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DESIGN AND OPERATION OF AN ELECTRIC PEAKING/INDUSTRIAL STEAM PRODUTION UNIT FOR SMRS

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Various methods of Thermal Energy Storage (TES) can be coupled to nuclear (or renewable) power sources to help absorb grid variability caused by daily load demand changes and renewable intermittency. Our previous research has shown that coupling a sensible heat TES system to a Small Modular Reactor (SMR) allows the reactor to run at effectively nominal full power during periods of variable electric demand by bypassing steam to the TES system during periods of excess capacity. In this paper we demonstrate that this stored thermal energy can be recovered; allowing the TES system to act as a peaking unit during periods of high electric demand, or used to produce steam for ancillary applications such as desalination. For both applications the reactor can operate continuously at approximately 100% power.

I. INTRODUCTION

Renewable energy technologies continue to become more attractive with improvements in efficiency and price-point. However, the variability of renewables creates additional challenges for the electric grid. The most common forms of installed renewable energy are wind and solar. Wind and solar energy, while zero carbon footprint energy sources, have energy outputs which cannot be directly controlled and instead are subject to the variability found in nature. This implies the energy production side of the equation is no longer 100% dispatchable and, depending on the amount of solar and wind installed on the grid, could mean large, uncontrolled variations in energy production. This can lead to mismatches between energy demand and energy production and, ultimately, system instabilities and blackouts. Furthermore, the integration of renewable energy can lead to over-generation potential as shown in Figure 1. This over-generation potential can result in negative electricity prices where the utility is forced to pay customers who are willing to take the power produced. Negative prices occur when a large amount of inflexible power generation occurs simultaneously with low demand.[1] This phenomenon occurs more frequently when a large amount of intermittent renewable energy is introduced to the grid.

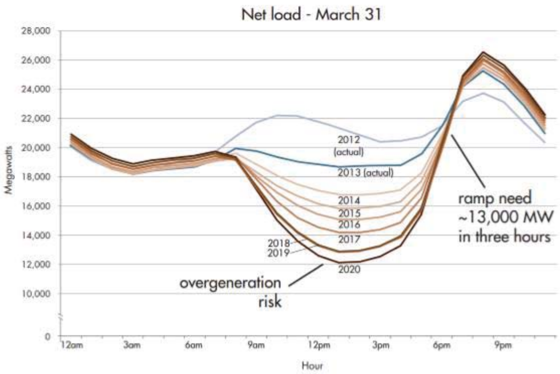

Figure 1: "Duck Curve" from substantial renewable energy (solar PV) integration in California.[2]

To maintain our current lifestyle, baseload plants will still be required. However, as the penetration of renewables increases, baseload plants need to be more flexible in their operation. Small Modular Reactors (SMRs) can potentially provide this flexibility in operation. SMRs offer increased site compatibility, advanced passive safety systems for the removal of decay heat, lower capital costs for construction, and reduced primary and secondary-side inventory.[3] With a nominal electrical output of 300 MWe or less, SMRs can be clustered in a single location to form a more traditional baseload nuclear power plant, or deployed to remote locations, such as military bases with limited grid access, to provide reliable emissions-free energy.[4] During times when the reactor is subjected to significant time varying electric load there are three options: operate in load follow mode, operate at or near steady state and bypass steam directly to the condenser, or maintain power and store excess energy for later use.[5] The first two options result in lost energy potential. Load follow operation can also result in additional stresses on the fuel and other mechanical components. The more attractive approach is to operate the reactor at or near steady state and bypass excess steam to a thermal energy storage system. The thermal energy can then be recovered, either as a supplement to the power plant during peak demand times, or for process steam applications.

II. SYSTEM DESIGN, CONNECTION, AND CONTROL

Integrated nuclear hybrid energy systems (NHES) involve the design and connection of several complex, standalone systems. The control algorithms involved are unique to each application and the particular design of the components. NHES architectures can include process steam applications, energy storage, and the presence of intermittent energy sources such as wind and solar.[6] The hybrid energy system described in this paper utilizes a B&W mPower[7] style SMR connected to a two-tank sensible heat thermal energy storage system.

II.A. Reactor Simulator

The target SMR in this work is a representative Integral Pressurized Water Reactor (IPWR) with operating parameters similar to those of the mPower reactor proposed by B&W.[7] Operating parameters are given in Table I. IPWRs are characterized by having all major primary system components (core, steam generators, pressurizer, etc.) contained within the reactor vessel. A diagram of a typical IPWR is provided in Figure 2 For the IPWR considered in this work the steam generators are a typical once through design, with steam generator pressure control via the turbine control valves (TCVs) located between the pressure equalization header and the high pressure turbine. Feed control valves modulate such that feed flow rate matches a feed demand signal that is proportional to the turbine load plus a shim that insures turbine output matches load. Steam generator level (boiling length) is allowed to float. To simulate the dynamics of an IPWR system, NCSU has developed high fidelity simulation tools for predicting the dynamic response of IPWR systems under normal and off-normal conditions.[8,9,10,11]

Table I: SMR Operating Parameters

Parameter	Value
Reactor Thermal Output	530 MWt
Electric Output	180 MWe
Primary System Pressure	14.134 MPa (2050 psia)
Core Inlet Temperature	297 ˚C (566 ˚F)
Core Exit Temperature	322 ˚C (611 ˚F)
Core Flow Rate	13.6x10^{6} kg/hr (30 Mlbm/hr)
Steam Pressure	5.68MPa (825 psia)
Steam Temperature	299 ˚C (571 ˚F)
Feed Temperature	212 ˚C (414 ˚F)
Steam Flow Rate	9.53x10^{5} kg/hr (2.1Mlbm/hr)

