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# An integrated multi-objective optimization model for determining the optimal solution in the solar thermal energy system

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A B S T R A C T

The STE (solar thermal energy) system is considered an important new renewable energy resource. While various simulations are used as decision-making tools in implementing the STE system, it has a limitation in considering both diverse impact factors and target variables. Therefore, this study aimed to develop an integrated multi-objective optimization model for determining the optimal solution in the STE system. As the optimization algorithm, this study utilizes GA (genetic algorithm) to select optimal STE system solution. Using crossover and mutation, GA investigates optimal STE system solution. The proposed model used GA based on the software program *Evolver 5.5*. The proposed model presents high available and efficient results as decision-making tools. First, to determine the optimal solution, a total of 30,407,832 possible scenarios were generated by considering various factors in terms of their high availability. Second, in terms of efficiency, an average of 131 s were used to determine the optimal solution out of the previously proposed various scenarios. The proposed model can become a tool for consumers to decide on the optimal solution for the design of the STE system.


## 1. Introduction

Due to the global increase in the use of fossil fuels, there have been various climate issues, such as global warming. To solve such environmental problems, the world has taken greater interest in diverse NRE (new renewable energy) technologies. Among NREs, the world has taken the greatest interest in solar energy [1–8]. Particularly, the STE (solar thermal energy) system is considered a highly efficient system that converts solar radiation to heat. It economically reduces $CO_2$ emissions by reducing the use of fossil fuels. It is one of the most widely available NRE technologies today that is applicable to households or industries [9–12].

According to the second energy master plan of South Korea, the country's final energy consumption rate from 2000 to 2012 increased at the yearly average of 2.8%, and energy consumption of households accounted for 38% of the total energy consumption. Therefore, the South Korean government is expanding the implementation of NRE, and is planning to expand the NRE share in the country's total energy portfolio to 11% by 2035 [13]. To promote such expanded implementation of NRE, the South Korean government supports the initial investment cost through incentive policies such as housing support or building support [14]. The total STE system area in South Korea is 48,473 $m^2$ as of 2013, producing 27,812 TOE (tons of equivalent) energy [15]. In the country's fourth basic plan for NRE, the South Korean government aims to increase the monthly primary energy production ratio of the STE system to the total energy production of NRE technologies from 0.3% in 2012 to 7.9% by 2035 (i.e., 21.2% of the yearly average increase rate), which is the maximum increase rate among NRE technologies [16].

Meanwhile, in South Korea, hot water heater of energy consumption has accounted for 17% of the total energy consumptions. In order to solve this problem, Korean government recommends high efficiency boiler to consumers, however most of them use near 90% efficiency boiler. In order to make up for what they lack at hot water demand, Korean government has promoted the implementation of the STE system [17]. Therefore, in this paper, the target use of the STE system has been set to solar hot water system.

In South Korea, the STE system is expected to show the biggest increase potential. Although the STE system has several advantages

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**Abbreviations**

| | |
|---|---|
| AHG | Annual Heat Generation |
| AHG/Unit | Annual Heat Generation per Unit |
| AoC | Azimuth of the installed Collector |
| BEP | Break-Even-Point |
| GA | Genetic Algorithm |
| $G_L$ | minimum electricity Generation Limit |
| IIC | Initial Investment Cost (with the government subsidy) |
| iMOO | integrated Multi-Objective Optimization |
| LCC | Life Cycle Cost |
| $LCCO_2$ | Life Cycle $CO_2$ |
| NoC | Number of the installed Collector on the rooftop area |
| NoC_L | Number of installed Collector along the Length of the rooftop area |
| NoC_W | Number of installed Collector along the Width of the rooftop area |
| NPV | Net Present Value |
| $R_L$ | Rooftop Length |
| $R_W$ | Rooftop Width |
| SIR | Savings-to-Investment Ratio |
| SoC | Slope of the installed Collector |
| ToS | Type of the Storage |
| ToC | Type of the Collector |
| VBA | Visual Basic for Applications |

