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Seasonal Solar Energy Storage System for Space Heating in Cold Climate

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Abstract

A seasonal solar energy storage system for space heating in cold climates is proposed. The system includes evacuated tube solar collectors integrated with double U-tube vertical borehole thermal storage coupled with a heat pump. The performance of the system is evaluated by computer simulations for a cluster of typical houses in four Asia-pacific cities: Ulaanbaatar (Mongolia), Harbin (China), Dras (India) and Lukla (Nepal). TRNSYS, a transient systems simulation program, was used to simulate the system. The typical detached house model for each city was developed based on the type of dwelling. The initial sizes of the system components were determined for the four cities. The average ground temperatures and energy balance of the system during charging and discharging modes were investigated. The seasonal heating coefficient of performance of the system in each city has been presented. The simple payback period (*SPBP*) of the proposed system was investigated by comparing convention system. It was found that the proposed system has the potential for fulfilling the space heating demand in cold climate cities of Asia-Pacific region.

Keywords: Solar energy, Space heating, Typical house, Cold climate

1. Introduction

As both the number of households and floor area increases in cold climate zones, space heating demand in the residential building sector grows rapidly (Ürge-Vorsatz et al. 2015). To meet the space heating demand, the seasonal solar energy storage (SSES) system has been introduced. In an SSES system, the solar energy available in summer is stored and used during winter. The SSES system is reported to be more energy efficient than the traditional ground source heat pump (GSHP) system for space heating applications. Furthermore, the borehole thermal energy storage (BTES) coupled with heat pump and evacuated tube solar collectors (ETSC) can enhance the utilisation of solar energy. However, adoption of SSES systems depends on the system performance and financial viability, which, in turn, are determined by the design and scale of the application. Multiple buildings application of SSES system integrated with a heat pump (HP) and solar collectors (SC) is financially cheaper than the single building application (Lhendup 2013). The double U-tube borehole heat exchanger (BHE) with GSHP and SCs system has been examined by several researchers (Cimmino and Eslami-Nejad 2016; Aydin and Sisman 2015). However, research studies done on double U-tube BHE applied various types of solar collectors except ETSC. Although BTES with GSHP and solar collectors system computer models have been verified and validated in other countries or climate zones, the results cannot be directly applied to all cold climate regions due to climate sensitivity (Lhendup 2013).

Therefore, this study focuses on four cities of cold climate zones in Asia-Pacific region, where investigations on the SSES system has taken less attention by researcher up to now. Ulaanbaatar (the coldest capital city in the world), Dras (the second coldest city in the world), Lukla (Nepal high altitude location), and Harbin (cold southern city of China) were selected for this study. Figure 1 shows the annual variations of ambient air temperature for the locations chosen. These locations require almost entire year-round space heating except few months. This study investigates the performance of SSES system in these cities based on the simulated heating demands of houses.

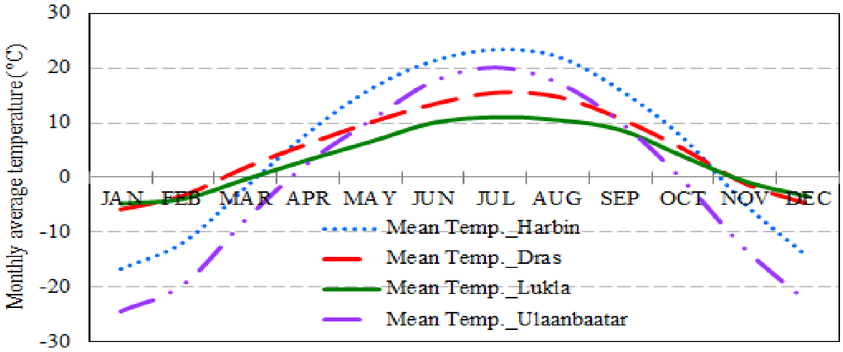

Figure 1: Monthly average annual ambient air temperature

2. Method

The main components of SSES system are solar collectors, borehole heat exchanger, and heat pump. The concept of SSES system with multi-buildings is shown in Figure 2. For multi-building applications, water-to-water heat pumps are more suitable since hot water can be distributed to the houses easily. In this study, a cluster of 30 houses was considered and assumed each house has fan coil units which can be individually controlled. Furthermore, the charging loop includes ETSCs and a circulation pump.

