Energy and Exergy Analysis of a Solar Combisystem using Engineering Equation Solver (EES)

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Abstract

This paper presents the thermodynamic analysis of a solar combisystem for a one-family residence. The system is composed of solar thermal collectors, water storage tank, ice storage tank, heat pump, radiant floor, hydraulic circulation loops with pumps and control valves. The solar combisystem is analyzed for given space heating load and domestic hot water consumption.

The hourly, monthly, and annual simulation results are presented. The calculated indices of operation performance of the whole combisystem and individual component equipment, such as the coefficient of performance and exergy efficiency are presented.

1 Introduction

Solar combisystems for residential application combine the production of domestic hot water and provision for space heating (Papillon et al., 2010). A typical solar combisystem for one-family residential application had the solar thermal collectors of 10 to 30 m^2 and the water storage tank of 0.3 to 3 m^3 (SHC T26, 2012). Solar combisystems in twenty-one configurations were studied by the International Energy Agency (IEA) task 26 Solar Combisystems from 1998 to 2002. The application of solar combisystems in Montreal, Canada was investigated through a series of simulation studies: Hugo et al. (2010) found that a solar combisystem with seasonal storage could lead to significant energy savings; Leckner & Zmeureanu (2011) found that with a solar combisystem a net zero energy house could be technically achieved; Ng Cheng Hin & Zmeureanu (2014) compared the optimal configuration of a solar combisystem in terms of life cycle cost, energy and exergy.

Large majority of studies of such systems was based on the analysis of energy used. The state-of-art building energy analysis programs solely use the energy balance to estimate the energy use in buildings (Rosen et al. 2001, Zmeureanu & Wu 2007). The exergy analysis could bring a different perspective of systems because both quantity and quality of energy flows are used. A few examples of exergy-based studies are presented in this section. Itard (2005) implemented the exergy calculation in the h.e.n.k. program (Itard 2003) for an early design of a building. A few exergy analysis tools for buildings and communities were developed based on the spreadsheet applications (e.g. the Microsoft Excel and the OpenOffice Calc), for instance the Pre-Design Tool (Schmidt 2004, Torío 2010) for the buildings, the Cascadia (Church, 2008) for the neighborhood design, and the Software for Exergy Performance (SEPE) (Molinari, 2011) for the exergy demands of cooling and heating in buildings. Developed for the design, pre-design, or general assessment, these tools suit the steady-state exergy analysis. Quasi-steady-state exergy analysis studies were reported by Wu (2004) and Zmeureanu & Wu (2007) for residential heating systems, using Energy Equation Solver (EES) program (Klein, 2012), and Wei (2006) for Variable Air Volume (VAV) systems of an office building. Gaggioli (2010) recommended the adoption of the EES program or a counterpart for thermodynamic problems. The EES program enables a user to write the mathematical formulations of every single component of an HVAC system and has built-in functions for the calculation of thermodynamic properties of substances, which make it to be an ideal environment for the exergy analysis in HVAC systems.

This paper presents the development of a computer model using the EES program for the energy and exergy analysis of a solar combisystem with storage tanks and a heat pump. The scope was to develop a simulation tool able to estimate the performance of such an integrated system.

2 Methodology

The solar combisystem was modeled under quasi-steady-state conditions. The input and output of computer model of the whole solar combisystem were identified at the beginning stage. The model input includes input parameters and input variables. The input parameters consist of equipment dimensions and operation constraints, while the input variables consist of heating requirements and boundary conditions. The model output includes the temperature and enthalpy of working fluids at the combisystem key locations, the heat transfer rate between system components, the energy used, and the performance indices of combisystem and component equipment.

The mathematical model of the whole solar combisystem was developed by using the component-based approach. The models of component equipment (Figure 1) include a solar thermal collector model, a water storage tank model, an ice storage tank model, a heat pump model, a radiant floor model, and three circulating pump models. The overall skeleton of solar combisystem and component equipment models were implemented in the EES program: An interface was created for model input, meanwhile, mathematical models were coded as procedures subject to a main routine.

To eliminate the impact of initial input values, the simulation was run for three consecutive years. The results of the third year were exported for treatment and analysis, using the MATLAB program (Mathworks, 2011) as a post-processor.

