IES
Integrated Energy Systems

Nuclear Thermal Energy Storage Use Case

IES Force Workshop

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IES Force Workshop

Integrated Energy Systems (IES)

Idaho Falls

April 5, 2023

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FY22 M2 Link: https://doi.org/10.2172/1890160
FY23 M4 link: https://doi.org/10.2172/1960133
FY22 Pub. link: https://doi.org/10.1016/j.enconman.2022.115872

Funding: USDOE Office of Nuclear Energy, DE-AC07-05ID14517

INL
Idaho National Laboratory

Introduction: High-level Project Scope

Motivating Problem

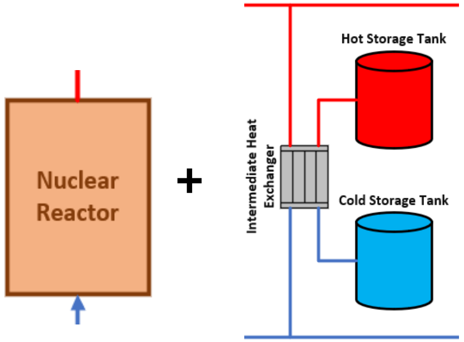
Advanced Reactor Company X: I want to add thermal energy storage. Which one makes the most sense? How do we choose? How does it work?

Why Thermal Energy Storage (TES) Coupling?

- TES enables NPPs to respond nimbly to market variability and to participate in restructured markets.
- TES systems store nuclear energy in its original form (heat), enabling a more flexible use on the back end, which provides electricity or heat.

Key Research Areas:

1. ***TES ranking*** tool that allows advanced reactor companies to down-select TES systems based on their system design.
2. ***Steady-state physical models development*** and design considerations of thermal storage coupling for three advanced nuclear reactor (A-LWR, HTGR, and LMFR), each coupled to TES in three different scenarios and different thermal extraction ratios.
3. ***System design cost analysis and stochastic optimization*** of NPP-TES based on market price signals in a selected market.
4. ***Transient modeling and grid-wide economics*** of each design.



Two Tank Sensible Heat

or

Concrete

or

TES Systems

1. Liquid-based sensible heat storage:
    - Two-tank molten salt
    - Two-tank thermal oil
    - Thermocline molten salt
    - Thermocline thermal oil
    - Hot/Cold water
2. Underground (bore-holes and aquifers)
3. Thermochemical
4. Latent heat storage
5. Solid media
    - Firebrick
    - Concrete
    - Ceramics, graphite, and alloys
6. Steam accumulators.

- * A-LWR: Advanced light water reactor; HTGR: High temperature gas cooled reactor; LMFR: Liquid metal fast cooled reactor

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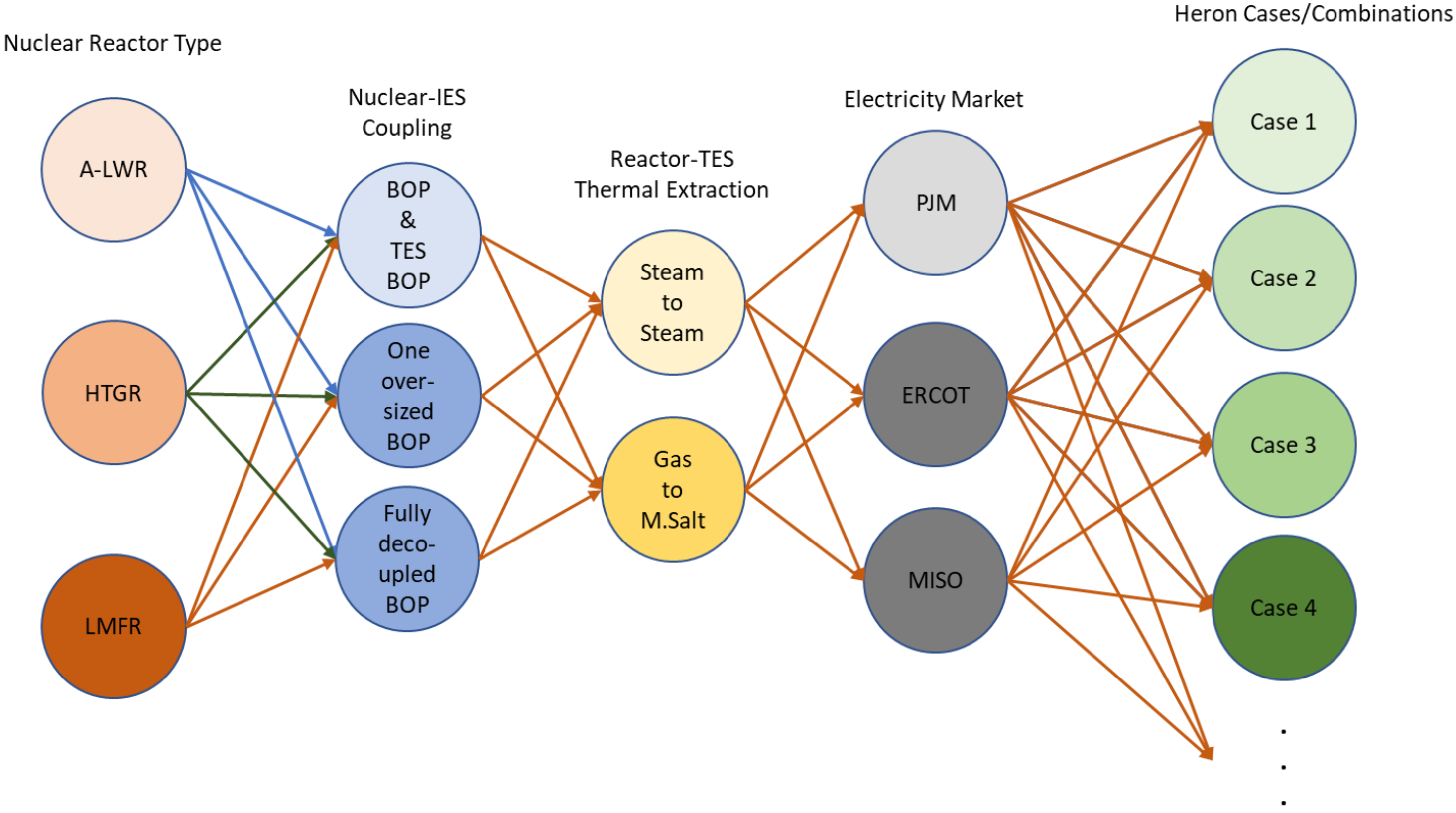


- * A-LWR: Advanced light water reactor; HTGR: High temperature gas cooled reactor; LMFR: Liquid metal fast cooled reactor

** PJM: PJM Interconnection LLC (mid-Atlantic); ERCOT: Electric Reliability Council of Texas; Miso: Midwest Independent Transmission System Operator

TES Use Case Methods and FORCE Tools

(Selected Results/Examples)

1. Steady-State and Physical Models Development

- Thermodynamic analysis of proposed systems
- What is the optimum Coupling approach?
- Develop fully-coupled TES-nuclear steady-state models
- Component-level analysis (heat exchange (HX) technology, geometries, sizes, etc.)
- Cost analysis and cost functions for discrete system sizes.

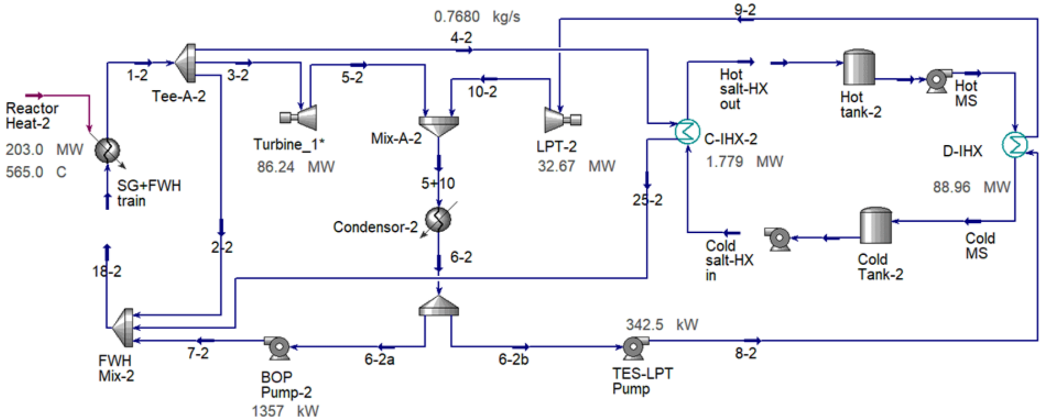
2. Stochastic Optimization Based on Market Price Signals

- Analyze and reproduce price signals from various markets
- What is the optimum system size for the highest net present value (NPV)?
- TES dispatch profiles of the IES system.

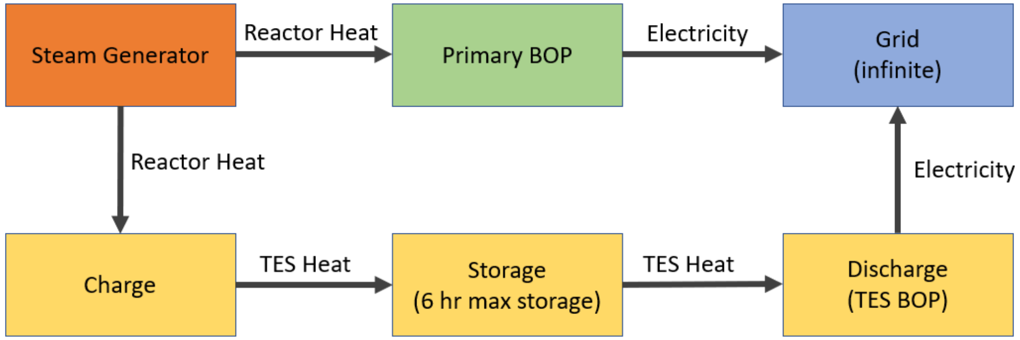
3. Transient Modeling and Dynamic Operation

- How do the dynamic behavior and system controls should look like?
- Is the dispatch profile with highest NPV feasible/reasonable dynamically?

TES-Coupling in Aspen HYSYS (Steady-State Models)



HERON Optimization Workflow



Steam Generator

Reactor Heat

Primary BOP

Electricity

Grid (infinite)

Reactor Heat

Electricity

Charge

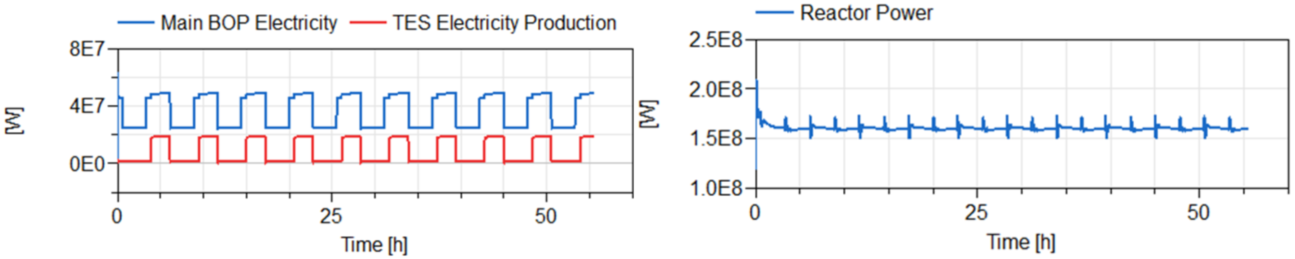
TES Heat

Storage (6 hr max storage)

TES Heat

Discharge (TES BOP)

Examples of Nuclear-TES Dynamic Modeling Results from Dymola



TES-Nuclear Coupling Analysis

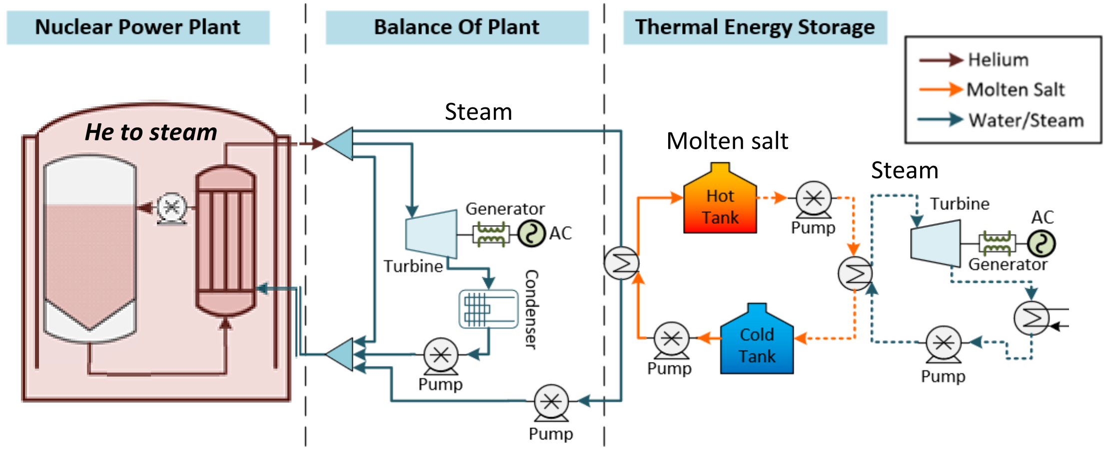
Two Phase vs. Direct/Single-Phase Heat Transfer to TES

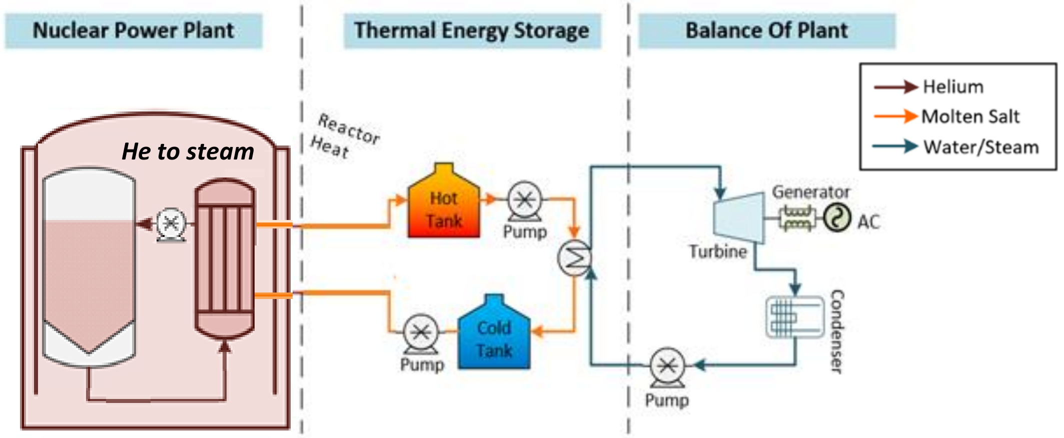
Previous Design Configurations (FY-22):

- Two-phase design approach: *BOP Steam → TES → BOP TES Steam*
- TES and BOP are coupled in parallel.
- Nuclear island and BOP are coupled as normal with the addition of IES.
- FY22 M2 Link: doi.org/10.2172/1890160

Current Design Considerations (FY-23): Reactor Fluid to TES to Steam

- Single-phase design approach: *Reactor fluid → TES → BOP TES Steam*
- TES and BOP are coupled in series.
- Nuclear island is fully decoupled from BOP.