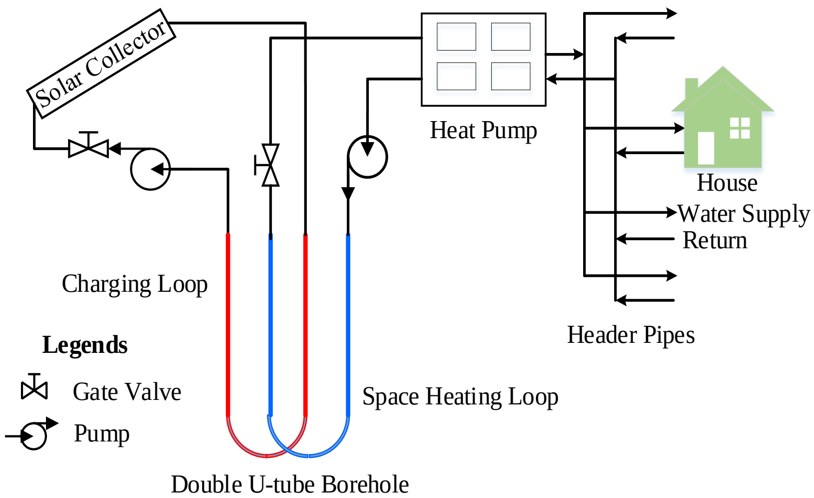

Figure 2: Concept of seasonal solar energy storage system with a cluster of houses

2.1 System sizing equations

The total area of solar collectors ($A_{col,}$ m^2) required for heat charging was determined by using Eq. (1).

$$A_{col} = Q_{solar} / (365 H_t \eta_{col}) \tag{1}$$

where Q_{solar} is the annual energy supplied by the solar collectors (MJ), H_t is the average daily solar radiation per unit area (MJ m^{-2} d^{-1}), and η_{col} is the solar collector efficiency. Q_{solar} in Eq. (4) is derived from Eq. (2) and (3).

$$Q_{solar} = Q_{heat} - W_{comp} + Q_{loss} \tag{2}$$

$$W_{comp} = Q_{heat} / SHCOP \tag{3}$$

$$Q_{solar} = Q_{heat}\left(1 - \frac{1}{SHCOP}\right) + Q_{loss} \tag{4}$$

Q_{heat} is the total heat supplied to the houses (MJ), W_{comp} is the heat pump compressor work input (MJ), Q_{loss} refers to heat losses at the ground and *SHCOP* is the seasonal compressor heating coefficient of performance. Heat losses were assumed to be negligible since low temperature storage system are considered This assumption has been justified by showing the long term ground temperature variation (Figure 5 and Table 4) in Section 3.3.

To determine the solar collector efficiency (η_{col}) the initial fluid temperate (T_i) and ambient temperature (T_a) in Eq. (5) (Zambolin and Del Col 2010) were used.

$$\eta_{col} = F_R(\tau\alpha) - F_R U_L (T_i - T_a)/G_t \tag{5}$$

where $F_R(\tau\alpha)$ and $F_R U_L$ refers to the intercept (or the optical efficiency) and the slope of the efficiency curve respectively. To determine the designed heat pump capacity, the method reported in (Lhendup 2013) was applied. The heat pump capacity ratio *Cap* (%) by using Eq. (6) and energy delivered ratio *Ene* (%) by using Eq. (7) (Banks 2012) were estimated.