3 System and case study

System configuration

The configuration of solar combisystem, illustrated by Figure 1, consists of solar thermal collectors, a water storage tank, an ice storage tank, a heat pump, a radiant floor, and three circulating pumps. Three circulation loops $(L1, L2, L3)$ make connections among the component equipment. The solar thermal collectors capture solar thermal energy to charge the water storage tank and the ice storage tank. Using the solar thermal energy and electricity, the combisystem covers the needs of residential space heating and domestic hot water. The radiant floor provides the space heating, using either the water storage tank or the heat pump as the heat source. The heat pump extracts heat from the ice storage tank to supply the radiant floor and the water storage tank in a controlled sequence that depends on the thermal loads to be satisfied, the operating conditions of equipment and the control setpoints. Details about the system operation are presented in (Wen, 2013).

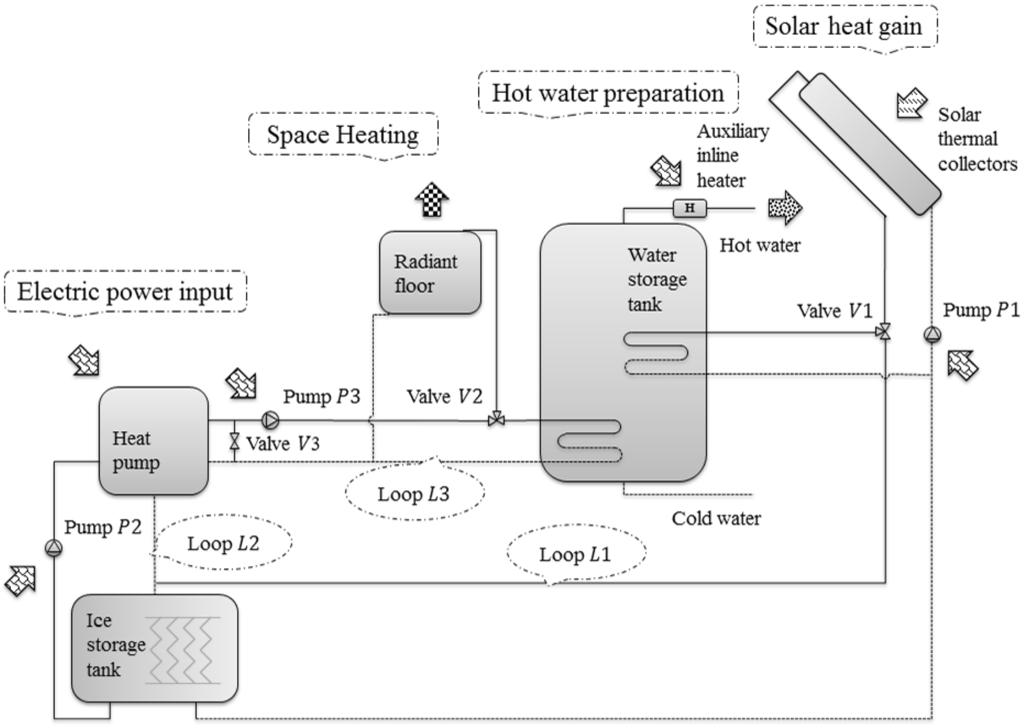

Figure 1: Schematic of solar combisystem configuration

Case study

The case study house was in Montreal, Canada with the design indoor temperature at 18 ℃**.** The building geometry and physical characteristics were given in a study by Leckner & Zmeureanu (2011), from which the hourly space heating needs were extracted. The simulated annual operation of solar combisystem included a heating season from October 17 to April 30 and a non-heating season through rest of the days of a year. The seasonal space heating demand was 8,323 kWh with a peak demand of 12.992 kW in January. The domestic hot water consumption was based on Jordan & Vajen (2001) with daily average of 266 L (Aguilar, White, & Ryan, 2005). The input cold water temperature was from Hugo (2008) based on the measurements of the temperature of water from city main of Montreal (Dumas & Marcoux 2004).

