Solar Radiant Floor and Sub-Surface Ground Heat Exchanger Thermal Storage System: Feasibility and Performance Assessment

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Abstract

Solar seasonal thermal energy storage (SSTES) has long been studied and implemented as a viable means of satisfying the thermal demands of both commercial and residential buildings. This paper introduces an SSTES system with the flexibility to direct thermal energy between a solar collector array, a hydronic radiant floor space heater, and/or a sub-surface ground heat exchanger storage medium, depending on the demands on and resources within the system. This SSTES system was modeled in TRNSYS, and the results demonstrated that the system balanced thermal storage charging and discharging over the year quite well, achieving a very high solar fraction (0.96). The SSTES system was then compared to five alternate space heating systems using conventional technologies such as boilers, air source heat pumps, and ground source heat pumps; while the COP of the SSTES system far exceeded the COP of any of the alternate conventional systems, the temperature control of the space was overall tighter for the conventional systems. Parametric studies of insulation thickness over the storage volume and solar collector array type were performed to assess the impact of these variables on system performance. Results demonstrated that both adequate insulation and quality solar collectors with some thermal loss protection (either via glazing or evacuated tubes) are necessary components of a high performance SSTES system.

Keywords: thermal storage, seasonal storage, space heating, solar heating

1. Introduction

A solar seasonal thermal energy storage (SSTES) system utilizes solar collectors to heat a fluid, phase-change material, or other thermal storage medium whenever sufficient solar radiation is available. With adequate production and storage capacity, the system can store enough solar energy in the peak solar summer months to offset or eliminate auxiliary thermal demands over the winter months. In recent years, research has focused transitioning the technology from large-scale (primarily commercial) to smaller-scale (primarily residential) applications, as well as on improving numerical modeling techniques for these systems.

Several studies in recent years have investigated proposed implementations of SSTES in smaller-scale applications, such as for single-family residences and smaller commercial buildings. Studies investigating using water as the thermal storage medium include Villasmil et al (2021), who compared alternative insulation materials and using building-integrated versus buried underground storage to cost-optimize installation of a hot-water tank and solar collector array system in a retrofit multifamily building. Their study ultimately concluded that external buried underground storage was more cost-effective for existing buildings than building-integrated storage, even after accounting for excavation costs and increased thermal losses. Pinamonti et al (2021) also studied using water tanks for seasonal thermal storage; their study integrating modulating water-water heat pumps into a solar system with a water tank for seasonal storage found that solar fraction was improved by approximately five percentage points by including the heat pumps, as compared to a reference system without the heat pumps.

While water is a viable thermal storage medium, most studies (including the current investigation) focus on sand, soil, and other common foundation and ground solids as the storage medium. Alkhalidi et al (2021) modeled a variation on solar thermal seasonal storage in which a composite thermal storage medium of sand, stone, and copper mesh was installed between the underground foundation pillars of a hypothetical four-story hotel. The system was modeled in three different climates, and the findings showed the systems' coverage of annual heat demand varied from 56% in a moderate climate (Potsdam, Germany) to 84% in a warm climate (Doha, Qatar). Using a fluidized rock bed as the storage medium, Sweet (2010) modeled SSTES radiant floor systems in six conceptual single-story houses in Richmond, VA, USA, ranging in size from 800 ft^2 (74.3 m^2) to 2400 ft^2 (223 m^2) to assess performance

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and optimal design parameters for a typical residence, such as storage bed size and solar collector area. The research found that, with 80% of the south-facing roof covered in solar collectors and an optimal storage bed size of 15 m3, the systems achieved comparable temperature profiles to homes without SSTES and satisfied 64%-77% of the annual heating demand.

Studies incorporating data gathered from implemented SSTES systems have also confirmed promising results. In the realm of water thermal storage systems, Meister and Beausoleil-Morrison (2021) reviewed long-term experimental results on a two-story research house in Ottawa, Canada that has long utilized a 36 m3 buried water tank for solar seasonal thermal storage and built a model simulation validated with the site data. By modeling simple improvements on the existing system, such as increased insulation and higher-performance solar collectors, their research demonstrated that solar fractions of 86%-100% were feasible. With regard to foundation and ground solids storage systems, Naranjo-Mendoza et al (2018a) and Naranjo-Mendoza et al (2019) ran several analyses of an installed system at a two-story, 70 m^2 floor area house in Leicester, UK, consisting of seven photovoltaic-thermal (PVT) collectors connected in series with an array of sixteen shallow (1.5-m deep) vertical boreholes. Using the vertical borehole array as an 'earth energy bank' for solar thermal storage for domestic heating, the experimental system performed well in offsetting the building's winter space heating needs after over one and a half years, resulting in a near net-zero building, though analysis did show that in addition to utilizing the energy stored from solar, heat extraction from the ground surrounding the storage contributed in part in meeting the building's energy demands. Hailu et al (2017) conducted a 14-week experimental study of an evacuated tube solar array and sand-bed thermal energy storage system at a home in Palmer, Alaska. The proof-of-concept study demonstrated excellent results, with sand-bed storage temperatures steadily increasing over the 14-week period in close agreement with system models, and it established sand-bed thermal storage as a viable option for regions with long periods of freezing temperatures. Following the initial study, Hailu et al (2019) revisited the system to conduct longer-term experiments and observations, presenting over a year of monitored data from the site. Comparison of site data to the authors' simulation models showed comparable to conservative performance estimates from the simulation model as compared to the site data, again asserting the viability of SSTES in cold climates.

