Performance Evaluation of Packed Bed Energy Storage System: A Simulation Study

Malesh Shah*[1,2], Migma Gurung[1], Sunam Amatya[1,2], Tilashmi Karki[1], Aayush Aryal[1], Sushant Dhungana[1,2], Kshitiz Koirala[1,2], Yaman Joshi[1,2]
[1] Department of Mechanical Engineering, Kathmandu University
[2] Project 22-05 Laboratory, Kathmandu University
Email: malesh.shah@ku.edu.np
Received: 14 April 2025; Revised: 9 June 2025; Accepted: 12 July 2025; Published: 17 August 2025

Abstract
Packed bed energy storage (PBES) is an alternative system for thermal energy storage through a sensible heat storage mechanism. With relatively local construction, PBES is suitable for various purposes for both low and high temperature applications. It is packed with materials that do not undergo phase change over the temperature range during the storage process. The materials have good thermal storage capacity and effective thermal conductivity. The outer tank, insulation, inlet and outlet pipelines, heat transfer fluid and energy source make up the system. This study aims to simulate the system, and analyse its thermal energy behaviour including, absorption and heat retention. For this study, the materials for the tank, insulation, and heat transfer fluid have been selected using the Pugh Matrix Method. Steatite, Basalt rock and Sand are chosen as packing materials due to their relatively desirable cost, availability and thermal properties. The simulation is conducted in TRNSYS with the components: pump, boiler, tank and segmented rock beds. Heat retention and the temperature change of the packed bed system are studied across different layers and arrangements. It is observed through the simulation that the layer of basalt, followed by steatite, and then sand showed better heat retention for identical ambient conditions and processes.
Key Words: *Thermal energy storage, Packed bed, Sensible heat, TRNSYS*

1. BACKGROUND

In the period of 2017-2022, annual heat consumption had expanded by 6% globally. Excluding traditional use of biomass, renewable energy increased from 11% from 2021 to 13% in 2022 in its share in global heat consumption. Use of bioenergy and renewable electricity accounted for more than two-thirds of global growth in renewable heat use(IEA, 2022, 2023). In 2021, the fuel mix of Nepal showed a dominance of fuelwood in energy with 62%, followed by 15% liquid petroleum, 7% coal, 4.3% hydropower electricity, 3.6% LPG, 3% animal waste, and 2.45% renewables(Water and Energy Commission Secretariat, 2022). Renewable electricity requires battery for backup. Batteries are great for providing backup power for lighting and appliances, but would be highly inefficient and costly to store energy in a battery to transform back to create instantaneous cooling or heating when compared to Thermal Energy Storage (TES)(Markets and Markets, 2020). TES are considered to be promising and economically attractive alternative to reduce the problem caused by renewable energy sources of the time mismatch between energy availability and energy demand(Kuravi et al., 2013; Markets and Markets, 2020). Sensible heat storage is a type of TES where materials that do not change phases over the temperature range for storage process are used. It is the simplest and the cheapest method to store thermal energy(Gil et al., 2010). Packed Bed Energy Storage (PBES) is an example of such TES.

Packed bed thermal energy storage consists of rock bed, ceramic bricks, or any other material with good thermal storage capacity as a heat transfer medium. The storage is charged or discharged, using heat transfer fluid (HTF) that passes through the narrow gaps between the solid particles with the help of a pipe, by exchanging heat with the packing element through surface contact(Cascetta et al., 2015). Several studies have explored Packed Bed as thermal energy storage. (Cascetta et al., 2015) conducted repeated charging and discharging cycles on packed bed with spheres of alumina and using air as HTF. As discussed by (White et al., 2016) a means of simultaneously attaining high storage efficiency and full utilization of the reservoirs was modelled by segmentation or layering of the packed beds into three different layers. (Cascetta et al., 2014) analysed transient behaviour of packed bed TES using different HTF, namely air, diathermic oil, and molten salts. It also proposed a solution to overcome thermal hysteresis occurring during repetitive cycles of charge and discharge. (McTigue et al., 2018) studied the impact of perturbations to the cycle length and found out that the results are predominantly influenced by exergy losses as the thermal front exits.

Study of packed bed energy storage and sensible heat storage is an opportunity to highlight its significance in Nepal as no substantial study or field implementation has been done. Nepal is rich in every component required to build a reasonably cost effective and simple functioning packed bed energy storage. The material used is depended on topography and geography of the location, hence the concept and operation can be modelled for different materials. In this work, a simulation is carried out using TRNSYS to explore the feasible of using locally available materials to construct an effective PBES with segmentation by studying parameters of heat retention by each layer.

2. LITERATURE REVIEW

There have been previous studies and experiments on thermal energy storage, where pebbles and stones have been used for storing heat. According to (Atalay, 2020) pebble stones have been used as packing material for drying processes of fruits and vegetables, proving to be more economical than paraffin wax (PCM) for the same mass. It was also seen that the pebbles lasted longer for drying process compared to paraffin wax while having similar energy efficiency. In another study (Katekar et al., 2023), pebbles have also been shown to extend system operation time and improve thermal system performance, while being naturally abundant near surface water reservoirs, where they can be employed for heating and water decontamination. The study examined 28 pebbles of various sizes and regardless of their mass, the temperatures were almost identical. But the pebbles emitted 77% less energy after losing 98% of their bulk mass. (Schlipf et al., 2015) showed that small-grained materials such as silica sand, gravel, and basalt are also used in PBES system due to their excellent heat storage potential and fast temperature distribution during charging and discharging. The result of theoretical models and experimental results showed that especially small grained materials offer a very good heat storage potential and therefore a very sharp behaviour of thermocline was observed. Likewise, (Marongiu et al., 2019) found out that horizontal flow rock beds using stones with sizes around 15 mm have shown to enhance temperature gradients and improve charge efficiency in high-temperature thermal energy storage systems. It also explored on charge phase with the focus on modification of rock size, air flow rate, rock type and insulation material. Another study (Knobloch et al., 2022) showed that rocks containing anhydrous minerals like pyroxene, olivine, and oxides are preferred for PBES because of their high heat capacity and thermal stability. The paper demonstrated that thermal storage based on rocks selected holistically, offers better lifetime cycle and avoids performance losses stemming from system-level aspects such as rock rearrangement and thermal ratcheting. According to (Salehudress et al., 2024), diabase rocks, despite experiencing slight density and heat capacity reduction after initial thermal cycles, have demonstrated stable long-term performance in PBES system applications. In river rock bed thermal storage systems, smaller stones (36 mm) have retained significantly more energy compared to larger ones (56 mm), underlining the importance of particle size in optimizing thermal performance. In the study (Amiri et al., 2024), rock thermal energy storage has gained attention due to its ability to store large amounts of heat at high temperatures and its relatively low cost, making it a promising solution for bridging the gap between energy supply and demand.

From the above literature, it is evident that rocks and sands can be used as a packing material for a thermal energy storage system. This study will take account of the above studies and select materials accordingly for the simulation of a PBES system.

3. DESIGN CONSIDERATION

3.1. Components Overview

The components to be used to consider a PBES system are insulated tank with packing materials, heat transfer fluid, boiler, and pump. HTF and materials that are to be used as packing material in the system are selected using the Pugh Matrix Method. Different properties of various materials are given score ratings ranging from 1-5 or 1-7 based on the importance of the particular property. The matrix is used to select insulation material, heat transfer fluid, and insulated tank material. Properties with more significance such as availability and cost, have a wider range for marking than other properties. While totalling, the materials having the highest overall score are to be chosen for their specific function.

The packing materials that are considered are steatite, basalt, and sand. Basalt is abundant in Nepal as they are found in the eastern Himalaya and Nar-Tsum region of northern Nepal, where they are up to 300m thick (Garzanti et al., 1999; Qureshy, 1969). Permian basalts are also found in the Bhote Kosi region, the north of the Langtang massif and just east of the Nepalese border. Similarly, non-metallic mineral like silica sand is known to exist in their natural form in Nepal. According to the report (Mines & Minerals Sector Profile, 2017), Nepal has 83% of its territory in mountainous regions and hence, endowed with minerals like sand, gravel, limestone, steatite, talc, marble, and more.The properties of the packing materials considered that are to be used during the simulation are as shown in Table 1.

Table 1 shows the properties of Steatite, Basalt rock, and Sand, which are selected as packing materials for the simulation of PBES. The selection took consideration into properties of the materials such as specific heat, thermal conductivity and diffusivity, density, and its availability in rural areas. Further calculations are required to determine the specific parameters of required tank size, pump sizing, and boiler specifications.

