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Sand-Based Thermal Storage for Building Heating Applications: A District Energy Case Study

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Abstract

Buildings account for 40% of global energy consumption and contribute to 30% of global carbon emissions. As energy from renewable sources increases in availability and building designers push for increased electrification, thermal energy storage (TES) systems will play a crucial role in extending the usable time horizon of renewable energy. While water, molten salt, and phase change materials are typically used for building TES heating applications, silica-sand has emerged as an alternative medium for concentrated solar power applications due to its low cost, wide availability, and comparable system efficiency. This paper proposes a new silica-sand particle-based TES system for building heating applications. In this work, a novel steam plant for district heating applications is first designed to utilize silica-sand TES, which can be used for different district energy systems. To demonstrate the silica-sand TES plant performance, the design is modelled in Modelica based on a case study on the University of Colorado Boulder's campus. The simulation results show that the sand TES plant is more costly to operate than a gas-boiler based plant due to the low cost of natural gas, while the site EUI and carbon intensity can be improved. This novel system shows initial promise as a low-carbon alternative to conventional natural gas steam boilers but will require further modelling and follow-up research to improve its energy efficiency. An eventual rise in natural gas prices, and reduction of electricity prices, could improve the economic viability of this system.

Keywords: Case study, District heating, Electrification, Modelica, Silica-sand, Thermal storage

1. Introduction

In North America, 35% of all primary energy is used for heating, ventilation, and cooling in buildings [1]. Additionally, renewable energy adoption is a crucial factor towards reducing the immediate and long-term effects of climate change. Carbon neutrality in the United States has been shown to be feasible and affordable by 2025, with the correct policy and financial incentives [2]. Grid-level frequency stability is shown to be adversely affected when sourcing >20% of its electricity from variable generating sources like PV or wind, with uncertain ramp times and unsustainable peak energy production [3]. Building heating, as an enormous energy end-use, will be a challenging system to electrify considering these renewable energy access hurdles. As a result of this uncertain energy availability, systems like district steam plants must adopt new technology and controls that will allow for system operation at times where electricity may not be readily available from renewable sources.

So that the energy can later be extracted from this medium for end-use, TES systems store energy in a heat medium. These storage systems in building applications are useful for two primary reasons. Firstly, they extend the amount of time that a heat transfer medium remains hot or cold. This does not reduce the magnitude of a building's heating or cooling load; rather, it creates a time buffer that shifts the load. This temporal buffer shifts the peak load into a timeframe where peak energy is lower, and therefore so are costs. The second reason TES systems are considered crucial is for their role in long-term integration of renewable energy. As renewable electricity is incorporated as a larger portion of the power production portfolio, uncertainties surround the infrastructure required to integrate such renewable systems with traditional grid-reliant end-uses. In buildings specifically, sensible and latent heat storage are most common [4].

In recent years, particle-based silica sand systems have emerged as an alternative energy storage media to liquid-based systems. Currently, such silica sand systems are found primarily as an alternative for molten salt in concentrated solar power (CSP) systems [5-9, 28-31]. While silica sand is generally not considered a "fluid" in these systems because it exists in a solid state, it is considered "fluidized" through its bulk movement of small particles. Silica sand has shown promise as a heat transfer fluid (HTF) in sand-to-air heat exchangers [10]. These heat exchangers can house silica sand in a packed-bed or gravity packed-bed configurations [11,12]. In such cases, the silica sand is either inert or moves at a fixed flow rate under the pressure of its own weight [9].

Silica sand, at atmospheric pressure, maintains its solid phase until approximately 1600 °C, while water reaches its point of vaporization at 100 °C [13]. At constant pressure, and after the phase change from liquid water to steam, silica sand has the capacity to hold significantly more energy than water, indicated by a higher specific heat capacity [14]. Further, the energy density of silica sand is several orders of magnitude higher than water above the temperature of vaporization for water [15]. For high temperature applications, this makes silica sand a better heat storage medium than water.

