Received: 8 June 2018 | Revised: 13 October 2018 | Accepted: 14 October 2018

DOI: 10.1002/er.4291

SPECIAL ISSUE RESEARCH ARTICLE

WILEY INTERNATIONAL JOURNAL OF ENERGY RESEARCH

Operation strategies guideline for packed bed thermal energy storage systems

Iñigo Ortega-Fernández[1] | Irantzu Uriz[1] | Asier Ortuondo[1] | Ana Belén Hernández[1] | Abdessamad Faik[1] | Iñaki Loroño[2] | Javier Rodríguez-Aseguinolaza[1]

[1] CIC Energigune, Miñano, Spain

[2] Departamento de Ciencias y Técnicas de la Navegación, Máquinas y Construcciones Navales (UPV-EHU), Portugalete, Spain

Correspondence
Iñigo Ortega-Fernández, CIC Energigune, Albert Einstein 48, 01510, Miñano, Álava, Spain.
Email: iortega@cicenergigune.com

Funding information
European Commission, Grant/Award Number: 642067

Summary

Packed bed thermal energy storage (TES) systems have been identified in the last years as one of the most promising TES alternatives in terms of thermal efficiency and economic viability. The relative simplicity of this storage concept opens an important opportunity to its implementation in many environments, from the renewable solar-thermal frame to the industrial waste heat recovery. In addition, its implicit flexibility allows the use of a wide variety of solid materials and heat transfer fluids, which leads to its deployment in very different applications. Its potential to overcome current heat storage system limitations regarding suitable temperature ranges or storage capacities has also been pointed out. However, the full implementation of the packed bed storage concept is still incomplete since no industrial scale units are under operation. The main underlying reasons are associated to the lack of a complete extraction of the full potential of this storage technology, derived from a successful system optimization in terms of material selection, design, and thermal management. These points have been evidenced as critical in order to attain high thermal efficiency values, comparable to the state-of-the-art storage technologies, with improved technoeconomic performance. In order to bring this storage technology to a more mature status, closer to a successful industrial deployment, this paper proposes a double approach. First, a low-cost by-product material with high thermal performance is used as heat storage material in the packed bed. Second, a complete energetic and efficiency analysis of the storage system is introduced as a function of the thermal operation. Overall, the impact of both the selected storage material and the different thermal operation strategies is discussed by means of a thermal model which permits a careful discussion about the implications of each TES deployment strategy and the underlying governing mechanisms. The results show the paramount importance of the selected operation method, able to increase the resulting cycle and material usage efficiency up to values comparable to standard currently used TES solutions.

Highlights

- Operation strategies and thermal management of packed bed TES systems.
- Cyclic and material use efficiencies in packed bed TES systems.
- Transient and stationary performance analysis of packed bed TES systems.

KEYWORDS

packed bed, thermocline, thermal energy storage (TES), operation strategy, thermal management

1 | INTRODUCTION

Thermal energy storage (TES) is today a proven technology to reach a sustainable and efficient management of any thermally driven process.[1] The inherent thermodynamic limitations associated to thermal systems, such as the unavailability of an appropriate heat source, the thermal losses, or the improvable cycle efficiencies, justify the implementation of a TES. In practice, numerous industrial processes present noticeable enhancement opportunities according to the mentioned gaps. In these terms, solar-thermal power production,[2] intensive heat demanding industries (steelmaking, glass, cement production, etc),[3] or compressed air energy storage[4] are representative examples with such optimization potential.

However, even if the deployment of a TES can be conceptually an effective solution, its implementation on real applications must satisfy very restrictive requirements, both technically and economically.[5] Considering these boundaries, the search of technically high-performing and cost-effective TES solutions has become a priority for the industrial and scientific communities.[6] Among other TES concepts, packed bed systems have been identified in the last years as a very promising technology.[7] The high operation flexibility, the relative implementation simplicity together with its highly technoeconomic effective nature confer to this TES alternative a particular interest.

The packed bed storage concept has been widely investigated.[7] However, its full implementation at commercial scale is still unclear. Some works have associated poor thermal efficiency to this TES alternative.[8] In this regard, the thermal efficiency of the standard molten salt double tank concept, extensively used in the concentrated solar power (CSP) environment due to its large thermal cycle efficiency, around 95%,[9] is considered as a benchmark efficiency target. Aligned to this objective, an appropriate system design optimization process[10] together with an optimized thermal management of the packed bed unit could lead to a similar high efficiency performance, as this work aims to demonstrate.

Another issue that needs to be addressed is the detailed analysis of the thermocline stability over multiple charge/discharge cycles. In this regard, only a reduced number of publications can be found dealing with this subject.[11-14] From these works, it is concluded that, among the different physical mechanisms which govern the thermal stability of the thermocline formation, the maximum temperature drop allowed in the fluid outlet during the charge/discharge of the TES system is one of the driving parameters. As a consequence, in order to advance towards the implementation of packed bed TES systems in real-scale storage applications, the full understanding of the thermal stability and performance under cycling conditions as a function of different operation parameters needs to be addressed. A good example of the large interest deposited on this storage technology oriented to the full understanding of the involved physical, chemical, mechanical, thermal, and material implications is the European Commission funded (Horizon 2020) project RESLAG,[15] in which this research has been performed.

In this project, different breakthrough concepts are being investigated aiming to search an optimum management of the available raw materials and energetic resources. One of its core contributions is the introduction of steel slag, a by-product of the steelmaking industry, as a material for high temperature heat storage.[16] In particular, it suggests the use of slag as a filler material in packed bed arrangements. The potential uses of this system are very wide. As also proposed in the same project, this low-cost and high-temperature storage could be exploited from the industrial waste heat recovery application to the heat storage units in solar-thermal power production plants.

Considering the aforementioned points, this work follows a double objective. First, it demonstrates the viability of packed bed TES technology based on low-cost solid by-products (steel slag) as efficient and high-temperature thermal storage systems. Second, the importance of an appropriate design and operation of the presented TES system is highlighted and carefully analysed. In this regard, different thermal management criteria are investigated introducing process boundaries and deployment requirements, depending on the TES implementation environment. In particular, three different strategies are analysed: (1) complete charge/discharge, (2) limited charge/discharge time exploitation imposed by the heat source or eventual final heat application, and (3) fixed maximum TES outlet fluid temperature variation. These three management alternatives are investigated under continuous charge/discharge conditions. The obtained results allow for a complete analysis of criticality, evidencing the specific benefits and shortcomings associated to each operational strategy. Overall, the obtained results show the impact of the management of the TES unit on the obtained thermal efficiency of the system, leading to a clear improvement and optimization gap with respect to the state-of-the-art packed bed deployment strategies.

