Optimization of a Residential Solar Combisystem for Minimum Life Cycle Energy and Cost

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Abstract

This paper presents the optimal configurations of a combisystem in terms of life cycle energy and cost given the Canadian climate, equipment, and energy costs. Additionally, the paper presents the effectiveness of certain optimization techniques when they are applied to solar combisystems.

The transient simulation software TRNSYS is used with a model of an energy efficient house in Montreal that is equipped with a solar combisystem. A hybrid particle swarm and Hooke-Jeeves optimization algorithm is used to determine the optimal configuration of the solar combisystem. Two separate objective functions are used to find two separate optimal configurations in terms of life cycle cost and life cycle energy.

1 Introduction

Residential buildings account for 17% of the total energy use in Canada (NRCan 2010). In this sector alone there are vast improvements to be made. Countless efforts are being made to find new and innovative technologies that will help with improving the energy efficiency of our homes. One such innovation is the solar combisystem. A solar combisystem consists of solar collectors and storage tanks that are used for both domestic hot water and space heating needs. In North America, solar collectors are typically used solely for domestic hot water (DHW) purposes (Weiss & Mauthner 2011).

Despite numerous international research initiatives, there is no single recommended way of determining the optimal configuration for a combisystem in a given climate, particularly the Canadian climate, since each combisystem configuration is highly dependent on the local weather and energy demand profile. Although the performance of solar combisystems has been studied extensively for decades in Europe, very little has been done to optimize the combisystem design in terms of life cycle energy and cost.

Literature review

Several extensive research projects have been completed in Europe between 1998 and 2010. The International Energy Agency Solar Heating and Cooling Programme (IEA-SHC) devoted one of their working tasks, Task 26, to solar combisystems. The project, which lasted from 1998 to 2002, involved the generalization and analysis of 21 different configurations of combisystems and further investigation of nine of those configurations (IEA-SHC 2002). For these nine configurations, a sensitivity analysis was performed on TRNSYS models of the systems to obtain optimal configuration parameters. The combisystem modeled for this project is not the same as any of the nine modeled in detail for Task 26.

From 2001 to 2003, the European Commission, under the Altener programme and in collaboration with IEA-SHC Task 26, studied over 200 combisystems in seven European Community countries, monitored 39 different systems and developed guidelines for installation and design (Altener, 2003). They also provided documents to aid with characterization and comparison of different systems.

Furthermore, from 2007 to 2010, Intelligent Energy Europe (IEE) commissioned a project known as Combisol (IEE, 2010). The objective of this project was to develop best practices, standards, and recommendations for manufacturers, installers, authorities and technical experts. The project reduced the proposed European combisystems to six different configurations. Again, the model considered for this project does not reflect any of those six.

Apart from those international research projects which attempted to study the performance of different combisystem configurations, several other individual research efforts have also attempted to apply optimization techniques to combisystems. Fraisse et al. (2009) studied optimization criteria to determine which is most suitable for optimization of solar combisystems. The study found that the financial and the energy-based optimization criteria of the combisystem are most suitable for optimization of combisystems and that the life cycle cost criterion is one of the most effective.

This paper presents a detailed analysis of one type of configuration of a solar combisystem using life cycle cost and life cycle energy as optimization criteria.

2 Methodology

A model of an energy efficient house equipped with a solar combisystem was created in the transient simulation software, TRNSYS (Klein et al. 2006), by Leckner and Zmeureanu (2008). For this study, the model was slightly modified and is coupled with the generic optimization program, GenOpt (Wetter 2009) for optimization purposes. Two individual objective functions are developed, the life cycle cost and life cycle energy, respectively, and the model is optimized separately using each of the functions. The optimization considers only the solar combisystem parameters.

Energy efficient house model

The energy efficient house model was developed in TRNSYS for the purpose of studying the life cycle cost and energy effects of converting a standard mid 1990's single family home in Quebec into a net-zero-energy home equipped with photovoltaic panels and a solar combisystem. For the purpose of this paper, the photovoltaics are removed from the model. The model uses weather data from a TRNSYS supplied Meteonorm weather file for Montreal, Quebec.

The house is a two story, detached, wood frame construction in Montreal with a total heated floor area of 210 m^2. The house is occupied by a family of two parents and three children. The energy efficiency upgrades to the house include: higher thermal insulation, better performing windows, higher window/floor area ratio, reduced air infiltration, energy efficient lighting and appliances, reduced domestic hot water use, installation of a drain water heat recovery unit, and finally the installation of a solar combisystem to supply heat for the domestic hot water system as well as the radiant floor heating system. Due to space limitations, only some details are presented in the paper. More details of the house design, including detailed dimensions, specifications, occupancy schedules, and demand profiles can be found in (Leckner 2008).

Base Case Solar Combisystem Design

The base case solar combisystem (BCSCS), used as the starting point in this study, uses two independent storage tanks for the radiant floor heating system and domestic hot water system respectively. Figure 1 shows a schematic diagram of the combisystem design.

