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A STUDY OF INTEGRATION OF LIQUID AIR ENERGY STORAGE (LAES) TECHNOLOGY TO NUCLEAR DISTRICT HEATING FACILITY TEPLATOR

Jan Škarohlíd
Czech Technical University in Prague
Jugoslávských partyzánů 1580/3
160 00 Praha 6, Czech Republic
Jan.Skarohlid@cvut.cz

Ondřej Burian, Radek Škoda, Hussein Abdulkareen Saleh Abushamah
University of West Bohemian
Sedláčkova 214
301 00 Plzeň 3, Czech Republic
buriano@fel.zcu.cz, skodar@fel.zcu.cz, abushama@fel.zcu.cz,

ABSTRACT

The increase in the share of renewable energy sources in power production increases the need for energy storage technologies. These technologies are necessary for the reliable and stable operation of power grids to compensate for differences between energy production from renewable sources and energy consumption. At the same time, there needs to be more sustainable heat sources for district heating. In this case, a sustainable source is meant for zero-emission and low-cost heat production.

One of the ways to integrate energy storage technologies into industrial-scale operations is by combining them with other technologies for energy production. This article focuses on the study of the integration of two unique energy technologies into one unit: Liquid Air Energy Storage (LAES) technology for electricity storage and the TEPLATOR technology for nuclear district heating generation. This combination is very specific due to the merging of large-scale electricity storage technology and heat generation technology. However, this combination promises an increase in energy production and storage compared to two separate technologies. The article introduces possible system interconnections and operating modes and critically evaluates the technical aspects of the introduced system integration.

1 INTRODUCTION

One significant disadvantage of renewable energy sources is their heavy dependence on local weather conditions. In the case of solar power systems, operation is also dependent on daylight hours. Consequently, electricity production might exceed consumption or vice versa. Such imbalances are unacceptable for maintaining a stable grid operation. To solve these problems, Energy Storage Systems (ESS) become imperative for power grids with a substantial share of renewables.

Another challenge on the horizon for the energy sector is finding alternative sources of heat for district heating. In many areas, district heating relies on fossil fuel combustion, often involving lignite or natural gas, which is unsustainable in the near and medium term. Some regions have transitioned to biomass sources, a more viable approach for the medium term. However, the broader adoption of these technologies increases the demand for biomass, potentially leading to increased greenhouse gas emissions due to the extensive production and transportation of biomass materials.

One potential solution to prevent this scenario is using nuclear power for heat generation. There are several projects in the design phase for small-scale nuclear reactors. Among these projects, TEPLATOR stands out as a unique facility for heat production using either new or used nuclear fuel. TEPLATOR is designed for cost-effective operation at low parameters and features an open architecture. It allows integration with other power systems, including thermal energy storage, cold generation or storage, and coupling with electric energy storage technologies.

One promising combination under discussion involves pairing TEPLATOR with Liquid Air Energy Storage Technology (LAES). This combination offers a solution for mitigating electricity production/consumption discontinuities and peaks. In the district heating sector while also addressing grid-level heat production/consumption issues simultaneously. The most significant advantage of this combination is the increased operational efficiency of both systems in comparison to operating these systems separately.

2 SYSTEM DESCRIPTION

The heat generated by TEPLATOR is utilized for district heating via an independent district heating network. This network operates separately from the system described earlier. The primary output of the presented system is heat. The LAES system stores surplus electricity from the electric grid during off-peak times and discharges it during high-demand periods. This process, known as time-shifting or load-shifting, is intentionally executed to stabilize the electric grid.

The central Thermal Energy Storage (TES) system stores heat produced by TEPLATOR during LAES operation. In addition, an Organic Rankine Cycle (ORC) is used as an additional source of electricity generation by converting excess heat into electricity. The comprehensive system layout is shown in Figure 3.

2.1 TEPLATOR

TEPLATOR is a unique nuclear facility determined to heat production from nuclear fuel. Its thermal power is 50 MW of heat, designed for new or used fuel VVER 440 type. The critical parameter is the possibility of using used fuel with a low content of Uranium 235. That enables cheap nuclear fuel from previous use in pressurized water reactors. The open design philosophy of TEPLATOR enables the redesign of other types of perspective fuels of western pressurized reactors design. The main parameters of TEPLATOR are in Table 1.

