International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 10 (2015) pp. 27031-27042

http://www.ripublication.com

Optimization Design for a Solar Water Heating System using the Genetic Algorithm

Doo-sung Choi

Department of Building Equipment & Fire Protection System, Chungwoon University, Incheon 402-803, South Korea.

Myeong-jin Ko*

Urban Development Institute, Incheon National University, Incheon 406-772, South Korea.
E-mail: whistlemj@nate.com

Abstract

This paper presents a methodology to optimize a solar water heating system (SWHS) while minimizing life cycle cost. The purpose of the proposed methodology is to determine the optimal sizing of main components such as solar collector, auxiliary heater and storage tank of a SWHS. Genetic algorithm is utilized for optimization. As a case study, we optimized a SWHS in an office building in Incheon, Republic of Korea. The results indicate that the proposed methodology can seek the optimal sizing in a reasonable time. The evolution of objective function and variation of main components size for a solar water heating system through generation are discussed.

Keywords: Solar Water Heating System, Optimization Design, Life Cycle Cost, Genetic Algorithm

1 Introduction

Solar thermal is one of the most cost-effective renewable energy technologies and has enormous market potential globally [1]. Solar water heating system (SWHS) is one of the most popular solar thermal systems and accounts for 80% of the solar thermal

market worldwide [2]. A critical issue in design for SWHS is the optimal sizing of the components such as collectors, auxiliary heater and storage tank. Therefore, in recent years, researchers have developed the some optimization methods i.e., linear and nonlinear optimization method [3-4] and genetic algorithm [5-7] that are conceptually different from the correlation and simulation based methods. However, these methods optimized the SWHS comprised of the particular component selected beforehand by researchers. Thus, it's difficult for them to conduct the optimization design reflecting the economic, technical and environmental characteristics of each device in the actual market.

Therefore, this paper presents a method to determine the optimal sizing for a SWHS based on an economic criterion using the genetic algorithm while reflecting characteristics of the components and satisfying constraints, such as the energy balance, the space available to install collectors and the solar fraction.

2 Solar Water Heating System Model

The schematic diagram of an SWHS is illustrated in Figure 1. Solar energy absorbed by a collector array is transferred to the tank by heat exchanger. When hot water is demanded, heat stored in the tank is supplied to the load. If tank temperature is below than the desired hot water temperature, auxiliary heater placed in series with tank in load supply line is switched on.

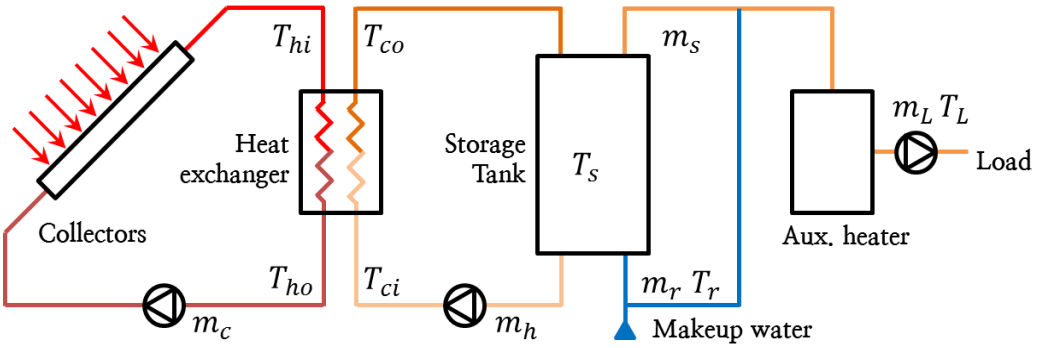

Fig 1. Schematic diagram of a solar water heating system

The energy balance of a well-mixed storage tank is described as follows [8]:

$$\rho_w C_{P,w} V_s \frac{dT_s}{dt} = q_s - q_l - q_{Ls} \qquad (1)$$

where T_s is the storage tank temperature (℃); ρ_w and $C_{P,w}$ are the density (kg/m^3) and the specific heat (J/kg℃) of water; V_s is the volume of the storage tank (m^3);

q_s, q_l and q_{Ls} are the solar energy supplied to the tank, the heat loss of the tank and the solar energy extracted from the tank, respectively.