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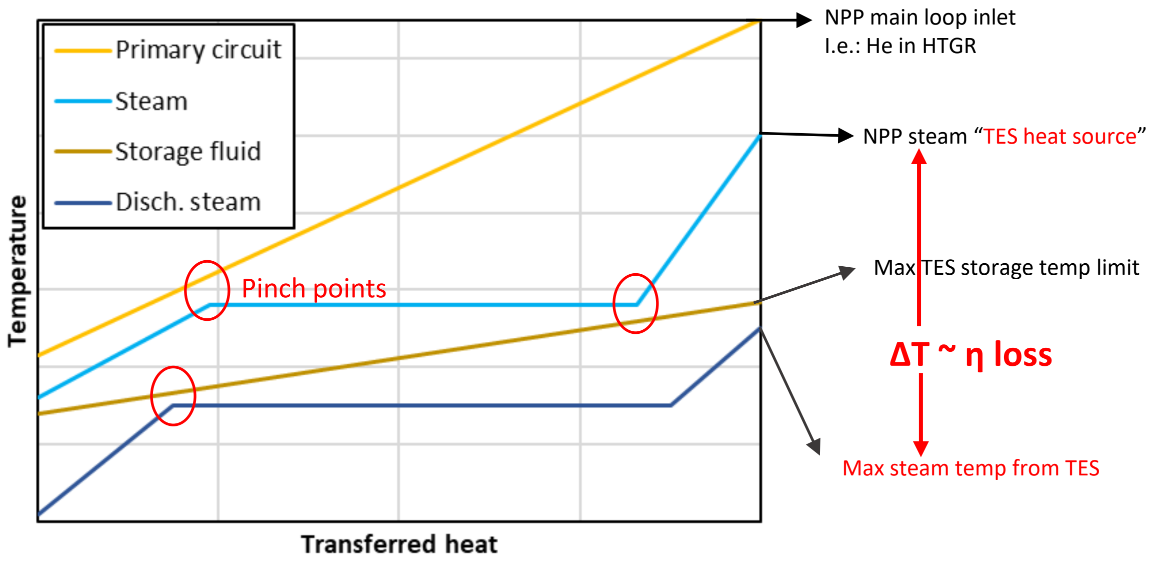
Two Phase vs. Direct/Single-Phase Heat Transfer to TES

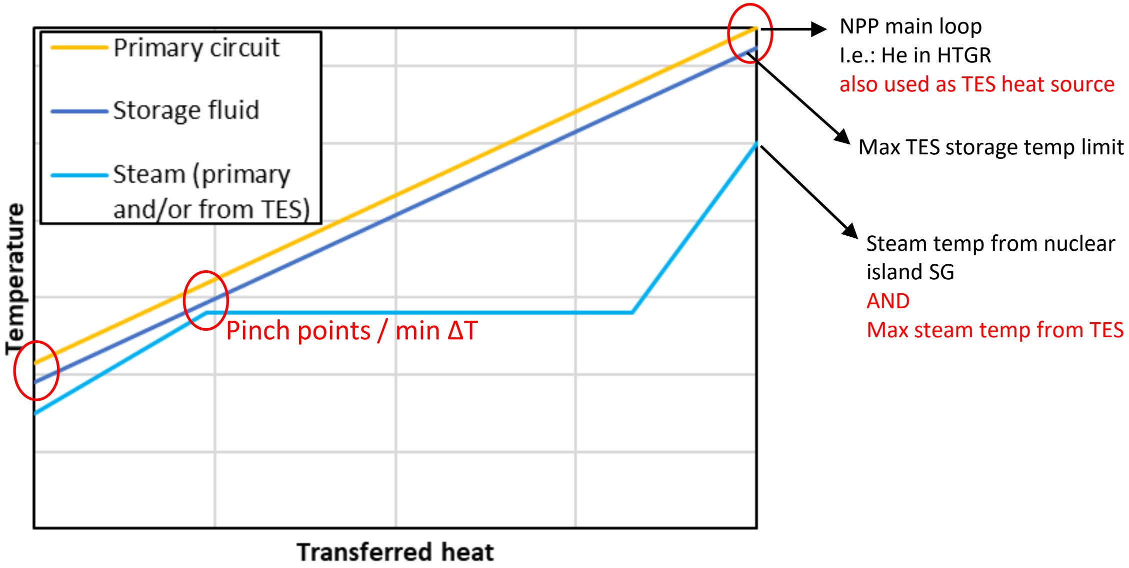
Previous Design Configurations (FY-22):

- Two-phase design approach: *BOP Steam → TES → BOP TES Steam*
- Existing balance-of-plant steam generator:
    - No modifications to the nuclear island or balance of plant (BOP).
- Large temperature (exergy*) loss between charging and discharging:
    - => Efficiency loss
    - Boosting the BOP output via TES comes with constraints on steam pressure and temperature delivery yet at a relatively higher normalized cost.

Current Design Considerations (FY-23): Reactor Fluid to TES to Steam

- Single-phase design approach: *Reactor fluid → TES → BOP TES Steam*
- Heat is transferred "directly" from nuclear island working fluid to TES
    - Minimal exergy loss and efficiency loss caused by TES.
- Discharge side has more flexibility for steam cycle design (higher temperature and pressure steam delivery).
- Heat from TES becomes available at higher temperature for industrial use.





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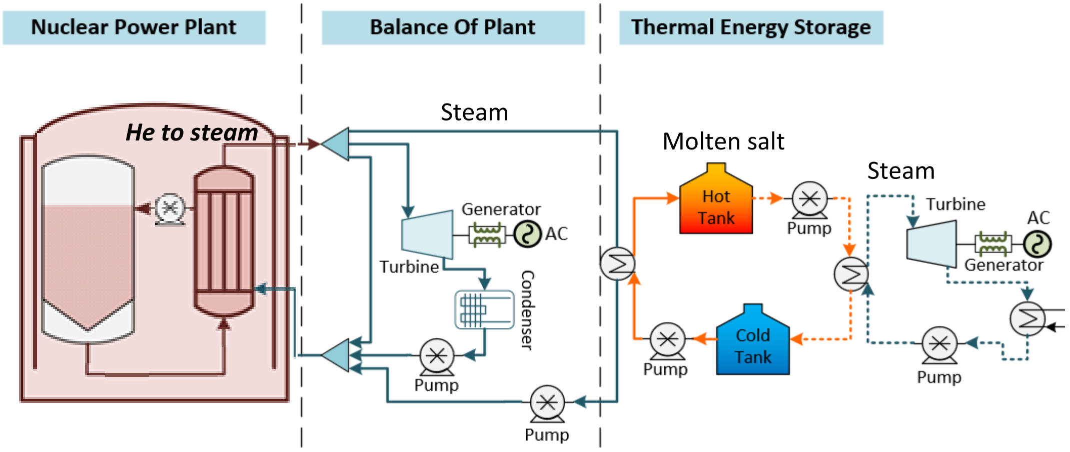
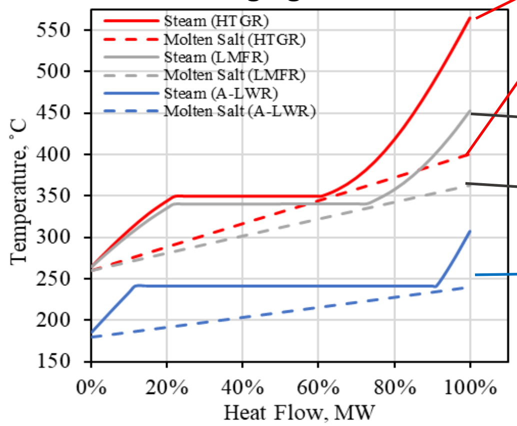
* Potential or energy content of heat that could be converted to work based on 2nd law of thermodynamics by ideal systems.

30% TES Boosting: BOP Operation (Single High Temperature TES)

Two Phase Coupling



TES charging QT curves



HTGR steam “TES heat source” Inlet

Max TES storage temp in HTGR

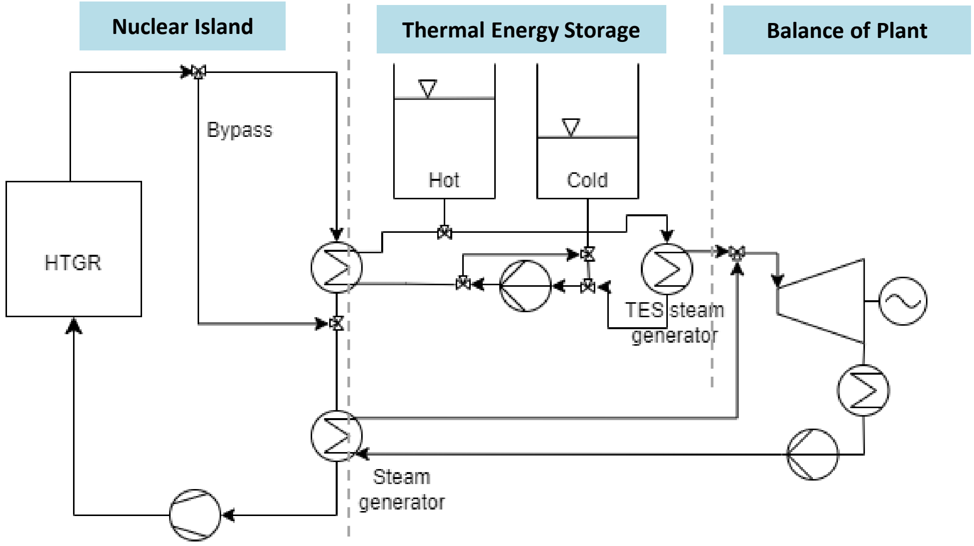
LMFR Steam “ TES heat source” Inlet

Max TES storage temp in LMFR

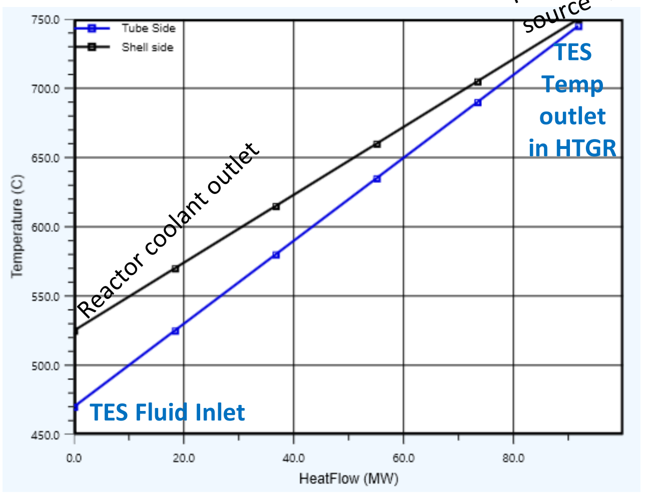
LWR

Features:
Phase change of fluid (water/steam) with single phase storage causes large inadverent temperature drop -> efficiency drop

Single Phase, 30% TES boosting



TES charging QT curves

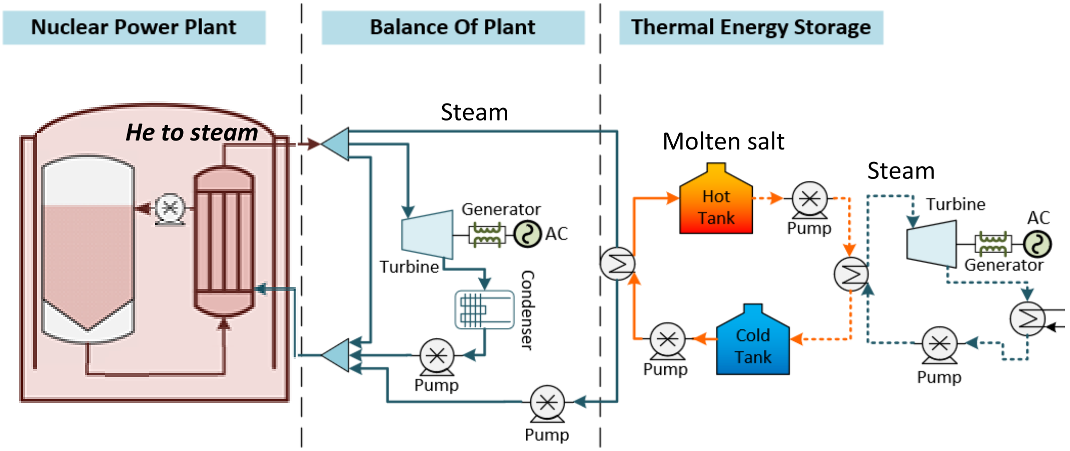


Features

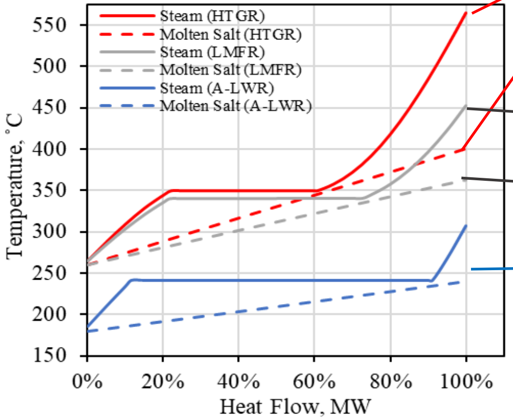
- Increased TES *T* from 420 to 745 °C
- Increased TES steam *T* from 395 to 565 °C (nominal)
- Increased TES steam *p* from 10 to 16.5 MPa (nominal)
- TES outlet matching main BOP (*p*, *T*)
- HT stored heat available also for e.g. Industry
- Economy of scale: one BOP only, with TES delivering same steam T and P as the NPP.