2 | SYSTEM DESCRIPTION

In order to obtain a fair representation of the selected slag based packed bed, a realistic deployment environment has been selected. In particular, the recovery of the waste heat generated in the electric arc furnace (EAF) steelmaking process is identified and investigated in this work, as well as in the RESLAG project. This application is proposed as a noticeable opportunity window for the thermal energy recovery and storage in general, and for the valorization of the steel slag as solid storage material in packed bed arrangements in particular.

Considering the strong implantation of the EAF steelmaking industry together with its large energetic demand and subsequent waste, the particular application of waste heat recovery from the flue gasses expelled from the EAF on the ferrous scrap melting process is selected as benchmark case for this work. Leaving apart the detailed description of this intensive energetic activity,[17-19] which is not the objective of this paper, a general layout of this process is presented in Figure 1.

While the EAF is operating, it expels gases at temperatures around 1200°C with a high dust content. Taking this into account, in the first stage of the proposed demonstration plant, these gases are passed through a temperature homogenizer and a filter to be stabilized and cleaned. After that, the EAF gas is directed to a gas-gas heat exchanger where it is used to heat up a clean air current to around 700°C. Once passed through the heat exchanger, the EAF gases are sent to the gas treatment plant of the steelworks. On the other hand, the heated air current is used to charge the TES packed bed. When the heat available in the TES is needed, atmospheric air (considered at 20°C) is directly introduced in the packed bed through the bottom part and extracted hot from the upper part. The detailed fluid insertion strategy during the charge/discharge operations is shown in Figure 1.

In addition to the novel application of the packed bed TES in the industrial waste heat recovery, as mentioned above, following the research performed in our laboratories, steel slag, a by-product generated in the same

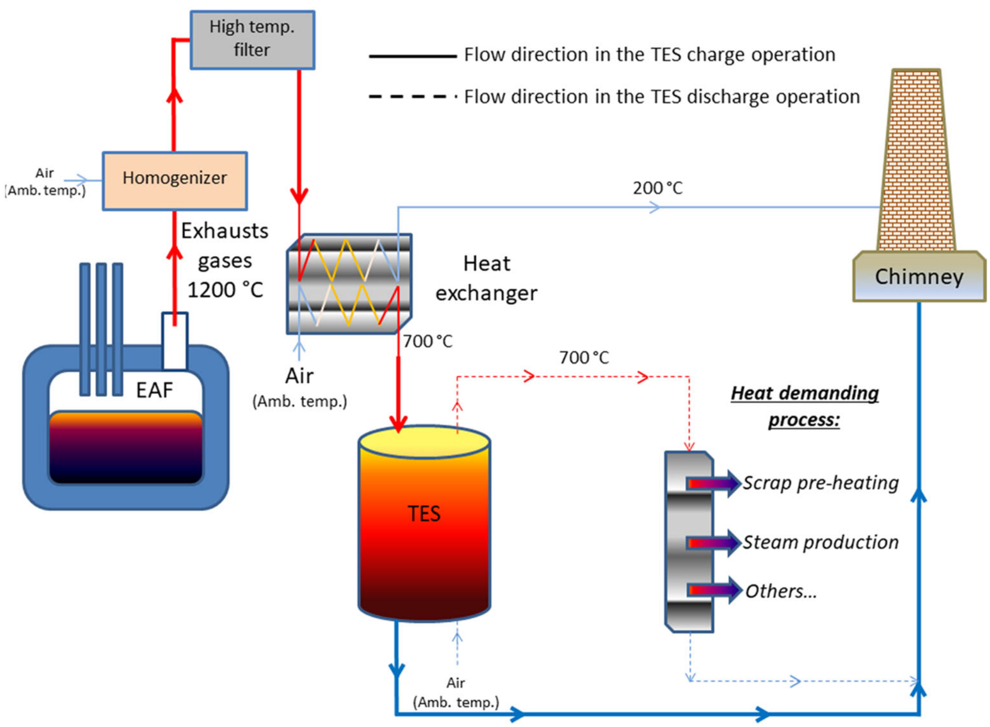

FIGURE 1 Layout of the waste heat recovery demonstration plant [Colour figure can be viewed at wileyonlinelibrary.com]

steelworks, is proposed as storage solid medium. Its appropriate thermophysical properties for packed bed TES systems have already been demonstrated.[16] This selection presents a very important added value, since its implementation in the packed bed TES system allows both a successful technical solution and a cost-effective alternative able to provide a low cost thermal energy storage concept.

The selection of the particular design parameters for the analysed benchmark case, shown in Table 1, has followed a systematic optimization analysis, performed in previous works.[10] As a consequence, the studied packed bed TES configuration presents an optimal energetic and exergetic storage performance with a negligible impact of nondesirable phenomena such as pressure drop or thermal losses. Quantitatively, the former is limited to a maximum of a 5% of the total storage capacity by an appropriate design of the system regarding the geometric aspects of the tank (geometry and aspect ratio selection), size of the solid particles, and fluid flow rate. On the other hand, thermal losses are minimized to values below 2% of the total storage capacity by means of a successful aspect ratio value of the tank, together with a suitable high-temperature insulation material. Overall, based on the results obtained in the mentioned previous works, both losses are considered negligible and will not be discussed in this paper, focused on the thermal operation and management of the TES. As a summary, the main design and working parameters of the investigated TES unit are summarized in Table 1.

