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ENERGY MANAGEMENT AND ENHANCED FLEXIBILITY OF POWER STATIONS VIA THERMAL ENERGY STORAGE AND SECONDARY POWER CYCLES

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ABSTRACT

The operation of power plants must meet a series of requirements in order to enable the increasing penetration of intermittent renewable energy and the consequent intensifying demand for flexible generation. It is proposed here that during off-peak demand, steam can be extracted from Rankine-cycle power stations for the charging of thermal storage tanks that contain suitable phase-change materials (PCMs); during peak demand time, these thermal energy storage (TES) tanks can act as the heat sources of secondary thermal power plants in order to generate power, for example as evaporators of organic Rankine cycle (ORC) plants that are suitable for power generation at reduced temperatures and smaller scales. This type of solution offers greater flexibility than TES-only solutions that store thermal energy and then release this back to the base power station, in that it allows both derating and over-generation compared to the base power-station. The approach is here applied to a case study of a 670-MW rated nuclear power station, since nuclear power stations are generally suitable for baseload generation and the proposed system configuration could increase the operational flexibility of such plants.

Keywords: energy management, flexible energy system, flexible generation, generation integrated energy storage, phase change materials, smart grids

NOMENCLATURE

Symbols	
T	Temperature
$\dot{W}$, $\dot{Q}$	Power, heat transfer rate
$\dot{m}$, $\dot{H}$, $\dot{S}$	Mass, enthalpy, entropy flow rate
c_{p}	Specific heat capacity
η	Efficiency

1. INTRODUCTION

The decarbonisation of the electricity system requires significant and continued investment in low-carbon and renewable energy sources as well as in electrification of the heat and transport sectors. The fast increasing penetration of intermittent renewable energy, and the integration of electricity vehicles or heat electrification technologies, is changing the traditional configuration of power systems, with growing need and opportunity for distributed energy resources (DERs) and for the provision of system balancing, flexibility and security services.

Coal-fired power stations often represent a large share of the power delivered to grids, and therefore their management can be used to improve grid stability with great effectiveness in the scenario of a significant generation of intermittent renewable electricity. An interesting option, for example, involves the conversion of heat to electricity at peak-demand times by integrating waste heat in the feedwater preheating systems of such plants, as investigated by Roth et al. [1] in a 390-MW coal-fired power plant. Furthermore, TES integration into coal-fired power plants is often proposed as a promising solution for enhanced flexibility and load-following operations as in Richter et al. [2].

This work goes beyond a previous study [2] that investigated thermal integration with stores in the preheating routes of power stations, by: (i) considering different configurations and strategies for integrating thermal energy stores (TES) in power stations; (ii) developing load following operations directly applicable to Rankine-cycle power stations, and in particular nuclear power stations; (iii) considering the conversion of stored thermal to electrical power via secondary power cycles.

2. CONCEPT DESCRIPTION

The enhanced flexibility concept is here applied to an existing Electricite de France (EDF) nuclear power station in the UK. The thermal input to the power station is 1,570 MW, the electrical power output is 670 MW and the thermal efficiency of the Rankine power cycle is 42.7%. We consider the integration of TES into this power station with the aim of modulating its electrical power output, as illustrated in the example in Fig. 1. At base conditions, the power output of the plant is nominally constant at the plant's rated power (i.e., at 670 MW; red line in Fig. 1). In our proposed Energy management Strategy (EMS), the power station operator is informed, e.g., day ahead, of the transmission network hourly electricity-exchange prices. An automated EMS then makes decisions for the charging-discharging of the TES stores by solving an optimization problem. As an example, Fig. 1 illustrates a scenario in which the thermal stores are charged twice per day, at 02:00 and 12:00 (signified by dips in the green area). After charging the tanks, these are considered autonomous units which are connected to the transmission grid as distributed generators in the same or in a separate bus from the one the main power station is connected to.

