Exergy Analysis of a Residential Thermal Storage System

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Abstract

An exergy analysis is reported for the thermal storage portion of a solar combisystem. The exergy calculation modules were integrated within a model of a solar combisystem, which was developed for this study using the TRNSYS environment. Four different combisystem configurations are presented: the base case and three optimized combisystems. The results include daily and monthly exergy storage profiles of the two storage tanks as well as the exergy efficiencies. The two storage tanks act more as exergy transmission tanks rather than storage tanks and larger collector areas increase the exergy efficiencies of the tanks.

Keywords: Exergy, solar collector, combisystem, thermal storage

Résumé

Une analyse exergétique est effectuée sur le stockage thermique d'un système solaire combiné. Les modules de calcul de l'exergie ont été intégrés dans un modèle de système solaire combiné, lequel a été développé en utilisant l'environnement TRNSYS. Quatre configurations différentes de système solaire combiné sont présentées : Le cas de base et trois cas optimisés. Les résultats comprennent les profils journaliers et mensuels de stockage de l'exergie des deux réservoirs, ainsi que ceux des rendements exergétiques. Les deux réservoirs se comportent plus comme des réservoirs de transmission exergétique plutôt que des réservoirs de stockage. L'augmentation de la surface des capteurs solaires accroît les rendements exergétiques des réservoirs.

Mots-clés: Exergie, capteur solaire, système solaire combiné, stockage thermique

1. Introduction

By reducing the energy use in residential buildings, which accounts for about 17% of total energy use in Canada [1], we may decrease our society's reliance on fossil fuels and thereby help mitigate climate change. Active solar thermal systems have been studied extensively over the past decades and are commonly used in countries with high energy prices in order to reduce residential energy use. Thermal storage is a particular area of research interest since solar thermal energy is most effectively captured during the daytime and in the summer, when the heating needs are small, negligible or even non-existent; therefore, thermal storage is advantageous for such systems.

A combisystem is an active solar collector system that utilizes solar heat for the purposes of space heating and for domestic hot water heating in a residential building. Combisystems are a typical example of a solar thermal system that makes use of thermal storage. Combisystems have been extensively studied in the past, including several international research efforts [2-4]. However, rarely have combisystems been studied in terms of exergy. Exergy is defined as the maximum amount of useful work that can be delivered from a system at a specified state when it is compared to a reference state [5, 6]. Exergy methods have been applied to thermal storage in the past [7]. One prior study determined the exergy efficiency of a solar combisystem and found that the storage tank had exergy efficiency between 15-17% [8]. However, that study did not focus on the exergy storage profiles of the system. The objective of this study is to compare and analyse the exergy storage profiles and performance of several configurations of a solar combisystem that have been optimized for different purposes.

2. Methodology

To perform an exergy analysis of a residential thermal storage system, a computer model of an energy efficient house equipped with a solar combisystem is first selected. Three independent objective functions are developed that aim to minimize the life cycle cost (LCC), life cycle energy use (LCE) and life cycle exergy destroyed (LCX) by the combisystem [9]. A hybrid particle swarm optimization and Hooke-Jeeves generalized pattern search optimization algorithm is then used three separate times (once with each objective function) to optimize the combisystem configuration based on eight configuration variables to produce three new optimal combisystem configurations. Exergy calculation modules are then implemented in the TRNSYS simulation environment in order to analyse the exergy performance of each of the optimal configurations as well as the base case configuration. The daily and monthly exergy storage profiles are then plotted and the exergy efficiency of the two storage tanks is determined for all the configurations.

2.1 Solar combisystem model

The solar combisystem used for this paper is modelled in the TRNSYS simulation environment. The combisystem is installed in a two story detached single family dwelling in Montreal, Canada, which has been modelled as a typical mid-1990s construction that has been renovated to be energy efficient [10]. Figure 1 shows a schematic diagram of the solar combisystem used for this study. The combisystem is composed of a series of south-facing flat plate solar collectors, a flow diverter, two fluid flow pumps, two hot water storage tanks with immersed heat exchangers and electric auxiliary heating elements, and a mixing valve. The upper electric heating element in the radiant floor tank (RFT) is turned on only during the heating season (October 17th to May 1st) and when the temperature in the top floor of the house drops below 21°C and the lower electric heating element is turned on when the temperature drops below 18°C. These temperatures are set back by 3°C during the night. The maximum temperature in the RFT is set at 55°C. The auxiliary heating element in the domestic hot water tank (DHWT) is turned on when the temperature in this tank drops below 55°C. The collector fluid will only flow to one of the tanks at a time, with priority given to the RFT during the heating season, when the temperature of the collector fluid is greater than the temperature of the water in the tank at the level of the collector fluid inlet.

