IES

Integrated Energy Systems

Pumped Heat and Thermal Energy Storage Solutions for Future Nuclear Systems

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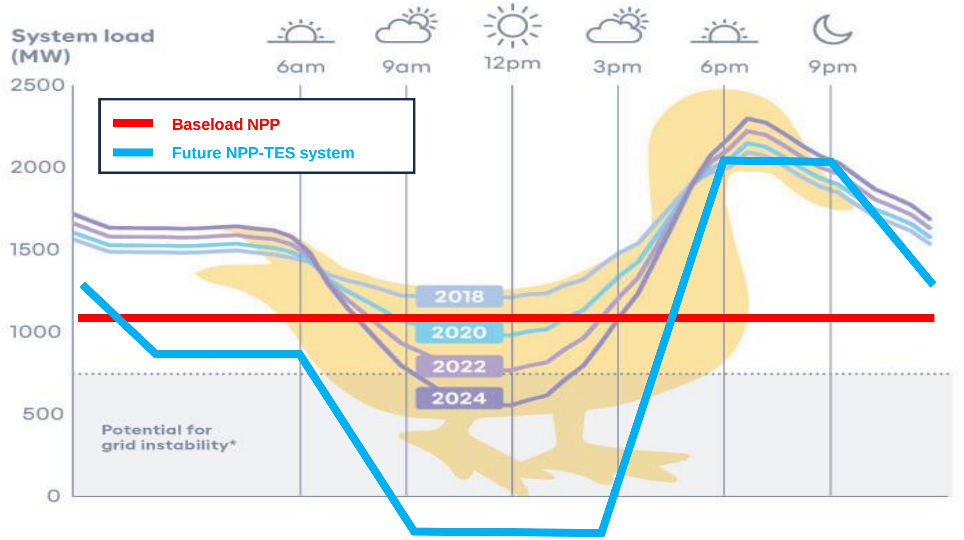
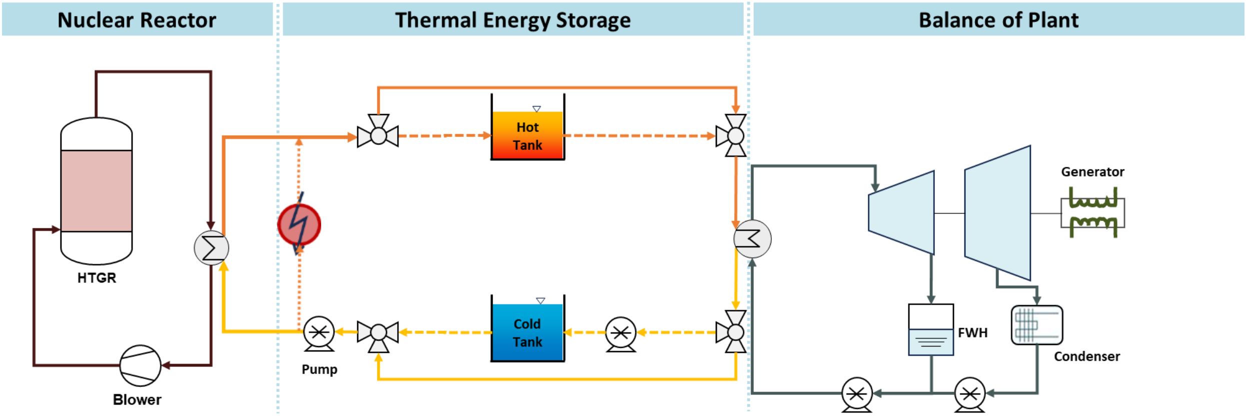
Past and Future Role of Nuclear Energy

Duck curve – system load changes in a day* and power supply from nuclear energy (past and future)



- **In the past…**
  - Nuclear energy functioned reliably to provide a constant baseload
  - Fossil and hydro energy were responsible for fluctuations in energy demand
- **In the future, NPP-TES system can contribute to…**
  - Flexible load following complementing renewable production
  - Low-carbon backbone of grid supply in prolonged deficit of renewables
  - Flexible combined heat and power supply