Table 1 *Properties of the packing materials*

S.N.	Property	Steatite(*Kyocera Fineceramics Europe Steatite Datasheet*, 2023)	Basalt(Siegesmund & Snethlage, 2014)	Sand(Cardarelli, 2008)
1	Corrected length of rock bed for retention time equivalence (m)	1	1	1
2	Cross-sectional area of rock bed (m^2)	0.8	0.8	0.8
3	Perimeter of rock bed (m)	4	4	4
4	Specific heat of pack bed material (kJ/kg.K)	0.75	0.8	0.77
5	Density of pack bed material (kg/m^3)	2800	2850	1650
6	Effective thermal conductivity of pack bed material (W/m.K)	2	1.85	0.31

3.2. Heat Transfer in PBES

TES has attracted increasing interest in thermal applications such as space and water heating, waste heat utilisation, cooling, and air conditioning (Sarbu & Dorca, 2019). The primary mode of heat transfer in the PBES with packing materials of steatite, basalt, and sand will be convection and conduction. The heat transfer in each of the following materials will be as follows:

Heat Transfer in Basalt:

According to an experimental investigation of basalt rocks (Nahhas et al., 2019a), the heat is transferred through the solid bed and the storage material, in this case two types of basalt, is heated up. The time behaviour of the temperature of basalt was characteristic. During the first phase, the temperature gradient of the basalt was very high, and was followed by a phase where increase of the temperature was slower. The average values of the thermal conductivity during thermal cycling from room temperature up to 700 °C lied in the range of (2.02-1.75) W/mK. The specific heat capacity increased substantially in the two basalts from almost 730 J/kgK to 1110 J/kgK with temperature rise 20–1000°C. Compared with other storage materials, basalt had promising properties in terms of the required characteristics in sensible heat storage material.

Heat Transfer in Sand:

To model the heat transfer in the sand, the temperature is considered constant. The heat transfer and temperature behaviour depend on two main factors: the thermal convection between the sand and the surrounding air and the heat conduction within the sands. With higher thermal contact and high packing density, sand tends to heat faster than the stones whose surface will heat up, but the inner core might remain cold. There is little to no air gap and with increased thermal contact in increased length of the packed bed, the temperature gradient is also smoother. The temperature gradient is high in the first charging phase and lowers in the second. Eventually, the packed bed temperature almost reaches the input temperature (Nahhas et al., 2019a).

Heat Transfer in Steatite:

The heat transfer in steatite is similar to basalt. Likewise, steatite has been used in Paraffin as powder form to enhance the heat transfer rate of PCM composite (Jidhesh et al., 2021). Steatite rock on itself has high heat resistance and is very suitable for kiln linings, and laboratory benchtops. This makes steatite suitable for increasing thermal contact in line with sand and basalt.

3.3. Calculations

Selection and sizing of insulated tank

In general, the increasing aspect ratio of tank (Diameter of Tank / Height of Tank) leads decreased heat loss for a cylindrical vessel because of smaller lateral wall surface area for same bed volume(Xie, 2022). (Zanganeh et al., 2015) reported a decrease in fraction of pumping energy when the ratio increases from 0.5 to 2. The overall efficiency decreased due to weaker heat transfer rate caused by decreased HTF velocity at constant mass flow rate at inlet. Hence, the theorized ratio of diameter to height of tank is taken as 1:1.

Insulation

The required critical radius of insulation of the cylindrical tank is given by (Cengel & Ghajar, 2018):

$$r_{cr} = \frac{k}{h} \qquad (1)$$

Where, r_{cr} is the critical radius of insulation, k is the thermal conductivity of the insulating material, and h is the external convection heat transfer coefficient.

4. SIMULATION

TRNSYS, which stands for Transient System Simulation Tool, is a sophisticated software environment for modelling and analysing dynamic systems over time. Although its ability for simulating thermal and electrical energy systems is well known, its uses go beyond these domains to include biological processes, environmental simulations, and transportation systems. TRNSYS is fundamentally made up of two parts. A simulation engine oversees receiving input data, iteratively solving equations, keeping an eye on system convergence, and producing graphical outputs for improved analysis. The second component is a large library of approximately 150 pre-built modules, each representing a distinct system part (*TRNSYS : Transient System Simulation Tool*, 2019). These parts range from basic elements like pumps and heat exchangers to more intricate systems like sophisticated HVAC (heating, ventilation, and air conditioning) units, power generating configurations, and multi-zone building simulations. TRNSYS is unique because it gives users the ability to create new models or alter preexisting ones, providing a flexible and scalable platform for engineering and research applications (*TRNSYS 16*, 2007). It has had a considerable impact on renewable energy research, building performance analysis, smart grid modelling, and large-scale power plant simulation that helps to test and optimize system designs in the real world and assess energy efficiency (*TRNSYS - Official Website*, 2017).

The system and building can be designed and studied individually. (Rashad et al., 2022) used TRNSYS for multi-zone building with Type56 and TRNBuild. According to (Jonas et al., 2017), TRNSYS is an alternative to complex and lengthy predefined solar thermal and heat pump concepts as it enables users to analyse different concepts with hardly any knowledge in modelling and simulation itself. In the comparison of experimental and numerical results of TRNSYS, (Hailu et al., 2017) collected data for 14 days of Seasonal Sand-bed solar thermal energy storage with extended freezing periods and obtained the measured average temperature of 8.1°C compared to simulated average temperature of 8.6°C. This explains the versatility of TRNSYS and the level of accuracy of the software making it ideal tool for pre-evaluation of working and efficiency of the model.

4.1. Setup

The simulation in TRNSYS has a setup to give an overview of real-life application of the PBES system. The simulation for the PBES has the components pump, buffer tank, boiler, rock bed storage, a climate file, and time-control module for pump and boiler. The pump is used to maintain the flow rate of the HTF, in this case, water, typically at temperature based on environmental conditions. The environmental data is set from Meteonorm for Kathmandu University, Dhulikhel, Nepal. The water is pumped into a buffer tank, which then passes on to the boiler whose set point temperature can be determined. Here, the set point temperature is kept at 80°C. Time control has been kept for 12:00-14:00 hours every day to turn on the pump and the boiler. After exiting the boiler, HTF is directed to PBES. The PBES is represented by 3 layers of rock bed storage from the TRNSYS library, which consists of the data of basalt, steatite, and sand, each of 1m length. The parameters for the components are inserted into the simulation.

The simulation will run for charging cycle for 2 hours per day. The loss coefficient for each of the rock bed storage layer was kept 3W/m^{2}K for viewing and comparing the thermal retention of each layer. It is setup so that the outlet temperature of the first rock bed layer is the inlet temperature of the second layer and so on. The simulation does not consider the medium of heat transfer in micro level from the HTF to the packing materials. It only gives an overview of the heat retention in the form of temperature of each layer. With this, it can be observed how each layer performs as a packing material for a PBES system.

5. RESULT AND DISCUSSION

The simulation was run for 6 different setups. The combination of the 3 layers were interchanged with each other in 6 different possible positions. Thereafter, for each of the setup, simulations were run for 1 day, 2 days, and 1 week separately to check the temperature of each stratified layer and hence, their performance in retaining heat.

5.1. Basalt, Steatite, Sand layer

This combination of 3 layers has the basalt on top, followed by steatite, and finally, sand. The water from the boiler passes through the basalt layer and continues down. The results of the simulation are shown in the figure **Fig.1**, **Fig.2**, and **Fig.3** below.