Table 1 shows the configuration of the base case solar combisystem (BCSCS), and three different combisystem configurations for minimum (i) life cycle cost (LCC), (ii) life cycle energy use (LCE), and (iii) life cycle exergy destroyed (LCX).

The most important difference between the four configurations presented in Table 1 is the number of solar collectors. The minimum life cycle cost and minimum life cycle exergy destroyed configurations both minimized the collector area (1 solar collector = 2.74 m^2). This is because the solar collectors are responsible for the majority of the life cycle cost of the system and are also responsible for the majority of the exergy destroyed of the system. Therefore, to minimize LCC and LCX, it is more beneficial to rely on the auxiliary heaters than on solar energy while the opposite is true in order to minimize LCE. The BCSCS is a fairly good compromise between the three objective functions [9].

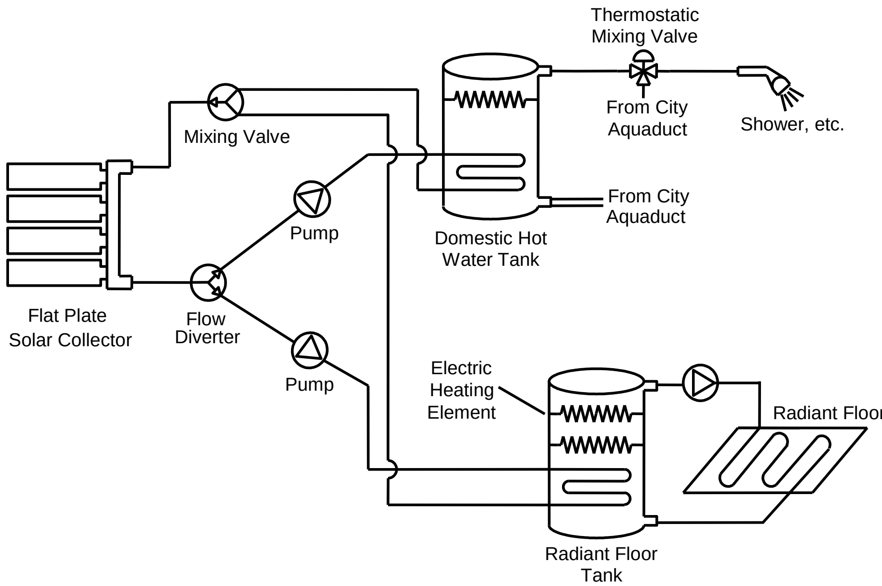

Figure 1. Schematic diagram of the solar combisystem [8]

Parameter	Configuration			
	BCSCS	Minimum LCC	Minimum LCE	Minimum LCX
Number of solar collectors	4	1	9	1
Collector slope (degrees)	45	57.5	75	70
Collector fluid flow rate ($kg/hr/m^2_{collector}$)	9.1	20.0	13.8	32.5
DHWT volume (L)	300	100	100	100
RFT volume (L)	300	300	300	300
DHWT auxiliary power (kW)	1	0.5	0.75	0.5
RFT auxiliary power (high) (kW)	2	3.0	0.5	2.6
RFT auxiliary power (low) (kW)	4	0.5	3.0	6.0

Table 1. Parameter values for several combisystem configurations

2.2 Exergy analysis

The exergy balances for the two storage tanks are based on the exergy flows depicted in Figure 2, which shows the exergy flows in and out of the storage tanks. The subscripts *L*, *aux*, *HX*, and *d* denote leaked, auxiliary, heat exchanger, and destroyed, respectively.