30% TES Boosting: BOP Operation (Single High Temperature TES)

Two Phase Coupling



TES charging QT curves



HTGR steam “TES heat source” Inlet

Max TES storage temp in HTGR

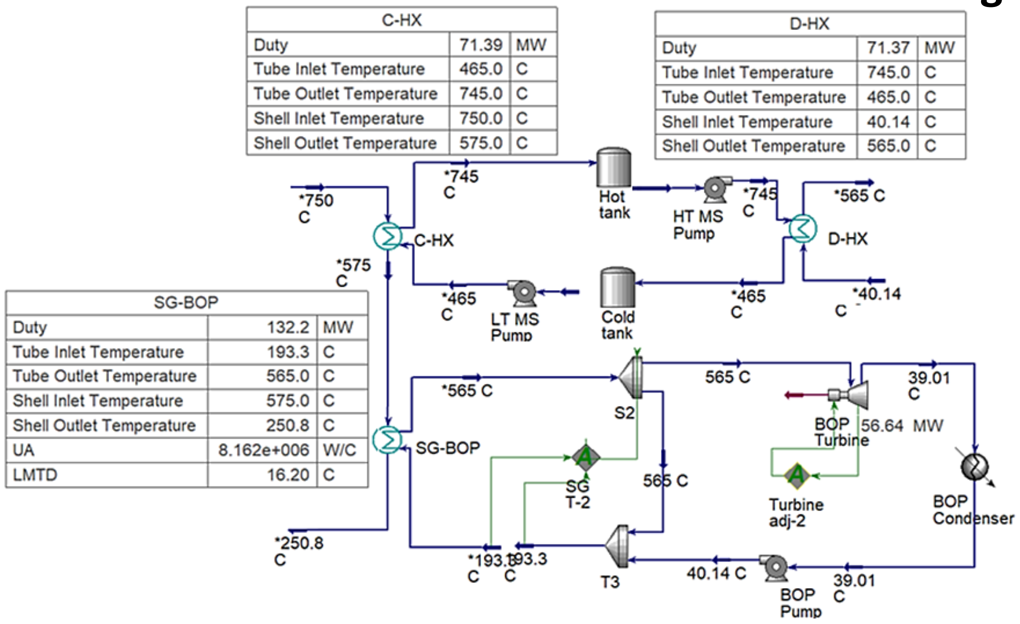
LMFR Steam “ TES heat source” Inlet

Max TES storage temp in LMFR

LWR

Features:
Phase change of fluid (water/steam) with single phase storage causes large inadvertent temperature drop -> efficiency drop

Single Phase, 30% TES boosting

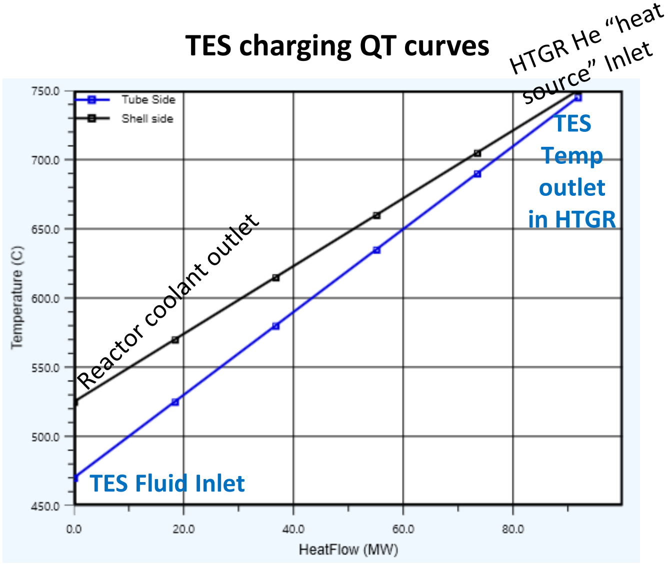


C-HX		
Duty	71.39	MW
Tube Inlet Temperature	465.0	C
Tube Outlet Temperature	745.0	C
Shell Inlet Temperature	750.0	C
Shell Outlet Temperature	575.0	C

D-HX		
Duty	71.37	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	465.0	C
Shell Inlet Temperature	40.14	C
Shell Outlet Temperature	565.0	C

SG-BOP		
Duty	132.2	MW
Tube Inlet Temperature	193.3	C
Tube Outlet Temperature	565.0	C
Shell Inlet Temperature	575.0	C
Shell Outlet Temperature	250.8	C
UA	8.162e+006	W/C
LMTD	16.20	C

TES charging QT curves



HTGR He “heat source” Inlet

TES Temp outlet in HTGR

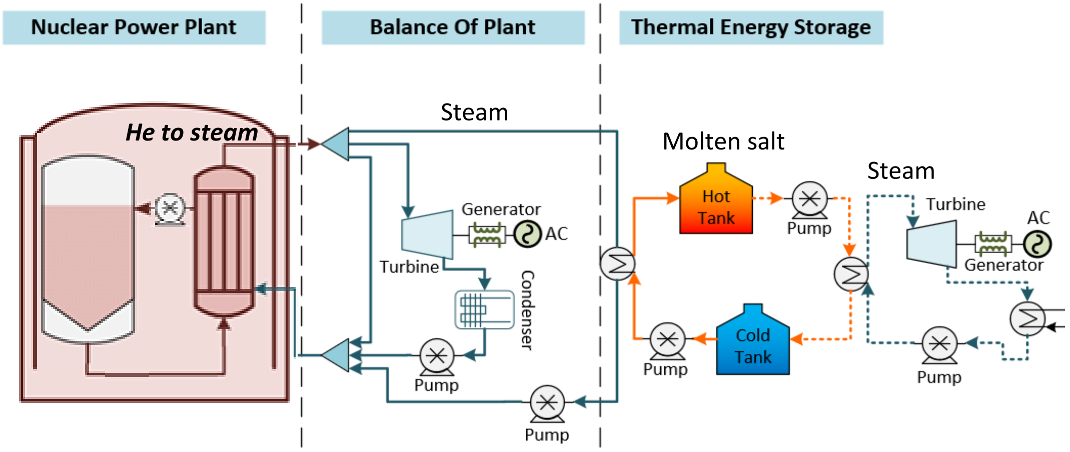
Reactor coolant outlet

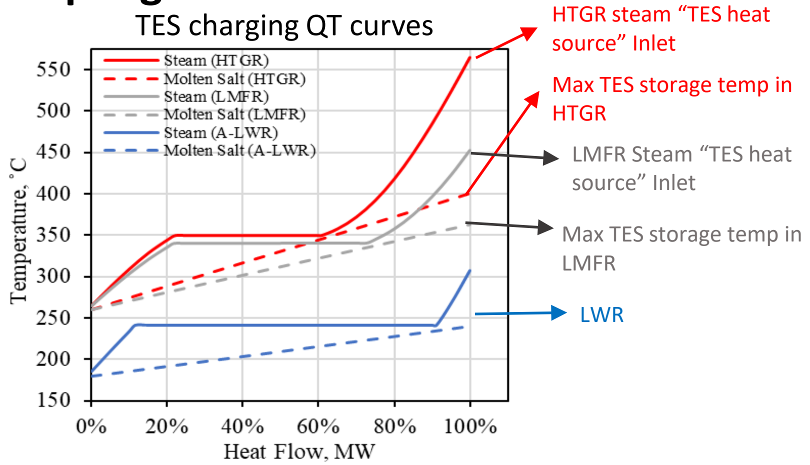
TES Fluid Inlet

Features
- Increased TES *T* from 420 to 745 °C
- Increased TES steam *T* from 395 to 565 °C (nominal)
- Increased TES steam *p* from 10 to 16.5 MPa (nominal)
- TES outlet matching main BOP (*p*, *T*)
- HT stored heat available also for e.g. Industry
- Economy of scale: one BOP only, with TES delivering same steam T and P as the NPP.

2X TES Boosting: BOP Operation (Two High and Low Temperature TES)

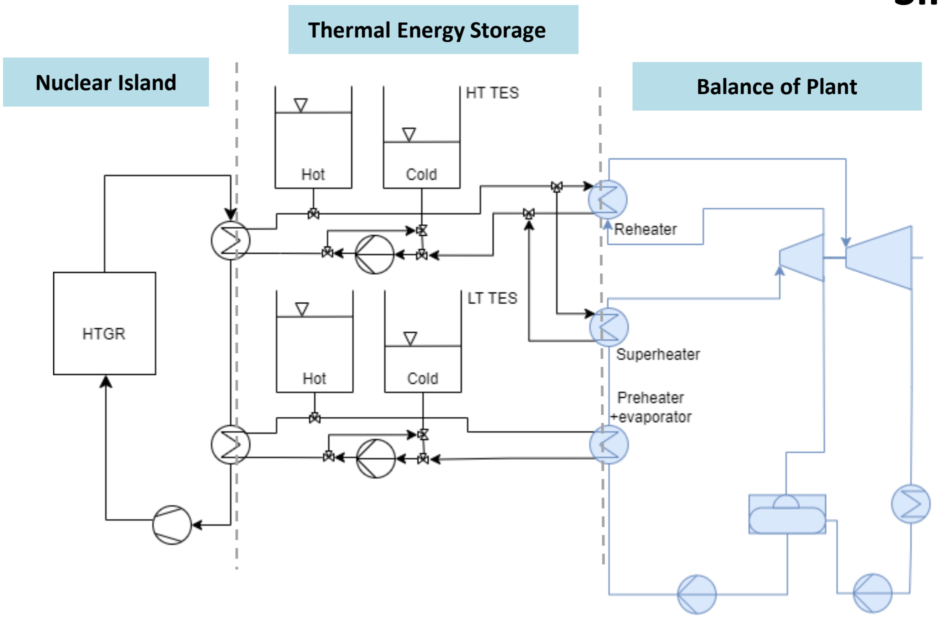
Two-Phase Coupling

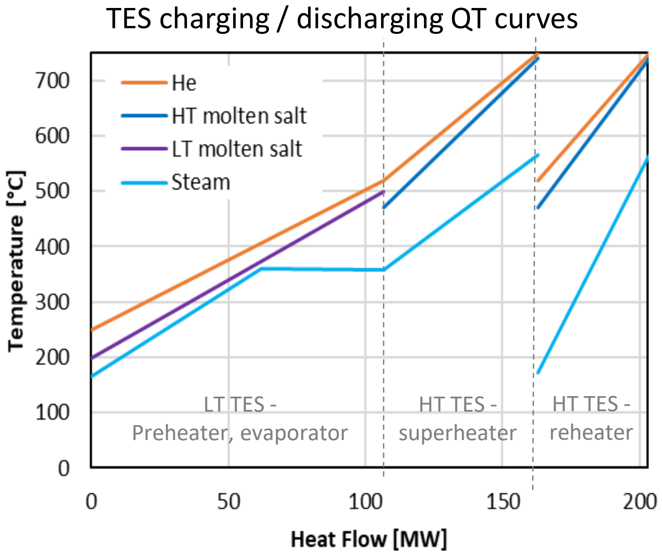




Features:
Phase change of fluid (water/steam) with single-phase storage causes large inadverent temperature drop -> efficiency drop.

