Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Preliminary study of thermal energy storage integration with nuclear power plant for flexible operation

Seungjoon Baik [a], Jeong Ik Lee [a*]
[a]*Dept. of Nuclear & Quantum Engineering, KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

Recently, as the utilization of renewable energy is increased, the influence on the electric gird from the intermittency of renewable energy (e.g. wind turbine, solar photovoltaic (PV), concentrated solar power (CSP)…) has become an issue in the energy market. As shown in the figure 1, the supply of electricity over time (orange) is shifting from the conventional supply curve (blue) due to the characteristics of the solar energy production (gray). This phenomenon is known as 'duck curve' which is mainly found in regions which have substantial contribution of energy from photo voltaic (PV) or concentrated solar power (CSP) power (e.g. Germany, France, Spain, and California). In this regard, existing PV power requires to store electric energy in the battery system while CSP systems requires thermal energy storages. Thus, with the further development of renewable energy technologies and increased capacity, it is expected that appropriate load following technology should be incorporate for future nuclear power plants to share the energy production share.

In this paper, load shifting of nuclear power by using the thermal energy storage (TES) system is studied for effective and stable utilization of nuclear energy.

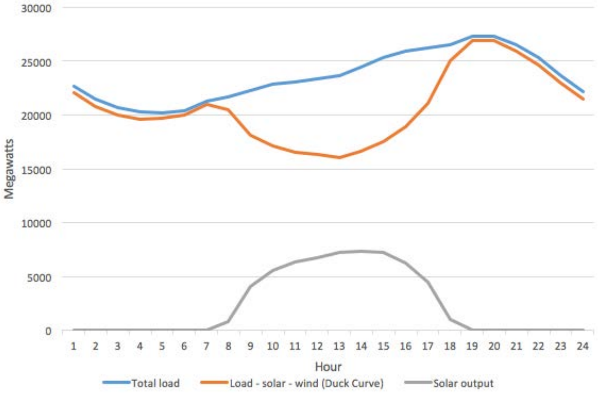

Fig. 1. Hourly electric load of California on October 22, 2016 [California ISO – Renewables Reporting]

2. Nuclear power plant & Thermal energy storage

In this section existing large scale nuclear power plant and thermal energy storage technology will be summarized to analyze their integration possibility.

2.1 Load-following operation with nuclear power plants

According to European Utilities Requirements (EUR), modern nuclear power plant must at least be capable of daily load cycling operation between 50% and 100% of its rated power with a rate of electricity output change 3-5% of rated power per minute. The APR1400 is also designed to allow part-load operation to meet the design requirements, but there are additional considerations for nuclear reactor power changes:

(1) Moderator effect
(2) Doppler effect
(3) Power distribution change in the core
(4) Xenon effect
(5) Fuel burn up

According to OECD-NEA report [1], those are important physical effects that can limit the possibilities of power variation in a light water nuclear reactor. From (1) to (3), these are related to temperatures of the primary coolant and fuel and axial distribution respectively. (4) and (5) can be categorized in to fission product poisoning. Especially, Xenon-135 is an extremely strong neutron absorber which is produced in several hours after the change of the reactor power level [2, 3].

For the long term operation, not only the physical effects but also the mechanical issues need to be considered for the control rod drive mechanism and cyclic thermal fatigue of the components. Due to these difficulties, nuclear power plants are producing electricity as a base-load operation in most of electric markets.

In order to overcome these drawbacks and improve the system, the authors propose the integration of thermal energy storage system with nuclear power plant for load following operation

2.2 Thermal energy storage (TES)

Existing general energy storage devices have a variety of ways on storing energy. From the flywheels which store mechanical energy, to large battery systems that store direct current electricity. Among the various types of energy storages, the authors focused on thermal energy storage type in this study [4].

The existing TES can be divided in to three types according to the heat storage medium: Sensible heat, Latent heat type and thermochemical type.

The thermochemical energy storage, which uses chemical reaction to store energy, has the largest energy density but it is still in the laboratory stage [5]. Also the latent heat storage type is possible with various phase change materials but it is difficult to store heat quickly and easily without additional heat transfer medium. Due to the limitations, sensible heat storage is only covered in this paper.