Sand-based TES currently holds a miniscule presence in building and district heating applications. In 2023, a first of its kind sand-based TES facility opened in Finland. This facility is a joint venture between a startup design team, Polar Night Energy (PNE), and a local utility provider, Vatajankoski. The facility design includes a large warehouse-style sand storage volume, which uses electricity from renewable sources and the grid to heat the sand. The heat from the sand is transferred into air, which is then used to heat liquid water, which is distributed within a local district heating network. This sand-based system has a maximum sand temperature of 1000 °C, an energy generation up to 8 MWh, and a storage time horizon between hours and months [16]. While these temperatures exceed standard heat exchanger limits, they are feasible with specialized high-temperature stainless steels such as Grade 310 [27].

Sand-based TES systems have been designed to produce saturated water for buildings, but never for steam. This paper aims to build upon the modeling knowledge of high volume CSP sand-based TES and validate component and system models to inspire broader pursuit of sand-based steam production in buildings. To do this, a sand-based TES system for building steam production is designed and modeled in Modelica. These models are tested using data from a university campus steam plant. This preliminary effort provides insights for opportunities of this silica sand TES application.

2. Materials and Methods

This paper tests silica-sand based steam production via physics-based models, with the goal to assess such a system's validity as an alternative to natural gas steam boilers for district energy systems. Operational conditions, such as water flow rates, water temperatures, and boiling heat flow rates were collected and used to size the steam production system. Next, silica sand data was gathered and used to calculate sizing requirements for TES and heat transfer to the water. The sand media properties, as well as operational temperature and flow regime ranges were sourced from literature [13, 17]. Finally, the newly sized sand-based steam boiler is implemented in Modelica and tested in a case study residential community on a university campus.

2.1 System Description

The system schematic is pictured in Figure 1. This system is comprised of three fluid loops and two controllers. Steam is produced from hot air, which is heated via energy from the sand in a TES tank. The controllers ensure that the sand and air flow rates are high enough to meet the desired enthalpy of steam, based on steam flow rate demands.

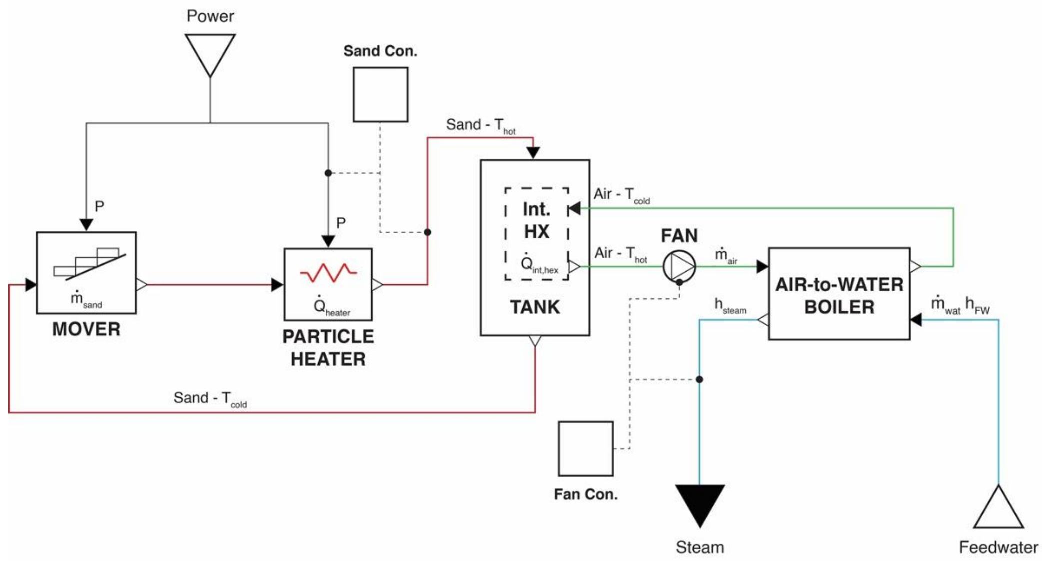

Figure 1 System schematic for the sand TES heating plant that discharges steam.