Single Phase, 2X Boosting





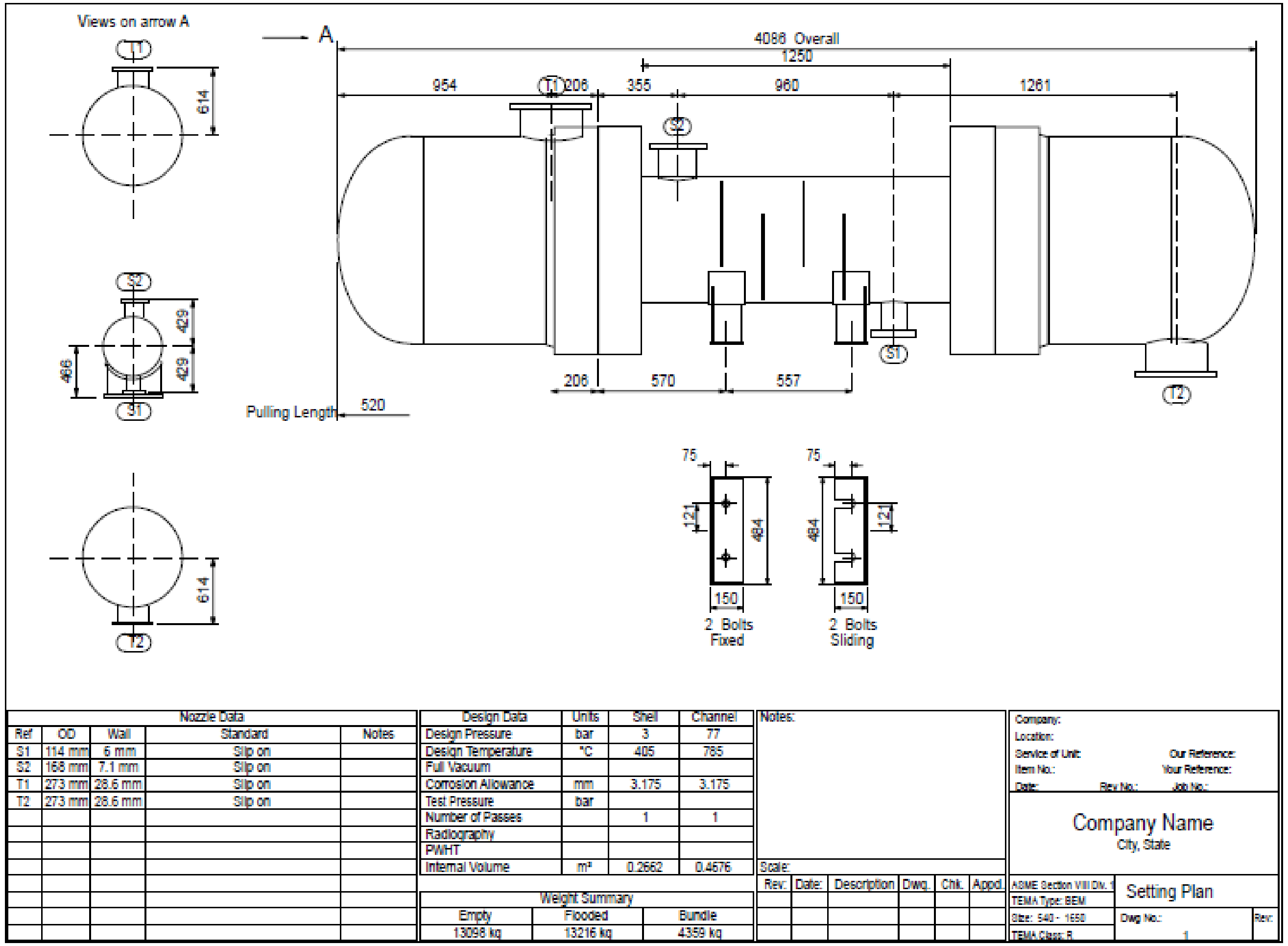
Features
- Requires thermodynamic optimization of heat flow between HT and LT TES
- Previous benefits of single TES plant plus these:
  - Fully decoupled nuclear island from BOP
  - Flexible power boosting
  - Reheat increases cycle efficiency (higher Generation capacity) and maintains heat balance between HT and LT TES plants
  - Reheat is standard in coal-fired plant and with molten salt.
    Reduce the wetness problem in the steam cycle.

*HT: High temperature; LT: Low Temperature

2X TES Boosting: BOP Operation (Two High and Low Temperature TES)

Two-Phase Coupling

Nuclear Power Plant | **Balance Of Plant** | **Thermal Energy Storage**



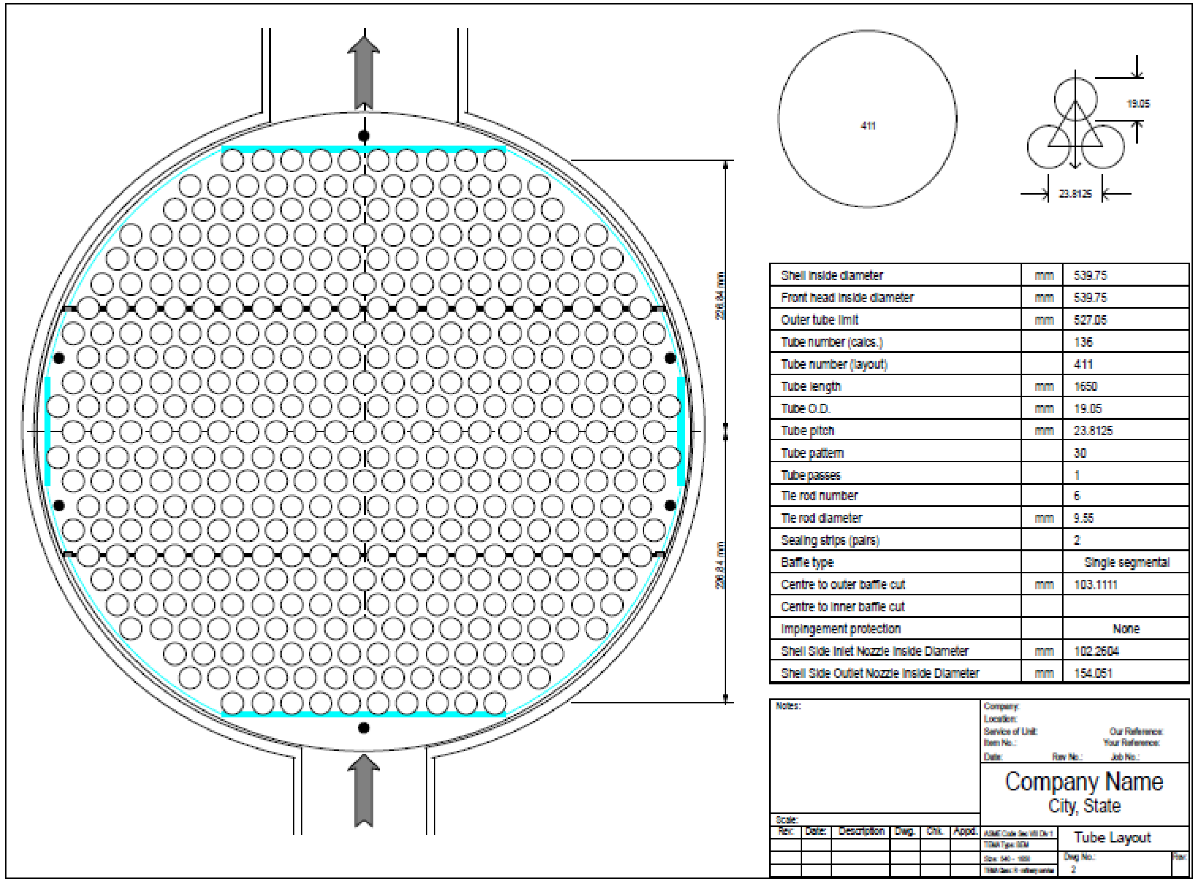
Nozzle Data				
Ref	OD	Wall	Standard	Notes
S1	114 mm	6 mm	Slip on	
S2	168 mm	7.1 mm	Slip on	
T1	273 mm	28.6 mm	Slip on	
T2	273 mm	28.6 mm	Slip on	

Design Data	Units	Shell	Channel
Design Pressure	bar	3	77
Design Temperature	°C	405	785
Full Vacuum			
Corrosion Allowance	mm	3.175	3.175
Test Pressure	bar		
Number of Passes		1	1
Radiography			
PWHT			
Internal Volume	m³	0.2662	0.4676

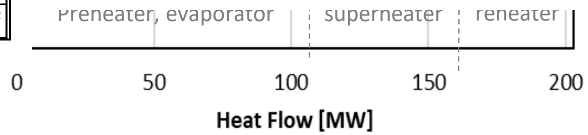
Weight Summary		
Empty	Flooded	Bundle
13098 kg	13216 kg	4359 kg

TES charging QT curves

HTGR steam “TES heat source” Inlet



Shell inside diameter	mm	539.75
Front head inside diameter	mm	539.75
Outer tube limit	mm	527.05
Tube number (calcs.)		136
Tube number (layout)		411
Tube length	mm	1650
Tube O.D.	mm	19.05
Tube pitch	mm	23.8125
Tube pattern		30
Tube passes		1
Tie rod number		6
Tie rod diameter	mm	9.55
Sealing strips (pairs)		2
Baffle type		Single segmental
Centre to outer baffle cut	mm	103.1111
Centre to inner baffle cut		
Impingement protection		None
Shell Side Inlet Nozzle Inside Diameter	mm	102.2604
Shell Side Outlet Nozzle Inside Diameter	mm	154.051



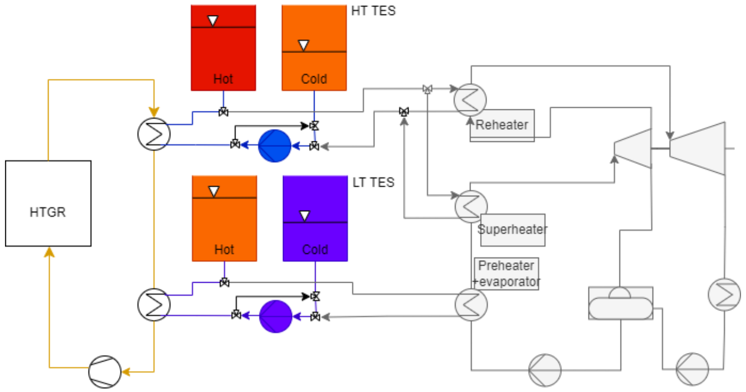
Reduce the wetness problem in the steam cycle.

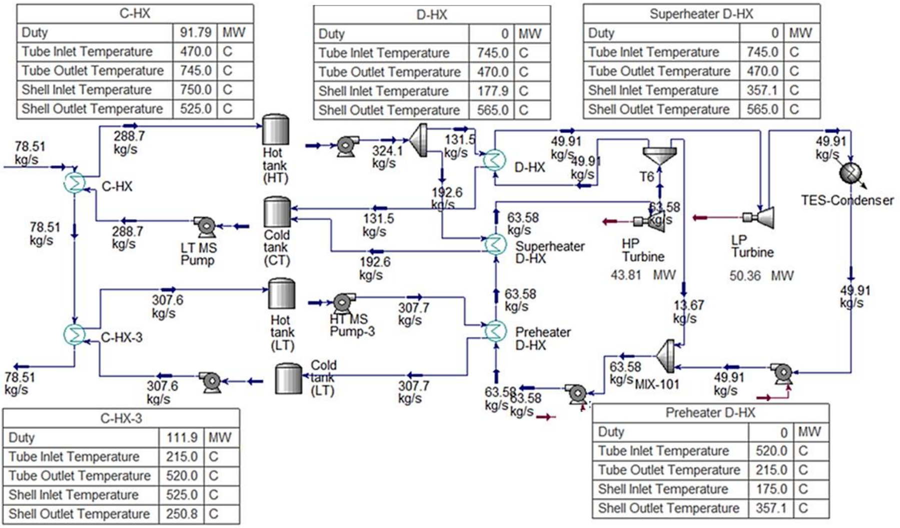
*HT: High temperature; LT: Low Temperature

2X TES Boosting: BOP Operation (Two High and Low Temperature TES)

Maximum Charge Mode

- Zero power output (standby)
- Salt only circulates between He HX and tanks.
- Tanks are getting charged.





C-HX		
Duty	91.79	MW
Tube Inlet Temperature	470.0	C
Tube Outlet Temperature	745.0	C
Shell Inlet Temperature	750.0	C
Shell Outlet Temperature	525.0	C

D-HX		
Duty	0	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	470.0	C
Shell Inlet Temperature	177.9	C
Shell Outlet Temperature	565.0	C

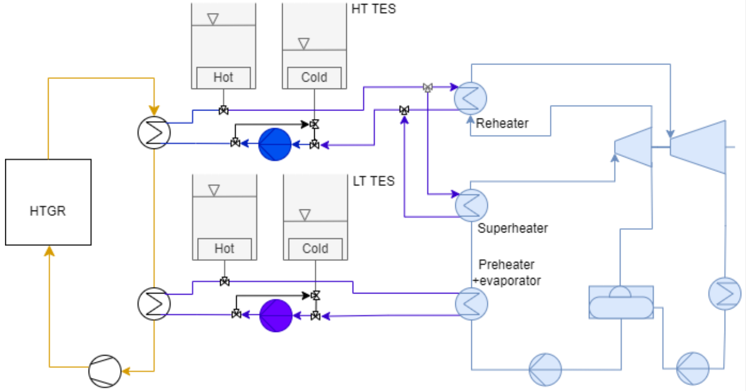
Superheater D-HX		
Duty	0	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	470.0	C
Shell Inlet Temperature	357.1	C
Shell Outlet Temperature	565.0	C

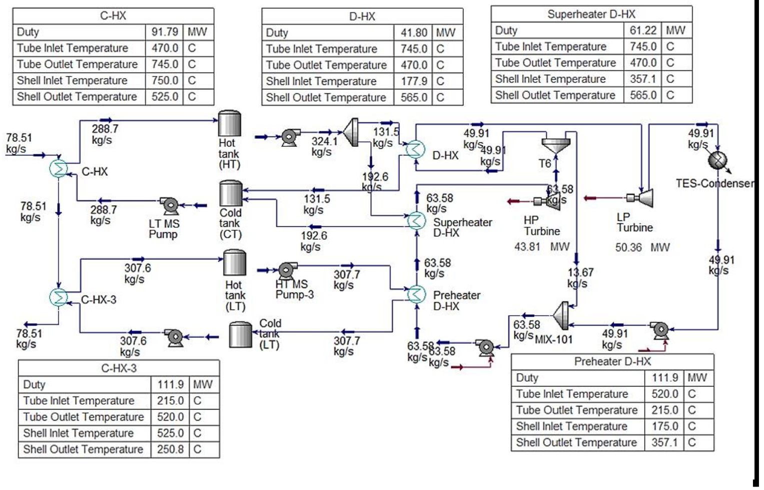
C-HX-3		
Duty	111.9	MW
Tube Inlet Temperature	215.0	C
Tube Outlet Temperature	520.0	C
Shell Inlet Temperature	525.0	C
Shell Outlet Temperature	250.8	C

Preheater D-HX		
Duty	0	MW
Tube Inlet Temperature	520.0	C
Tube Outlet Temperature	215.0	C
Shell Inlet Temperature	175.0	C
Shell Outlet Temperature	357.1	C

Nominal Operation

- Nominal (baseload) power output; 94 MWe
- Salt acts as an intermediate heat transfer fluid between He and steam.
- Tanks bypassed.