3. POWER STATIONS WITH INTEGRATED THERMAL ENERGY STORAGE

The TES charging characteristics depend strongly on the materials used, with materials selection in the proposed TES schemes determined by the temperature at which steam is extracted at various points from the case-study nuclear power station. Following consultation with EDF, we consider the possibilities that steam can be extracted: (i) before the reheater at 353 ^{o}C and 45.2 bar; and/or (ii) before the low-pressure turbine (LPT) at 265 ^{o}C and 5.2 bar.

3.1 TES Integration – Charging with Steam Extraction before the Reheater

The selected power plant presents an allowable steam-extraction rate of up to 54 kg/s for diversion from the reheater to Thermal Tank 1 (and also Thermal Tank 2, which is in series with the first tank; see Fig. 2). This represents 12% of the total steam passing to the reheater under normal conditions. As a result, thermal energy can be stored in the Thermal Tank 1 at a maximum heat transfer rate of 107 MW and in Thermal Tank 2 at a rate of 26 MW during the storage charging.

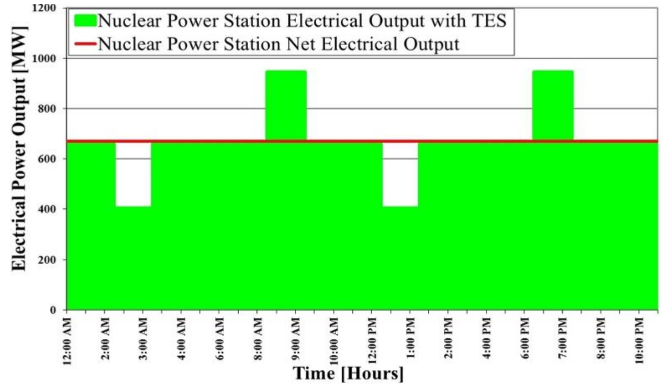

Fig. 1. Baseline net electrical energy production from the nuclear power station (670 MW) and electrical energy production after integration of the TES system.

In more detail, superheated steam at 353 ^{o}C and 45.2 bar is extracted before the reheater and condensed isobarically in Thermal Tank 1 to a stream of saturated liquid water at 258 ^{o}C (45.2 bar). The storage medium in this tank is a PCM mixture of potassium and sodium nitrates ($NaNO_3$ + KNO_3) with a melting point of 250 ^{o}C [3], which is just below the minimum temperature of the steam in the tank. Downstream, and in series with Thermal Tank 1, heat transfer also occurs to Thermal Tank 2 where the condensed, high-pressure (initially saturated) water-stream cools further, again isobarically, as it charges this second tank. The inlet temperature of this tank is 258 ^{o}C (at 45.2 bar) and the outlet temperature is 154 ^{o}C, at 45.2 bar. This tank employs a salt mixture (HITEC, composition: 7 wt.% $NaNO_3$ + 35 wt.% KNO_3 + 40 wt. % $NaNO_2$) with a melting point of 142 ^{o}C [4].

Finally, after the two TES tanks, the subcooled liquid (water) is compressed in a feedpump and returned to the boiler/reactor. The electrical power consumption of the additional feedpump is estimated at 1.23 MW, by using an isentropic efficiency value of 80% for this component. The partial diversion of the steam flow to the reheater during the charging of the two cascaded thermal tanks, leads to a drop in the thermal input of the power station (from 1,570 MW) to 1,540 MW, as the electrical power output of the plant is derated by 9.4% (from 670 MW) to 607 MW and the corresponding thermal efficiency reduces (from 42.7%) to 39.3%.

3.2 TES Integration – Charging with Steam Extraction before the Low-Pressure Turbine

In an alternative scheme to that presented above, also shown in Fig. 2, involves the integration of PCM-based TES in an arrangement whereby steam is extracted before the LPT along with its associated *T–S* diagram. In more detail, superheated steam at 265 ^{o}C (and 5.17 bar) is extracted after the intermediate-pressure turbine and before the LPT, and is condensed isobarically in Thermal Tank 3 to a stream of saturated liquid water at 153 ^{o}C (and 5.17 bar). HITEC is again selected as the storage material for Thermal Tank 3, with a melting temperature of 142 ^{o}C.