With respect to modeling techniques, Naranjo-Mendoza et al (2018b) ran studies of sinusoidal, semi-infinite, and finite-difference method (FDM) models of soil temperatures at shallow depths (0.75-m to 2.75-m) compared to hourly measured data at a site in Leicester, UK. The results favored FDM with air temperature as a boundary condition as the most accurate modeling approach for both short- and long-term applications. Naranjo-Mendoza (2020) also showed preference for FDM as a faster and more accurate model than conventional infinite-line source and infinite cylindrical source analytical models for studying the thermal response of very shallow boreholes. Loveridge et al (2020) studied numerical modeling and field testing of a variety of geostructures for thermal storage. Sweet (2010) also studied models of an SSTES system in the ground with no load attached and found that the models reached steady state after 1.5 years to 5 years of simulation, with systems with high loss coefficients requiring longer to reach steady state operation than systems with lower loss coefficients.

Informed by this research and by prior modeling experience, this paper investigates a solar seasonal thermal storage system for a cold-climate warehouse. The heating system's components include an array of evacuated tube solar thermal collectors (the source), radiant floor heating in the warehouse (the load), and a modified horizontal ground heat exchanger in the building sub-surface (the thermal storage). An auxiliary boiler is integrated prior to the radiant floor supply to boost the supply temperature as needed. An innovative control algorithm balances the competing loads of the radiant floor and the underground storage, directing any solar resource available to its most effective load while also prioritizing discharging from underground storage over running the auxiliary boiler.

The current investigation models the ground using three-dimensional FDM models with building heat flux as the boundary condition between the soil and the building and a sinusoidal ambient air temperature as the soil boundary condition between the soil and the air. The coupling between the sub-surface soil model and the building model solves simultaneously for both boundary temperatures and heat flux between building and soil, meaning the integrated system is a function of the boundary temperature as well as the heat flux. The system is modeled for a three-year period, with steady-state behavior in the second and third year visually confirmed by temperature plots. All results are reported from the final twelve months of simulation.

2. Configuration of Radiant Floor and Sub-Surface SSTES System

The target building in the current investigation is a single-story, single-zone warehouse located in Calgary, Alberta, Canada. The warehouse has a footprint of about 464 m^2 and an overall air volume of just over 2,500 m^3. The building has no active cooling and is heated solely by a hydronic radiant floor heating system, which is comprised of a network of 28 parallel serpentine pipes evenly distributed within the warehouse floor. The warehouse thermostat maintains the space at 21 °C (± 0.55 °C) and calls for auxiliary if the space temperature drops below 19.5 °C. The minimum supply temperature set-point for the radiant floor system is 30 °C, or 33 °C if the thermostat calls for auxiliary heating. If the solar array and/or the ground thermal storage are insufficient to meet the heating demand, the system is modeled with an auxiliary boiler of infinite capacity and perfect thermal efficiency to maintain the minimum supply temperature set-points as specified. The circulation pump for the radiant floor only runs when the warehouse thermostat calls for heating.

The primary heat source of the system is an array of 60 fixed-position, evacuated tube solar thermal collectors in parallel, with a total collector surface area of 240 m^2. A variable-speed circulation pump for the solar array modulates speed as needed to maintain a desired set-point of 35 °C when the floor heating is active, or to maintain a temperature difference of 10 °C above the return temperature from the ground heat exchanger when the floor heating is inactive and the ground storage system is charging. The solar array pump will turn off if the collector array outlet temperature falls below the array inlet temperature.

The sub-surface ground directly beneath the warehouse provides thermal storage for the system. The storage volume's footprint matches that of the warehouse (464 m^2) and extends 2.25-m below the ground surface, for a total storage volume of 1,037 m^3. Within the storage volume, a system of 26 parallel serpentine pipes is buried in two layers about 0.8-m and 1.7-m, respectively, below the ground surface. The storage volume is insulated with 7.6-cm (3 inches) of insulation on the top surface and 31-cm (12 inches) of insulation on the bottom surface and its four vertical side surfaces. The system may charge the ground heat exchanger when the solar array outlet temperature exceeds the return temperature from the ground heat exchanger by 5 °C or more. Once the system is in charge mode, it remains in charge mode until the difference between the solar collector outlet temperature and the return temperature from the ground heat exchanger reduces to 2 °C or less. The system discharges to the radiant floor when the return temperature from the ground heat exchanger exceeds the return temperature from the building radiant floor by 1.66 °C. Once the system is in discharge mode, it remains in discharge mode until the difference between the ground heat exchanger temperature and the radiant floor return temperature reduces to 0.55 °C or less. A minimum run-time and minimum reset time of 15 minutes each are enforced by the model to prevent short cycling of the pumps. Table 1 below summarizes the equipment sizing of the investigated system.

Table 1. Equipment Specifications, Radiant Floor and Sub-Surface SSTES System

System Specifications		
Solar Collector System	**Value**	**Units**
Evacuated tube solar collection area	240	m^2
Solar array pump rated power	900	W
Solar array pump rated flow rate	3.78	$l.s^{-1}$
Warehouse and Radiant Floor System	**Value**	**Units**
Building footprint	464	m^2
Building volume	2.548	m^3
Building capacitance	30.582	kJ/K
Floor heating pump rated power	900	W
Floor heating pump rated flow rate	3.78	$l.s^{-1}$
Auxiliary heater capacity	Infinite	W
Auxiliary heater efficiency	100	%
Sub-Storage Ground HX System	**Value**	**Units**
Total ground storage volume	1.037	m^3
Ground storage footprint	464	m^2
Insulation thickness, top	0.076	m
Insulation thickness, sides and bottom	0.3048	m
Ground heat exchanger pump rated power	900	W
Ground heat exchanger pump rated flow rate	3.78	$l.s^{-1}$

3. Modeling and Controls of the Radiant Floor and Sub-Surface SSTES System

The warehouse building, solar collector array, and sub-surface ground storage system were all modeled as an integrated system within the TRNSYS transient system simulation software. The Type 56 multi-zone building model from the standard TRNSYS model library was used to model the warehouse and its radiant floor heating, and Types 1345 and 1268 from the TESS model library were used to model the solar collector array and sub-surface ground storage system, respectively.

