NENE
International Conference
Nuclear Energy for New Europe

Thermal Energy Storage Combined with a Molten Salt Reactor

Pia Fackovič Volčanjk
GEN energija, d.o.o.
Vrbina 17
8270 Krško, Slovenija
pia.fackovic@gen-energija.si

Assoc. Prof. Dr. Andrej Senegačnik
Faculty of Mechanical Engineering, University of Ljubljana
Aškerčeva cesta 6
1000 Ljubljana, Slovenija
andrej.senegacnik@fs.uni-lj.si

ABSTRACT

Electricity plays a crucial role in contemporary society and is becoming even more vital with the expansion of electrification. This is causing a worldwide surge in demand for power, the production of which has to be decarbonized to approach the goal of zero greenhouse gas emissions. This can be achieved by increasing the share of low carbon energy sources, particularly renewables and nuclear energy. As the share of variable renewable energy systems, such as solar and wind, continues to rise, the need for power plants, which can adjust their load to match changes in electricity demand and variable supply from renewables, also increases.

Nuclear power plants contribute to maintaining electricity security and power grid stability. They can adjust their operations to a certain extent in response to changes in demand and supply, however they are primarily utilized as base load sources due to their low operational cost. The combination of advanced nuclear reactors and thermal energy storage presents a promising solution for achieving greater flexibility of nuclear power plants, which would allow better alignment with fluctuating demands and supply shifts.

Molten salt nuclear reactors are an advanced form of nuclear power technology. They can operate at high temperatures and low pressure, conditions which result is an increased power plant efficiency and a lower risk of fatal release of volatile radioactive materials. Moreover, the high operating temperature of these reactors makes it capable for integration of high temperature thermal energy storage.

This article describes a concept for thermal energy storage using molten salt combined with a conceptual molten salt nuclear reactor that has a thermal power of 750 MW. With this system the nuclear reactor can operate at full power even at times of low power demand and store the surplus heat into the tanks with molten salt for the later use during peak power demand periods. Accumulated heat is used for steam production and extra power in range of 240-600 MW depending on grid demand.

1 INTRODUCTION

Nuclear power plants that are currently in operation are not designed for frequent load adjustment, meaning they are not well-suited for rapidly adjusting their output to match fluctuations in power demand. These reactors are typically operated at a relatively constant power output, serving as stable baseload sources of electricity. One of the promising solutions for better synchronization with fluctuating demands and changes in energy supply is thermal energy storage combined with nuclear reactor. Integrating energy storage solutions for current pressurized water reactors (PWRs) is considered economically unviable because of the low operating temperatures (~300°C). On the other hand, some advanced nuclear reactors, including molten salt reactors (MSRs), operate at much higher temperatures (500–700°C), which makes them suitable for potential utilization in combination with thermal energy storage systems [1]. This enables conceptual MSRs to operate at full power at all times (or at least at constant power) while thermal energy is being stored, which can later be converted to electricity during peak demand periods.

Variation of the electricity demand in Slovenia and many other countries follows a characteristic ‘’two peaks, one valley’’ curve, which is shown in Figure 1. The first morning peak occurs around 8:00–9:00 and the second evening peak occurs around 19:00–21:00, while the valley corresponds to nighttime 22:00–06:00. The absolute and relative magnitudes of these peaks are influenced by various factors, including the season, climate, and, to a lesser extent, local peculiarities.

