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Nuclear Heat Storage and Recovery in a Renewable Energy Future

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1. Introduction

The Korean government, following policy recommendations from a select committee, has established a plan to gradually phase out coal and nuclear power generation, while expanding renewable energy to 20% of the power supply by 2030. To meet these goals, it is expected that more solar and wind power installations will be required. Considering the number of Nuclear Power Plants (NPPs) operating in the country at present (24) and their share of non-carbon baseload power, a role as reserve grid capacity for these units is of interest.

Due to a combination of: (i) high sunk construction costs, (ii) fixed operating costs, and (iii) low fuel costs, load following is not economical for NPPs. However, coupling thermal energy storage to the base load output of nuclear reactors may significantly improve the viability of NPPs in an electric grid containing a significant fraction of renewable energy sources.

For a nuclear unit, with continuous operation of the reactor at full power, the turbine cycle could be re-engineered to supply a portion of reactor heat to Thermal Energy Storage (TES) (i.e., via transport by secondary side main steam). This heat could later be recovered, generating steam, and converting it to electricity using existing plant and equipment during peak load periods. Due to the transition time from storage to recovery for NPPs as configured here, the TES would diurnally provide supplemental power to the grid on an established schedule.

For electric grids with auction pricing from independent power producers, NPP TES storage may also prove to be an attractive solution for storing excess energy for periods with low prices. This condition is highly dependent on several factors, not the least of which include: (i) government subsidies for 'green' energy, (ii) daily, weekly, and seasonal load characteristics of the grid, and (iii) dependability and predictability of 'green' source supply (e.g., cloudiness, wind variability).

Granted that reserve power is required for all electric grids, the need for reserve power can be severely amplified by an over-reliance on green energy sources (e.g., see the German electricity market). Planning for this reserve is important for the Korean grid and other grids where there is a proposed dramatic and rapid change to the source mix. Here, the outlined TES for NPPs in Korea is compared to the leading source for non-fossil and non-hydro reserve power, namely battery storage as represented by the world's largest electric battery based storage system, the Hornsdale power reserve (HPR) in South Australia.

2. Background

A workshop on '*Light Water Reactor (LWR) Heat Storage for Peak Power and Increased Revenue*' was conducted in 2017 [1]. With attendees from academia, national laboratories, and industry, the workshop goals were to define and understand the market, regulatory, and technical options for coupling heat storage for variable power to existing and future LWRs with recommendations for the path forward to improve LWR economics. A range of thermal energy storage options was considered and discussed at the meeting, including:

a) steam accumulators,
b) sensible heat fluid systems,
c) cryogenic air systems,
d) packed bed thermal energy storage,
e) hot rock storage (using hot air), and
f) geothermal heat storage system

After considering many variants, the two most promising options for coupling a heat storage system to light water reactors were identified as:

Stand-alone Storage Systems**:** With this option steam is diverted before the high-pressure turbine and sent to a storage system that is coupled with its own power generation system. Condensate is returned to the nuclear steam cycle.

Integrated Storage Systems: With this option steam is diverted to storage at times of low demand and heat is sent back to the turbine island at times of high demand to produce added supplemental electricity. The main turbine-generator (T/G), main power transformers, T/G control and protection systems, and existing switchyard are used to deliver the additional electricity.

The second option, integrated storage and recovery, is considered here assuming a 'backfit' to operating NPPs in Korea. This option is selected primarily to minimize capital expenditures (including grid interconnections) and to simplify licensing, operations, and maintenance.

3. Hornsdale power reserve

The Hornsdale Power Reserve (HPR) project is touted as the world’s largest lithium ion battery storage facility (see Fig.1.). With a footprint of ~57-m x 120-m (~0.74-ha), it was connected to the South Australia electricity grid in December 2017. Built adjacent to the 309 MWe Hornsdale Wind Farm, the primary function of the HPR is grid voltage and frequency stabilization. The facility also engages in grid storage and supply, profiting through arbitrage of variations in pricing, particularly following to supply disruptions.

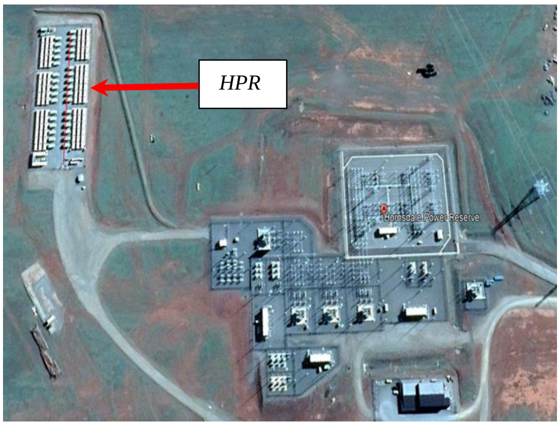

Fig.1. Hornsdale power reserve (33°5’8.8”S, 138°31’6.4”E)

The South Australia energy market is not typical of that for developed economies. In a country with abundant coal reserves and a vibrant coal export market, South Australia residential electricity rates are very high, reported at ~$0.34 US/kW-hr. Along with Germany and Denmark, these high penetration adopters of green energy operate a majority of the highest priced electricity in the industrialized world. Therefore, selection of this technology is not necessarily an endorsement of the economic potential of battery storage for grid applications. However, since this installation is relatively large, recent, and with published cost data, and since the South Australia grid exhibits some of the characteristics for the proposed changes to the Korea grid, it provides a good candidate for a case study comparison with the TES cycle proposed here.