Figure 1 through Fig. 3 depict the major flow paths and connections in the TRNSYS model, highlighting the following three primary flow paths for the thermal fluid: serving the space heating load from solar (Fig. 1), charging the sub-surface thermal storage from solar (Fig. 2), and discharging from the sub-surface thermal storage to serve the space heating load (Fig. 3). Note that these figures do not represent the complete or full expression of the TRNSYS model, as several piping, controls, and output components have been removed or hidden in these views for clarity.

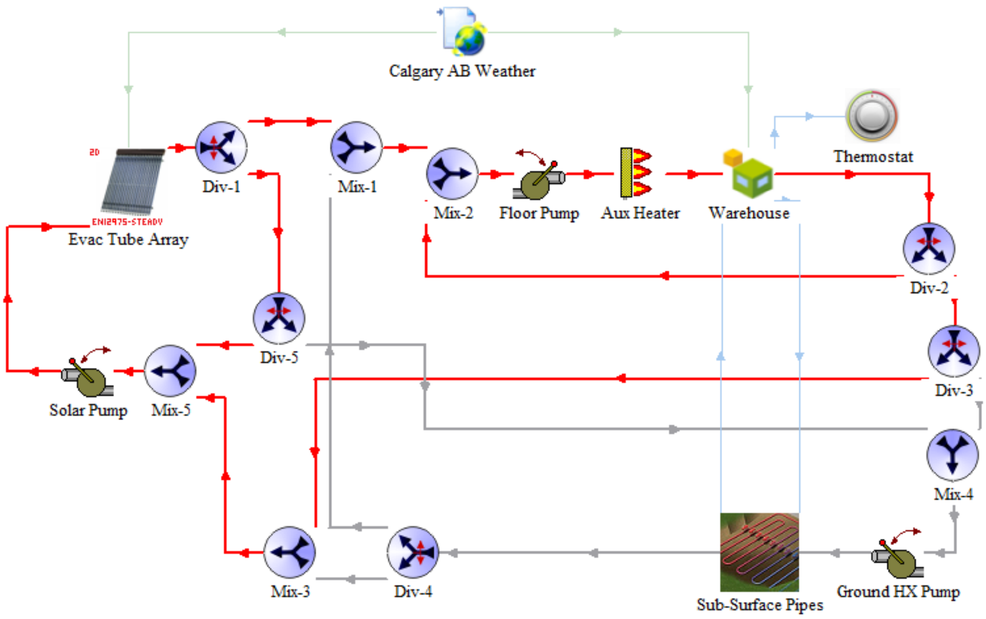

Fig. 1: TRNSYS model of radiant floor and sub-surface SSTES system, highlighting flow paths (in red) when the system is serving the space heating load from the solar array.

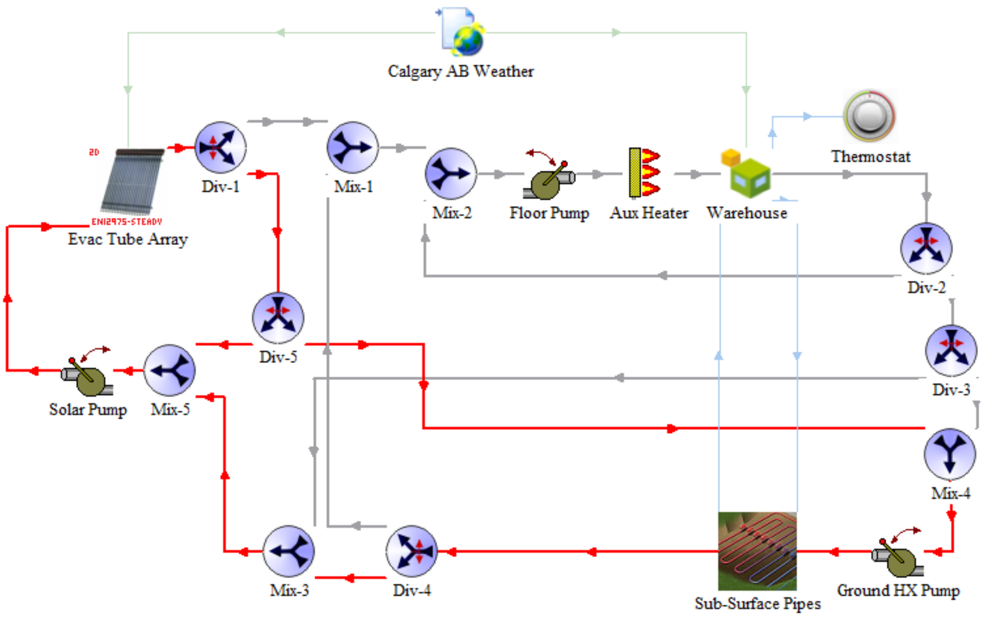

Fig. 2: TRNSYS model of radiant floor and sub-surface SSTES system, highlighting flow paths (in red) when the system is charging the sub-surface thermal storage from the solar array.

