A Methodology for Optimizing Solar Thermal Combisystems: From Data Collection to Multi-Objective Optimization

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Abstract

This paper presents a methodology for optimizing solar thermal combisystems from data collection to multi-objective optimization, which is applied to an existing residential solar thermal combisystem installed in Massachusetts, USA. This solar combisystem, installed in an occupied house, is composed of two distinct arrays of flat-plate collectors of 15.8 m² connected to a thermal storage tank of 617 litres, and provides for domestic hot water and space heating. The methodology comprises: (i) presentation of the solar combisystem, (ii) outliers detection and uncertainty analysis of measurements, (iii) model validation, (iv) trend data analysis, and (v) multi-objective optimization.

Introduction

Solar energy is one of the most suitable renewable energy sources for residential buildings. As mentioned in (Bornatico et al., 2012), solar thermal combisystems have the advantage of providing thermal energy for both domestic hot water (DHW) and space heating (SH) needs. Such systems have been studied since 1990s, Task 26 (Suter et al., 2000) being an early example. Most research studies were simulation-based such as (Lund, 2005; Anderson and Furbo, 2007; Leckner and Zmeureanu, 2011; Žandeckis et al., 2016). Techno-economic feasibility of retrofitting solar combisystems to houses in Canada in (Asaee et al., 2016) showed that approximately 40% of houses in the Canadian housing stock are eligible for such a retrofit. The annual energy consumption is expected to be reduced by 19%.

Few experiment-based studies have been conducted on solar thermal combisystems since experiments require higher investments and are less flexible than building performance simulation (BPS) programs. Experiments are however necessary for model validation. The analysis of the solar thermal market in Latvia was performed in (Žandeckis et al., 2011), followed by a data analysis of a solar combisystem implemented in a multi-family building. This study showed that reducing the use of natural gas by installing solar combisystems could ensure a more stable price for DHW and SH needs. The energy analysis of an experimental solar thermal combisystem was conducted in (Kaçan and Ulgen, 2012). Experiments were conducted to verify and increase the solar combisystem's performance, which led to the annual solar fraction of approximately 83%. The energy and exergy

analysis of a solar combisystem was performed in (Kaçan and Ulgen, 2014) based on an experimental setup built in Turkey. Tank volume was found to be one of the most important parameters to reduce the energy use. Experimental data from a solar thermal combisystem, installed in Ireland, were used to calibrate a TRNSYS model in (Clarke et al., 2014). The effect of solar combisystem components on the overall system exergy efficiency was assessed in (Kaçan, 2015). The optimum overall exergy efficiency of 11.95% was obtained. The lack of uncertainty analysis associated with building performance simulations was reported in (Attia et al., 2013).

Only a few studies have focused on the optimization of solar thermal combisystems. Some examples are mentioned here. The optimization of a simulation-based solar combisystem was performed in (Bornatico et al., 2012) using MATLAB. Three objective functions (solar fraction, energy use, and cost of the installation) were combined into one global objective function, then a single-objective optimization algorithm was used for the sizing of the given combisystem configuration. (Kusyy and Vajen, 2012) optimized the fluid mass flow rate of the solar combisystem. The hybrid particle swarm optimization/Hooke and Jeeves (PSO/HJ) algorithm was used in (Ng Cheng Hin and Zmeureanu, 2014) to minimize the life cycle cost, life cycle energy use, and life cycle exergy destroyed of a solar combisystem. The results show that the life cycle cost, life cycle energy use, and life cycle exergy destroyed were reduced by 19%, 34%, and 33%, respectively, compared with the initial design. Multi-objective optimizations of the same residential solar combisystem were performed in (Rey and Zmeureanu, 2016a; Rey and Zmeureanu, 2017).

This review showed that none of the aforementioned studies have covered all phases of the study of a solar combisystems from data collection to multi-objective optimization. Therefore such an approach is presented in this paper with the aim of helping the market penetration of solar thermal combisystems.

