Open-Source Models for Sand-Based Thermal Energy Storage in Heating Applications

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Abstract

This paper presents a new open-source modeling package in the Modelica language for particle-based silica-sand thermal energy storage (TES) in heating applications, available at `https://github.com/sbslab/modelica-sand`. Silica sand is an abundant, low-cost, and efficient storage medium for concentrated solar power and electricity generation. Although uncommon today, solid particle TES could benefit building and district heating systems, particularly as building electrification and renewable energy penetration increases. To enable heating system design and evaluation with sand TES, this work developed and open-source released Modelica models from base classes through complete systems with both physical equipment and controls. This paper first presents the new models. Then, we demonstrate their application with a heating plant that supplies steam for district heating, while also providing power-to-heat grid services by storing excesses renewable electricity as thermal energy.

Keywords: District Energy, Load Shift, Modelica, Power-to-X, Renewable Energy, Silica Sand, Thermal Storage

1 Introduction

As renewable energy penetration increases with decarbonization efforts, silica sand has emerged as an effective low-cost, low-toxicity option for thermal storage of excess renewable power (Gifford, Ma, and Davenport 2020). To date, most applications of solid sand particle thermal energy storage (TES) replace molten-salt in concentrated solar power (CSP) systems for long-duration energy storage for electric power (Ma, Glatzmaier, and Mehos 2014; Mahfoudi, Moummi, and Ganaoui 2014; Gomez-Garcia, Gauthier, and Flamant 2017). For heating applications, a test pilot site at Vatajankoski's district heating network in Kankaanpää, Finland adopted sand-based heat storage (Polar Night Energy 2022). However, scientific research on the application of sand-based TES for heating applications is limited.

To enable wide-scale testing and evaluation of sand-based TES for heating applications, this work developed and open-source released equation-based, object-oriented, multi-domain models with the Modelica language at `https://github.com/sbslab/modelica-sand` (Hinkelman, Milner, and Zuo 2023). Our application domain is thermofluid and electrical simulation of building and district heating systems with silica-sand particle-based TES in support of design, operation, and energy analysis. Water, molten salt, and phase-change materials are typically used for building TES heating applications (Sarbu and Sebarchievici 2018). Packed-bed TES with rocks/pebbles or ceramic bricks also exist where a fluid, typically air, circulates through the static bed (Sarbu and Sebarchievici 2018). In contrast, this work adopts *fluidized* particle-based TES and heat exchangers where the packed sand particles themselves move through the system, which to our knowledge, has not been evaluated in scientific literature for heating purposes.

To address this gap, we develop computationally efficient models for fluidized silica-sand particle-based TES in heating applications. This includes a polynomial medium model for the thermodynamics of silica sand, several equipment, and a novel heating plant as demonstration. Further, this paper focuses on the assembly of multiple heating equipment into *plants*, such that sand TES can be leveraged to provide heating for buildings or districts. The new models introduced with this paper are open-source (Hinkelman, Milner, and Zuo 2023). In the following sections, we present the new models. First, section 2 summarizes the overall package, while section 3 details the primary contents. As an example, section 4 presents the model and simulation results for a silica sand particle-based heating plant under two control scenarios. Lastly, conclusions are in section 5.

2 Package Overview

Following Modelica standards, model packages are assembled hierarchically, as shown in Figure 1. Designed for compatibility with the Modelica Buildings Library (MBL) v9.0.0 (Wetter et al. 2014) and the Modelica Standard Library (MSL) v4.0.0, this small package contains 9 instantiable models – from control base classes to a complete plant – and two medium models. For each of these, there is at least one runnable validation or example model with a pre-programmed *Simulate and Plot* script.

