[1.] **Iulian JINGA,** [1.] **Pimploy MEKKLUAN,** [1.] **Marcel TOPOR**

SYSTEM FOR STORING ENERGY IN THE FORM OF HEAT IN THERMAL BATTERIES CONNECTED TO PHOTOVOLTAIC POWER GENERATION SOURCES

[1.] University Politechnica of Timisoara, Faculty of Engineering Hunedoara, Hunedoara, ROMANIA

Abstract: The present application relates to a thermal battery heat storage system designed for efficiently recovering and storing electrical energy obtained from renewable sources as thermal energy. The system incorporates a unique method of charging the thermal battery using a charge control system, providing an efficient means of storing and recovering thermal energy for various applications including but not limited to industrial processes, home heating, and renewable energy integration. Efficient thermal energy storage is crucial for addressing the intermittency of renewable energy sources and optimizing energy consumption in various sectors. Conventional methods often suffer from energy losses and inefficiency. This proposal introduces a new thermal battery heat storage system that uses a heat controller to regulate the temperature and charging current.
Keywords: renewable energy sources, sand thermal battery, thermal/heat energy storage

1. INTRODUCTION

The problem of optimizing the use of photovoltaics involves finding an efficient way to manage the variable output of solar energy and use it when needed, taking into account the periods of no sunlight.

Sand thermal batteries are an energy storage system that uses the specific properties of sand to store and release thermal energy. Essentially, solar energy is used to heat the sand during the day and the stored heat is then used to provide thermal energy at night or during periods when solar energy production is low.

Attaching a thermal energy storage battery to a solar system is a good way to use excess solar energy when electricity consumption is low.

Sand battery technology has emerged as a promising solution for thermal/heat energy storage due to its high efficiency [1], low cost and long lifetime.

This innovative technology uses an abundant and widely available material, sand, as a storage medium to store thermal energy. The sand battery [2] works on the principle of heat storage, which means that thermal energy is stored as heat in the sand particles. In a sand battery, the sand is heated using renewable energy sources, such as wind, solar or geothermal energy, during peak hours when energy demand is low. This stored thermal energy can then be used during peak hours when energy demand is high.

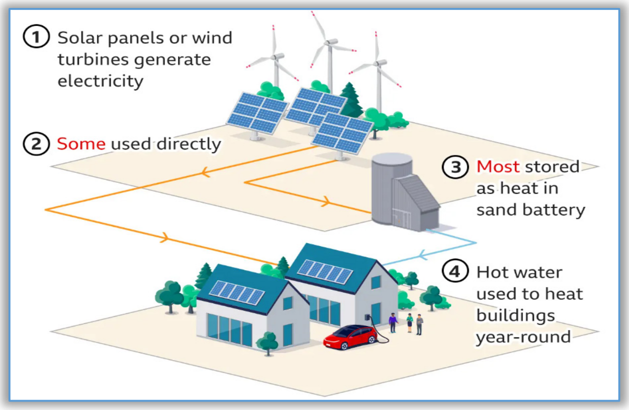


Figure 1 : Storing renewable energy in thermal sand batteries

The sand battery has numerous advantages over other thermal energy storage solutions, such as the ability to store large amounts of energy, low maintenance cost and scalability.

2. DETERMINING THE THERMAL ENERGY STORAGE CAPACITY OF A SAND BATTERY

According to Table 1, there are several types of solid or liquid materials that can fulfill the role of thermal energy storage medium.

In this paper we consider the storage of thermal energy in a quartz sand medium. The thermal energy that can be stored in a cube with a volume of $2\mathrm{m}^3$ filled with quartz sand heated to 200 degrees Celsius can be determined using the following formulas.

The density of quartz sand is typically about 2.65 grams per cubic centimeter (g/cm³). So for a 1 m³ cube, the mass of quartz sand would be about:

$$2.65 \times 2000 = 26502.65 \times 1000 = 2650 \text{ kg}$$

The specific heat capacity of quartz sand is about 0,84 J/(g-°C).