The radiant floor had a minimum supply temperature of 25 ℃ (Olesen, 1977), and a return temperature of 20 ℃ (ASHRAE, 2004). The water storage tank of 2.2 m^3 had the initial temperature of all nodes of 40 ℃, a maximum allowable temperature of 60 ℃ avoiding the Legionella disease (ASHRAE, 2007), and an auxiliary heater turn-on temperature of 40.5 ℃ (California Energy Commission, 2005). The ice storage tank of 14 m^3 had the maximum ice fraction of 70% (Sunwell, 2012), and the maximum water temperature of 37.8 ℃ relating to the operation of heat pump (GeoSmart, 2012). The heat pump of 13.0 kW had Coefficient of Performance (COP) of 3.1 under rated capacity of 13.0 kW, the source temperature at 0 ℃ and load temperature at 40 ℃. The solar thermal collectors had the gross area of 27.58 m^2 (SunEarth, 2012) tilted at 60° facing due south. The equipment capacity and settings were finalized after several analyses performed using the developed computer model.

4 Results and discussion

This section presents the results of simulated solar combisystem. First the annual energy flows are graphically presented, followed by indices of performance in tabular format. The operating conditions and performance are presented, as examples, for three successive days, from January 11 to January 13. Note that the peak of space heating load was on January 12.

Overview of system energy flows

The simulated annual energy flows among the solar combisystem components are presented in Figure 2, starting from the energy supply (top box) of incident solar energy and electricity required to meet the residential heating needs.

