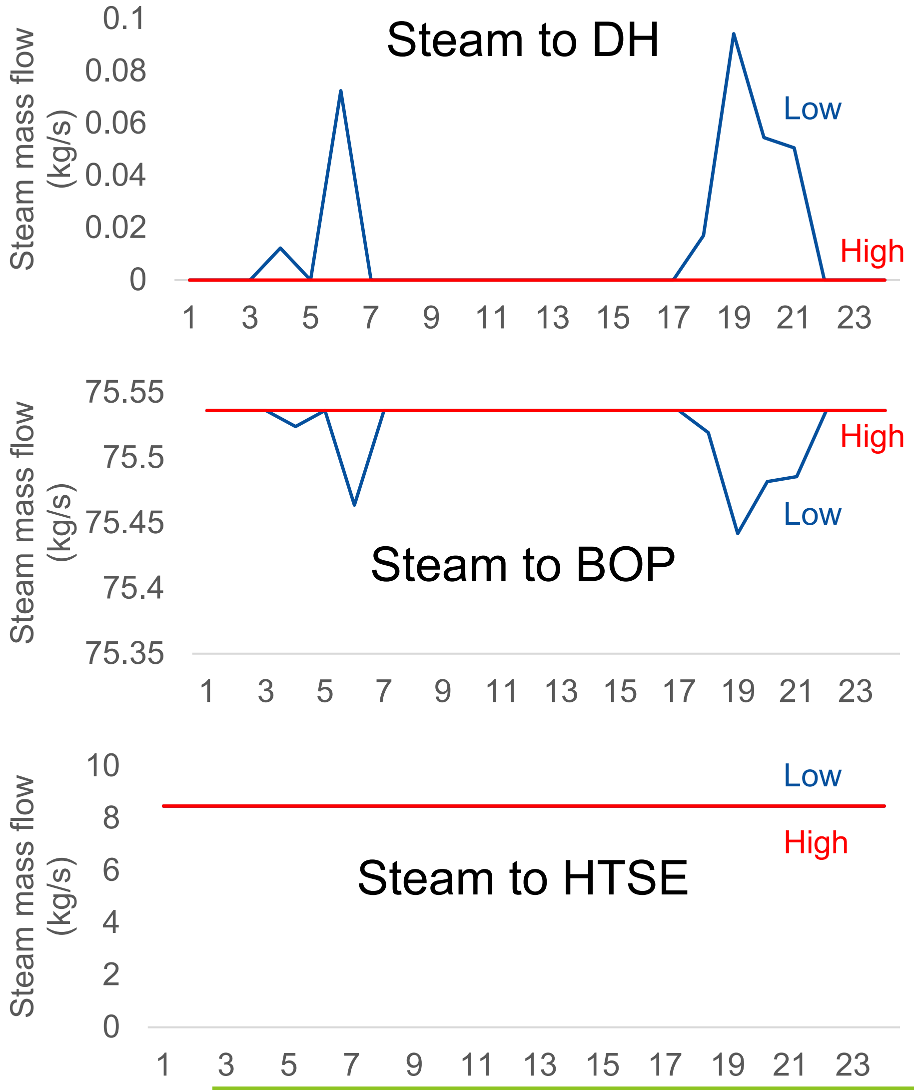
24-h heat demand profile

Source: B. Poudel et al., “Design, Modeling and Simulation of Nuclear-Powered Integrated Energy,” Journal of Renewable and Sustainable Energy, 2023. (in press)