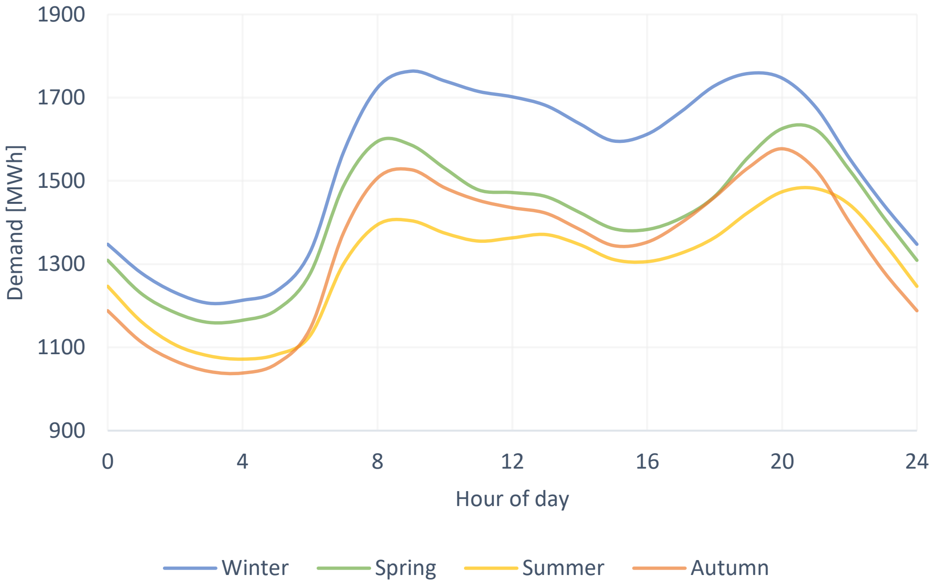

Figure 1: Average electricity demand curves for Slovenia in 2022 [2]

Electricity prices in the day-ahead market are influenced by a complex interplay of supply and demand factors. These factors include the availability and cost of fuel for fossil fuel power plants, weather conditions that affect demand and the amount of electricity produced by renewable energy sources, market regulations, and cost associated with carbon emission allowances. Conceptual MSRs combined with thermal energy storage systems represent a promising solution for times of high electricity demand and price.

2 MOLTEN SALT REACTORS

General MSRs use molten salts as the primary coolant and operate at atmospheric pressure. They can operate with fast or thermal neutrons and can utilize various fuels, such as uranium and plutonium or thorium and uranium. Graphite is commonly used as a moderator, because it is chemically compatible with the molten salts. There are two main types of MSRs:

- reactors with liquid fuel,
- reactors with solid fuel.

The salts used as primary coolant are typically lithium-fluoride salts. The melting point of these substances at atmospheric pressure is approximately 500 °C, and the boiling point is around 1400 °C [3]. This allows general MSRs to operate at much higher temperatures compared to PWRs, in which primary coolant pressure is set around 150 bar and an outlet temperature is about 315°C [1]. The highest operating temperature of general MSRs is limited by material corrosion, while the lowest is constrained by the salt's melting temperature [4]. In Table 1 operational parameters are shown for PWRs and general MSRs.

Table 1: Characteristics of PWRs and MSRs [1]

	PWR	**MSR**
Thermal Capacity [MWt]	2400	704
Coolant inlet temperature [°C]	281	596
Coolant outlet temperature [°C]	315	697
Coolant temperature difference[°C]	34	99
Average Core power density [kW/L]	90	34
Plant efficiency net [%]	33	44

General MSRs generally have lower average thermal power and core power density compared to PWRs. Inlet-outlet temperature difference in the primary loop is approximately three times greater in general MSRs than in PWRs. In terms of efficiency, general MSRs achieve around a 10% higher efficiency compared to PWRs [1].

3 SYSTEM

Figure 2 shows a simplified schema of the system, which consists of a general MSR concept as hear source, heat exchangers, a cold and hot reservoir for thermal energy storage, a steam generator and a steam superheater, a turbine and a condenser. In Figure 2, the red colour represents the secondary coolant of the molten salt reactor (fluoride salt), the green colour represents the medium for thermal energy storage (solar salt), and the blue colour represents the steam cycle.