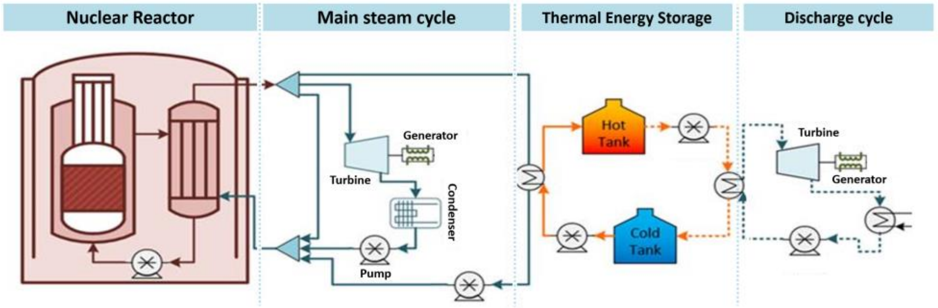
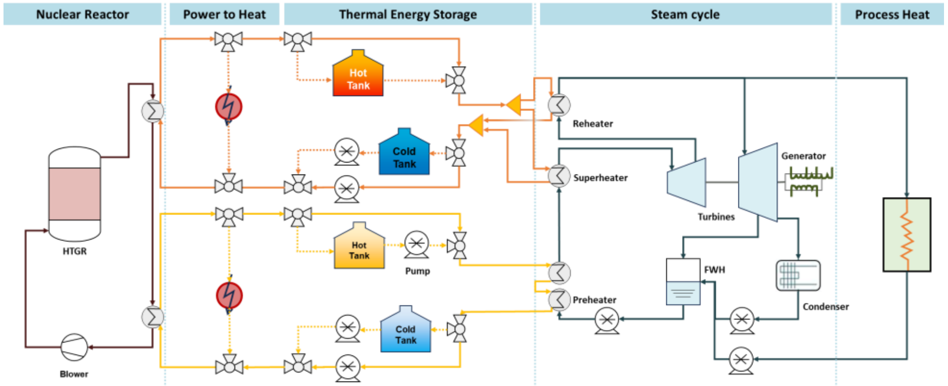
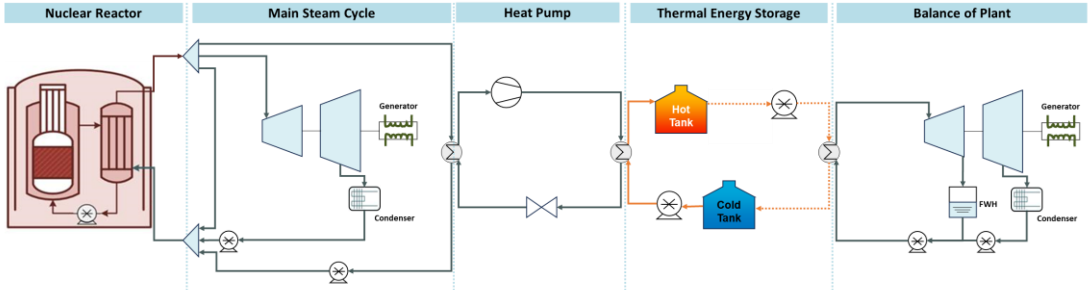
Nuclear power integrated with thermal energy storage (TES)



- **Economics**
  - TES significantly cheaper than electrochemical storage
  - TES systems store nuclear energy in its original form (heat), allowing for solution without penalty of storage conversion efficiency
- **Flexibility**
  - TES enables NPPs to respond nimbly to market variability and to participate in restructured markets
- **Market readiness**
  - Heater + TES + Steam cycle can be operational before nuclear reactor is bult or vice versa and operate standalone

*Source: https://www.synergy.net.au/Blog/2021/10/Everything-you-need-to-know-about-the-Duck-Curve

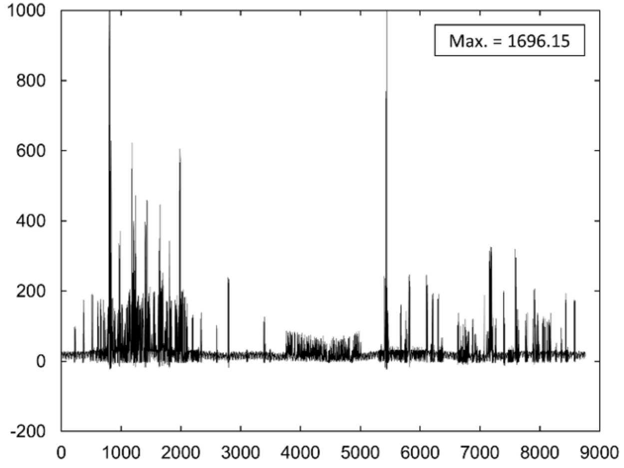
Nuclear Power Integrated with TES – Design Investigation

<table>
<tr><th>Design Type</th><th>Heat Source</th><th>Design Schematics</th><th>Advantages</th><th>Challenges</th></tr>
<tr><td>Steam-charged TES</td><td rowspan="2">High temp. nuclear reactor</td><td>
</td><td>
• Takes advantage of current design of steam generator in containment</td><td>
• Loss in power production efficiency, specific example: 40% original → 28%TES</td></tr>
<tr><td>TES between primary and secondary loop</td><td>
</td><td>
• Efficiency can be boosted further; Steam cycle design independent to containment limitations
• Full decoupling of steady nuclear heat production and power generation
• Additional electric heaters can utilize negative electricity price</td><td>
• Need for redesign of heat transfer from primary loop
• Power-to-heat-to-power roundtrip efficiency ~40%</td></tr>
<tr><td>Pumped TES</td><td>Low- & high-temp. nuclear reactor</td><td>
</td><td>
• Enables TES also for LWR
• Storage temperatures independently tuned
• Works well also for negative electricity price</td><td>
• Complex additional system
• Power to heat to power efficiency ~ 70%</td></tr>
</table>

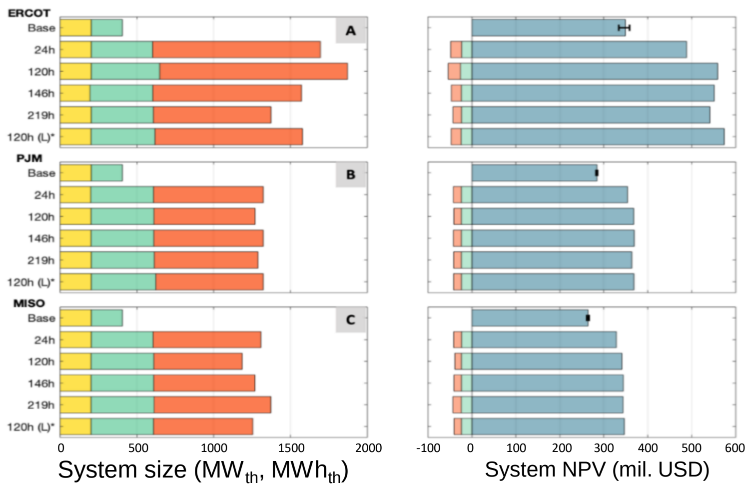
Nuclear Power Integrated with TES – Capacity and Energy Dispatch Optimization