C-HX		
Duty	91.79	MW
Tube Inlet Temperature	470.0	C
Tube Outlet Temperature	745.0	C
Shell Inlet Temperature	750.0	C
Shell Outlet Temperature	525.0	C

D-HX		
Duty	41.80	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	470.0	C
Shell Inlet Temperature	177.9	C
Shell Outlet Temperature	565.0	C

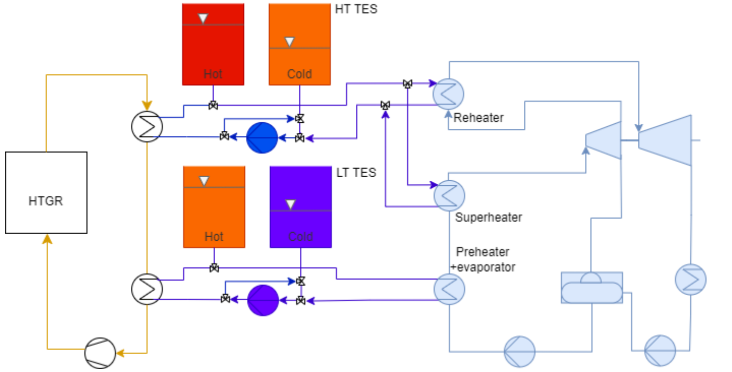
Superheater D-HX		
Duty	61.22	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	470.0	C
Shell Inlet Temperature	357.1	C
Shell Outlet Temperature	565.0	C

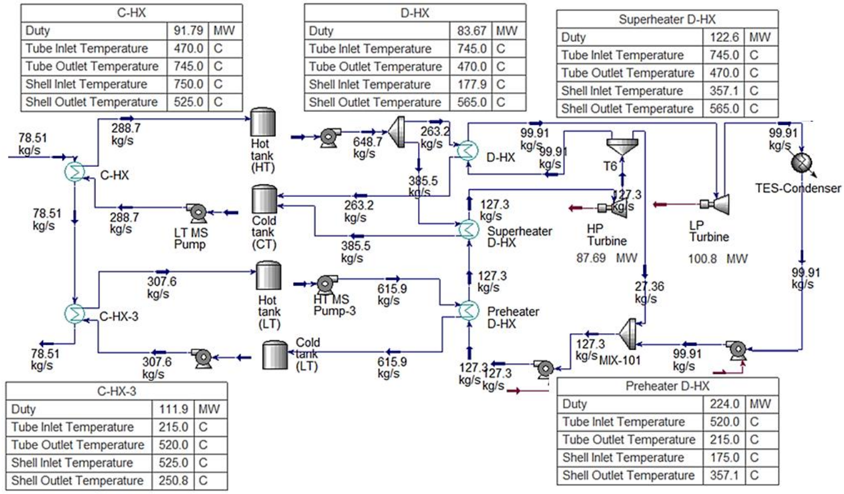
C-HX-3		
Duty	111.9	MW
Tube Inlet Temperature	215.0	C
Tube Outlet Temperature	520.0	C
Shell Inlet Temperature	525.0	C
Shell Outlet Temperature	250.8	C

Preheater D-HX		
Duty	111.9	MW
Tube Inlet Temperature	520.0	C
Tube Outlet Temperature	215.0	C
Shell Inlet Temperature	175.0	C
Shell Outlet Temperature	357.1	C

2X Boosting Discharge Mode

- Power output at 2X nominal; 188 MWe
- Hot salt from He HX is mixed with salt from hot tank and goes to steam cycle.
- Tanks are being discharged.
- Practical design might involve parallel turbines.





C-HX		
Duty	91.79	MW
Tube Inlet Temperature	470.0	C
Tube Outlet Temperature	745.0	C
Shell Inlet Temperature	750.0	C
Shell Outlet Temperature	525.0	C

D-HX		
Duty	83.67	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	470.0	C
Shell Inlet Temperature	177.9	C
Shell Outlet Temperature	565.0	C

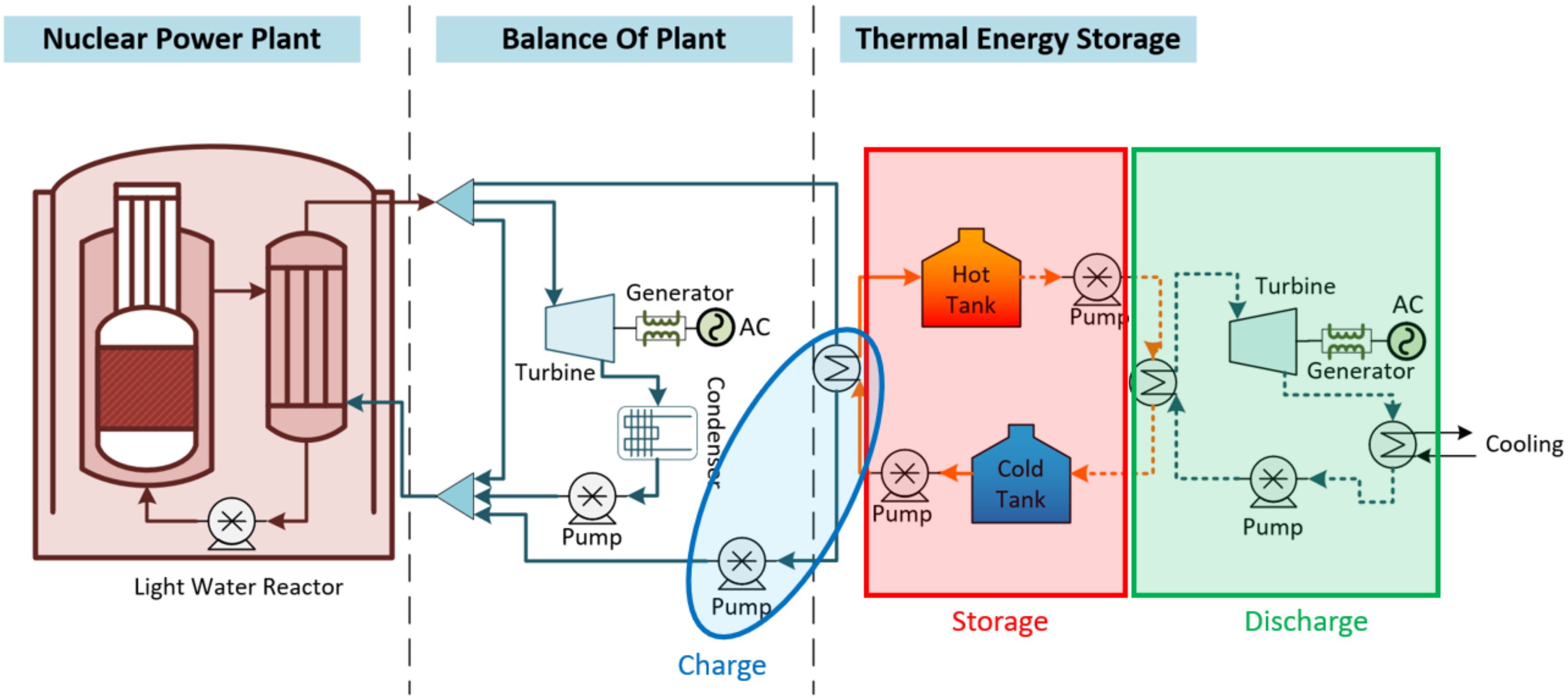
Superheater D-HX		
Duty	122.6	MW
Tube Inlet Temperature	745.0	C
Tube Outlet Temperature	470.0	C
Shell Inlet Temperature	357.1	C
Shell Outlet Temperature	565.0	C

C-HX-3		
Duty	111.9	MW
Tube Inlet Temperature	215.0	C
Tube Outlet Temperature	520.0	C
Shell Inlet Temperature	525.0	C
Shell Outlet Temperature	250.8	C

Preheater D-HX		
Duty	224.0	MW
Tube Inlet Temperature	520.0	C
Tube Outlet Temperature	215.0	C
Shell Inlet Temperature	175.0	C
Shell Outlet Temperature	357.1	C

Technoeconomic Analysis (HERON)

Component groupings for HERON



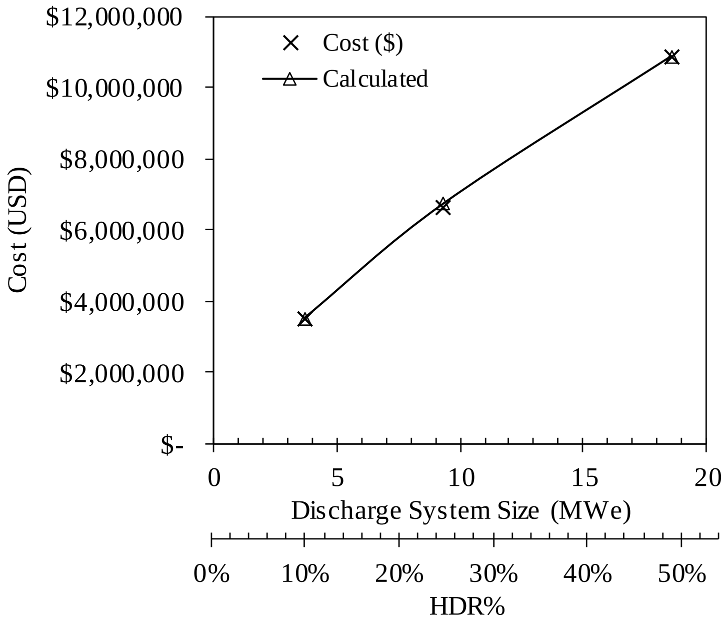
Charge rate in MWth

Storage size in MWhth

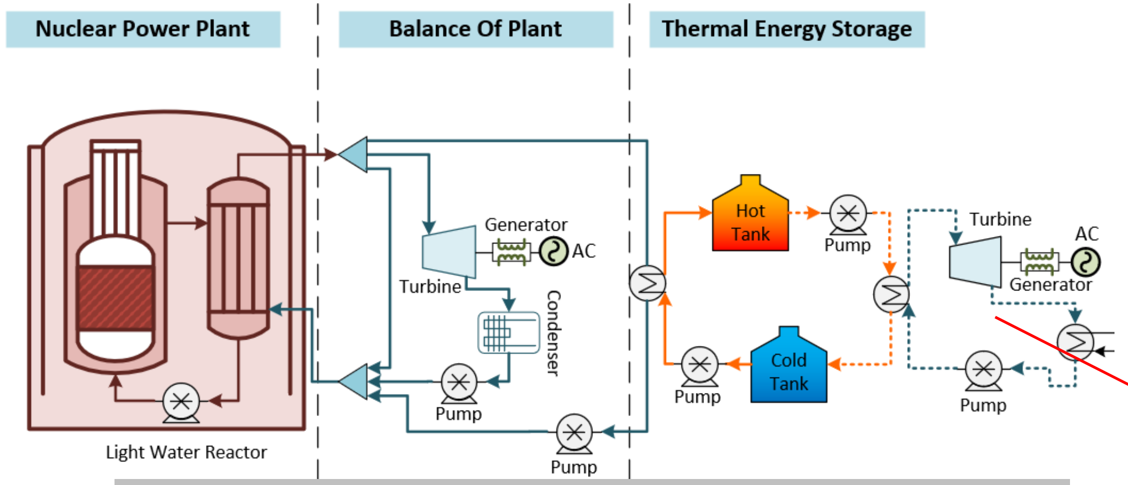
Discharge rate in MWth

$$Y = A \,.\, (D / D')^x$$

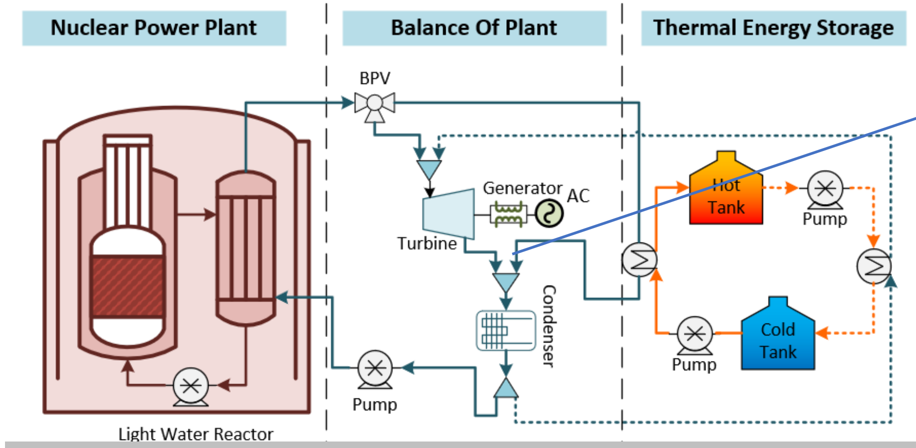
One example showing a cost function curve for the discharge system (IHX, turbine, condenser, condenser feedwater pump, TES power cycle pump)



