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Authors: Emin Selahattin UMDU, Levent BİLİR

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Economic And Technical Performance Assessment of a Thermal Energy Storage System for Ancillary Services

Emin Selahattin UMDU[1], Levent BİLİR*[1]

Abstract

Increasing renewables in energy mix results in lower emissions but also increased fluctuations in the electricity grid. Current thermal energy conversion-based systems will stay as main electricity generation in the grid, and they will support base loads of the system. Whether these systems are fossil or geothermal sourced they need adaptive technologies to harmonize with the changing network. This study aims to investigate feasibility and performance to satisfy response demands for a proposed thermal energy storage system connected to feed stream of thermal power generation to support ancillary services in a case study in Turkey. Tin is selected as the phase change material for its good inductive properties. It is demonstrated numerically that the evaluated heat storage tank, filled with tin, provides adequate time for thermal discharging within time limits to benefit from hourly ancillary power market. Using hourly pricing data for entire 2020, it is found that proposed system shows better economic performance than investment requirement of ROI over 11% as stated in various literature for renewable energy systems. Analysis of system economic performance shows a ROI of 16% and NPV is 17.8% higher than required investment.

Keywords: Thermal energy storage, ancillary services, NPV, economic analysis, ansys-fluent

1. INTRODUCTION

European Union’s (EU) ambitious target of achieving at least an 80% reduction in greenhouse gas (GHG) emissions below 1990 levels by 2050, while maintaining or improving today’s levels of electricity supply reliability, energy security, economic growth, and prosperity [1]; requires overcoming a series of technical obstacles. The resolution of the European Parliament stresses the important role of energy storage in addressing the flexibility needs of the energy system to reach our climate neutrality target. Further its vital role in security of electricity supply is highlighted.

Ancillary services refer to functions that help grid operators maintain a reliable electricity system. These services maintain the proper flow and direction of electricity, address imbalances

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* Corresponding author: levent.bilir@yasar.edu.tr
[1] Yaşar University
E-mail: selahattinumdu@gmail.com
ORCID: https://orcid.org/ 0000-0002-8227-6267, https://orcid.org/0000-0003-3950-5367

between supply and demand, and help the system recover after a power system event. In systems with significant variable renewable energy (RE) penetration, additional ancillary services may be required to manage increased variability and uncertainty. Ancillary services can be renovated to use renewable energy sources. For this purpose, renewable energy cannot be injected into the electricity grid due to lack of demand can be stored and deliver it to the grid in peak times. These applications vary in size starting from 100 (kW) to 2 (MW) with a target discharge range of 20 (mins) to 1.5 (hrs). It helps electricity system for supply and demand balancing and reduce emissions by helping to displace fossil fuels with renewable energy. In this respect (1) European Council, EC economic recovery plan ‘Next Generation EU’ includes storage as one of the investment priorities to boost economic growth and resilience in the EU, (2) support the uptake of energy storage to achieve the EU decarbonization objectives, (3) will support investments in the next financing period [2].

The power generation capacity in power plants cannot be utilized to the grid in periods where demand is reduced, and this results in economic losses and increased environmental impact. For example, energy demand decreases significantly during night-time. Because of the tariff schemes and variable pricing, geothermal and other thermal power plants become uneconomical for up to six hours during low grid demand. In addition, due to the decrease in heat supplying fluid temperatures coming from either furnaces or geothermal wells in all operating periods of power generation, nominal power generation decreases, and efficiency losses are observed.

Similarly, in power plants that use any other energy sources such as wind, solar, fossil fuel, nuclear etc., there is a decrease in capacity utilization and thus efficiency losses in periods of low demand. In this case, the power generation can be kept at a nominal value and when the demand is low and generated power can be stored as sensible or latent heat, which can be used later directly or indirectly for power generation to supply peak loads on the grid. Thus, providing both economic, operational, and environmental benefits.

There are three types of methods in thermal energy storage where their advantages and disadvantages are summarized in Table 1. These methods are sensible thermal energy storage (STES), latent thermal energy storage (LTES) and thermo-chemical energy storage (TCES) [3].