The reactor simulator is capable of simulating IPWRs operating under forced and natural circulation conditions. Additional features include: a) reactor kinetics with overlapping control rod banks, Xenon, fuel and moderator temperature feedback, b) decay heat, c) hot channel models including Critical Heat Flux and peak fuel centerline temperatures, d) pressurizer with heaters and sprays, e) conventional and helical coil Once Through Steam Generators, f) Balance of Plant and g) associated control functions. Models exist for IPWR concepts spanning a range of thermal outputs, including designs similar to the Westinghouse IRIS, B&W mPower, and NuScale reactor concepts.[7]

II.B. Sensible Heat Storage System

Sensible heat storage involves the heating of a solid or liquid without phase change and can be deconstructed into two operating modes: charging and discharging. A two tank thermal energy storage system is a common configuration for liquid sensible heat systems. In the charging mode, cold fluid is pumped from a cold tank through an Intermediate Heat Exchanger (IHX), heated, and stored in a hot tank. In the discharge mode, the TES fluid is pumped from the hot tank to some energy recovery process (e.g. a boiler) and returned to the cold tank. Such systems have been successfully demonstrated in the solar energy field as a load management strategy.[12]

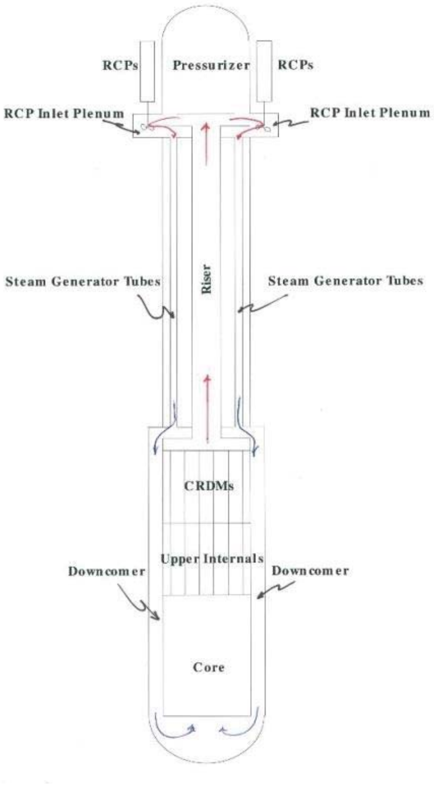

Figure 2: Representative IPWR

II.B.1. Connection Point

The performance of a Thermal Energy Storage (TES) System is a strong function of the connection point to the secondary side of the IPWR. For plants incorporating

Once Through Steam Generators (OTSG) the turbine control valves (TCVs) act as pressure control valves to maintain Steam Generator pressure at a given set point. Shown in Figure 3, Turbine Bypass Valves (TBVs) can be configured such that bypass steam can either be taken off the steam line at the pressure equalization header upstream of the turbine control valves (Aux 1), downstream of the turbine control valves prior to entering the high-pressure turbine (Aux 2), or at some low-pressure turbine tap (Aux 3). For the sensible heat TES system assumed here, it is desired to have roughly constant steam conditions since the shell side pressure in the Intermediate Heat Exchanger directly affects the TES fluid temperature leaving the IHX and ultimately stored in the hot tank. This makes taking bypass steam from the pressure equalization header upstream of the turbine control valves the preferred operating mode. Steam conditions downstream of the TCVs are a strong function of the load profile. Taking bypass steam downstream of the turbine control valves can result in highly varying steam pressures and temperatures and unacceptably low IHX pressures.

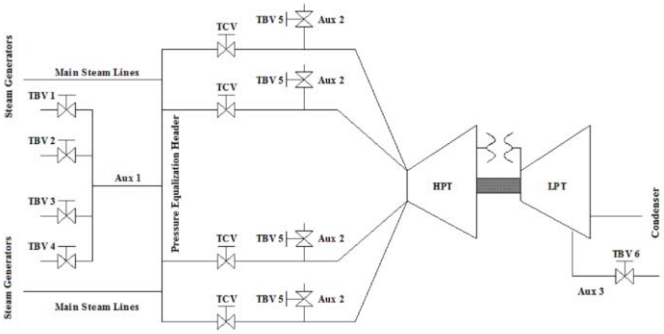

Figure 3: Bypass Steam Options

II.B.2. Sensible Heat Storage System Design

The proposed sensible heat Thermal Energy Storage System, shown in Figure 4, is configured as an electrical peaking unit. An outer loop interfaces with the reactor's Balance of Plant (BOP) directly through four parallel auxiliary turbine bypass valves (TBV) connected at the pressure equalization header. Bypass steam is directed through an intermediate heat exchanger (IHX) and discharged to the main condenser. An inner loop containing a TES fluid consists of two large storage tanks along with several pumps to transport the TES fluid between the tanks, the IHX and a steam generator. The TES system is designed to allow the reactor to run continuously at ~ 100% power, storing the excess power during times of low demand and operating the TES system as a peaking unit during periods of high demand.