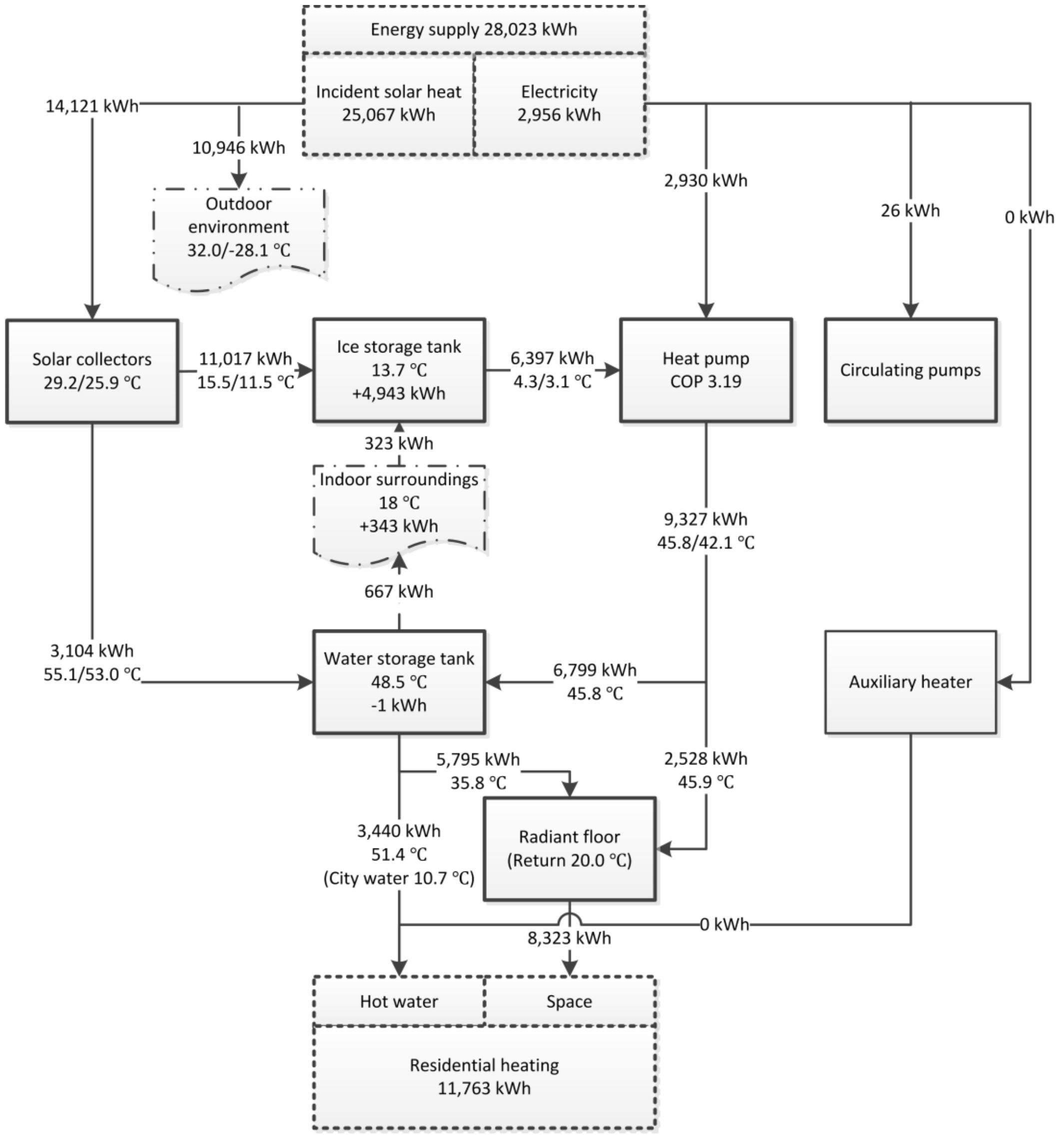

Figure 2: Flowchart of energy flows of solar combisystem annual operation

The flow path of energy is directed by arrows that connect to the boxes. The rectangular boxes by continuous line represent the system components; the rectangular boxes by dotted line represent the supply of energy (at the top) and the heating load (at the bottom);

the boxes in irregular shape represent the outdoor environment and indoor surroundings. The annual energy use was quantified in kWh. The amount of change of energy was indicated for the storage tanks, where the positive values of changes correspond to the energy storage and the negative values correspond to the energy discharged or extracted. The operation temperature of the component equipment was labeled, for instance, in the case of solar collectors, $\bar{T}_{out}/\bar{T}_{in}$ that represent the mean outlet temperature followed by the mean inlet temperature; and in the case of outdoor environment, T_{max}/T_{min} that represents the upper limit of outdoor temperature followed by the lower limit of outdoor temperature. Some of the cases were labelled with one temperature: mean temperature of the ice storage tank water-layer, mean temperature of the water storage tank nodes, or supply temperature along the flow path.

System COP

The annual COP of solar combisystem was estimated at 3.98, calculated as follows:

$$COP^{Sys} = \frac{Q_{load}^{Sys}}{W_{ele}^{Sys}} \quad (1)$$

where,

$$Q_{load}^{Sys} = Q^{DHW} + Q^{RF} \quad (2)$$

and COP^{Sys} is the Coefficient of Performance of the solar combisystem; Q_{load}^{Sys} is the heating load of the solar combisystem, kWh; W_{ele}^{Sys} is the electricity used by the solar combisystem operation, kWh; Q^{DHW} is the heating load of domestic hot water, kWh; Q^{RF} is the space heating load, kWh. The results indicate that the solar combisystem provides on average four times more heating to the residence than the purchased electricity.

Solar energy contribution

The combisystem stores the solar energy in thermal storage tanks before distributing to meet the heating requirements. The charge and discharge of solar energy took place at the water storage tank during an entire year, whereas at the ice storage tank over the heating season only. Overall, the annual solar energy contribution of solar combisystem was estimated at 89.5%, calculated as follows:

$$SC_E^{Sys} = \frac{Q_{sol}^{Coll}}{E_{supp}^{Sys}} \quad (3)$$

where,

$$E_{supp}^{Sys} = Q_{sol}^{Coll} + W_{ele}^{Sys} \quad (4)$$

and SC_E^{Sys} is the solar energy contribution of the solar combisystem; Q_{sol}^{Coll} is the incident solar energy on the solar thermal collectors, kWh; E_{supp}^{Sys} is the energy supplied to the solar combisystem, kWh. About 56.3% of incident solar radiation was collected by the system and used to satisfy the annual heating needs.

Energy efficiency

Energy efficiency is estimated as the ratio of the heating load delivered by the solar combisystem over the overall energy input to the solar combisystem:

$$\eta^{Sys} = \frac{Q_{load}^{Sys}}{E_{supp}^{Sys}} \quad (5)$$

where, η^{Sys} is the energy efficiency of the solar combisystem. Table 1 presents the monthly and annual energy efficiency estimated for the solar combisystem. Over one year, on average 42.0% of total energy input (solar plus electricity) was used to satisfy the heating needs. The average efficiency in January was 71.7% because of heating needs, while in August is only 27.4%. The results show that the solar combisystem received and used more solar energy input during the heating season. In general, the energy efficiency in non-heating months is lower than in heating months; however, less electricity was needed.