Table 1
Overview of heat storage applications for power generation type

	Advantages	**Disadvantages**
STES	the simplest and the most technologically advanced	Low thermal energy storage density is achieved
LTES	Moderate energy intensity among the three methods Energy storage and reuse process takes place at constant temperature	There is low thermal conduction for the materials used In long-term use, material structure deterioration may occur There is a loss of heat
TCES	Long-term storage is possible The volume required for storage is comparatively small There is no heat loss	The system is complex Requires high initial investment

In the present study, a thermal energy storage tank, filled with tin as the storage medium, is also taken into consideration and its behaviour during discharge is investigated. Time dependent numerical simulations are performed using Ansys-Fluent software for different thermal oil flow rate values. The use of metals and alloys or molten salts provides a high phase change temperature, which in turn enables a high sensible heat storage capacity along with a high latent heat storage opportunity. The high temperature values obtained in power plants require such storage media. For instance, Vigneshwaran et. al [4], performed an experimental and numerical investigation on a heat storage system which uses cast iron as the storing medium. They tested the system’s thermal behaviour for different temperature ranges. Bashir and Giovannelli [5] evaluated Mg_2Si, MgSi and AlSb, which have very high melting temperature values, as thermal energy storage mediums integrated with a solar receiver. They reported the optimum design point of the receiver. Zeneli et. al [6] evaluated silicon based latent heat energy storage system to achieve storage at very high temperatures. Different vessel designs and their effect on silicon melting rate were considered. Royo et al. [7] evaluated an energy storage tank for an industrial furnace and analysed the melting and solidification of the molten salt used as the phase change material.

This study aims to investigate performance of thermal energy storage system connected to feed stream of a power plant other standalone systems to support ancillary services for a case study in Turkey. System aims to balance grid by integrating into daily ancillary power market for load flow. Emphasis is put on the capability of responding economic benefits of the thermal energy storage system for grid operations.

2. SYSTEM DESCRIPTION AND SELECTION OF HEAT STORAGE MEDIA

A thermal power plant is selected as a case since it already has thermal energy to electricity conversion capacity, and proposed system can be applied with a minimum capital investment for current infrastructure. The layout of the proposed system is given in Figure 1. The system store heat in times of grid needs load management of demand side and increases the temperature of the fluid fed to turbines when demand increases, and grid need reserve power. In case there is no demand for load from the system, energy is stored from grid tariff which is lower than reserve prices. Induction is used to store thermal energy and system discharge is through a network of heat exchangers.

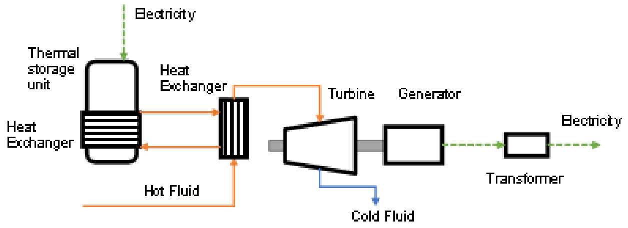

Figure 1 Proposed system layout

Firstly, different metals are inspected for their capacity to satisfy requirements for curtailment applications of heat storage by proposed system. Curtailment minimization services use energy storage to absorb that cannot be injected into the electricity grid due to lack of demand, either delivering it to the electricity grid when needed or converting it into another energy vector to be delivered to the relevant grid. These services are utilized a few times a day and typically they have an energy storage range of size range of 1 kW to 1 GW, discharge duration range of 20 minutes to 1.5 h. In the proposed system, turbines are already operational and increased steam input can be reflected to nominal values in less than 30 seconds [8].

Induction heating (IH) is preferred since it offers contactless, fast, and efficient heating of conductive materials with delivered power efficiency of 90% [9]. Because of its contactless nature and fast response times, it is selected for thermal energy loading for the system. Thus, fast load use and charge of the system can be applied within grid management criteria for load management systems. There is a wide range of parameters for selection of thermal storage material which can be charged by induction heating yet density, latent and sensible heat, and penetration dept of the material during induction are considered in selection.

The depth of this current flow is influenced by different material properties. This depth is called penetration depth and is given by Eq. 1;

$$\delta = \sqrt{\frac{\rho}{\pi\, f\, \mu}} \tag{1}$$

where, ρ is specific electrical resistance, μ is permeability and f is frequency. This effect causes approximately 86% of the power will be concentrated in the current penetration depth [10]. Thus, to achieve a fast and uniform heating through induction of the heat storage material zinc, aluminum, copper, mild carbon steel, nickel and tin are considered as candidates and penetration depths are calculated and compared.