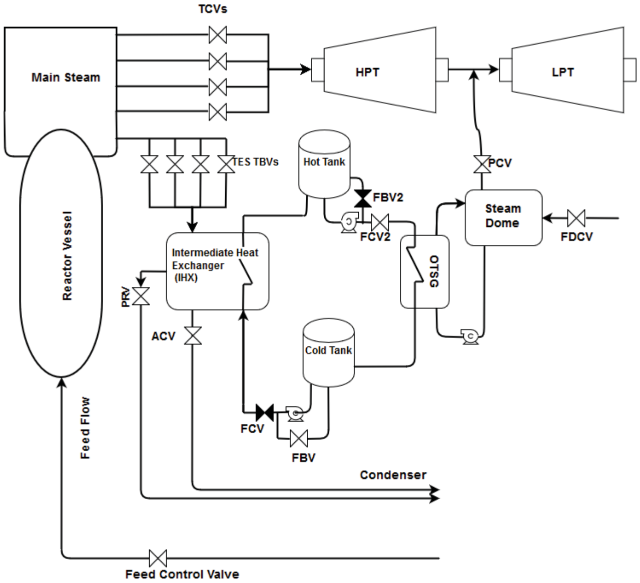

Figure 4: Schematic of an IPWR connected to a two-tank sensible heat thermal energy storage system, discharge mode

During periods of excess capacity, steam is directed through the auxiliary bypass valves where it condenses on the shell side of the IHX. TES fluid is pumped from the Cold Tank to the Hot Tank through the tube side of the IHX at a rate sufficient to raise the temperature of the TES fluid to a reference set point value. Condensate is collected in a hot well below the IHX and drains back to the main condenser through an auxiliary control valve (ACV). Conversely, the system is discharged during times of high turbine demand by pumping TES fluid from the Hot Tank to the Cold Tank through the tube side of a Once Through Steam Generator (OTSG) producing a saturated liquid-vapor mixture. This two-phase mixture flows into a steam dome where it is separated into the gas and liquid phases. The saturated steam is then reintroduced into the power conversion cycle at the high-pressure turbine exhaust, prior to entering the moisture separator/reheaters. A nitrogen cover gas dictates the tank pressures during charging and discharging operation. Flow Bypass Valves are included in the discharge lines of both the Hot and Cold tanks to prevent deadheading the pumps when the Flow Control Valves are closed. Common TES fluid properties are given in Table II. While the models are sufficiently general to handle any TES fluid, Therminol-66 is chosen as the TES fluid in this work as it is readily available, can be pumped at low temperatures, and offers thermal stability over the range (-3°C - 343°C) which covers the anticipated operating range of the TES system (203°C - 260°C). Molten salts (e.g. 48% $NaNO_3$ – 52% KNO_3) were not considered in this study, as the anticipated operating temperatures fall below their 222°C freezing temperature.[13]

Table II: Properties of Possible TES fluids at ~260 degrees Celsius (500 degrees Fahrenheit)

Heat Transfer Fluid	Boiling Point (°C)	Heat Storage (W*hr/m³°C)	Operating Range (°C)
Therminol®-66 (Ref. 14)	358 (678°F)	1039 (576.95 W*hr/m³°F)	-2.7 to 343.3 (27°F to 650°F)
Therminol®-68 (Ref. 15)	307 (586°F)	1013 (563.03 W*hr/m³°F)	-25.5 to 360 (-14°F to 680°F)
Therminol®-75 (Ref. 16)	342 (649°F)	992 (551.54 W*hr/m³°F)	79.44 to 385 (175°F to 725°F)

Other benefits of using Therminol-66 include its Material Safety Data Sheet (MSDS) classification as a nonhazardous material.[17] In addition, as hydrocarbons do not readily exchange hydrogen atoms with other materials,[18] tritium migration would be mitigated in the rare event simultaneous leaks in the steam generator and an IHX tube allowed activated primary water to mix with the TES fluid. In this event, the TES tanks would act as holding tanks for the activated water. In previous work, details on the equation sets and solution strategy used for solving the charging system have been provided.[19] Governing equations of the steam dome/steam generator model are discussed below.

II.B.3. Discharge Model Development

A three equation Global Compressibility Model is assumed for the shell side of the steam generator, where thermodynamic equilibrium is assumed between the phases. The steam dome model assumes the vapor region is saturated and the liquid region is subcooled. It is currently assumed that a pump will be used to provide a constant flow rate between the liquid region of the steam dome and the steam generator inlet. This can be changed later to eliminate the pump and allow for natural circulation to drive the steam generator flow if desired.

OTSG (Shell Side) Equation Set

Mass

$$V_j\left\{\frac{\rho_j^{t+\Delta t}-\rho_j^t}{\Delta t}\right\}+\rho_{j+1/2}^t v_{j+1/2}^{t+\Delta t}A_{j+1/2}-\rho_{j-1/2}^t v_{j-1/2}^{t+\Delta t}A_{j-1/2}=0 \quad (1)$$

Energy

$$\begin{aligned}&V_j\left\{\frac{\rho u_j^{t+\Delta t}-\rho u_j^t}{\Delta t}\right\}+\rho u_{j+1/2}^t v_{j+1/2}^{t+\Delta t}A_{j+1/2}-\rho u_{j-1/2}^t v_{j-1/2}^{t+\Delta t}A_{j-1/2}\\&=-P^t\left\{v_{j+1/2}^{t+\Delta t}A_{j+1/2}-v_{j-1/2}^{t+\Delta t}A_{j-1/2}\right\}+q_j^t \qquad (2)\\&-\left\{\frac{\alpha_l\alpha_g\rho_f\rho_g}{\rho}\left(u_{fg}+P_{SG}v_{fg}\right)v_rA_{xSG}\right\}_{j-1/2}^{j+1/2,t}\end{aligned}$$