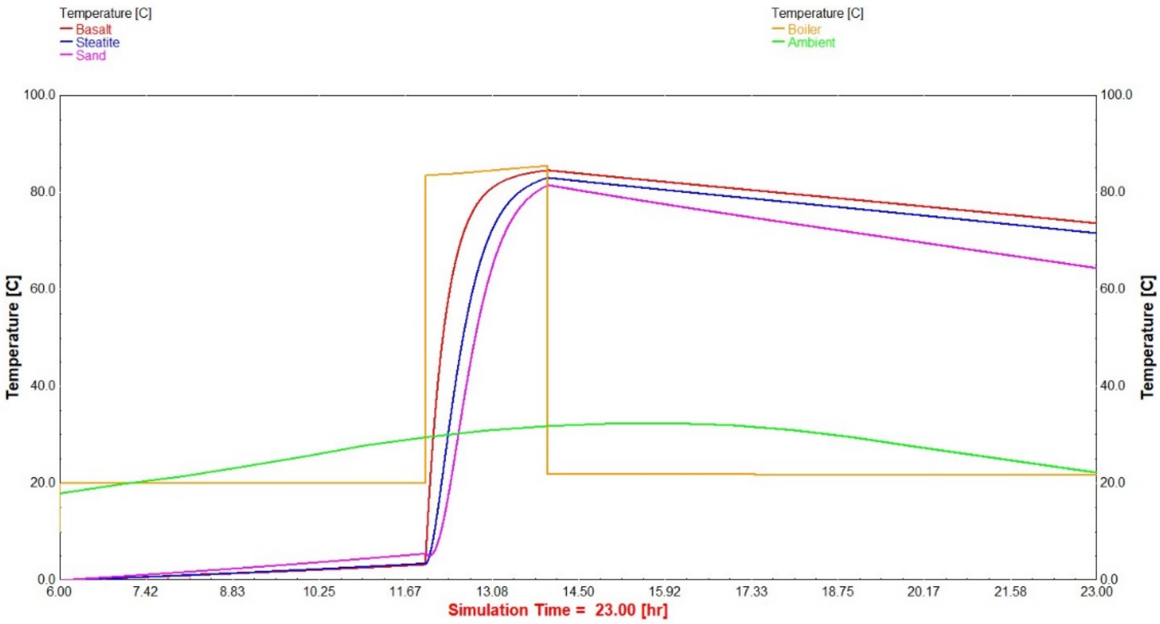

Fig. 1: *1 day simulation of basalt, steatite, and sand layer*

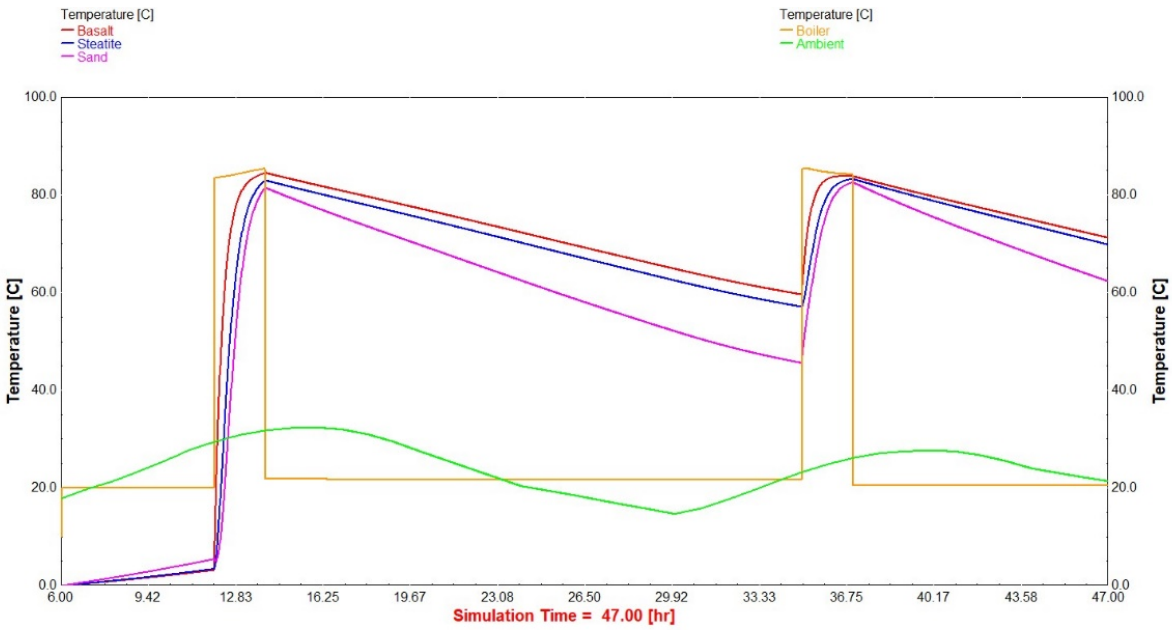

Fig. 2: 2 days simulation of basalt, steatite, and sand layer

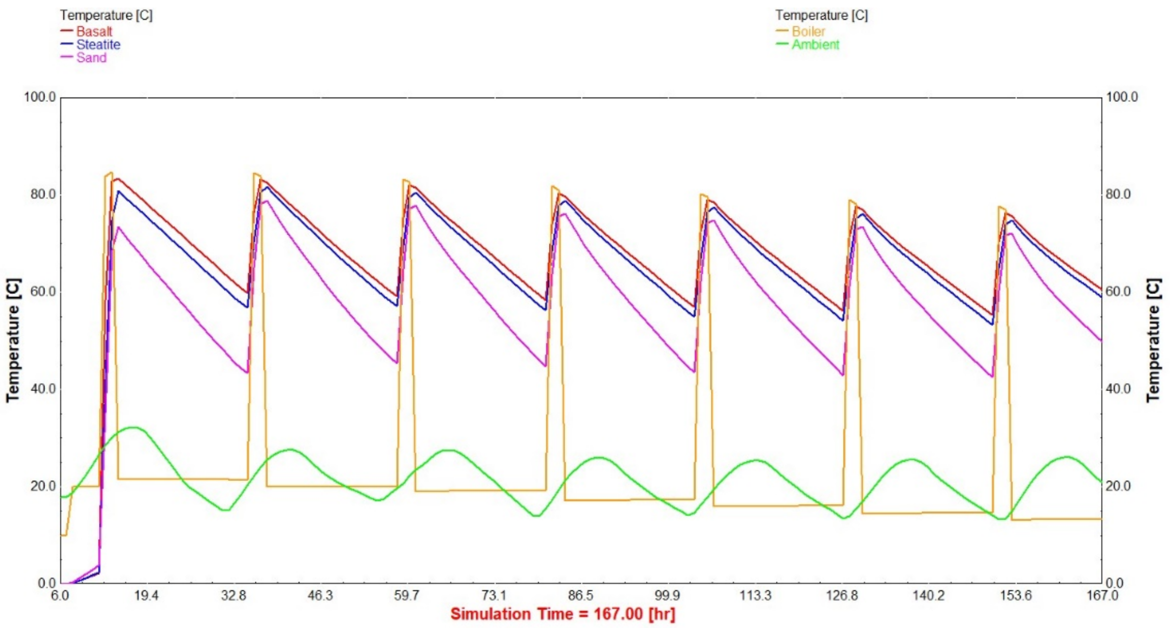

Fig. 3: *1 week simulation of basalt, steatite, and sand layer*

The above figures **Fig.1**, **Fig.2**, and **Fig.3** show the simulation for 1 day, 2 days, and 1 week of the charging cycle and temperature range of the PBES. Here, basalt has the highest temperature of 78°C after the charging cycle is completed. Likewise, the HTF flows down to steatite which has the next highest temperature, followed by sand. As the results show, the layer of sand loses heat quicker than the rest of the layers. Even at a $3W/m^2K$ loss coefficient, the layer of basalt holds 60°C temperature until the next charging cycle. Similarly, steatite also reaches 56°C until the next charging cycle. This shows good heat retention property which is necessary for energy storage.

During the 2-day simulation in **Fig.2**, with high initial temperature in the charging cycle, the temperature of steatite comes very close to basalt. Likewise, the maximum temperature that sand layer reaches is also higher in the second charging cycle. This shows that the outlet temperature in the preceding layer starts becoming closer to that of the temperature from the boiler. Similarly, the properties uphold even in the 1-week simulation as the temperature during charging cycle is closer after the second day as shown in **Fig.3**.

5.2. Basalt, Sand, Steatite layer

Here, the HTF flows through the layers arranged as basalt to sand to steatite.