System Description

As illustrated in Figure 1, the monitored solar combisystem is composed of two distinct arrays of three flat-plate collectors each, giving a total of six solar thermal collectors. Both arrays of solar thermal collectors (i.e., arrays A1 and A2) are south-facing, but have two distinct tilt angles equal to 90° and 65° above the horizontal, respectively. Solar energy is harvested by a heat-transfer fluid, which is a 40% glycol-water mixture, circulated by pumps through the flat-plate collectors.

Figure 1: Scheme of the monitored solar thermal combisystem installed in Massachusetts, USA.

One storage tank, which allows solar energy to be stored, is used for both domestic hot water and space heating needs. Additional energy is provided, when it is required, by an electrical boiler for the radiant floor and by an electrical heater for domestic hot water. Temperature sensors and flow meters are installed at the locations indicated in Figure 1 and record measurements every minute. Average values are calculated to provide other data resolutions over five-minute interval, one hour, and one day. In this paper the hourly values are used, unless otherwise stated. Table 1 lists all the available sensors. The mass flow rates are recorded in L/min and converted

to kg/s, unless otherwise stated. The solar combisystem is installed in a house of approximately 110 m², inhabited by a family; however, no detailed information about the house nor about the energy-related people's behavior is available. As the outside air temperature and solar radiation are not measured on site during the studying period, both were obtained for the year 2014 from Weather Analytics (Weather Analytics, 2015) and for the year 2016 from (IES, 2017).

Energy Performance Indices

Two performance indices are used to assess the energy performance of the solar combisystem:

- Thermal efficiency of the solar collectors;
- Thermal energy stored in the storage tank.

As shown in Figure 1, the residential solar thermal combisystem has two different flat-plate collector arrays, A1 and A2, which have two distinct tilt angles equal to 90° and 65°, respectively. The hourly average thermal efficiency of the solar flat-plate collectors is calculated as follows (Equation 1) (Duffie and Beckman, 2006):

Table 1: List of the sensors installed on the solar thermal combisystem.

Sensor	Measured physical quantity	Unit
S0	Outdoor air temperature (available only since March 2015)	°C
S1	Outlet heat-transfer fluid temperature of A2 array	°C
S2	Water temperature of the lower part of the storage tank	°C
S3	Water temperature leaving the storage tank for the radiant floor	°C
S4	Water temperature of the upper part of the storage tank	°C
S5	Average heat-transfer fluid temperature leaving both arrays of solar collectors	°C
S6	Outlet heat-transfer fluid temperature of A1 array	°C
S7	Supply water temperature for the radiant floor	°C
S8	Supply domestic hot water temperature	°C
S9	DHW temperature leaving the electrical water heater	°C
S10	Temperature of the city water	°C
S11	Temperature of the hot water leaving the thermal storage tank	°C
S12	Heat-transfer fluid temperature entering the solar thermal collectors	°C
S13	Return water temperature from the radiant floor	°C
F1	Heat-transfer fluid mass flow rate through the solar collectors	L/min
F2	City water mass flow rate entering the storage tank	L/min
F3	Water mass flow rate through the radiant floor	L/min

$$\eta_{coll} = \frac{\Sigma \dot{m}_{coll,F1} c_{p,coll} (T_{S5} - T_{S12})}{\Sigma (A_{A1} G_{T,A1} + A_{A2} G_{T,A2})} \times 100 \quad (1)$$

$$Q_{SH,aux} = \dot{m}_{SH,F3} c_{p,water} (T_{S7} - T_{S13}) \Delta t \quad (7)$$

where T_{S9} and T_{S7} are the temperatures of the water

Figure 2: Hourly average thermal efficiency of the flat-plate collectors without the outliers versus time.

where $\dot{m}_{coll,F1}$ is the heat-transfer fluid mass flow rate [kg/s]; $c_{p,coll}$ is the specific heat of the heat-transfer fluid at constant pressure [kJ/(kg.°C)]; T_{S5} and T_{S12} are the outlet and inlet average heat-transfer fluid temperatures of the flat-plate collector arrays [°C], respectively; A_{A1} and A_{A2} are the gross surface areas of the flat-plate collector arrays A1 and A2 [m²], respectively; $G_{T,A1}$ and $G_{T,A2}$ are the total solar irradiances incident on the flat-plate arrays A1 and A2 [W/m²], respectively. The summation is carried out over one hour.