The q_s transferred from useful heat gain of the collector array (q_u) by heat exchanger according to the differential temperature control. The solar useful heat gain is calculated as follows [9]:

$$q_u = A_c N_c [F_R(\tau\alpha) I_T - F_R U_L (T_{ho} - T_a)]^+ \quad (2)$$

where A_c and N_c are the area (m^2) and the number of the collector; I_T is the solar irradiation on the tilted surface; F_R, U_L and $\tau\alpha$ are the heat removal factor, overall heat loss coefficient and average transmittance-absorptance product of a collector; T_{ho} and T_a are the hot stream outlet temperature of the heat exchanger and the ambient temperature; + sign indicates, hot water from the collector array circulates the hot stream only when solar useful heat gain becomes positive, respectively.

The T_{ho} and T_{co} of the heat exchanger are calculated by using equations (3)-(4). Therefore the q_s can be estimated using equation (6).

$$T_{ho} = T_{hi} - P(T_{hi} - T_{ci}) \quad (3)$$

$$T_{co} = T_{ci} - PR(T_{hi} - T_{ci}) \quad (4)$$

$$T_{hi} = T_{ho} + q_u / (m_c C_{P,c}) \quad (5)$$

$$q_s = m_h C_{P,w} (T_{co} - T_s) \quad (6)$$

where T_{hi} is the hot stream inlet temperature; m_c and $C_{P,c}$ are the flow rate (kg/s) and the specific heat (J/kg℃) of collector fluid; P and R are the cold or hot fluid temperature effectiveness and heat capacity flow rate ratio of the heat exchanger, respectively.

The storage tank losses (q_l) are estimated to be

$$q_l = U_s A_s (T_s - T_e) \quad (7)$$

where U_s and A_s are the heat loss coefficient (W/m^2℃), the surface area (m^2) of the tank, and T_e is the temperature of the environment surrounding the tank.

The solar energy supplied from the tank to the load (q_{Ls}) can be estimated using equation (8) according to the storage tank temperature. If the tank temperature (T_s) is greater than the desired hot water temperature (T_L), the flow rate drawn from the tank (m_s) is determined by considering the mass and energy balance at the mixing junction ($m_s = m_L \left[(T_L - T_r) \div (T_s - T_r) \right]$). The opposite case ($T_s \le T_L$), m_s is discharged at a rate equal to that (m_L) of the load.

$$q_{Ls} = \begin{cases} m_s C_{P,w} (T_s - T_r), & T_s > T_L \\ m_L C_{P,w} (T_s - T_r), & T_s \le T_L \end{cases} \tag{8}$$

At the end of a time step, the final storage temperature ($T_{s,f}$) is obtained by solving equation (1) on the basis of initial tank temperature:

$$T_{s,f} = T_s + \left[\frac{(q_s - q_l - q_{Ls}) 3600}{\rho_w C_{P,w} V_s} \right] \Delta t \tag{9}$$

3 Optimization Methodology

3.1 Decision Variable

Design methodology in this paper is developed to determine the optimal sizing for a SWHS composed of solar collector, auxiliary heater and storage tank, Here, the sizing means the combination of the selected components is computed using its unit capacity and quantity. Therefore, a SWHS is expressed as a decision vector composed of 5 integer variables that represent the type and number of each component.

$$x = (a, b, c, d, e)^T \tag{10}$$

where a and b are the type and the number of solar collector; c and d are the type and the number of auxiliary heater; e is the type of storage tank.