For the mechanical system, the sand loop consists of a sand particle conveyor, a particle heater, and a gravity fed sand storage tank with an integrated heat exchanger. The air loop consists of a fan, which runs air through the integrated sand-to-air heat exchanger, as well as the air-to-water boiler. Finally, the water loop consists of a pump that feeds water into the air-to-water boiler, which is sent to the buildings in a district heating network. The final fluid loop, sand, presumes the sand moves as a bulk "fluidized" solid, as mentioned above. Two controllers are employed to mediate the flow of sand and air, to meet the desired steam flow rate. All components are powered using electricity, from either the grid or renewable sources. A schematic below shows the components and three fluid loops: sand (red), air (green), and water (blue).

For the control system, two control blocks in this system regulate the air loop and the sand loop based on steam consumption The fan control block ensures that the air has the correct flow rate by comparing the measured steam enthalpy to the steam enthalpy setpoint. The sand control block produces hot sand based on the storage tank temperature. When relying on the grid, the controller measures the hot sand temperature, and ensures the measured value is converging to the setpoint. If there is renewable energy available and the tank temperature is already at the nominal hot sand setpoint, then the controller continues to produce hot sand, and increases its temperature to a higher setpoint. This control sequence produces sand at a temperature higher than the nominal setpoint when excess energy is available.

2.2 Equipment Design

Equipment is designed based on given information from the steam plant, and calculated information in Engineering Equation Solver (EES). Governing parameters for steam production, such as design heat and fluid flow, are known, while operating parameters for sand-based components are calculated to meet building heating loads. In the subsections below, the rationale for each component design is outlined.

The sand is heated by a particle heater, based on a component developed by researchers at the National Renewable Energy Laboratory for a CSP application [18]. The component is an electric resistant heater, with an assumed efficiency of 99% [13]. Using (Equation 1), the power draw (P_{heater}) and the heat transfer ($\dot{Q}_{heater}$) are calculated based on the nominal flow rate and change in temperature of the sand, m_{sand} and ΔT_{sand} respectively.

$$\dot{Q}_{nominal} = P_{heater}\eta_{heater} = \dot{m}_{sand} cp_{sand} \Delta T_{sand} \tag{1}$$

For the sand TES with an integrated heat exchanger, the hot storage volume is a large, well-insulated storage silo that can store sand at the nominal hot temperature for the design storage period. In (Equations 2 and 3), the volume of sand, V_{sand}, is calculated based on the energy required to produce steam at the nominal rate, Q_{stor}, for the storage period, $t_{storage}$.

$$Q_{stor} = \dot{Q}_{sand,nominal}(t_{storage})^{-1} \quad (2)$$

$$\rho_{sand}V_{samd} = Q_{stor}(h_{sand}T_{sand,hot})^{-1} \quad (3)$$

With a cylindrical tank geometry, the tank size can be set based on a desired tank radius or tank height.

$$V_{stor,sand} = \pi r_{\text{tank}} L_{\text{tank}} \quad (4)$$

The insulation calculation for the silica sand tank is based on insulation for a long duration energy storage tank in a concentrated solar power application [17]. The tank size is significantly larger for a CSP application than a building heating application. To scale the silo design down, each layer of insulation material is described based on its ratio to the radius of silica sand. Each insulation material has a thickness relative to the radius of the silica sand inside the tank. The heat is transferred between each insulation layer in series, meaning the combined thermal conductivity for the tank wall is the sum of each insulation material’s thermal conductivity value, as shown in (Equation 5).

$$k_{wall} = k_{refA} + k_{refB} + k_{concrete} + k_{CaSi} \quad (5)$$

Any heat lost through the tank envelope is a result of conductive heat transfer, which can be expressed using Fourier’s Law of Conduction. Heat loss is a function of wall thermal conductivity, wall thickness, hot sand temperature, and ambient air temperature.

$$\dot{Q}_{loss} = k_{wall}(T_{sand,hot} - T_{air,amb})(x_{wall})^{-1} \quad (6)$$

The energy from the sand is transferred to a secondary heat transfer fluid, air, via a crossflow heat exchanger integrated within the storage tank. This configuration can be found below in (Figure 2).