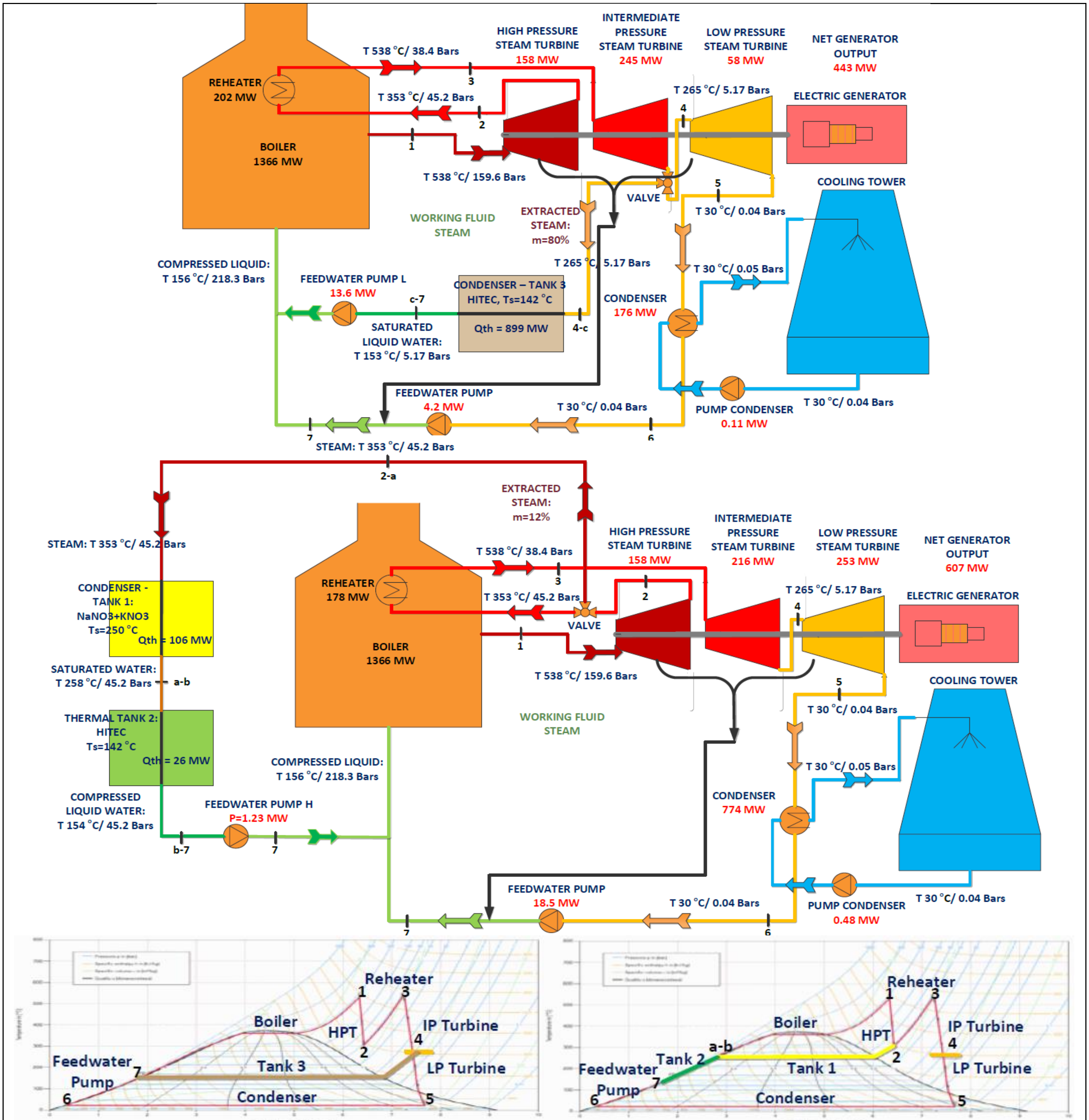

Fig. 2. Integration of: (top) two PCM-based TES tanks with steam extracted before the reheater, (middle) PCM-based TES tank with steam extracted before the LPT in the EDF nuclear power station, and (bottom) corresponding *T–S* diagrams for the two cases.