The six main-level packages are as follows. First, *Blocks* contains key performance indicators for building energy analysis, including source/site energy calculations, operational carbon emissions, and thermal discomfort. Then, *Equipment* and *Media* contains physical equipment

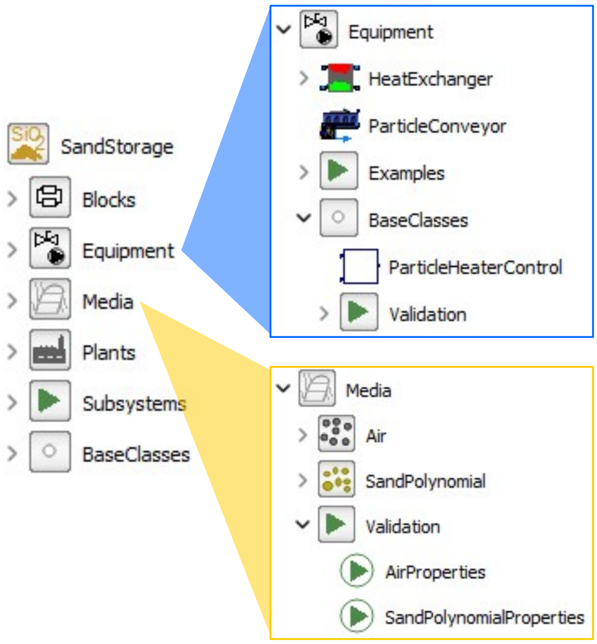

Figure 1. Package structure.

(e.g., heat exchanger) and fluid medium models (e.g., silica sand), respectively. In Figure 1, the internal contents for these two packages are shown. The *Plants* package contains sand-based TES plants, which will be demonstrated in section 4. Lastly, *Subsystems* contains several runnable examples with assemblies of equipment and controls, while *BaseClasses* contains fundamental models that can apply to several sub-packages.

3 Model Contents

While further details for the models included with this open-source release are in the Modelica code itself, here we will present some of the primary contributions. Below, we include the physics and modeling assumptions for the sand medium, particle conveyor, and renewable responsive particle heater control. Validation results for thermodynamic properties of silica sand are also included. For models not described herein, please see the documentation included within the *annotation()* of each respective model (Hinkelman, Milner, and Zuo 2023).

3.1 Sand Medium

The sand medium is modeled as silica (SiO_2, i.e. quartz), which at atmospheric pressure maintains a solid state until 1800°C (Gifford, Ma, and Davenport 2020). Consisting of two of the most common elements in the Earth's crust – silicon and oxygen – silica sand is highly abundant and nontoxic. In nature, solid silica can exist in one of seven unique crystalline structures (Huang and M. Wang 2005), but "the bulk of silica at Earth's surface is stable in the form of low-temperature α-quartz with traces of [other polymorphs]" (Davenport et al. 2020). When heated at atmospheric pressure, quartz undergoes a fast, reversible *displacive transformation*, where around 573°C, the molecular structure of low-temperature α-quartz shifts to high-temperature β-quartz (Davenport et al. 2020). This transition – also known as *quartz inversion* – is visible in silica's specific heat during a heating process (as depicted in Figure 2).

This model covers the solid phase of silica quartz at atmospheric pressure (temperatures from 298–1800K). For heating applications, we assume the sand has constant density and remains tightly packed in all states without mass loss. While the complete thermodynamic formulation is available in the open-source model (Hinkelman, Milner, and Zuo 2023), we will present the details for a critical function: specific heat. Specific heat at constant pressure c_p is formulated as two polynomial functions with a cubic Hermite spline over the quartz inversion temperature as

$$c_p(T) = \begin{cases} a_1T^3 + a_2T^2 + a_3T + a_4 & T \leq 847 - \delta \\ \tilde{c}_p & 847 - \delta < T < 847 + \delta \\ b_1T + b_2 & T \geq 847 + \delta \end{cases} \tag{1}$$

where coefficients a_i, b_i are polynomial fits to the NIST Thermochemical Tables (Chase 1998) with values given in Table 1; T is temperature in units Kelvin; the small temperature transition δ is 10^{-6}; and $\tilde{c}_p$ is a smooth approximation for specific heat defined as a cubic Hermite spline with end positions and first order derivatives that are continuous with the upper and lower polynomials. Other than temperature as a function of specific entropy $T(s)$ – which takes on a similar form as $c_p(T)$ with a Hermite spline – we implemented either pure polynomials (e.g., specific enthalpy $h(T)$ as cubic) or thermodynamic relationships (e.g., internal energy $u = h - p/d$, where pressure p and density d are both constant) for all remaining functions.