3 | MODEL DESCRIPTION

In order to carry out the operation analysis presented in this work, a complete physical model accounting for the most representative heat transfer and fluid flow mechanisms associated to the packed bed storage concept was developed and extensively validated with experimental data.[10,20] This model is based on the porous media formulation available in the commercial CFD software ANSYS Fluent. In addition to the standard momentum and mass conservation equations, the developed approach solves separately two coupled energy equations: one for the solid and one for the fluid phases. The detailed description of the implemented equations was already included in previous works.[10] It has to be noted that the developed model not only accounts for standard conduction and convection heat transfer phenomena but also includes radiative heat transfer mechanisms, which show a critical importance at high temperatures, above 400°C.[21]

TABLE 1 Geometric and operation characteristics of the investigated packed bed

Tank Geometry	Cylindrical
Tank height, m	2.48
Tank diameter, m	1.24
Insulation thickness, m	0.25
Slag pebble size, m	0.01
Air mass flow rate, kg/s	0.3
Charge temperature, °C	700
Discharge temperature, °C	20
Thermal capacity, MWh_t	1

Considering the wide temperature range of the investigated TES system, from 20°C to 700°C, thermophysical properties of both the solid and fluid are included in the model as temperature-dependant functions. In this regard, the experimental results published by Ortega-Fernández et al[16] are considered for the steel slag. Air properties are calculated following the Peng-Robinson Equation of State.[22] Finally, thermophysical properties of the Mullite insulation material are taken from the product datasheet.[23]

In order to evaluate the thermal performance of the modelled packed bed unit in terms of energy and efficiency, the following expressions are used to calculate the charged and discharged energies to/from the packed bed:

$$E_{charged} = \int_{t_{start\ charge}}^{t_{end\ charge}} \dot{m} c_p^f \left(T_{hot}^f - T_{cold}^f \right) dt \tag{1}$$

$$E_{discharged} = \int_{t_{start\ discharge}}^{t_{end\ discharge}} \dot{m} c_p^f \left(T_{out}^f - T_{cold}^f \right) dt \tag{2}$$

From these calculated energies, two efficiency criteria are considered within this work. The "cycle efficiency" defined as Equation 3 and the exploitation of the TES material calculated following Equation 4 (henceforth called "material efficiency"). Even if the cycle thermal efficiency is a parameter usually investigated in related literature,[24-27] the material efficiency is not. The introduction of this material efficiency value, defined in this paper, adds a second performance criterion that allows the determination of an appropriate exploitation of the TES material in packed bed storages. This could be a critical factor on the calculation of the economic viability of the complete system. As a consequence, this paper follows a correctly balanced efficiency approach, in terms of both energetic and material deployment.

$$\eta_{cycle} = \frac{E_{discharged}}{E_{charged}} 100 \tag{3}$$

$$\eta_{material} = \frac{E_{discharged}}{E_{max.}} 100 \tag{4}$$

4 | RESULTS

Three different thermal exploitation scenarios are investigated for the packed bed TES system: complete charge/discharge, limited charge/discharge times, and limited outlet temperature variation.

4.1 | Complete charge and discharge operation

The analysis of the thermal performance of a TES unit operated in a complete charge/discharge strategy is addressed in this section. In order to carry out such analysis, the calculated outlet fluid temperatures during the charge and discharge operations are presented in Figure 2. Going through the results obtained in the charge (red curve), it is observed that during the first 3 hours, the introduced heat is effectively transferred to the solid storage material, since the outlet fluid temperature does not exceed the cold fluid one (20°C). However, a continuous outlet fluid temperature raise is observed for the following 3 hours of charge operation up to values close to the hot fluid temperature (700°C). From this time, as the overall temperature of the solid storage material is near to the maximum system temperature, a poor thermal transport governs the storage system, leading to negligible energy storage. Even if an approximated calculation frame could consider the TES unit charged after the mentioned 6.5 hours, a more precise calculation also needs to consider the slight asymptotic outlet temperature trend between 6.5 and 8 charging hours. Taking this into account, the precise time required to completely charge the packed bed was fixed when the difference between the energy introduced (upper part) minus the energy released (bottom part) with the air equals the energy lost through the tank external wall. After this time, the TES system is considered completely charged.

In the discharge operation (blue curve), slight differences are found if compared with the charge one. The most relevant one is the extension of the constant outlet fluid temperature at 700°C in the first 3.75 hours. The different time extension compared with the charge process is associated to a double phenomenology. First, the considered thermal insulation is initialized at the cold system temperature (20°C) in the first charge operation. Consequently, this operation is affected by larger thermal losses due the heating of the insulation material. Second, the large operation temperature range implies a noticeable change on the thermal properties of the involved materials, which directly affects the energy balance of the system. After these 3.75 hours of constant outlet temperature, the thermocline is extracted from the TES between the 3.75 and 5.5 discharge hours. From this time until the end, the outlet fluid temperature asymptotically reaches the cold fluid temperature, with a minimum thermal variation.

$$P_{charged} = \int_{T_{cold}}^{T_{hot}} \dot{m} c_p^f dT \quad (5)$$

$$P_{stored} = \int_{T_{out}}^{T_{hot}} \dot{m} c_p^f dT - \int_{T_{ambient}}^{T_{wall}} h_{loss} A_{tank} dT \quad (6)$$

$$P_{discharged} = \int_{T_{cold}}^{T_{out}} \dot{m} c_p^f dT \quad (7)$$

The instantaneous power values in the charge and discharge operations are presented in Figure 3. The red line corresponds to the power introduced with the air

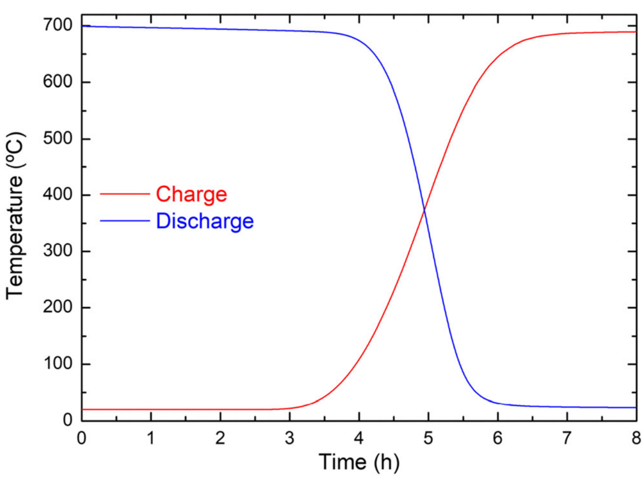

FIGURE 2 Outlet air temperature during the complete charge and discharge operation [Colour figure can be viewed at wileyonlinelibrary.com]