For the case-study power station, EDF has provided a maximum allowable steam extraction rate of 383 kg/s for diversion from (i.e., before) the LPT to Thermal Tank 3, which represents 80% of the total steam flow to the turbine under normal conditions. The corresponding heat transfer rate during charging of the tank is 899 MW. Further, during the charging of Thermal Tank 3 the thermal input to the power station is unchanged from the nominal value of 1,570 MW, and its electrical power output is derated by 33.9% to 443 MW as its thermal efficiency reduces to 28.3%. The power consumption of the pump is 13.6 MW, based on an isentropic efficiency of 80%.

3.3 TES Integration – Charging with Steam Extraction before Reheater and Low-Pressure Turbine

In this scheme, steam is extracted at the same time from before the reheater (as in Section 3.1) and before the LPT (as in Section 3.2). Due to the steam extraction before the reheater, the minimum allowable steam flow rate through the LPT, which must still be 80% of the remaining steam after the reheater, is now 337 kg/s (as opposed to the 383 kg/s that was permissible in the scheme in Section 3.2), and the heat transfer rate to Thermal Tank 3 is now 791 MW (rather than 899 MW).

3.4 Thermodynamic assumptions

Generally, the overall exergy efficiency associated with the charging and discharging of TES tanks is lower when exploiting latent-heat (PCM) storage compared to sensible-heat storage and the heat-source temperature is variable (e.g., when storing the sensible enthalpy of a hot fluid stream in the absence of phase change) [5,6]. However, the generation-integrated energy storage solutions examined in this work feature a heat-source (condensing steam from the main Rankine cycle) temperature that is, to a large extent, constant during the storage-tank charging phase, and furthermore, the stored thermal energy is later used, during discharge, to drive (as an example) a secondary power-plant (e.g., an ORC) by evaporating the organic working-fluid, again at constant temperature [7-12]. This makes latent (PCM-based) TES an interesting alternative with trade-offs necessary for achieving the maximum ("round-trip") efficiency of the overall system. Further, beyond efficiency considerations, it can be argued that affordability is an even more desirable factor, e.g., with larger temperature differences between the heat source and the material in the thermal store (up to a point) leading to smaller heat transfer areas (i.e., sizes) and costs, even though the thermodynamic performance is lower [13]. Assuming a negligible temperature difference between the heat source and the PCM in a TES tank, the maximum useful stored power $\dot{W}$ during the charging of this tank is the rate change of exergy of the heat-source stream, which can be isothermal or experience temperature variations:

$$\dot{W} = \Delta\dot{H} - T_0\Delta\dot{S} = \begin{cases} \dot{Q} - \dot{m}T_\mathrm{a}\Delta s \text{ ; for isothermal source} \\ \dot{Q} - \dot{m}c_pT_\mathrm{a}\ln\left(\frac{T_\mathrm{in}}{T_\mathrm{out}}\right) \text{ ; for temp-varying source} \end{cases} \quad (1)$$

where $\dot{H}$ and $\dot{S}$ are the enthalpy and entropy of both the heat-source stream and PCM in the tank, $\dot{m}$ and c_p are the heat-source stream mass flow-rate and specific heat capacity, T_in and T_out are the inlet and exit temperatures of the stream to/from the tank when its temperature is varying, and T_o = T_a is the dead-state temperature (ambient temperature T_a = 25 °C).