Using these values, we can calculate the stored heat energy :

$$q = V \cdot \rho \cdot cp \cdot dt = m \cdot cp \cdot dt \tag{1}$$

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

where: q = heat stored in the material (J); V = volume of storage material ($m3$); ρ = density of the material (kg/m3); m = mass of substance (kg); cp = specific heat of the substance (J/kg℃); dt = temperature variation (℃)

Table 1.Thermal heat storage - energy dense materials

Name Material	The range of temperatures (℃)	Density, ρ (kg/m³)	Specific heat, c_p $\left(\frac{J}{kg°C}\right)$	Energy density $\left(\frac{kJ}{m^3°C}\right)$
Water	0 - 100	1000	4190	4190
Therminol 66	-9 - 343	750	2100	1575
Taconite		3200	800	2560
Molted salt - 50% KNO3 - 40% NaNO2 - 7% NaNO3 (by weight)	142 - 540	1680	1560	2620
Liquid sodium	100 - 760	750	1260	945
Granite		2400	790	1896
Shamot		2200	1000	2200
Rock salt - 50% NaNO3 - 50% KNO3)	220 - 540	1733	1550	2686
Dowtherm A	12 - 260	867	2200	1907
Concrete		2305	920	2122
Font	max. 1150 (melting point)	7200	540	3889
Brick		1969	921	1813
Aluminum	max. 660 (melting point)	2700	920	2484
50% Ethylene glycol - 50% water	0 - 100	1075	3480	3741

We exemplify this solution by considering the following situation: heat is stored in a 2 m^3 mass of quartz sand by heating it from 20 ℃ to 200 ℃. The density of the quartz sand is 2400 kg/m^3, and the specific heat of the sand is 790 J/kg℃. The thermal heat energy stored in this mass of sand can be calculated as:

$$q = (2\ m^3)\left(2400\frac{kg}{m^3}\right)\left(790\frac{J}{kg\cdot °C}\right)[(200\ °C) - (20\ °C)] = 758400\ kJ$$

$$q_{kWh} = \frac{(758400\ kJ)}{(3600\ s/h)} = 210.66\ kWh \quad (2)$$

In this example we consider that this energy is used to heat a house in Romania. In order to calculate the thermal energy needed to heat a dwelling in Romania during the cold season for a well-insulated dwelling of 100 square meters, the average outdoor temperature during winter in that area is about 0 degrees Celsius. We also assume that the heating system has good efficiency.

To estimate heat energy needs we use a rough formula:

$$q_{demand} = S_{space} \cdot \Delta T \cdot k_{insulation} \quad (3)$$

where: q_{demand} is the heat demand; S_{space} living space; ΔT temperature difference between indoor and outdoor temperature; $k_{insulation}$ thermal insulation coefficient

The temperature difference is the difference between the desired indoor temperature and the average outdoor temperature. In general, for a comfortable home, the indoor temperature is set at about 20-22 degrees Celsius.

The thermal insulation factor depends on the quality of the thermal insulation of the house and can be expressed in W/m²-°C. For a well-insulated dwelling, this factor can be around 0.1-0.2 W/m²-°C.

So, in our case: $S_{space} = 100m^2$, $\Delta T = (22°C - 0°C) = 22°C$, $k_{insulation} = 0.15\frac{W}{m^2°C}$. Therefore, we have:

$$q_{demand} = 100m2 \times 22°C \cdot 0.15\frac{W}{m^2°C} \cdot °C = 330kWh \quad (4)$$

3. PROBLEM DESCRIPTION

Instead of "wasting" energy from solar panels, we can store this energy in thermal form. This will transfer energy that can no longer go into the electric battery or that is injected into the grid at a very low cost to the thermal battery increasing the overall efficiency of the solar system. Figure 2 shows the respective total annual output of a 6Kw solar system without storage and in isolated mode without grid feed-in. It can be seen that the consumption is not always at the level of energy production.