- **Optimization for arbitrage on electricity markets**
  - Stochastic optimization approach using synthetic price histories
  - NPV improved by 41%, 14%, and 13% for the ERCOT, PJM, and MISO markets, respectively, in comparison to nominal baseload production
  - Optimal storage size ~ 5 hours, discharge capacity ~ 2x of charging

Real time market LMPs for ERCOT's West LZ (2020)

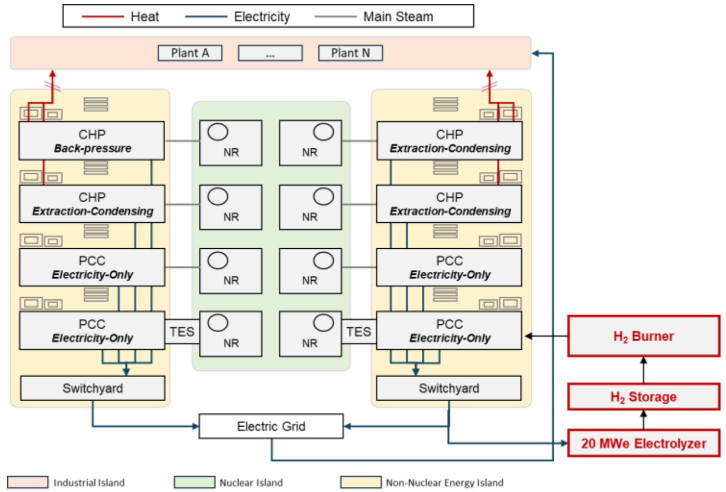


Optimized cases for the HTGR-TES coupling superset capacity (left) and NPV (right)

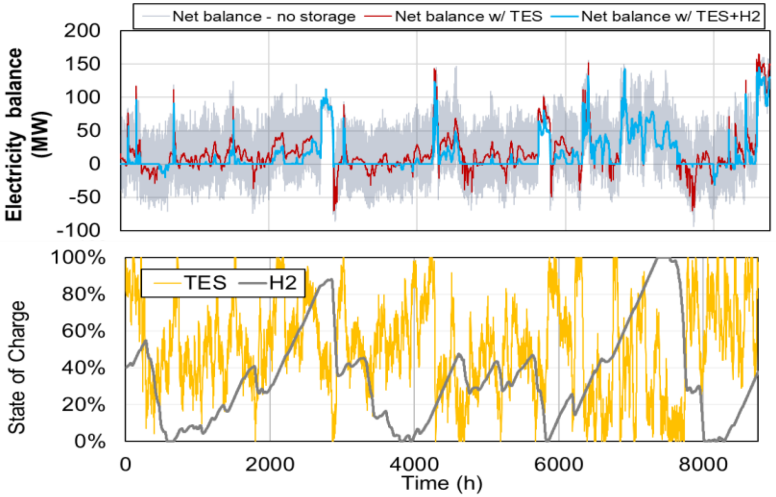


- **Industrial heat and power integration**
  - TES can smooth peaks otherwise transmitted to the grid
  - Relatively small storage at single unit out of a multi-pack reactor installation might be sufficient
  - Combination of optimally sized storage systems

System configurations of nuclear and TES integration



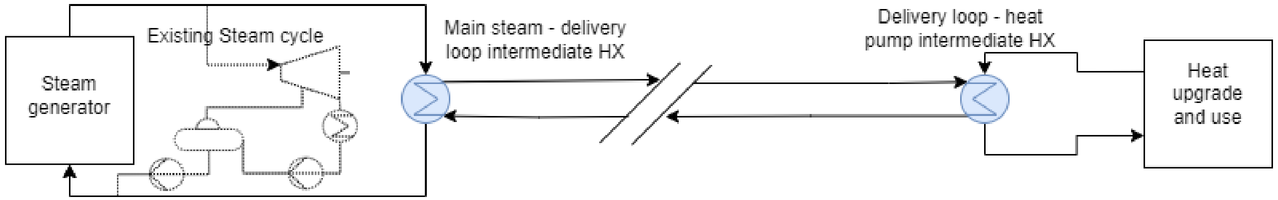
Net electricity balance before and after [*TES integration (top) and state of charge (bottom)*]



Heat Pumping from LWR to HT Industrial Use

Research Objective

- **Upgrade LWR plant steam to high temperature (~550°C) and send it to energy demanding industries**
    - Generic NPP 6 MPa saturated steam, return nominally 225°C

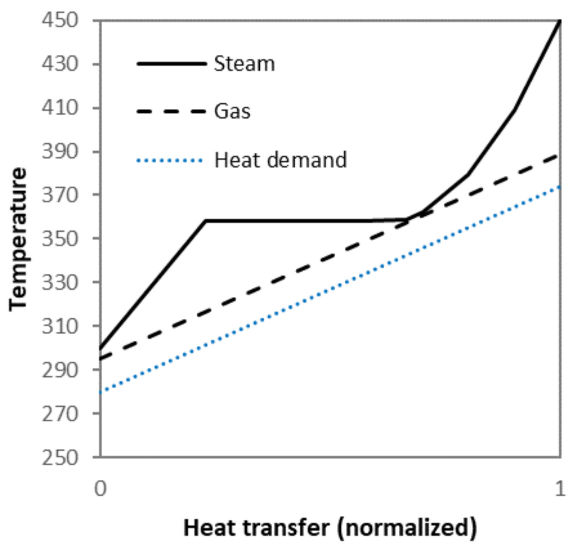


- **How the industrial heat demand looks like?**
    - illustrative cases are developed