During the discharging of a TES tank, the stored exergy is converted to electrical power in secondary power plants. Reversible (Carnot) predictions are a useful starting point in setting an upper thermodynamic limit to the performance (i.e., power, efficiency) attainable by these plants. However, these predictions are significant overestimates of the practical performance of real systems [7]. Instead, an endoreversible analysis considers a heat-engine cycle and its components as internally reversible except for the heat exchangers (i.e., the heat addition/rejection processes) which are both irreversible, and thus allowed to give rise to exergy losses. This analysis leads to the 'Novikov' thermal efficiency expression, which is known to provide much better predictions of the performance of actual power systems [7]. Similarly to the Carnot engine, the Novikov engine is based on a constant source/storage tank temperature, $T_\mathrm{h} = T_\mathrm{st}$, and a constant sink/ambient temperature, $T_\mathrm{c} = T_\mathrm{a}$. The Carnot and Novikov efficiency expressions are:

$$\eta_\mathrm{C} = 1 - \frac{T_\mathrm{a}}{T_\mathrm{st}} \text{ ;} \quad (2)$$

$$\eta_\mathrm{N} = 1 - \sqrt{\frac{T_\mathrm{a}}{T_\mathrm{st}}} \quad (3)$$

In both cases (Carnot and Novikov), a measure of thermal efficiency can be used to obtain the generated electrical power, $\dot{W}_\mathrm{cycle}$, from an engine given a thermal-energy input rate, $\dot{Q}_\mathrm{in}$, via:

$$\eta_\mathrm{th} = \frac{\dot{W}_\mathrm{cycle}}{\dot{Q}_\mathrm{in}} \Rightarrow \dot{W}_\mathrm{cycle} = \eta_\mathrm{th} \cdot \dot{Q}_\mathrm{in} \quad (4)$$

where η_th can be either η_C or η_N, and the sink for the secondary power plants is the environment.

The thermal-energy inputs to the tanks, secondary heat-to-power conversion efficiencies and electrical-power outputs from the proposed TES systems considering both reversible (Carnot) and endoreversible (Novikov) power cycles, are presented in Table 1.

Table 1. Summary of simple TES results and secondary power-plant outputs for the three EMS scenarios.

	Thermal Tank 1	**Thermal Tank 2**	**Thermal Tank 3**
Heat rate input (MW)	107	26	899
Reversible (Carnot) efficiency (%)	43	28	28
Reversible electrical power (MW)	46	7	254
Endoreversible (Novikov) efficiency (%)	25	15	15
Endoreversible electrical power (MW)	26	4	137

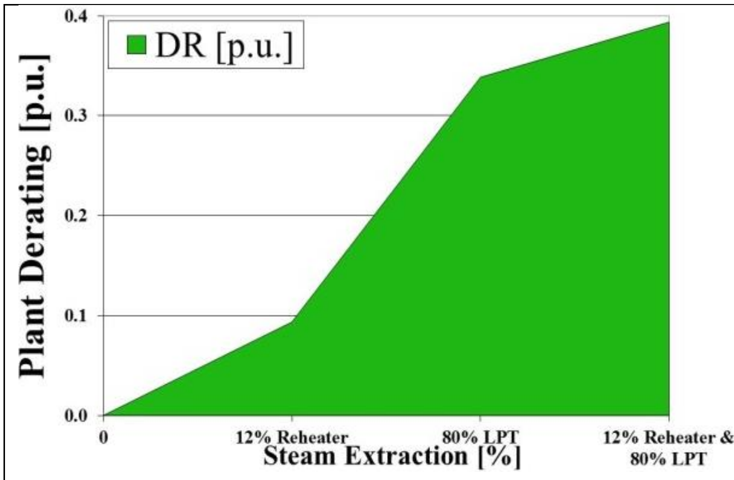

Fig. 3. Fractional plant derating, of main/base nuclear power station and stored thermal energy during TES charge, for the three EMS schemes proposed herein.