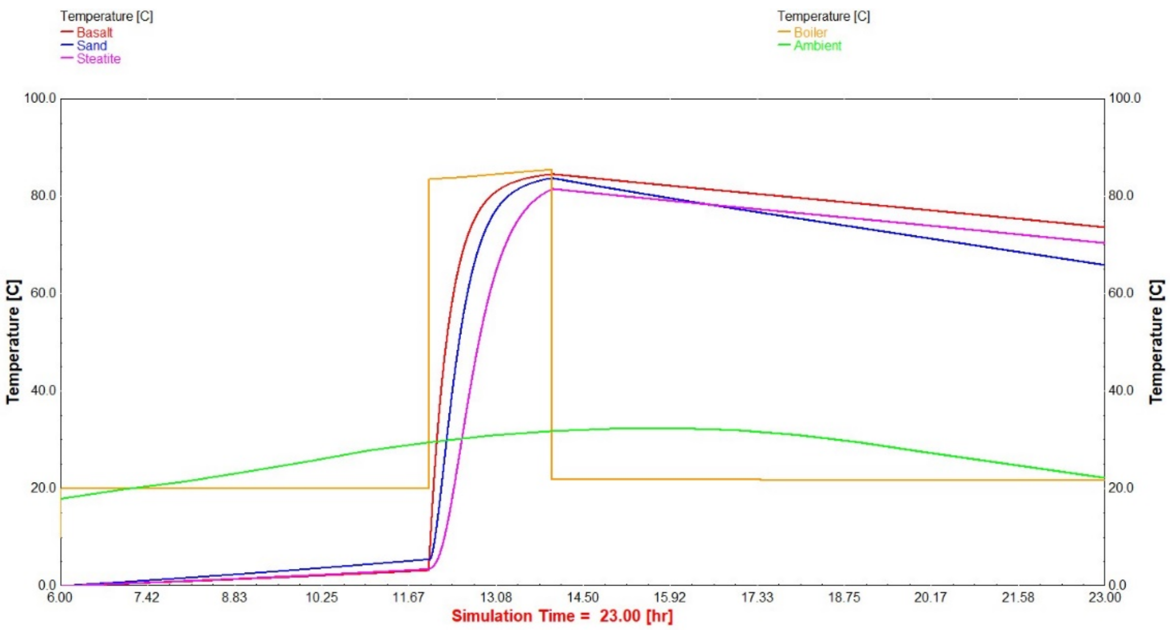

Fig. 4:*1 day simulation of basalt, sand, and steatite layer*

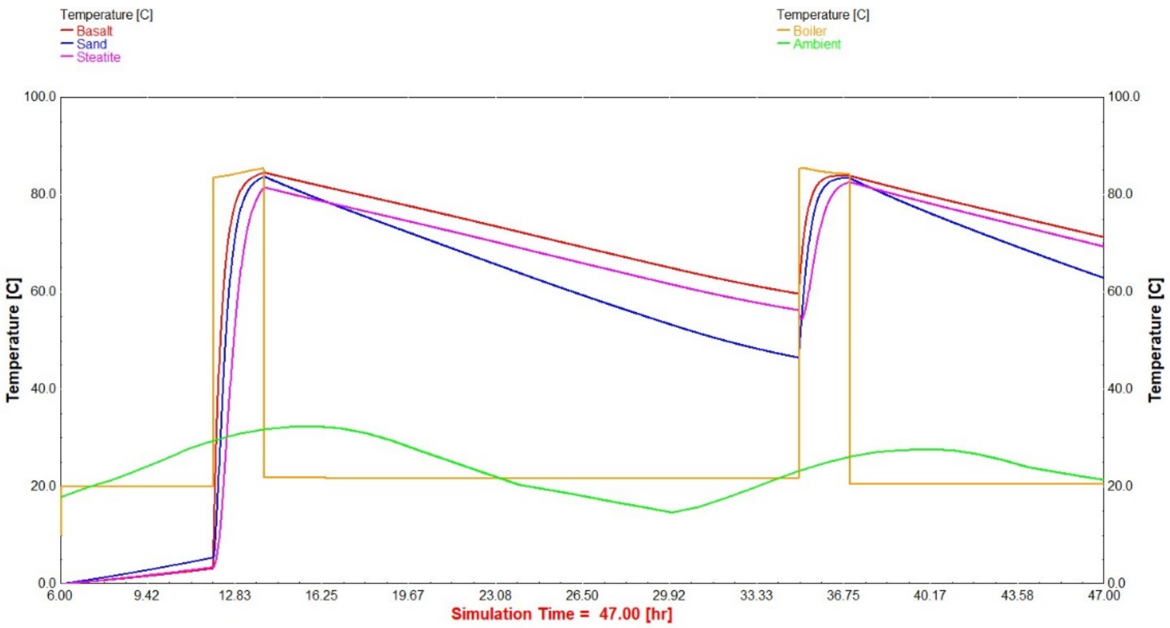

Fig. 5: *2 days simulation of basalt, sand, and steatite layer*

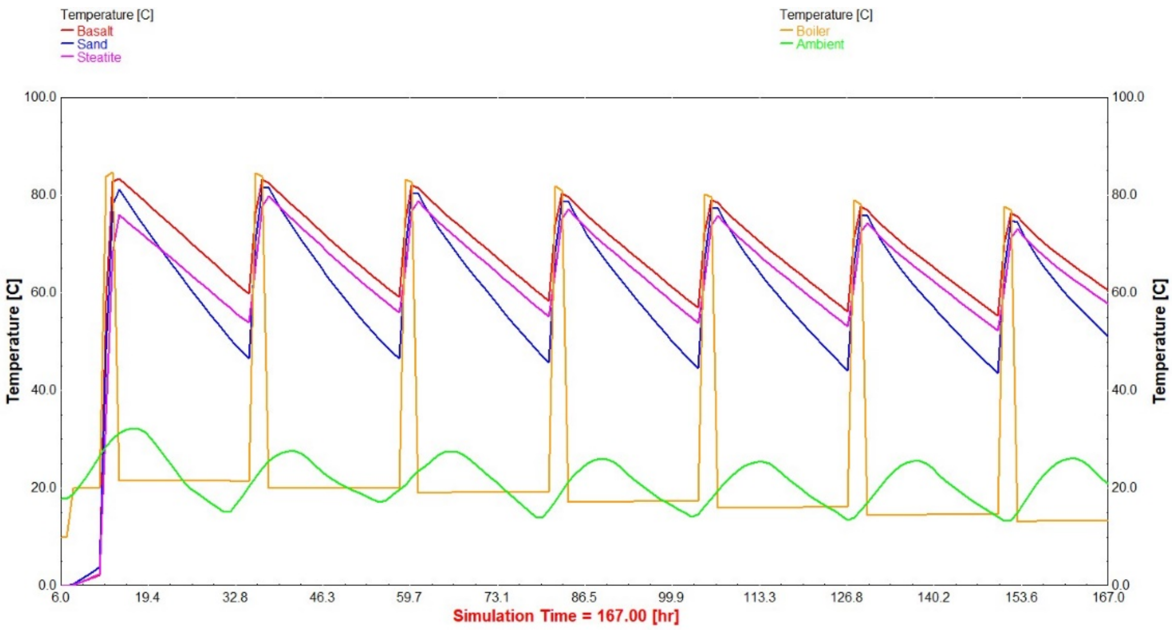

Fig. 6: *1 week simulation of basalt, sand, and steatite layer*

In this simulation, it is clear from the results shown by figures **Fig.4**, **Fig.5**, and **Fig.6**, the layer of sand rapidly loses heat compared to that of basalt and steatite. For the same loss coefficient, the temperature gradient of the sand is very high compared to the other storage materials. In the end of the first charging cycle, the initial temperature of steatite is lower than that of sand as it receives less heat being in the lowest layer. But, it is observed that the temperature of steatite by the end of each charging cycle is increased compared to the end of the previous charging cycle. By the start of the second charging cycle, the initial temperature of sand is significantly lower than that of the basalt and the steatite. This shows that steatite has a better thermal retention property than that of the sand.

5.3. Sand, Basalt, Steatite layer

This arrangement is done by keeping sand on the top layer, followed by basalt, and lastly steatite.