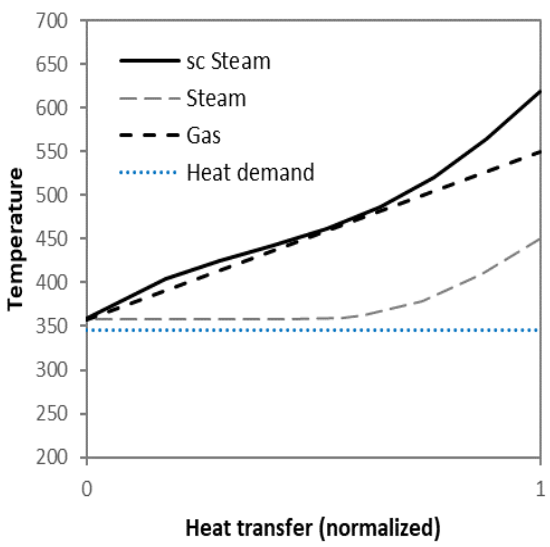
Case 1. Sensible process heating between two temperatures

Case 2. Constant temperature demand at specified temperature

Case 1



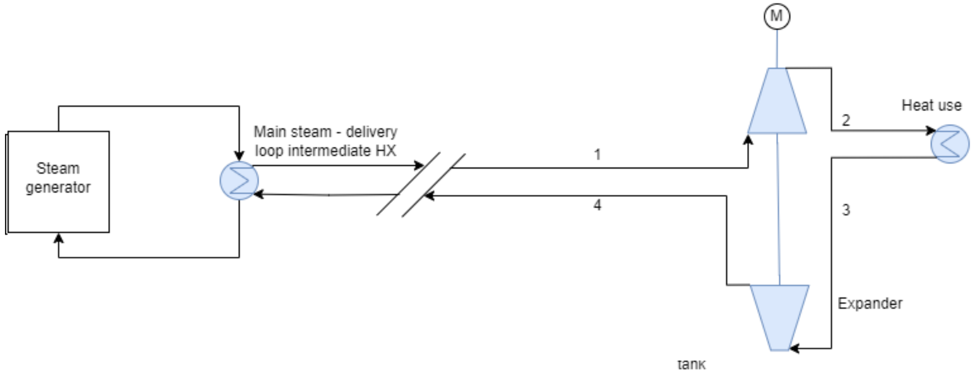
Case 2

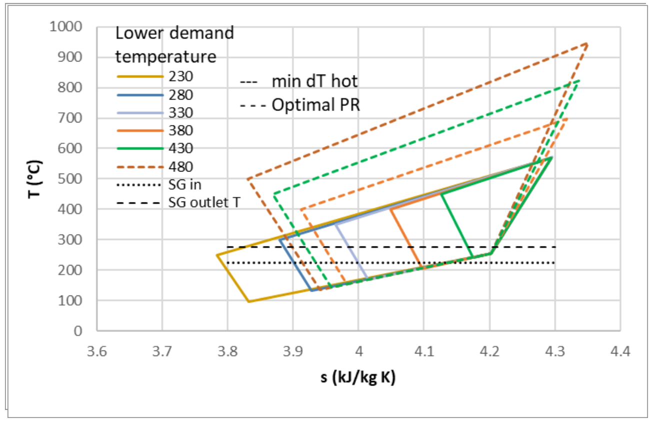


Heat Pumping from LWR –
Heat Pump Configurations & Thermodynamic Modeling

Type	Configuration	Thermodynamic Representation	Cycles

