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

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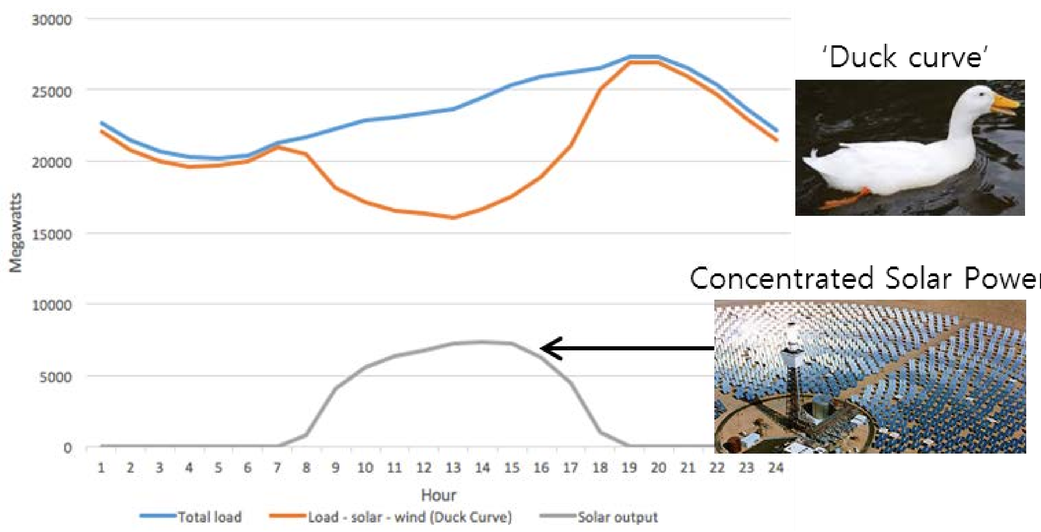
Introduction

▣ 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 recent energy market.

As shown in the figure, 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.



▲ *Hourly electric load of California on Oct., 2016*

Nuclear power plant & Thermal energy storage

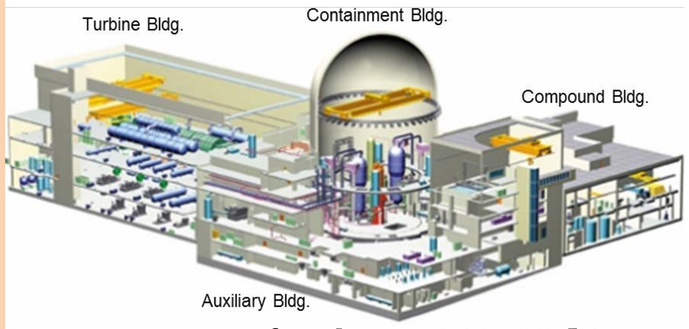
▣ Load-following operation with nuclear power plants

- 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.
- According to OECD-NEA report, following physical effects are needed to be considered 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

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.

▣ Nuclear power plant – APR1400, developed in 2002

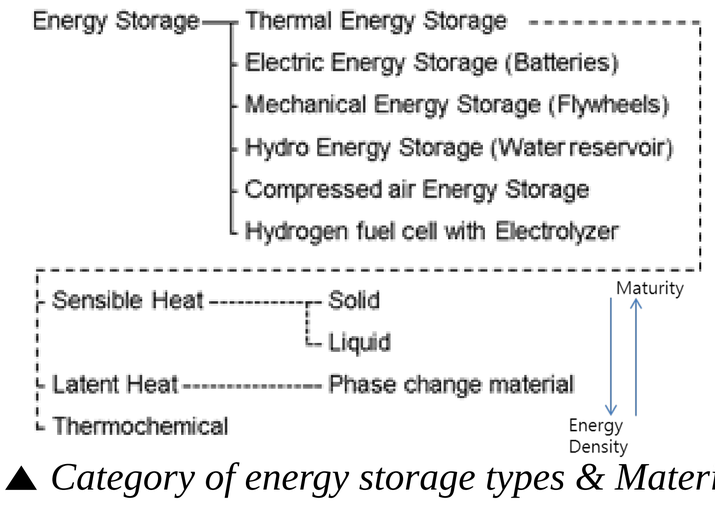
The APR1400 is also designed to allow part-load operation to meet the design requirements, but there are additional considerations for nuclear reactor power changes. However it is not good for economy in current method.



General plant data			
Reactor thermal output	3983MWth	Power plant output	1400MWe
Power plant efficiency	35.1%	Plant design life	60 years
Primary coolant		**Secondary coolant** x 2	
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 ℃

▲ *A cut-away of a plant APR1400 [Doosan]* & Technical specifications

▣ Thermal energy storage (TES)



Material	Water @100℃	Ther-minol66 @300℃	Solar salt @300℃	Rock @500℃
Density [kg/m³]	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/m³]	4037	1887	2831	2083
Cost [US$/kWh]	-	43	3-12	-

▲ *Category of energy storage types & Material selection of sensible heat storage and their thermodynamic properties*

Results

▣ The Andasol CSP Station is referred for practical size comparison, which was constructed in Spain in 2009. 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.

Materials	Solar salt [Andasol]	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 (59%)			
Capacity [MWh]	1050	800			

▲ *150MW scale Andasol CSP station in Spain & Preliminary design result of suggested system*

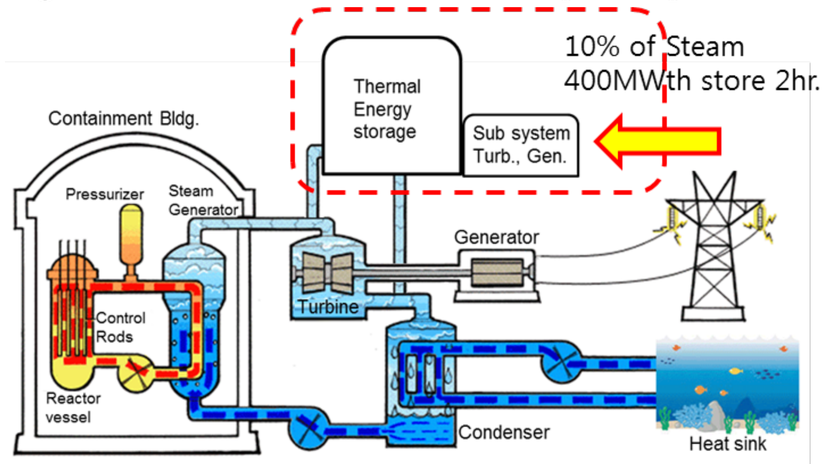
▣ The results are 800MWh thermal energy storage depending on heat storage mediums. By using the same size of storage tank, different materials can be utilized to store 2 hours of thermal output. Due to the difference of thermal capacity, each storage tank shows different size.

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.

Conclusions and Further Works

▣ 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.

To consider 2 hours of 10% load shifting operation of APR1400, preliminary design result of TES is suggested. By comparing the size of TES with existing Andasol CSP station (1050MWh) the technical feasibility of TES integration into conventional nuclear power plant is studied.



▲ *A schematic diagram of suggested TES integrated nuclear power plant system*

▣ 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.

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