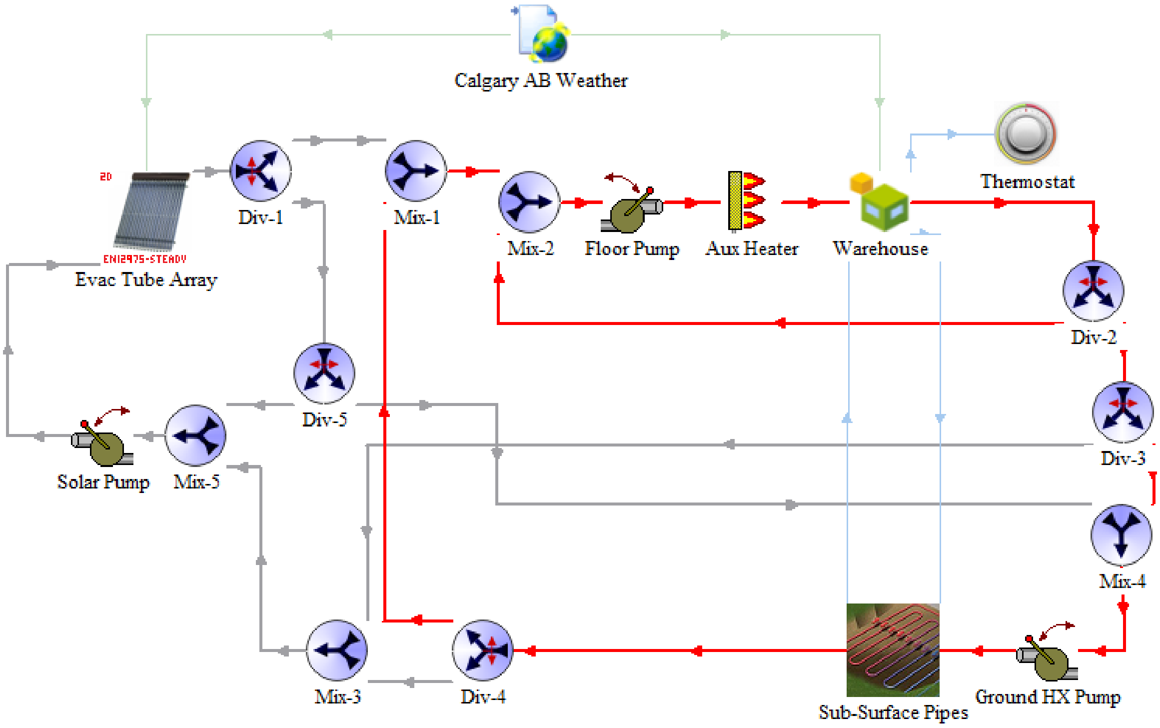

Fig. 3: TRNSYS model of radiant floor and sub-surface SSTES, highlighting flow paths (in red) when the system is discharging the sub-surface thermal storage to serve the space heating load.

In addition to the flow paths illustrated in the TRNSYS model screen captures in Fig. 1 through Fig. 3, the system may operate in some combination of these service modes; for example, the system may use the solar array to both serve the space heating load and charge the sub-surface thermal storage, or it may use both the solar array and discharge from the sub-surface thermal storage to serve the space heating load. In all, the controls algorithm allows the system to operate in any of the following eight 'modes,' depending on the solar resource available, the demand of the radiant floor, and the thermal balance in the ground storage system:

1. If the ground temperature is low, there is very good solar available, and the warehouse thermostat is not calling for heat, the system may send up to 100% of the fluid out of the solar array directly to the sub-surface ground heat exchanger for thermal storage.

2. If the ground temperature is high, there is very good solar available, and the warehouse thermostat calls for heat, the system will satisfy the thermal load of the radiant floor system from solar energy.

3. If the ground temperature is low, there is very good solar available, and the warehouse thermostat also calls for heat, the system will both satisfy the radiant floor load and charge the ground storage.

4. If there is no solar available, the warehouse thermostat calls for heat, and the ground temperature is high, the system will discharge from the ground storage to satisfy the radiant floor load.

5. If there is no solar available, the warehouse thermostat calls for heat, and the ground temperature is low, the system will run the radiant floor heat loop using only the auxiliary boiler for source heat, bypassing both the underground storage and the solar array.

6. If there is fair solar available, the warehouse thermostat calls for heat, and the ground temperature is neutral, the system will satisfy the thermal load of the radiant floor system from solar energy as much as possible.

7. If there is fair solar available, the warehouse thermostat calls for heat, and the ground temperature is low, the system will prioritize serving the radiant floor heat and use any additional thermal resource to charge the ground storage.

8. If there is very little solar available, the warehouse thermostat calls for heat, and the ground temperature is high, the system will use both solar and discharge from the underground storage to serve the radiant floor system.

Table 2 below summarizes the eight control modes available, as well as the general resource criteria and flow paths for each scenario.

Table 2. Control Mode Summary for Radiant Floor and Sub-Surface SSTES System

Scenario	Solar Resource	Underground State of Charge	Warehouse Call Heat?	Solar Flow	Flow to Floor?	Flow to Charge?	Flow to Discharge?
1	High	Low	No	High	No	Yes	No
2	High	High	Yes	High	Yes	No	No
3	High	Low	Yes	High	Yes	Yes	No
4	None	High	Yes	None	Yes	No	Yes
5	None	Low	Yes	None	Yes	No	No
6	Low	High	Yes	Low	Yes	No	No
7	Low	Low	Yes	Low	Yes	Yes	No
8	Low	High	Yes	Low	Yes	No	Yes

4. Comparable Alternate (Non-Solar Assisted) Heating System Configurations

To provide a reference point for performance metrics, the modeled radiant floor and sub-surface SSTES system was compared against models of the following five alternate warehouse space heating systems:

(a) Represents a conventional boiler-fed radiant floor heating system. The boiler is modeled as a theoretical heating source with infinite capacity and no thermal or conversion losses. The thermostat set-points, floor supply temperature set-points, and pump controls are the same as those described for the radiant floor and sub-surface SSTES system.

(b) Represents a 2-stage cold-climate air-source heat pump (CCASHP) system. The air-source heat pump modeled in this investigation is a Daikin 2-stage cold climate air source heat pump with a rated high-speed capacity and power draw of 175 kBtu/hr (51.3 kw) and 12.4 kW, respectively. The heat pump also has two auxiliary heat stages with rated capacities of 75 kW each. A three-stage thermostat commands the heat pump either at low speed, at high speed, or at high speed with auxiliary heat, depending on how long the building has been below the desired setpoint of 21 °C. The air conditioning feature of this heat pump is not used in this application.

(c) Represents the same radiant floor and sub-surface heat exchanger layout as the SSTES system, only the heating load is met from one of two water-water heat pumps (WWHP), using the sub-surface heat exchanger as the heating source. The two single-stage water-water heat pumps modeled are each Water Furnace Envision NDW180 units with a rated heated capacity and rated heating power of 222.7 kBtu/hr (65.3 Kw) and 13.6 kW, respectively. The units are staged by a 2-stage thermostat controller such that only one runs if the building temperature falls below 21 °C, but the second will turn on if the temperature falls below 20 °C. An auxiliary boiler runs as needed to maintain the supply temperature to the sub-surface and ground heat exchanger at or above -3.88 °C.