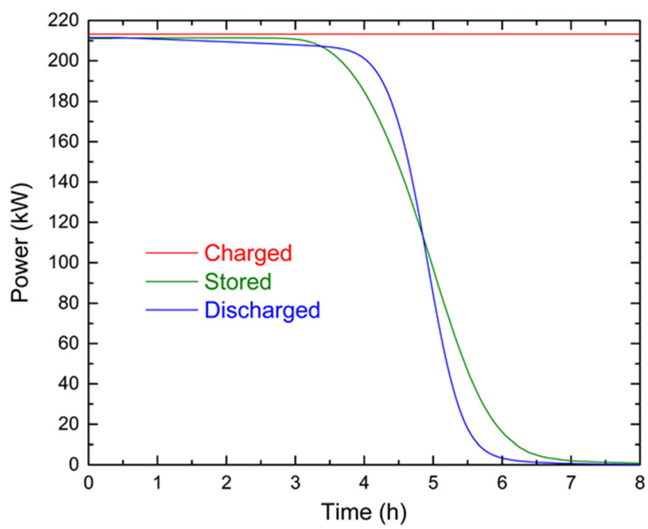

FIGURE 3 Power in the complete charge and discharge operation [Colour figure can be viewed at wileyonlinelibrary.com]

flow in the TES unit (henceforth "charged") and calculated with Equation 5; the green line to the power transferred, during the charge operation, from the air to the TES material, ie, stored, and evaluated with Equation 6; and the blue line to the power extracted from the packed bed during the discharge operation obtained with Equation 7. Focusing on the stored power, an important decrease on this value is observed after 3 hours, associated to the power introduced in the packed bed and not transferred to the TES material. This period, from the third hour to the end of the discharge, corresponds to the thermocline expulsion from the tank. In the discharge curve, a similar behaviour is obtained. In this case, the maximum power is obtained during the first four discharge hours, and from this time, it starts decreasing up to reach a value close to 0 after 7 hours.

Aiming to evaluate the separate charge and discharge performances, in Figure 4, two efficiency criteria are presented. For the charge operation, depicted in the red line, the ratio between the stored energy and the charged energy is defined. The results show that this parameter maintains a high efficiency value above 95% for the first three charge hours, whereas after this time suffers a drastic decrease. On the other hand, for the discharge operation, depicted in blue line, the ratio between the discharged energy and the total energy discharged from the system in the 8-hour operation is defined. From these results, a 95% of the total discharged energy is released during the first 5 hours. Meanwhile, for the extraction of the remaining 5%, another 3 hours are necessary.

Overall, considering the total energy introduced in the charge operation and the one released in the discharge run, a cycle efficiency of 59.5% is obtained. This value is clearly affected by the energy disposed during the charge process. Besides, the material efficiency (Equation 4) reaches a 98.8%.

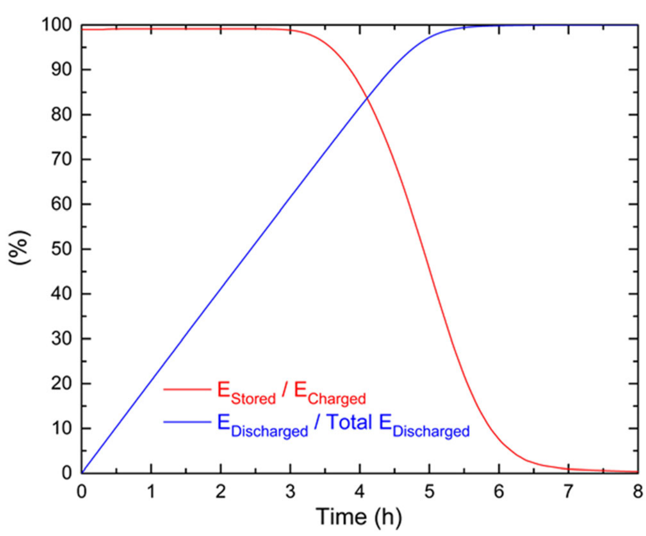

FIGURE 4 Efficiencies in the complete charge and discharge operations [Colour figure can be viewed at wileyonlinelibrary.com]

Even if this operation strategy maximizes the use of the storage material, the obtained cyclic efficiency is noticeably low. This last constrain could make the complete charge/discharge strategy unattractive or worthless for real applications. It has to be mentioned that this charging strategy results in a very inefficient procedure, since a large amount of heat is lost. However, this energy disposal can be palliated by the subsequent use of the heat expulsed from the TES during the charge operation in a different application, if any, on the same industrial stream. As a consequence, this heat could be considered as useful, and it would not penalize the overall thermal cycle efficiency anymore. In any case, in the absence of an eventual application for this noncaptured energy, this heat disposal could be identified as one of the main drawbacks of this operation strategy.

4.2 | Limited time operation

This section addresses the performance of the investigated packed bed TES unit considering a predetermined time for the charge and discharge operations. In this case, the operation time is selected to attain a partial charge/discharge state of the TES. With this objective, a charge/discharge time of 4 hours is selected, according to the full capacity of the investigated storage tank.

The partial charge/discharge of the packed bed TES unit presents strong differences when compared with the complete charge/discharge operation. The most representative one is the effect of the thermocline/energy left inside the tank and its evolution in consecutive charge/discharge cycles. The thermal transport mechanisms, responsible for the thermocline formation, become in this operation strategy a capital governing phenomenon. The null or eventually partial extraction of this thermal gradient region from the tank during its cyclic operation leads to different initial conditions for consecutive charge or discharge processes. Consequently, a nonrecurring transient behaviour can be expected. For this reason, the transient behaviour of the TES and the overall system performance up to 10 consecutive charge/discharge cycles are analysed in this section.

The results of the performed continuous cycling calculations under the mentioned partial charge/discharge conditions are shown in Figure 5. In this plot, the temperature in the central axial coordinate of the tank, once the charge (lower curves) and the discharge (upper curves) processes are finished, is presented. The extremes 0 and 1 *x*-coordinates correspond to the lower and upper parts of the tank, respectively.