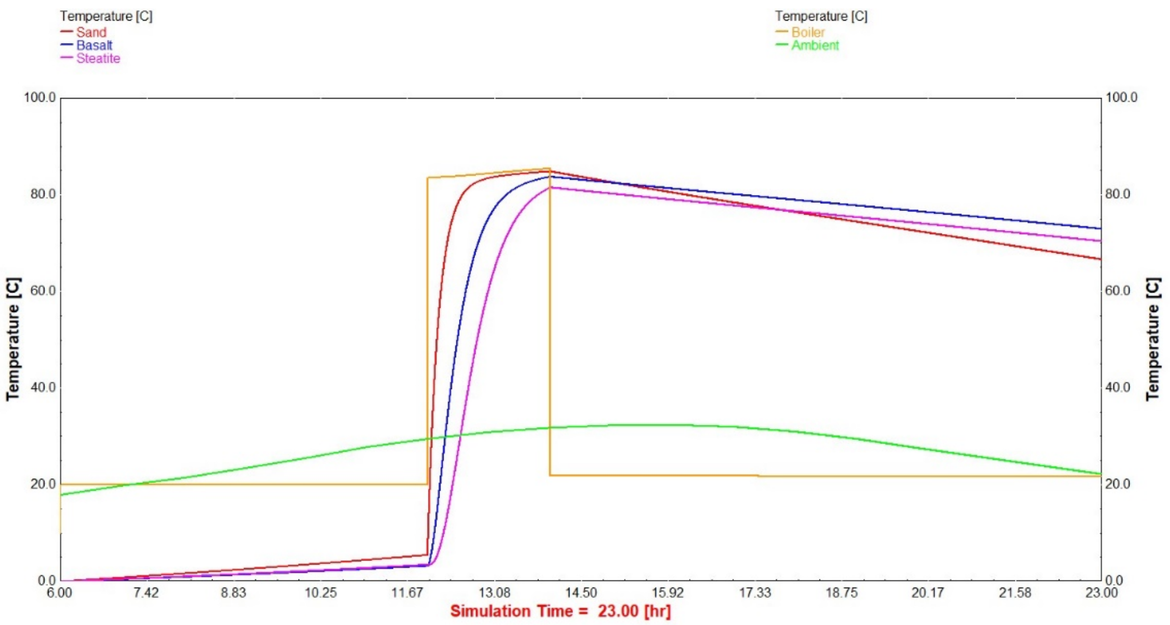

Fig. 7: *1 day simulation of sand, basalt, and steatite layer*

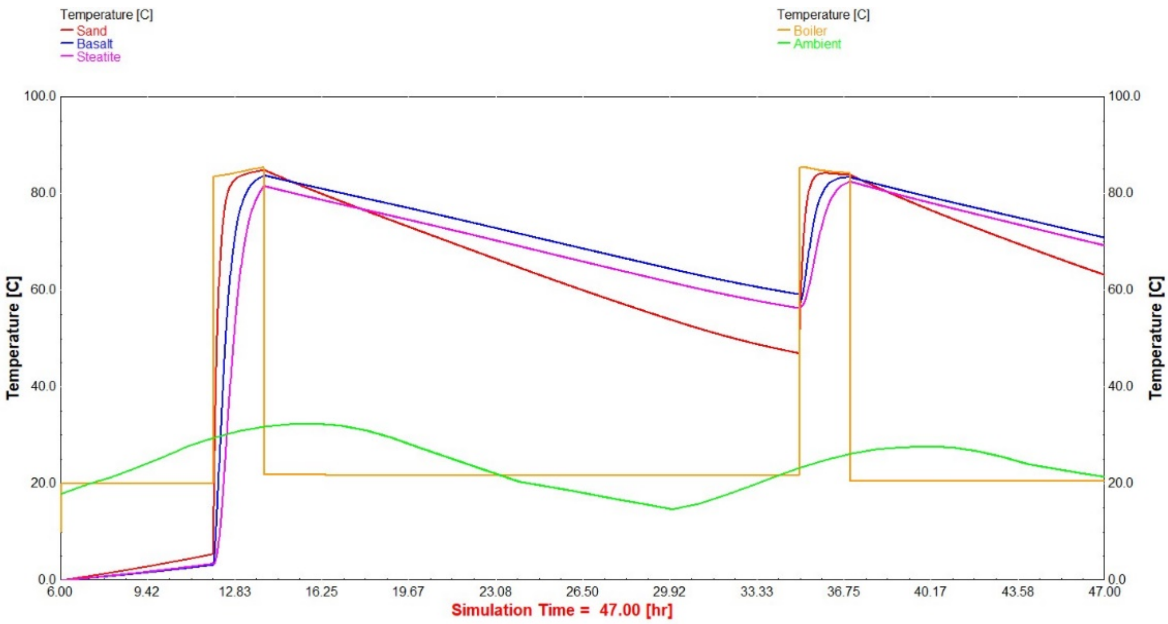

Fig. 8: *2 days simulation of sand, basalt, and steatite layer*

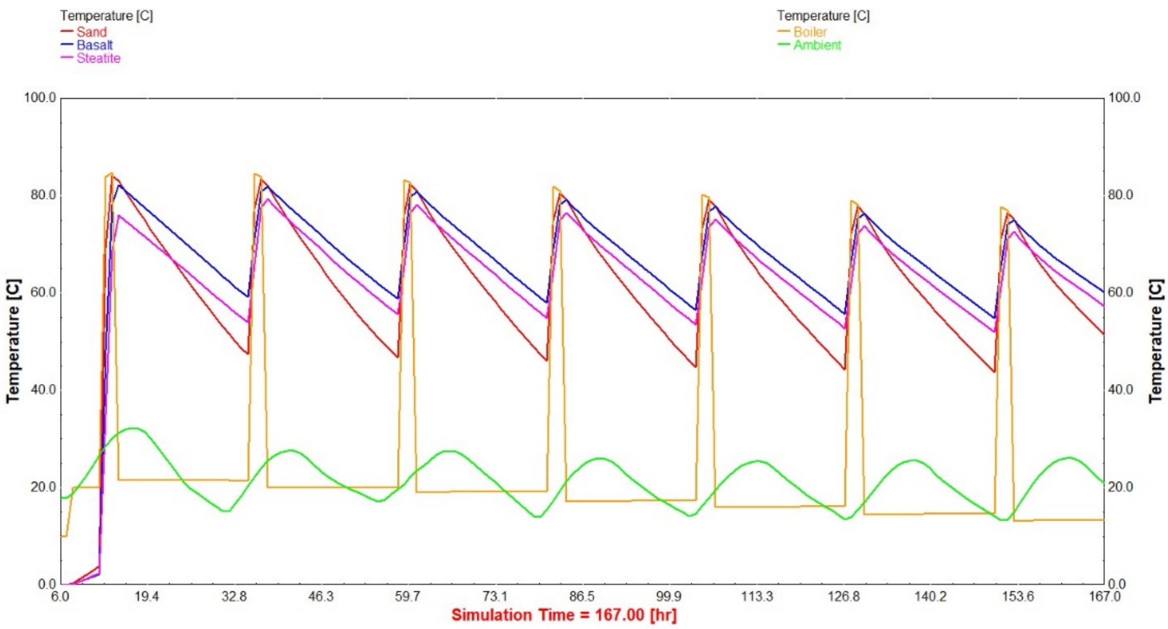

Fig.9: *1 week simulation of basalt, steatite, and sand layer*

In this simulation result, from figure **Fig.7**, **Fig.8**, and **Fig.9**, it is evident that sand, although on the top layer, still has the lowest temperature by the start of the next charging cycle. The layer of steatite has a lower temperature gained from the first charging cycle but gradually increases as the PBES goes through consecutive charging cycles. Likewise, basalt and steatite have lower temperature gradient as the charging cycle goes on.

5.4. Sand, Steatite, Basalt layer

This simulation has the layers arranged as sand, steatite and then basalt.

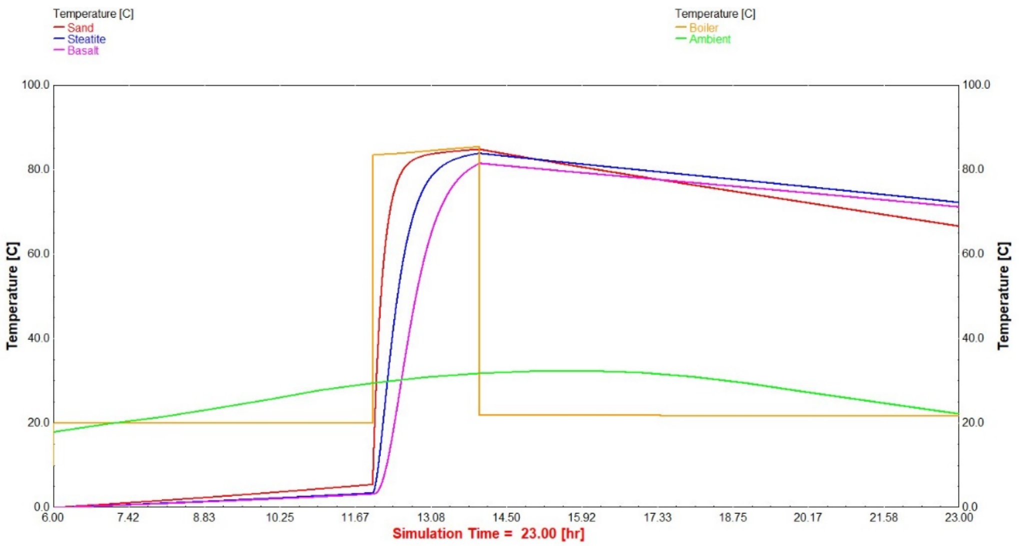

Fig.10: *1 day simulation of sand, steatite, and basalt layer*

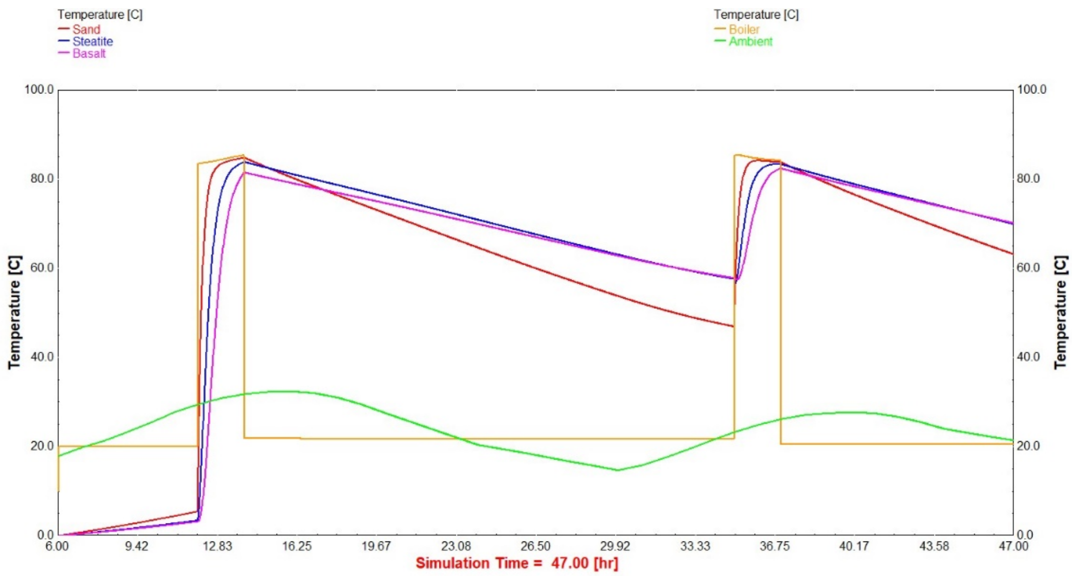

Fig.11: *2 days simulation of sand, steatite, and basalt layer*

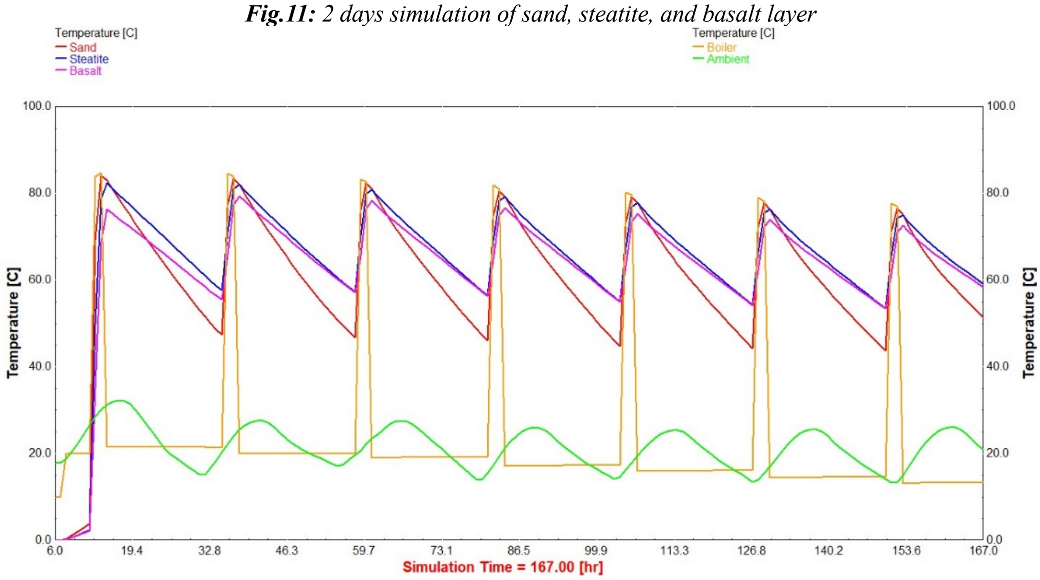

Fig.12: *1 week simulation of sand, steatite, and basalt layer*

Similar to sand, basalt, and steatite layer, sand here has a bigger temperature gradient than the other storage materials. The sand, while being on top, has the highest temperature, but has the lowest temperature when reaching the next charging cycle. Likewise, it is observed that the layer of basalt has slightly higher temperature than steatite, close to the next charging cycle. It is observed that basalt has higher heat retention than steatite in the same physical conditions, which are, same loss coefficient, and same ambient conditions.