The reactor is specially designed for operation with a low content of Uranium 235. For this reason, heavy water is used as a moderator in a separate vessel - calandria. For the same reason, heavy water is used as a coolant. These media are not connected, and heavy water in the moderator vessel is kept under 60 °C for better moderation.

TEPLATOR consists of primary and intermediate cycles, see Figure 1. The primary cycle is intended for heat production. It consists of a nuclear reactor and a main circulation pump in a primary heat exchanger. The intermediate cycle is intended for the separation of the district heating network from the primary cycle. In case of low possible leakage of the primary cycle through primary heat exchangers, there will be hypothetical leakage catch in an intermediate cycle. As a coolant in the intermediate cycle is used light water. The heat from the primary cycle is transferred to the intermediate cycle via the primary heat exchanger. Similarly, is heat transferred from the intermediate cycle to the district heating network via an intermediate heat exchanger. The final temperature of delivered district water can be in range from 100 °C to 165 °C.

The connection of TEPLATOR to the district heating network is an open design that can be localized to local network parameters and is possible to set final parameters of hot water to local specific conditions. For this reason is also possible to connect to facility-appropriate thermal energy storage systems with power and capacity that will fit local requirements and heat consumption fluctuations. More about TEPLATOR in [1][2].

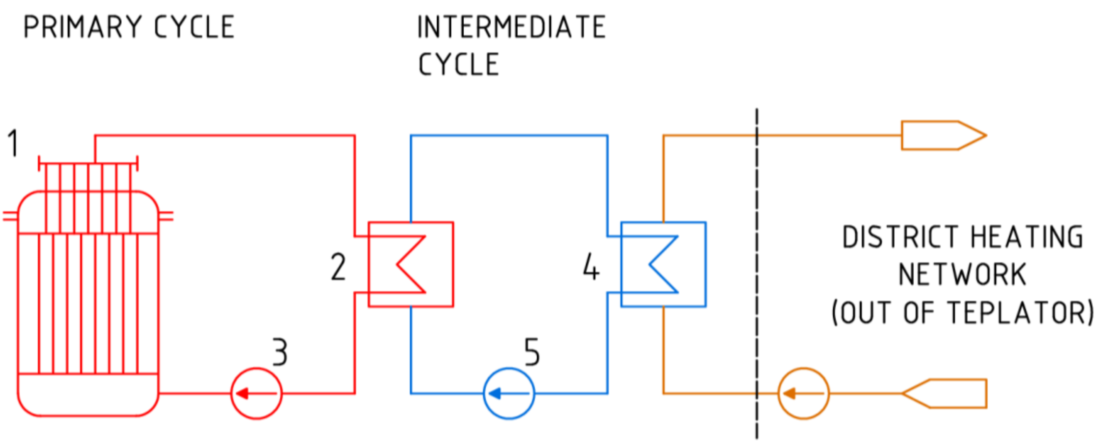

Figure 1: Basic layout of TEPLATOR facility
Legend: 1 – nuclear reactor, 2 – primary heat exchanger, 3 – main circulation pump, 4 – intermediate heat exchanger, 5 – intermediate circulation pump

Table 1: TEPLATOR main parameters

Nominal thermal power	50 MW_t
Type of the reactor	Heavy water cooled and moderated, channel pressurized type, 55 fuel assemblies
Parameters of the primary cycle	192 / 180 °C, 2 MPa
Parameters of the intermediate cycle	185 / 175 °C, 1.6 MPa
Parameters of output hot water	100 – 165 °C, 0.5 – 2 MPa (variable for localization)

2.2 LAES system

Liquid Air Energy Storage is a perspective technology used to store electric power in the form of heat energy in liquid air. The most advanced actual application of this technology is a grid-scale demonstration facility in Manchester (UK) by the company Highview Power. This facility has about a power of 5 MW and a capacity of 15 MWh [3]. The more extensive facility builts company Higview Power also in Manchester. This facility will have a power of 50 MW and a capacity of 300 MW [4]. Many other technologies-based LAES principles are in different stages of development [5-6].

The operation process of LAES technology can be divided into energy charging, energy storage, and energy discharging. Some of the known air liquefaction thermal cycles are used for the charging process. The presented system uses a cycle that is based on the Linde-Hampson cycle. The advantage of this cycle is its simplicity. This cycle has no additional expander. The crucial part, “cold box” is somewhat simple. The disadvantage is a relatively higher pressure after compression, which is 22 MPa. In the standard Linde-Hapson cycle is, this pressure 20 Mpa, but in this case, pressure must be shifted up due to deep cooling near to the triple point of air.