Penetration depts calculations of candidate metals that were used select heat storage materials are given in Figure 2. Mild carbon steel and tin has the highest and very similar penetration depths.

Tin is selected over iron since tin melts at 232 °C and its phase change in target heat storage range gives an opportunity to use latent heat together with sensible heat unlike mild carbon steel which melts at between 1350 to 1530 °C based on its carbon concentration.

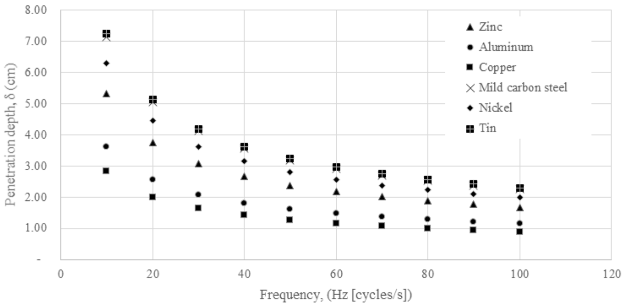

Figure 2 Calculated penetration depth of the storage material candidates.

3. CONSIDERED THERMAL ENERGY STORAGE TANK

3.1. Dimensions of the Thermal Energy Storage Tank

The schematic view of the considered thermal energy storage tank is presented in Figure 3. It is consisted of a cylindrical tank with a 0.5 (m) diameter and 0.5 (m) height. The total volume of the tank is approximately 0.1 (m^3). There are 41 vertical cylindrical pipes made of aluminum with an inside and outside diameter of 26.9 (mm) and 33.7 (mm), respectively.

Table 2
Thermophysical Properties of Tin and Therminol XP Heat Transfer Fluid

	Tin [11]	**Therminol XP [12]**
Density (kg/m^3)	6990	761
Specific heat solid (J/kg.K)	209.34	2600
Thermal conductivity (W/m.K)	28.28	0.0933
Viscosity (kg/m.s)	1.2×10^{-3}	8.41×10^{-4}
Latent heat of fusion (J/kg)	59,000	-
Melting point (°C - K)	232 (505)	-

The inside of the tank is filled with tin metal with the thermophysical properties given in Table 2. The energy extraction is modelled and solved in the current study, so therminol XP heat transfer fluid is sent to the tank through the the cylindrical pipes with different velocities in order to observe what will be the extraction of the storage thermal energy inside the tank. The thermophysical properties of the therminol XP heat transfer fluid is also summarized in Table 2.

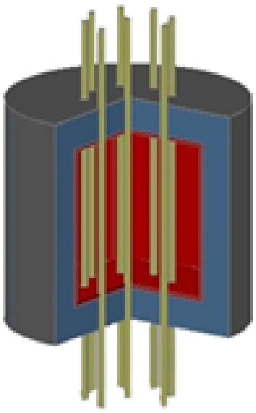

Figure 3 Schematic view of the considered thermal energy storage tank.

3.2. Numerical Modelling of the Thermal Energy Storage Tank

As the tank and the pipes passing through the tank constitute a symmetrical geometry, only ¼ of the whole tank is modelled with Space Claim software and then meshed using Ansys-Fluent R19 software as illustrated in Figure 3 and Figure 4. As it can be seen from Figure 4, the inside part of the pipes, through which therminol XP heat transfer oil flows, is meshed finer with a fine boundary layer in order to solve the flow field.

Side view of the generated meshes can be seen in Figure 4. After many trials, it is decided to use 500 elements along the height of the storage tank model in order to get stable and physically realistic results. The total control volume number for the entire storage tank model is 10,773,600. As, the storage tank is symmetrical, the side surfaces except the curved one which is the wall of the storage tank, are defined as symmetry. All the other surfaces are defined as wall, and it is assumed that the entire storage tank is perfectly isolated. The inside of the storage tank is defined as tin material, while the pipes are defined as aluminum and the inside volumes of the pipes are defined as therminol XP heat transfer fluid. The upper sides of the pipes are defined as velocity inlet surfaces, where the velocity of therminol XP is defined as 0.01, 0.05 and 0.1 (m/s) for different cases and the inlet temperature is defined as 102 °C (375 K), which is a typical value of the return geothermal fluid for a geothermal plant, for all cases. The exit surfaces of the pipes are defined as outflow. The initial temperature is taken as 250 °C (523 K) for the thermally full charged storage tank. Finally, the time step is taken as 5 (s) and iterations are continued until the convergence criteria of 10^{-3} for continuity, 10^{-6} for momentum and 10^{-8} for energy equations are achieved.