5.5. Steatite, Basalt, Sand layer

This simulation arrangement consists of steatite on top, followed by basalt, and then sand.

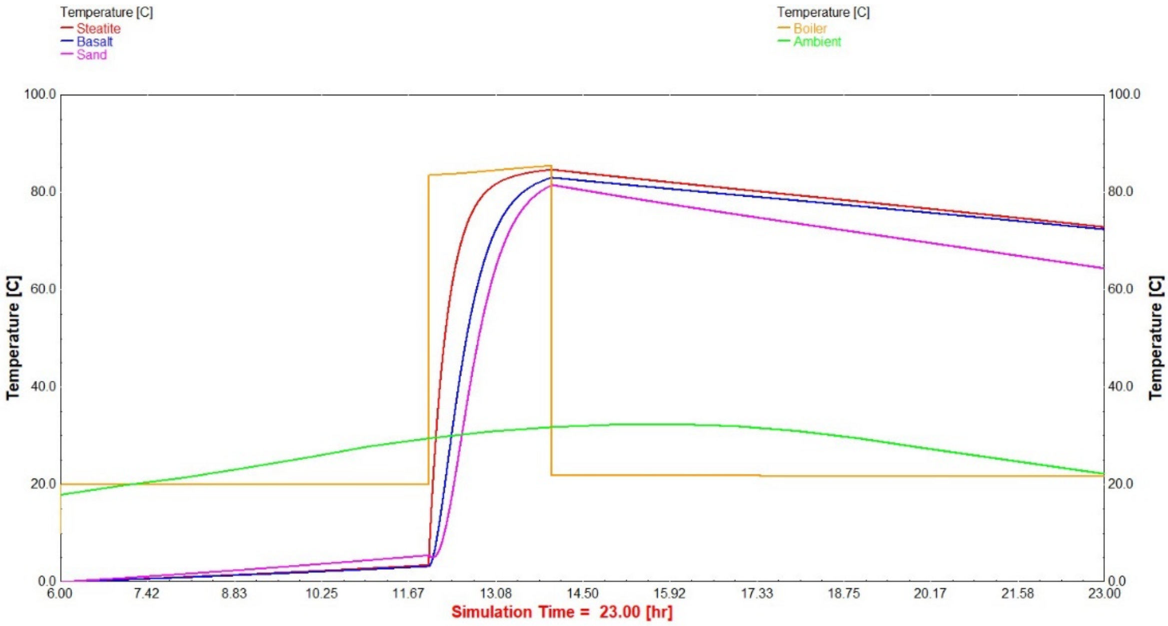

Fig. 13: 1 day simulation of steatite, basalt and sand layer

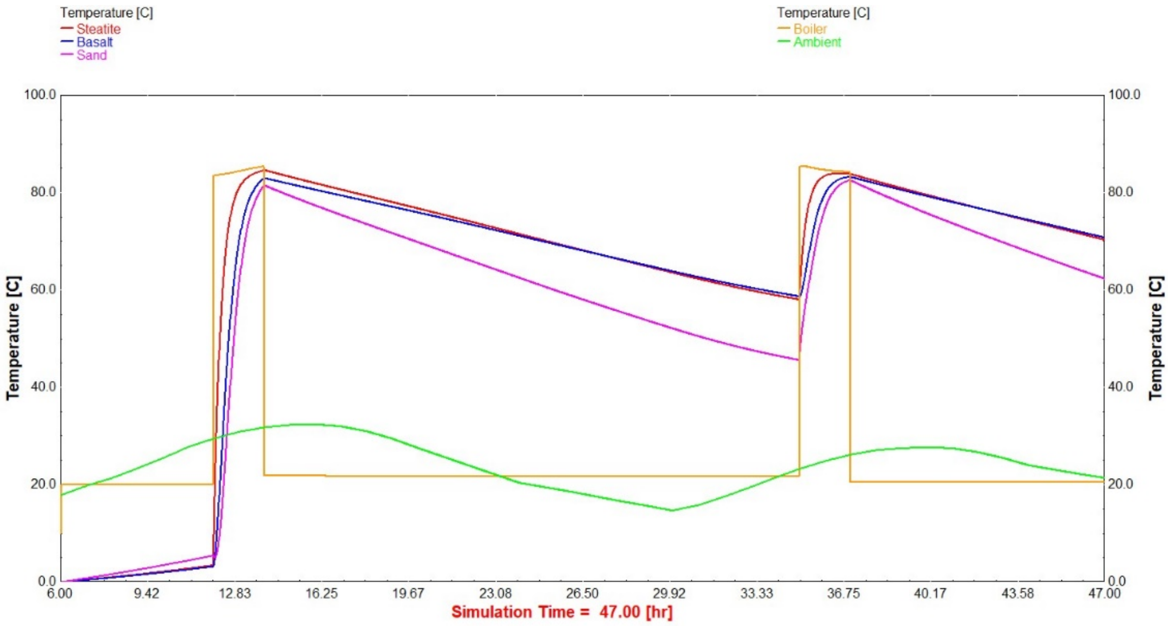

Fig. 14: 2 days simulation of steatite, basalt and sand layer

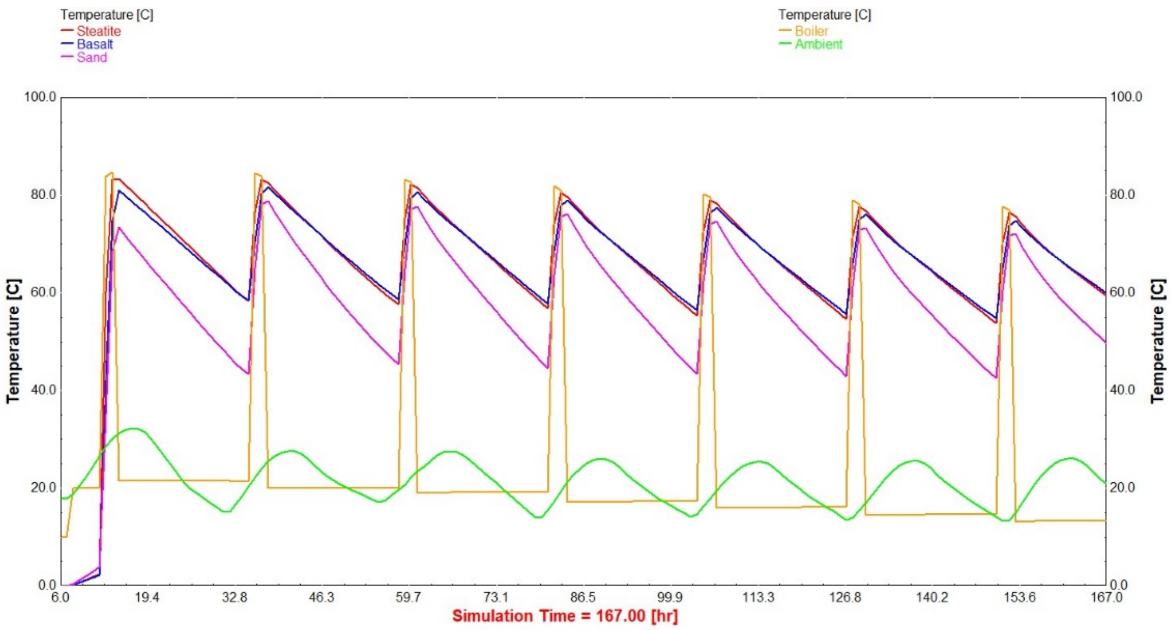

Fig. 15: *1 week simulation of steatite, basalt and sand layer*

From the results of the simulation, it is observed that the temperature of steatite and basalt come close to each other by the end of the first day in **Fig.13**. It is also observed in **Fig.14** and **Fig.15** that after the second charging cycle, the temperature of basalt is slightly higher when compared to steatite by the start of the next charging cycle. This shows that basalt has higher heat retention and is an excellent material when it comes to storing heat in a locally constructed PBES system.

5.6. Steatite, Sand, Basalt layer

This layer is arranged as steatite on top, followed by sand, and then basalt.

