Preliminary Assessment on Life Cycle of High Temperature Thermal Energy Storage System using Liquid Sodium

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1. Introduction

Great attention to Energy Storage System (ESS), a key component to renewable energy that is intermittent and volatile, of cost effectiveness with long duration has been being paid recently over the world, especially in US, for instance, ARPA-E (Advanced Research Projects Agency-Energy)'s DAYS (Duration Addition to electricity Storage) projects empowered by USDOE [1]: this projects intend only application from electric grid to electric supply for duration of 10 to approximately 100 hours. P2H (Power to Heat) using Joule heating with no loss of power and Thermal energy storage(TES) gives another option to ESS such that it can open a different market on process heat of low price with little carbon. A TES of high temperature up to 700 degrees in Celsius using Liquid sodium, which is kept under single phase, may be a good option of a ESS with low price and a competitor to TES in molten salt up to around 550 degrees in Celsius.

Starting with assigning a set of tentative Top-Tier Requirements(TTR) on a high Temperature TES, a preliminary assessment is given on life cycle of a high temperature TES using liquid sodium so that a gap could be identified between a lab-scale test facility and a realizable system to enter real energy markets. A set of information is being added for evaluating techno-economic analysis on a high temperature TES using liquid sodium. This assessment will be continuously updated such that an economic option can be established based on liquid sodium TES of high temperature.

2. Assignment of TTRs on TES of high T

A set of requirements on Energy Storage System (ESS) are given as in table I [1]. The most important parameter appears to be levelized cost of storage (LCOS), 5 cents/kWh-cycle keeping in mind that the electricity purchase price is assumed to be 2.5 cents/kWh.

Table I: Requirements of DAYS projects [1]

ID	Metric name	Value
1	Duration at rated power	10 to approximately 100 hours
2	Levelized cost of storage (LCOS)	5 cents/kWh-cycle RTE(Round Trip Efficiency) > 50%
3	Electricity purchase price	2.5 cents/kWh
4	Siting requirements	No geographic constraints
5	Energy form for charge and discharge	Only electricity in / only electricity out
6	Minimum final, full-scale system size	100 kW based on peak electrical output
7	Duty cycle	Applicants must use the duty cycles shown in Figure, which result in the cost-duration curves.

Considered are electricity market change such as increase in share of renewables, remote and district demands on energy of various types, and shown in Table II performance parameters in order to assign a set of tentative Top-Tier Requirements on ESS in addition to the those of the DAYS from the references [2][3][4][5][6] covering various types of ESS as well as TES.

3. Assessment on Life Cycle of TES of high T

The life cycle of the TES is investigated within a framework of the specific safety principles for nuclear power plants by IAEA [7] in a comprehensive and systematic manner.

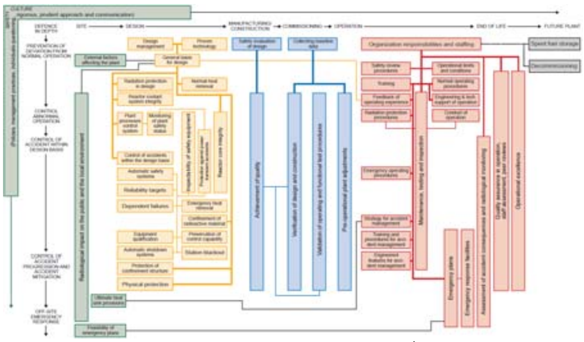

Fig. 1. Schematic presentation of the INSAG* specific safety principles showing their coherence and their interrelations.
 * International Nuclear Safety Advisory Group

8 specific safety principles are as follows:

- Siting
- Design
- Manufacturing and construction
- Commissioning
- Operation
- Accident management
- Decommissioning
- Emergency preparedness.

Table II: Performance parameters of ESS [2][3][4][5]

No	Performance parameters	Units
1	Storage capacity	kWh(or MWh)
2	Available power	kW
3	Power transmission rate	hr
4	Efficiency	%
5	Discharge time	hr
6	Durability cycling capacity	cycles (charing /discharging)
7	Autonomy	hr
8	Self-discharge	% (or T, kWh)
9	Adaptability to the generating systems	qualitatively
10	Costs	$/kWh
11	Energy density	kg/kWh, m3/kWh
12	Operational constraints	N/A
13	Reliability	failure rate
14	Monitoring and control equipment	N/A
15	Environmental aspect	N/A
16	Other characteristics	N/A

A preliminary assessment on life cycle of TES of high temperature, for instance, from the siting point of view is as shown in Table III.