TES Coupling with Advanced Reactors (Dedicated vs Oversized BOP)

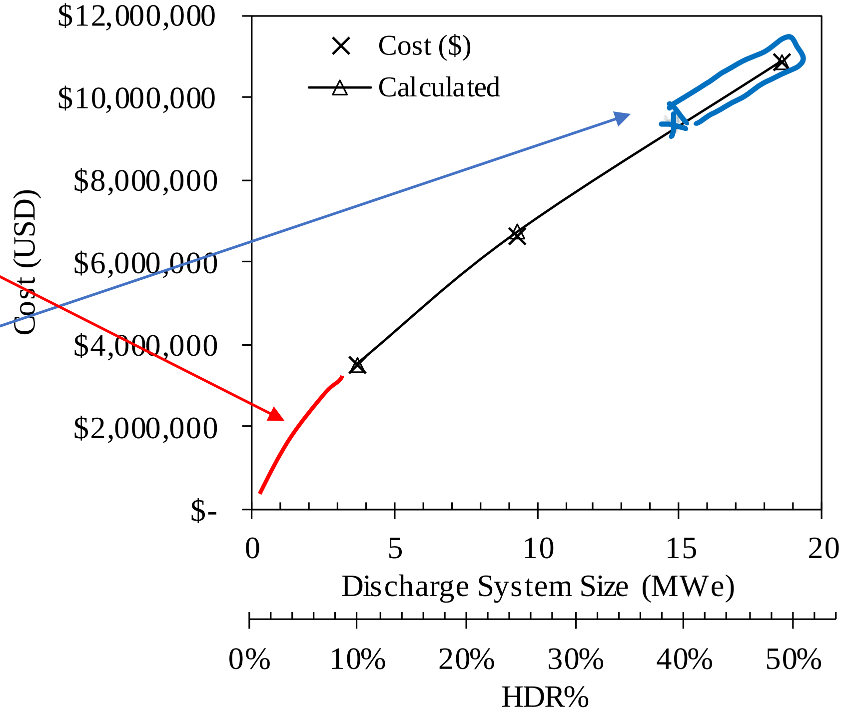


Parallel – Steam “two phase” - Two separate BOP



Parallel – Steam “two phase” - Single “oversized” BOP

One example additional cost realized for adding 4MWe of electric power generation via a separate BOP or oversized BOP equipment (example showing turbine cost function)

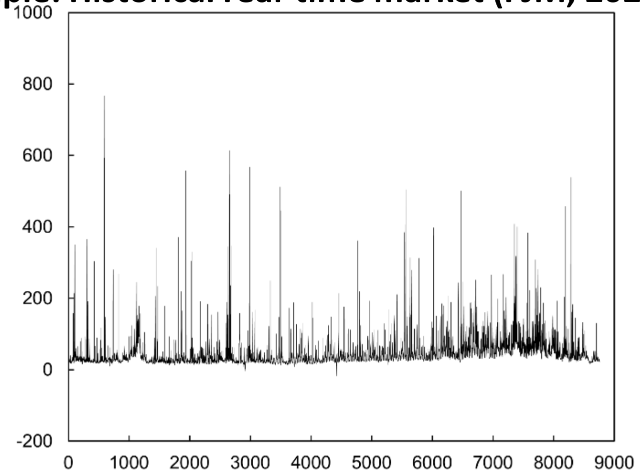


IES
Integrated Energy Systems

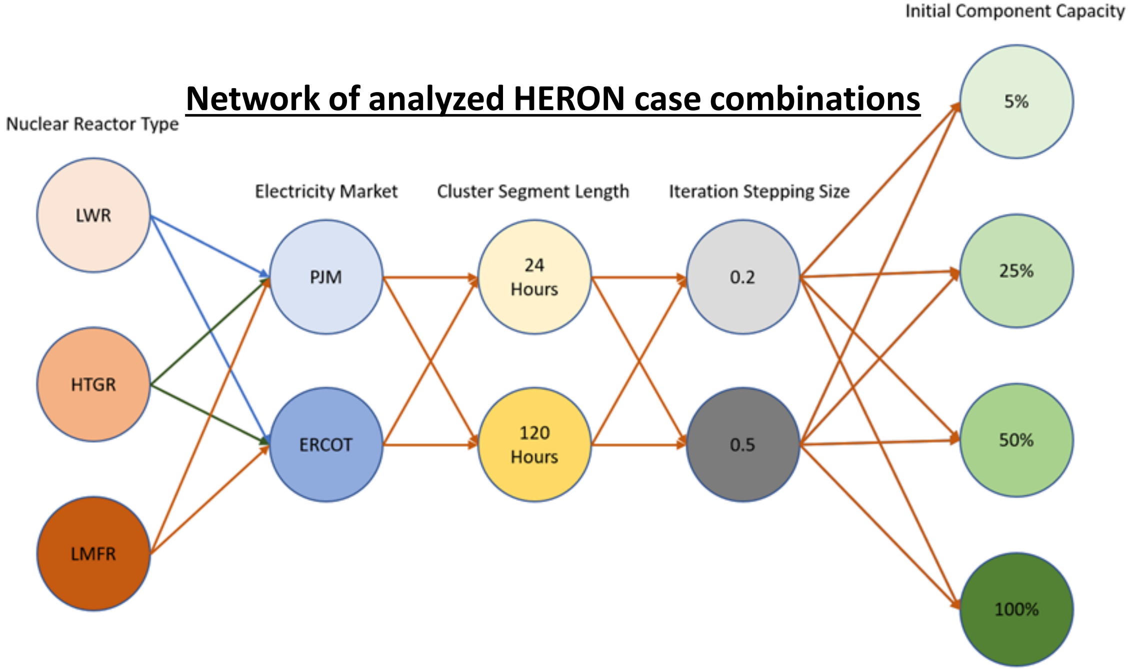
TES Coupling with Advanced Reactors (Steam-Molten Salt for TES heat)

- **SYNTHETIC HISTORY GENERATION**
  - Real-time hourly market for PJM and ERCOT
  - Historical real-time market data using Raven (2018-2047)
  - Synthetic history data used in HERON runs
- **Analysis of a network of possible HERON case combinations**
  - 3 reactor types for the Steam to molten salt TES heat extraction
  - Each in two different markets
  - Using two different cluster segment lengths in Heron and different iteration stepping size
  - Two different cluster segment lengths and 2 iteration stepping size
  - 4 initial component capacities used [avoid incorrect local maximum for NPV values (finding global maximum)]
  - 43 cases for each reactor (~129 cases in total)
- **TES optimization results**
  - Cont’d (next slide)

Example: Historical real-time market (PJM, 2021)



Network of analyzed HERON case combinations



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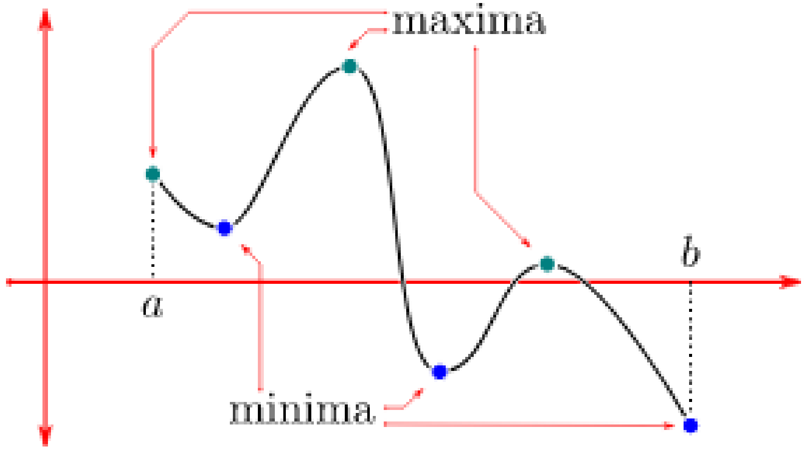
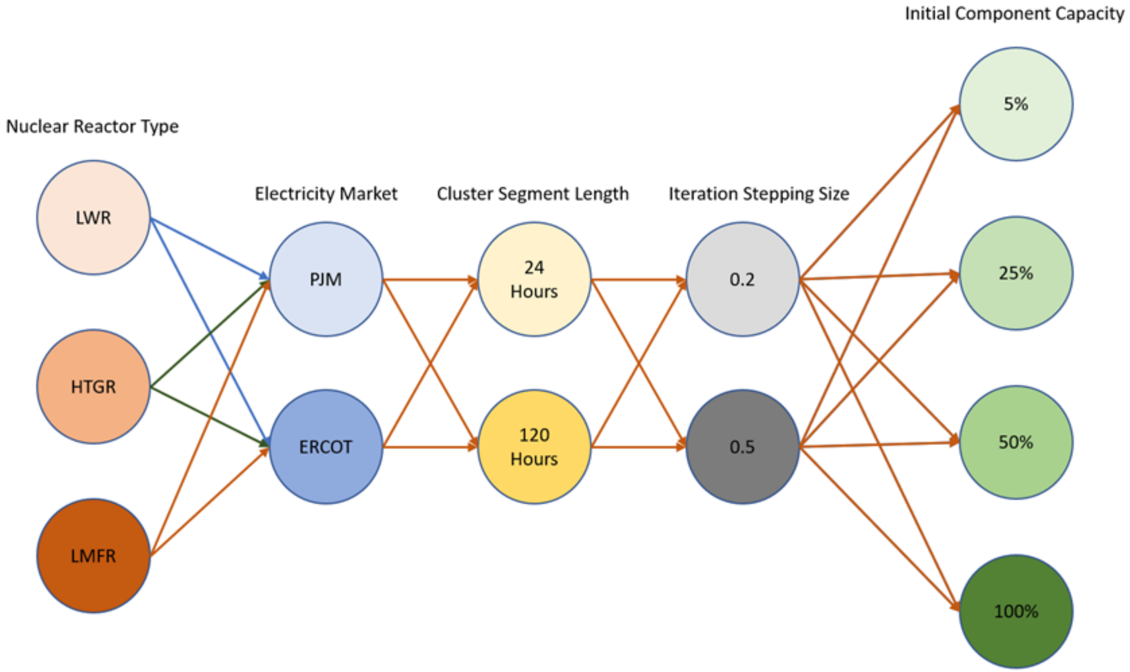



Nuclear Reactor Type
LWR
HTGR
LMFR

Electricity Market
PJM
ERCOT

Cluster Segment Length
24 Hours
120 Hours

Iteration Stepping Size
0.2
0.5

Initial Component Capacity
5%
25%
50%
100%

TES Coupling with Advanced Reactors (Steam-Molten Salt for TES heat)

Coupling analysis results from HERON (blue 🟦: Baseline [No TES]; gray ⬜: Negative ΔNPV; gold 🟨: Very Low Capacities; light green 🟩: Successful Cases; dark green 🟩: Maximum ΔNPV).

Initial Capacities	Step size	Segment Length (hrs)	Market
Baseline	N/A	24	PJM
Default	0.2	24	PJM
Default	0.5	24	PJM
25%	0.2	24	PJM
25%	0.5	24	PJM
50%	0.2	24	PJM
50%	0.5	24	PJM
100%	0.2	24	PJM
100%	0.5	24	PJM
Baseline	N/A	120	PJM
Default	0.2	120	PJM
Default	0.5	120	PJM
25%	0.2	120	PJM
25%	0.5	120	PJM
50%	0.2	120	PJM
50%	0.5	120	PJM
100%	0.2	120	PJM
100%	0.5	120	PJM
Baseline	N/A	24	ERCOT
Default	0.2	24	ERCOT
Default	0.5	24	ERCOT
25%	0.2	24	ERCOT
25%	0.5	24	ERCOT
50%	0.2	24	ERCOT
50%	0.5	24	ERCOT
100%	0.2	24	ERCOT
100%	0.5	24	ERCOT
Baseline	N/A	24	ERCOT
Default	0.2	120	ERCOT
Default	0.5	120	ERCOT
25%	0.2	120	ERCOT
25%	0.5	120	ERCOT
50%	0.2	120	ERCOT
50%	0.5	120	ERCOT
100%	0.2	120	ERCOT
100%	0.5	120	ERCOT