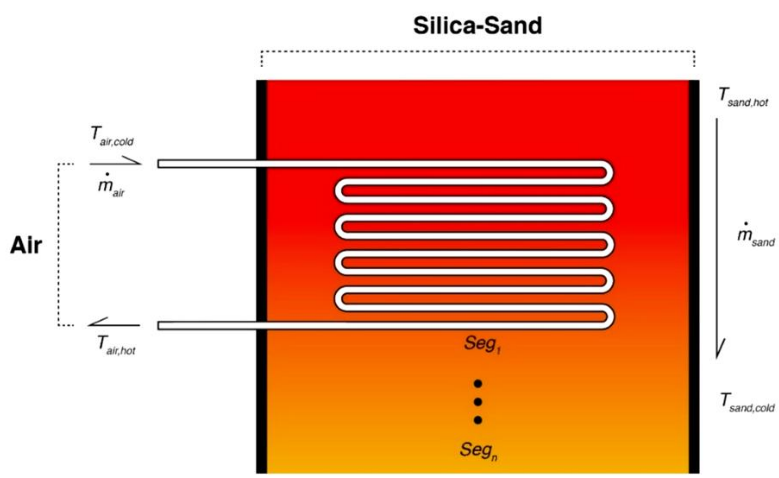

Figure 2 Silica sand storage tank with integrated heat exchanger.

The heat exchanger is configured in a crossflow geometry, with a mixed hot fluid (silica sand), and an unmixed cold fluid (air). To calculate the heat exchanged between fluids, an epsilon number of transfer units (ε -NTU) method is used [19].

For the sand particle mover, the hot silica sand is transported from the heater to the storage volume via a particle mover, which is assumed to work like an ideal vertical pump. This mover operates binarily: the sand is either being transported at constant volume flow rate, or it is inert. The mover power, P_{conv}, is calculated based on sand flow rate, $\dot{m}_{sand}$, and the mover efficiency, η_{conv}. The gravitational constant, g, and the height of the mover, L_{conv}, are given values.

This mover is also based on a similar flow application as CSP researchers at the National Laboratory of the Rockies, and therefore assumes the same efficiency [20].

$$P_{conv} = \dot{m}_{sand} g L_{conv} (\eta_{conv})^{-1} \tag{7}$$

For the air-water heat exchanger, the air-to-water boiler is calculated using a simple first law energy calculation. This method is employed at the air-to-water boiler as the air flow, water flow, energy transfer, and boiler efficiency are known.

2.3 Model Implementation

An initial parametric model created in EES produced nominal system conditions, which are used as inputs for the system and component models in Modelica. While EES produces an extremely course design condition, Modelica allows for dynamic simulation of components and systems.

In the Engineering Equation Solver, the equations outlined in this section are parameterized based on data from the local utility, and information found in literature review. Subsequent variables are calculated at their nominal conditions using the equations outlined in Section 2.2.

To solve the annual simulations with nominal operating conditions for each component, the system is implemented in the Modelica language, an open-source, equation-based, multi-domain modeling environment for dynamical systems. These nominal conditions create upper and lower bounds whereby the components and system are simulated to operate within. The implementation in Modelica provides the opportunity to simulate this complex model for longer durations, in this case one year.

2.4 Performance Evaluation

The case study simulations are evaluated based on four metrics: site and source energy use intensity (EUI), equivalent carbon emissions, and operational cost. Baseline carbon emissions for the natural gas boiler are the product of annual natural gas, provided by the utility, and an associated carbon emission factor, from the Greenhouse Gases Equivalencies Calculator by the Environmental Protection Agency [21]. The cost of electricity for the retrofit is the product of simulated power from the grid, and the billed cost of electricity based on the utility's pricing scheme [22].