3.2 Objective Function

An economic objective function is defined as minimization of life cycle cost (LCC) comprises of the initial cost (C_I), the maintenance cost (C_M), the replacement cost (C_R), the energy cost (C_E) and the subsidy cost (C_S). It can be formulated as follows:

$$C_{LCC} = C_I + C_M + C_R + C_E - C_S \tag{11}$$

$$C_I = (C_{c,j} N_c + C_{aux,j} N_{aux} + C_{s,j}) \times (1 + R_I) \tag{12}$$

$$C_M = C_I R_M \left[\frac{(+i)^{n_p} - 1}{i(+i)^{n_p}} \right] \tag{13}$$

$$C_{R,c} = \sum_{n_{r,c}=1}^{n_{r,c}} \left\{ C_{I,c} \left[\frac{1}{(+i)^{l_{l,c} n_{r,c}}} \right] \right\} \tag{14}$$

$$C_E = UPA_{ele}^{*} \sum_{t=1}^{8760} C_{ele}(t) + UPA_{gas}^{*} \sum_{t=1}^{8760} C_{gas}(t) \tag{15}$$

$$C_S = \begin{cases} C_I R_S, & A_R > A_{c,j} N_c \\ \left\{ \left[floor\left(\frac{A_R}{A_{c,j}} \right) C_{c,j} \right] + C_{aux,j} N_{aux} + C_{s,j} \right\} (+R_I) R_S, & A_R \le A_{c,j} N_c \end{cases} \tag{16}$$

where $C_{c,j}$, $C_{aux,j}$ and $C_{s,j}$ are the purchasing price of the *j*th collector, auxiliary heater and storage tank; N_{aux} is the number of the *j*th auxiliary heaters; R_I is the supplementary cost ratio against the direct purchasing cost; R_M is the annual maintenance cost ratio of each component; n_p and i are the planning period and the real discount rate; $C_{R,c}$ and $C_{I,c}$ are the replacement and initial cost for each component; $n_{l,c}$ and $n_{r,c}$ are the life time of each component, the number of times for replacement; C_{ele} and C_{gas} are the hourly electricity and LNG cost; UPA_{ele}^{*} and UPA_{gas}^{*} are the uniform present value factor adjusted to reflect the fuel price escalation rate; R_S is the subsidy cost's supporting range; A_R is the maximum collector array's area available to receive the subsidy cost.

3.3 Constraint Conditions

In this study, the constraints are categorized into three parts, namely an energy balance, the penetration of solar energy and the available space to install the collector array, which are detailed, respectively as follows.

$$q_{L,peak} \le q_{aux,j} N_{aux} \tag{17}$$

$$F_{S,\min} \le F_S \le F_{S,\max} \tag{18}$$

$$N_c W_{c,j} H_{c,j} \left(\cos\beta + \frac{\sin\beta}{\tan\alpha_{s,w}} \right) \le A_{c,\max} \tag{19}$$

where $q_{L,peak}$ is the peak load; $q_{aux,j}$ is the capacity of a certain type of auxiliary heater; F_S, $F_{S,\min}$ and $F_{S,\max}$ are a certain, the minimum and maximum solar fraction; $W_{c,j}$ and $H_{c,j}$ are the width and height of a certain type of each collector; β is the slope of the collector array; $\alpha_{s,w}$ is the meridian altitude in winter season, $A_{c,\max}$ is the available space to install the collectors, respectively.

4 Simulation Results and Discussion

4.1 Simulation Parameters

The proposed method was applied for optimal sizing of a SWHS of an office building located in Incheon, South Korea. The annual hot water load was examined using a data profile of hot water use in office buildings [10], as illustrated in Figure 2. The meteorological conditions during the year are illustrated in Figure 3.