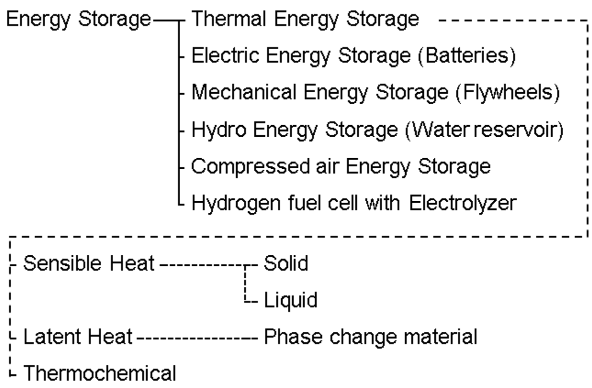

Fig. 3. Category of energy storage types

Sensible heat storage can be also divided according to whether the medium is solid or liquid. This kind of technology is mainly developed and utilized in CSP applications. It is already proven technology, so that the examples of large scale applications and design parameters can be found in open literatures. Also the design limitation or thermal physical properties are available [3-5, 8].

Table I: Specification of heat storage mediums

Material	**Water** @100℃	**Ther-minol66** @300℃	**Solar salt** @300℃	**Rock** @500℃
Density [kg/m^3]	959	817	1900	2480
Specific heat [kJ/kg]	4.21	2.31	1.49	0.84
Thermal conductivity [W/mK]	0.677	0.096	0.45	2-7
Viscosity [mPas]	0.283	44	1.3-1.6	-
Melting Temperature [℃]	0	-3	220	-
Maximum Temperature [℃]	100	350	700	1650
Volume Specific heat capacity [kJ/m^3]	4037	1887	2831	2083
Cost [US$/kWh]	-	43	3-12	-

Particularly in solid storage type, packed bed of rocks is often used in high temperature application (over 500℃). Also the convective gas circulation is mainly used for the heat transfer. On the other hand, in the case of liquid storage, molten salt or thermal oil is often used for medium temperature application (200-400℃). With the configuration of two-tank storage, the heated medium can be easily stored and utilized without mixing with cold medium.

2.3 Nuclear power plant – APR1400

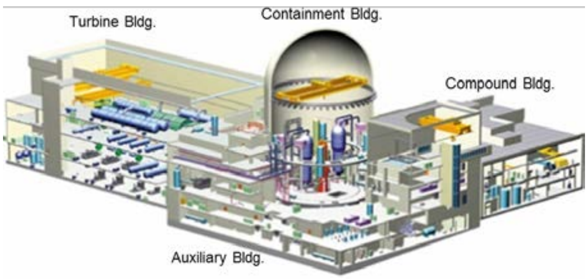

Fig. 2. A cut-away of a plant based on the APR1400 [Doosan]

The Advanced Power Reactor 1400 (APR1400) is a standard evolutionary advanced light water reactor in the Republic of Korea developed in 2002. From the international atomic energy agency (IAEA) advanced reactors information system, only the necessary technical specifications for this study are summarized in the following table [6, 7].

Table II: APR1400 Description

General plant data			
Reactor thermal output	3983 MWth	Power plant output	1400 MWe
Power plant efficiency	35.1%	Plant design life	60 years
Primary coolant		**Secondary coolant**	
Material	Light water	Material	Light water
Flow rate	20991 kg/s	Flow rate	1130.8 kg/s
Pressure	15.5 MPa	Pressure	6.9 MPa
Inlet Temp.	290.6 ℃	Inlet Temp.	232.2 ℃
Outlet Temp.	323.9 ℃	Outlet Temp.	285.0 ℃

3. Results

3.1 TES design for APR1400

The authors aimed to design a thermal storage system capable of storing 400MWth, which is 10% of the reactor heat output, for 2 hours (total 800MWh). The 2 hours of heat storage is expected to be available to mitigate the steep ramping of demand in the afternoon shown in Figure 1. Technically, it is difficult to change the design of the primary side of reactor cooling system. Therefore the steam flow from the secondary side is utilized to transfer heat to the TES.

The schematic diagram of the suggested TES integrated nuclear power plant is shown in the figure 3. Due to the overloading limitations of large-scale saturated steam turbines, additional subsystems for converting heat to electricity will be needed.