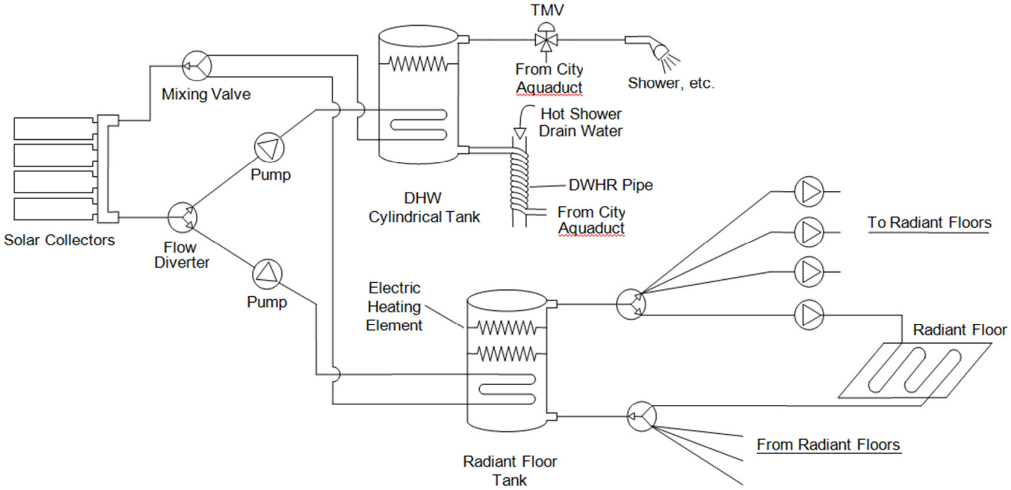

Figure 1: Schematic diagram of the base case solar combisystem (Leckner 2008)

The BCSCS uses four of these collectors in series, each having an area of 2.73 m^2. The collector fluid is composed of a 60% glycol-water mixture. The collector fluid flow rate of the BCSCS is set at a constant 100 kg/hr when the pumps are running.

Both the radiant floor tank (RFT) and the domestic hot water tank (DHWT) are 300 L vertical cylinder tanks. Each tank contains an internal heat exchanger through which the collector fluid circulates before returning to the collectors. Auxiliary energy is provided directly to the tanks via internal heating elements when the available solar energy is insufficient to cover the demand of the house. The DHWT contains one element of 1 kW while the RFT contains two elements of 2 kW and 4 kW, respectively. Heating of the house is accomplished by a closed loop radiant floor heating system, which is supplied with hot water from the RFT. The total annual electricity use of the base case house is shown by end use in Figure 2.

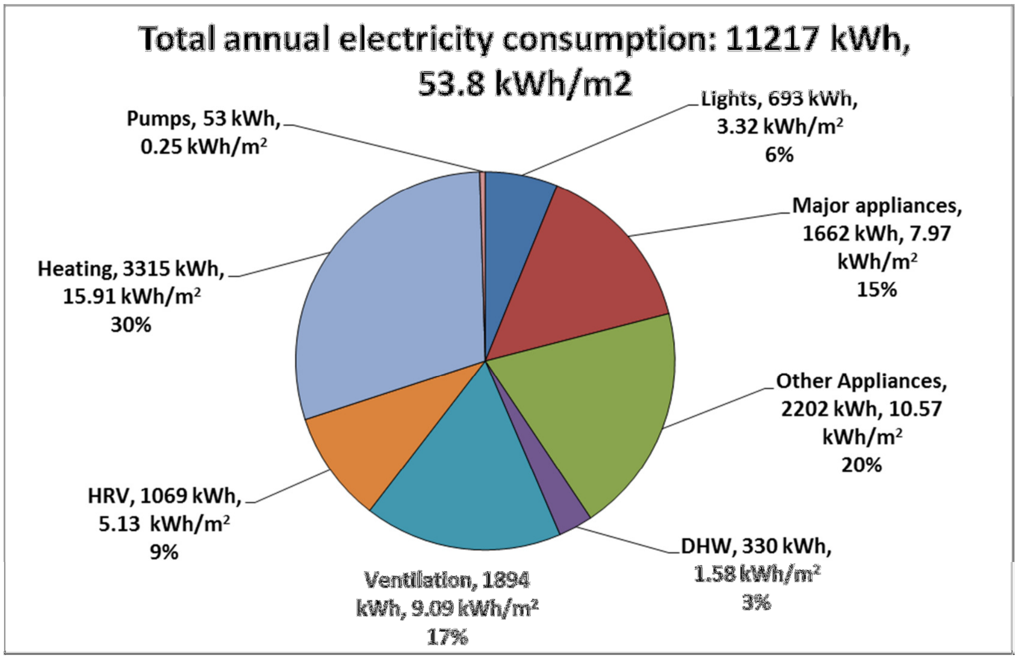

Figure 2: Annual electricity consumption by end use of the energy efficient house with the base case solar combisystem

Optimization variables

The combisystem variables selected for the optimization are based on the analysis performed by Streicher and Heimrath (2003). Of the 13 variables studied by Streicher and Heimrath, eight variables were found to have the most effect on this combisystem, and are used for this optimization. Table 1 shows the variables selected for the optimization, the range within which they are optimized, their initial step size, and the initial value (starting point).