State Equations

$$\rho=\rho_l(u_l,P) \text{ or } \rho=\alpha_l\rho_l+\alpha_g\rho_g \quad (3)$$

$$\rho u=\rho(u_l,P)u_l \text{ or } \rho u=\alpha_l\rho_lu_l+\alpha_g\rho_gu_g \quad (4)$$

Steam Dome Equation Set

Liquid Mass

$$\begin{aligned}&V_{SD}\left\{\frac{\alpha_l\rho_l^{t+\Delta t}-\alpha_l\rho_l^t}{\Delta t}\right\}=\rho_{FD}^t v_{FD}^{t+\Delta t}A_{FD}+\alpha_{lSG}^t\rho_f^t v_{SG}^{t+\Delta t}A_{xSG} \qquad (5)\\&-\rho_{lSD}^t v_{FCV}^{t+\Delta t}A_{FCV}-\left.\frac{\alpha_l\alpha_g\rho_f\rho_gv_r}{\rho}\right|_{SG}^{t}A_{xSG}\end{aligned}$$

Total Mass

$$\begin{aligned}&V_{SD}\left\{\frac{\rho_{SD}^{t+\Delta t}-\rho_{SD}^t}{\Delta t}\right\}=\rho_{FD}^t v_{FD}^{t+\Delta t}A_{FD}+\rho_{SG}^t v_{SG}^{t+\Delta t}A_{xSG} \qquad (6)\\&-\rho_{lSD}^t v_{FCV}^{t+\Delta t}A_{FCV}-\rho_g^t v_g^{t+\Delta t}A_{Steamline}\end{aligned}$$

Total Energy

$$\begin{aligned}&V_{SD}\left\{\frac{\rho u_{SD}^{t+\Delta t}-\rho u_{SD}^t}{\Delta t}\right\}=\left(\rho_{FD}u_{FD}+P_{SD}\right)^t v_{FD}^{t+\Delta t}A_{FD}\\&+\left(\rho u_{SG}+P_{SD}\right)^t v_{SG}^{t+\Delta t}A_{xSG}-\left(\rho_lu_{lSD}+P_{SD}\right)^t v_{FCV}^{t+\Delta t}A_{FCV} \qquad (7)\\&-\left(\rho_gu_g+P_{SD}\right)^t v_g^{t+\Delta t}A_{Steamline}\\&+\left\{\frac{\alpha_l\alpha_g\rho_f\rho_g}{\rho}\left(u_{fg}+P_{SD}v_{fg}\right)^t v_rA_{xSG}\right\}_{SG}^{t}\end{aligned}$$

State Equations

$$\left(\alpha_l\rho_l\right)_{SD}=\alpha_{lSD}\rho_l(u_{lSD},P_{SD}) \quad (8)$$

$$\rho_{SD}=\alpha_l\rho_l(u_{lSD},P_{SD})+\alpha_g\rho_g(P_{SD}) \quad (9)$$

$$\rho u_{SD}=\alpha_l\rho_l(u_{lSD},P_{SD})u_{lSD}+\alpha_g\rho_g(P_{SD})u_g \quad (10)$$

Momentum Equations

$$P_{SD}^{t+\Delta t}+\Delta P_{pFCV}=P_{SG}^{t+\Delta t}+\rho_{lSD}^t\left(K_{FCVLine}\right)\frac{\left(v_{FCV}^{t+\Delta t}\right)^2}{2} \quad (11)$$

$$P_{SD}^{t+\Delta t}=P_{LPT}^{t+\Delta t}+\rho_{lSD}^t\left(K_{PCV}^t+K_{PCVLine}\right)\frac{\left(v_g^{t+\Delta t}\right)^2}{2} \quad (12)$$

$$P_{cond}+\Delta P_{pFD}=P_{SD}^{t+\Delta t}+\rho_{lcond}^t\left(K_{FDCV}^t+K_{FDCVLine}\right)\frac{\left(v_{FD}^{t+\Delta t}\right)^2}{2} \quad (13)$$

$$P_{SG}^{t+\Delta t}=P_{SD}^{t+\Delta t}+\rho_{SG}^t\left(K_{SG}\right)\frac{\left(v_{SG}^{t+\Delta t}\right)^2}{2} \quad (14)$$

These equations are nonlinear in the new time values. Using a Newton-Iteration scheme, equations (1)-(14) can be reduced to a (n+2) by (n+2) matrix providing solutions for the new iterate (k+1) values $v_{FCV}^{k+1}, v_{1+1/2}^{k+1}, \ldots, v_{j+1/2}^{k+1}$, $v_{SG}^{k+1}, P_{SG}^{k+1}, P_{SD}^{k+1}$ where n is the number of steam generator nodes. The remaining new iterate values can be obtained directly by back substitution. The equations are iterated to convergence based on the maximum relative difference for any single variable between iterations. The converged values become the solution for the new time values.

II.C. Discharge System Control

The TES system can be operated in two different discharge modes. It can operate either as an electrical peaking unit to supplement electric production during times of high demand, or it can be used as a source of industrial steam production. Both modes are considered, each with its own set of control algorithms.