There are three main ways we can divert excess power by using energy storage in thermal sand batteries. These are:

- The use of a special relay to be included on an MPPT charge controller of an electric battery. In this case the heating elements are supplied with direct current.

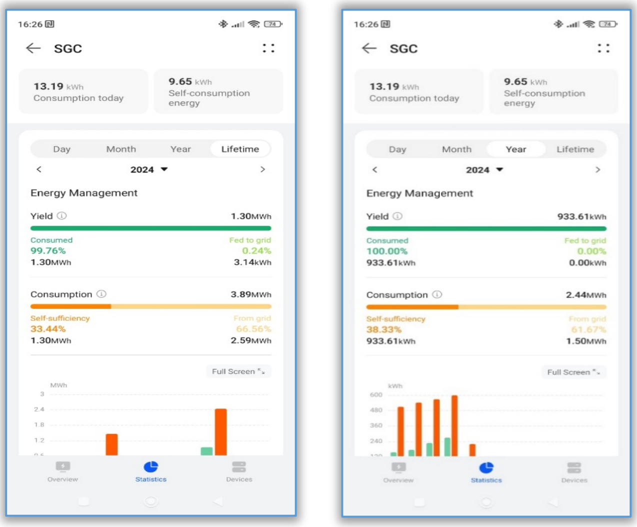
- In systems with off grid or hybrid inverters, a smartmeter can be used to detect the flow of power injected into the grid and to activate the storage system in thermal form.
- Manual start of the thermal energy storage system
- Connect a dedicated charge controller that tracks electricity production.

4. SOLUTIONS AND APPROACHES

In this paper we describe a solution to realize a thermal battery heat storage system. This system shown in Fig. 3 consists of three main components: a container containing the thermal energy storage medium i.e. a well-insulated container filled with quartz sand type material of grain size 1mm with thermal insulation of RIO PLUS type mineral wool type with thermal conductivity coefficient - λ_D=0. 055, a battery thermal charging (heating) system utilizing power resistors with temperature controller and variable charging current control, respectively a system for extracting and converting thermal energy from the storage medium with heat recirculation pump, heat exchanger and radiator (Figure 3).

5. TEMPERATURE CONTROL SYSTEM

For temperature control we used a REX C100 digital temperature controller.



a) Total production b) Anual production
Figure 2 : Electricity production of a 5KW solar system