The number of solar collectors is limited by the available space on the south facing roof, which is approximately 60 m^2, or enough for 22 collectors. The maximum tank volumes are limited by the space available in the basement of the house and the minimum tank volumes are set as standard volumes of 300 l (60 gal) generally used in houses. The authors did not explore smaller tank volumes or smaller auxiliary heaters, however, it will be considered in the next phase of this study. Also, the collector fluid flow rate is limited by the manufacturer's recommendations.

Table 1: Optimization variables, variable range, step size and initial value

Variables	Range	Initial Step Size	Initial Value	Units
Number of solar collectors	1 - 22	1	4	each
RF tank volume	300 – 30 000	100	300	liters
DHW tank volume	100 - 1000	100	300	liters
DHW auxiliary power	0.5 - 5	0.5	1	kW
RF auxiliary power high	0.5 - 10	0.5	2	kW
RF auxiliary power low	0.5 - 15	0.5	4	kW
Collector tilt	0 - 90	5	45	degrees
Collector flow rate	10 - 115	5	45	$kg/hr/m^2_{collector}$

Objective functions

The objective functions used in this paper are: the life cycle cost (LCC) and the life cycle energy (LCE) of the solar combisystem. These functions only take into account equipment and energy consumption related to the combisystems and do not include any other aspects of the house. The two objective functions are based on the life cycle of the house, which is assumed to be 40 years.

Life cycle cost

The LCC of the solar combisystem is composed of three parts: 1) the initial cost; 2) the replacement costs of all of the components upstream of, and including, the two tanks; 3) annual operating costs which include the cost of the auxiliary energy used for the electric heating elements of both tanks as well as the electricity used for the two collector fluid circulating pumps upstream of the two tanks. The radiant floor heating system and the drain water heat recovery system are not included in the cost of the combisystem. The cost of disposing each component is not considered in this paper since there is presently little information in literature about the disposal costs of these technologies.

The initial cost of each component of the combisystem is set as a function of the variables being optimized based on cost data from various manufacturers of each component. Some of the components must be replaced within the life cycle of the house. To accurately account for these replacement costs, the effects of inflation must be considered. Therefore, the present worth of the replacement costs, PW_N, is calculated using the Equation 1:

$$PW_N = R * \left(\frac{1+i}{1+d}\right)^N \tag{1}$$

where:

R = Replacement cost of equipment [\$];

i = Annual inflation rate, 2% (Bank of Canada 2011);

d = Discount rate, 6% (MNECCB 1997);

N = Replacement period [years]

Table 2 shows the formulas for the initial cost of each component of the combisystem as well as their replacement periods. The present worth of equipment costs comes from adding the initial cost of all of the components with the present worth cost of all the replacement equipment over 40 years.

Table 2: Initial cost and replacement period of all the combisystem components

Component	Initial Cost (\$)	Replacement Period (years)
Solar collectors	1548.9 x $N_{collector}$ + 1146.8	25
Radiant floor tank	2.746 x V_{RFT} + 952.35	15
Domestic hot water tank	2.746 x V_{DHWT} + 952.35	15
Glycol	15.53 x $N_{collector}$ + 148.26	3
Pumps (x2)	827 (each)	10
Controller	227	15
Pipes	318	--

Where: $N_{collector}$ = number of collectors, V_{RFT} = RFT volume (Liters), V_{DHWT} = DHWT volume (Liters)

One other factor to consider is the reduction in the cost of the solar collector technology over time. Based on a report published by the International Energy Agency (IEA 2007), the investment cost for solar thermal systems (including solar domestic hot water preparation, combisystems, large scale systems, and thermo-siphon systems) is expected to decline by 35% - 50% by 2030. The lower end of the range of 35% is used as the reduction in the cost of the solar collectors over the 25 year replacement period.

As with the replacement cost of the equipment, inflation must be taken into account when estimating the annual operating cost over the life cycle of the house. The rise in the cost of electricity per year must also be taken into account. Therefore, Equation 2 is used to convert the annual operating costs over the life cycle of the house into present worth dollars.

$$PW_{Energy\ cost} = C * \frac{1-(1+a)^{-n}}{a} \tag{2}$$

where:

$PW_{energy\ cost}$ = Present worth of annual heating costs over n years [\$];

C = Annual heating cost in 1st year [\$];

a = Effective interest rate (MNECCB 1997);

$$a = \frac{(i_d - e)}{(1+e)}$$

e = Increase rate of energy costs, 2.15% (Hydro Quebec 2006-2010);

i_d = Discount rate including inflation, 8% (MNECCB 1997);

n = Life span of house, 40 years.