II.C.1. Electrical Peaking Unit

Operation as a peaking unit assumes three control valves: a Pressure Control Valve (PCV) on the steam dome to ensure constant pressure steam conditions in the boiler, a Feed Control Valve between the condenser and the steam dome, and a Flow Control Valve on the tube side of the boiler to regulate the amount of TES flow from the hot tank to the cold tank. Feed control to the steam dome is based on a standard three element controller where the error signals are steam dome level and steam flow/feed flow mismatch. TES flow control assumes the TES flow demand is proportional to the maximum design TES flow plus a correction term (shim). The shim term modifies the demand signal such that the instantaneous electric load is met. During times of discharge the reactor power is held constant by switching the feed signal on the main system feed control valve from regulating turbine output to maintaining constant reactor power. This modification allows the reactor to remain at approximately 100% power while the thermal energy storage system matches the increased turbine demand.

II.C.2. Industrial Steam Production

The control strategy for industrial steam production also assumes three control valves: a Pressure Control Valve (PCV) on the steam dome to ensure constant pressure steam conditions in the boiler, a Feed Control Valve to allow for level control within the steam dome and a Flow Control Valve on the tube side of the boiler to regulate the amount of TES flow from the hot tank to the cold tank. Feed control and pressure control strategies are the same as for operation as a peaking unit. TES flow control assumes the required TES flow is proportional to the maximum design TES flow plus a correction term (shim). The shim term modifies the demand signal such that the instantaneous steam demand is met.

III. NHES DYNAMIC SIMULATIONS

The goal of coupling a TES system to an IPWR is to operate the reactor at nominal full power, storing excess energy during periods of low demand and then recovering that energy during periods of high demand. Previous results show the advantages of having a TES system as a means of heat storage and load management.[19] The simulations shown here demonstrate the system's ability to operate as an effective peaking unit or as a continuous source of process steam. Three simulations were performed: a 24-hour typical summer day, three winter days with solar where day two is cloudy, and a 24-hour desalination run. On cloudy or rainy days solar panels are assumed to run at only 10% capacity.[20] For these simulations an mPower style reactor with the geometry and design parameters specified in Table I was utilized. TES design parameters are given in Table III.

Table III: TES Design Parameters for connection to a mPower-size IPWR

Parameter	**Value**
Hot Tank Volume	61,164 m^3
Cold Tank Volume	61,164 m^3
IHX Reference Exit Temperature	260 °C (500°F)
Number of TBV's	4
Maximum Steam Accommodation	~45% nominal steam flow
Pressure Relief Valve Upper Setpoint	5.377 MPa (780 psia)
Pressure Relief Valve Lower Setpoint	5.240 MPa (760 psia)
Turbine Header Pressure	5.688 MPa (825 psia)
Shell Side (outer loop) IHX Volume	101.94 m^3 (3600 ft^3)
Number of Tubes in IHX	19140
Length of Tubes	11.25 m (36.9 ft)
Tube Inner Diameter	0.013 m (0.044 ft)
Tube Outer Diameter	0.018 m (0.058 ft)
Steam Dome Reference Pressure	1.379 MPa (200 psia)
Steam Dome Volume	509.7 m^3 (18000 ft^3)
LPT reentrance point	1.207 MPa (175 psia)
Number of TES SG tube count	32761
TES Steam Generator volume	42.475 m^3 (1500 ft^3)
TES Steam Generator Height	9.144 m (30 ft)

III.A. Electrical Peaking Unit

This set of simulations illustrates the TES system's ability to operate as an electrical peaking unit. The unit is designed to accommodate ~35 MWe peaking potential. It is assumed the low-pressure turbine, generator and other Balance of Plant components have been sized to accept the additional thermal loads. The deployability of these systems requires that a single design be sized to accommodate a large range of load profiles. To demonstrate this capability the system was subjected to load profiles reflecting both diurnal and seasonal power demands.[21,22] It should be noted that a load profile could be chosen purely for economic reasons. A system with this storage capability could be operated to store heat during times of low electric prices and then discharged during times of high electric prices. Simulations run here assume the system is the main source of power as opposed to being a component of a larger generation network where such a strategy is feasible.

III.A.1 Typical Summer Day

As illustrated in Figure 5 and Figure 6, the TES system is able to maneuver such that the electric demand is satisfied while keeping reactor power effectively constant. Bypass flow, illustrated in Figure 7, is approximately an x-axis reflection of the load profile up until the load reaches the nominal turbine "rated" output of 180 MWe. The mass flow rate from the cold tank to the hot tank follows this same shape. At this point the charging mode shuts off and the discharge mode activates automatically. From about 8am to 9pm the system is operating as an electrical peaking unit. During this time the mass flow rate from the hot tank to the cold tank is modulated to ensure the electrical demand is being met. Once demand drops below 180 MWe, the discharge mode deactivates and charging mode operation is reinitiated. During charging mode operation, the TES fluid temperature entering the hot tank is maintained at the reference set point as seen in Figure 9. Over the 24-hour simulation period the tank levels oscillate about 25% of maximum as illustrated in Figure 8.