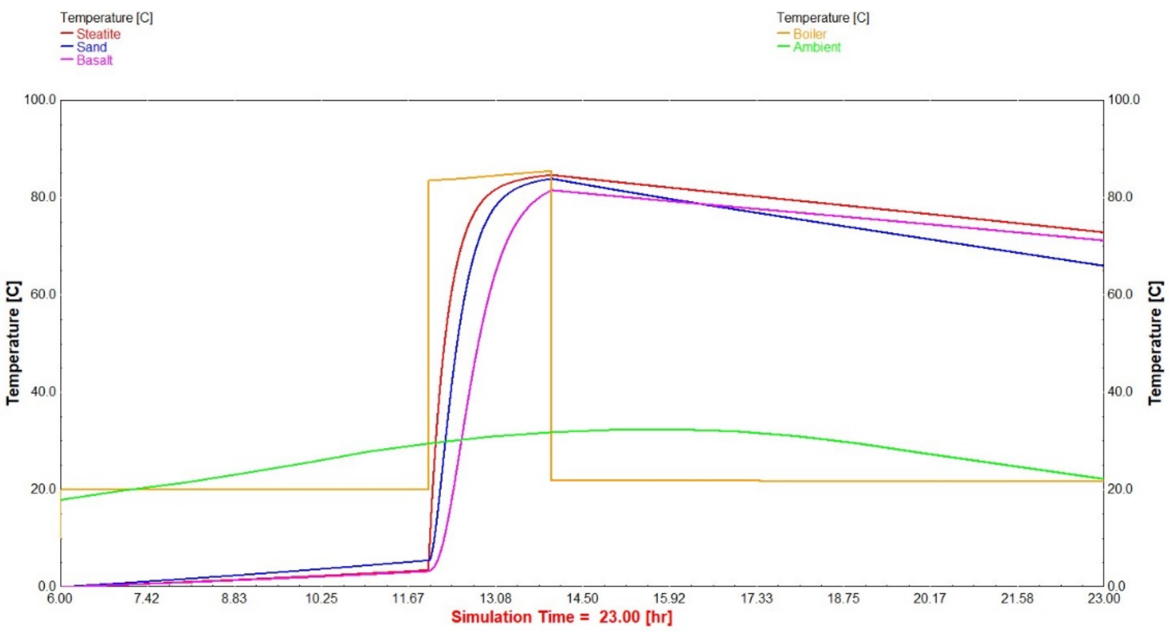

Fig. 16: *1 day simulation of steatite, sand, and basalt layer*

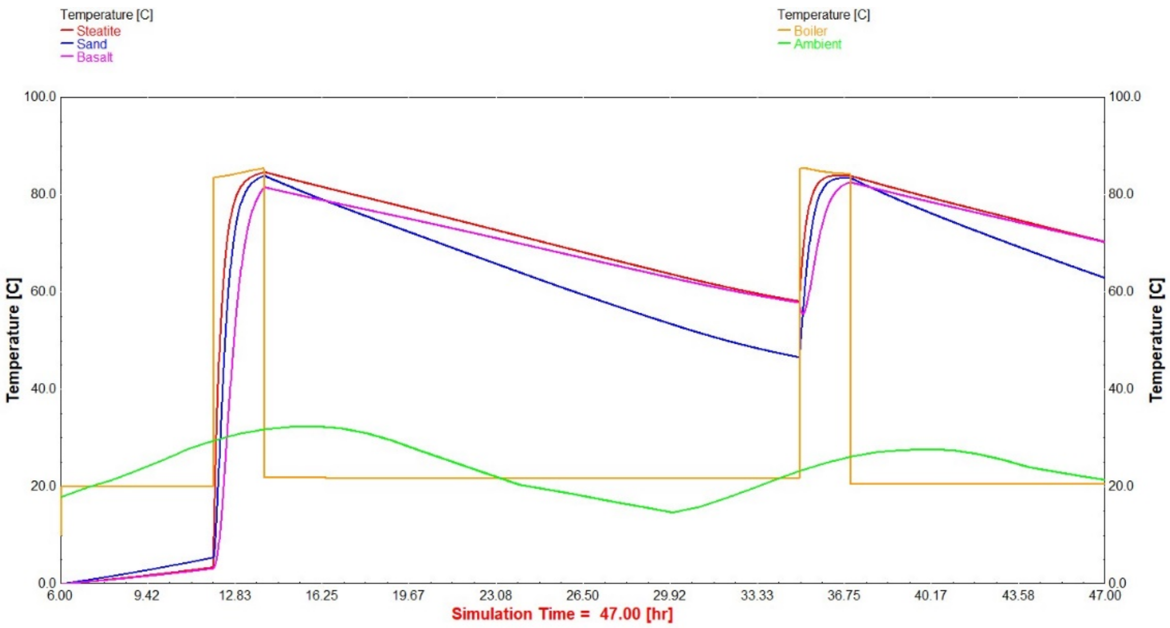

***Fig. 17:** 2 days simulation of steatite, sand, and basalt layer*

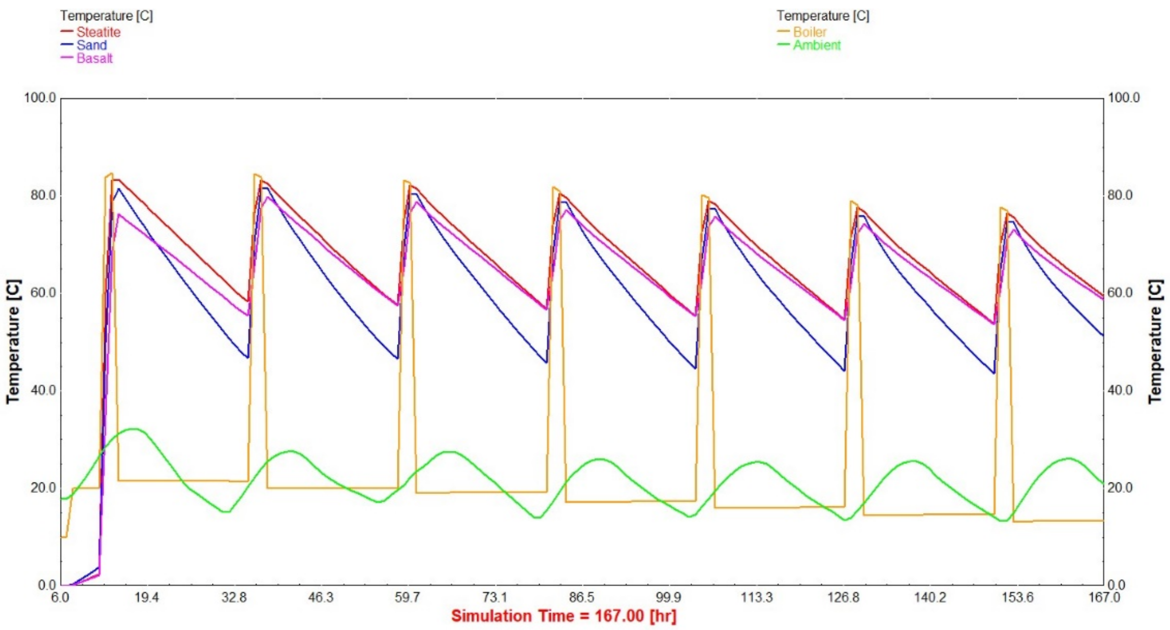

***Fig. 18:** 1 week simulation of steatite, sand, and basalt layer*

From the simulation of this layer, it is observed that sand has the highest temperature gradient while basalt has the lowest. It is also observed that even though basalt is in the lowest layer, its temperature reaches that of steatite when coming close to the next charging cycle.

From all the above simulations, it is evident that basalt is a very suitable packing material for PBES system when compared to commonly used sand. In the context of Nepal, which was previously discussed, basalt is in abundance, especially in the Himalayan region. PBES made of basalt, steatite, and sand could be a very viable option for thermal storage that can be used for space heating, heat water for domestic purposes, or any other activities that require heat. The simulation was done with the ambient condition of a hilly region in Nepal. Hence, this simulation result can be translated for other hilly and some Himalayan regions as well where the above used materials are locally available.

(Ucler et al., 2022) investigated a heat storage system using water, basalt stones, and paraffin wax and the trend that basalt showed when storing heat was similar to the simulation. Likewise, (Nahhas et al., 2019b) used fine grained basalt to store heat for high temperature concentrated solar power plants and showed it suitable for packing materials with heat retention trend as the simulation. Similarly, (Mahfoudi N. et al., 2016) conducted a numerical study of sand in a thermal energy storage. The study had similar results with the simulation when it came to the temperature gradient of the sand in the energy storage. Hence, the simulation results can be verified by the above literatures.

6. CONCLUSION

PBES is an effective thermal energy storage system that stores sensible heat for use in space heating, domestic hot water, or any other thermal applications. With review on previous works of packed bed thermal energy storage, it was evident that segmentation of packed bed showed higher efficiency of the entire system which led to this research of packed bed consisting of three different layers. This study explored the performance of a segmented PBES system using the materials basalt, steatite and sand, which were selected by the criteria of availability, thermal properties, and cost. The materials were used to run a simulative study of the packed bed in segregated layer in TRNSYS software. With high temperature range, the materials were suitable for the simulation where water, whose boiling temperature is 100°C, was used as heat transfer fluid. The simulation result obtained from TRNSYS indicated that basalt had the best thermal retention among the three materials used, followed by steatite, and then sand. The six different combinations of the three materials were simulated and in each of the simulation, basalt had the lowest temperature gradient. This showed that basalt could retain heat for a longer time which is a useful property for packed bed energy storage system. Basalt being a common material in the Himalayan and the hilly region of Nepal, which tend to have colder climates, could be used to store heat in households and communities for domestic purposes. This study was conducted for hilly region area where PBES could be a reliable storage of thermal energy. Furthermore, experimental validation and piloting are recommended to evaluate its long-term performance.