$$Cap\ (\%) = \frac{\text{Rated output of HP}}{\text{Peak heating demand}} \times 100 \tag{6}$$

$$Ene\ (\%) = \frac{\text{Total heating supplied}}{\text{Total heating demand}} \times 100 \tag{7}$$

The length of the borehole ($L_{BHE,}$ m) for double U-tube SSES system were determined by using Eq. (8) and Eq. (9) (Sailer, Taborda, and Keirstead 2015).

$$L_{BHE} = P_{ground} / (N_{tot} \times P_{BHE}) \tag{8}$$

$$P_{ground} = q_{hp}\left(1 - \frac{1}{SHCOP}\right) \tag{9}$$

where N_{tot} is the total number of boreholes, P_{BHE} is specific heat extraction rate (W per borehole), P_{ground} is the rate of heat to be extracted from the ground (W), and q_{hp} refers to total heat pump capacity (W). *SHCOP* is the seasonal compressor heating coefficient of heat pump.

2.2 Weather data and the building simulated

The daily average solar radiations on the horizontal plane are 18.9, 18.1, 24, and 23.9 MJ m^{-2} a^{-1} for Ulaanbaatar (47.93N, 106.9E), Harbin (45.75N, 126.65E), Dras (34.43N, 75.75E), and Lukla (27.68N, 86.73E) respectively. The house dimensions and envelop characteristics for each location were selected based on the typical local detached house reported in the available literature for Ulaanbaatar (Bohuslav, Petr, and Klkra 2013), Harbin (Qu 2009), Dras (Bhat et al. 2009) and Lukla (Fuller, Zahnd, and Thakuri 2009). The total heated areas of 30 houses are 1806, 2086, 1833, and 1673 m^2 for Ulaanbaatar, Harbin, Dras, and Lukla respectively. To determine the annual heating load (Q_H) of the house, Eq. (10) (where Δt is an hour time interval) was used.

$$Q_H = \sum_{1}^{8760} \dot{Q}_H \Delta t \tag{10}$$

2.3 TRNSYS model

A validated TRNSYS project developed by (Lhendup 2013) for multi-building applications was employed. All relevant parameters of the existing TRNSYS project were changed to reflect the selected cities. In the TRNSYS project, the main components are ground heat exchanger (double U-tube borehole), ETSC, heat pump, circulation pump and building. Type 257a, Type 1228, Type 927 were used for the borehole heat exchanger, ETSCs and the heat pump respectively. The TMY weather data files generated by Meteonorm Software (Remund et al. 2016) were based on 1991-2010 for solar radiations and 2000-2009 for dry bulb and wet bulb temperatures.

2.4 System parameters, energy balances, and performance

The parameters for borehole heat exchanger, solar collectors, and heat carrier fluid of SSES system for all locations are presented in Table 1 and Table 2. The thermostat settings for the houses were assumed to be 18 °C during the day and the 16 °C night setback. The night set back times were based on the local sleeping schedule of each city as shown in Table 2. To avoid freezing, water with 35% propylene glycol solution (the heat transfer fluid) which freezes below -18 °C is applied.

Table 1: Common parameters for the seasonal solar energy storage system

Parameter	Value	Parameter	Value
Borehole depth (m)	40	Outside diameter of U-tube (mm)	25.0
Distance between the borehole (m)	8	Thermal conductivity of pipe (W $m^{-1}K^{-1}$)	1.4
Diameter of borehole (mm)	115	U-tube centre to centre distance (mm)	75
No of borehole in a series (-)	6	Density 35% glycol water solu^{n}. (kg m^{-3})	1032
Number of U-tube per borehole (-)	2	Specific heat of the fluid (kJ $kg^{-1}K^{-1}$)	3.7
Inside diameter of U-tube (mm)	21.3	Assumed initial collector efficiency (%)	50

The energy balance of the system was investigated by using Eq. (11) based on law of conservation of energy.