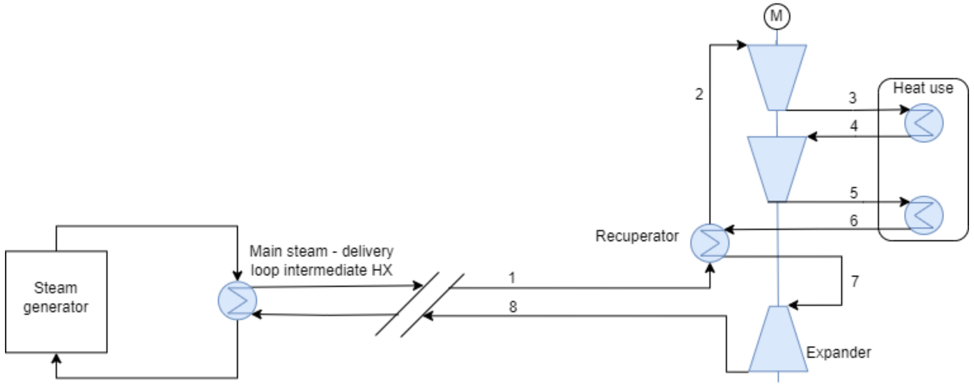
Simple System

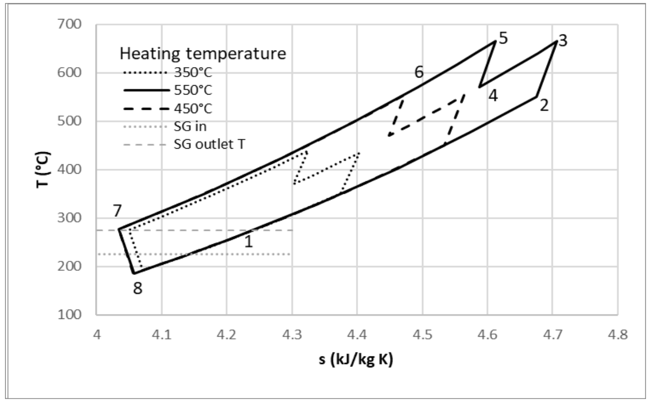




- Steam Compression Cycle
- Reverse Brayton Cycle

Split Compression Recuperated System

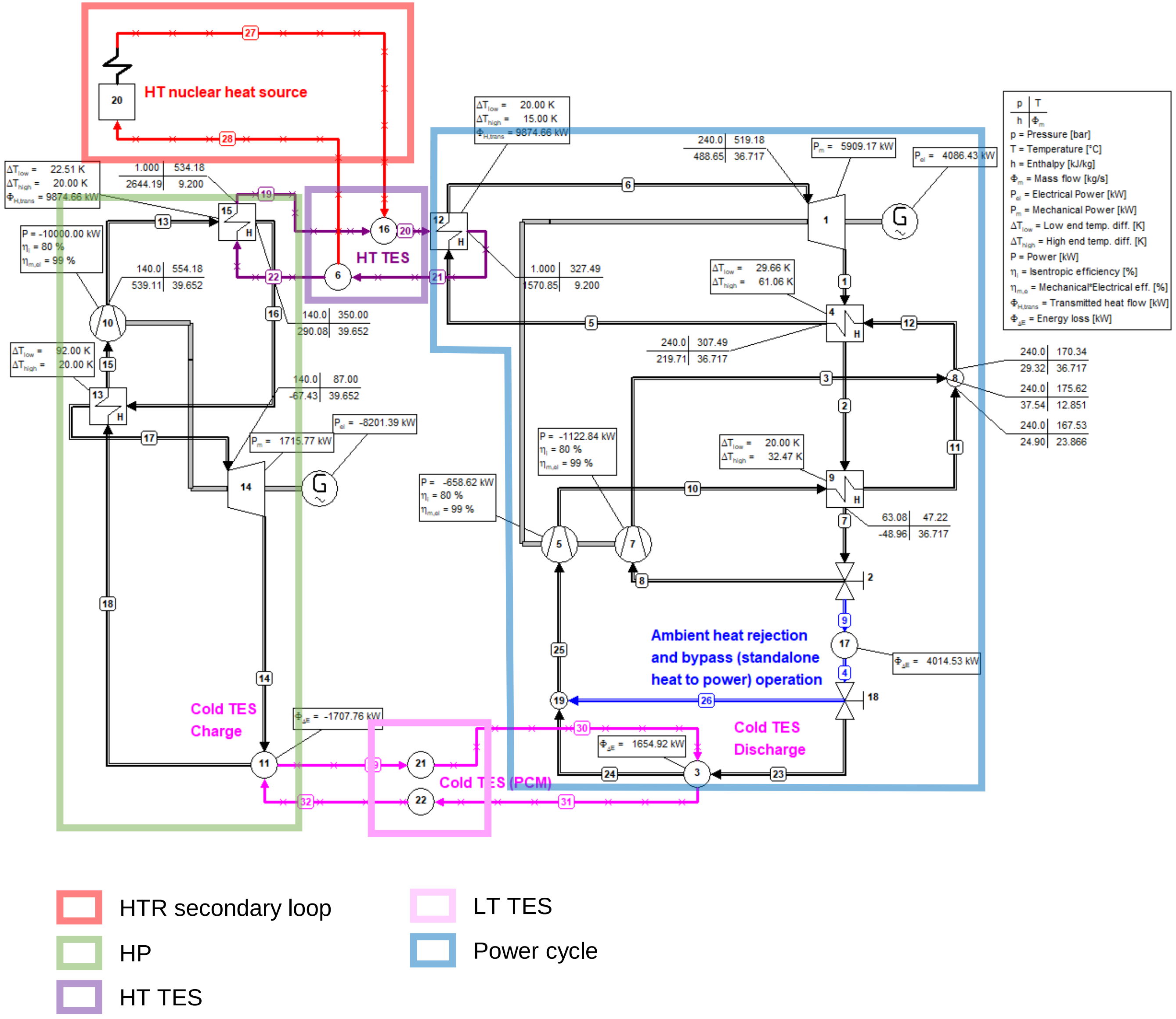




- Steam Compression Cycle
- Reverse Brayton Cycle

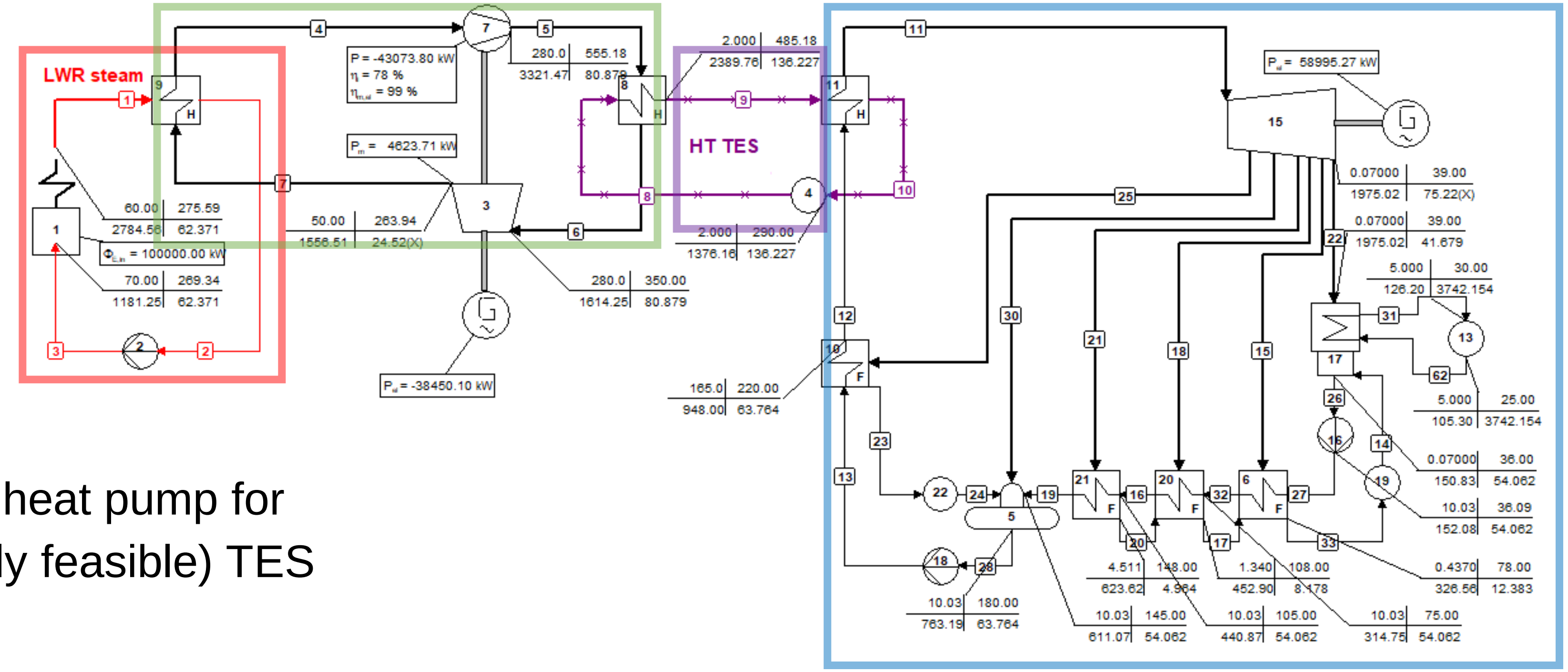
Pumped Thermal Energy Storage with Nuclear