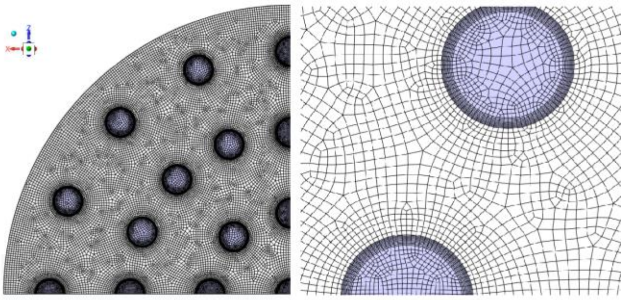
(a) (b)

Figure 4 a) Upside view of the meshes for the evaluated ¼ segment of the thermal energy storage tank, b) Closer view of the meshes

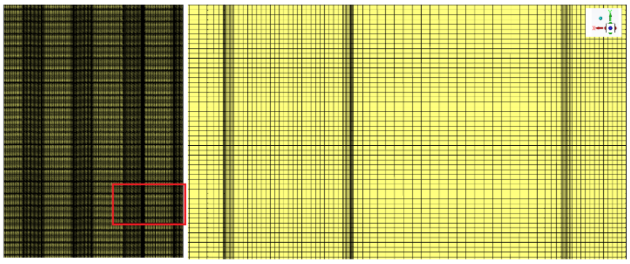
(a) (b)

Figure 5 a) Side view of the meshes for the evaluated ¼ segment of the thermal energy storage tank b) Closer view of the meshes

3.3. Numerical Results

As a result of simulations with therminol inlet velocities of 0.01 (case 1), 0.05 (case 2) and 0.1 (case 3) (m/s), it is found that the discharge period is the longest for case 1 as expected, followed by case 2 and the shortest discharge period is for case 3. It is also concluded that the discharge time can be kept between 15 minutes and 1 hour with the evaluated configuration, which falls inside the recommended discharge time of 20 (mins) to 1.5 (hrs). In Figures 6, 7 and 8, the temperature distribution and the liquid fraction of tin material are illustrated. It can be seen from Figure 6 that for the case 1, with a 0.01 (m/s) therminol XP inlet velocity, there is still some small portion of unsolidified tin even at the end of one hour, and the temperature of the tin starts to decrease from the solidifying temperature of 505 (K). When the therminol velocity increases to 0.05 (m/s) (case 2), a similar case is encountered at the end of 30 minutes. However, for the case 3, where the inlet velocity of therminol XP is 0.1 (m/s), the solidifying process is significantly faster and at the of 15 minutes, nearly all tin material solidifies. The reason of this fast solidifying process for the case 3 is that the therminol flow becomes turbulent when its velocity is 0.1 (m/s), while the flow is laminar for the velocity values of 0.01 (m/s) and 0.05 (m/s). As a final outcome, the heat discharge rate and the complete solidifying process time can be controlled by adjusting the therminol inlet velocity and the desired discharge time can be reached in the therminol XP inlet velocity range.

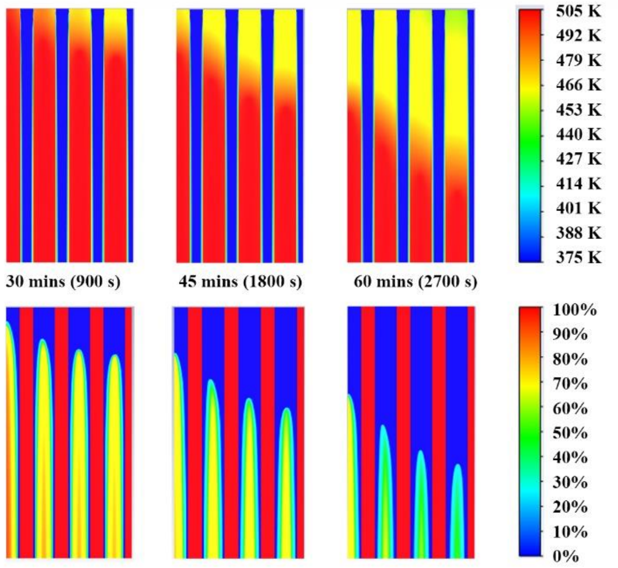

Figure 6 The temperature distribution (upper figures) and the liquid fraction (lower figures) of tin material for case 1