The price of electricity is taken as \$0.0776/kWh, which is the average price of electricity, as of April 1st, 2010, for residential customers using an average monthly consumption of 1000 kWh in Montreal (Hydro Quebec 2010).

One last factor to consider for the life cycle cost is that there is a possibility that the heating system could be undersized if, for example, the smallest values for each variable are selected during the optimization process. Therefore, in order to ensure that the heating system is capable of keeping the temperature of each room at or above the set point temperature, a penalty function is applied. It is assumed that it is reasonable for the house to allow all of the rooms to be under the set point temperature for a half hour each day. This equates to approximately 550 hours that all of the rooms are allowed to cumulatively spend under the set point temperature during the heating season. If the optimization algorithm selects a combisystem configuration that allows the house to spend more than 550 hours under the set point temperatures, it will automatically add an arbitrarily large cost penalty ($200,000) to the LCC of the system. For comparison, the BCSCS has an approximate LCC of $28,000, thus the penalty definitively eliminates that particular configuration as a potential optimal value. Considering these three costs of the system described above, the objective function for the LCC of the system is calculated using Equation 3.

$$Minimize: LCC = Initial\ Cost + PW_{Replacement\ cost} + PW_{Energy\ cost} + lt(550, HUSP) * 200000 \tag{3}$$

where:

Initial cost = the summation of the values found in the ‘initial cost’ column of Table 3.

$PW_{Replacement\ cost}$ = the present worth of all of the replacement equipment over the life cycle of the house.

$PW_{Energy\ cost}$ = the present worth of the operating costs (Equation 2).

HUSP = the total number of hours that all rooms spend under the set point temperatures during the heating season.

The function *lt(550,HUSP)* returns 1 if 550 is less than HUSP and 0 if 550 is greater than HUSP.

Life cycle energy

The life cycle energy objective function is composed of two separate parts: 1) the embodied energy of the equipment and materials of both the initial and replacement parts; and 2) the life cycle operating energy use. The life cycle energy analysis considers only energy that is paid for. Solar or geothermal energy is not normally included in such analysis. However, the reviewer’s question brought a different view on the energy used that is worth investigating.

The embodied energy of the equipment is difficult to estimate. Few studies have attempted to accurately estimate the embodied energy of the components of a combisystem due to the complexities that arise from estimating certain variables such as location, methods of manufacturing, transportation methods, and primary energy considerations. For this paper, the embodied energy of each component of the combisystem is estimated individually and the total embodied energy of the combisystem is the sum of the embodied energy of each component considering the amount of times they are replaced over the life of the house.

Table 3 summarizes the embodied energy of flat plate collectors from current literature. The data in this table represents only the embodied energy for the collectors and does not include the shipping or piping. The average value of 516 kWh/m^2 is used for this study.

Shipping for the flat plate solar collectors is estimated at 50 kWh/collector (Leckner 2008). The embodied energy of copper piping is estimated at 27 kWh/m (Leckner 2008). It is assumed that the combisystem requires 24.8 L of propyle glycol solution for one collector, and an extra 2.25 L for each additional collector (Leckner 2008) and it is assumed that the 60% propylene glycol solution has an embodied energy of 21.5 kWh/kg (Ardente et al 2005). Insufficient information is currently available to make a reasonable assumption of the embodied energy of the pumps and controller. Therefore, the embodied energy of these two components is ignored.

For the two hot water storage tanks, the embodied energy is estimated by using current data in literature as well as estimates of materials and energy used for common storage tanks. Table 4 shows a summary of the embodied energy of hot water storage tanks in published literature. The problem with this data is that only one estimate considers a tank that is larger than 160 L, so it is difficult to extrapolate the embodied energy for larger tanks.

Table 3: Summary of embodied energy of flat plate solar collectors in literature

Area of Collectors (m^2)	Embodied Energy (kWh)	Embodied Energy (kWh/m^2 of collector area)	Source
1.4	740	548	Kalogirou 2009
2.13	976	458	Ardente et al 2005
2	1,000	500	Gurzenich and Mathur 1998
98.4	74,167	754	Gurzenich and Mathur 1998
5	1,780	356	Streicher et al 2004
5	2,398	480	Streicher et al 2004
	AVERAGE	516	

Table 4: Summary of embodied energy of hot water storage tanks in literature

Tank volume (L)	Total Embodied Energy (MJ)	Total Embodied Energy (kWh)	Total Embodied Energy per Litre of Tank (kWh/L)	Source
100	1540	427.8	4.3	Gurzenich and Marthur 1998
135	1521	422.5	3.1	Gurzenich and Marthur 1998
160	4126.9	1146.4	7.2	Ardente et al 2005
38600	68126	18923.9	0.5	Hugo 2008

The embodied energy of larger solar hot water storage tanks is estimated by calculating the amount of materials used in typical storage tank constructions and determining the embodied energy using the respective weight of each material. Using this method combined with the data of Table 4, a correlation between embodied energy and tank volume is developed and shown in Figure 3.