- **Synergy of shared components**
- **Solutions for HTGR**
  - Reactor and heat pump (or electric heaters) coupled to same TES
  - Multiple operating modes (and related efficiency)



Pumped Thermal Energy Storage with Nuclear

- **Solutions for LWR**



- Upgrading reactor heat by heat pump for subsequent (and technically feasible) TES
- Discharge by
  - Dedicated power conversion cycle (steam / sCO_2)
  - Dedicated HP section and joint LP section with original steam cycle

LWR secondary loop

HP

TES

Power cycle

Summary

- **Nuclear power integrated with TES**
  - Feasible solution for high-temperature reactors, opportunity to further improve efficiency
  - Attractive business case when nuclear power already considered — only moderate increase in system capital costs
  - Fitting to existing reactor design can result in a somewhat more complex solution (two TES systems for specific HTGR)

- **Heat pumping from LWR**
  - Similar technology as PTES systems — future development in either field will benefit the other
  - Heat pump may be based on both steam and Brayton cycles

- **Integrated nuclear + Carnot battery concept**
  - Both systems utilize same parts of technology
  - Opportunity for building and commissioning one part (CB) of system with prospect of future integration with other, as technologies become available
  - Opportunity also for LWR, which otherwise provides very limited TES integration opportunities

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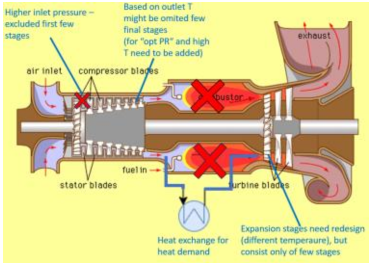
Heat Pumping from LWR – Technical Feasibility

Possible technical solutions

- **Steam cycle**
  - Extreme parameters
  - Pressures possible for specialty applications, but...
    - ...not at required temperatures
    - ...definitely not for steam

Driver	Electric motor, gas turbine or steam turbine
Min. suction pressure [bara]	≤ 1
Discharge pressure [bara]	Max. 800 bara (calculated & designed) Tested and referenced up to 650 bara
Flow rate [m3/h]	Max. 230,000 m3/h
Power range [MW]	Up to 60 MW
Efficiency [%]	approx. > 80% overall efficiency possible
No of impeller stages	Max. 10

- **Brayton cycle**
  - Reconfiguring gas turbine technology may be feasible
  - Pressure and PR not an issue



- **Heat transfer @ industrial site?**
  - Often considered for radiative heat transfer
  - Not within scope here but another major issue

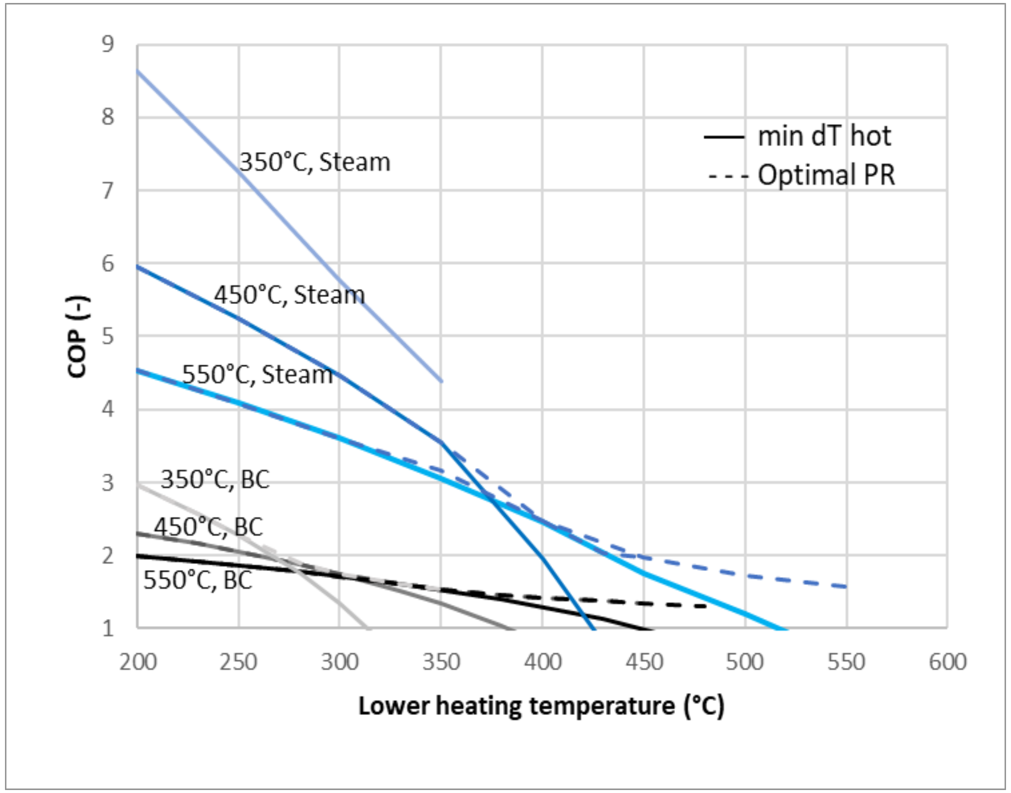
Map of Technical Feasibility and System Parameters