(d) Represents the same radiant floor and water-water heat pumps as system (c), only the system utilizes a conventional vertical ground heat exchanger as the heat source for the heat pumps. The vertical ground heat exchanger modeled here is a 20-borehole system with a bore depth of 100 meters, with insulation over the top surface of the borefield. In this system, without the size constraint of the building footprint, the ground heat exchanger may be sized as needed to adequately meet the building load.

(e) Same as system (d), only using a conventional horizontal ground heat exchanger instead of a vertical borefield ground heat exchanger. The horizontal heat exchanger is modeled as two layers of 50 pipes at 30.47 meters in length. The layers are buried at very shallow depths of 1-m and 2-m, respectively, and have no insulation surrounding the heat exchanger system.

For consistency, all systems model the building sub-surface with the same composition and thermal contacts as for the SSTES system; however, with the exception of system (c), there are no buried pipes in the ground and no actively managed energy exchange between the building and its sub-surface.

Figure 4 through Fig. 6 depict the TRNSYS models of these alternate systems and Table 3 summarizes key technologies and use of the ground use (if any) in the SSTES system and the five alternate modeled systems.

Table 3. Summary of Technology and Ground Use, SSTES versus Alternate Systems

	SSTES	Boiler *(a)*	CCASHP *(b)*	WWHP, sub-surf HX *(c)*	WWHP, vertical GHX *(d)*	WWHP, horizontal GHX *(e)*
Building heat conveyance	radiant floor	radiant floor	forced air	radiant floor	radiant floor	radiant floor
Primary heating technology	Evac tube solar	Boiler	Air-source heat pump	Water-water heat pumps	Water-water heat pumps	Water-water heat pumps
Auxiliary heating technology	Boiler	N/A	Heat pump auxiliary	Boiler	N/A	N/A
Heat pump source	N/A	N/A	Ambient air	Building sub-surface ground	Ground uncoupled from building	Ground uncoupled from building
Thermal storage	Horizontal ground heat exchangers	N/A	N/A	Horizontal ground heat exchangers	Vertical ground heat exchanger	Horizontal ground heat exchanger
Thermal storage location	Building sub-surface ground	N/A	N/A	Building sub-surface ground	Ground uncoupled from building	Ground uncoupled from building

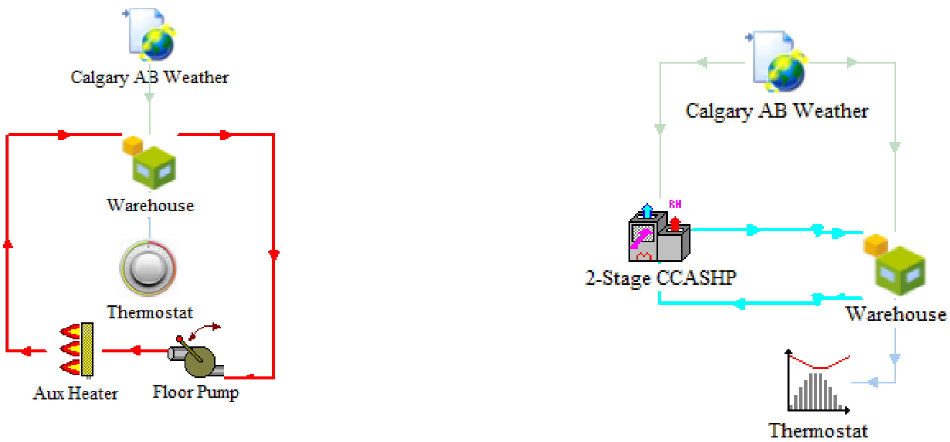

Fig.1: TRNSYS models of conventional boiler-fed radiant floor heating system *(a)* and conventional 2-stage cold-climate air-source heat pump *(b)*.

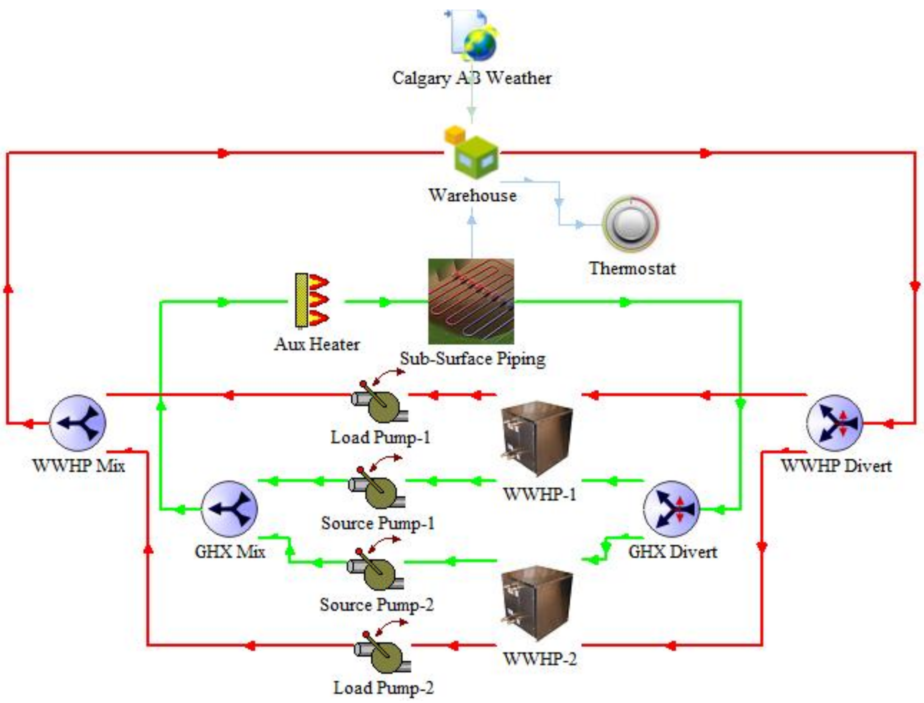

Fig. 5: TRNSYS model of conventional water-water heat pump heating system using the sub-surface ground as the heat source (c).