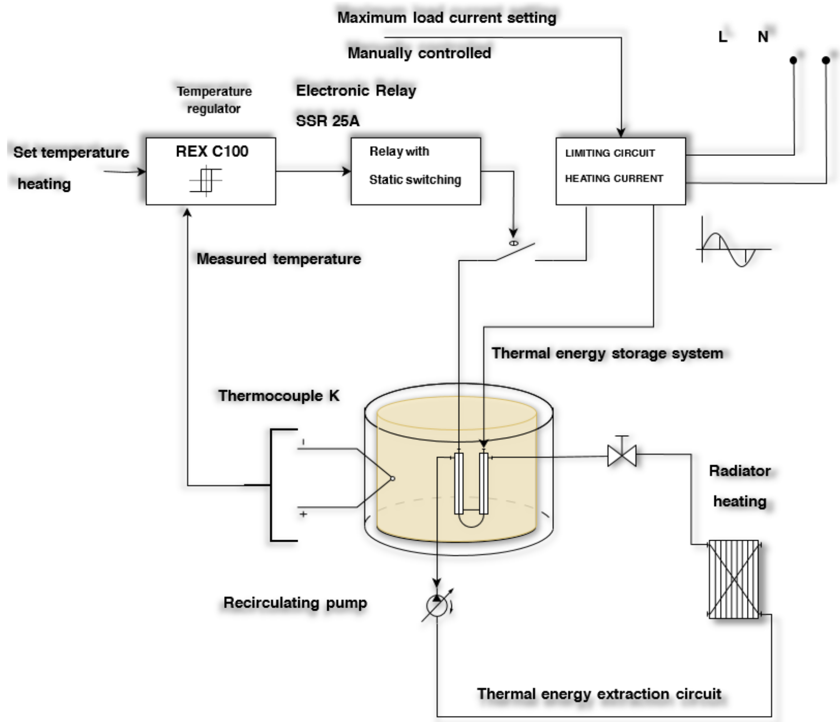


Figure 3 : Main schematic of the thermal energy storage system in a sand battery

Figure 4 : REX C100 temperature regulator

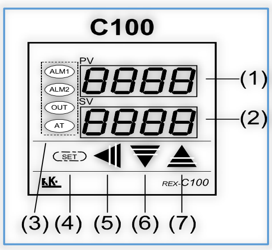


Figure 5 : REX-C100 front panel

The meaning of the different parameters in the interface of the rex C100 (Figure 5):

(1) Measured value (PV) display [Green] Displays PV or various parameter symbols.

(2) Set Value (SV) Display [Orange] Displays SV or various parameter set values (or CT input value).

(3) Alarm output indication LEDs (ALM1, ALM2) [Red]

ALM1: Lights when alarm output 1 is activated.

ALM2: Lights when alarm output 2 is on.

Auto-tuning (AT) LED [Green] Flashes when the auto-tuning mode is activated. (After autotuning is completed: AT LED turns off)

Controller output status LEDs

(OUT1 [Yellow], OUT2 [Green])

OUT1: Lights up when the controller output is turned on.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

The REX-C100 temperature controller is a device used to control and maintain temperature in various industrial and domestic applications. It has several functions and features that allow it to be used in a variety of environments and configurations.

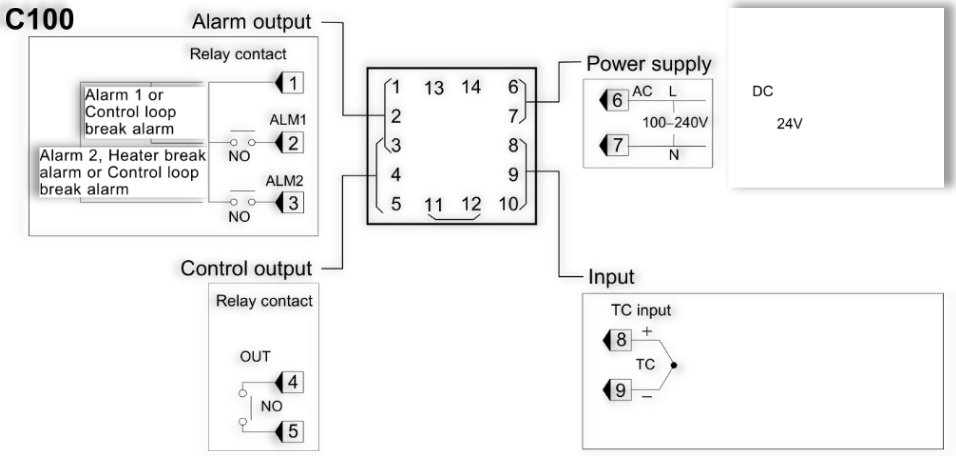


Figure 6 : How to connect the inputs and outputs of the REX C100 controller

The following is how to use a REX-C100 temperature controller.

First, the controller must be mounted in a suitable place so that it can monitor the temperature correctly. The electrical connections must be made according to the device-specific instructions as shown in Figure 6.

REX-C100 allows users to set various parameters such as target temperature, temperature difference (hysteresis), mode of operation (e.g. PID or ON/OFF control) and others. These settings can be adjusted using the buttons or keyboard of the device, depending on the specific configuration. To ensure measurement accuracy and precise temperature control, it is advisable to calibrate the controller using a known temperature source or a reference thermometer.