The basic simple layout of LAES with the Linde-Hapson cycle is shown in Figure 2. In this layout, air is compressed by the compressor, is further cooled, and in the last step, compressed air expands through the J-T valve to a lower pressure level. By this expansion, some portion of air is liquefied. Liquefied air is then stored in insulated pressure vessels.

During discharging, liquid air is pumped to the evaporator-heater, where air is evaporated and heated to expansion temperature. The last step is expansion through an air expansion turbine where stored energy is transformed back to electricity.

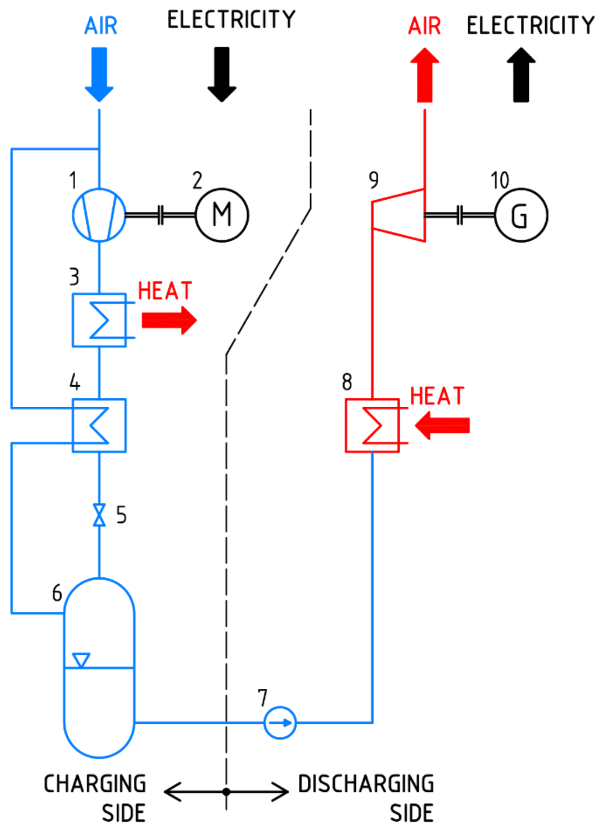

Figure 2: Basic layout of LAES system based on the Linde-Hampson cycle
Legend: 1 – compressor, 2 – compressor electric drive, 3 – after-cooler, 4 – Cold Box (regeneration cooler), 5 – J-T valve (throttling valve), 6 – liquid air separator, 7 – liquid air pump, 8 – heater, 9 – air expander, 10 – electric generator

The scale of the effectivity of energy storage technologies is called a Round Trip Efficiency (RTE), which represents a ratio of energy discharged and energy charged, by the Eq. (1).

$$RTE = \frac{energy\ discharged}{energy\ charged} \quad (1)$$

Crucial for the high storage efficiency is a rational working with heat. The heat and cold management of the proposed system is inspired by [8], which is based on a stand-alone LAES system with highly integrated heat and cold energy storage. In the case of a simple LAES cycle, RTE is relatively low, only around 30 %.

For higher Efficiency, it is essential to regenerate compression heat and also regenerate cold production during discharging when it needs evaporated air at about – 196 °C and heated up to as high as possible. LAES systems with heat regeneration reach RTE from 45 % to 60 % by the system solution. That is a close RTE to CAES (Compressed Air Energy Storage) and PTES (Pumped Thermal Energy Storage) technologies [5]. These technologies are principally closed due to thermal cycle adoption.

In the presented systém, all compressed heat is utilized. Compression is divided into four stages intercooling, and aftercooling in the last stage. The compression temperature of each stage is set to 185 °C. That is the same temperature as in the TEPLATOR intermediate cycle. Of this fact, it is possible to store compression heat in the same Central TES, and all produced compression heat can be further utilized.

Another key heat management feature is the liquefaction internal cold storage system. This system is dedicated to storing cold energy, which is produced during discharge. It consists of two independent loops, which differ by operational temperature.

Thermal energy storage in a range of temperatures from – 196 °C to – 75 °C is used as a thermal energy storage system based on a propane loop. Thermal energy storage in a range of temperatures from – 75 °C to 35 °C is used as a thermal energy storage system based on a methanol loop.