Since the thermal storage tank is not equipped with electric heater, its thermal energy stored, Q_{stored} , is calculated as follows:

$$Q_{stored} = Q_{supply} - (Q_{DHW,tank} + Q_{SH,tank}) \quad (2)$$

where:

$$Q_{supply} = \dot{m}_{coll,F1} c_{p,coll} (T_{S5} - T_{S12}) \Delta t \quad (3)$$

$$Q_{DHW,tank} = \dot{m}_{DHW,F2} c_{p,water} (T_{S11} - T_{S10}) \Delta t \quad (4)$$

$$Q_{SH,tank} = \dot{m}_{SH,F3} c_{p,water} (T_{S3} - T_{S13}) \Delta t \quad (5)$$

where Q_{supply} is the solar energy supplied to the thermal storage tank [kWh]; $Q_{DHW,tank}$ and $Q_{SH,tank}$ are the amounts of energy supplied by the tank for domestic hot water and space heating purposes [kWh], respectively; Δt is the time step of 1 hour [h]; $\dot{m}_{DHW,F2}$ and $\dot{m}_{SH,F3}$ are the water mass flow rates for DHW and SH needs [kg/s], respectively; $c_{p,water}$ is the specific heat of water at constant pressure [kJ/(kg.°C)]; T_{S11} and T_{S10} are the temperatures of the DHW leaving and entering the thermal storage tank [°C], respectively; T_{S3} and T_{S13} are the temperatures of the water leaving and entering the internal heat exchanger within the thermal storage tank for space heating [°C], respectively.

The domestic hot water and space heating energy needs $Q_{DHW,aux}$ and $Q_{SH,aux}$, which take into account additional auxiliary energy use, are expressed as:

$$Q_{DHW,aux} = \dot{m}_{DHW,F2} c_{p,water} (T_{S9} - T_{S10}) \Delta t \quad (6)$$

leaving the electric water heater and electric boiler [°C], respectively. The data set from that solar system had no measurements to lead to the calculation of those heat losses. Rather than assuming a relative value of losses (e.g. in percentage of thermal input), we prefer to assume the case of a storage tank well insulated.

Data analysis of the monitored solar combisystems

Data collection gives the opportunity of gathering information that can provide valuable insights; however, the misuse of data can lead to false conclusions. Missing data are replaced or removed (Reddy, 2011). Three periods of missing data from the sensor S5 for the year 2014 are: (i) March 8th to March 11th, (ii) September 15th from 1:00 am to 2:00 am, and (iii) November 27th from 3:00pm to 5:00pm. These three periods are removed and not used in the data analysis.

The outlier detection consists in the identification of data which differ significantly from the remaining data. If one measurement value is outside the interval of $\mu \pm Z \cdot S_x$, where μ is the mean value of data set, and S_x is the standard deviation, that value is identified as an outlier. For $Z=2$, 95.5% of data are within the confidence interval, while the remaining data are outliers (ASHRAE, 2015). As mentioned in (Leys, et al., 2013), three problems arise from this method of outlier identification: (i) the distribution is assumed to be normal (including outliers) for which Z is calculated, (ii) both the mean and standard deviation are strongly influenced by outliers, and (iii) it is very unlikely to detect outliers in small sample (Cousineau & Chartier, 2010). The median absolute deviation (MAD) was proposed as an alternative in (Leys, et al., 2013), which is defined as:

$$MAD(x) = b \cdot M(|x_i - M(x)|) \quad (8)$$

where x_i is the i -th occurrence of a batch of observations denoted by x ; $M(x)$ is the median operator applied to x ; b is equal to 2.5 as suggested in (Leys, et al., 2013).

The outlier detection of the thermal efficiency of the flat-plate collectors uses the MAD (see Eqs 8 and 9).

$$\eta_{coll,i} \text{ is } \begin{cases} \text{outlier,} & \text{if } \eta_{coll,i} > MAD(\eta_{coll,i}) \\ \text{not outlier,} & \text{otherwise} \end{cases} \quad (9)$$

where $\eta_{coll,i}$ is the i -th occurrence of the batch of thermal efficiency values calculated with Equation 1.