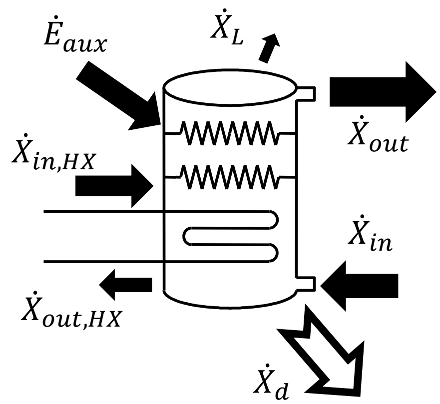

Figure 2. Exergy flows in the storage tanks

The water inlet and outlet exergy flow rates ($\dot{X}_{in}$ and $\dot{X}_{out}$ in Figure *2*) are calculated by combining the change in specific enthalpy and entropy compared to ambient conditions [5] and can be re-formulated based on the ambient temperature and the water inlet and outlet temperatures, as follows:

$$\dot{X}_{in} = \dot{m}_w \cdot C_{p,w} \cdot [T_{in} - T_a - T_a \cdot ln\left(\frac{T_{in}}{T_a}\right)] \quad (1)$$

$$\dot{X}_{out} = \dot{m}_w \cdot C_{p,w} \cdot [T_{out} - T_a - T_a \cdot ln\left(\frac{T_{out}}{T_a}\right)] \quad (2)$$

Similarly, the rate of exergy flowing into and out of the storage tank with the collector fluid are calculated as follows, where the collector fluid inlet and outlet temperatures are used instead of the water inlet and outlet temperatures, as used in equations (1) and (2):

$$\dot{X}_{in,HX} = \dot{m}_f \cdot C_{p,f} \cdot [T_{in,HX} - T_a - T_a \cdot ln\left(\frac{T_{in,HX}}{T_a}\right)] \quad (3)$$

$$\dot{X}_{out,HX} = \dot{m}_f \cdot C_{p,f} \cdot [T_{out,HX} - T_a - T_a \cdot ln\left(\frac{T_{out,HX}}{T_a}\right)] \quad (4)$$

The rate of exergy leakage from the storage tank by heat loss through the surface of the tank is calculated as

$$\dot{X}_L = U_L \cdot A \cdot (T_{tank} - T_r) \cdot \left(1 - \frac{T_a}{T_{tank}}\right) \quad (5)$$

The rate of exergy added to the storage tanks by the auxiliary electric heaters is determined by multiplying the auxiliary power ($\dot{E}_{aux}$) by the primary energy factor for the energy mix in Quebec, which is taken as 1.37 [11]. The exergy that is stored in the storage tank water is taken into account when determining the amount of exergy destroyed. To determine the amount of exergy stored in the tank, the volume of water is considered to be a heat source with respect to the environment. The exergy stored in the tank depends on the temperature of the water in the tank at the current time step and the temperature of the water during the previous time step.

Equation (6) is used to calculate the exergy content of the storage tank at any given time step while equation (7) is used to estimate the amount of exergy that is stored in the tank between time *t* and time *t*-1.

$$X_{tank} = \alpha \cdot m_w \cdot C_{p,w} \cdot \left[T_{tank} - T_a - T_a \cdot \ln(\frac{T_{tank}}{T_a})\right] \quad (6)$$

$$X_s^t = X_{tank}^t - X_{tank}^{t-1} \quad (7)$$

To find the cumulative exergy stored in the tank over a given time period, the exergy stored at each time step is summed over the given time period. Note that the exergy stored in the tank is measured in kWh, therefore the exergy content is multiplied by a factor of α (α = 0.00028 kWh/kJ) in order to convert from kJ to kWh. Finally, the exergy destroyed by the storage tank, in kWh, is evaluated as follows:

$$X_d = \Delta t \cdot (\sum \dot{X}_{in,HX} + \sum \dot{X}_{in} - \sum \dot{X}_{out,HX} - \sum \dot{X}_{out} - \sum \dot{X}_L + F_p \cdot \sum \dot{E}_{aux}) + X_s \quad (8)$$

Another measure of the performance of the storage tanks is the exergy efficiency, which is calculated for the two tanks as follows:

$$\eta_{II} = 1 - \frac{X_{d,tank}}{\Delta X_{HX} + E_{p,aux}} \quad (9)$$

The exergy supplied to the tank is composed of two terms: (i) the net exergy input through the heat exchanger, calculated as the difference between the incoming and outgoing exergy through the immersed heat exchanger, and (ii) the primary electric energy supplied to the tank by the auxiliary electric heaters.

3. Results and discussion

In order to study the daily load profiles of the two storage tanks, the cumulative energy and exergy storage profiles are plotted together for the BCSCS and the LCX optimal configuration between January 20 and 22. These winter dates were chosen arbitrarily to represent the storage profiles in a typical winter climate. The exergy storage is calculated using equations (6) and (7) and is summed after each time step to show the cumulative net storage. The energy storage profile is included for comparison and is calculated considering the rise or drop in temperature of the storage tanks at each time step. The storage profiles are shown in Figure 3 for the RFT and Figure 4 for the DHWT.