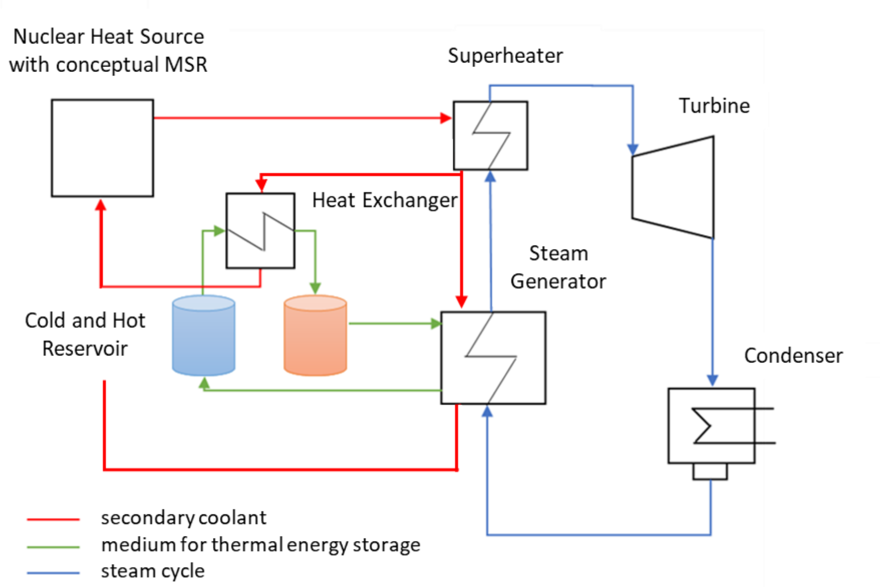

Figure 2: Schematic diagram of hypothetical thermal energy storage combined with nuclear hear source (general MSR) [5]

The thermal power of the conceptual molten salt reactor is 750 MWt. Two reservoirs are used for thermal energy storage, using a medium called "solar salt." The operating temperature of the hot reservoir is limited by the stability of solar salt and is set at 565 °C, while the temperature of the cold reservoir is determined by the melting point of solar salt and is set at 270 °C [6]. The estimated capacity of the thermal energy storage system is 3000 MWh.

3.1 Operation types

We use two different types of charging and discharging of molten salt reservoirs, which are shown in Table 1:

- Type 1 (1 × 240 MW and 1 × 360 MW turbines and 3000 MWh thermal storage capacity)
- Type 2 (2 × 200 MW turbines and 3000 MWh thermal storage capacity)

Type 1 operation is based on the 4 h/20 h principle. The basic state or heat storage charging takes 20 hours. During this period, the turbine operates at 240 MWe. During the four hour discharging phase, at the time of the highest electricity prices on the day-ahead market, both turbines operate at 100% capacity, providing up to 600 MW of electrical power.

Type 2 operates on the principle of 12 h/12 h. Charging and discharging of the heat reservoirs are divided into two parts, with charging taking place for 6 hours, discharging for 6 hours, another charging for 6 hours, and a second discharging for 6 hours. During the charging period, when electricity prices are lower, only one turbine operates at full capacity - 200 MW. During the discharging of the heat reservoir, both turbines operate at full capacity, providing up to 400 MW of electrical power.

Table 2: Operating types

Hours [h]	**Reactor load [%]**	**Turbine load [MW]**	**Thermal storage**
Type 1			
20	100	240	Charging
4	100	240 + 360	Discharging
Type 2			
6	100	200	Charging
6	100	200 + 200	Discharging
6	100	200	Charging
6	100	200 + 200	Discharging

3.2 Electricity price behaviour

From the data on the day-ahead electricity market the average marginal electricity price per hour for each month was calculated. Based on the hourly marginal electricity price, the time periods for charging and discharging thermal energy storage reservoirs were determined. During periods of highest prices, discharge is predicted, and during periods of lower prices, charging the reservoirs with thermal energy is predicted. Predicted time periods for both types of operation are shown in table 3.

Table 3: Operating time periods for both types

Time [Hour of day]	Turbine load [MW]	Thermal storage
Type 1		
00:00 – 18:00	240	charging
18:00 – 22:00	600	discharging
22:00 – 24:00	240	charging
Type 2		
00:00 – 06:00	200	charging
06:00 – 12:00	400	discharging
12:00 – 18:00	200	charging
18:00 – 24:00	400	discharging

4 RESULTS

The average day-ahead marginal electricity prices per hour in Slovenia from January 2019 to July 2023 and average annual daily electricity consumption for Slovenia are shown on Figures 3 and 4 on the left axis. Hypothetical generated power and stored thermal energy for thermal system with conceptual MSR for operation type 1 and type 2 are shown on Figures 3 and 4 on the right axis.