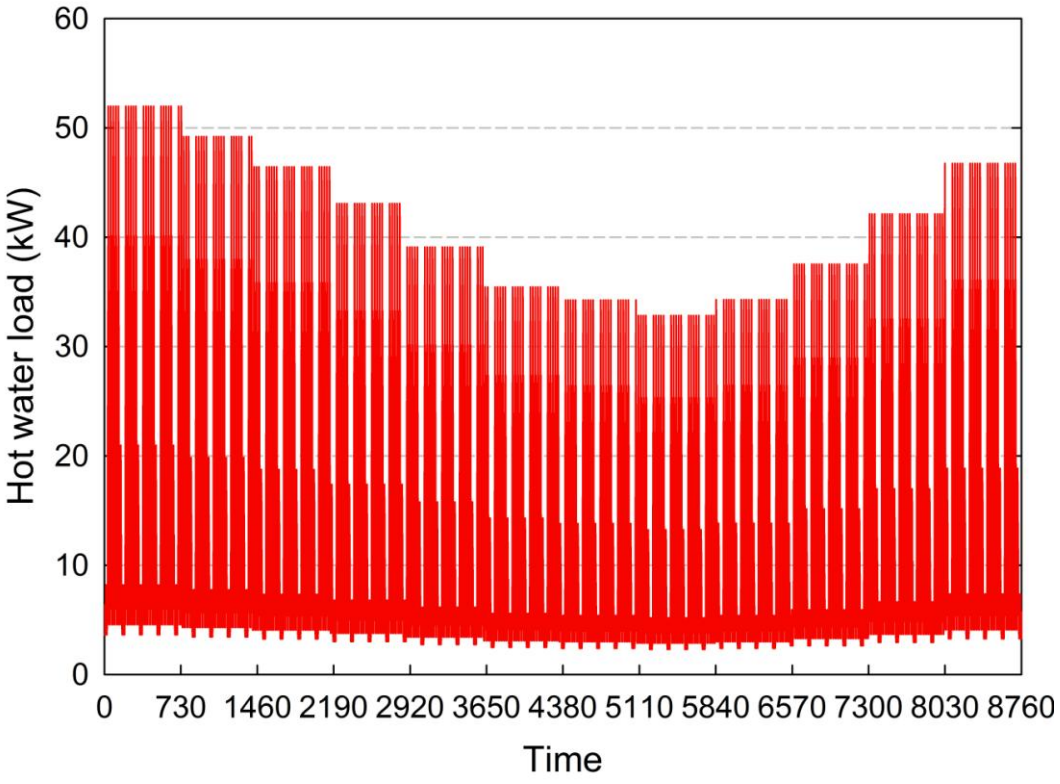

Fig 2. Hourly hot water loads over one year in an office building for a case study