It is important to note that the storage profiles are influenced by several factors including the amount of incident solar radiation on the collectors, the outdoor air temperature, the tank volumes, the thermostat settings as well as the domestic hot water usage profile. The biggest difference between the BCSCS and the LCX optimal configuration that has a major influence on the exergy storage profile is that the LCX optimal configuration has only one solar collector (2.7 m^2) as opposed to four (10.9 m^2) for the BCSCS, so the amount of solar radiation converted to heat is significantly smaller in the case of LCX optimal configuration. Also, the DHWT of 100 L for the LCX optimal configuration is also smaller than the BCSCS with DHWT of 300 L.

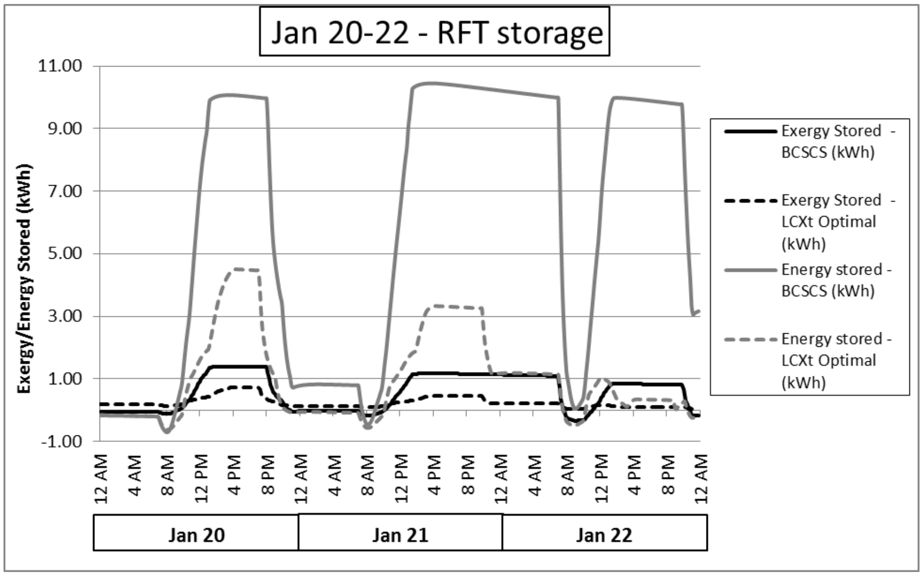

Figure 3. Exergy and energy storage profiles for the radiant floor tank for January 20-22

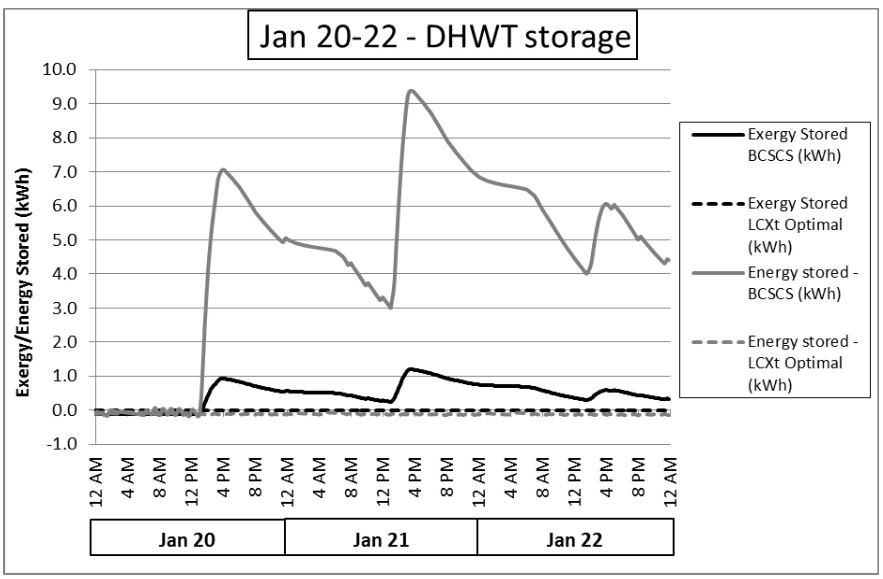

Figure 4. Exergy and energy storage profiles for the domestic hot water tank for January 20-22