LWR - TES Coupling

Market	Mean NPV (USD)	Capacity (Charge, Storage, Discharge)	Delta NPV (USD)
PJM	$147,773,046	0, 0, 0	
PJM	$145,143,366	-6.49, 1.32E-07, -8.91	-$2,629,680
PJM	$147,842,171	0,0,0	$69,125
PJM	$138,099,411	-0.585, 0.623, -69.19	-$9,673,635
PJM	$147,862,954	0,0,0	$89,908
PJM	$136,012,707	-90.85, 116.97, -45.12	-$11,760,339
PJM	$132,184,918	-160, 0,-70.06	-$15,588,128
PJM	$147,823,874	-2.492, 0.101, -0.0307	$50,828
PJM	$147,918,817	0,0,0	$145,771
PJM	$150,154,838	0, 0, 0	
PJM	$150,205,613	0,0,0	$50,775
PJM	$150,211,742	0,0,0	$56,904
PJM	$150,168,268	0,0,0	$13,430
PJM	$150,205,438	0,0,0	$50,600
PJM	$150,199,696	0,0,0	$44,858
PJM	$150,205,063	0,0,0	$50,225
PJM	$150,170,901	0,0,0	$16,063
PJM	$131,211,751	-133.34, 165.26, -159.99	-$18,943,087
ERCOT	$173,267,567	0, 0, 0	
ERCOT	$171,195,297	0,28.6,0	-$2,072,270
ERCOT	$175,505,510	-8.2,17.7,9.8	$2,237,943
ERCOT	$178,748,433	-43.9,71.3,36	$5,480,866
ERCOT	$172,762,829	-22.7,16.7, -35	-$504,738
ERCOT	$162,281,264	-86.9, 326.8, -129	-$10,986,303
ERCOT	$175,220,880	-98.7, 173, -148.7	$1,953,313
ERCOT	$161,692,273	-159.6, 630.8, -159.9	-$11,575,294
ERCOT	$170,972,789	-159.7,350.4,-155.6	-$2,294,778
ERCOT	$189,398,404	0, 0, 0	
ERCOT	$190,602,460	-3.05, 0.04, -0.23	$1,204,056
ERCOT	$189,669,980	-105.6, 1.94, -0.96	$271,576
ERCOT	$186,681,379	-41.9, 84.3, -14.7	-$2,717,025
ERCOT	$190,756,456	-42, 0.9, -0.04	$1,358,052
ERCOT	$194,443,952	-100, 131, -104.7	$5,045,548
ERCOT	$195,182,643	-86.3, 160.5, -122.3	$5,784,239
ERCOT	$197,601,129	-155.6 ,548.2, -157.5	$8,202,725
ERCOT	$196,681,297	-117.6, 354.7, -131.1	$7,282,893

HTGR - TES Coupling

Market	Mean NPV (USD)	Capacity (Charge, Storage, Discharge)	Delta NPV (USD)
PJM	$258,575,648	0, 0, 0	
PJM	$258,690,576	0,0,0	$114,928
PJM	$258,727,400	0, 115.64, -5.62	$151,753
PJM	$255,749,588	-42.21, 206.59, -57.09	-$2,826,059
PJM	$254,913,855	-43.77, 236.79, -44.61	-$3,661,792
PJM	$253,707,912	-73.94, 322.94, -69.61	-$4,867,736
PJM	$253,430,658	-154.91, 253.87, -85.02	-$5,144,990
PJM	$248,357,111	-202.46, 990.29, -202.61	-$10,218,537
PJM	$252,635,286	-149.43, 439.95, -118.49	-$5,940,362
PJM	$262,698,245	0, 0, 0	
PJM	$262,713,606	0,0,0	$15,361
PJM	$262,622,391	0,0,0	-$75,853
PJM	$251,969,081	-59.44, 205.91, -62.25	-$10,729,164
PJM	$262,641,080	0,0,0	-$57,165
PJM	$252,463,614	-174.92, 428.1, -159.04	-$10,234,631
PJM	$252,089,693	-188.61, 335.05, -101.04	-$10,608,552
PJM	$253,501,444	-201.42, 548.21, -184.21	-$9,196,800
PJM	$253,454,930	-202.86, 587.78, -202.64	-$9,243,314
ERCOT	$302,911,238	0, 0, 0	
ERCOT	$303,557,416	-4.6, 148.7, -20.5	$646,178
ERCOT	$307,862,929	-9.8, 60.4, -10.5	$4,951,691
ERCOT	$311,215,653	-52.5, 332.8, -48.8	$8,304,415
ERCOT	$342,067,044	-205, 1218, -205	$39,155,806
ERCOT	$327,717,451	-99.4, 360.9, -108.9	$24,806,213
ERCOT	$344,141,760	-165.1, 699.4, -176.6	$41,230,522
ERCOT	$343,886,881	-200.2, 1214, -200.6	$40,975,643
ERCOT	$350,963,466	-188.4, 762, -202	$48,052,228
ERCOT	$331,215,757	0, 0, 0	
ERCOT	$330,356,799	-11.3, 85.4, -9.6	-$858,958
ERCOT	$330,245,347	-11.7, 85.4, -13.7	-$970,410
ERCOT	$345,657,555	-63, 506, 71	$14,441,798
ERCOT	$375,522,679	-94, 470.3, -154	$44,306,922
ERCOT	$371,286,637	-167.3, 227.4, -154.3	$40,070,880
ERCOT	$391,071,440	-198.3, 976.2, 193.5	$59,855,683
ERCOT	$401,735,694	-202.4, 1218, -201.6	$70,519,937
ERCOT	$403,027,448	-200.8, 1203.6, -202.9	$71,811,691

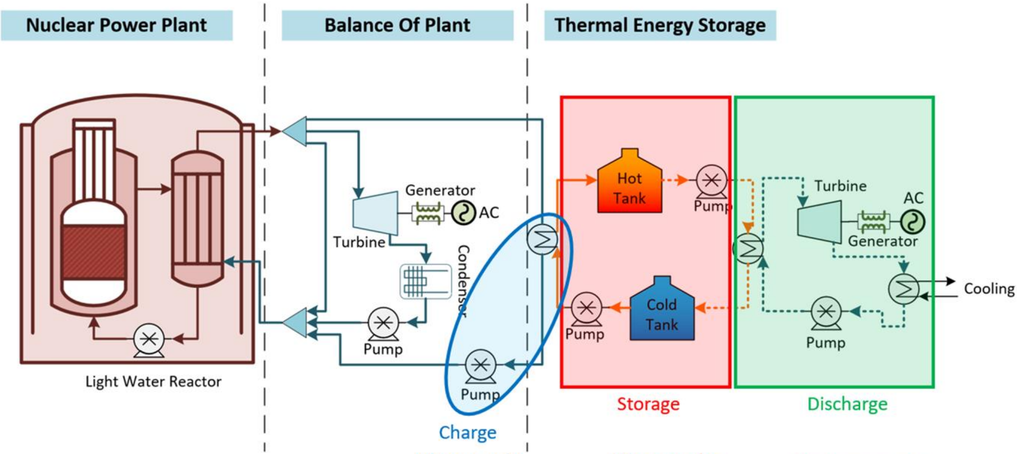
LMFR - TES Coupling

Market	Mean NPV (USD)	Capacity (Charge, Storage, Discharge)	Delta NPV (USD)
PJM	$1,837,278,574	0, 0, 0	
PJM	$1,834,553,149	0,0,0	-$2,725,425
PJM	$1,830,055,859	0,0,0	-$7,222,715
PJM	$1,823,705,468	-474.54, 1411.81, -520.46	-$13,573,106
PJM	$1,823,066,542	-544.65, 1595.08, -720.79	-$14,212,032
PJM	$1,830,483,636	-742.47, 2416.47, -923.34	-$6,794,938
PJM	$1,877,403,749	-1680, 4786.57, -1617.12	$40,125,175
PJM	$1,874,213,266	-1680, 6115.83, -1680	$36,934,692
PJM	$1,888,576,897	-1675.21, 4719.85, -1665.77	$51,298,323
PJM	$1,862,989,320	0, 0, 0	
PJM	$1,863,529,957	0,0,0	$540,637
PJM	$1,863,542,269	0,0,0	$552,949
PJM	$1,896,256,614	-828.57, 2341, -1078.5	$33,267,294
PJM	$1,870,040,327	-566.46, 1716.67, -740.79	$7,051,007
PJM	$1,948,440,997	-1210.42, 4081.88, -1676.11	$85,451,677
PJM	$1,966,609,642	-1677.54, 4533.75, -1679.48	$103,620,323
PJM	$1,898,939,479	-1680, 10080, -1680	$35,950,160
PJM	$1,964,267,755	-1637., 4773.23, -1673.6	$101,278,435
ERCOT	$2,154,163,005	0, 0, 0	
ERCOT	$2,291,607,968	-463.4, 1971.4, -358.6	$137,444,963
ERCOT	$2,308,034,577	-326.3, 1363.3, -531.8	$153,871,572
ERCOT	$2,221,576,136	-334.2, 2880.2, -473.5	$67,413,131
ERCOT	$2,545,872,657	-981.6, 6945, -1460.4	$391,709,652
ERCOT	$2,421,523,450	-903.1, 5770.9, -959.6	$267,360,445
ERCOT	$2,388,581,887	-1096.7, 1728.4, -900	$234,418,882
ERCOT	$2,628,654,807	-1679.6, 9985.8, -1603.5	$474,491,802
ERCOT	$2,655,816,129	-1595.2, 9515.8, -1628	$501,653,124
ERCOT	$2,299,782,706	0, 0, 0	
ERCOT	$2,483,402,651	-305.1, 1773.9, -314.2	$183,619,945
ERCOT	$2,440,500,538	-144.2, 2721.9, -571.6	$140,717,832
ERCOT	$2,680,035,145	-626.2, 3403.8, -905	$380,252,439
ERCOT	$2,809,964,929	-1170.4, 3039, -1190	$510,182,223
ERCOT	$2,686,940,783	-844.4, 4915.8, -826.9	$387,158,077
ERCOT	$3,119,321,494	-1676.6, 5596.5, -1664.4	$819,538,788
ERCOT	$3,122,781,527	-1611.5, 10080, -1679	$822,998,821
ERCOT	$3,064,986,593	-1559.9, 9638.9, 1636.3	$765,203,887

TES Coupling with Advanced Reactors (Steam-Molten Salt for TES heat)

Optimization result for maximum NPV

Reactor Type	Initial Capacities	Step Size	Segment Length (hours)	Electricity Market	ΔNPV (USD)	Capacity of Charge, Storage, Discharge (MW_{th}, MWh_{th}, MW_{th})
A-LWR	50%	0.5	24	ERCOT	$1,953,313	-98.7, 173, 148.7
A-LWR	100%	0.2	120	ERCOT	$8,202,725	-155.6, 548.2, -157.5
HTGR	100%	0.5	24	ERCOT	$48,052,228	-188.4, 762, -202
HTGR	100%	0.5	120	ERCOT	$71,811,691	-200.8, 1203.6, -202.9
LMFR	100%	0.5	24	PJM	$51,298,323	-1675.2, 4719.9, -1665.8
LMFR	50%	0.5	120	PJM	$103,620,323	-1677.5, 4533.8, -1679.5
LMFR	100%	0.5	24	ERCOT	$501,653,124	-1595.2, 9515.8, -1628
LMFR	100%	0.2	120	ERCOT	$822,998,821	-1611.5, 10080, -1679