An important step is connecting the temperature sensor. The REX-C100 uses a temperature sensor in our case a K thermocouple to measure the temperature of the medium. The sensor must be properly connected to the controller according to the manufacturer's specifications.

In the case of this temperature regulator the output is of relay type and is limited to a maximum current of 3 A. In order to integrate this relay into the battery heating control scheme it is necessary to use a 25A SSR (static switching relay). The control of this relay is DC and is provided by a 15V supply, which is connected in series with the output of the REX C100 temperature controller REX C100 as shown in Figure 7.

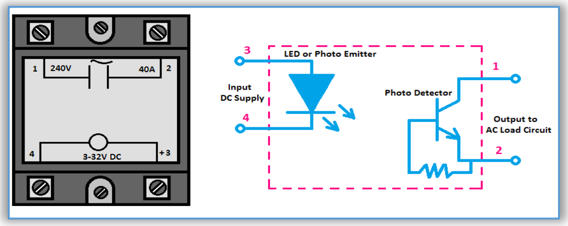


Figure 7 : SSR static SSR relay

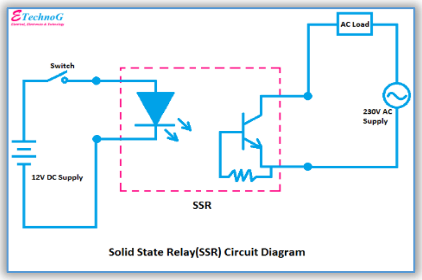


Figure 8 : SSR static relay connection diagram

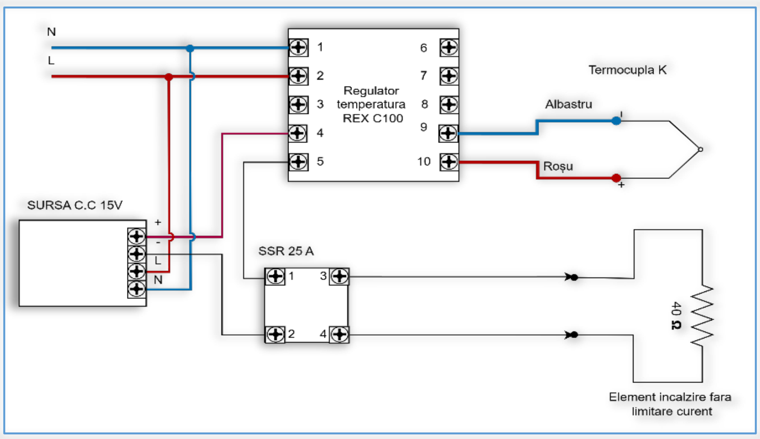


Figure 9 : Connecting the REX C100 controller

To function correctly the load neutral must be connected directly to the neutral of the power supply in our case the AC variable voltage AC drive acting as a current limiter. The power supply phase must be connected to one terminal of the SSR and the load phase must be connected to another terminal of the SSR (Figures 8 and 9).

Once the settings are made and the sensor is connected, the controller can be switched on. It will monitor the ambient temperature and turn on or off heating or cooling devices according to the settings made. Users can monitor the temperature displayed by the controller and adjust the settings in real time according to their needs or changes in the environment. It is important to perform regular maintenance on the controller and investigate any problems or faults that may occur in its operation. This may involve checking electrical connections, replacing the temperature sensor or recalibrating the device. Therefore, the use of a REX-C100 digital temperature controller allows for tailoring to the specific application, i.e. real-time monitoring as well as periodic maintenance to ensure proper operation and precise temperature control in a variety of applications.