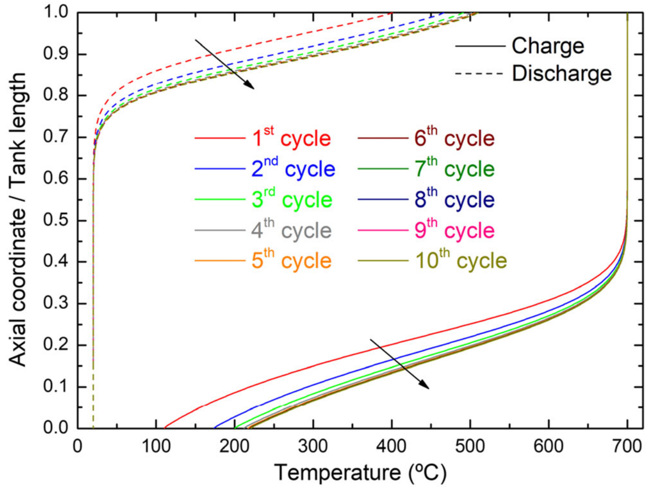

FIGURE 5 Time-limited operation: axial temperature distribution in the packed bed [Colour figure can be viewed at wileyonlinelibrary.com]

The calculations show a monotonously increasing energy not extracted from the packed bed TES unit with the continuous cycling in the discharge operation. After 5 to 6 cycles, the obtained temperature distribution in the TES becomes recurrent. As direct consequence, the system attains a stationary behaviour with reproducible thermal performance. This stationary condition of the packed bed is satisfied once the partial extraction of the thermocline region in a thermal cycle equals the thermocline spreading during the charge and discharge operations.

In order to discuss the quality of the released heat during the charge and discharge operations in terms of its temperature level, in Figures 6 and 7, the fluid temperature in the tank outlet is represented for the 10 modelled cycles. As it can be observed in the charge curves (Figure 6), in the first run, this temperature is kept at 20°C during the first 3 hours. From this threshold time, the temperature starts increasing continuously up to 110°C at the end of the charge (4 hours). In consecutive cycles, the time, in which air is released at 20°C, is shortened, and the maximum outlet temperature reached at the end of the charge increases significantly. The reason of this phenomenon is the energy left inside the tank after each discharge operation (see Figure 5). Finally, after 5 to 6 cycles, when the stationary thermal performance of the storage is reached, the fluid is released at 20°C during 1.5 to 2 hours, when it starts increasing up to reach 220°C at the end of the four charging hours.

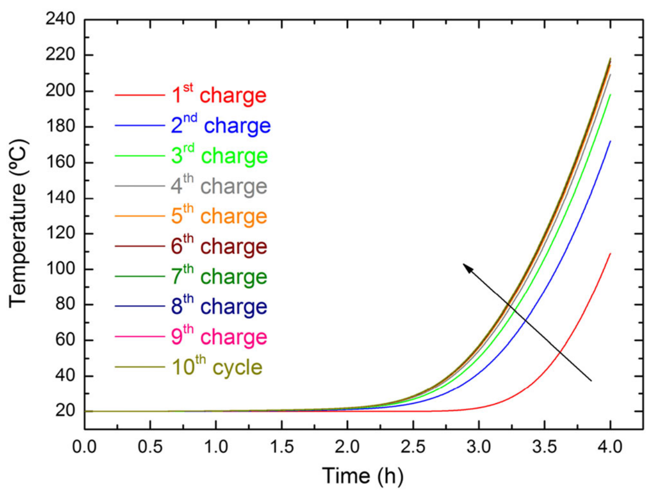

FIGURE 6 Time-limited operation: tank outlet fluid temperature in the operation [Colour figure can be viewed at wileyonlinelibrary.com]

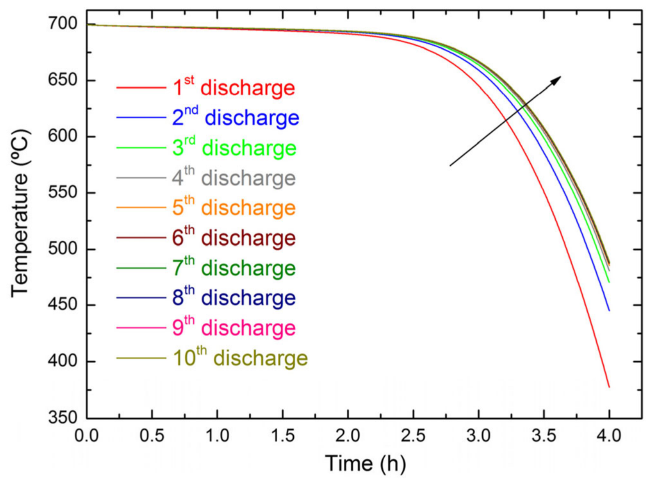

FIGURE 7 Time-limited operation: tank outlet fluid temperature in the discharge operation [Colour figure can be viewed at wileyonlinelibrary.com]

During the discharge operation, an opposite trend is observed. As shown in Figure 7, in the first cycle, the outlet fluid temperature is kept at around 700°C during 2 hours, only decreased by the container thermal losses. After this time, it shows a continuous decrease up to 375°C at the end of the discharge revealing a partial extraction of the thermocline from the packed bed. In consecutive cycles, the outlet temperature shows longer times at values close to 700°C, hence the thermal performance of the TES is improved. Once the transient behaviour is finished, the temperature remains almost constant at 700°C during 2.5 hours, before decreasing up to 480°C at the end of the discharge process.

Overall, in the time-limited operation strategy, the thermal behaviour during a continuous cycling of the packed bed TES system is associated to the thermocline evolution and to its displacement through the storage tank. In this regard, the limited time operation leads to the displacement of the thermocline region to the bottom part of the storage tank with the cycles. As a consequence, an increasing amount of thermocline is extracted during consecutive charge processes, whereas hotter outlet fluid temperatures are obtained in subsequent discharge operations.

Finally, aiming to the discussion of the released heat quality in terms of energies and efficiencies, these magnitudes are presented in Figure 8. In particular, in Figure 8 A, the charged (red line) and discharged (blue line) energies in each cycle are collected, whereas, in Figure 8B, the cycle and material efficiencies are presented in red and blue lines, respectively, for each thermal cycle.

Considering the discharged energy and both efficiency criteria, a continuous increasing trend is observed with the number of cycles. The maximum values are obtained once the stationary thermal performance condition is satisfied. This behaviour is caused by two main reasons: the energy associated to the thermocline formation during the first cycles and the increasing discharged energy (higher temperature level).