The life cycle operating energy use is calculated by multiplying the annual auxiliary energy use and pump electricity use over 40 years. Also, a factor of 1.3 is used to convert the site operating energy into primary energy use by considering, the Quebec electricity mix, the respective efficiencies of each type of power plant (Hugo 2008), and transportation and distribution losses of 6% (Zmeureanu and Wu 2007).

A penalty function similar to the LCC objective function is also considered for the LCE objective function. If the combisystem design allows the rooms of the house to accumulate over 550 hours under the set point temperature, an energy penalty of 300,000 kWh (where the BCSCS has an approximate LCE of 225,000 kWh) is added to the LCE of that system.

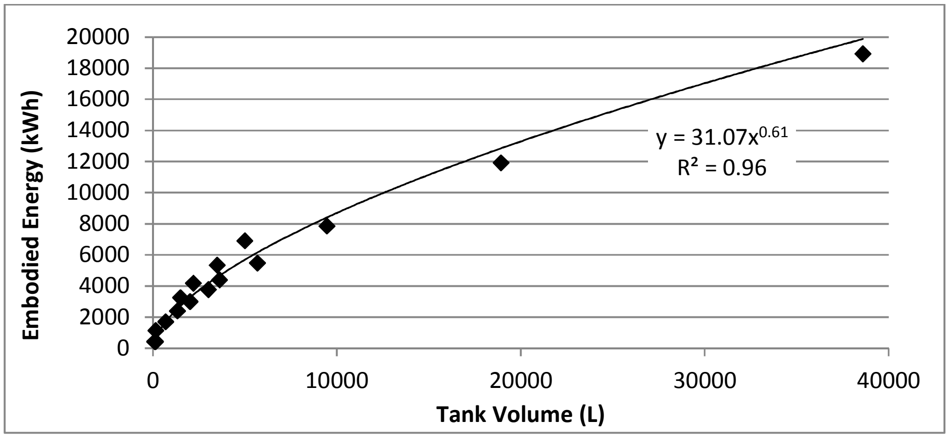

Figure 3: Estimated embodied energy of solar water storage tanks

Finally, Equation 4 is used to estimate the total LCE of each combisystem design:

$$Minimize\ LCE = EE_{Equip} + EE_{Repl} + 1.3 * 40 * E_{op} + lt(550, HUSP) * 300{,}000 \quad (4)$$

where:

EE_{Equip} = Embodied energy of all the initial equipment including: solar collectors, storage tanks, pipes, and glycol [kWh];

EE_{Repl} = Embodied energy of all the replacement equipment [kWh];

E_{op} = Annual combisystem electricity use [kWh].

The function *lt(550,HUSP)* returns 1 if 550 is less than HUSP and 0 if 550 is greater than HUSP. The replacement time for each piece of equipment is found in Table 3.

Optimization algorithm

The algorithm used to optimize the BCSCS design is a hybrid particle swarm (PSO) and Hooke-Jeeves (HJ) generalized pattern search algorithm (Wetter 2009). The algorithm begins with a particle swarm optimization (Kennedy & Eberhart 1995) on a mesh, which is used as a stochastic global search method for a user-specified number of generations; then the Hooke-Jeeves algorithm (Hooke & Jeeves 1961) is started using, as a starting point, the optimum solution that produced the lowest objective function value from the particle swarm optimization. The hybrid algorithm is used because it is found to be a good compromise between its ability to find an optimal solution, the computation time required and the complexity of applying it (Wetter 2004). Also, this algorithm comes built-in to the GenOpt software, thus making it relatively simple to apply to a TRNSYS model.

GenOpt works with TRNSYS by creating TRNSYS input files based on a template and replacing each variable in the template with values determined by the algorithm in GenOpt. Then, based on the results of each simulation, the algorithm determines new variables to place into the TRNSYS input file. For this paper, this process is repeated until the Hooke-Jeeves portion produces no further reductions, that is, the change in the value of the objective function is at most zero.

3 Results

Two separate optimizations are performed for each objective function, resulting in four separate optimizations. For each objective function, two different initial starting points are used. In all four cases the algorithm parameters remain constant. Table 5 shows the initial starting points used for each optimization. The BCSCS is used as the starting point for both objective functions while a relatively expensive configuration is arbitrarily selected as the second case for each objective function. The objective of this is to confirm results of the optimizations by forcing the algorithm to take a different path.

Table 6 shows the results of each optimization in terms of LCC, LCE and the design variables for all four optimizations as well as the BCSCS for comparison purposes.