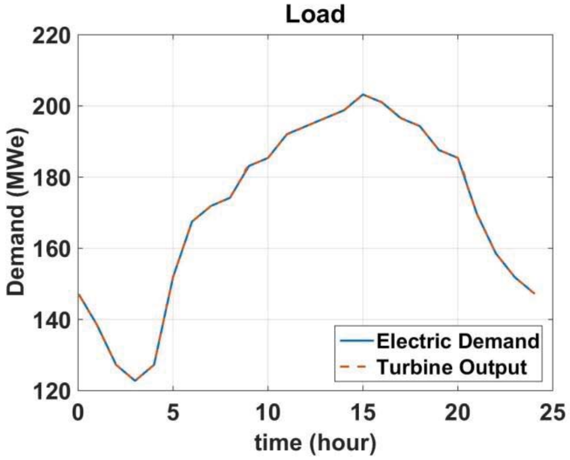

Figure 5: Turbine Load and Output

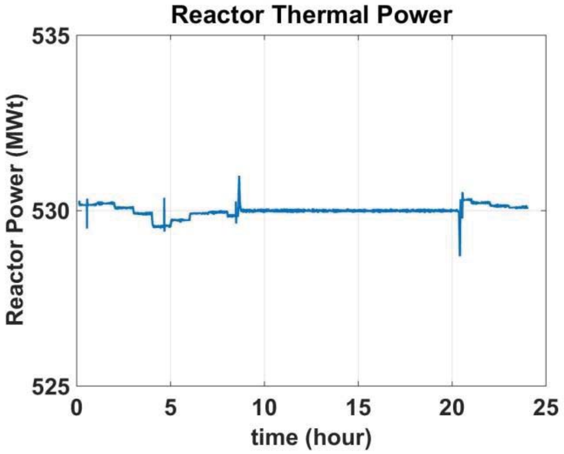

Figure 6: Reactor Power

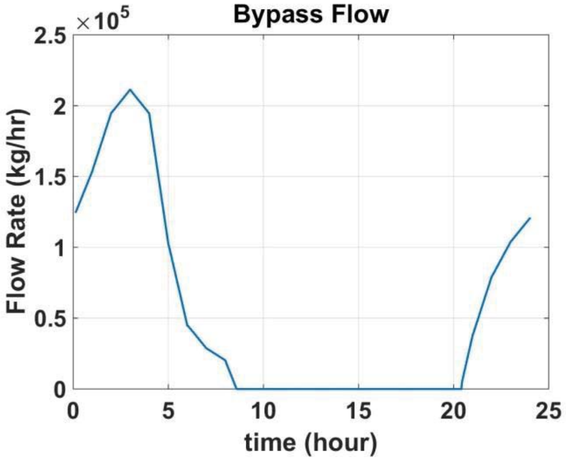

Figure 7: Auxiliary Bypass Flow

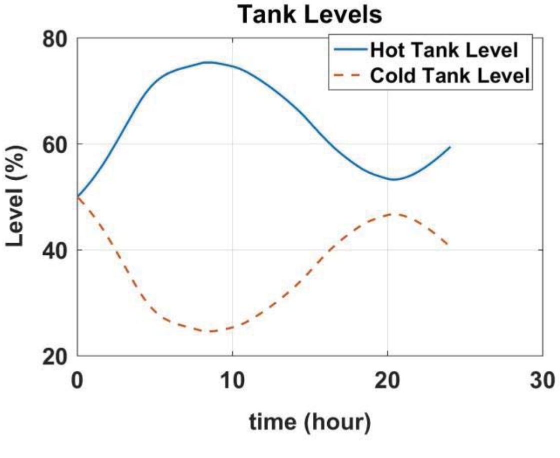

Figure 8: Hot Tank and Cold Tank Level

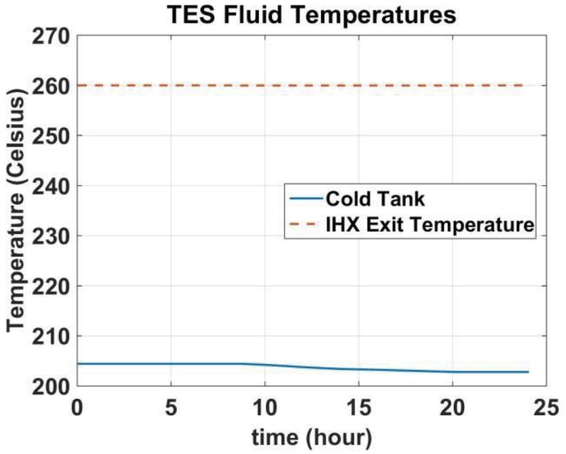

Figure 9: TES Fluid Temperature

III.A.2. Three Winter Days with 15% solar penetration

In addition to typical diurnal electric demand there is also seasonal demand. To further test system versatility, a three-day winter run was completed with 15% solar penetration. The first and third days are sunny days with nominal solar output while the second day is rainy and overcast. It can be seen in Figure 10 and Figure 11 that the load is met while reactor power is maintained at approximately 100%. Tank levels are shown in Figure 12. TES exit fluid temperature is maintained at the reference 260°C throughout, as shown in Figure 13.