- **At constant heating demand temperature and technical limits**

	550°C		450°C		350°C	
Steam cycle:	Simple	Advanced	Simple	Advanced	Simple	Advanced
Pressures (MPa)	n/a	30	30	30	17.6	17.6
Temperatures (°C)	n/a	750	630	551	450	450
Vol flow	n/a	Ok	Ok	Ok	Ok	Ok
Return T	n/a	Complications	Complications	Complications	Complications	Complications
Readily available HX	n/a	PCHE	PCHE	PCHE	S&T/PCHE	S&T/PCHE
Readily available comp	n/a	limits	limits	limits	Potentially iss	Potentially issues
COP	n/a	1.39	1.60	1.75	4.39	4.56
COP_corr	n/a	1.22	1.32	1.39	2.01	2.03
Air Brayton:						
Pressures (MPa)	2.0	0.4	2.0	0.4	1.3	0.4
Temperatures (°C)	750	670	750	550	620	440
Vol flow	High	High	High	High	High	High
Return T	Ok	Ok	Ok	Ok	Ok	Ok
Readily available HX	Fin & tube	Fin & tube	Fin & tube	Fin & tube	Fin & tube	Fin & tube
Readily available comp	Temp limits	Temp limits	Temp limits	Yes	Temp limits	Yes
COP	1.1	1.5	1.3	1.6	1.5	1.9
COP_corr	1.0	1.3	1.2	1.3	1.3	1.5

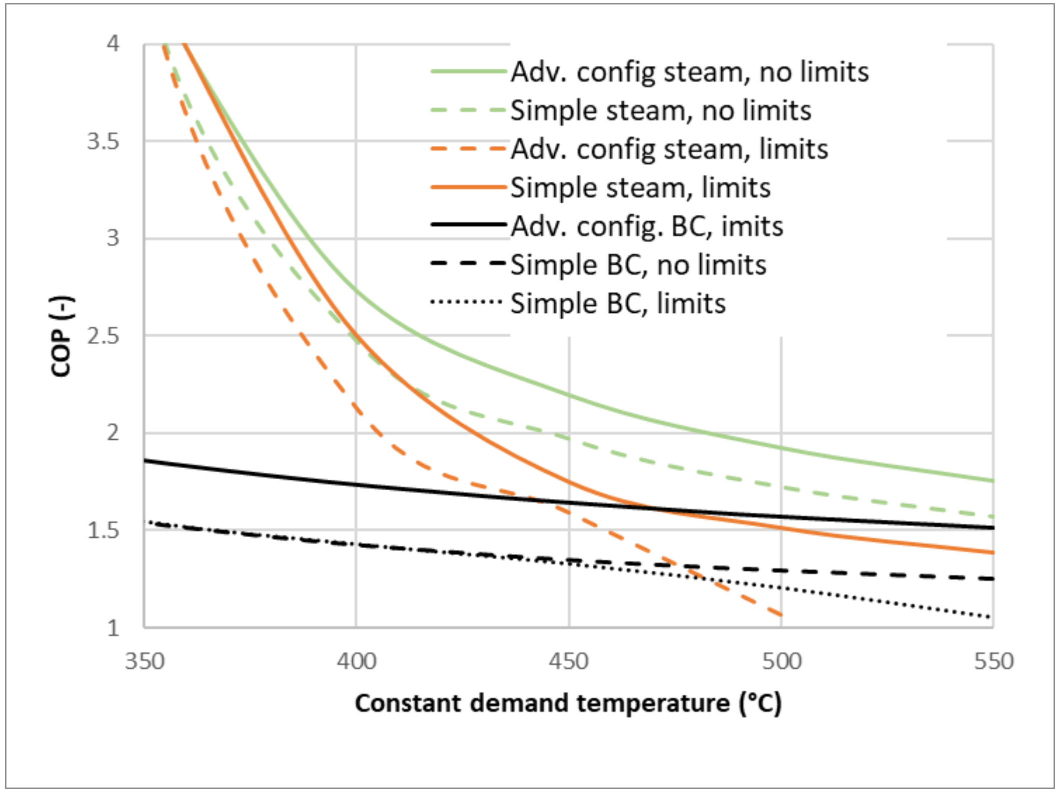
Heat Pumping from LWR –
Heat Pump Configurations & Thermodynamic Modeling

Sensible industrial process heating



- **Without imposed technical limits**
- **Simple cycle**

Const. T heating, impact of advanced configuration



- **Technical limits on maximal parameters, constant demand temperature**
  - 750°C, 30 MPa—optimistic, but not entirely sci-fi