Table 1: Estimated energy efficiency of solar combisystem

	Energy input, kWh			Heating load, kWh	Energy efficiency
	Incident solar energy	Electricity	Overall		
January	2,823.18	859.75	3,682.93	2,640.14	71.7%
February	3,680.97	568.06	4,249.02	2,014.13	47.4%
March	4,714.15	267.79	4,981.94	1,295.93	26.0%
April	4,015.50	102.22	4,117.72	504.91	12.3%
May	1,200.62	0.78	1,201.40	351.81	29.3%
June	948.72	0.67	949.39	279.79	29.5%
July	725.36	0.47	725.83	233.21	32.1%
August	758.99	0.55	759.53	208.46	27.4%
September	875.64	0.51	876.16	284.46	32.5%
October	1,783.80	66.08	1,849.88	431.87	23.3%
November	1,530.94	370.39	1,901.33	1,224.29	64.4%
December	2,008.93	719.06	2,728.00	2,294.88	84.1%
Year	25,067	2,956	28,023	11,764	42.0%

Solar energy fraction

Solar energy fraction is the ratio of solar energy collected to the total energy required for satisfying the heating needs without using a solar system. Those needs are calculated for a reference system that meets the same heating requirements, however without any solar device (Table 2). In this study, an all electrical heating system was regarded as the reference system composed of electric water heater and electric baseboard heaters, because the electric only heating system is normally installed in the vast majority of homes in Quebec. For instance, in January the solar energy collected was equal to 65% of the heating needs. In August, the reference system needs were about 100 kWh; while the solar system was able to collect 274 kWh of solar energy; therefore the solar energy fraction shows that the solar combisystem has the potential of supplying 2.72 times more energy than it was required by the reference system.

Table 2: Estimated solar energy fraction of solar combisystem

	Reference system			Solar combisystem	
	Electricity consumption of baseboard heater, kWh	Electricity consumption of water heater, kWh	Reference system total energy use, kWh	Solar energy collection, kWh	Solar energy fraction, dimensionless
January	2,331.04	277.51	2,608.55	1,707.84	0.65
February	1,721.11	262.53	1,983.64	2,222.92	1.12
March	949.38	306.54	1,255.92	2,807.75	2.24
April	182.27	283.44	465.72	2,511.75	5.39
May	0.00	213.88	213.88	433.03	2.02
June	0.00	156.79	156.79	342.73	2.19
July	0.00	117.67	117.67	298.52	2.54
August	0.00	100.80	100.80	274.45	2.72
September	0.00	145.52	145.52	350.41	2.41
October	171.68	171.73	343.41	1,018.88	2.97
November	976.15	218.15	1,194.30	974.43	0.82
December	1,991.79	271.83	2,263.62	1,178.00	0.52
Year	8,323	2,526	10,850	14,121	1.30

Exergy destroyed

Table 3 presents the exergy destruction estimated for the monthly and annual operation of solar combisystem, calculated as follows:

$$X_{dest}^{Sys} = X_{dest}^{Coll} + X_{dest}^{HP} + X_{dest}^{Pump} + X_{dest}^{Aux} + X_{dest}^{IT} + X_{dest}^{WT} + X_{dest}^{RF} \quad (6)$$

where, X_{dest}^{Sys} is the exergy destroyed during the solar combisystem operation, kWh; X_{dest}^{Coll} is the exergy destroyed by the solar thermal collectors, kWh; X_{dest}^{HP} is the exergy destroyed by the heat pump, kWh; X_{dest}^{Pump} is the exergy destroyed by the circulating pumps, kWh; X_{dest}^{Aux} is the exergy destroyed due to the use of the auxiliary electric heater, kWh; X_{dest}^{IT} is the exergy destroyed by the ice storage tank, kWh; X_{dest}^{WT} is the exergy destroyed by the water storage tank, kWh; X_{dest}^{RF} is the exergy destroyed by the radiant floor, kWh.