Quantitatively, the cycle efficiency ranges from values slightly above 90% in the first cycle to 93% when the stationary condition is reached. This cycle efficiency values are very close to those reported[9] for the standard molten salt double tank TES technology (around 95%). On the other hand, the material efficiency also presents high values, ranging from 75% in the first cycle up to 77.5% in the stationary. As can be seen, both efficiency values present a more balanced behaviour compared with the full charge/discharge operation method. This implies a much better exploitation of the packed bed TES in terms of energy and material deployment. In addition, these results clearly show that after thermal stabilization of the thermocline, the energy efficiency obtained approaches the state-of-the-art efficiency values on usual molten salt heat storage systems.[9] As a consequence, an appropriate design and management of packed bed systems are critical in order to extract the full potential of this TES technology, leading to a fully competitive storage alternative in terms of economic and energetic evaluation criteria.

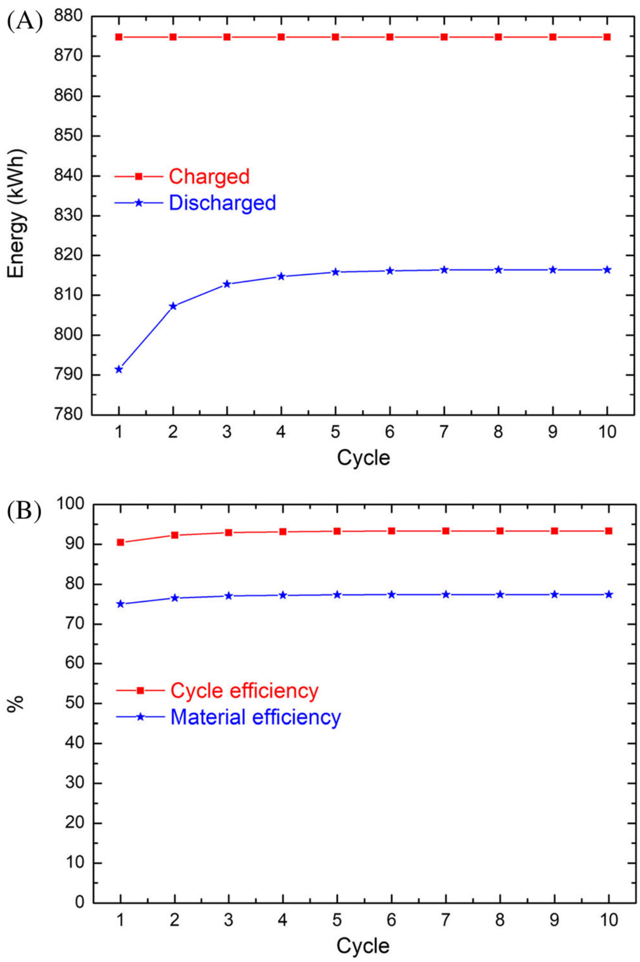

FIGURE 8 Time-limited operation: A, energy balances and B, efficiencies [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | Limited outlet fluid temperature variation operation

To complete the analysis of the three proposed operation methodologies, in this section, a predetermined outlet fluid temperature criterion is selected to consider the end of the charge and discharge operations. In the following, this maximum allowed outlet fluid temperature variation is denoted as "temperature tolerance". For the sake of clarity, if a temperature tolerance of T_{tol} is selected for both the charge and discharge operations, the system is considered charged or discharged once the outlet fluid temperature is $T_{cold} + T_{tol}$ or $T_{hot} - T_{tol}$, respectively. In this work, as a case study, a temperature tolerance of 100°C has been fixed for the analysis.

Similarly to the limited time operation strategy, when a temperature tolerance criterion is considered, the thermocline is not completely removed at the end of the charge and/or the discharge operation. Taking this into account, a detailed analysis of the transient performance of the packed bed TES unit under cyclic conditions is also required. With this purpose, the temperature stratification evolution in the packed bed is presented in Figure 9 for the 10 modelled charge/discharge cycles.

Considering the axial temperature profiles of the charged system (lower curves), it can be observed that the width of the thermocline region grows as the number of thermal cycles increases. The same phenomenon is observed in the discharge curves (upper curves). Thereby, the size of the thermocline ranges from a temperature stratification of around 40% of the tank in the first charge to a 65% in the last one.

On the contrary to the effect observed in the limited time operation strategy, the axial temperature profiles in

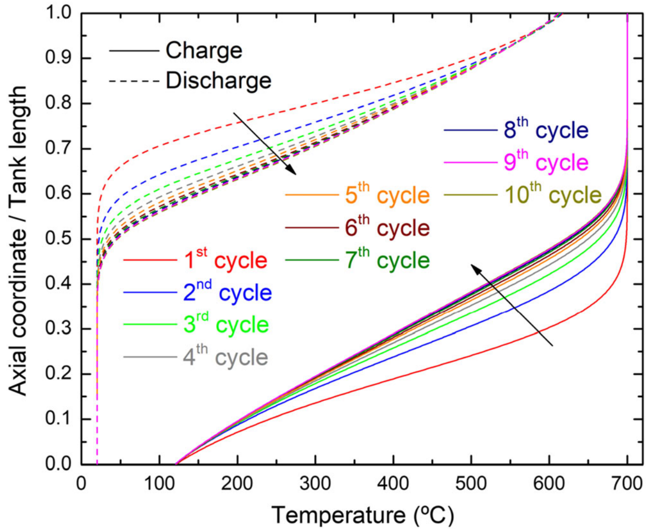

FIGURE 9 Limited outlet temperature variation: axial temperature distribution in the packed bed [Colour figure can be viewed at wileyonlinelibrary.com]

the charged and discharged states under the limited outlet temperature variation criterion show a continuous reduction of the storage capacity with thermal cycling. However, the observed difference between consecutive cycles is gradually reduced during the transient period. As a consequence, this indicates the possibility of reaching a reproducible stationary performance after certain number of cycles (6-7 for the modelled system). The underlying reason of this phenomenon, as mentioned in the previous section, is the equilibrium between the energy released from the TES within the selected temperature tolerance and the growth of the thermocline between two consecutive cycles.

Figure 10 shows the outlet fluid temperature during the consecutive discharge operations. As expected from the thermocline results discussed above, the total time releasing air at a temperature within the tolerance value (100°C) is noticeably shortened with cycling. In this particular case, comparing the 1st and the 10th cycles, a time reduction in the discharge operation of around a 25% is obtained.