Table 1. Coefficients for Equation 1.

i	a_i	b_i
1	$2.799\,140 \times 10^{-6}$	$1.671\,556 \times 10^{-1}$
2	$-5.394\,235 \times 10^{-3}$	$9.804\,303 \times 10^{2}$
3	$4.181\,354 \times 10^{0}$	–
4	$-9.929\,403 \times 10^{1}$	–

The medium implementation is validated with respect to NIST Thermochemical Tables (Chase 1998). Figure 2 depicts the validation results for $c_p(T)$ and $h(T)$. The coefficient of variation of the root mean square error was less than 1% for all thermodynamic functions.

3.2 Particle Conveyor

Sand is moved from low to high elevations by a vertical conveyor. Conveyors have been used in silica-sand CSP systems and have simple physics with large maximum allowable flow rates (Ma, X. Wang, et al. 2021). In this Modelica package, the conveyor is based on a *skip hoist*, which can be used to transport high density particles like

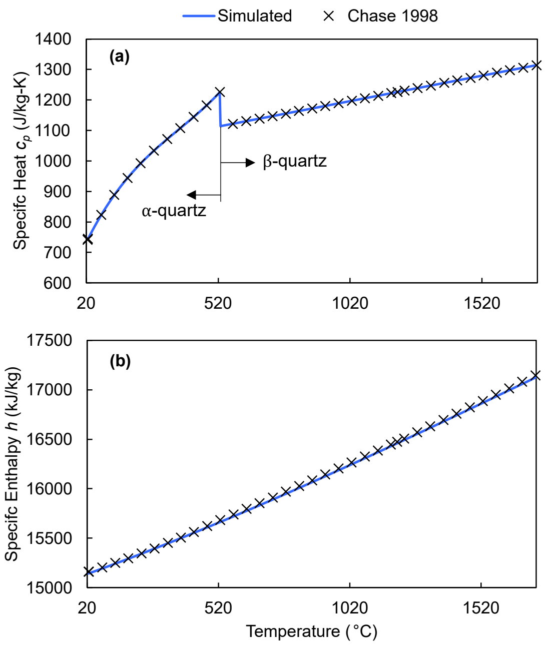

Figure 2. Validation of silica sand medium implementation. The molecular transition from α- to β-quartz is apparent in (a).

concrete or grain over short distances. The power consumed by the hoist P is

$$P = \frac{\dot{m}gh}{\eta}, \tag{2}$$

where $\dot{m}$ is the mass flow rate of the bulk sand, g is the gravitational constant, h is the total lifted height, and η is the conveyor efficiency.

3.3 Particle Heater Control

Typically, the particle heater is responsible for most of the energy consumption of sand-based heating systems. As such, the control design is paramount. Designed with this work, the particle heater control (model diagram in Figure 3) maintains a minimum silica-sand tank temperature, unless renewable energy is present. If the amount of renewable power is greater than the power required by the heater, then the sand is heated above the nominal setpoint up until but not exceeding a maximum value. We refer to this design as *renewable responsive control*.

4 Example

As a demonstration of the new library components, we modeled a novel sand-based heating plant for a steam-service district heating system. In the United States, steam is the most common heat transfer medium for district heating, representing 97% of all installations (ICF LLC and International District Energy Association 2018). The objective of this plant is to meet the steam heating load of the district without on-site fossil fuel consumption and *power-to-heat* thermal storage response when there is a surplus of on-site renewable energy. In addition to the new sand heating models presented in sections 2 and 3, this example also uses two additional open-source libraries: the MBL v9.0.0 (Wetter et al. 2014) and the MSL v4.0.0. The following sections present the system description and models, followed by the simulation results.

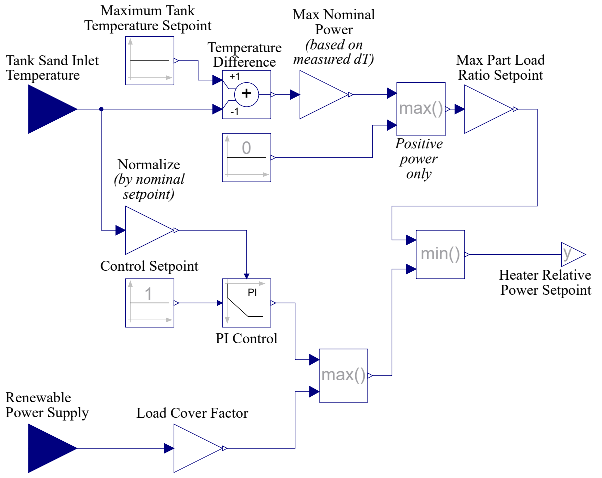

Figure 3. Modelica diagram of the renewable responsive particle heater control.