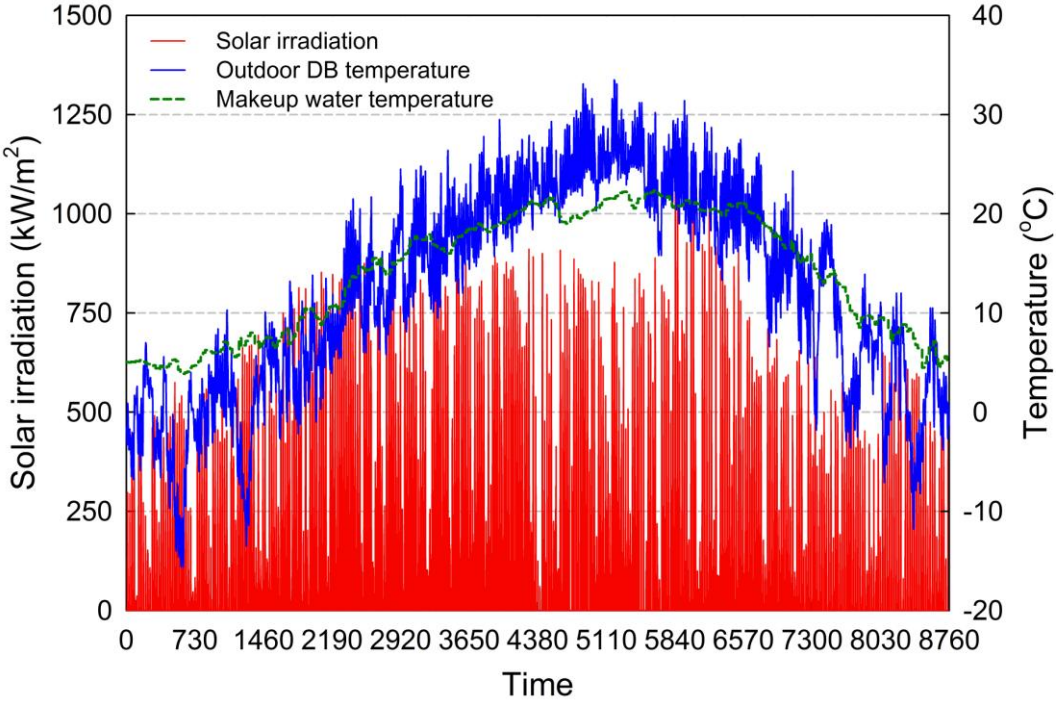

Fig 3. Hourly meteorological conditions over one year in Incheon, Korea

The types and the respective technical and economical characteristics of the components used in the optimization design are presented in Tables 1 ~ 3. These devices are commercially available and the list of devices included in these tables can be extended by the designer. Parameters and assumptions required for the optimization process are summarized in Table 4. Table 5 shows the electricity and natural gas tariff for a case study. These data are based on the actual conditions in South Korea.

Table 1. Technical and economic parameters of the collector

Parameters	Type 0	Type 1	Type 2	Type 3	Type 4
Useful gain [kWh/ m^2day]	2.228	2.361	2.417	2.444	2.556
Intercept of the collector efficiency [-]	0.720	0.721	0.745	0.704	0.720
Slope of the collector efficiency [W/m^2℃]	4.090	4.800	4.848	4.537	3.949
Flow rate of the fluid [kg/s]	0.040	0.037	0.038	0.037	0.053
Overall height [m]	2.00	2.00	2.00	2.00	2.40
Overall width [m]	1.00	1.00	1.00	0.99	1.18
Lifetime [years]	20	20	20	20	20
Purchase price [10^3 KRW/ea.]	520	530	545	540	820

Table 2. Technical and economic parameters of the auxiliary heater

Parameters	Type 0	Type 1	Type 2	Type 3	Type 4
Rated heating capacity [kW]	15.12	18.61	23.26	29.07	34.89
Rated efficiency [%]	82.5	84.3	84.5	85.5	85.5
Lifetime [years]	15	15	15	15	15
Purchase price [10^3 KRW/ea.]	807	845	910	965	1,040

Table 3. Technical and economic parameters of the storage tank

Parameters	Type 0	Type 1	Type 2	Type 3	Type 4
Tank volume [m^3]	0.96	1.72	2.65	3.76	4.91
Tank heat loss coefficient [W/℃]	0.695	0.695	0.695	0.695	0.695
Overall height [m]	1.22	1.52	2.00	2.44	2.44
Overall width [m]	1.00	1.20	1.30	1.40	1.60
Lifetime [years]	10	10	10	10	10
Purchase price [10^3 KRW/ea.]	7,150	9,493	10,725	12,650	15,884

Table 4. Technical and economic parameters of the storage tank

Parameters	Value	Parameters	Value
Slope of collector array [°]	30	Nominal interest rate [%]	6
Azimuth of collector array [°]	0	Inflation rate [%]	3
Meridian altitude in winter [°]	29	Electricity cost escalation rate [%]	4
Ground reflectance [-]	0.2	Gas cost escalation rate [%]	4
Minimum solar fraction [%]	10	Supplementary cost ratio [%]	30
Maximum solar fraction [%]	60	Maintenance cost ratio of SWHS [%]	1.5
Area available to install SWHS [m^2]	500	Maximum supporting range [%]	50
Maximum collector's area [m^2]	500	Emission by electricity [$kgCO_2eq/MWh$]	469
Project lifetime [years]	40	Emission by LNG [$kgCO_2eq/MWh$]	202