The annual operation of solar combisystem destroyed 15,657 kWh of exergy out of the total 26,421 kWh of exergy supplied in forms of incident solar exergy and electricity. Less amount of exergy was destroyed from May to September compared to other months. Among the component equipment, the greatest amount of exergy was destroyed by the operation of solar thermal collectors, which accounted for 77.6% of the total exergy destruction. Other equipment had the following contributions: the heat pump 11.2%, the radiant floor 4.3%, the water storage tank 3.8%, the ice storage tank 2.9%, and the circulating pumps 0.2%.

Table 3: Estimated exergy destruction by solar combisystem operation (units: kWh)

	Solar combisystem	Solar thermal collectors	Heat pump	Pumps	Auxiliary heater	Ice storage tank	Water storage tank	Radiant floor
January	2,390.27	1,548.87	512.22	4.85	0	21.93	111.51	190.87
February	2,590.32	1,985.22	335.54	4.04	0	35.82	94.76	134.94
March	2,845.44	2,401.82	160.30	3.29	0	140.03	68.58	71.42
April	2,420.35	2,141.41	62.53	2.78	0	172.75	27.54	13.34
May	361.54	329.09	-	0.78	0	0.03	31.65	-
June	285.56	259.60	-	0.67	0	0.01	25.28	-
July	247.54	225.75	-	0.47	0	0.01	21.31	-
August	227.53	207.43	-	0.55	0	0.00	19.55	-
September	289.35	265.39	-	0.51	0	0.00	23.44	-
October	992.11	862.60	38.84	1.44	0	49.06	27.04	13.12
November	1,246.33	870.53	216.00	2.75	0	22.11	54.18	80.76
December	1,760.89	1,053.20	423.84	4.08	0	20.00	95.58	164.18
Year	15,657	12,151	1,749	26	0	462	600	669
	100%	77.6%	11.2%	0.2%	0.0%	2.9%	3.8%	4.3%

Second law efficiency

Table 4 presents the second law efficiency estimated for the annual operation of solar combisystem and the system component equipment, calculated as follows:

$$\eta_{II} = 1 - \frac{X_{dest}}{X_{supp}} \tag{7}$$

where, η_{II} is the second law efficiency; X_{dest} is the exergy destruction, kWh; X_{supp} is the exergy supply, kWh. The simulated solar combisystem had an annual exergetic efficiency of 40.7%.

Table 4: Estimated annual exergetic efficiency of solar combisystem

Solar combisystem	Solar thermal collectors	Heat pump	Ice storage tank	Water storage tank	Radiant floor
40.7%	9.3%	42.6%	19.0%	61.0%	17.8%

Operating conditions

Operating conditions of the solar combisystem are illustrated for three days (from January 11 to January 13). Figure 3 presents the solar combisystem heating load, for the space heating and the domestic hot water. The domestic hot water was prepared in the water storage tank. The space heating was supplied by the radiant floor, using heat from the water storage tank and the heat pump. The graph shows that the heat pump provided most of the amount of heat, when the space heating load was high. Figure 4 presents the electricity consumption of the heat pump and circulating pumps ($P1, P2, P3$) of the solar combisystem.