4.1 System Description and Model

As shown in Figure 4, this 100% electric plant provides steam service to a district network with sand-based TES to convert excess renewable electricity to high-quality thermal energy that can be stored for later use. Inspiration for the heating plant stems from a Brayton combined cycle power system (Gifford, Ma, and Davenport 2020), where silica sand is used for long-duration storage in electrical power generation. However in this case, steam is exported to the district for heating rather than for generating electricity in a turbine.

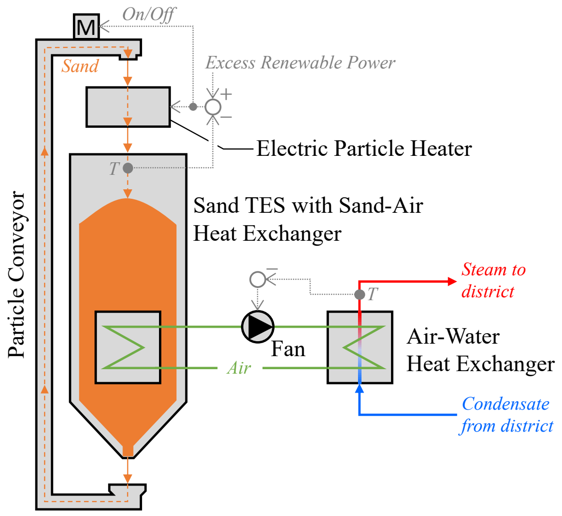

Figure 4. System schematic for the sand TES heating plant.

The plant system design is as follows. This plant contains three fluid loops: (1) a fluidized, packed-bed sand particle loop, (2) an air loop, and (3) a water/steam

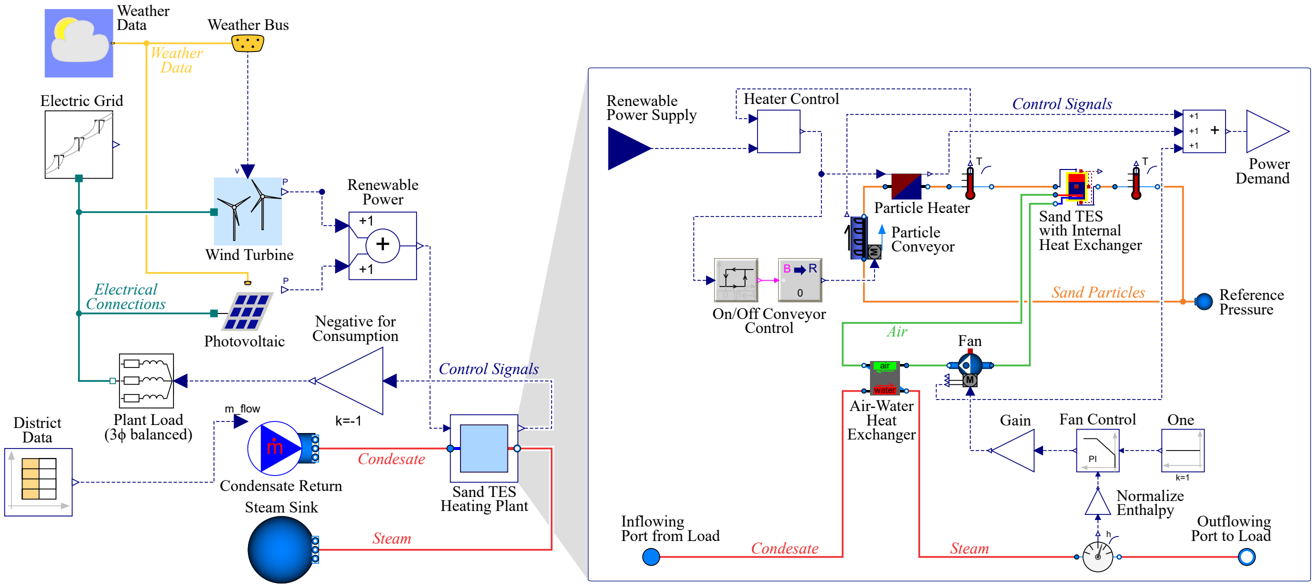

Figure 5. Modelica diagrams of the top-level example (left) and the sand TES heating plant (right).