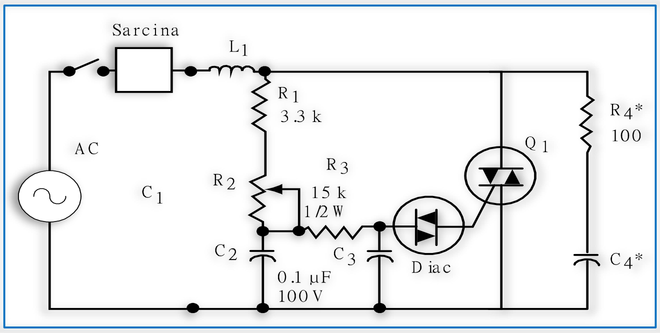


Figure 10 : Triac charging current control circuit

6. CHARGING CURRENT CONTROL SYSTEM

As the storage system is powered from a 6kW photovoltaic system it is necessary to include a current limiting circuit using a triac voltage regulator. This element will limit the current drawn from the system. In this first phase the control is manual and later we will automate the system by connecting an automatic system.

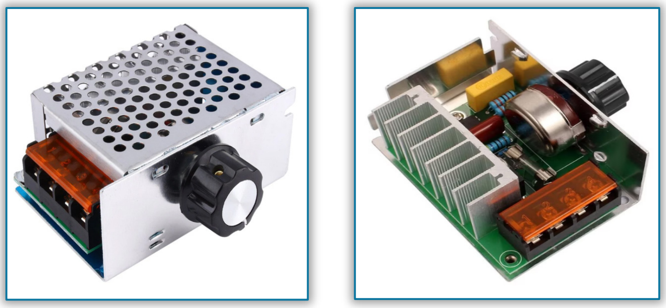
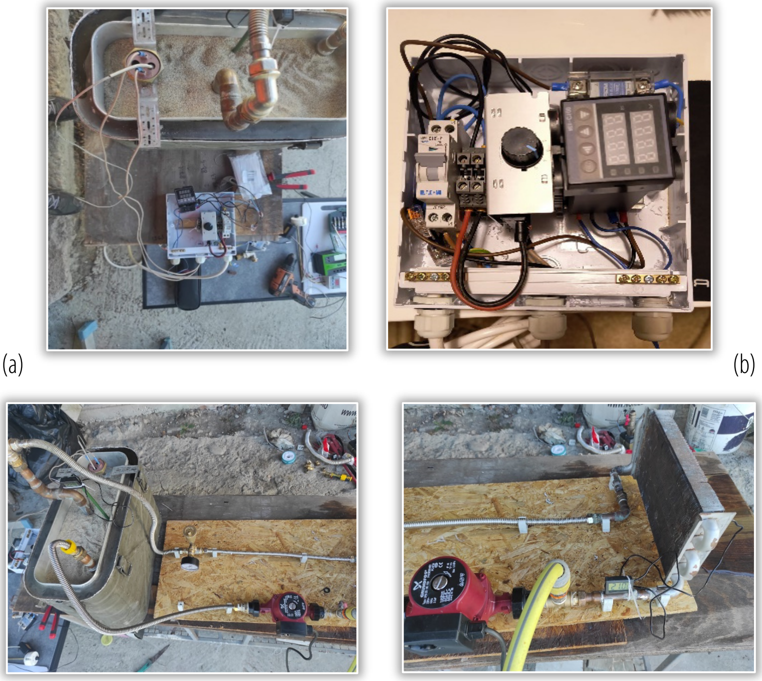


Figure 11 : Variable voltage drive in alternating current with triac [14]

In this circuit, the triac acts as a voltage-controlled switch that regulates the power delivered to the resistive heating element. Depending on the amount of voltage applied across the gate of the triac and when it is tripped in the AC cycle, the power delivered to the heater can be precisely controlled.

7. TESTS AND EXPERIMENTAL RESULTS

The final shape of the assembled system is shown in Figure 11. A 40 L container filled with quartz sand from a specialized store was used as storage medium. To extract the heat from the storage medium we used a copper heat exchanger element with a ¾ inch diameter coil connected with a Grundfos recirculation pump and an automatic aerator, the heating load is represented by a copper car radiator for heating the passenger compartment with the following dimensions 153/184,5/26mm.