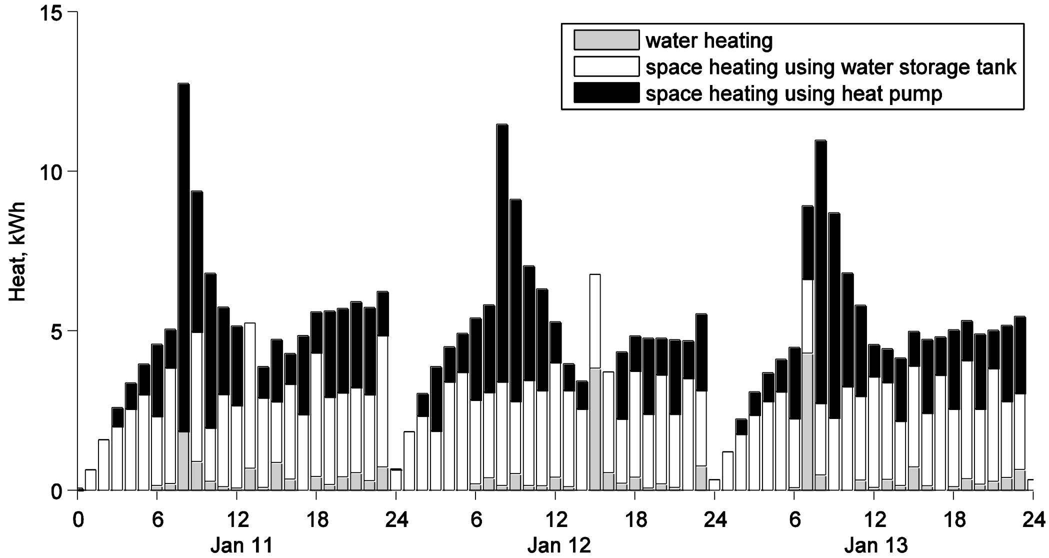

Figure 3: Heating load of solar combisystem from Jan. 11 to Jan. 13

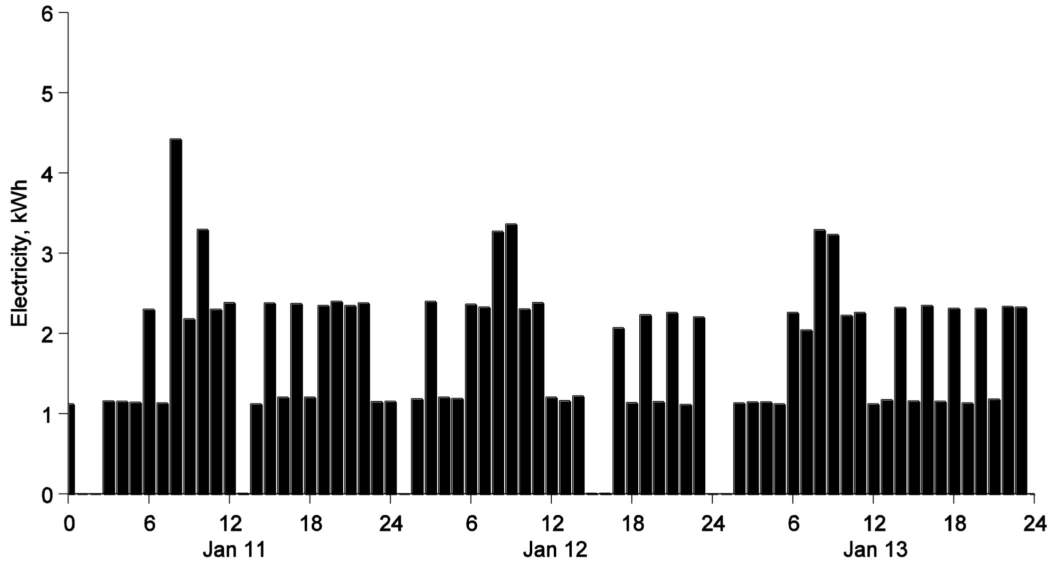

Figure 4: Electricity consumption of solar combisystem from Jan. 11 to Jan. 13

Solar energy was the sole source of heat to the solar combisystem. Figure 5 presents the incident solar radiation on solar thermal collectors and the charge of solar heat to two storage tanks. The graph shows that the ice storage tank received heat more than the water storage tank over the illustrated days. On January 12 when the peak of space heating occurred, the solar thermal collectors had been operated during most of the time when solar heat was available to charge the two storage tanks. Figure 6 presents the thermal efficiency of solar thermal collectors operated with the ice storage tank and the water storage tank, respectively. The plotted distribution of efficiency indicates that the use of water from the ice storage tank, with lower temperature entering the solar thermal collectors, contributes to the increase of thermal efficiency of solar thermal collectors, when it is compared to the case of using higher temperature water from the water storage tank. These results coincide with the conclusions from a previous study by Hugo et al. (2010).