$$CO_2e_{baseline} = gas_{kWh} \alpha_{CO_2EPA} (A_{site})^{-1} \tag{8}$$

The cost associated with the natural gas baseline is the annual sum of monthly statements provided by the utility. The cost associated with the fully electric case study scenarios, shown below in Equation (22), is the sum of the annual energy cost and monthly peak power cost. The energy cost, Eann, is priced at a flat rate per kWh, α, while the power cost, β, is priced monthly at a higher rate per kW, based on the peak power consumed in that month, $P_{peak,n}$.

$$Cost_{elec} = [\alpha E_{ann}] + \sum_{i}^{n=12} \beta P_{peak,n} \tag{9}$$

The energy use intensity is calculated in kWh per m2. The natural gas baseline energy consumption is given by the utility provider. Each case study's energy consumption is calculated in Modelica based on the annual net negative energy consumed by the plant model. All results are normalized based on the area of the buildings being served by the plant. Site and source EUIs are differentiated based on conversion factors from ASHRAE Standard 100-2015.

2.5 Model Implementation

For this paper, Modelica is employed to implement the designed system model. Modelica excels as an engine to model and simulate complex and heterogenous physical systems [23]. To produce component and system models that were replicable, this modeling effort is founded on the open-source Modelica Buildings Library (MBL) and Modelica Standard Library (MSL). The MBL and MSL are continually developed and tested by Lawrence Berkeley National Laboratory and the Modelica Association Project, respectively.

The system model incorporates all components from the system design in Section 2. Figure 3 shows the integration between each fluid loop via heat exchangers and movers. Energy and power consumption across each component is calculated accordingly. In Figure 3, the system schematic is implemented in Modelica. The Sand Con., Mover, and Air-to-Water Boiler components are new models, while all other components are sourced from MBL and MSL. The new Modelica models developed as part of this work are open-source released in the Sand Heating Library; further information regarding the new models is available [24]. In the sand heating plant model (Figure 3), the plant power is the sum of the heater power consumption, fan power consumption, and conveyor power consumption. The power draw is based on the heat and flow required to meet the flow rate of the feedwater and change in enthalpy from saturated liquid to vapor. The part load ratio from renewable sources is the difference between the total plant power draw and the available renewable energy.

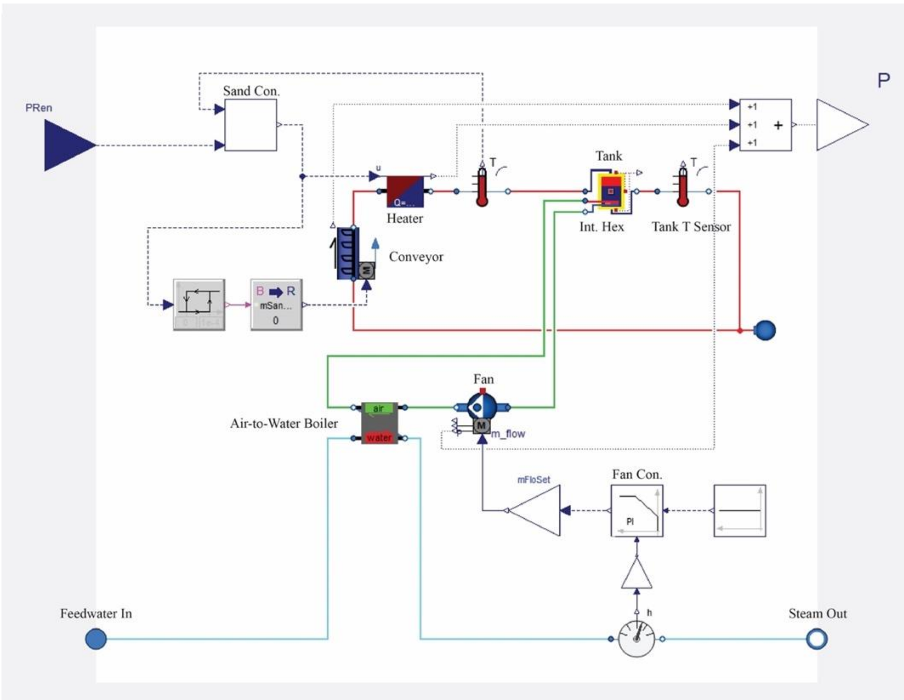

Figure 3 Modelica model diagram of sand heating plant system.