$$Q_{solar} + W_{comp} + Q_{gain} = Q_{heat} + Q_{loss} + \Delta Q_{store} \text{ where } Q_{net\ gain} = Q_{gain} - Q_{loss} \tag{11}$$

where Q_{gain} is the natural heat gain from the surrounding of the ground and ΔQ_{store} is the amount of heat store in between years. Further, the energy efficiency of SSES system can be expressed by the system coefficient of performance (COP_{sys}) and seasonal heating COP of the compressor (*SHCOP*). Eq. (12) and Eq. (13) were used to calculate these system performance parameters.

$$SHCOP = Q_{heat} / W_{comp} \tag{12}$$

$$COP_{sys} = Q_{heat} \Big/ \left(W_{comp} + W_{pump} + W_{fan} \right) \tag{13}$$

where *W* refers to the energy consumed by components. Subscripts: *comp* = heat pump compressor, *pump* = circulations pumps, and *fan* = fans.

Table 2: Location specific parameters for the system simulated

Parameter ↓ \ Location →	Ulaanbaatar	Harbin	Dras	Lukla
Reference surface temperature of ground (°C)	-0.69	5.49	5.29	3.45
Thermal conductivity of ground (kJ $hr^{-1}m^{-1}K^{-1}$)	6.98	6.05	5.54	12.96
Specific heat of ground (kJ $kg^{-1}K^{-1}$)	1.04	1.34	1.09	0.82
Density of ground (kg m^{-3})	1730	1400	1380	1900
Air temperature phase delay to peak (day)	255	257	245	255
Sleeping schedule, begin	23:30	23:50	21:30	21:45
Sleeping schedule, end	06:30	07:20	05:00	05:45

2.5 *Simple payback period analysis*

The simple payback periods (*SPBP*) of the SSES system are determined by using Eq. (14).

$$SPBP = IC_{SSES} / (OC_{SSES} - OC_{conv}) \tag{14}$$

where the initial cost (IC_{SSES}) includes the cost of each system component (ETSC, HP, BHE, and heat distribution network), OC_{SSES} is the annual operational cost of the SSES and OC_{conv} is the annual operational cost of the existing conventional system. Table 3 shows these costs for each climate zone and the data applied. The 10 % assumption was made for ETSC and BHE as transportation cost from China to Mongolia and India to Nepal.

Table 3: Prices and other parameters used in estimating *SPBP*

Item (unit)↓\Location→	Ulaanbaatar	Dras	Lukla	Harbin
Exchange rate (US$$^{-1}$)	2442.83 MNT (XE 2017)	64.73 INR (XE 2017)	103.51 NPR (XE 2017)	6.58 RMB (XE 2017)
ETSC (US$ m^{-2})	68*	41 (Sarkhej 2017)	72 (HK 2017)	62 (Vision 2017)
BHE (US$ m^{-1})	23*	20 (Information 2017)	22#	21 (Yu & Cheng 2015)
GCHP (US$ kW^{-1})	292 (Lhendup 2013)	292 (Lhendup 2013)	292 (Lhendup 2013)	292 (Lhendup 2013)
Electricity (US$ kWh^{-1})	0.045 (Travel 2017)	0.047 (JKSERC 2016)	0.079 (Himalayan 2015)	0.086 (Travel 2017)
Fuel (US$ kg^{-1})	0.042 (World-Bank 2009)	0.029 (Divisional 2011)	0.097 (Kanel et al. 2012)	0.03× (Mendes et al. 2014)
Heating efficiency (%)	30.0 (Fuller et al. 2009)	24.7 (Tripathi 2017)	30.0 (Fuller et al. 2009)	55.0 (ADB 2017)
Heating value (MJ kg^{-1})	14.70 (World-Bank 2009)	16.97 (Tripathi 2017)	15.00 (Fuller et al. 2009)	-

*Assume 10% more than Harbin; #Assume 10% more than Dras; ×Unit of Gas price (US$ kWh^{-1})

In this study, coal burned stove (World-Bank 2009), wood fuel stove (Docplayer 2011) and smokeless metal stove (Fuller, Zahnd, and Thakuri 2009) and gas powered heating system (Zhai et al. 2011) were selected for Ulaanbaatar, Dras, Lukla and Harbin respectively. The annual consumption of coal or wood (m_f, kg) was determined by using Eq. (15).

$$m_f = Q_{heat} / (HV \eta_{heating}) \tag{15}$$

where *HV* is the heating value of the fuel used and $\eta_{heating}$ (-) is the efficiency of heating.