The HPR essentially consists of an interconnected set of factory assembled battery modules termed ‘Power Packs’ from Tesla. Each pack in turn consists of a set of sixteen (16) individual ‘Power Pods’. Each pod then is made up of a large assemblage of individual lithium ion battery cells, reportedly equivalent to the standard industry specification 21700 (with each cell measuring 21-mm x 70-mm, hence the name). This type of cell is a standard ‘high capacity’ Li-ion cell producing 3.7 V with a capacity in the range of 4200~5000 mA-hr (see Fig. 2).

Fig.2. Li-ion 21700 battery cell

With such a small capacity per cell, a very large number of cells is required for the HPR installation, estimated here at between 6 and 10 million. Tesla reports typical specifications for a ‘generic’ Powerpack as follows [2]:

Table .1. Tesla Powerpack Specifications[1]

Parameter	Value
AC Voltage	380 to 480 V, 3ϕ
Power	50 kW
Scalable Inverter Power	50 to 625 kVa
Depth of Discharge	100%
Dimensions, l-w-h (mm)	1308 x 822 x 2185
Weight	1622 kg
Capacity	210 kWh (AC)
System Efficiency (2-way)	88%

1) Typical, not HPR specific.

The proposed TES for an operating APR1400 NPP will be compared in broad terms to the HPR with a configuration as described above.

4. APR1400 TES- NHS&R

The TES system considered here consists of heat storage (using the condensing of secondary side steam) and heat recovery (using the boiling of secondary side feedwater) as interfaced to the prototypical APR1400 nuclear reactor plant. The tertiary side consists of the heat transfer medium (Therminol 66), heat storage tanks and storage medium (Hornfels rock), heat exchangers, drain coolers, pumps, surge tanks, and oil separators.

The conceptual TES design for storage and recovery of heat from an operating APR1400 NPP assumes heat transfer within the security boundary from high pressure steam to transport oil. This heat is then transported to an offsite storage location.

Note that energy export or storage in the form of sensible heat is a mature and practical method of storing energy in large quantities for later use. Several LWRs operate or have operated using a cogeneration cycle, producing both electricity and heat for offsite customers in Canada and Europe [1]. There is considerable real world experience of operating NPPs with the export of steam on demand for various uses. Historically, such services have represented an advantage in scale and economy.

The TES system evaluated here is sized to accommodate eight (8) hours charging using 20% of total NSSS thermal power, equivalent to 800 MWt. The high pressure steam diversion away from the main turbine for this amount of heat is considered to be a practical upper limit for storage.

This heat is later recovered to produce steam which is returned to the turbine cycle over a period of sixteen (16) hours. This rate of recovery limits required modifications to turbine cycle components. The goal of the proposed TES is to increase revenue by selling electricity when prices are high and storing heat when prices are low. Alternatively, with high penetration of green energy sources, payments for reserve capacity may also be involved.

Proposed transport of heat within the TES system is to and from packed bed storage tanks using Therminol 66 oil as the transfer medium and crushed Hornfels rock as the storage medium. The diagram below illustrates the general configuration for charging of the storage system.

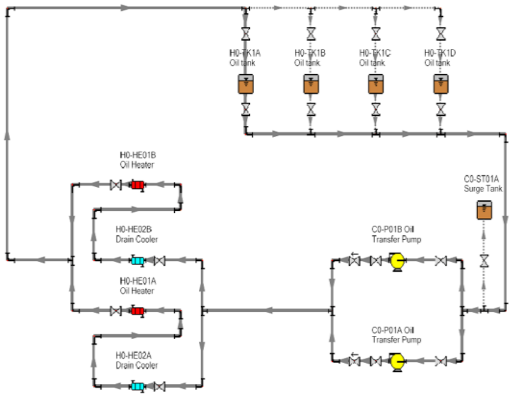

Fig.3. TES hydraulic model

5. Comparison – TES vs. HPR

In the following sections, the HPR is compared to the proposed APR1400 TES in terms of space utilization, life expectancy, capacity, and cost effectiveness.

5.1. Space use

The HPR installation covers slightly less than one hectare, located close to a collector switchyard which interfaces with an array of wind turbines, thus making use of an existing interface to the grid.