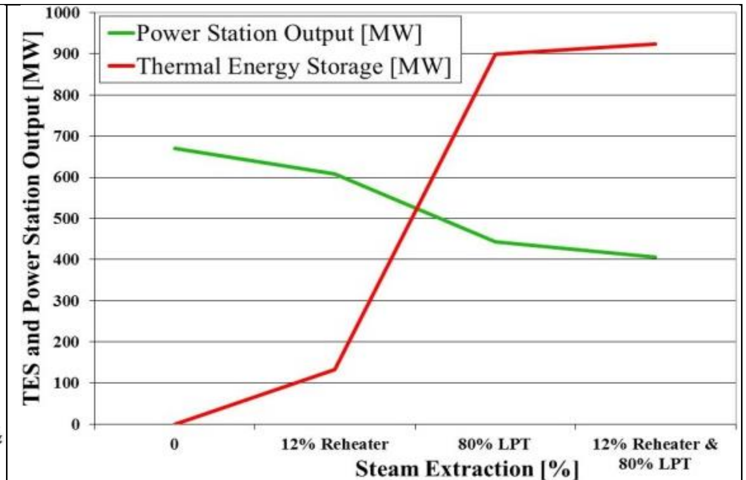

Fig. 4. Power output of main/base nuclear power station and stored thermal power during TES charge, for the three EMS schemes proposed herein.

4. RESULTS

4.1 Plant derating during TES charging

Figure 4 shows the fractional plant derating during TES charging versus the degree of steam extraction when the three TES schemes in Section 3 are applied to the EDF nuclear power station. The fractional derating is the ratio of the net generator output from the base plant with steam extraction vs the net output without steam extraction. From left-to-right the schemes include: (i) 12% steam extraction before the reheater (for details, see Section 3.1); (ii) 80% steam extraction before the LPT (for details, see Section 3.2); and (iii) 12% steam extraction before the reheater and 80% extraction of the remaining steam before the LPT. As a result, the electrical power output of the power station decreases and the amount of stored thermal energy increases (from left to right in Fig. 5).

This figure suggests that it is possible to use existing nuclear power plants (Gen. I and II) for flexible power generation in load following with a maximum derating of 40%, with minimum loads down to 60% of the plant's rating. The stored thermal energy increases up to a total of 925 MW, as the net power output reduces by 40%, from 670 MW to a minimum of 406 MW. It is interesting to note that the greatest flexibility of the power station, and therefore the largest potential for load following operations, is attained for low-temperature TES, when extracting steam before the LPT.

4.2 Secondary and total generation during discharging

The base-only power plant output together with the maximum (reversible) secondary power available after heat conversion from the thermal stores during TES discharge are shown in Fig. 6. The heat rejection rate at the condenser reduces from 879 MW, when the nuclear power plant operates as usual, to 155 MW when steam is extracted before the reheater and before the LPT.

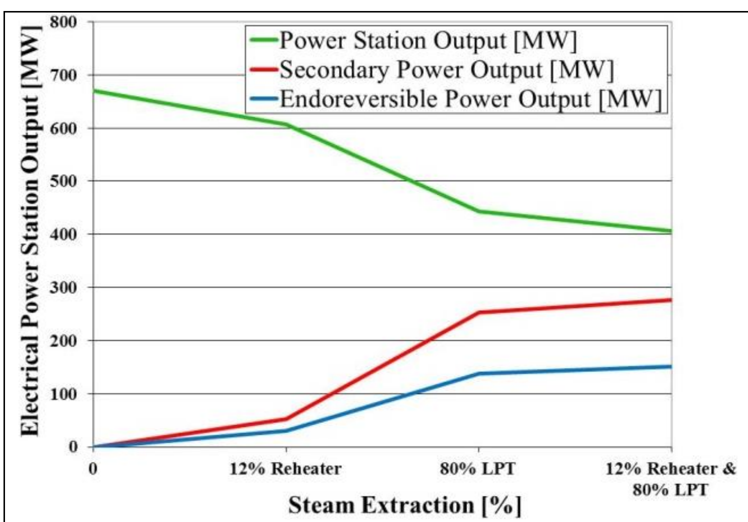

Fig. 5. Main/base nuclear power-plant output during TES charge, secondary (reversible) power output during TES discharge.