Figure 2 presents the calculated hourly average thermal efficiency after the outliers are removed by using the MAD approach. Solar radiation and outside air temperature were obtained for the year 2014 from Weather Analytics, which estimates the outside air temperature and solar radiation based on a full atmospheric model using observational data and past model verifications. This might be one of the reasons for the presence of outliers.

The relative frequency of thermal efficiency of the flat-plate collectors over the heating season, from October 15 to May 10, 2014 is illustrated in Figure 3. In the heating season, the thermal efficiency varies from 0% to 52%, with median and average values of 21%. The average thermal efficiency of 21% not out of the normal range for such a residential solar thermal combisystem. For-

The model validation of the residential solar thermal combisystem studied in this paper was presented in (Rey and Zmeureanu, 2016b). Due to space limitations, only

some results are reported herein. The simulated temperatures fit relatively well the measurements, which gives confidence in the model. Larger differences are noticed between the measured and simulated values of the two performance indices. Since there are not standards for the model calibration of solar combisystems, the authors used two acceptance metrics from (ASHRAE, 2002): the normalized mean bias error (NMBE), and the coefficient of variation of the root mean square error (CVRMSE).

In the case of hourly simulation, the predictions of thermal efficiency of solar collectors close to the measurements: NMBE=7.5% less than target value of 10%; CVRMSE=29.3% less than 30%. In the case of thermal energy stored, NMBE=7.6% less than target value of 10%; CVRMSE=35.5%. Due to the propagation of errors, the uncertainty of predictions of thermal energy stored is greater than the uncertainty of the measured temperatures.

Figure 4: Box-plots representing the temperatures measured by each available sensor for the year 2016 (non-heating season at the top and heating season at the bottom).

Figure 3: Relative frequency of thermal efficiency.

Trend data analysis

Additional insights about the solar combisystem can be gained by using data statistics. For example (Figure 4), the water temperature at the upper part of the thermal storage tank, recorded by sensor S4, is higher than at the lower part, measured by sensor S2, on average (52.1°C vs. 50.0°C, respectively). The temperature TS6, which corresponds to the array A2 having the tilt angle of 65°C, reaches higher values during the non-heating than the temperature TS1, which corresponds to the array A1 having the tilt angle of 90°C. The tilt angle of 65°C enables harvesting more solar energy than one of 90°C during the non-heating season. The monthly auxiliary energy for DHW and SH are shown in Figure 5. Over the entire year 2016, 555.7 kWh and 1,287.5 kWh of electricity are used for DHW and SH, respectively.

Figure 5: Monthly auxiliary energy for DHW and SH during the year 2016.

Figure 6 represents the relative frequency of the DHW temperature measured by sensor S9 for the year 2016, which follows a normal distribution with average temperature of 45.0°C and standard deviation of 1.7°C.

Figure 6: Relative frequency of the DHW temperature for the year 2016.

The water temperature measured by sensor S7 also follows a normal distribution with average temperature of 29.0°C and standard deviation of 2.1°C. Hence, the set point temperatures for DHW and SH are set in the simulation at 45.0°C and 29.0°C, respectively.

Multi-Objective Optimization

Optimization techniques can be applied to enhance the overall predicted performance of the solar combisystem. Two problems arise: (i) the selection of the optimum configuration, and (ii) the time-consuming simulations required to size and predict the performance of the solar combisystem. The former is addressed with a multi-objective optimization framework based on mixed-integer non-linear programming (MINLP) models, as shown in Figure 7, and the latter with a micro-multi-objective optimization algorithm, called micro-TVMOPSO (Rey and Zmeureanu, 2017). This approach was also applied in (Rey and Zmeureanu, 2018). The initial design was used in the optimization as one of the starting points. In the selection of the alternative configurations, the physical limitations were not defined directly as constraints in the optimization problem. However, the range of values of each variable considered such limits. For instance, by limiting the capacity of storage tanks, the constraint of available space was solved.

Figure 7: Network flow diagram of the optimization model for the residential solar thermal combisystem.