For the TES, the heat exchange buildings (heat transfer to and from the oil transfer medium) are to be erected adjacent to the power block. The packed beds are installed within tanks which make up the heat storage tank farm. The location for these tanks will be based on adequate separation of identified hazards from the power block. Pumping power for distant locations is not a particular concern, but oil inventory in the pipeline is. Existing nuclear licensing has addressed such issues, including US NRC Regulatory Guide 1.91, minimum distance for flammable liquids.

Space requirements for the APR1400 TES tank farm are illustrated in Fig.4. Note that the power flow from the HPR and APR1400 TES are similar at ~75-100 MWe. However, the storage capacity of the TES is ~10 times higher than for the HPR. From inspection, the unit area for storage capacity (kW-hr/m^2) for the TES is approximately equal to that for the HPR.

Fig.4. Comparison of land requirements – HPR vs. TES

5.2 Life expectancy

Li –ion battery lifetime is determined based on the number of charge-discharge cycles. One cycle is a period of use from fully charged, to fully discharged, and fully recharged again. HPR is based on Li-ion battery technology which will see capacity gradually deteriorate during use due to unwanted chemical reactions (i.e., precipitate growth) thereby limiting the lifetime. Cited lifetime for storage battery installations similar to HPR is often quoted as 15~20 years, although additional operating experience is required to judge these claims [3].

As for TES, Hornfels rocks are abundant and freely available in many areas. Since crushing and sorting costs are low, the economy of supply is determined primarily by transport to the site. This type of rock is considered to be thermally and chemically stable over a wide temperature range. This medium exhibits high specific heat, good thermal conductivity, a very low thermal expansion coefficient, and high mechanical resistance to thermal cycling [4]. As such, the life expectancy of the storage medium is expected to outlive that for the NPP.

The heat transport medium (Therminol 66) is a synthetic oil which is resistant to oxidation, thermal cycling, and oil sludge problems, while exhibiting shear stability. The heat storage process involves an indirect heating of oil with high pressure steam, this makes the oil more stable for longer period. However, the cost of the required inventory of transport oil is a large contributor to the overall project cost, and must be carefully examined.

5.3. Cost effectiveness and environmental risk

The HPR uses a huge number of a highly technical manufactured product, the Model 21700

Li-ion batteries as the storage medium. Sourcing of battery materials, lithium, and secondarily for cobalt, as used in Li-ion batteries has ben questioned by several industry experts, bringing the economics of utility scale exploitation into question.

In contrast, the storage medium for the proposed APR1400 TES is crushed rock, an unlimited resource. This is essentially a product produced onsite or near site using civil engineering production methods, methods which are optimized for producing huge tonnage of product. From an economic perspective, the rock bed storage concept seems promising for use on an industrial scale. The preliminary installation cost for large quantities can be below $10 US/kWt [5] while the installed cost of the Hornsdale Power Reserve was reported at ~$66M US, with ~$50M US going toward the battery modules. A comparison of various parameters for the HPR and TES is provided in Table.2 below:

Table.2. Comparison between HPR and TES Specifications

Parameter	HPR	TES
Recoverable energy (MWe-hr)	109	1150
Recovery rate (MWe)	100	>75[1]
Life Expectancy (yr)	15~20	>60
Space requirements (kW-hr/m^2)	16	~16
Discharge time (hr)	~1	16
Round trip efficiency (%)	88	~55-66[1]
Installed cost ($M US)	$66	TBD

1) Pending optimization studies.

6. Summary

In electricity grids with high penetration of 'green' energy supply, coupling of thermal energy storage and recovery to operating NPPs may become economically viable. Packed beds for thermal energy storage are easily scalable and are not constrained by manufacturing capabilities or by competitive demands for product (e.g., electric cars).

When only considering the cost of the storage medium, Li-ion battery technology cannot be expected to compete, currently being on the order of fifty (50) times more expensive. Other costs are obviously inherent in either project, with the TES having the majority of the cost tied up in non-storage expenditures.

Note that a severe limitation of the HPR is the meager amount of stored energy in the facility. With the storage medium representing ~2/3 of the installed cost, economies of scale will be hard to find for this technology.

From an environmental perspective, disposal of spent Li-ion batteries continues to be a topic for discussion, particularly since they are packaged in an unfriendly configuration for bulk recycling (i.e., with steel, copper, insulation, and plastics all intermingled with the lithium).

As for the environmental impact of the proposed TES, the principal challenge is considered to be represented by the heat transport medium (Therminol 66). However, this challenge is considered to be much lower than that experienced at oil refineries and transport facilities. With accepted engineering practice, this is not considered to represent a significant risk.

7. Future work

Overall, TES for backfit to operating NPPs is considered to represent interesting and potentially promising technology for huge amounts of non-carbon based storage and recovery of energy for electricity production. Follow-on steps are planned as listed below:

(1) thermodynamic (heat balance) modelling of the nuclear heat storage and recovery process (in progress),
(2) process optimization to include parametric variation,
(3) process economics and efficiency,
(4) system design and layout,
(5) detailed hydraulic modeling, and
(6) process impact on APR1400 steam cycle process.

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