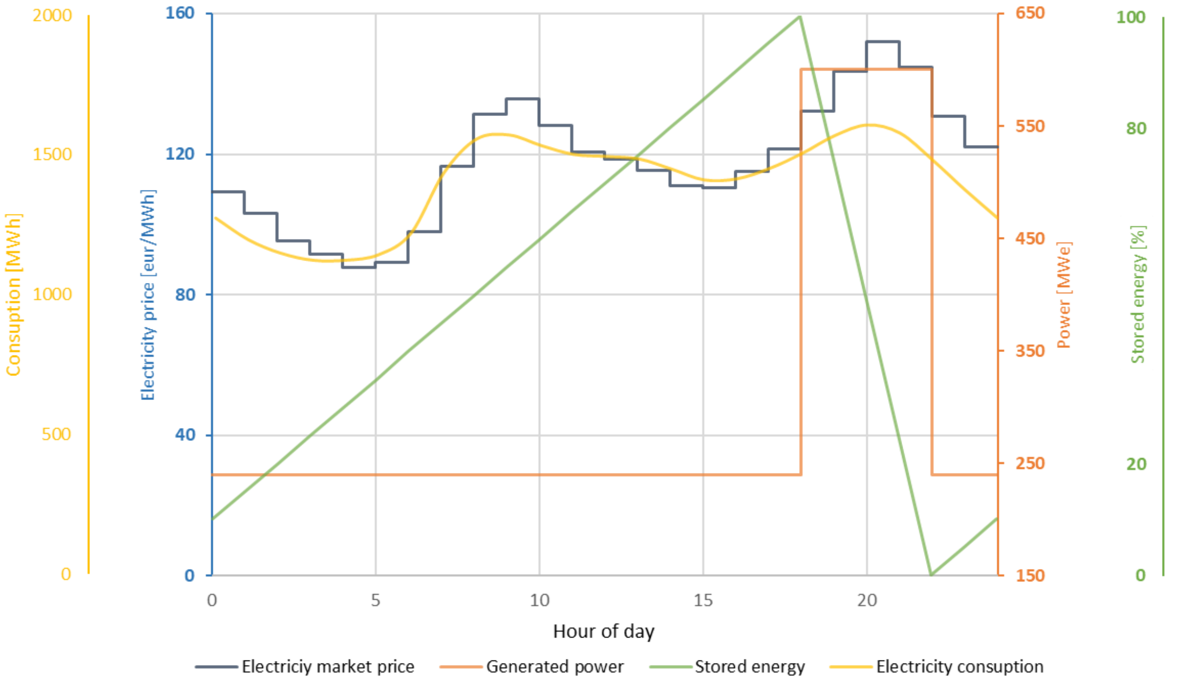

Figure 3: Generated power and electricity price for operational type1 [7]