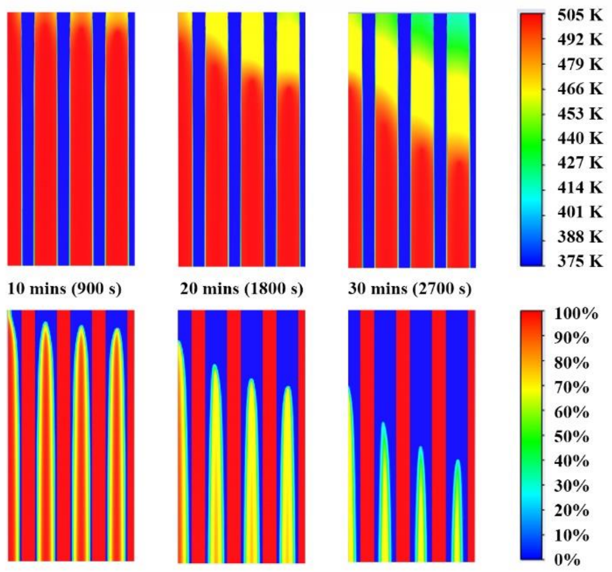

Figure 7 The temperature distribution (left figures) and the liquid fraction (right figures) of tin material for case 2.

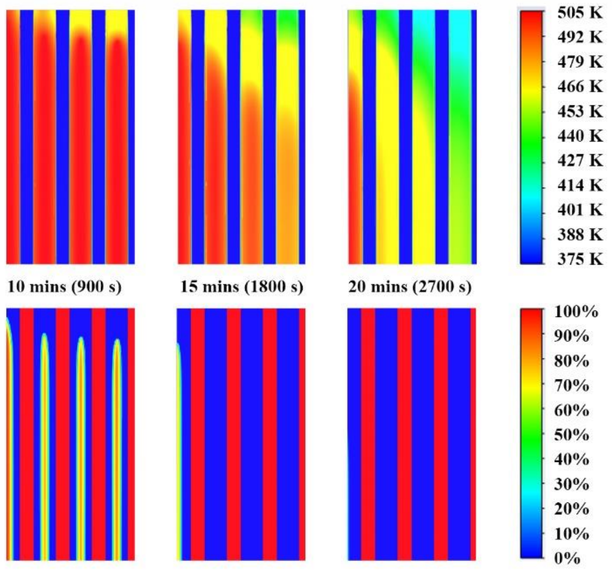

Figure 8 The temperature distribution (left figures) and the liquid fraction (right figures) of tin material for case 3.

4. ECONOMIC ANALYSIS

Study on the entire 2020-year hourly grid data supplied from Turkish Electricity Transmission Corporation energy market management system transparency tool [13] shows that 6,268 hours system support need for a total of 5,332 GWh energy, and demand site management requires 5,776 hours of operation with 3,203 GWh energy to be used to balance the system. Hourly demands for both operations are studied to find possible points for storage and discharge cycles for the described system. The hourly grid support and load management data are given Figures 9 and 10.

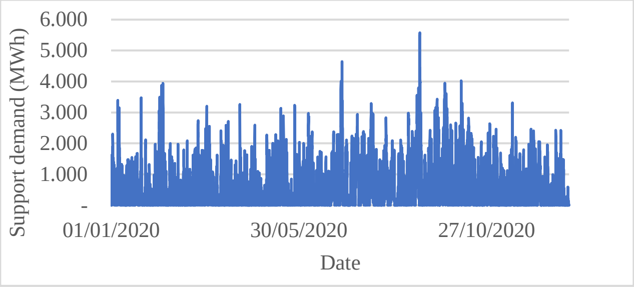

Figure 9 Turkey electric grid ancillary systems hourly support demand data.