loop with service to end-use heating loads. On the sand side, sand is heated electrically with a packed-bed particle heater per Ma, Gifford, et al. (2022), which was designed for thermally storing off-peak electricity for later on-peak usage. From the heater, sand is gravity fed into the packed-bed TES, which contains an internal shell-and-plate heat exchanger. This TES/heat exchanger design is similar to Albrecht and Ho (2019), except the heat exchanger is particle-to-air rather than particle-to-sCO$_2$ (supercritical carbon dioxide). From the cold sand hopper at the TES discharge, the particle conveyor (i.e., skip hoist) transports the sand back up to the particle heater. The air loop transfers heat from the sand TES to an air-to-water heat exchanger, where condensate water returned from the district is heated to a superheated state. It is worth noting that direct heat transfer from sand to water is theoretically possible, but previous studies that could validate this design are lacking. Thus, the sand-air-water configuration was selected for this first demonstration case.

The plant controls are as follows. On the sand side, the particle heater is as described in section 3.3 with nominal and maximum temperature setpoints of 1200°C and 1600°C, respectively. In the results, this is called *renewable responsive control*. As a basis for comparison, we also implement a *constant setpoint control* with the heater maintaining the nominal setpoint only. The skip hoist control is on/off (on if the particle heater is on) with a constant mass flow rate of 19.8 kg/s. Lastly, the fan is variable speed (nominal mass flow rate of 14.6 kg/s), and it is modulated with a PI controller to maintain the steam discharge temperature setpoint.

Figure 5 depicts the Modelica model diagrams for the top-level simulation example and the internal blocks for the sand TES heating plant. In the top-level simulation example (left), the plant is tied to the electric grid and contains an on-site photovoltaic (PV) array and wind turbine. At the top-level, this site – located in Denver, Colorado, USA – contains a 2 MW wind turbine, a 2 MW PV array, and a 480V/3ϕ electric service. The heating plant (nominal heating load 3.5 MW) supplies superheated steam to a district network at 180°C and 9.6 bar. The district demand is input as a table-look up based on a typical January heating load profile for a small university campus. Except for the plant, this top-level example uses MBL and MSL models. For example, all electrical components are from *Buildings.Electrical.AC.ThreePhasesBalanced*. Specifically, the PV model is *PVSimpleOriented*.

The Modelica diagram for the sand TES heating plant (Figure 5, right) contains the physical and control systems depicted schematically in Figure 4. In this plant model, the sand medium, air-water heat exchanger, particle conveyor, and heater control are from the new sand heating package. The water/steam medium is modeled with the *StandardWater* model from the MSL, which implements the commonly-adopted IF97 model (Wagner et al. 2000). Air is modeled as *Modelica.Media.Air.ReferenceAir.Air_pT*, which is a detailed dry air model based on the Helmholtz equations of state (Lemmon et al. 2000). For the particle heater, we adopt the MBL model *HeaterCooler_u* from the *Fluid* package, which is an ideal heater that prescribes the heat flow rate and is suitable for energy analysis purposes. For the sand TES with internal heat exchanger, we model this equipment using the *StratifiedEnhancedInternalHex* from the MBL, which represents the desired geometry and general physical principles.

4.2 Results

We simulate the sand plant system for a typical winter day with two control scenarios for the particle heater (1) constant setpoint and (2) renewable responsive. Figure 6 shows how the temperature trajectories at the sand TES with internal heat exchanger responded during periods