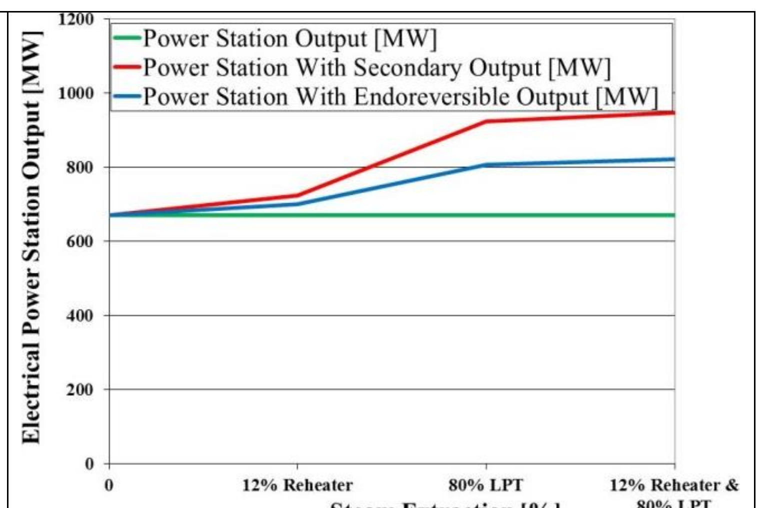

Fig. 6. Total power output with and without TES at peak demand (discharge).

This reduced degree of condensation, and waste-heat rejection to the environment, compensates the increased thermal energy that is sent to the secondary-generation power units, which are relatively efficient in converting this to electrical power. This allows a secondary power generation during the discharging of Thermal Tank 3 of 137 MW (endoreversible) for a drop in base generation during charging of 227 MW, and a secondary generation during discharging of all three thermal tanks of 151 MW (endoreversible) for a drop in base generation during charging of 264 MW, corresponding to conversion efficiencies around 60%.

When performing these calculations based on fully-reversible secondary units (254 MW of electrical power from Thermal Tank 3 and 276 MW from all tanks) round-trip efficiencies in excess of 100% are obtained. Since the maximum available power from the station is directly correlated to its flexible operation, this suggests that a trade-off exists needed between the overall conversion efficiency of heat to electricity and the power station's load-following capability.

Finally, Fig. 7 presents the maximum total electrical power delivered during discharge at peak-demand times, when heat stored in the thermal tanks is converted to electricity by the secondary power units in addition to the base plant. It can be observed that, when steam is extracted before both the reheater and the LPT, the maximum total power output is 946 MW (reversible limit) or 821 MW (endoreversible estimate). Hence, a reasonable expectation from the practical implementation of these TES solutions is that these would allow a 23% over-generation relative to the case-study nuclear plant's full-load rating. Together with the -40% maximum plant derating during TES changing at off-peak demand times, this is equivalent to reducing the load to below 50% of the plant's rating, even for old Gen. I and II reactors. This represents a reasonably flexible unit dispatch and an acceptable capability for load-following operations in particular during peak/off-peak demand periods.

5. CONCLUSIONS

An energy management system (EMS) for the flexible operation of power stations based on generation-integrated thermal energy storage (TES) has been proposed, and considered specifically in the context of an existing 670-MW Rankine-cycle nuclear power station operated by EDF as a case study. The possibilities of steam extraction before the reheater and/or the low-pressure turbine (LPT) of the power station during off-peak demand have been investigated. It has been found that when charging the PCM-TES tanks during off-peak demand in a proposed scheme with three TES tanks, a maximum plant derating of 40% can be achieved, i.e., down to 406 MW. At peak demand, when discharging the PCM-TES tanks, an endoreversible thermodynamic analysis has suggested that a maximum combined power of 821 MW can be delivered, which includes the 670 MW generated by the nuclear power plant and an additional 151 MW from secondary generation ORC plants. This is 23% higher than the nuclear plant's full-load rating.

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