3. Results

3.1 Space heating loads

Figure 3 shows the space heating loads for a cluster of 30 houses in the selected cities. Dras and Lukla require almost year-round space heating due to low ambient air temperature throughout the year. The annual heating loads per unit floor area were found to be 1.48, 1.18, 1.57, and 1.74 GJ m^{-2} a^{-1} for Ulaanbaatar, Harbin, Dras, and Lukla respectively.

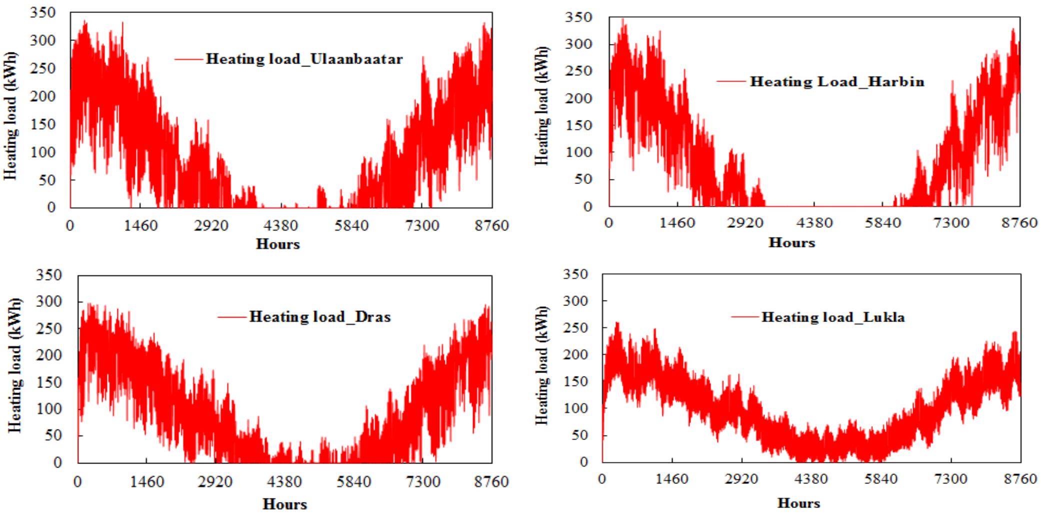

Figure 3: Hourly space heating loads for 30 typical houses

3.2 System sizing

Figure 4 shows the relation of heat pump capacity ratio (%) with the energy delivered ratio (%). It was found that 80% of the heat pump capacity ratio could able to supply 93%, 94%, 88%, and 96% of energy delivered ratio for Ulaanbaatar, Harbin, Dras, and Lukla respectively. Therefore 80% heat pump capacity ratio was selected for this study.

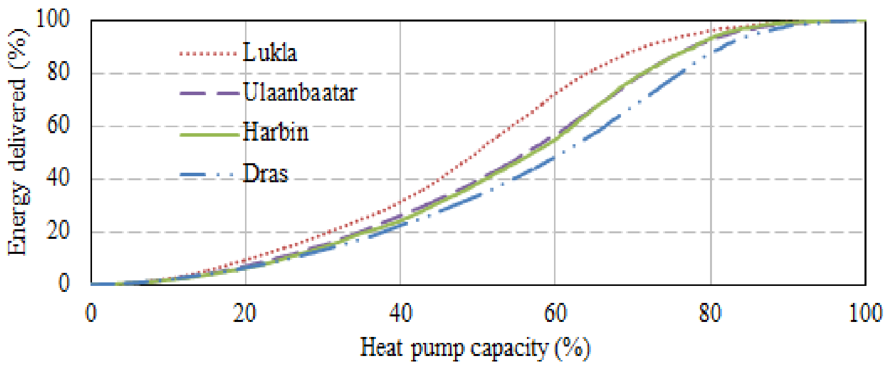

Figure 4: Heat pump capacity ratio Vs. energy delivered ratio (%)