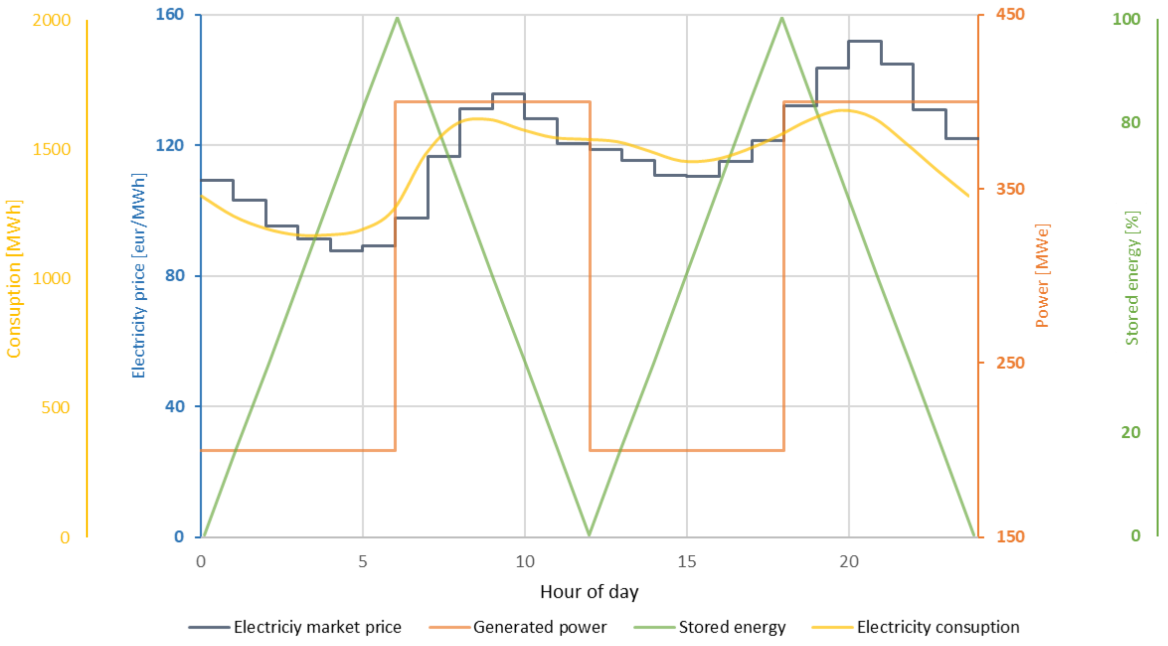

Figure 4: Generated power and electricity price for operational type 2 [7]

The marginal electricity prices for Slovenia in the day-ahead market exhibit two distinct peaks, in the morning and in the evening, and two operational types are optimised to match market conditions. In operational type 1, discharging of heat reservoirs occurs between 18:00 and 22:00, while charging takes place from 22:00 to 18:00. In operational type 2, charging occurs from 00:00 to 6:00 and discharging from 6:00 to 12:00, followed by another charging phase from 12:00 to 18:00 and discharging from 18:00 to 24:00.

In Figures 3 and 4, we can see that the peaks of electricity consumption and electricity prices in the day ahead market align. For operational type 1, the system is charged during the night when electricity consumption is lower and throughout the day, when some electricity can be generated from renewable energy sources – solar power plants. In the evening, during periods of elevated consumption and reduced solar radiation, the conversion of stored thermal energy into electricity would be initiated. Similarly, this applies to operational type 2, however, in this case, enhanced electricity production would occur during the morning and evening peaks, while the system would be charged during the night and daytime.

4.1 Benefits and challenges

The integration of thermal energy storage system with conceptual MSR has numerous benefits that address key challenges in current energy situation.

- *Grid flexibility*

By strategically charging thermal energy storage reservoirs during periods of lower electricity demand and discharging them during peak demand times, the system effectively shifts energy production to match market needs. This capacity to adjust power generation based on market conditions helps stabilize the electricity grid by lowering the risk of blackouts and overloads during periods of high/low consumption.

- *Reduced stress on nuclear reactor components*

Nuclear reactors experience stress corrosion cracking when subjected to frequent load changes. Conceptual MSRs coupled with thermal energy storage systems can operate at steady-state conditions that reduce stress on critical components, which can prevent damage in reactor core. This results in prolonged conceptual MSRs lifespan and decreased maintenance requirements, contributing to higher operational, safety efficiency and cost-effectiveness over the reactor's lifetime.

- *Cost optimization and revenue maximisation*

Combination of thermal energy storage with conceptual MSR is very profitable for areas where electricity prices vary throughout the day. During periods when electricity demand and electricity prices are lower, the conceptual MSR generates excess thermal energy that is efficiently stored in reservoirs. As the electricity demand peaks and prices surge, the stored thermal energy is converted to electricity for sale, enabling the owner to maximise revenue by selling electricity at highest rates.