Due to this internal cold storage system, it is possible to reach a higher liquefaction yield and improve the RTE of all systems. For LAES with these parameters but without cold storage loops, the yield will be poor, less than 20 %. With an internal cold storage yield of around 58 %, what is a perfect result.

LAES discharge is a system equipped with three three-stage air expander with reheating. The expansion temperature on the expander stages inlet is 175 °C. This air heating is provided heat from central TES. Other ends of LAES internal cold storage loops the liquefied air evaporation and preheating.

2.3 Central TES

Central Thermal Energy Storage system is intended for storing of all produced heat from LAES and consequently for storing excess heat from TEPLATOR operation. This stored heat can be used for heat supply to the district heating network or for heat supply for air preheating in LAES during discharge. An additional ORC unit can utilize the excess stored heat.

The design of central TES is based on a two-tank design, which consists of two tanks with different storage temperatures. The heat is stored in specific heat form as a temperature difference between these tanks. As a storage media was chosen a thermal oil Therminol has an ideal parameters for this storage temperature. The only disadvantage is the higher price of this media. One of the next goals of this work will be to focus on replacing this media and improving the central TES design features and the design economy.

2.4 Aditional ORC

It is an additional system for peak electricity production from excess stored heat in central TES. It is based on the supercritical Organic Rankine Cycle. As a working media, the R134a refrigerant. The highest temperature in a system, expander inlet temperature, was set as 175 °C for connection of central TES. The lowest temperature can be 45 °C - 35 °C if an air cooling cycle is used. It is possible to reach better ORC efficiency if a cold from LAES cold storage is utilized. The study of the best integration of ORC unit will be the subject of the next research.