At 7:00 AM each day in the RFT, a discharge in energy and exergy stored in the tank is observed. This is due to the set-back temperatures used overnight being disabled in the morning. Similarly, at somewhere between 7:00 PM and 9:00 PM there is another discharge observed on the 20th and 22nd, but not on the 21st for the BCSCS. This is likely because on the 20th, with the BCSCS installed, the temperature in the house remained above the set point temperature all day and thus the radiant floor pumps remained off and there was no significant draw from the RFT while on the other two days, colder outdoor temperatures resulted in a larger heating load and thus a discharge in the storage tank of both energy and exergy. Usually, at night between 12:00 AM and 7:00 AM, the heating system remains off since the set point temperatures are three degrees lower than during the day and therefore there is no charging or discharging occurring in the RFT. In general, however, the RFT of the LCX optimal configuration acts less like an exergy storage tank and more like an exergy transition tank, where exergy is constantly flowing into and out of the tank such that storage of any significant magnitude hardly occurs.

For the DHWT, the LCX optimal configuration accommodates practically no storage. This is because of the smaller collector area where little to no extra radiation heat is available to supply the DHWT during the cold winter months. Thus, the temperature in the DHWT is mostly regulated by the auxiliary heating element and the temperature in the tank remains relatively constant during the winter months.

As with the daily exergy storage profiles, the monthly exergy storage profiles can also be plotted in order to observe the annual storage performance of the two tanks. The same equations are used as for the daily exergy storage profiles except that the average monthly tank temperatures are used instead of the temperature at any given time step. Figures 5 and 6 show the average monthly tank temperatures for the RFT and the DHWT respectively, for all four configurations. Figures 7 and 8 show the exergy storage profiles for the RFT and the DHWT, respectively.

The actual amount of exergy stored in the tank is relatively low (maximum of 1.2 kWh for the RFT and 2.4 kWh for the DHWT) due to the relatively low change in average tank temperatures. However it is still interesting to examine the trends of exergy stored and how they are affected by the combisystem configuration. The tanks can be considered as exergy transition tanks rather than storage tanks since, in fact, very little exergy is stored. For the RFT, the BCSCS and LCE configurations begin storing exergy earlier in the year (January vs. March) due to the larger collector arrays, reaching a maximum charge of approximately 1.0 kWh for the BCSCS RFT and nearly 1.2 kWh for the LCE optimal configuration. However between April and May there is a much larger discharge for the BCSCS and the LCE optimal configuration than the LCC and LCX optimal configurations. This occurs because the configurations with the larger solar collector arrays have a higher average tank temperature in May than those with minimal collector areas.

When the heating system is turned off in May, the average RFT temperature drops to nearly the same temperature for all four configurations. The greater temperature drop in the BCSCS and the optimal configuration accounts for the deeper exergy discharge in May. It is also important to note that although the collector area of the LCE optimal configuration is more than twice the area of the BCSCS (24.6 m^2 vs. 10.9 m^2), the maximum amount of exergy stored in the RFT for the LCE optimal configuration is only 14% higher. This is possibly because the 300 liter storage tank simply cannot store more exergy since the maximum temperature of the tank is capped at 55°C.

For the DHWT, a similar trend is observed where the larger collector areas of the BCSCS and the LCE optimal configuration allow these two systems to store more exergy in the colder months of the year while the other two are not capable of doing so due to lack of incident solar radiation on the smaller collector area. The volume of the DHWT for the LCC, LCE and LCX optimal configurations is only 100 Liters, so the maximum amount of exergy stored in these tanks is four times less significant than the BCSCS, which has a DHWT volume of 300 Liters. The exergy storage capacity in the DHWT of the BCSCS is much higher than the other configurations. By April the LCE optimal configuration has already reached the maximum temperature allowed in the tank (80°C) and therefore no more exergy can be stored at this point and the storage remains relatively constant throughout the spring and summer. The BCSCS reaches this point in May while the LCC and LCX optimal configurations never reach the maximum allowable tank temperature. The LCC optimal configuration plateaus at approximately 75°C while the LCX optimal configuration plateaus at approximately 67°C.