The sizes of the main components of the system for a cluster of 30 houses in each location were determined. The area of SC and length of borehole were found to be 709, 717, 590, and 534 m^2 and 3120, 3360, 2880, and 2640 m for Ulaanbaatar, Harbin, Dras, and Lukla respectively.

3.3 Average ground temperature and energy balance

The average ground temperature of the storage borehole for each climate zone is presented in Figure 5 for the 20 years operating period. It was found that the system can balance the ground temperature over 20 years and ground temperature was found higher than reference temperature for all locations. In addition the ground temperature was found within ranges of low temperature (0-40 °C) storage system for each climate zone. At summer heating demand is low but high heat is injected by solar therefore the ground temperature was raised at Harbin then Ulaanbaatar, Dras and Lukla. However, in case of Lukla ground temperature was found to be more stable and lower than other three locations due to heat extraction occur every month. As a result ground temperature could not rise at summer period like other cities. For the case of Harbin, Ulaanbaatar and Dras there are initial few years to reach the steady condition of ground temperatures due to their high ambient temperature and low heating demand during the summer period. On the other hand, ground temperatures were found to be lower for all locations without solar charging.

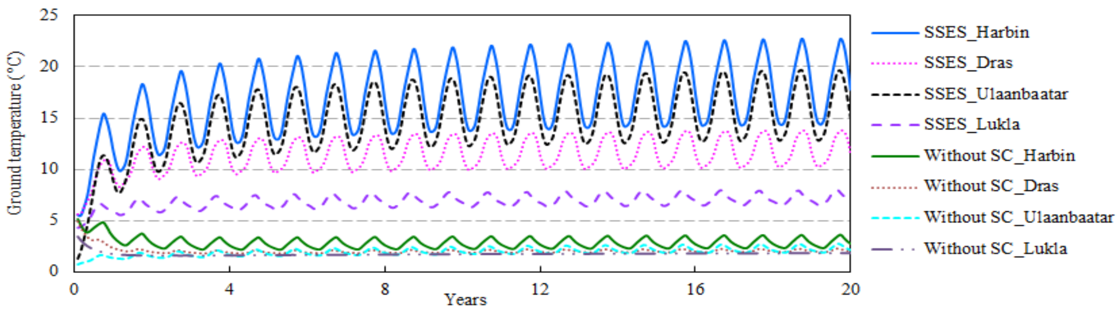

Figure 5: Ground temperature status

The annual energy balance of the system at a 20th year was presented in Table 4. In Harbin and Ulaanbaatar were found heat losses is more than the heat gain, therefore net heat gain value is negative. On the other hand, there is a small amount of heat losses occur in Dras; however, net gain is positive due to heat gain more than heat losses. In Lukla was found no heat loss due to the ambient temperature is lower and heat requires throughout the year. Further, the change in annual heat store varied over the 20 years period at all locations even the changes of heat store varied in every month. On the others hand, the annual heat store changes were found positive at 20th year period in Harbin, Ulaanbaatar and Lukla except for Dras. Further, the annual energy balances were found very closure (%) at all locations.