2.6 Case Study

The case study steam plant serves a community of six buildings. The name, building type, relative size, and peak heating load for each of these six buildings is provided below in Table 1.

Table 1 Buildings served by the steam plant.

Name	Building Type	Gross Area (m^2)	Peak Heating Load (kW)
Bldg 1	Residential	17,734	371.9
Bldg 2	Residential	17,732	398.9
Bldg 3	Mixed-Use	10,676	1055.3
Bldg 4	Residential	11,423	464.3
Bldg 5	Residential	23,173	826.0
Bldg 6	Residential	13,256	424.4
Total		93,994	3540.4

The nominal operational conditions for this system are calculated in EES. Water flow and enthalpy were known conditions from the steam plant. Additionally, the design boiler load was assumed to be the same as the current steam plant system. Therefore, the air flow and temperature were calculated to meet the current design steam conditions. The hot sand temperatures were sourced from available literature. Sand flow was then calculated such that it could heat the air to the required temperature for adequate steam production. Storage insulation was based on the volume hot sand required for adequate storage time, and height limitations at the case study site.

The scenarios explore the effect of different renewable energy capacity and increased energy storage from the renewable energy control. The results from each case scenario model are compared to operational data from the current natural gas boiler for one annual simulation. The four scenarios, and the breakdown of renewable contribution to the system, are shown below.

Table 2 Renewable energy capacity for each case study scenario.

	P_{PV} (kW)	P_{wind} (kW)
Scenario 1 (S1)	0	0
Scenario 2 (S2)	1.65 e3	0
Scenario 3 (S3)	1.65 e3	9.00 e2
Scenario 4 (S4)	3.30 e3	1.80 e3

3. Results and Discussion

The case study simulations are compared to the baseline steam plant data using four metrics: site and source EUI, carbon intensity, and operational costs. Figure 4 shows the site and source EUI results in kBtu per square foot. In every case study scenario, the site EUI outperforms the baseline. Scenario 4 uses the least site energy due to the increased renewable energy capacity, which returns electricity to the grid in summer months, and drastically reduces annual site electricity consumption. However, the baseline source EUI is lower than Scenario 1, and competitive with Scenarios 2 and 3. This is due to the lossy nature of electricity production and distribution, which is cited and incorporated into ASHRAE Standard 100-2015, the source used to calculate this metric.

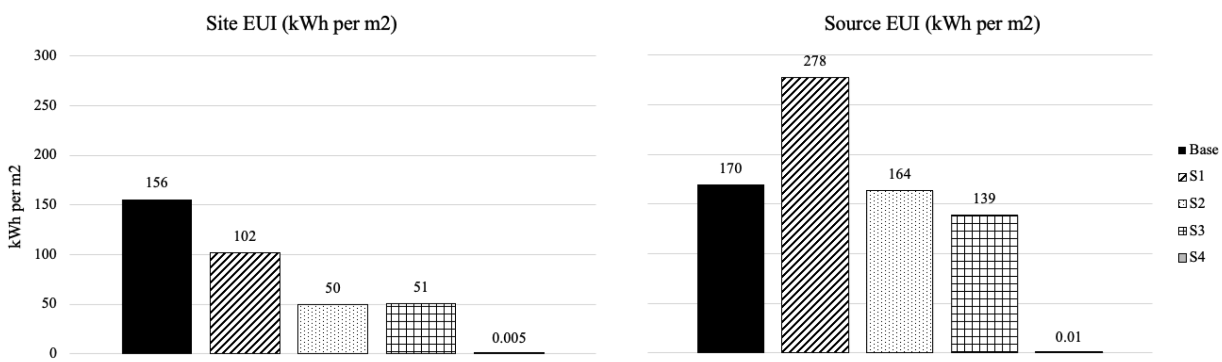

Figure 4 Site (left) and source (right) EUI results.