The site is the area within which a facility, i.e., a thermal energy storage (TES) system is located and which is under the effective control of the operating organization. The selection of an appropriate site is an important process since local circumstances can affect safety. The choice of site is a balance between competing factors including economic interests, public relations and safety. 4 principles related to external factors affecting the plant, radiological impact (this factor was intended for nuclear application but in this application of principles to TES this is considered as any environmental impact including the asset, i.e., TES and the facility near it) on the public and the local environment, feasibility of emergency plans, ultimate heat sink provisions are there in the siting. While assessing life cycle of the TES, licensing elements should be identified at the same time as shown in Fig. 2 [8]: sodium specific (or technology inclusive), risk-informed, performance-based (RIPB) should be prepared for implementing a new technology in a real world.

Table III: Applicability of Specific Safety Principles to TES (Siting)

No	Principles	Applications to TES
1	External factors	Applicable
2	(Radiological) impact on the public	Applicable
3	Feasibility of emergency plans	Applicable
4	Ultimate heat sink provisions	Not applicable

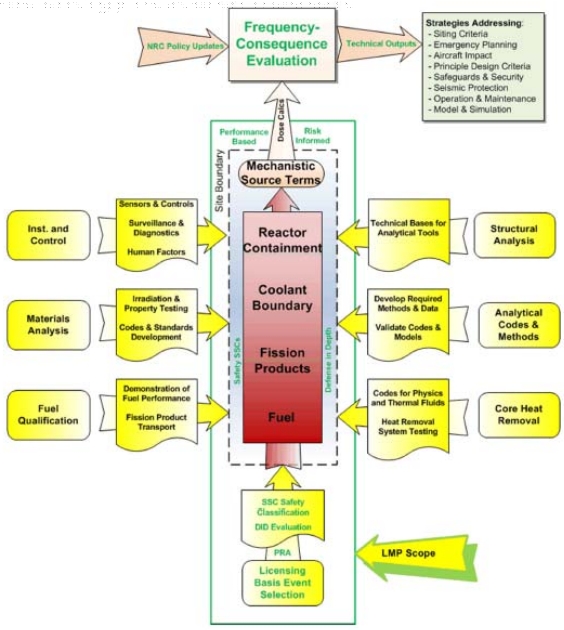

Fig. 2. Licensing elements addressed by LMP**.
 **LMP: Licensing Modernization Plan.

4. Techno-Economic Analysis

As shown in Table I, techno-economic analysis is a must for providing a technical option for ESS. The metric, Levelized Cost of Storage (LCOS) per cycle, the most important parameter of TES is defined as following equation (1).

$$LCOS = \left[A + OM + C\right] \Big/ \sum_{t=1}^{T} \frac{n_c(t)}{(1+r)^t} \quad (1)$$

$$, A = \left(\frac{1}{\eta_{RTE}} - 1\right) P_C \sum_{t=1}^{T} \frac{n_c(t)}{(1+r)^t}$$

$$, OM = \sum_{t=1}^{T} \frac{O\&M(t)}{(1+r)^t},$$

$$, C = \left(\frac{C_E}{\eta_D} + \frac{C_P}{d}\right)$$

, where η_{RTE} and η_D are round-trip and discharge efficiencies at rated power, respectively, P_C is the input electricity price during charging, r is the discount rate, T is system lifetime in years, O&M(t) is the combination of fixed and variable operations and maintenance costs over time interval in $/kWh (including periodic replacement of any system components), C_E is the capital cost for (usable) energy-specific components and associated balance of plant ($/kWh), C_P is the capital cost for power-specific components and associated balance of plant at rated power ($/kW), d is the storage duration at rated power, $n_c(t)$ is the total number of equivalent full charge-discharge cycles the system performs over time interval t. Input electricity price during charging is fixed as 2.5 cents/kWh, discount rate is set to 10%, the system lifetime in years is assigned as 20.

The cost information comes from the combination of 1) history of STELLA2-sodium integrated thermal-hydraulic effects test facility, 2) preliminary up-to-dated lab-scale construction cost evaluation, and 3) open literatures.

The system architecture to analyze the cost reference for a liquid sodium TES of high temperature comprises of mainly both sodium storage tanks with heavily shielded (one for hot around 700 degrees in Celsius and one for cold around 200 degrees in Celsius), pumps, measuring device such as flowmeters, temperature sensors, level detectors, loop-heater for simulating electricity supply from renewables, inert gas system, monitoring and control system, fire protection and mitigating system including leak detection, and structures withstanding severe environment with very long fatigue life (~ hundreds of thousands hours) under very high temperature up to 700 degrees in Celsius.

5. Concluding Remarks

This paper deals with a variety of aspects that Thermal Energy Storage using liquid sodium under high temperature will meet during life cycle.

- a set of tentative Top-Tier Requirements(TTR) were assigned based on the references covering a variety of ESSs;
- a framework to consider life cycle of a TES was proposed based on nuclear safety principles and licensing elements;
- A set of information is being added for evaluating techno-economic analysis.

These works should be updated continuously to reach an optimal point where liquid sodium TES of high temperature will have competiveness to competing options.

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