In order to discuss the performance of this operation strategy in terms of charge/discharge energy and efficiency values, in Figure 11, the complete energy (Figure 11A) and efficiency balances (Figure 11B) for each of the 10 modelled cycles are presented.

Aligned with the results observed in Figure 10, Figure 11A shows an equivalent thermal storage capacity reduction with cycling. In these terms, the energies discharged in the 1st and 10th cycles are 690 and 500 kWh_t, respectively. These energies represent around a 65% and 50% of material efficiency respectively (Figure 11B).

Regarding the cycle efficiency (Figure 11B), an increasing behaviour is observed during the transient period. Starting from a value of around 70%, after 4 cycles,

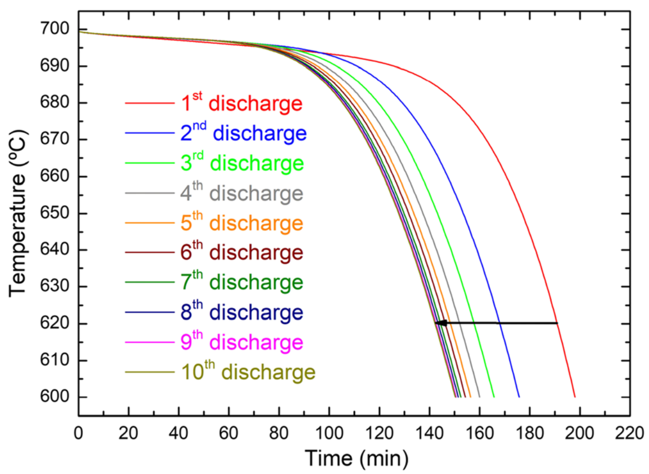

FIGURE 10 Limited outlet temperature variation: tank outlet fluid temperature in the discharge operation [Colour figure can be viewed at wileyonlinelibrary.com]

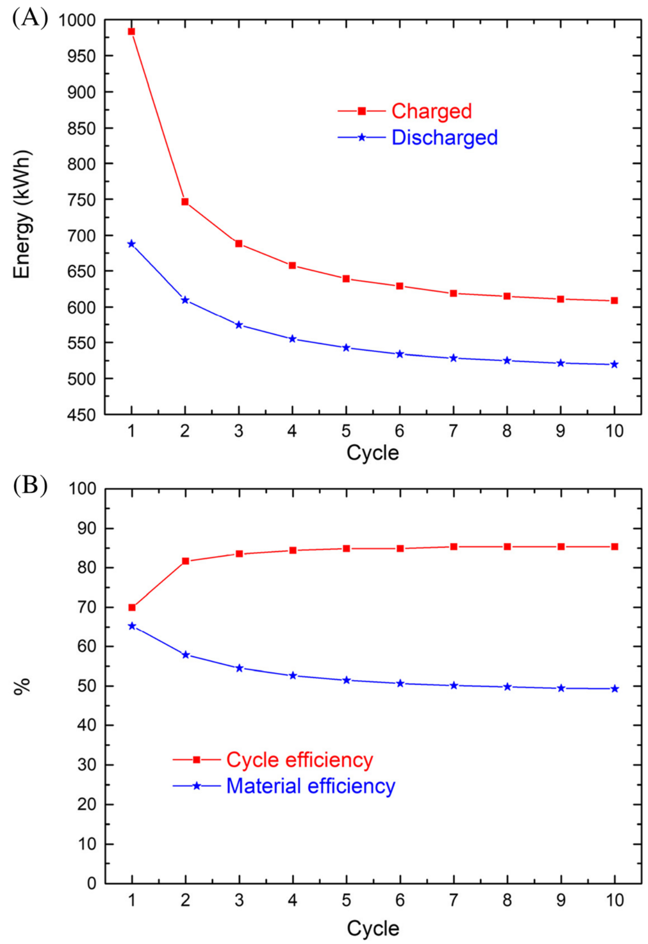

FIGURE 11 Limited outlet temperature variation: A, energy balances and B, efficiencies [Colour figure can be viewed at wileyonlinelibrary.com]

the resulting efficiency is enhanced up to around 85% and maintained in subsequent cycles with a slightly increasing trend. The underlying reason for the low efficiency in the first cycles is the energy required in the development of the thermocline region. As a consequence, the resulting temperature distribution leads to the degradation of the inlet energy, showing a thermal level out of the required tolerance, which penalizes the cycle efficiency.

5 | CONCLUSIONS

In this paper, the thermal performance of a TES packed bed as a function of the selected operation strategy has been investigated. The results have demonstrated that the particular operation of the system is, together with its satisfactory design optimization, a key issue to promote the full potential of the packed bed TES alternative. Its influence on the cyclic efficiency, material use efficiency, and overall system performance has been studied in detail as a function of three different deployment scenarios: complete charge/discharge, time limited charge/discharge, and limited outlet temperature variation in the charge and discharge. The main conclusions obtained regarding the implications of each scenario on the thermal stabilization of the thermocline and the cycle efficiencies are stated in the following:

- The complete charge and discharge strategy allows operating the TES unit under reproducible stationary conditions from the first cycle. Regarding the material efficiency, values around 99% are found, only penalized by the assumed thermal losses. However, the cycle efficiency shows a value much lower, around 60%. This low efficiency is associated to the large amount of energy released during the charge operation with the tank outlet fluid before reaching the complete charge condition. A subsequent use of the noncaptured heat results a very recommendable option in this case.
- The limited time operation in the charge and discharge results in an initially transient performance of the packed bed before attaining recurrent conditions. The underlying reason of this performance is the energy left inside the tank after each cycle. In the modelled system, this transient performance is extended during five to six charge/discharge cycles. Concerning the cycle efficiency, under this operation strategy, it is kept above 90% from the first cycle, reaching values of 93% once the reproducible conditions of the TES are reached. Besides, material efficiency values of around 75% are observed. The best balance between thermal and material efficiency values are obtained in this TES management option.
- The limited maximum outlet fluid temperature variation strategy also reveals a transient performance of the storage before attaining recurrent thermal conditions. However, under this operation strategy, a continuous growth of the thermocline region is observed while increasing the number of cycles leading to a reduction of the storage capacity of the tank. Overall, at steady state, this operation strategy shows high cycle efficiency values (~85%) together with a reduced material efficiency (~50%).