- *Renewable energy integration*

The integration of renewable energy sources, such as solar and wind, is inconsistent in terms of electricity production due to their dependence on weather conditions. Conceptual MSRs combined with thermal energy storage system can provide a reliable and adjustable energy source that can compensate to a certain extent for the fluctuations in renewable energy generation. During periods of high production from renewable energy sources, the surplus thermal energy from conceptual MSR can be stored, which enhances the overall efficiency of the energy system and reduces the need for limiting the utilization of renewable energy sources.

While thermal energy storage combined with conceptual MSR offers notable advantages, it is essential to acknowledge potential challenges that may influence its practical implementation.

- *Licensing*

The licensing status of molten salt in nuclear reactors is currently pre-commercial, as no reactor utilizing molten salt has yet obtained a commercial license for regular operation. Despite studies, experiments, and prototypes, there is still a need for research, validation, safety assessments, and adaptation of existing regulatory frameworks for the novelty that MSRs represent. The licensing process for molten salt technologies requires collaboration among research institutions, industry, and regulators to ensure the safe and reliable operation of these promising nuclear systems in the future.

- *First of a kind project (FOAK)*

Securing financing for a FOAK project like conceptual MSR combined with thermal energy storage system poses a considerable challenge. Investors and financial institutions may be cautious due to the absence of a proven track record for such novel technologies. The capital costs for designing, constructing and commissioning of MSR can be substantial, and uncertainty regarding returns on investment could discourage potential funders. Moreover, technical and maintenance costs for a FOAK project can be higher due to the lack of established operational experience and maintenance procedures. Developing expertise, training personnel, and sourcing components specific to the new technology may increase initial expenses.

5 CONCLUSION

In conclusion, the integration of thermal energy storage with conceptual MSRs provides a promising solution to tackle prevailing energy challenges. While aiming to achieve carbon emission reduction targets, the incorporation of renewable energy sources like solar and wind is pursued. However, this endeavor introduces challenges due to their intermittent nature, resulting in energy generation fluctuations and potential grid instability.

By strategically shifting energy production to match market demand through the efficient thermal storage and converting thermal energy to electricity, this hypothetical system could enhance grid flexibility, reduce stress on nuclear reactor components, maximize revenue, and facilitate the integration of renewable energy sources. However, while the potential benefits are significant, it is important to acknowledge the challenges that must be overcome. The licensing process for MSRs requires careful collaboration to ensure safety and regulatory compliance. Additionally, securing financing for such FOAK presents a challenge due to the absence of a proven track record and initial higher costs. Overcoming these obstacles demands a collaborative endeavor involving research institutions, industry collaborators, regulators, and financial stakeholders. Despite these trials, integrated thermal energy storage with conceptual MSR presents a promising step toward a more sustainable and flexible energy future, paving the way for sustainable, more effective, and responsive energy systems capable of fulfilling the requirements of a swiftly evolving world.

REFERENCES

[1] IAEA: Advanced Reactors Information System (ARIS) - Technical Data, https://aris.iaea.org/sites/overview.html, (accessed 17 August 2023)

[2] ELES: Proizvodnja in prevzem, https://www.eles.si/prevzem-in-proizvodnja, (accessed 18 August 2023)

[3] T. J. Dolan: Introduction. Molten Salt Reactors and Thorium Energy. Eodhead Publishing Series in Energy, Cambridge, 2017, pp. 1–12.

[4] R. Yoshioka, M. Kinoshita, I. Scott.: Materials. Molten Salt Reactors and Thorium Energy. Molten Salt Reactors and Thorium Energy. Eodhead Publishing Series in Energy, Cambridge, 2017, pp. 189–207.

[5] Moltex Energy: Grid scale nuclear peaking plant that enables renewables, from Moltex. Moltex Energy, Toronto, 2017

[6] A. Caraballo, S. Galán-Casado, Á. Caballero, S. Serena, "Molten Salts for Sensible Thermal Energy Storage: A Review and an Energy Performance Analysis", Energies 14, no. 4: 1197.

[7] ENTSO-E: Day-ahead prices, https://transparency.entsoe.eu/dashboard/show, (accessed 18 August 2023)