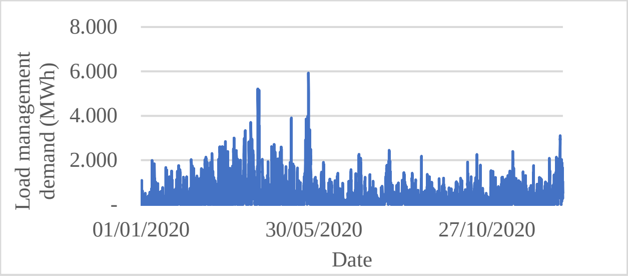

Figure 10 Turkey electric grid ancillary systems hourly load management data.

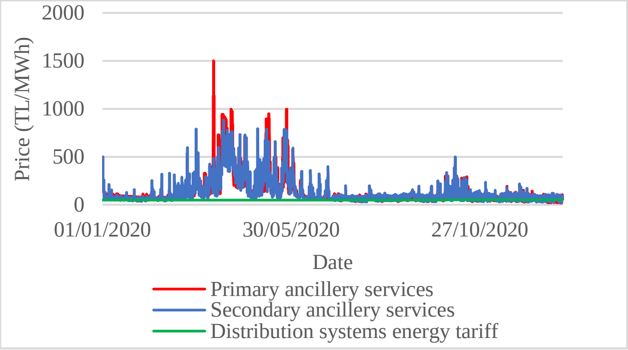

Figure 11 Hourly dynamic rates for ancillary services for both services and grid system tariffs throughout 2020

Modelling studies show that the system can satisfy response time needs stated for ancillary services, and different operational temperature capacities are compared for 1 unit with 1 m^3 of heat storage material tin and shown in Figure 11. The stored thermal energy at maximum temperature is calculated by the relationship given below;

$$Q = m_{sto}C_{p,solid}(T_{melt} - T_{min}) + m_{sto}L_{sto} + m_{sto}C_{p,liquid}(T_{max} - T_{melt}) \qquad (2)$$

where, m_{sto} = mass of thermal storage material

$C_{p,solid}$ = specific sensible heat of thermal storage material in solid phase

$C_{p,liquid}$ = specific sensible heat of thermal storage material in liquid phase

L_{sto} = latent heat of fusion of thermal storage material

T_{melt} = melting temperature of the of thermal storage material

T_{min} = Minimum practical operational temperature of the unit

T_{max} = Maximum thermal storage temperature of the unit

As expected, heat storage capacities are increasing as the maximum heat storage temperature increases as shown in Figure 12. Yet maximum temperature that can be applied when conventional materials used in the feasibility study is limited to approximately 1,000 °C. Thus, this temperature is chosen as the maximum operating temperature for economic analysis. Designed storage unit contains 1m^3 of tin for heat storage. Details of each storage unit is given in Table 3 where 2 units working together were considered for economic analysis.

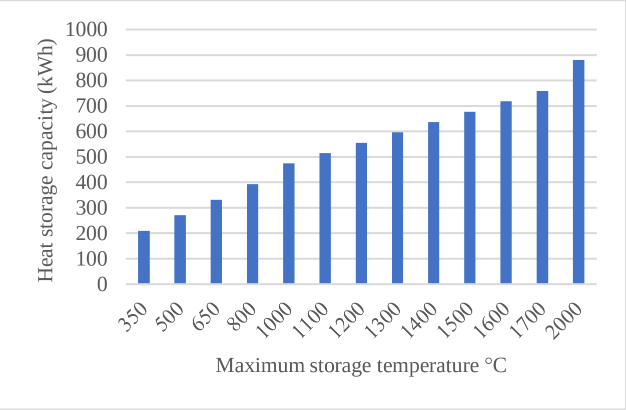

Figure 12 Calculated heat storage capacities of units with 1 m^3 of heat storage material.