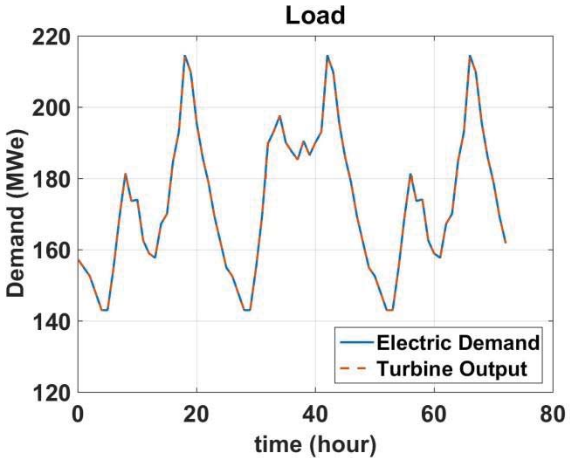

Figure 10: Turbine Output and Demand

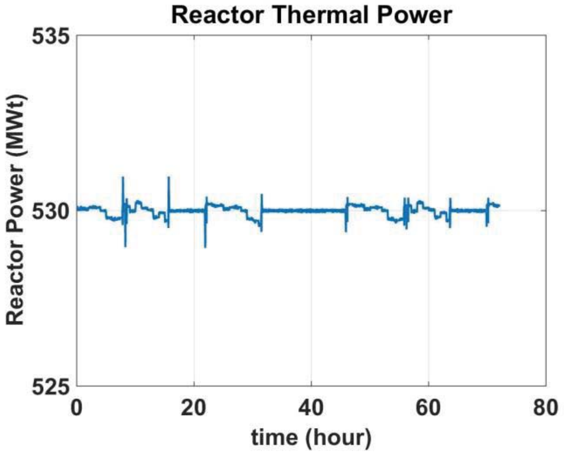

Figure 11: Reactor Power

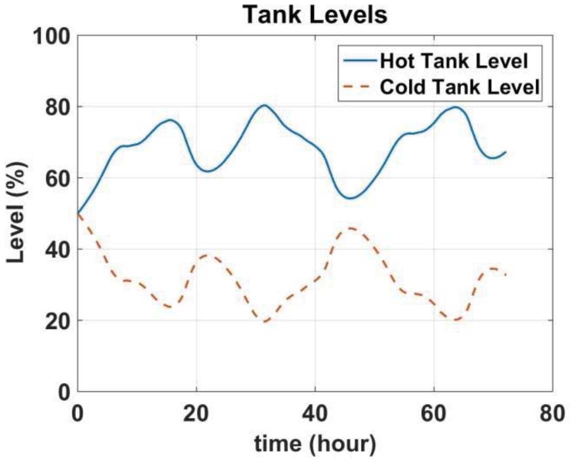

Figure 12: Hot Tank and Cold Tank Level

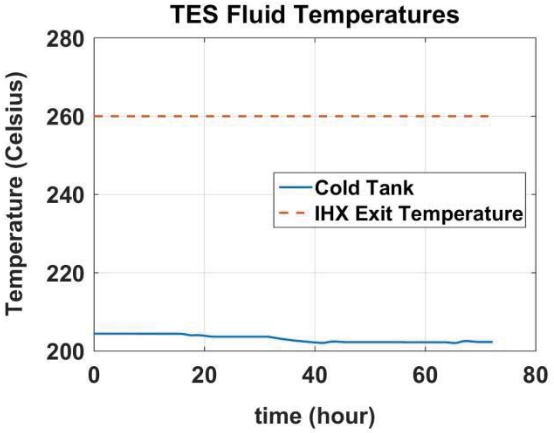

Figure 13: TES Fluid Temperature

III.B. Steam Applications

As opposed to using the TES system to supplement electric demand, the system can alternatively be used for process steam applications.[19,23] Desalination can be accomplished through two main methods: Reverse Osmosis, which just requires electrical input, and multi-stage flash (MSF) desalination, which requires a constant steam supply.[24] Chilled water production using absorption chillers has been demonstrated in previous work; this process also requires low temperature, low pressure steam.[23]

III.B.1. Multi-Stage Flash Desalination

The desalination process simulated is a 24 stage MSF system used to produce 7.2 MGD of product water.[25] The TES storage tanks were resized to accommodate the steam demand profile. A 24-hour desalination run was simulated starting at midnight on a typical summer day. While operating under these conditions, the TES system is both charging and discharging simultaneously. Over the 24-hour simulation period, turbine demand was satisfied and reactor output was kept at approximately 100% as shown in Figure 14 and Figure 15. Bypass flow into the IHX is an x-axis reflection of the load. As illustrated in Figure 17 TES fluid temperature entering the hot tank is maintained at the reference temperature. Figure 18 shows the target steam flow is met throughout the run. For this 24-hour simulation a 226,534 m^3 tank size is sufficient for a single day. However, support for this level of continuous desalination over the long term would require the tanks to be sized consistent with expected daily demands. These results show that a TES system operating in conjunction with MSF desalination is feasible while maintaining reactor power at 100%.