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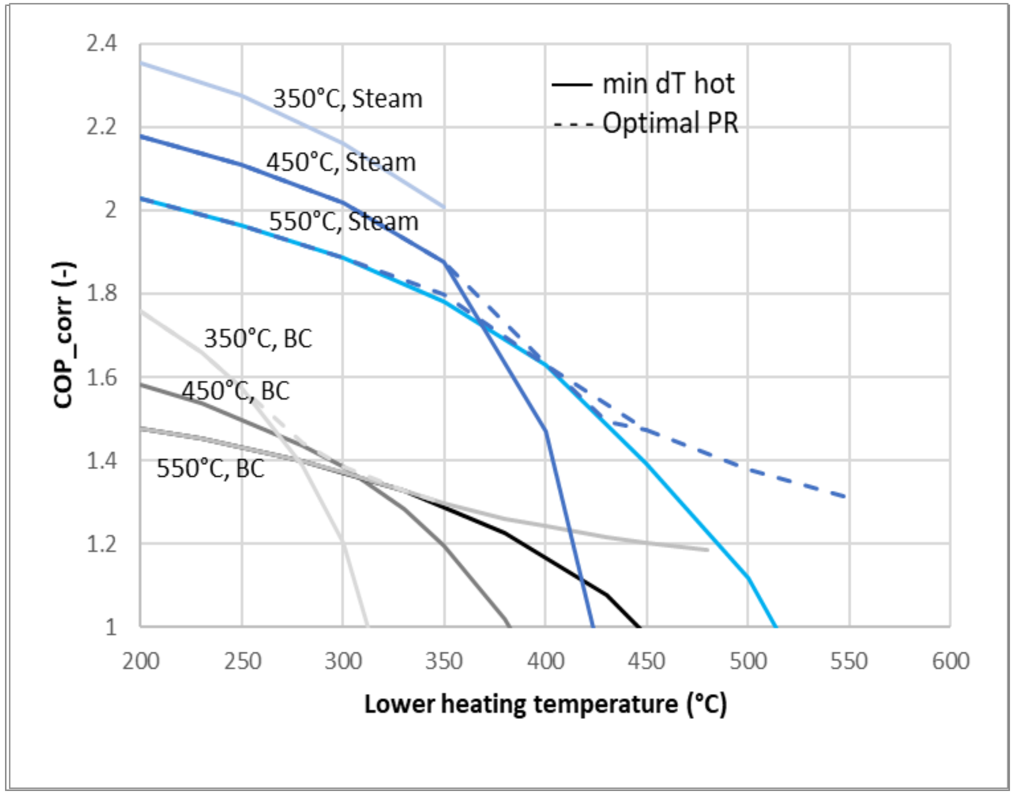

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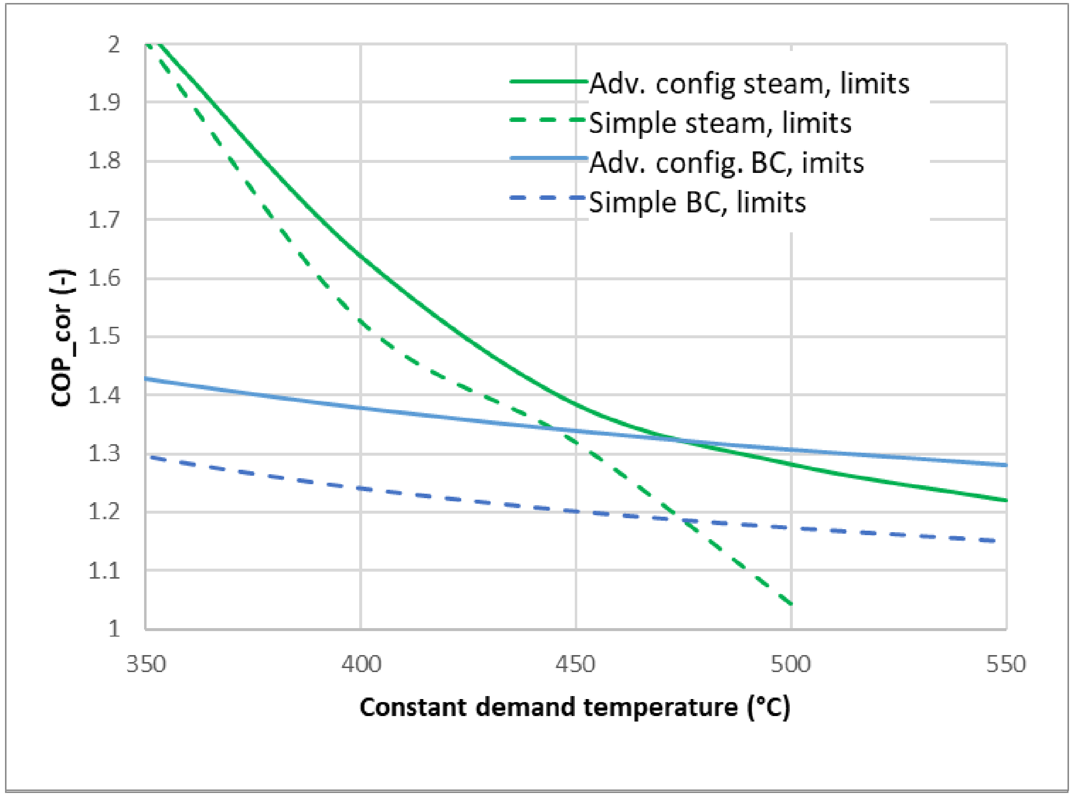

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