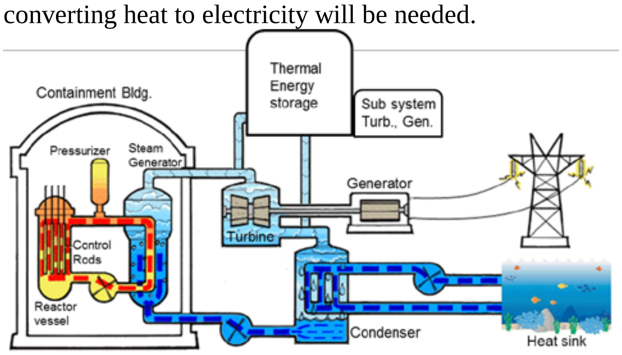

Fig. 3. A schematic diagram of suggested TES integrated nuclear power plant system

3.2 Preliminary design

The authors referred to the Andasol CSP Station, which was constructed in Spain in 2009 for practical size comparison. The Andasol station is a parabolic trough type CSP consisting of three 50MWe steam turbines with three pairs of molten salt TES. One pair of them is shown in the figure below. [5]

Fig. 4. 150MW scale Andasol CSP station in Spain.

Following results are 800MWh thermal energy storage depending on heat storage mediums. By using the same size of storage tank, different materials can be utilized to store 2 hours of thermal output. Due to the difference of thermal capacity, each storage tank shows different size. In water storage case, at least 7MPa is needed to store 285℃ of steam in state of water. This requires a large pressure vessel, which is not a proper choice in economical view. The results of these simplified thermodynamic calculations will be followed by a detailed consideration of heat loss and charge & discharge rate.

Table I: Specification of heat storage mediums

Materials	Solar salt [And-asol]	Water	Ther-minol-66	Solar salt	Rock
Size [m]	36×14 (D×H)				
# of pairs	3	1	2	1.5	1.8
Inventory [tons/storage]	28000	13000	12000	24000	35000
Hours of use	7.5	2			
Temperature difference [℃]	90	53			
Capacity [MWh]	1050	800			

4. Conclusions

In this paper, load shifting of nuclear power plant through utilizing the thermal energy storage system is studied for effective and stable utilization of nuclear energy with renewable energy. The technical information of 1400MWe scale Advanced Power Reactor (APR1400) is used to consider 2 hours, 10% load shifting operation. Also the 1050MWh size thermal energy storage of Andasol CSP station is compared with the suggested thermal storage system. The technical feasibility of TES integration into conventional nuclear power plant is studied.

For the further works, economic analysis of storage medium and proper power conversion technology will be studied. The authors believe that carbon dioxide based mixture power cycle can be suitable because it is small and efficient systems in this temperature range. Also the exergy analysis will be conducted to show the optimized TES-NPP matching system.

REFERENCES

[1] LOKHOV, A. Technical and Economic Aspects of Load Following with Nuclear Power Plants. Nuclear Development Division. 2011.

[2] LOKHOV, Alexey. Load-following with nuclear power plants. NEA news, 2011, 29.2: 18-20.

[3] GJORGIEV, Blaže; ČEPIN, Marko. Nuclear power plant load following: problem definition and application. In: Proc. 20th Int. Conf. Nuclear Energy for New Europe 2011. 2011. p. 506-515.
[4] LI, Pei-Wen; CHAN, Cho Lik. Thermal energy storage analyses and designs. Academic Press, 2017.
[5] BAUER, Thomas, et al. Overview of molten salt storage systems and material development for solar thermal power plants. In: Proceedings of the 2012 National Solar conference for (SOLAR 2012), Denver. 2012. p. 1-8.
[6] IAEA_ARIS_Status report 83-Advanced Power Reactor 1400 MWe (APR1400)
[7] KIM, Han-Gon, et al. The Design Characteristics of the Advanced Power Reactor 1400. ICONE-13, Beijing, China, 2005.
[8] WOJCIK, Jacek D.; WANG, Jihong. Technical Feasibility Study of Thermal Energy Storage Integration into the Conventional Power Plant Cycle. Energies, 2017, 10.2: 205.