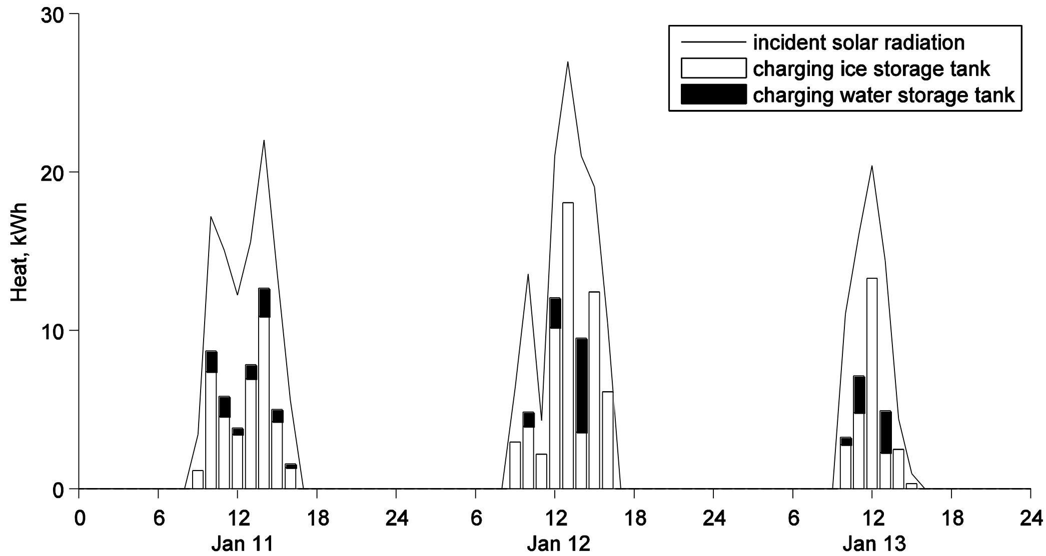

Figure 5: Solar incidence and storage of solar combisystem from Jan. 11 to Jan. 13

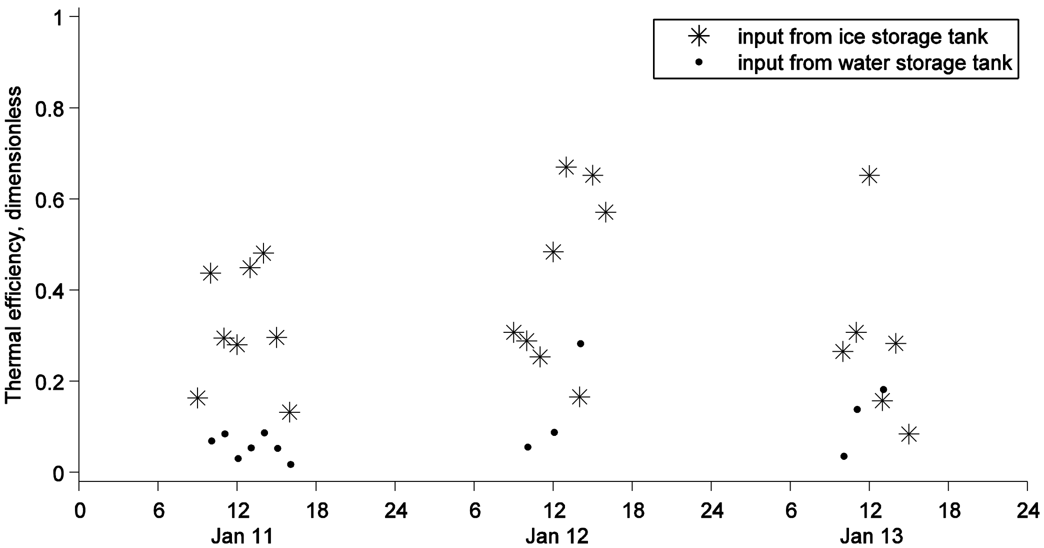

Figure 6: Thermal efficiency of solar thermal collectors from Jan. 11 to Jan. 13

5 Conclusions

This paper presents the energy and exergy analysis of a solar combisystem for a one-family residential application. The solar combisystem model was developed and implemented using the EES program. The simulated solar combisystem was supplied with 25,067 kWh of solar energy and 2,956 kWh of electricity over the annual operation; the corresponding COP of solar combisystem was estimated at 3.98, solar energy contribution of 89.5%, and solar energy efficiency of 42.0%. Compared to an electric heating system, the solar combisystem had an annual solar energy fraction of 1.30. The annual operation of solar combisystem destroyed 15,657 kWh of exergy out of the total 26,421 kWh of incident solar exergy plus electricity. The annual second law efficiency was 40.7% for the solar combisystem, 9.3% for the solar thermal collectors, 42.6% for the heat pump, 19.0% for the ice storage tank, 61.0% for the water storage tank, and 17.8% for the radiant floor.

Further studies will focus on the optimization of the system components.

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