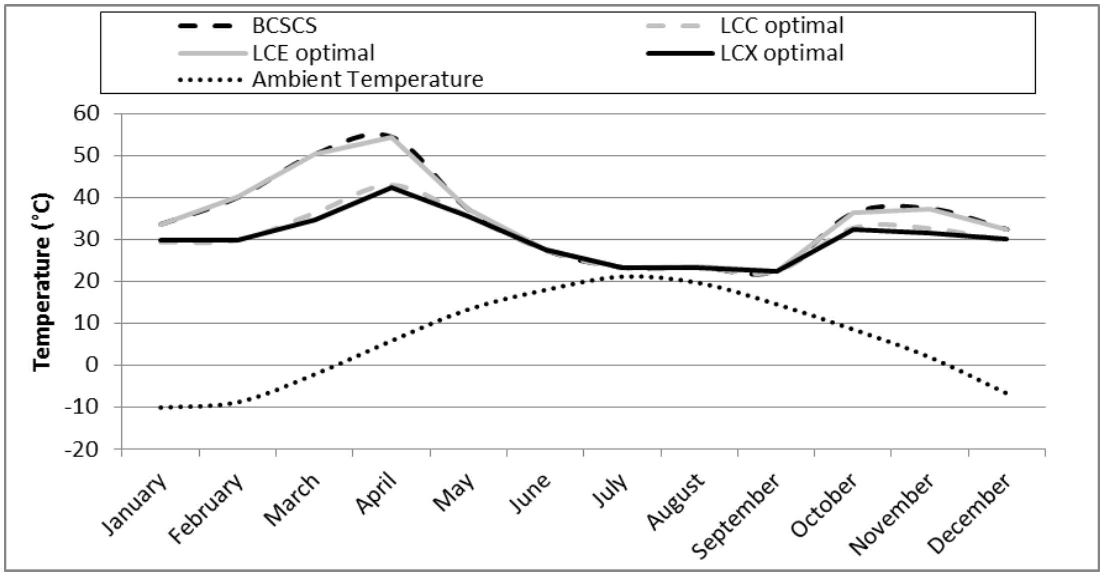

Figure 5. Average monthly tank temperatures in the radiant floor tank

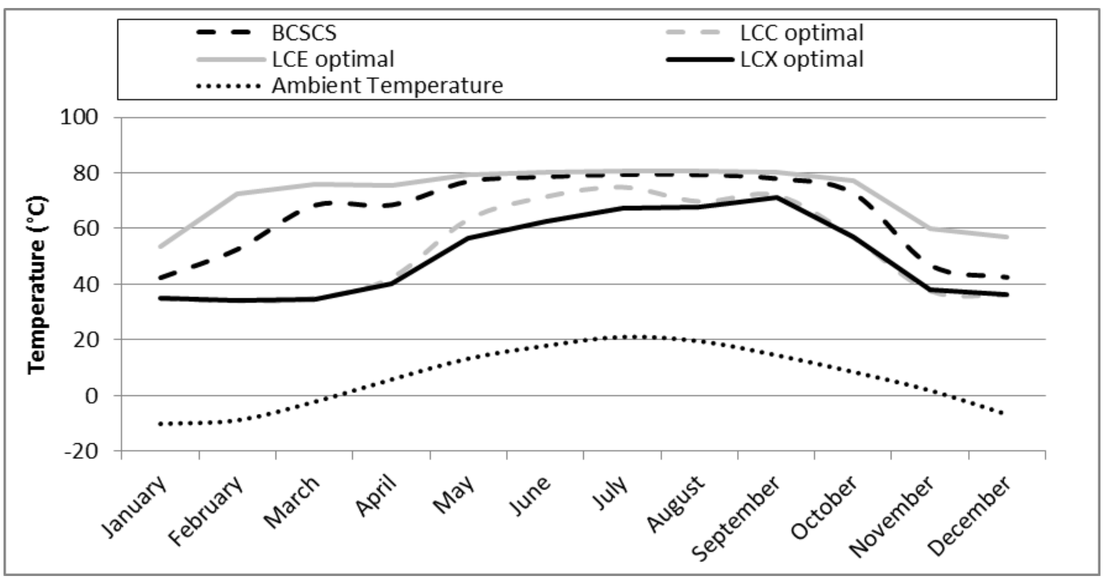

Figure 6. Average monthly tank temperatures in the domestic hot water tank

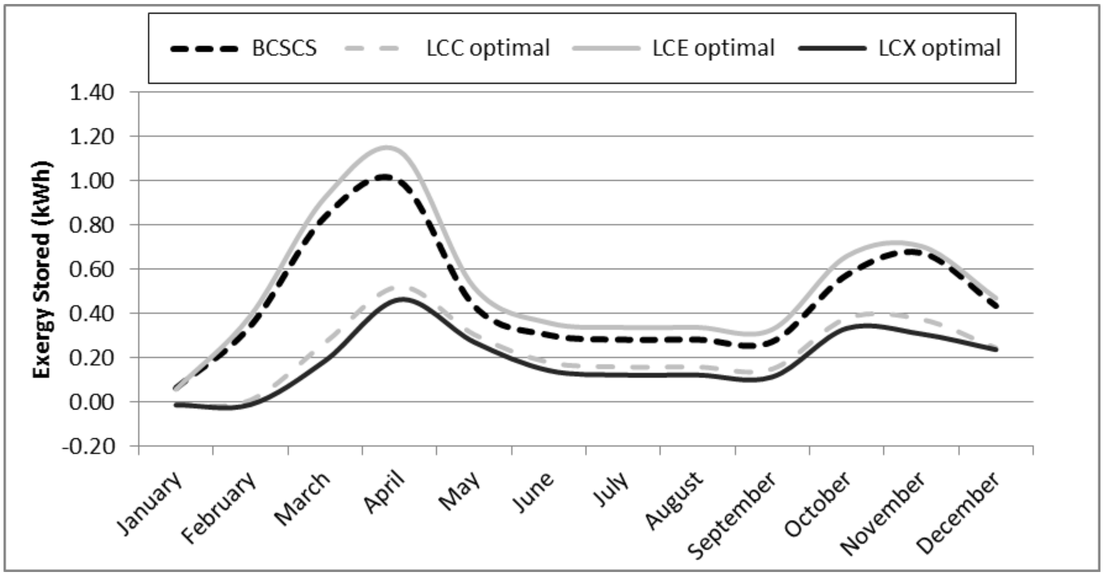

Figure 7. Monthly exergy storage profiles of the radiant floor tank

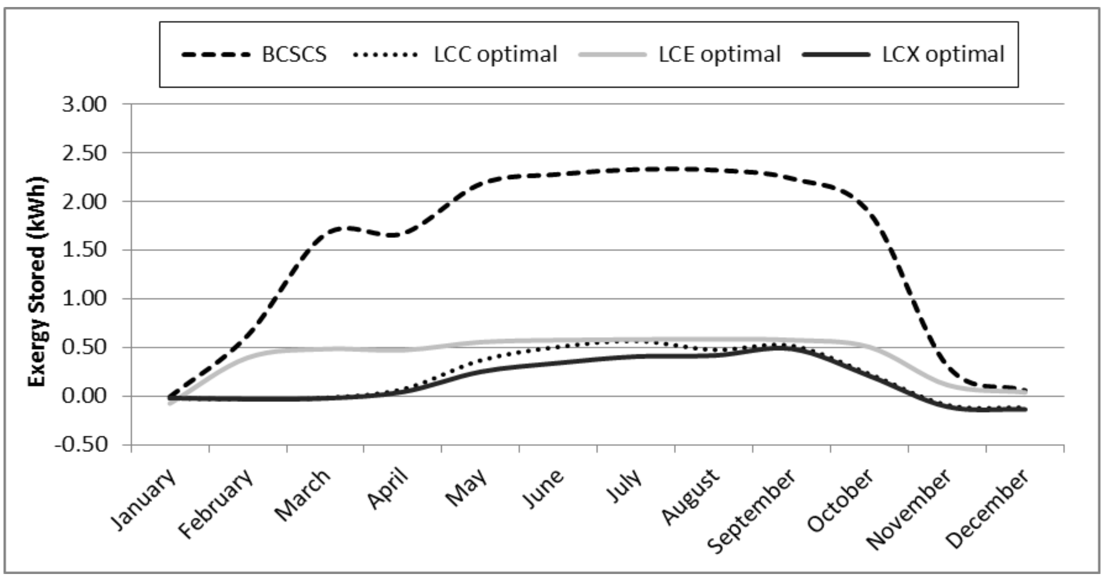

Figure 8. Monthly exergy storage profiles of the domestic hot water tank

In October, the average tank temperature for the DHWT drops significantly when the heating season is turned on because the RFT has priority for the available solar heat, and this allows the temperature of the DHWT to drop to the minimum allowed. This causes a relatively large exergy discharge in all cases.