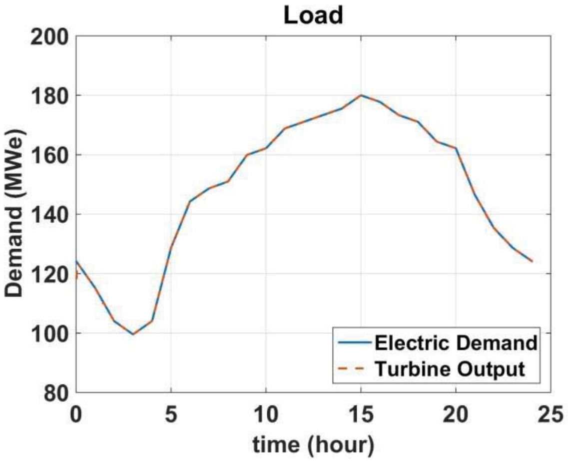

Figure 14: Turbine Output and Demand

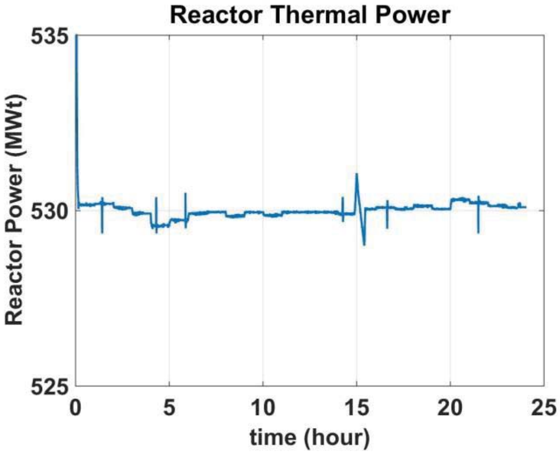

Figure 15: Reactor Power

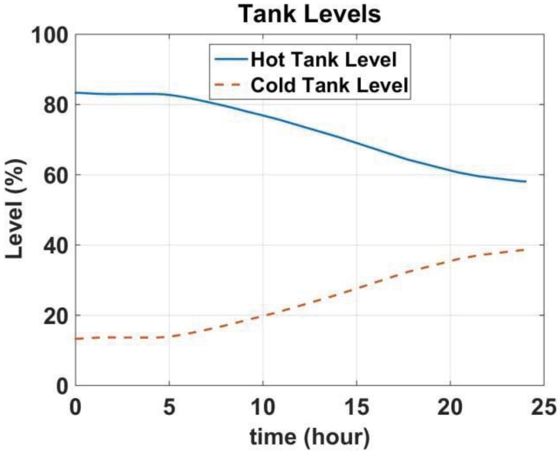

Figure 16: Hot Tank and Cold Tank Level

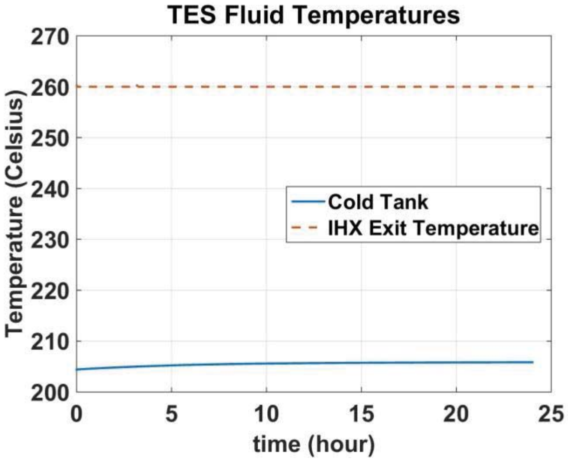

Figure 17: TES Fluid Temperature

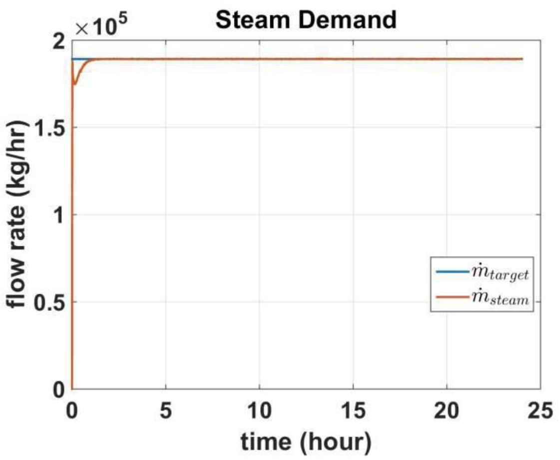

Figure 18: Ancillary Steam Demand and Flow

IV. CONCLUSIONS

If SMRs are to be deployed in conjunction with intermittent power sources such as wind and solar, electric load variations can be significant. Current SMR designs allow for steam bypass off the pressure equalization header prior to the pressure control valves thus providing approximately constant steam conditions perfect for sensible heating thermal energy storage systems. This study investigates the coupling of representative small modular reactor designs with a two-tank sensible heat thermal energy storage system to minimize power swings during periods of variable electric load. During times of low electric demand, excess steam is bypassed to the TES system at a rate sufficient to maintain full reactor power. The thermal energy can be recovered later for either electricity production during periods of peak electric demand, or ancillary applications requiring steam such as multistage flash desalination. With the implementation of these TES systems, decreases in capacity factor and increased stresses on plant components associated with load follow operation can be minimized, improving economic return over the lifespan of the reactor.

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NOMENCLATURE

α	void fraction
A	area
ACV	auxiliary control valve
BOP	balance of plant
FBV	feed bypass valve
FDCV	feed control valve
FCV	flow control valve
HPT	high pressure turbine
IHX	intermediate heat exchanger
IPWR	integral pressurized water reactor
K	loss coefficient
LPT	low pressure turbine
$\dot{m}$	mass
MGD	million gallons per day
MWe	megawatts electric
MWt	megawatts thermal
OTSG	once through steam generator
P	pressure
ρ	density
PCV	pressure control valve
PRV	pressure relief valve
ΔP	pressure drop
$\dot{Q}$	heat transfer rate
SMR	small modular reactor
Δt	change in time
t	time
TBV	turbine bypass valve
TES	thermal energy storage
u	internal energy
v	velocity
ν	specific volume
V	volume
$\dot{W}$	Work

Subscripts

cond	condenser
f	saturated liquid
fg	range between saturated liquid and vapor
g	saturated vapor
HDR	header
IHX	intermediate heat exchanger
j	node “j”
l	liquid phase
Line	losses in lines
p	pump
ref	reference
r	relative
SD	steam dome
SG	steam generator
x	cross sectional area

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