The Modelica model calculates carbon emissions using time-dependent carbon emissions associated with electricity consumption at a certain location in the USA. The carbon intensity results are shown below in Figure 5. Only Scenario 4 outperforms the baseline from a carbon intensity standpoint. This high carbon intensity is a consequence of the high emissions factor for the case study site, Denver, CO, in Cambium. The median annual Cambium factor in Denver is 10 times larger than the EPA's emission factor for electricity consumption. These high emissions in Cambium are due to the increased use of natural gas and coal for electricity production in Denver when compared to other parts of the country [25]. While this result is an accurate portrayal on the site of the case study, an identical plant design in another part of the country would likely have a far lower carbon intensity because of the cleaner grid portfolio.

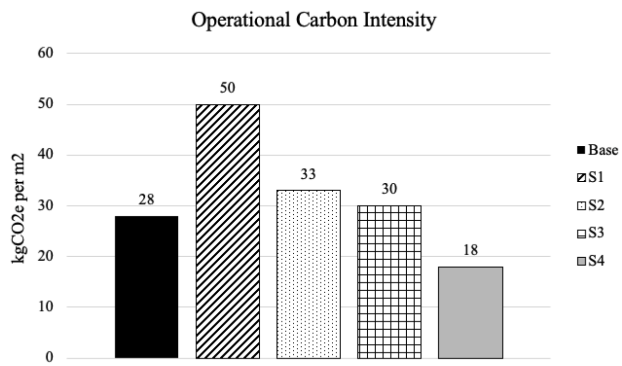

Figure 5 Operational carbon intensity results over an annual simulation period.

The cost of the baseline system is dwarfed by the cost of the proposed retrofit in Figure 6. This result, however, is influenced by several key assumptions from the utility provider. Firstly, the commercial cost of natural gas per kWh on-site for the case study has nearly doubled since the pricing data was sourced [26]. Also, the pricing scheme extracted from the utility provider is opaque and does itemize taxes or fees.

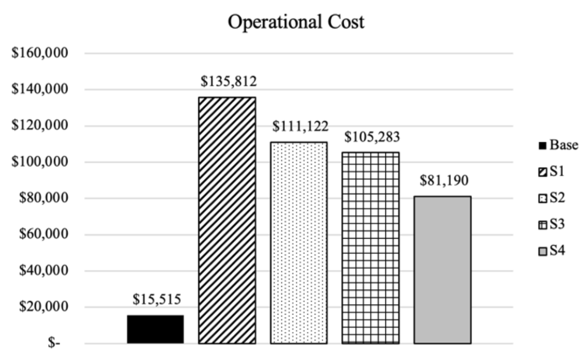

Figure 6 Operational cost of the case study scenarios over an annual simulation period.

The pricing schemes are calculated with appropriate and recent data, but it is difficult to identify potential additions in the cost of natural gas and potential deductions in the cost of electricity. Therefore, while the cost of natural gas and electricity are compared in USD per kWh, there is a higher potential for fees to be included in the cost of electricity, and lower potential for fees to be included in the cost of natural gas. Lastly, prices of natural gas can be up to three times more expensive than electricity per kWh in residential environments in Colorado.

4. Conclusion

In this paper, a novel silica sand thermal energy storage system is evaluated, designed, and tested in a building steam heating application. The case study results show that as renewable capacity increases, carbon consumption and EUI decrease, while electrifying steam production increases costs. The open-source Modelica models used in this study, both new and existing, show proof of successful simulation of saturated steam production using hot silica sand. However, these models require further pursuit in district steam environments for more accurate carbon and cost results. Finally, because these models can successfully simulate sand-to-steam production, they can and should be modeled down to test smaller communities than the one in this case study.

5. Acknowledgment

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6. Author Contributions

D.M. conducted the literature review, carried out the simulations, and wrote the manuscript with input from all authors. K.H. designed and coded the models that were used in simulations, contributed to the manuscript, and provided critical analytical input at all stages of the project. W.Z. helped scope and define the research question, guided the model design, and provided input during the data collection and manuscript drafting and revision phases. J.G. and Z.M. provided technical insight on the sand-based components, and aided in model design and manuscript revision.

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