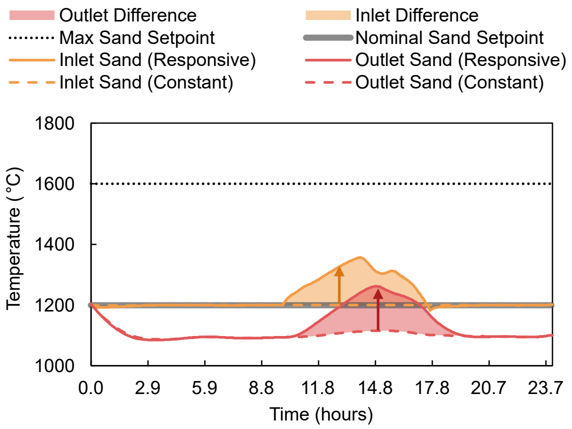

Figure 6. Temperatures at the ports of the sand TES with integrated heat exchanger with both constant setpoint control and renewable responsive control for the particle heater. Arrow direction indicates changes from constant to responsive.

with excess renewable energy. As expected, the constant control scenario maintains the 1200°C inlet sand temperature during the entire simulation period. In contrast, the renewable responsive control uses excess renewable power to increase the sand temperature above the nominal setpoint. This effectively stores the surplus electricity as high-quality heat for later use (i.e., power-to-heat).

In addition to the thermal performance, Figure 7 shows the electrical power results. This includes the power generated by renewable sources (PV and wind turbine), power consumed by the plant, and power provide from the grid (positive if consumed, negative if exported). Before 9:00 and after 18:00, the heating demand is high; because onsite renewable energy production is also low during these times, the electric grid contributes most of the electricity, and there is negligible difference between the two control scenarios.

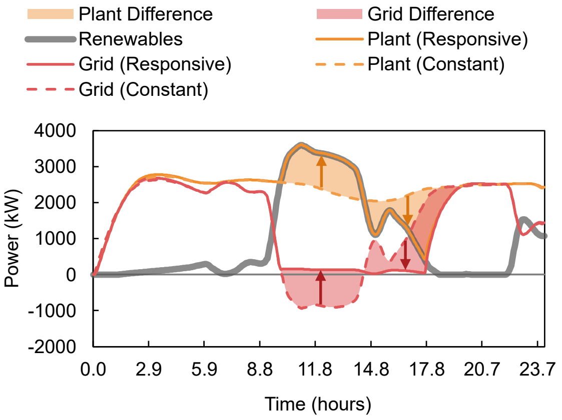

Figure 7. Power generated by renewable sources, consumed by the plant, and provided from the grid (negative if exported), with both constant setpoint control and renewable responsive control for the particle heater. Arrow direction indicates changes from constant to responsive.

In contrast, differences between the constant setpoint and renewable responsive control occur during the middle of the day when renewable generation is high. With the constant control scenario (dashed lines), the site exports surplus renewable energy back to the grid from approximately 10:00 to 14:00. Meanwhile, the plant electrical load is relatively constant. With the renewable responsive control (solid lines), no electricity is exported to the grid, and most of the energy demanded by the plant is from renewable sources (from approximately 9:30 to 17:30). In brief, the renewable responsive control produced a *load shifting response* where excess renewable energy from peak sunlight hours stored thermal energy in the sand for later use. This is evident by the arrows changing direction from up (higher power consumption) two down (lower power consumption) in Figure 7.

5 Conclusion

This paper presented new open-source Modelica models for particle-based silica-sand TES in heating applications. While most of the previous TES with fluidized sand have been developed for CSP and electric power systems, building and district heating applications are also viable use cases that, to date, remain largely unexplored. To enable silica sand as a low-cost, low-toxic storage medium for heating applications with power-to-heat grid service capabilities, we developed several Modelica models and open-source released them in a Modelica package on GitHub (Hinkelman, Milner, and Zuo 2023). As demonstration, we modeled a sand TES heating plant for steam district heating applications with onsite renewable energy (PV and wind turbine). The plant was simulated with two control scenarios for the particle heater: a constant setpoint control and a renewable responsive control.

Results indicated that the renewable responsive control increased the sand tank temperature when excess renewable power was present. This resulted in a load-shift demand response, where excess electricity stored during peak sunlight hours reduced the electricity demand from the grid later in the day. While this paper released the new models and provided a first demonstration case study with promising outcomes, future work is merited before conclusions can be drawn regarding the validity of sand TES for heating applications. Most importantly, this work did not compare the performance of sand TES plants with other designs; thus the impact on financial cost, energy consumption, and carbon emissions remain unexplored. Future work also includes the improvement and thorough validation of equipment models (primarily, the sand TES with internal heat exchanger), detailed design of sand TES for heating purposes, and wide-scale evaluation of silica sand in this new application domain.