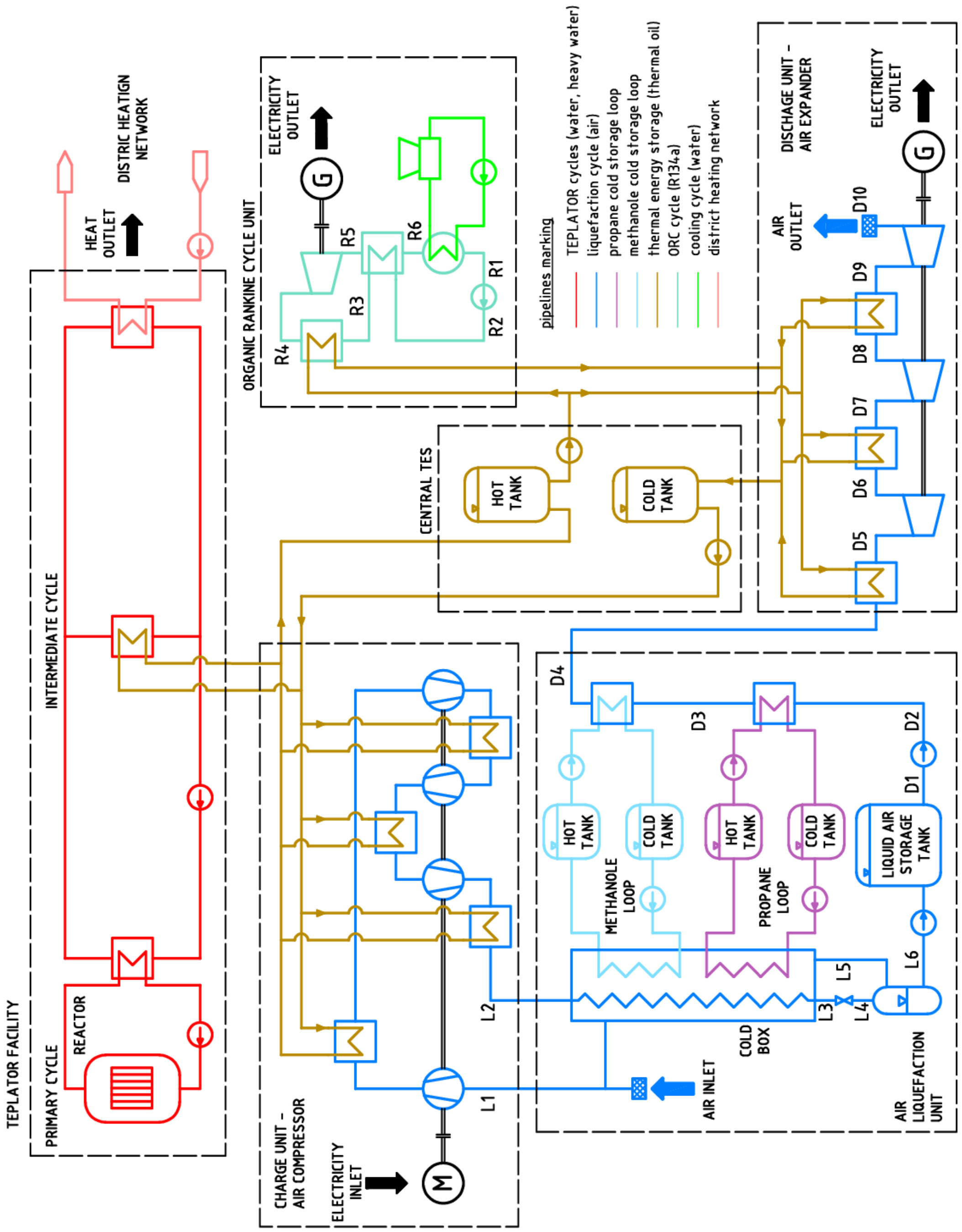

Figure 3: Overal layout of a proposed integrated system (the ORC is with an air cooling loop and the interconnection of central TES and heating network is not drawn)

3 SYSTEM OPERATION

One of the most critical parameters for further design and comparison with other energy storage systems is the Round Trip Efficiency. This parameter was calculated for a proposed system to compare and assess its effectiveness. The calculation provided is based on the system thermodynamic analysis based on energy balance equations and mass flow equations, which were solved by an “in-house” thermodynamic cycle solver in Python. The results of RTE calculation are in Table 2.

Table 2: System RTE in different configurations

Configuration	RTE [%]
Single LAES without internal cold storage	< 19
Single LAES with internal cold storage	50.1
TEPLATOR + LAES	68.1
TEPLATOR + LAES + ORC (without stored cold utilization)	78.6
TEPLATOR + LAES + ORC (with stored cold utilization)	85.2

By Table 2, we can see that the integration of LAES with TEPLATOR brings a significant increase in RTE. It is calculated that all heat produced during charging by LAES is used for discharging, and the remaining heat is partially delivered to the district heating network. The best configuration of TEPLATOR with LAES and ORC calculates that all produced compression heat is spent to discharging a LAES, producing electricity by ORC, and the remaining heat is delivered to the district heating network. In this hypothetical case, all heat is spent, and RTE is very high.

Based on the known data about hypothetical heat consumption during the season [2][3], the predesigned and preoptimized capacity of LAES to 10 $MW_{e,}$ and the thermal capacity of central TES was preoptimised to 350 MW_t. For this configuration, the best power of additional ORC is 2 MW_e.

These parameters were set by simple MIP (mixed integer programming) optimization based on a simple model of heat and electricity consumption.

4 CONCLUSION

The introduced system is the first study of the possibility of such systems integration with TEPLATOR. Based on the first results of RTE, it seems to be a promising solution for future applications where there will be a need for energy storage technologies regarding the increase of renewable energy sources in grids.

Properly determining the power capacity of the central TES and LAES system is crucial for future analyses. Also, it is crucial to determine the nominal power of LAES and ORC units. This determination is not so trivial because it depends on local daily, monthly, and seasonal power and heat demand, which can be different from place to place. These parameters are needed to determine the operational cost of technology (OPEX). The second important parameter is the investment cost of the system (CAPEX)

With knowledge of power and heat demand and a good estimation of investment cost, optimizing the crucial parameters above to the best solution with the best operational and economical results during the system's lifetime is possible.In the future work will use a Mixed Integer Programming (MIP) method for the best estimation (optimization) of the key system's parameters which is described above. With this method is possible to find the best ratio between the capacity of LAES and the capacity of central TES.

The best standard configuration of a system is design, which must be based on the knowledge of sets of several accurate daily, monthly, and yearly heat and power demands. In future work, this comparative study will be done to find the best standard configuration of the system..

From the system RTE point of view, there is a space for further improvement. There is a question of the right integration of ORC. This unit efficiency can be improved by increasing the temperature in the condenser. The excellent temperature in the condenser should be around – 35 °C. This can be done by using some portion of cold from LAES internal storage of absorption refrigeration cycle, which will use heat from central TES.

These questions will be the subject of the following research.

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