Considering all the aforementioned, the obtained results demonstrate that the correct optimization of the packed bed thermal storage system, together with its satisfactory thermal management, can lead to large thermal efficiency values, comparable to the usual molten salt double tank standard (around 95%). As a consequence, the customization of the packed bed system design and operation is revealed as a critical issue in order to obtain the full potential of this TES system, in terms of thermal and technoeconomic viability.

ACKNOWLEDGEMENTS

Financial support received from the European Commission through the H2020-WASTE-2014-two-stage (WASTE-1-2014) program (642067—RESLAG—IA) is gratefully acknowledged.

ORCID

Iñigo Ortega-Fernández http://orcid.org/0000-0003-2583-5007
Irantzu Uriz http://orcid.org/0000-0001-6915-6490
Asier Ortuondo http://orcid.org/0000-0002-1451-1034
Ana Belén Hernández http://orcid.org/0000-0003-4424-0906
Abdessamad Faik http://orcid.org/0000-0003-2379-2242
Javier Rodríguez-Aseguinolaza http://orcid.org/0000-0001-8676-5108

REFERENCES

1. Gil A, Medrano M, Martorell I, et al. State of the art on high temperature thermal energy storage for power generation. Part 1—concepts, materials and modellization. *Renewables and Sustainable Energy Reviews*. 2010;14(1):31-55.
2. Py X, Olives R. Thermal energy storage for CSP processes. In: *Handbook of Clean Energy Systems*. John Wiley & Sons, Ltd; 2015.

3. Fernández A, Barreneche C, Miró L, Brückner S, Cabeza L. Thermal energy storage (TES) systems using heat from waste. In: *Advances in Thermal Energy Storage Systems*. Cambridge, UK, Waltham, MA, USA, Langford Lane, Kidlington, UK: Elsevier; 2015:479-492.
4. Geissbühler L, Becattini V, Zanganeh G, et al. Pilot-scale demonstration of advanced adiabatic compressed air energy storage, part 1: plant description and tests with sensible thermal-energy storage. *Journal of Energy Storage*. 2018;17:129-139.
5. Thaker S, Olufemi A, Kumar A. Techno-economic evaluation of solar-based thermal energy storage systems. *Energ Conver Manage*. 2017;153:423-434.
6. Alva S, Liu L, Huang X, Fang G. Thermal energy storage materials and systems for solar energy applications. *Renew Sustain Energy Rev*. 2017;68:693-706.
7. Esence T, Bruch A, Molina S, Stutz B, Fourmigué J-F. A review on experience feedback and numerical modelin of packed-bed thermal energy storage systems. *Solar Energy*. 2017;153:628-654.
8. Yang Z, Garimella S. Cyclic operation of molten-salt thermal energy storage in thermoclines for solar power plants. *Appl Energy*. 2013;103:256-265.
9. Hameer S, van Niekerk J. Thermodynamic modelling of molten salt thermal energy storage system. *International Journal of Scientific Research and Innovative Technology*. 2015;2(10):83-96.
10. Ortega-Fernández I, Loroño I, Faik A, Uriz I, Rodriguez-Aseguinolaza J, D'Aguanno B. Parametric analysis of a packed-bed thermal energy storage system. *AIP Conference Proceedings*. 2017;1850:08021.
11. Geissbühler L, Kolman M, Zanganeh G, Haselbacher A, Steinfeld A. Analysis of industrial-scale high-temperature combined sensible/latent thermal energy storage. *Appl Therm Eng*. 2016;101:657-558.
12. Odenthal C, Breidenbach N, Bauer T. Modelling and operation strategies of DLR's large scale thermocline test facility (TESIS), in *SolarPACES Conference*, Abu Dhabi (Emiratos Arabes Unidos), 2016.
13. Bayón R, Ricas E, Rojas E. Study of thermocline tank performance in dynamic processes stand-by periods with an analytical function. *Energy Procedia*. 2014;49:725-734.
14. Biencinto M, Bayón R, Rojas E, González L. Simulation and assessment of operation strategies for solar thermal power plants with a thermocline storage tank. *Solar Energy*. 2014;103:456-472.
15. [Online]. Available: http://www.reslag.eu/
16. Ortega-Fernández I, Calvet N, Gil A, Rodríguez-Aseguinolaza J, Faik A, D'Aguanno B. Thermophysical characterization of a by-product from the steel industry to be used as a sustainable and low-cost thermal energy storage material. *Energy*. 2015;89:601-609.
17. U.S. Department of Energy, Waste heat recovery: Dent Tech and opportunities in the U.S. industry, 2008.
18. Worldsteel Association, 2016. [Online].
19. Worldsteel Association, 2016. [Online].
20. Ortega-Fernández I, Zavattoni S, Rodríguez-Aseguinolaza J, D'Aguanno B, Barbato M. Analysis of an integrated packed bed thermal energy storage system for heat recovery in compressed air energy storage technology. *Appl Energy*. 2017;205:280-293.
21. Zanganeh G, Pedretti A, Zavattoni S, Barbato M, Steinfeld A. Packed-bed thermal storage for concentrated solar power—pilot-scale demonstration and industrial-scale design. *Solar Energy*. 2012;86(10):3084-3098.
22. Peng D, Robinson D. A new two-constant equation of state. *Industrial and Engineering Chemistry: Fundamentals*. 1976;15(1):59-95.
23. Morgan Thermal Ceramics, MAFTEC Blanquet.
24. Wu M, Xu C, He Y-L. Dynamic thermal performance analysis of a molten-salt packed-bed thermal energy storage system using PCM capsules. *Appl Energy*. 2014;121:184-195.
25. Bayón R, Rojas E. Simulation of thermocline storage for solar thermal power plants: from dimensionless results to prototypes and real-size tanks. *International Journal of Heat and Mass Transfer*. 2013;60:713-721.
26. Yang Z, Garimella S. Thermal analysis of solar thermal energy storage in a molten-salt thermocline. *Solar Energy*. 2010;84(6):974-985.
27. Flueckiger S, Garimella S. Second-law analysis of molten-salt thermal energy storage in thermoclines. *Solar Energy*. 2012;86(5):1621-1631.

How to cite this article: Ortega-Fernández I, Uriz I, Ortuondo A, et al. Operation strategies guideline for packed bed thermal energy storage systems. *Int J Energy Res*. 2019;43:6211–6221. https://doi.org/10.1002/er.4291