The azimuth angle of the system, which is south-facing, was assumed to be already “optimal” and was not considered as an optimization variable. Solar collectors A1 are installed on the roof, facing south and can have

any tilt angle. Solar collectors A2 only be installed on the south-facing vertical wall, but can take any tilt angle.

Node no. 1 corresponds to one array of south-facing flat-plate or evacuated tube collectors. Node no. 2 corresponds to two distinct arrays of south-facing flat-plate or evacuated tube collectors, each one having its own tilt angle. Node no. 3 represents the auxiliary energy supplied from immersed electrical resistances or water heaters using either electricity or natural gas. Node no. 4 is used to select one thermal storage tank equipped with an internal or an external heat exchanger on the solar loop side, where the latter comes with a stratifying device installed inside the storage tank. Node no. 5 allows for two thermal storage tanks with either an internal or an external heat exchanger on the solar loop side. One tank is dedicated to DHW and the other to SH. Finally, node no. 6 corresponds to the demand for DHW that is satisfied by the solar combisystem, and node no. 7 corresponds to the radiant floor heating system that covers the SH needs.

Any connection between two nodes i and j is controlled by a Boolean decision variable $B_{i,j}$. A Boolean variable B_i^k can also be used inside a node i to select an equipment or a technology over another, which is denoted by k .

Figure 9: Configuration of the Pareto Solutions found by micro-TVMOPSO for LCE vs. LCC and initial configuration.

Boolean variables are used in the TRNSYS input file (inside equation blocks) to select the final solar combisystem configuration. For example, the node no. 1 ($i = 1$) can have either flat-plate ($k = 1, B_1^1 = 1$) or evacuated tube collectors ($k = 2, B_1^2 = 1$), with the constraint $B_1^1 + B_1^2 = 1$ so that only one type of collector is selected. Four independent objective functions are minimized to optimize the residential solar combisystem: (i) life cycle cost (LCC); (ii) life cycle energy use (LCE); (iii) life cycle exergy destroyed using the technical boundary ($LCX_{\text{technical}}$); and (iv) life cycle exergy destroyed using the physical boundary (LCX_{physical}). Each of these objective functions depend on decision variables that are listed in Table 2.

Developed in (Rey and Zmeureanu, 2017), micro-TVMOPSO is a micro-version of the multi-objective

particle swarm optimization (MOPSO) algorithm which is more suitable for time-consuming optimization problems. The micro-TVMOPSO algorithm is used along with the multi-objective optimization framework to find feasible solar combisystem design solutions. Due to the time-consuming nature of one single TRNSYS simulation (around 40 minutes), a maximum number of 100 generations was selected. The micro-TVMOPSO algorithm used five particles, which results in 500 TRNSYS simulations (five particles times 100 generations). For 500 TRNSYS simulations, micro-TVMOPSO lasted approximately 79 hours (i.e., three days and seven hours) and found 32 non-dominated solutions. Figure 8 shows the four non-dominated solutions out of the 32, when only two objective functions are taken into consideration: LCE vs. LCC. Compared to the initial design solution, micro-TVMOPSO found non-dominated solutions whose LCC and LCE values were decreased by 8.3% and 25.8%, respectively.

Two configurations were found, each one with different equipment sizing, as illustrated in Figure 9. The main difference between the initial design and the non-dominated solutions is the number of arrays of solar

collectors. Each configuration found by micro-TVMOPSO is equipped with only one array. As reported in Table 6, configuration A, with solutions 1A, 2A, and 4A, use flat-plate collectors ($B_1^1 = 1$) and one thermal storage tank without stratifying devices ($B_4^1 = 1$). Solutions 1A and 4A have higher numbers of flat-plate collectors and a larger thermal storage tank, compared to solution 2A, which enable them to harvest more solar energy and therefore reduce auxiliary energy needs. Solution 2A has a lower initial cost (fewer flat-plate collectors and a smaller thermal storage tank), but relies more on auxiliary electric energy. Both configurations A and B have one thermal storage tank without stratifying devices; the configuration A is equipped with flat-plate collectors ($B_1^1 = 1$) whereas configuration B is equipped with evacuated tube collectors ($B_1^1 = 0$).