Table 5. Electricity and LNG tariffs

Classification		Value
Energy charge of electricity [KRW/kW]	Summer (June, July and Aug.)	105.7
	Spring/Fall (Mar., April, May, Sep., and Oct.)	65.2
	Winter (Nov., Dec., Jan. and Feb.)	92.3
Energy charge of LNG [KRW/MJ]	Summer (May, June, July, Aug. and Sep.)	13.7
	Spring/Fall (April, Oct. and Nov.)	21.7
	Winter (Dec., Jan., Feb. and Mar.)	21.2

4.2 Results of the Optimization Design

The design for determining the optimal sizing of a SWHS for an office building based on LCC using genetic algorithm is performed as an application example. Using a computer with the Windows 7 operating system, Intel(R) Core(TM) i5-2310 @2.90GHz_CPU, and 4 GB memory, developed method has consumed approximately 30 seconds to find the optimal solution of the case study. The genetic algorithm [11] parameters selected for this case study are the following: number of generation and population are 100 and 40; crossover and mutation probability are 0.9 and 0.7, respectively.

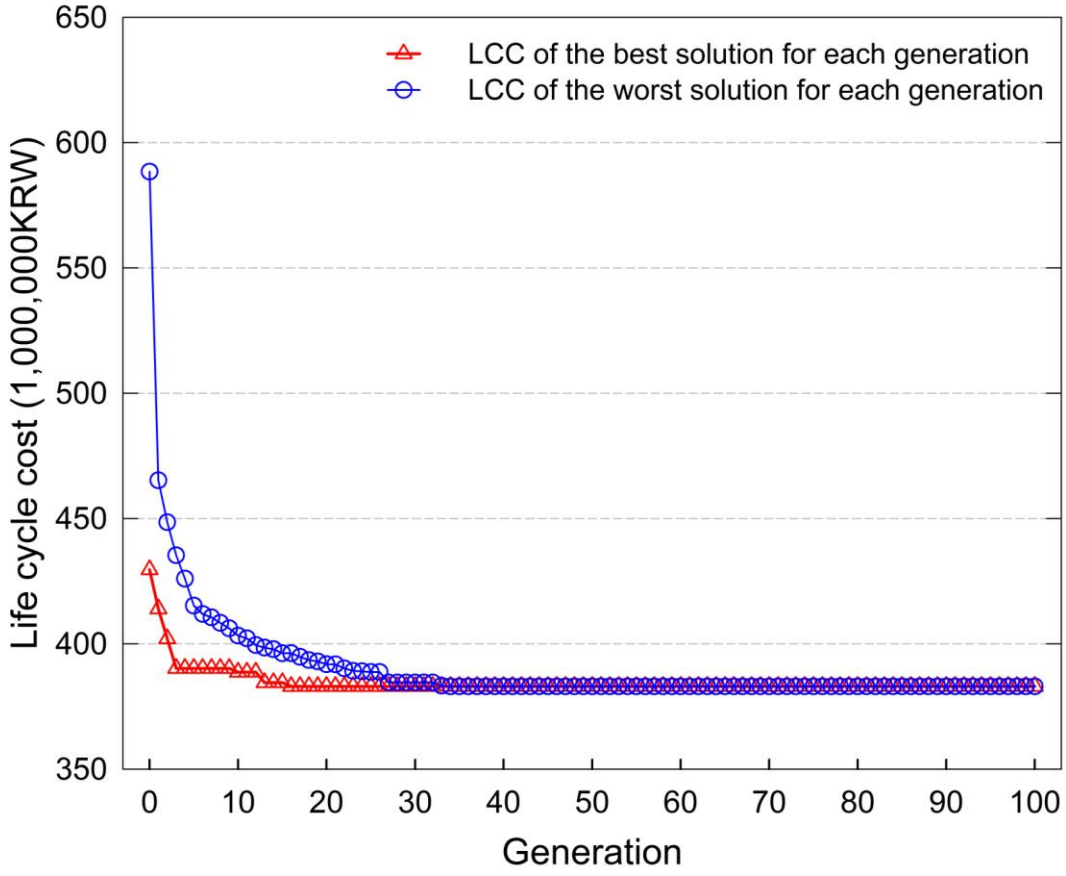

Fig 4. Variation of the objective function (life cycle cost) for each generation

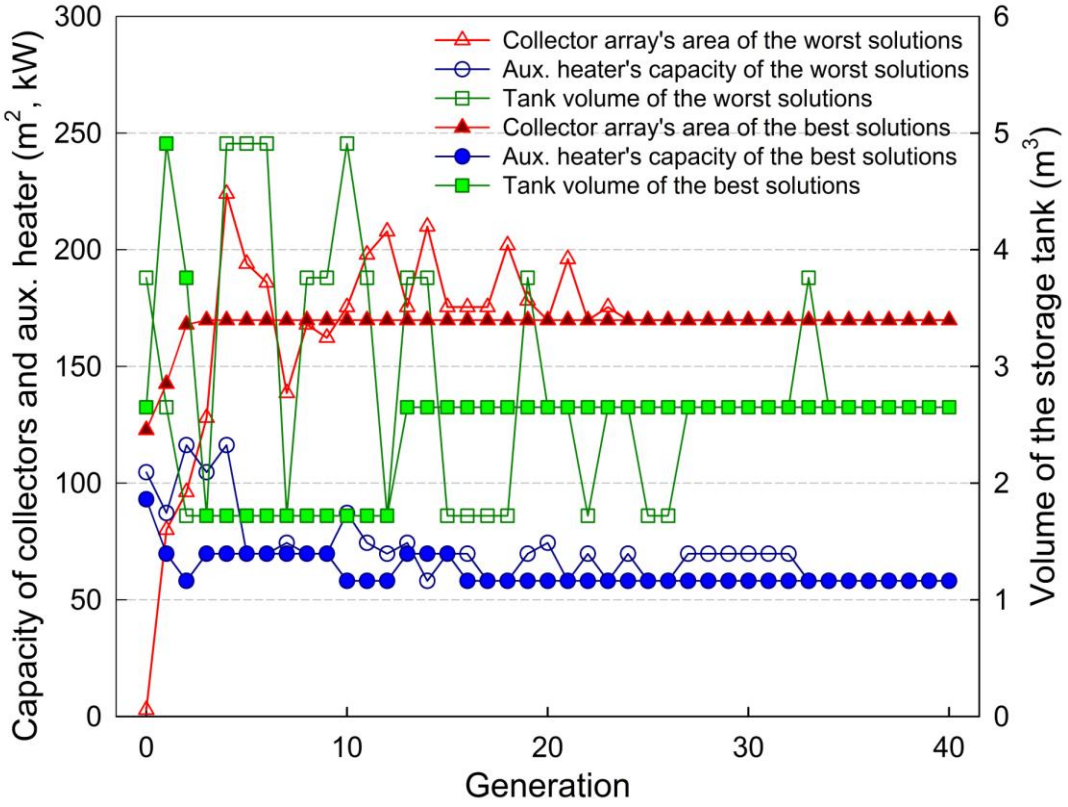

Fig 5. Variation of component size of the best and worst solution for each generation

Figure 4 and 5 show the variation of the LCC and components size of the best and worst combinations during 100 generations. It can be seen that there are a wide range of values for objective function at the beginning of the optimization (until about the 20th generation), which mainly identified and assessed the various possible SWHSs. In the subsequent generations, the probabilities of identifying new solutions that are able to improve the objective function decrease and most solutions of the parent population reform the offspring population. Finally, the algorithm is terminated at the last generation.