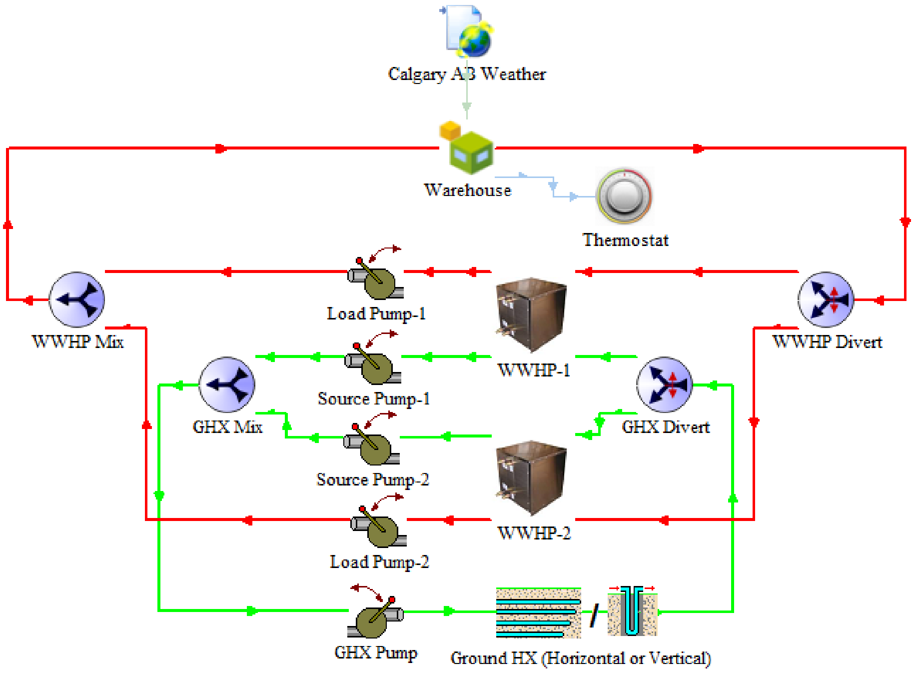

Fig. 6: TRNSYS model of conventional dual water-water heat pump heating system, using either a vertical (d) or horizontal (e) ground heat exchanger as the heat source.

5. Simulation Results

5.1. Thermal Delivery, Power Consumption, and Coefficients of Performance

Table 2 compares the net thermal energy delivery of the SSTES system and each of the five alternate heating systems, including equipment gains to load and net thermal exchange with the farfield ground (if applicable). All annual values represent totals from the last twelve months of the three-year simulation.

Table 2. Thermal Energy Delivery, By System

	Thermal energy delivered [MWh/yr]					
Gains To Load	SSTES	Boiler	CCASHP	WWHP – sub-surf HX	WWHP – vertical GHX	WWHP – horizontal GHX
Solar Array	114.93	-	-	-	-	-
Boiler	4.00	86.31	-	15.59	-	-
CCASHP - heat pump	-	-	64.72	-	-	-
CCASHP- auxiliary	-	-	13.05	-	-	-
WWHP 1	-	-	-	85.49	79.72	76.73
WWHP 2	-	-	-	7.89	5.26	6.10
System pumps (all)	1.63	0.38	-	-	-	-
Total:	**120.55**	**86.69**	**77.77**	**108.98**	**84.99**	**82.84**
Exchange With Surroundings	SSTES	Boiler	CCASHP	WWHP – sub-surf HX	WWHP – vertical GHX	WWHP – horizontal GHX
System piping (all)	-19.52	-0.89	-	3.46	2.74	7.25
From ground farfield	-0.01	-	-	-	26.42	38.48
Total:	**-19.53**	**-0.89**	**0.00**	**3.46**	**29.16**	**45.73**
Net Total:	**101.02**	**85.80**	**77.77**	**112.43**	**114.14**	**128.56**

As shown in Table 4, the net thermal gain of the systems modeled varies from 77 to 128 MWh/yr, with the SSTES representing the middle of the range. With only 4.00 MWh/year of thermal energy supplied from the boiler in the SSTES system, the solar fraction for the SSTES system is 0.96, or near net-zero thermal system performance over the year. The SSTES loses about 19.5 MWh/yr to the surroundings, or about 17% of its net gains from the solar collector array, though very little of this is due to leakage from the ground storage volume to the farfield ground.

Note that the alternate ground-source water-water heat pump systems (d) – (e) draw net energy from the farfield ground of 26 to 38 MWh/yr, with the less-insulated and shallower horizontal GHX system drawing almost 50% more energy from the farfield as compared to the deeper vertical GHX system with surface insulation. Net draws of this magnitude from the farfield suggest the systems would be unsustainable over several years of operation without better insulation or ground use design. Also note that the alternate system with the sub-surface ground source (c) required 15.59 MWh/year from the auxiliary boiler to maintain the ground temperature, or almost one-fifth of the auxiliary boiler's annual energy use when meeting the radiant load directly.

Table 5 compares the power consumption of the SSTES and the alternate systems by equipment, as well as the overall coefficient of performance (COP) of each system.