Table 5: Initial values for each optimization

Variables	Initial values			
	Life cycle cost (LCC) optimization		Life cycle energy (LCE) optimization	
	Case 1	Case 2	Case 1	Case 2
Number of solar collectors	4	4	4	20
Collector slope (Degrees)	45	20	45	25
Collector fluid flow rate ($Kg/hr/m^2_{collector}$)	10	10	10	70
DHWT volume (L)	300	500	300	700
RFT volume (L)	300	3000	300	25000
DHWT auxiliary power (KW)	1	2	1	2.5
RFT auxiliary power high (KW)	2	4	2	4
RFT auxiliary power low (KW)	4	8	4	7.5

Table 6: Optimization results: optimal configurations, life cycle cost and life cycle energy

Variables	BCSCS	Life cycle cost (LCC) optimization		Life cycle energy (LCE) optimization	
		Case 1	Case 2	Case 1	Case 2
Number of solar collectors	4	2	1	9	9
Collector slope (Degrees)	45	67	58	69	75
Collector fluid flow rate ($Kg/hr/m^2_{collector}$)	10	20	20	10	13.75
DHWT volume (L)	300	100	100	100	100
RFT volume (L)	300	300	300	300	300
DHWT auxiliary power (KW)	1	0.5	0.5	0.56	0.75
RFT auxiliary power high (KW)	2	2.4	3	1	0.5
RFT auxiliary power low (KW)	4	0.5	0.5	0.5	3
Objective functions					
Life cycle cost ($)	**26,606**	**22,408**	**21,461**	**33,757**	**33,749**
Reduction of life cycle cost from base case	**--**	**16%**	**19%**	**-27%**	**-27%**
Life cycle energy (kWh)	**228,193**	**260,927**	**307,253**	**150,727**	**150,350**
Reduction of life cycle energy from base case	**--**	**-14%**	**-35%**	**34%**	**34%**

Figure 4 shows the electricity use of the BCSCS as well as for the LCC and LCE optimal solutions. The electricity use is split up between the auxiliary heaters of the DHWT and the RFT as well as the electricity required to run the collector fluid pumps.

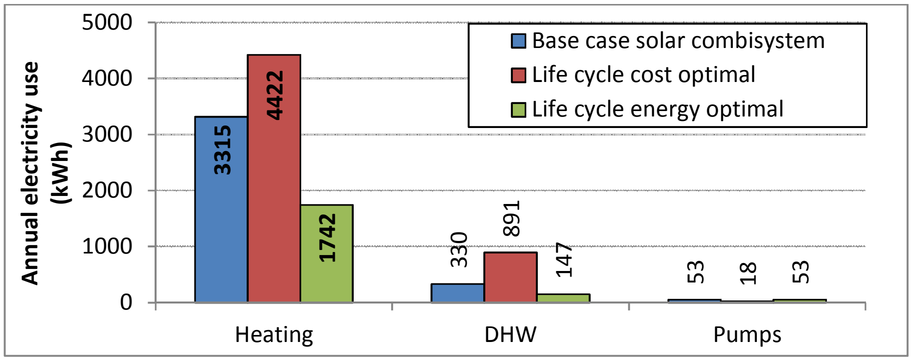

Figure 4: Annual combisystem electricity use of base case solar combisystem and of optimum configurations for life cycle cost and life cycle energy

Algorithm performance

Figures 5 and 6 show the progression of the value of the LCC and LCE objective functions during each optimization, respectively. Here, the difference between the two different algorithms can be observed. The PSO portion is intended to find a solution near the optimal solution in a relatively small number of simulations while the HJ portion requires more simulations for smaller gains, but improves the solution found by the PSO portion. The major spikes are caused by the penalty functions.

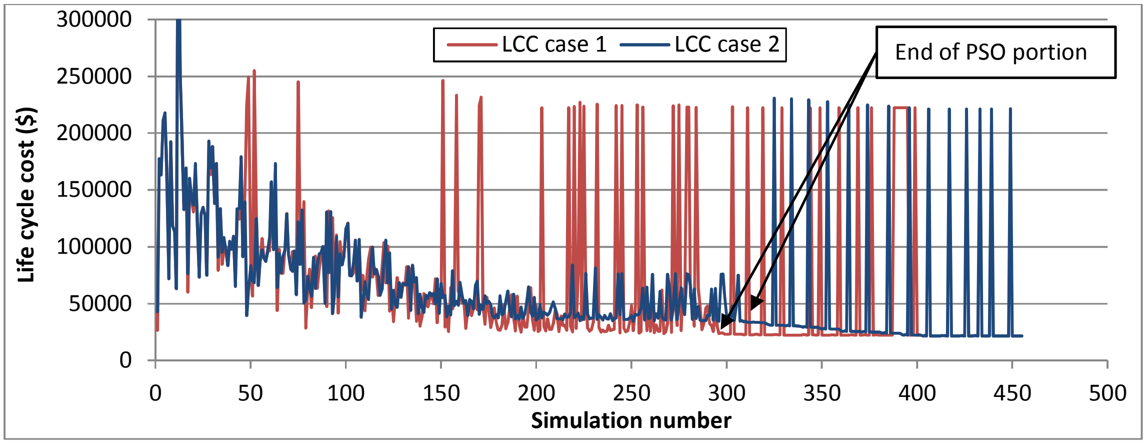

Figure 5: Evolution of objective function during the life cycle cost optimization