Table 2 shows the annual exergy destroyed as well as the annual exergy efficiency of the two storage tanks for each of the configurations. It can be seen that there is a link between the number of solar collectors the configuration uses, and the amount of annual exergy destroyed in the storage tanks.

Configuration	Radiant Floor Tank		Domestic Hot Water Tank	
	Exergy destroyed [kWh]	Exergy efficiency [%]	Exergy destroyed [kWh]	Exergy efficiency [%]
BCSCS	4184	14.5	472	40.2
LCC optimal	5511	10.8	1140	16.8
LCE optimal	2271	23.4	302	51.8
LCX optimal	5481	11.0	1156	15.9

Table 2. Annual exergy destroyed and exergy efficiency of the two storage tanks

The configurations that use more solar collectors, the BCSCS and the LCE optimal configuration, destroy less exergy in the storage tanks than the configurations that use fewer solar collectors. Consequently, the exergy efficiency of the both storage tanks becomes greater with more solar collectors. The problem, however, is that it is the solar collectors that is largely responsible for the destruction of exergy in the solar combisystem [10], therefore when more solar collectors are used, the overall system destroys more exergy because the savings in exergy destroyed by the storage tanks are offset by the extra exergy destroyed by the solar collectors.

4. Conclusions

For all four configurations of the solar combisystem studied, the two independent storage tanks, the radiant floor tank and the domestic hot water tank, act more as exergy transition tanks rather than exergy storage tanks. This is because very little exergy is actually stored for any significant amount of time. Larger storage tank volumes are required for more exergy storage.

The exergy efficiency of the storage tanks is influenced by the collector area, as larger collector areas result in less exergy destroyed in the storage tanks and thus higher exergy efficiencies. However, more exergy is destroyed in the solar collectors when larger collector arrays are used, therefore the savings in exergy destroyed in the storage tanks are negated by the additional exergy destroyed in the solar collectors with larger collector areas.

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6. Nomenclature

BCSCS	Base case solar combisystem
$C_{p,w}$	Specific heat of water
DHWT	Domestic hot water tank
$\dot{E}_{aux}$	Auxiliary electricity rate
$E_{p,aux}$	Primary auxiliary electricity
F_p	Primary energy factor
LCC	Life cycle cost
LCE	Life cycle energy use
LCX	Life cycle exergy destroyed
$\dot{m}_f$	Mass flow rate of collector fluid
m_w	Mass of water
$\dot{m}_w$	Mass flow rate of water
RFT	Radiant floor tank
T_a	Ambient temperature
T_{in}	Incoming temperature of tank water

$T_{in,HX}$	Incoming collector fluid temperature of the immersed heat exchanger
T_{out}	Outgoing temperature of the tank water
$T_{out,HX}$	Outgoing collector fluid temperature of the immersed heat exchanger
T_r	Room temperature
T_{tank}	Average tank temperature
U_L	Overall heat loss coefficient through the tank walls
$\dot{X}_d$	Rate of exergy destroyed
$\dot{X}_{in}$	Rate of incoming exergy
$\dot{X}_{in,HX}$	Rate of incoming exergy in the immersed heat exchanger
$\dot{X}_L$	Rate of exergy leakage
$\dot{X}_{out}$	Rate of outgoing exergy
$\dot{X}_{out,HX}$	Rate of outgoing exergy in the immersed heat exchanger
X_s	Exergy stored
X_{tank}	Exergy content of the storage tank
α	kJ to kWh conversion factor
η_{II}	Exergy efficiency

7. Acknowledgements

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8. Biographies

Jason Ng Cheng Hin has recently completed a Master of Applied Science degree in Building Engineering at Concordia University in Montreal. His work focused on the optimization of a model of a solar combisystem.

Dr. Radu Zmeureanu is a Professor of Building Engineering at Concordia University in Montreal, and Associate Dean, Student Academic Services, of the Faculty of Engineering and Computer Science.

Dr. Marc A. Rosen is a Professor of Engineering at the University of Ontario Institute of Technology, where he served as founding Dean of the Faculty of Engineering and Applied Science. He is a Director of Oshawa Power and Utilities Corporation, and has been President of the Engineering Institute of Canada and the Canadian Society for Mechanical Engineering. He is Editor-in-Chief of the journal Sustainability and Editor of Energy Conversion and Management.