Characteristics of the optimal SWHS for the case study can be observed in Table 6. The obtained optimal SWHS with LCC of about 383 million KRW is comprised of 60 solar collectors, 2 auxiliary heaters and a storage tank of 2.65 m^3.

Table 6. Characteristics of the optimal solar water heating system for the case study

Characteristics	Value	Characteristics	Value
Type of solar collectors [-]	4	Capacity of auxiliary heaters [kW]	58.14
Unit area of a solar collector [m^2]	2.83	Type of storage tank [-]	2
Number of collectors [ea]	60	Volume of a storage tank [m^3]	2.65
Area of solar collector array [m^2]	169.80	Peak hot water load [kW]	51.97
Type of auxiliary heater [-]	3	Annual hot water load [MWh/year]	114.41
Unit capacity of aux. heater [kW]	29.07	Life cycle cost [million KRW]	383.03
Number of auxiliary heaters [ea]	2	Annual solar fraction [%]	57.97

5 Conclusion

This paper has presented a design method to determine the optimal sizing for a SWHS based on LCC using the genetic algorithm. As an application example, we carried out a design for determining the optimal sizing of a SWHS for an office building in Incheon, South Korea. With the case study, the optimal solution was obtained from a number of possible solutions within a reasonable computation time. Future work includes applying the technical and environmental objectives as multiple conflicting objectives and sensitivity study of parameters such as the energy charge, the pattern and magnitude of hot water load.

Acknowledgments.
This work was supported by Business for cooperative R&D between Industry, Academy, and Research institute funded Korea Small and Medium Business Administration (Grants No. C0220699).

References

[1] Z. Wang, W. Yang, F. Qiu, X. Zhang, X. Zhao, “Solar water heating: From theory, application, marketing and research”. Renewable and Sustainable Energy Review, 41, (2015), 68-84.

[2] G. Boyle “Renewable energy: power for a sustainable future”, UK: Oxford University Press, 2004.

[3] E. Michelson, “Multivariate optimization of a solar water heating system using the Simplex method”, Solar Energy, 29, 2, (1982), 89-99.

[4] K.K. Matrawy, I. Farkas, “New technique for short term storage sizing”, Renewable Energy, 11, 1, (1997), 129-141.

[5] M. Loomans, H. Visser, “Application of the genetic algorithm for optimization of large solar hot water systems”, Solar Energy, 72, 5, (2002), pp.427-439.

[6] S.A. Kalogirou, "Optimization of solar systems using artificial neural-networks and genetic algorithm", Applied Energy, 77, 4, (2004), 383-405.
[7] D.M. Atia, F.H. Fahmy, N.M. Ahmed, H.T. Dorrah, "Optimal sizing of a solar water heating system based on a genetic algorithm for an aquaculture system", Mathematical and computer modelling, 55, 3-4, (2012), 1436-1449.
[8] G.N. Kulkarni, S.B. Kedare, S. Bandyopadhyay, "Determination of design space and optimization of solar water heating systems", Solar Energy, 81, 8, (2007), 958-968.
[9] J.A. Duffie, W.A. Beckman, "Solar Engineering of Thermal Processes", Hoboken, NJ: Wiley, 2006.
[10] National Renewable Energy Laboratory, http://www.nrel.gov/docs/fy11osti/46861.pdf
[11] K. Deb, "Multi-Objective Optimization Using Evolutionary Algorithm", Chichester, UK: Wiley, 2009.
[12] M.J. Ko, D.S. Choi, "Optimal Sizing for a Solar Water Heating System based on Life Cycle Cost using Genetic Algorithm", Advanced Science and Technology Letters, 89 (Architecture and Civil Engineering 2015), (2015), 67-73.