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References

Albrecht, Kevin J. and Clifford K. Ho (2019). "Design and operating considerations for a shell-and-plate, moving packed-bed, particle-to-sCO2 heat exchanger". In: *Solar Energy* 178, pp. 331–340. DOI: 10.1016/j.solener.2018.11.065.

Chase, M.W. Jr. (1998). "NIST-JANAF Themochemical Tables, Fourth Edition". In: *Journal of Physical and Chemical Reference Data Monographs* 9, pp. 1–1951. URL: https://webbook.nist.gov/cgi/cbook.cgi?ID=C14808607&Mask=2.

Davenport, Patrick et al. (2020). *Thermal stability of silica for application in thermal energy storage: Preprint*. Tech. rep. NREL/CP-5700-77426. Golden, CO: National Renewable Energy Laboratory, pp. 1–12. URL: https://www.nrel.gov/docs/fy21osti/77426.pdf.

Gifford, Jeffrey, Zhiwen Ma, and Patrick Davenport (2020). "Thermal Analysis of Insulation Design for a Thermal Energy Storage Silo Containment for Long-Duration Electricity Storage". In: *Frontiers in Energy Research* 8. ISSN: 2296598X. DOI: 10.3389/fenrg.2020.00099.

Gomez-Garcia, Fabrisio, Daniel Gauthier, and Gilles Flamant (2017). "Design and performance of a multistage fluidised bed heat exchanger for particle-receiver solar power plants with storage". In: *Applied Energy* 190, pp. 510–523. DOI: 10.1016/j.apenergy.2016.12.140.

Hinkelman, Kathryn, David Milner, and Wangda Zuo (2023-07). *Modelica Sand Heating Package*. v1.0. URL: https://github.com/sbslab/modelica-sand.

Huang, P.M. and M.K. Wang (2005). *Minerals, Primary*.

ICF LLC and International District Energy Association (2018). *U.S. District Energy Services Market Characterization*. Tech. rep. Washington DC: U.S. Energy Information Administration.

Lemmon, Eric W. et al. (2000). "Thermodynamic properties of air and mixtures of nitrogen, argon, and oxygen from 60 to 2000 K at pressures to 2000 MPa". In: *Journal of Physical and Chemical Reference Data* 29.3, pp. 331–362. DOI: 10.1063/1.1285884.

Ma, Zhiwen, Jeffrey Gifford, et al. (2022). "Electric Charging Particle Heater for Thermal Energy Storage". US 20220021239A1.

Ma, Zhiwen, Greg Glatzmaier, and Mark Mehos (2014). "Fluidized bed technology for concentrating solar power with thermal energy storage". In: *Journal of Solar Energy Engineering* 136.3, p. 031014. DOI: 10.1115/1.4027262.

Ma, Zhiwen, Xingchao Wang, et al. (2021). "Economic analysis of an electric thermal energy storage system using solid particles for grid electricity storage". In: *The ASME 15th International Conference on Energy Sustainability, ES2021*, pp. 1–10. DOI: 10.1115/ES2021-61729.

Mahfoudi, Nadjiba, Abdelhafid Moummi, and Mohammed El Ganaoui (2014). "Sand as a heat storage media for a solar application: Simulation results". In: *Applied Mechanics and Materials* 621, pp. 214–220. DOI: 10.4028/www.scientific.net/AMM.621.214.

Polar Night Energy (2022). "Store Wind and Solar Power as Heat in Sand". In: URL: https://polarnightenergy.fi/technology.

Sarbu, Ioan and Calin Sebarchievici (2018). "A comprehensive review of thermal energy storage". In: *Sustainability* 10.1, p. 191. DOI: 10.3390/su10010191.

Wagner, W. et al. (2000). "The IAPWS industrial formulation 1997 for the thermodynamic properties of water and steam". In: *Journal of Engineering for Gas Turbines and Power* 122.1, pp. 150–180. ISSN: 07424795. DOI: 10.1115/1.483186.

Wetter, Michael et al. (2014). "Modelica Buildings library". In: *Journal of Building Performance Simulation* 7.4, pp. 253–270. DOI: 10.1080/19401493.2013.765506.