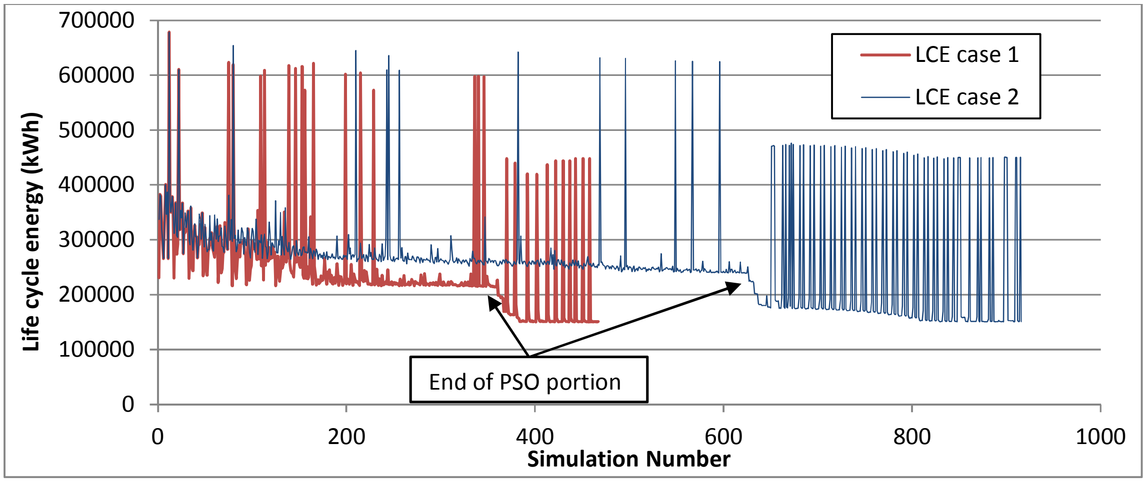

Figure 6: Evolution of objective function during the life cycle energy optimization

4 Discussion

The results demonstrate that the combisystem design has potential for vast improvements if the design focus is shifted from performance to life cycle cost or life cycle energy. The separate optimizations decreased the LCC and LCE of the BCSCS by 16-19% and 34%, respectively. However, the improvements in LCC and LCE come at the cost of the other objective function. The LCC optimal solution increased the LCE of the BCSCS by 14-35% while the LCE optimal solution increased the LCC of the BCSCS by 27%. The BCSCS could perhaps be considered as a reasonable compromise between the two objective functions, but a Pareto front solution would need to be obtained in order to determine the real optimal compromise between LCC and LCE. In general, however, the life cycle cost optimal solution requires more energy while the life cycle energy optimal solution requires more money.

The LCC optimal solution is obtained with a small (1-2) number of solar collectors, thus increasing the amount of auxiliary electricity required, as demonstrated in Figure 4. This reduction of initial cost of solar collectors, combined with the relatively inexpensive electricity in Quebec, which at $0.0776/kWh is the least expensive electricity in Canada (Hydro Quebec 2010), makes it more cost effective. The LCE optimal solution is obtained with a greater number of solar collectors (9). These two optimum configurations have the same storage tanks: RFT of 300 l, and a DHWT of 100 l.

Figures 5 and 6 demonstrate the advantages of the hybrid PSO and HJ algorithm. In all the optimizations the PSO portion is successful at reducing the value of the objective function however only in the LCC case 1 optimization did the PSO portion find a solution very near the optimal found by the HJ portion. In the other cases, the HJ portion reduced the value of the objective function by a significant additional amount, particularly in LCE case 2. The problem with this is that it requires significantly more time to complete the same number of simulations during the HJ portion as compared to the PSO portion since the latter is capable of running simultaneous simulations on multi-core processors within the same generation while the Hooke-Jeeves portion cannot. For example, the LCE case 1 optimization required 352 simulations for the PSO portion and 115 simulations for the HJ portion (total = 467) and took approximately 85 hours to complete while the LCE case 2 optimization required 618 simulations for the PSO portion and 298 for the HJ portion (total = 916), but took approximately 183 hours to complete (both optimizations were completed with an Intel Xeon processor with 6 cores @ 2.4 GHz). Therefore, if a computer with a multi-core processor is being utilized, as is the case for this study, it is more efficient to improve the results of the PSO portion to minimize the time spent during the HJ portion. This can be achieved by forcing the particles to spread out more during the PSO portion so that the swarm explores more of the solutions space. This can be done by either increasing the maximum velocity gain for continuous variables or increasing the constriction gain.