Table 4: Annual energy balance of the system at the end of 20th year

Location	Q_{solar} (GJ)	W_{comp} (GJ)	$Q_{net\ gain}$ (GJ)	Q_{heat} (GJ)	ΔQ_{store} (GJ)	Heat balance* (GJ)	Closure (%)
Harbin	2051.39	370.65	- 106.64	2316.13	+ 3.91	- 4.64	100.23
Ulaanbaatar	2196.46	410.24	- 82.41	2521.85	+ 2.08	+ 0.36	99.98
Dras	2115.60	455.25	+ 143.29	2714.75	- 1.13	+ 0.52	99.98
Lukla	2004.25	429.34	+ 288.49	2717.39	+ 4.10	+ 0.58	99.97

*Discrepancy = sum of left hand side terms in Eq.(11) – sum of right hand side terms in Eq.(11)

3.4 Performance analysis

Figure 6 shows the simulated *SHCOP* and COP_{sys} of the proposed SSES system. The *SHCOP* were found 6.33, 6.25, 6.15, and 5.96 for Lukla, Harbin, Ulaanbaatar, and Dras respectively. Further, the simulated COP_{sys} were found to be 3.11, 3.33, 3.48, and 3.49 for Lukla, Dras, Ulaanbaatar, and Harbin respectively. In addition, maximum annual heating load per unit area was found at Lukla and least at Harbin.

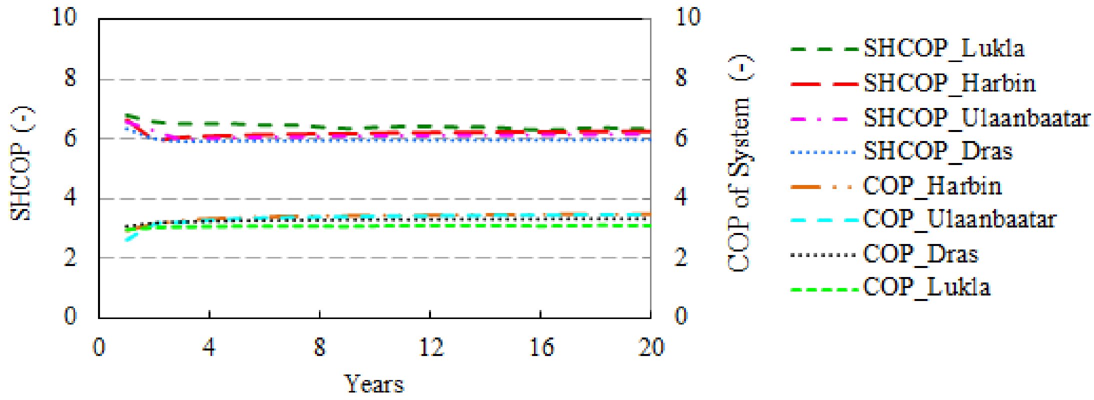

Figure 6: Performance of the SSES system for the selected cities.

3.5 Simple payback period

The simple payback period of SSES system for each location shows in Table 5. The low *SPBP* was found at Lukla then Harbin due to higher OC_{conv} of the system. Among the fuel wood/coal system, the *SPBP* was found lower at Lukla than Dras, and Ulaanbaatar, because of the high price of fuelwood at Lukla. The higher *SPBP* found at Ulaanbaatar then Dras due to less annual operational cost due to the lower price of electricity.

Table 5: Payback period of SSES system

Location	IC_{SSES} (US$)	OC_{SSES} (US$)	OC_{conv} (US$)	*SPBP* (a)
Harbin	252311	9450	37434	9.0
Ulaanbaatar	339910	5449	25569	16.9
Dras	201605	6331	20198	14.5
Lukla	206728	10025	62362	3.9

4. Conclusions

This study investigated the performance of SSES system in four cold climate cities in Asia-Pacific region. The typical detached house in each location was selected. The building model was developed in TRNSYS project with other major components. The performance of the proposed SSES system was investigated over the 20 year simulation period. The space heating demand per unit area in each location was determined. The initial sizes of the system components for each location were determined. The ground temperature in each location was found steadiness, and it is referred to the system would fulfil the space heating demand. The highest *SHCOP* and lowest *SPBP* was found at Lukla.

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