Table 3. Power Consumption and COP, By System

	Power consumption of system [MWh/yr]					
Equipment	SSTES	Boiler	CCASHP	WWHP – sub-surf HX	WWHP – vertical GHX	WWHP – horizontal GHX
Solar array pump	1.18	-	-	-	-	-
Floor heating pump	2.06	1.26	-	-	-	-
Ground HX pump	2.19	-	-	-	0.00*	0.00*
Boiler	4.00	86.31	-	15.59	-	-
CCASHP - compressor	-	-	17.17	-	-	-
CCASHP - fans	-	-	4.89	-	-	-
CCASHP - auxiliary	-	-	13.05	-	-	-
WWHP1	-	-	-	34.38	29.95	30.19
WWHP2	-	-	-	3.79	2.43	2.95
WW Source Pump 1	-	-	-	1.31	1.11	1.13
WW Source Pump 2	-	-	-	0.13	0.08	0.10
WW Load Pump 1	-	-	-	1.31	1.11	1.13
WW Load Pump 2	-	-	-	0.13	0.08	0.10
Total:	**9.42**	**87.57**	**35.11**	**56.65**	**34.76**	**35.60**
Thermal to load (from Table 4)	101.02	85.80	77.77	108.98	84.99	82.84
COP, system:	**10.73**	**0.98**	**2.21**	**1.92**	**2.44**	**2.33**

**The ground HX pump was modeled with a rated power of 0 W in these systems.*

Total auxiliary and parasitic power consumption for the SSTES system are 9.42 MWh/year, including the auxiliary boiler, solar field pump, floor heat pump, and ground heat exchanger pump. The SSTES system obtains a coefficient of performance of 10.7 as compared to the net thermal energy delivered by the SSTES system, or 9.1 as compared to the thermal energy delivered by the conventional boiler system (the nearest directly comparable system). In other words, the SSTES system returns 9.1-10.7 MWh of thermal energy for every MWh of energy consumed to operate the system. Compare this to the COPs of the five alternate systems, which range from 0.98 for the auxiliary boiler system to 2.44 for the water-water heat pump system with the vertical borefield ground source, the best of the four heat pump-powered systems.

5.2. Solar Ground Storage Charge, Discharge, and Net Storage

The ultimate goal of the SSTES design is to store solar heat when it is seasonally available and use it over the rest of the year to offset or eliminate auxiliary heating from fossil fuel sources. Fig. *2* shows the net energy stored in (or discharged from) the radiant floor and sub-surface SSTES system, by month, over the last 12 months of the simulation.

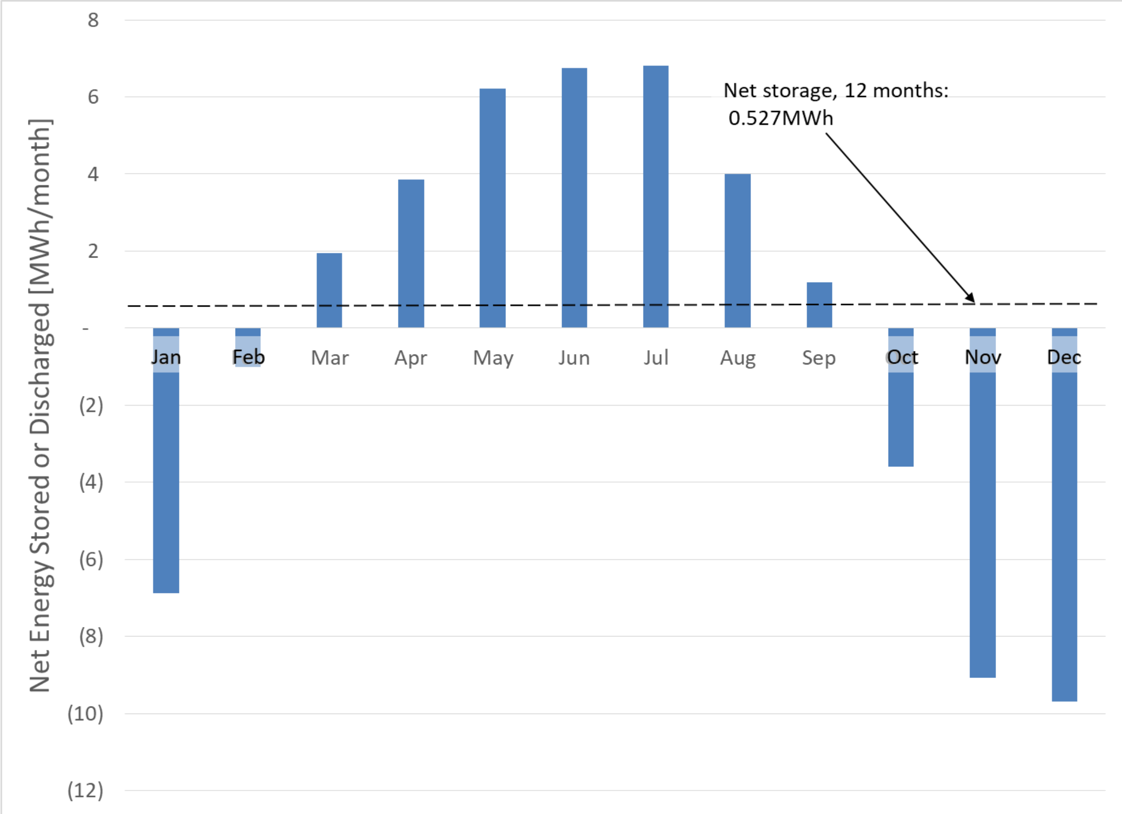

Fig. 2: Net energy stored or discharged by SSTES system, by month

5.3. Temperature Control

All six systems had a desired space heating set-point of 21 °C (± 0.55 °C). Table 4 compares the performance of the six systems in satisfying the space heating set-point over the year. With respect to temperatures well above set-point, recall that the building has no active cooling and some 'float' above set-point is expected, especially in the summer months.