The results of the two LCE optimizations (case 1 and case 2) show somewhat different values for some variables such as collector tilt (69 vs. 75 degrees), collector fluid flow rate (10.00 vs. 13.75 kg/hr/m^2), DHWT auxiliary power (0.56 vs. 0.75 kW), RFT auxiliary power high (1 vs. 0.5 kW) and RFT auxiliary power low (0.5 vs. 3 kW).

One disadvantage of the hybrid algorithm is the way that discrete and continuous variables are dealt with. Variables set as continuous are in fact not actually continuous since they can only ever take values that are multiples of the initial step size during the PSO portion and reduced step sizes during the Hooke-Jeeves portion. In the case of this paper, the only variable set as discrete is the number of solar collectors. This was done to avoid ending up with a solution that uses a fraction of a collector. The PSO portion of the algorithm treats all variables as discrete variables, since they can only be modified by a multiple of the intial step size within their range. For example, the DHWT volume can only take values that are multiples of 0.1 m^3 between 0.1 and 1.0 m^3, even though it is set as continuous.

During the HJ portion, the step sizes of the continuous variables are systematically reduced to find the optimum solution. The discrete variables, however, are held constant at the value found by the PSO portion. That is, if the PSO portion selects a value for a discrete variable that will not produce an optimum solution, the HJ portion will not be able to correct it. This is seen in the LCC case 1 optimization, where the PSO portion ended with a value of two for the number of solar collectors, which proved to be incorrect when the LCC case 2 optimization converged at one collector and had a lower LCC.

During the LCE case 2 optimization, the PSO portion ended with a value of 11.6 m^3 for the RFT volume, which is part of the reason for the high LCE at the end of the PSO portion. The HJ portion, however, was able to modify that value to eventually reach the minimum of 0.3 m^3 in the final solution since the RFT volume is set as a continuous variable.

Future work

Future work for this project includes performing the optimization in at least two different climate conditions in Canada to see the influence of weather on LCC and LCE. It was beyond the scope of this project to test the sensitivity of the house model to parameters such as occupancy schedules, or the financial parameters. This is a topic of future work. Other future work include:

- Testing different optimization settings to streamline the optimization process and improve reliability;
- Optimize combisystem for minimum life cycle exergy loss;
- Improve combisystem design and optimize the improved design;
- Optimize the combisystem for different houses, locations and energy prices.

5 Conclusions

The hybrid particle swarm optimization and Hooke-Jeeves algorithm is effective at reducing the value of the objective functions regardless of which objective function is considered. The LCC of the combisystem was reduced by 16 - 19% and the LCE was reduced by 34%compared to the base case combisystem which was designed based on design recommendations to meet the needs of the house. However, several inefficiencies with this algorithm exist. If the wrong algorithm parameters are selected, the algorithm can take twice as much time to find a solution than the same algorithm with more optimal parameters selected. Also, using discrete variables with the hybrid algorithm increases the risk of not finding a global optimum because the Hooke-Jeeves portion of the hybrid algorithm does not modify discrete variables. Finally, it is more time-effective to select algorithm parameters that will increase the effectiveness of the particle swarm optimization portion if a computer that uses a multi-core processor is being used since this portion of the hybrid algorithm is capable of running simultaneous simulations while the Hooke-Jeeves portion cannot.

For the combisystem parameters, in terms of both life cycle cost and life cycle energy, it is best to use smaller tank volumes. In every optimization case, the tank volumes were reduced to 300 L for the RFT and 100 L for the DHWT. To minimize life cycle cost, fewer solar collectors are required because electricity rates are low in Quebec. For this particular house and combisystem configuration, one solar collector is optimal for LCC. To minimize life cycle energy, nine flat plate solar collectors is optimal. The remaining variables such as collector tilt, collector fluid flow rate, and auxiliary power have little impact on the life cycle energy. However, for the collector tilt, the optimum value is between 58 - 75 degrees, which is greater than the value usually recommended for solar collectors in Montreal. Also, for optimal LCC, the DHWT and lower RFT auxiliary heating elements are set at 0.5 kW while upper RFT auxiliary heating element is increased to 3 kW. For optimal LCE, the DHWT auxiliary heating element ranges from 0.56 - 0.75 kW while the lower RFT element ranges from 0.5 – 1 kW and the upper RFT element ranges from 0.5 – 3 kW. The RFT auxiliary heating element arrangement seems to have little effect on the LCE of the combisystem. The collector fluid flow rate is set at 20 kg/hr/m^2 for optimal LCC, but for optimal LCE, it is set between 10 – 13.75 kg/hr/m^2. Finally, a combisystem that performs well in terms of life cycle cost will perform poorly in terms of life cycle energy and vice-versa.

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