REFERENCES

Amiri, L., Ermagan, H., Kurnia, J. C., Hassani, F., & Sasmito, A. P. (2024). Progress on rock thermal energy storage (RTES): A state of the art review. *Energy Science & Engineering*, *12*(2), 410–437. https://doi.org/10.1002/ESE3.1478

Atalay, H. (2020). Assessment of energy and cost analysis of packed bed and phase change material thermal energy storage systems for the solar energy-assisted drying process. *Solar Energy*, *198*, 124–138. https://doi.org/10.1016/J.SOLENER.2020.01.051

Cardarelli, F. (2008). *Materials Handbook* (2nd ed.). Springer London.

Cascetta, M., Cau, G., Puddu, P., & Serra, F. (2014). Numerical Investigation of a Packed Bed Thermal Energy Storage System with Different Heat Transfer Fluids. *Energy Procedia*, *45*, 598–607. https://doi.org/https://doi.org/10.1016/j.egypro.2014.01.064

Cascetta, M., Cau, G., Puddu, P., & Serra, F. (2015). Experimental investigation of a packed bed thermal energy storage system. *Journal of Physics: Conference Series*, *655*(1), 12018. https://doi.org/10.1088/1742-6596/655/1/012018

Cengel, Y. A., & Ghajar, A. J. (2018). Critical Radius of Insulation. In *Heat and Mass Transfer* (5th ed.). McGraw Hill Education.

Garzanti, E., Le Fort, P., & Sciunnach, D. (1999). First report of Lower Permian basalts in South Tibet: tholeiitic magmatism during break-up and incipient opening of Neotethys. *Journal of Asian Earth Sciences*, *17*(4), 533–546. https://doi.org/10.1016/S1367-9120(99)00008-5

Gil, A., Medrano, M., Martorell, I., Lázaro, A., Dolado, P., Zalba, B., & Cabeza, L. F. (2010). State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews*, *14*(1), 31–55. https://doi.org/https://doi.org/10.1016/j.rser.2009.07.035

Hailu, G., Hayes, P., & Masteller, M. (2017). Seasonal sand-bed solar thermal energy storage in a region with extended freezing periods: Experimentally verified numerical simulation. *Journal of Renewable and Sustainable Energy*, *9*(6). https://doi.org/10.1063/1.5001362/286344

IEA. (2022). *Renewables 2022*. https://doi.org/https://doi.org/10.1787/25202774

IEA. (2023). *Renewables 2023*.

Jidhesh, P., Arjunan, T. V., & David Rathnaraj, J. (2021). Experimental investigation on heat transfer characteristics of phase change composite for thermal energy storage system. *Materials Today: Proceedings*, *42*, 618–625. https://doi.org/10.1016/J.MATPR.2020.10.949

Jonas, D., Theis, D., Meiers, J., & Frey, G. (2017). Model-based analysis of solar thermal and heat pump systems using TRNSYS. *ISES Solar World Congress 2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings*, 2216–2227. https://doi.org/10.18086/SWC.2017.33.05

Katekar, V. P., Rao, A. B., & Sardeshpande, V. R. (2023). An experimental investigation to optimise pebbles-based sensible heat storage system: An exploration to improve thermal efficiency of solar devices. *Journal of Energy Storage*, *73*, 108964. https://doi.org/10.1016/J.EST.2023.108964

Knobloch, K., Ulrich, T., Bahl, C., & Engelbrecht, K. (2022). Degradation of a rock bed thermal energy storage system. *Applied Thermal Engineering*, *214*, 118823. https://doi.org/10.1016/J.APPLTHERMALENG.2022.118823

Kuravi, S., Trahan, J., Goswami, D. Y., Rahman, M. M., & Stefanakos, E. K. (2013). Thermal energy storage technologies and systems for concentrating solar power plants. *Progress in Energy and Combustion Science*, *39*(4), 285–319. https://doi.org/https://doi.org/10.1016/j.pecs.2013.02.001

Kyocera Fineceramics Europe Steatite Datasheet. (2023). KYOCERA Fineceramics Europe GmbH.

Mahfoudi N., Kheiri A., El Ganaoui M., & Moummi A. (2016). *THERMAL ENERGY STORAGE USING DESERT SAND: A NUMERICAL STUDY OF THE THERMOFLUIDIC PERFORMANCES*.

Markets and Markets. (2020). *Thermal Energy Storage Market by Technology (Sensible, Latent, Thermochemical), Storage Material (Water, Molten Salts, PCM), Application (Power Generation, District Heating & Cooling, Process Heating & Cooling), End User and Region - Global Forecast to 2025*. https://www.marketsandmarkets.com/Market-Reports/thermal-energy-storage-market-61500371.html

Marongiu, F., Soprani, S., & Engelbrecht, K. (2019). Modeling of high temperature thermal energy storage in rock beds – Experimental comparison and parametric study. *Applied Thermal Engineering*, *163*, 114355. https://doi.org/10.1016/J.APPLTHERMALENG.2019.114355

McTigue, J. D., Markides, C. N., & White, A. J. (2018). Performance response of packed-bed thermal storage to cycle duration perturbations. *Journal of Energy Storage*, *19*, 379–392. https://doi.org/https://doi.org/10.1016/j.est.2018.08.016

Mines & Minerals Sector Profile. (2017). www.ibn.gov.np

Nahhas, T., Py, X., & Sadiki, N. (2019a). Experimental investigation of basalt rocks as storage material for high-temperature concentrated solar power plants. *Renewable and Sustainable Energy Reviews*, *110*, 226–235. https://doi.org/10.1016/J.RSER.2019.04.060

Nahhas, T., Py, X., & Sadiki, N. (2019b). Experimental investigation of basalt rocks as storage material for high-temperature concentrated solar power plants. *Renewable and Sustainable Energy Reviews*, *110*, 226–235. https://doi.org/10.1016/J.RSER.2019.04.060

Qureshy, M. N. (1969). Thickening of a basalt layer as a possible cause for the uplift of the Himalayas — A suggestion based on gravity data. *Tectonophysics*, *7*(2), 137–157. https://doi.org/10.1016/0040-1951(69)90003-1

Rashad, M., Żabnieńska-Góra, A., Norman, L., & Jouhara, H. (2022). Analysis of energy demand in a residential building using TRNSYS. *Energy*, *254*, 124357. https://doi.org/10.1016/J.ENERGY.2022.124357

Salehudress, Z. M., Habtu, N. G., Admasu, B. T., Delele, M. A., & Asemu, A. M. (2024). Performance study of low temperature air heated rock bed thermal energy storage system. *Energy Storage*, *6*(4), e621. https://doi.org/10.1002/EST2.621

Sarbu, I., & Dorca, A. (2019). Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials. *International Journal of Energy Research*, *43*(1), 29–64. https://doi.org/10.1002/ER.4196

Schlipf, D., Schicktanz, P., Maier, H., & Schneider, G. (2015). Using Sand and other Small Grained Materials as Heat Storage Medium in a Packed Bed HTTESS. *Energy Procedia*, *69*, 1029–1038. https://doi.org/10.1016/J.EGYPRO.2015.03.202

Siegesmund, S., & Snethlage, R. (Eds.). (2014). *Stone in Architecture* (5th ed.). Springer Berlin, Heidelberg.

TRNSYS - Official Website. (2017). https://sel.me.wisc.edu/trnsys/faq/faq.htm

TRNSYS 16 (5th ed., Vol. 1). (2007). http://sel.me.wisc.edu/trnsys

TRNSYS : Transient System Simulation Tool. (2019). https://www.trnsys.com/

Ucler, K., Kibar, A., Metin Ertunc, H., & Yigit, K. S. (2022). Investigation of a heat storage system consisting of basalt stones, water and a phase change material. *Journal of Energy Storage*, *50*, 104196. https://doi.org/10.1016/J.EST.2022.104196

Water and Energy Commission Secretariat. (2022). *Nepal Energy Sector Synopsis Report - 2022*.

White, A. J., McTigue, J. D., & Markides, C. N. (2016). Analysis and optimisation of packed-bed thermal reservoirs for electricity storage applications. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *230*(7), 739–754. https://doi.org/10.1177/0957650916668447

Xie, B. (2022). *Thermocline study of packed-bed thermal energy storage system*. https://doi.org/10.34894/VQ1DJA

Zanganeh, G., Pedretti, A., Haselbacher, A., & Steinfeld, A. (2015). Design of packed bed thermal energy storage systems for high-temperature industrial process heat. *Applied Energy*, *137*, 812–822. https://doi.org/https://doi.org/10.1016/j.apenergy.2014.07.110

Appendix

Table Pugh Matrix

S.N.	Materials	Temperature Range (1-5)	Availability (1-9)	Thermal conductivity (1-5)	Specific heat capacity (1-5)	Cost (1-9)	Thermal Diffusivity (1-5)	Total
	HTFs							
1	Thermal oil	1(70ºC)	5	1(0.1W/mK)	1(2000-2500(J/kg)	1	3	12
2	Ethylene glycol	5(125ºC)	1	3(0.2W/mK)	3(2400)	5	1	18
3	Water	3(0-100ºC)	9	5(0.6W/mK)	5(4181)	9	5	36
	Tank's Material(>100c)							
1	GI Sheet	1	9	3(45W/mK)	5	9	3	30
2	Stainless Steel	5	5	1(15)	1	5	1	18
3	Aluminum	3	1	5(247)	3	1	5	18
	Packing Materials							
1	Granite	1	5	1	1	5	1	14
2	Steatite	5	1	5	3	1	5	20
3	Basalt	3	9	3	5	9	3	32