Figure 8: LCE vs. LCC approximation of the true Pareto front using micro-TVMOPSO.

Evacuated tube collectors can harvest more solar energy, but come with a significant extra cost. The characteristics of the four non-dominated solutions, out of the 32 non-dominated solutions found, are reported in Table 2. Compared to the initial design solution, one array of flat-plate collectors with a tilt angle of 65° and one of evacuated tube collectors with a tilt angle of 75° were found to be more suitable for each objective function than two arrays of flat-plate collectors with different tilt angles.

Conclusion

A methodology for optimizing solar thermal combisystems from data collection to multi-objective optimization was presented in this paper and applied to an existing residential solar thermal combisystem installed in Massachusetts, USA. Missing data and outliers should be addressed at the beginning. The median absolute deviation (MAD) offers a straightforward means of detecting outliers. Uncertainty should be the next step after analyzing data. Future work might consider different level of heat losses, and the potential impact of the optimum solution. When performance indices are involved, the propagation of errors should be calculated. Model validation plays a key role before optimizing a residential solar thermal combisystem or seeking alternative designs. The lack of standards for model calibration criteria was emphasised. Acceptance criteria for the calibration of the whole building energy use from (ASHRAE, 2002) can be taken as a relative reference for validation. Future research should be carried out to find acceptance criteria for HVAC systems such solar thermal combisystems. Trend data analysis can bring valuable insights. Boxplots and histograms provide a visual support for better understanding the thermal behavior of a solar combisystem. Solar thermal combisystems should be approached as multi-objective optimization problems. For time-consuming engineering problems, micro-algorithms offer a good compromise between time and effectiveness. Compared to the initial design solution, micro-TVMOPSO was able to reduce the LCC and LCE by 8.3% and 25.8%, respectively, as well as LCXtechnical and LCXphysical by 64.3% and 40.1%, respectively.

Table 2: Decision variable values of some non-dominated solutions found by micro-TVMOPSO for LCE vs LCC.

Decision variables	Solution				
	No. 1	No. 2	No. 4	No. 5	No. 3
Configuration	A	A	A	B	C
$B_{1,4}$	1	1	1	1	0
$B_{1,5}$	0	0	0	0	0
$B_{2,4}$	0	0	0	0	1
$B_{2,5}$	0	0	0	0	0
$B_{3,4}$	1	1	1	1	1
$B_{3,5}$	0	0			
$B_{4,6}$	1	1	1	1	1
$B_{4,7}$	1	1	1	1	1
$B_{5,6}$	0	0	0	0	0
$B_{5,7}$	0	0	0	0	0
B_1^1	1	1	1	0	0
B_1^2	0	0	0	1	0
B_2^1	0	0	0	0	1
B_2^2	0	0	0	0	0
B_3^1	0	0	0	0	0
B_3^2	1	1	1	1	1
B_3^3	0	0	0	0	0
B_4^1	1	1	1	1	1
B_4^2	0	0	0	0	0
B_5^1	0	0	0	0	0
B_5^2	0	0	0	0	0
Number of flat-plate collectors	11	4	8	-	6
Number of evacuated-tube collectors	-	-	-	13	-
Tilt angle of array A1 [$^\circ$]	75	75	75	65	65
Tilt angle of array A2 [$^\circ$]	-	-	-	-	90
Flow rate per collector area [kg/h/m ² _{coll}]	16.4	10.0	12.7	10.0	variable
Volume of tank no. 1 [L]	1,200	300	1,100	1,000	600
Volume of tank no. 2 [L]	-	-	-	-	-
DHW heater auxiliary power [kW]	8	1.5	2	1.5	4.5
Auxiliary power for radiant floor heater [kW]	0.5	7.5	7.5	6.5	10
Objective functions					
Life cycle cost [k\$]	28.9	29.7	32.6	75.9	31.5
Life cycle energy [MWh]	67.5	66.3	65.5	62.3	83.9
Life cycle exergy technical [MWh]	338.9	449.3	636.2	763.0	637.3
Life cycle exergy physical [MWh]	181.3	227.5	336.4	323.2	380.2

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