Case studies: Steam dispatch

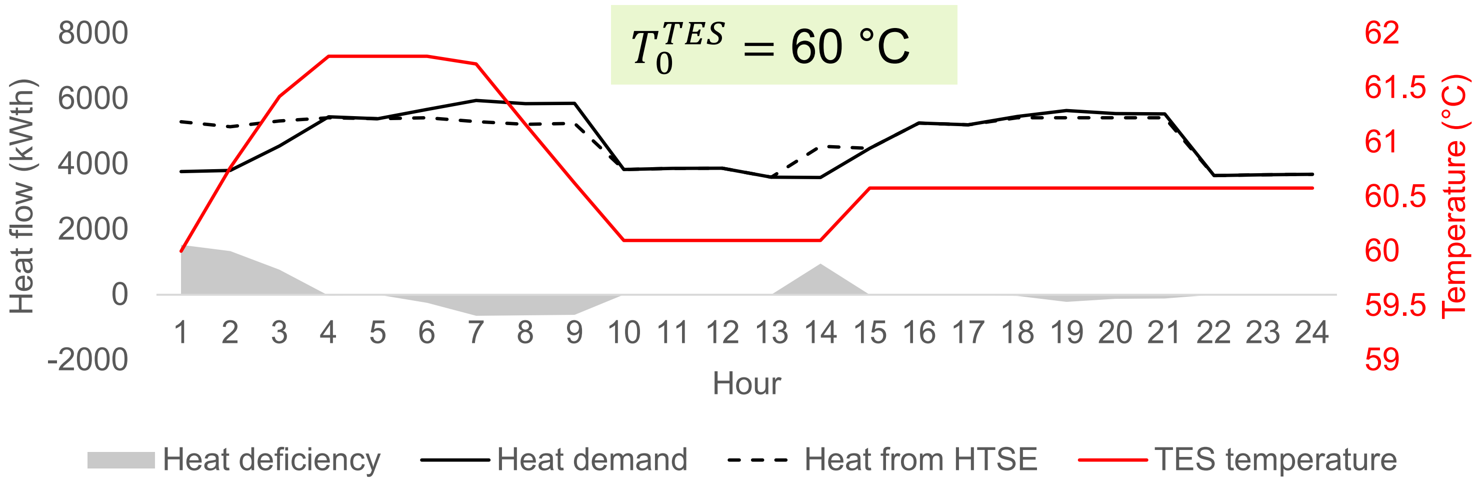
- Examine two cases
  - Low TES initial temperature (T_0^{TES}) : 60 °C
  - High TES initial temperature (T_0^{TES}) : 98 °C
- Steam dispatched to HTSE is constant in both cases, H_2 production is maximized
- No steam is wasted (i.e., all steam goes to H_2 production, DH, or BOP)

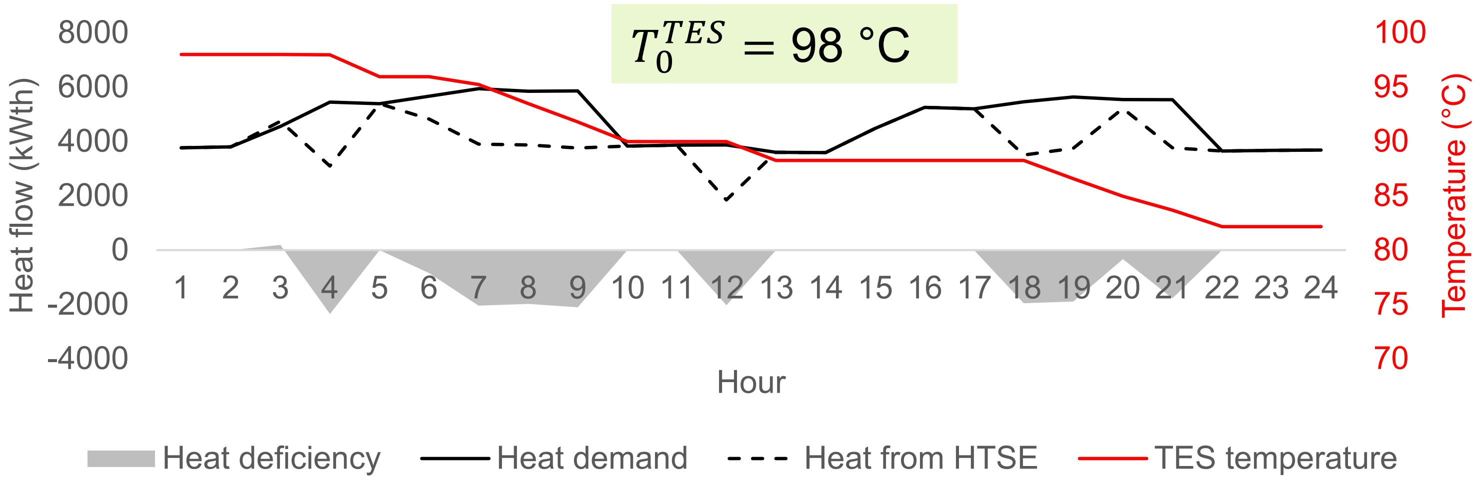




Case studies: Sensitivity to initial TES temperature

- The high case makes slightly more profit than the low case
  - Low: $194,966
  - High: $194,974
- Lower T_0^{TES}, more steam is diverted to DH
- Higher T_0^{TES} case does not need additional SMR steam to meet DH heat demand





Discussion

- Summary
  - Physics model to inform operational characteristics of IES
  - Develop linearized economic dispatch model of IES

- Future works
  - Fine-tune the model to better represent physical systems
  - More heat application designs
  - Uncertainties: renewable energy, electricity/hydrogen prices, demand
  - Apply reinforcement learning-based control to optimize the dispatch under uncertainties

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