Table 3
Details on heat storage unit

Heat storage medium	Tin
Density of heat storage medium (g/cm^3)	6.99
Mass of heat storage medium (kg)	6,990
Volume of heat storage medium (m^3)	1
Module geometry	cylinder
Specific Heat Capacity Solid (j/g°C)	0.2177
Specific Heat Capacity liquid (j/g°C)	0.2093
Latent Heat of Fusion (j/g)	59
Melting Point (°C)	232
Boiling Point (°C)	2,602
Lowest operational Temperature (°C)	120
Highest operational Temperature (°C)	1,000
Heat storage capacity (j)	1,706,657,732
Heat storage capacity (Kcal)	40,7901.4
Heat storage capacity (kWh)	474.1

The revenue streams are calculated by hourly pricing scheme described in detail by Electricity Market Ancillary Services Regulation [14]. Energy supplied to the grid is calculated with storage and conversion efficiencies of 98% and 60% respectively. Following discharge operation system is charged with the benefit of load management services to gain extra revenue, else grid system services tariff is used for charging of the system where induction heating efficiency of 90% was used. 2020 daily market data shows that a total of 6312 cycles can be completed with a 0.95 MW thermal energy stored and 0.50 MW delivered to the system. Hourly prices vary between 18 to 1499 TL/MWh with an average of 135.2 TL for primary and 25 to 844 TL/MWh with an average of 139.1 TL for secondary markets. Hourly data are directly used in calculations rather than averages, which yields to 133.68 TL/cycle average revenue. And yearly cumulative total revenue for 2020 case is calculated as 843,811.72 TL for 2-unit system.

Net present value (NPV) and return of investment (ROI) methods are used to evaluate the performance of the system. The NPV value of required investment by the discounted sum of all cash flows received is shown below.

$$NPV = \sum_{1}^{n} \frac{R_t}{(1+i)^n} \qquad (3)$$

where,

R_t = Net cash flow at time t

i = interest rate

t = time of the cash flows

Average yearly interest rate, 12.43%, where operational lifetime of the system is taken as 20 years. ROI is calculated by;

$$ROI = \frac{Net\ return\ of\ investment}{cost\ of\ investment} \times 100\% \qquad (4)$$

The results for the calculations of economic analysis are given in Table 4, where ROI is 16% and NPV is 6,136,685.64 TL, which is 17.8% higher than current investment required. Based on study of Zhou et. al., investors typically require making returns of at least 10 – 11% since renewable or green energy markets are considered as stable [15], thus the proposed system is found above investor requirements.

Table 4
Results of economic analysis.

Number of units	2
Unit system cost (TL)	2,027,057.50
Unit Storage material cost (TL/kg)	165.50
Unit Total Storage material cost (TL)	578,422.50
Total system Cost (TL)	5,210,960.00
Interest	12.43%
Investment lifetime	20
NPV (TL)	6,136,685.64
ROI	16%

5. CONCLUSIONS

This study investigates the performance and economic benefits of the thermal energy storage system for Turkey as a case for ancillary services. The following conclusions are gained:

- The evaluated heat storage tank, filled with tin, provides adequate time for discharging the stored energy.
- Current regulations of daily energy market make it possible to use the proposed system with a 0.95 MW thermal energy stored and 0.50 MW delivered to the system for 6,312 cycles. Larger systems can also benefit similarly yet there is a trade-off for slightly lower market opportunities.
- Proposed system shows better economic performance than investment requirements where system ROI is 16% and NPV is 6,136,685.64 TL, which is 17.8% higher than investment required.
- The real obstacle for reaching higher economic and practical gain is materials and equipment that can withstand higher temperatures above 1,000 °C. Also, higher temperature heat transfer fluids are required.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The authors contributed equally to the study.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission, or any special permission" should be included under this heading.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science

List of symbols

T_{melt}	Melting Temperature of the of Thermal Storage Material
T_{min}	Minimum Practical Operational Temperature of the Unit
T_{max}	Maximum Thermal Storage Temperature of The Unit
m_{sto}	Mass of Thermal Storage Material
$C_{p,solid}$	Specific Sensible Heat of Thermal Storage Material in Solid Phase
$C_{p,liquid}$	Specific Sensible Heat Of Thermal Storage Material in Liquid Phase
L_{sto}	Latent Heat of Fusion of Thermal Storage Material
R_t	Net Cash Flow at Time t
I	Interest Rate
t	Time of The Cash Flows
ρ	Specific Electrical Resistance
μ	Permeability
f	Frequency
δ	Penetration Depth

List of Abbreviations

EU	European Union’s
GHG	Greenhouse Gas
RE	Renewable Energy
EC	European Council
IH	Induction heating
NPV	Net present value
ROI	Return of Investment
STES	Sensible Thermal Energy Storage
LTES	Latent Thermal Energy Storage
TCES	Thermo-Chemical Energy Storage

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