Table 4. Annual Hours By Temperature Bin At, Above, or Below Set-Point, By System

Hours	SSTES	Boiler	CCASHP	WWHP – sub-surf HX	WWHP – vertical GHX	WWHP – horizontal GHX
Above 23.5°C	38%	25%	8%	23%	24%	25%
23.5°C to 22.5°C	11%	15%	5%	13%	15%	14%
22.5°C to 21.556°C	13%	26%	7%	18%	19%	19%
21.556°C to 20.444°C	**21%**	**32%**	**78%**	**36%**	**35%**	**34%**
20.444°C to 19.5°C	9%	2%	1%	10%	7%	8%
19.5°C to 18.5°C	4%	0%	0%	1%	0%	0%
Below 18.5°C	3%	0%	0%	0%	0%	0%

As evidenced in Table 4, the cold-climate air source heat pump (CCASHP) system provided noticeably tighter temperature control than either the SSTES or any of the alternate systems, maintaining a temperature range between 21.556 °C and 20.444 °C for over 78% of the year and only falling below 20.444 °C for about 1% of the year. It is the only system of those studied that did not use the radiant floor for space heating, and it is also the only system for which the space was above 22.5 °C for only 13% of the year, as compared to 49% for the SSTES system and 36%-40% for the other alternate systems. This observation suggests the radiant floor system, regardless of its heat source, cannot be as thermally responsive as the CCASHP system and favors overheating in this application. The boiler system and the three water-water heat pump systems all performed comparably to each other in satisfying the space, though the boiler-fed radiant floor system did not under-heat nearly as often as the three water-water heat pump systems. The SSTES system maintains the space within the desired range only 21% of the year, is overheated 62% of the year, and is under-heated 16% of the year. Notably, it is also the only system that ever falls below 18.5 °C and one of only two systems out of the six that ever falls below 19.5 °C.

5.4. Effects of Insulation and Collector Technology on Radiant Floor and Sub-Surface SSTES System

Modeling of the baseline radiant floor and sub-surface SSTES system began with best-practice or best-available technologies to the extent possible, including using an evacuated tube array for the solar field and very good insulation on all sides of the thermal storage medium. To assess the impact of these design choices on the performance of the system, the baseline SSTES model was compared against models with the following design adaptations:

1) Double the baseline insulation is applied on the six surfaces of the thermal storage volume.
2) Half the baseline insulation is applied on the six surfaces of the thermal storage volume.
3) A glazed flat plate array of the same area is substituted for the evacuated tube array.
4) An unglazed flat plate array of the same area is substituted for the evacuated tube array.

Table 5 compares the net thermal energy delivered and power consumed in the baseline SSTES system and in the four design-adapted systems.

Table 5. SSTES Thermal Delivery and Power Consumption vs Insulation and Collector Type

	Thermal energy delivered to system [MWh/yr]				
Equipment	SSTES - baseline	SSTES – double insul	SSTES – half insul	SSTES – glazed FP	SSTES – unglazed FP
Solar Field	114.93	110.44	119.56	121.75	18.92
Boiler	4.00	0.17	11.13	24.70	76.79
Total:	**118.92**	**110.60**	**130.69**	**146.45**	**95.71**
	Power consumption of system [MWh/yr]				
Equipment	SSTES - baseline	SSTES – double insul	SSTES – half insul	SSTES – glazed FP	SSTES – unglazed FP
Solar array pump	1.18	1.13	1.23	0.66	0.08
Floor heating pump	2.06	2.02	2.14	0.82	1.41
Ground HX pump	2.19	1.77	2.43	0.97	0.08
Boiler	4.00	0.17	11.13	24.70	76.79
Total:	**9.42**	**5.08**	**16.93**	**27.14**	**78.37**

As shown in Table 5, increasing the insulation to twice its baseline value decreased auxiliary boiler use by more than 95%, from 4 MWh/year to only 0.17 MWh/year, and reduced parasitic pump power use by about 10% as well. When the insulation was decreased by half from its baseline value, the overall parasitic pump power use increased by about 7%, and the auxiliary boiler use increased over 275%, from 4 MWh/yr to over 11 MWh/yr. The results demonstrate the magnitude by which insulation affects the auxiliary support required to meet the same heating load. Adequate insulation surrounding the storage volume, therefore, must be part of the optimal SSTES system. Both the glazed flat plate collector system and the unglazed flat plate collector system underperformed as compared to the baseline evacuated tube collector system, with the glazed flat plate system and the unglazed flat plate system requiring about 600% and 1900% more auxiliary boiler use, respectively, than the baseline system. The glazed flat plate collector modeled has higher efficiency at lower temperatures as compared to the evacuated tube collector, but also higher thermal losses as the collector temperature rises above the ambient air temperature, as well as a very different incidence angle modification (IAM) profile, making it somewhat difficult in the absence of a full simulation to anticipate which collector will perform better overall in different scenarios. In this case, it appears the evacuated tube collector system is preferable for thermal performance to the glazed flat plate collector system, though the glazed flat plate system may be more cost-effective once capital costs are considered. The unglazed flat plate array performed poorly.

6. Conclusions

A solar seasonal thermal energy storage (SSTES) system consisting of a solar collector array, a hydronic radiant floor space heater, and a sub-surface ground heat exchanger, has been demonstrated via simulation to successfully balance thermal storage charging and discharging over the year for a warehouse in a cold climate, achieving a very high solar fraction (0.96). Comparison of the SSTES system to alternate conventional systems showed some trade-off between system COP and temperature control of the space, with the excellent COP of the SSTES system coming at the cost of a somewhat wider temperature range in the conditioned space over the year. For applications with loose to moderate temperature control requirements (such as the lightly-occupied warehouse of this investigation), this may be more than adequate; further investigation is needed to assess the extent to which temperature control may be improved. Modeling different insulation thicknesses and solar collector array types demonstrated that both adequate insulation and quality solar collectors with some thermal loss protection (either via glazing or evacuated tubes) are necessary components of a high performance SSTES system.

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9. List of Acronyms

CCASHP	cold-climate air-source heat pump	**PVT**	photovoltaic-thermal
FDM	finite-difference method	**SSTES**	solar seasonal thermal energy storage
GHX	ground heat exchanger	**WWHP**	water to water heat pump