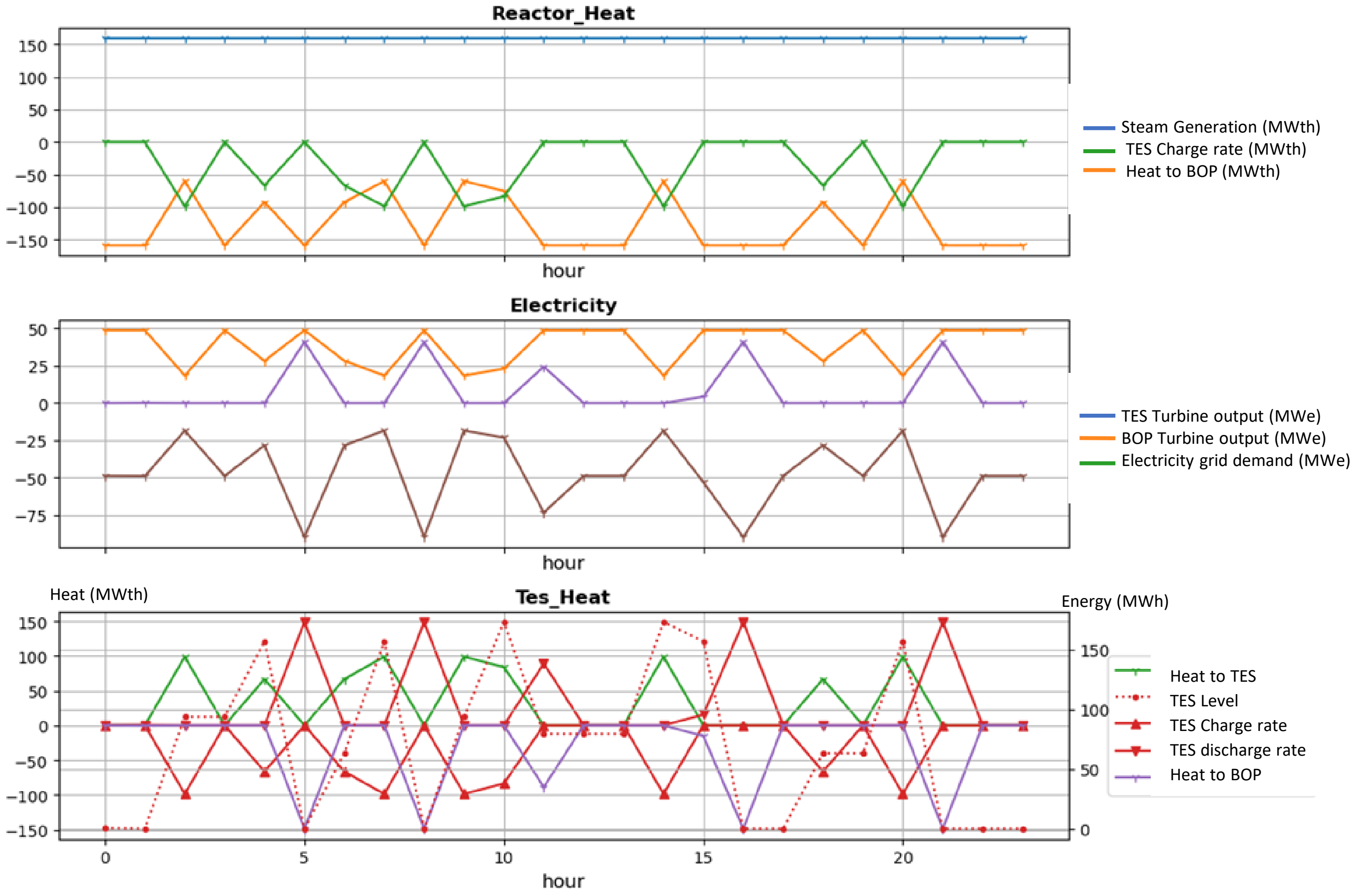


Charge rate in MWth

Storage size in MWhth

Discharge rate in MWth

Selected example for A-LWR in ERCOT



DYMOLA TRANSIENT MODELING

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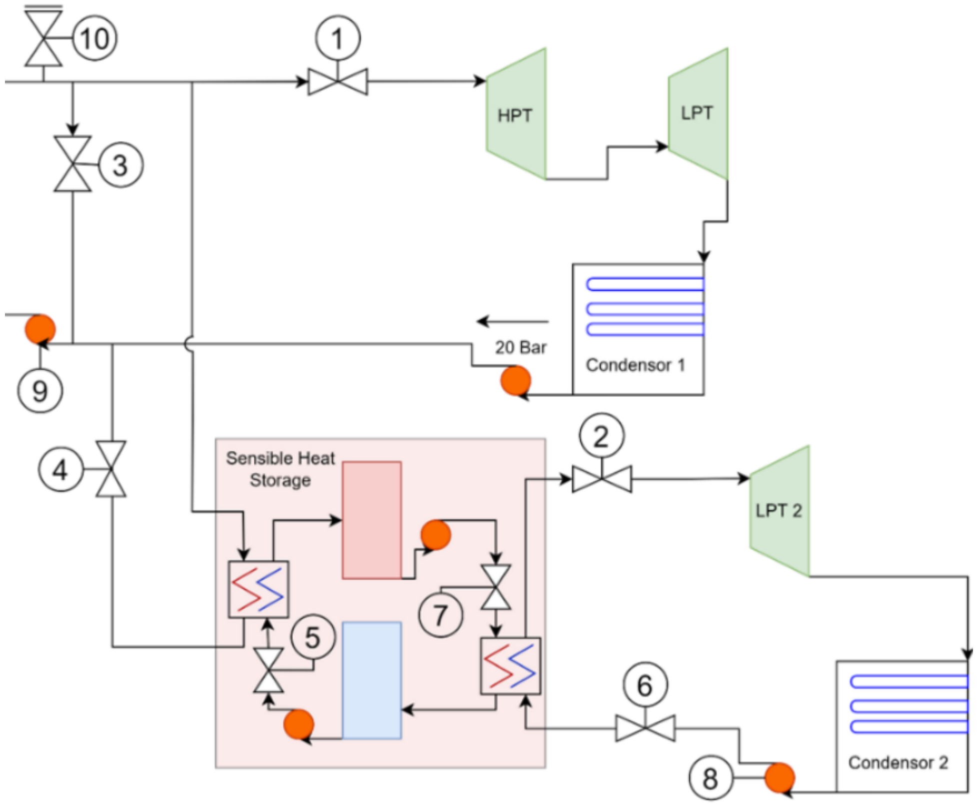
- **Motivation**
  - To understand the dynamic behavior of IES and to evaluate systems' controls
  - Further evaluation of integration techniques in transient state conditions
- **Control Scheme**
  - HPT and LPT turbines and a simple TES BOP. Feedwater is sourced directly from the TES BOP.
  - Testing severe cyclical ramping to establish expectations for how the system should respond to dynamic dispatching. i.e.: forcing the system to periodically ramp from full charging mode to a brief full discharge standby period, before demand immediately reverts to full charging mode.

Block diagram of in Dymola model.



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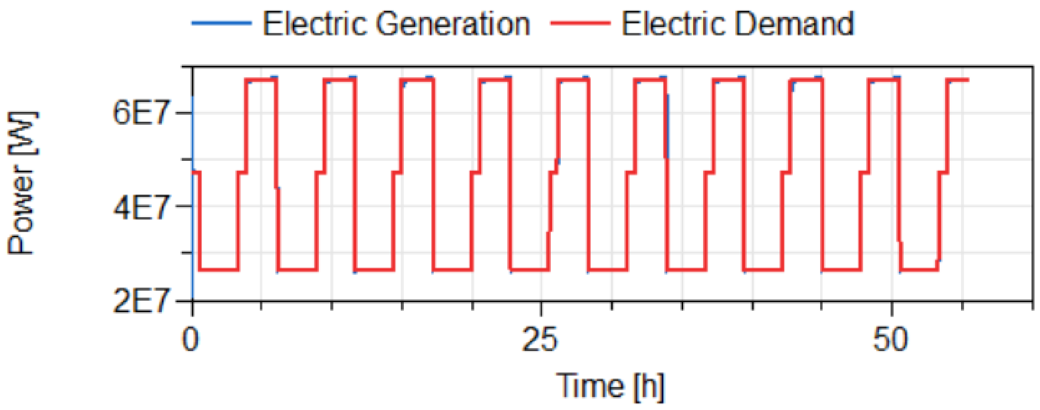
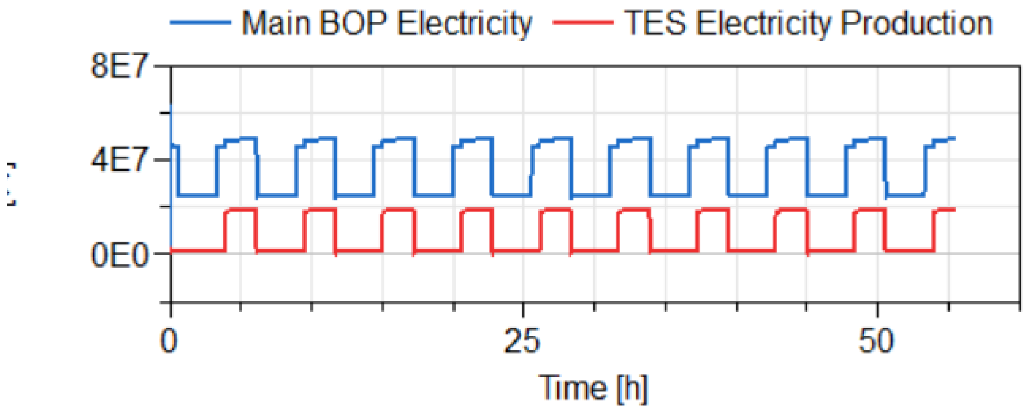
  - Aside from small demand misses immediately before and after demand ramps, the system was capable of meeting demand at all three power levels.

Electric demand and power production curves



Power production from the primary BOP and TES BOP



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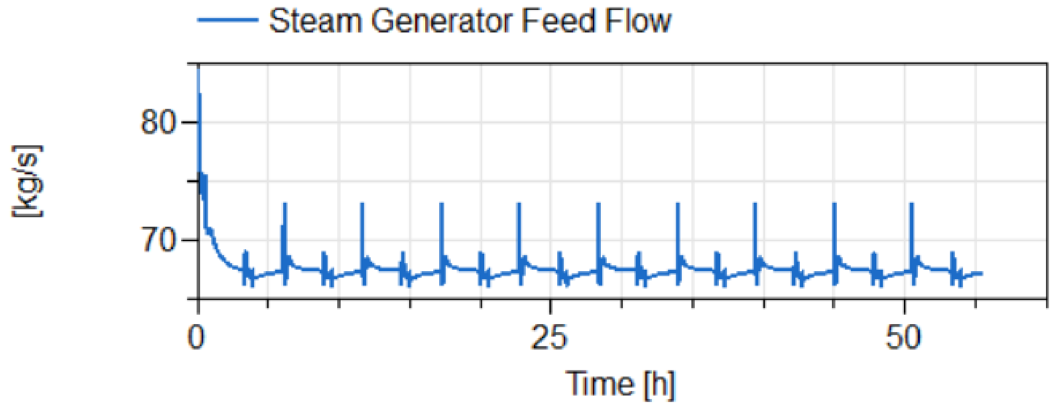
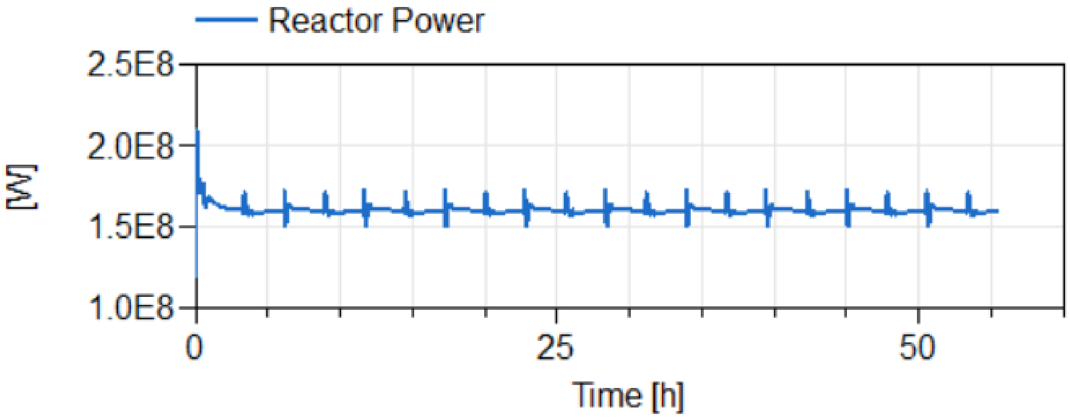
  - Brief changes steam generator mass flow occur due to "less-than-ideal" heating power changes within the feedwater system (over-simplification in the feedwater system design).
  - Minimal changes on the primary-side impacts within the nuclear core via coolant feedback mechanisms, control rods respond effectively and maintain the reactor power within +/- 5% of nominal power throughout the simulation.

Steam generator mass flow rate



Reactor thermal power, mainly maintained within +/- 5%



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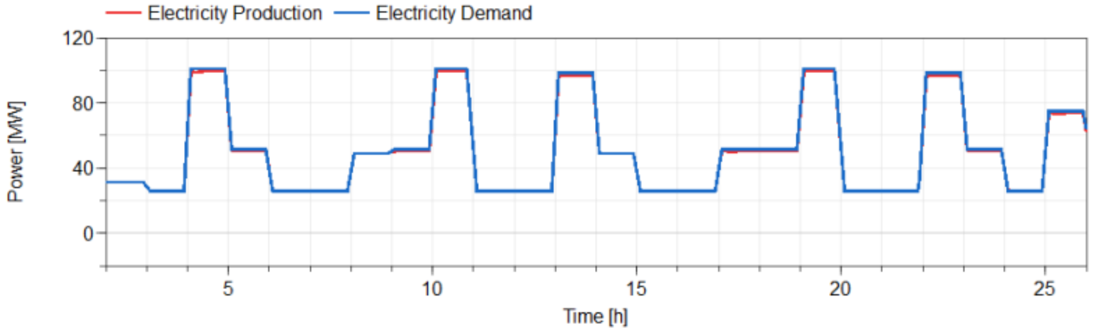
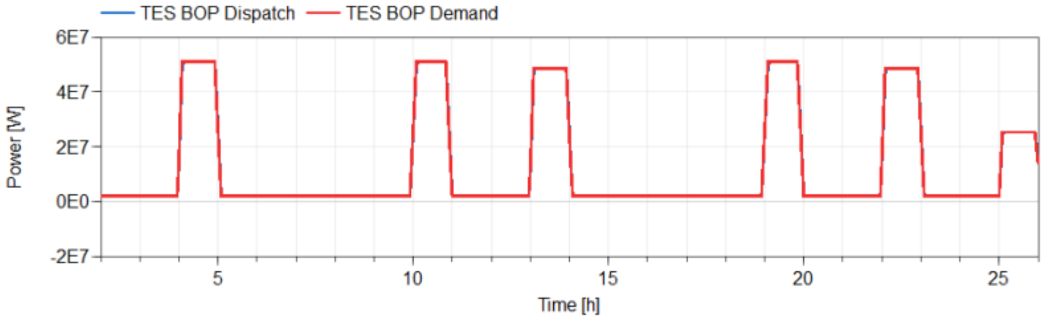
  - Heat dispatch demand tests (true demand vs production)

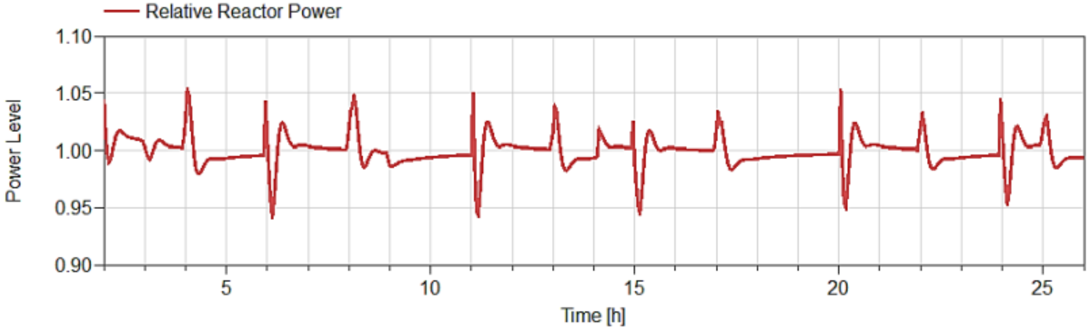
Electricity production vs. demand throughout a 24-hour dispatch



TES BOP dispatch throughout a 24-hour dispatch test



Relative reactor power throughout the dispatch test. The power is generally maintained within +/- 5% of nominal power.



Thanks for your attention…

Questions?

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Rami.Saeed@inl.gov

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