(a) (b)

(c) (d)

Figure 12 : Schematic of system operation test: a) Storage environment; b) temperature and charging current control system;c) stored heat extraction system; d) radiator used for cooling;

The heating temperature on the REX C100 controller was set to 100 °C.

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665

It was experimentally determined that the time required to heat 40 liters of sand from 20°C to 100°C using a 2000 W resistor with a regulated charging current of 4.65 A is approximately 35.84 minutes. The current was measured with a UNI-T UT202R digital clampmeter which is also capable of measuring RMS values of the current (it has TRUE-RMS function).

8. CONCLUSIONS

A sand battery thermal energy storage system is extremely useful in the context of a sustainable economy and the transition to renewable energy sources. These batteries provide an efficient solution for managing fluctuations in renewable energy production, such as solar and wind energy, which are influenced by weather variability. By capturing the excess energy produced during peak periods and storing it as heat in sand, these systems allow the thermal energy generated at times of high demand or during periods of darkness to be used later. Sand batteries thus contribute to reducing dependence on non-renewable energy sources, increasing the reliability of heat supply and reducing carbon emissions, playing a significant role in the transition towards a more sustainable and equitable energy system.

Future improvements can be made and further research is necessary in order to implement the idea into a working, functioning automated modular design system.

Bibliography

[1] Chu, G., Liu, X., Ping, P., Sun, J., Wang, Q. & Zhao, X. (2019). Thermal energy storage materials and systems for concentrating solar power plants. Applied Energy, 233, 524-546.
[2] Buddhi, D., Chen, C. R., Sharma, A. & Tyagi, V. V. (2009). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.
[3] Barreneche, C., Cabeza, L. F., Castell, A., de Gracia, A., & Fernández, A. I. (2016). Materials used as PCM in thermal energy storage in buildings: A review. Renewable and Sustainable Energy Reviews, 60, 1470-1497.
[4] Kaygusuz, K., Kaygusuz, A. & Sarı, A. (2011). Energy storage systems for solar thermal power plants. Renewable and Sustainable Energy Reviews, 15(6), 3139-3147.
[5] Sagara, K. & Sharma, A. (2015). Development and prospects of thermocline thermal energy storage systems. Renewable and Sustainable Energy Reviews, 43, 99-122.
[6] Dincer, I., & Rosen, M. A. (2010). Thermal energy storage: systems and applications. John Wiley & Sons.
[7] Barreneche, C., Cabeza, L. F., Castell, A., de Gracia, A. & Grágeda, M. (2017). Thermal energy storage systems for concentrated solar power plants. Renewable and Sustainable Energy Reviews, 67, 450-469.
[8] Feldhoff, J. F., Grafl, A., & Körner, W. (2015). Current state of thermal energy storage and future trends. Energy, 93, 578-589.
[9] Cabeza, L. F., Marín, J. M., Mehling, H. & Zalba, B. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering, 23(3), 251-283.
[10] Yu, Y., & Zhao, C. Y. (2014). Review of electrical energy storage system for vehicular applications. Renewable and Sustainable Energy Reviews, 32, 437-447.
[11] Climate change: 'Sand battery' could solve green energy's big problem (bbc.com)
[12] https://www.dedeman.ro/ro/nisip-pentru-constructii-adeplast-interior/-exterior-25-kg/p/5008953
[13] https://www.emag.ro/modul-regulator-tensiune-4000w-220v-tri230/pd/DQWYW3MBM/
[14] https://www.emag.ro/regulator-de-temperatura-230-v-rex-c100-e568/pd/DVPMSDYBM/
[15] Littelfuse_Thyristor_Phase_Control_Using_Thyristors_Application_Note.pdf.pdf

ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN-L 1584 – 2665