(i.e., the government's support policies and its high efficiency), it is difficult to widely implement due to its high IIC (initial investment cost) and its unstable performance against climate conditions. To overcome these challenges, the full life-cycle cost of the STE system must be analyzed before it is implemented. In other words, through the overall analysis of the life-cycle cost, the economic feasibility of the STE system should be confirmed with decision-makers. Toward this end, one of the most important steps is to estimate the amount of heat generated by the STE system. There are several impact factors that should be considered in estimating the amount of heat generated by the STE system. Those factors include (see Table S1, Supplementary material (SM)): (i) the regional factors and (ii) the building characteristics. Previous studies have analyzed the target variables of the STE system (i.e., heat generation, economic effect, and environmental effect) by considering the aforementioned impact factors [2–4,9–12,18–35], [36–55]. There are many impact factors affecting solar collection cycle, however aforementioned impact factors (i.e. regional factors, building characteristics) are sufficient technical factors to considered for the design of STE systems [10,11,23,24,40]. If decision maker wants to adopt the STE system, the proposed model could be decision support tool as intuitive model in the early design phase. Using proposed model, easily, decision maker can easily select the STE system by considering heat generation, economic and environmental analysis from life cycle perspective.

First, some studies have analyzed the heat supply demand of a building by considering the heat generation of the STE system. The analysis of the heat generated by the STE system considered the regional factors and the physical information of the STE system [i.e., the ToC (type of collector) and the ToS (type of storage)] [2,4,21,27,33]. Allouhi et al. [4], aimed for technical evaluations of the STE system in Morocco, used the flat plate collector and the apricus collector to analyze the energy generated by the STE system in six regions. Hobbi and Siddiqui [27], proposed an STE system that could satisfy the hot water demand of single households in Canada. For maximum heat generation, they set the characteristic of the collector as the design variable. Other studies have focused only on the heat supply and demand of a building with the installation of the STE system, but have not analyzed the economic and environmental effects.

Second, recent studies have analyzed the economic effect of the installation of the STE system. These studies selected the optimal ToC and ToS by considering mainly the IIC and heat generation of the STE system [9,10,31,40]. Bornatico et al. [9] calculated the optimal STE system that would satisfy the minimum initial cost and maximum energy generation through an optimization algorithm. Szargut and Stanek [31] determined the optimal cost by setting the design value as the characteristic of the solar collector in the economic analysis. However, their analysis did not consider the full life cycle and the environmental effect.

Third, recent studies have also analyzed the environmental effect of the installation of the STE system. These studies mainly considered the regional factor and heat generation of the STE system [17,41,43,51,54]. Zambrana-Vasquez et al. [41], performed the life cycle assessment for the environmental assessment based on the characteristics of the STE system. Bessa and Prado [51], conducted a comparative analysis of the $CO_2$ emissions of the electrical heating system and of the STE system in 24 regions in Brazil to propose an optimal solution. Though they analyzed the environmental effect based on the regional factor, they did not simultaneously consider the life cycle cost. Based on the previous researches, it can be concluded that several types of target variables should be simultaneously considered to analyze the economic and environmental feasibility of the STE system [56–62].

Therefore, this study aimed to develop an iMOO (integrated Multi-Objective Optimization) model that would satisfy several target variables by simultaneously considering various impact factors. The proposed model was developed in six steps: (i) establishment of a database, (ii) generation of the STE system's installation scenarios, (iii) analysis of the STE system's installation scenarios, (iv) economic and environmental assessment from the life cycle perspective, (v) establishment of an iMOO process using a GA (genetic algorithm), and (vi) systemization of the proposed model using a Microsoft-Excel-based VBA (Visual basic application) (see Fig. 1). Using the optimal solution, these five objectives can be attained: (i) minimization of the IIC (with government subsidy); (ii) maximization of the AHG (annual heat generation), (iii) maximization of the NPV (net-present value), (iv) maximization of the SIR (savings-to-investment ratio), and (v) maximization of the AHG/unit. In addition, Fig. 2 showed the decision-making process in the iMOO model.

## 2. Materials and methods

### 2.1. Step 1: establishment of database

To select the optimal STE system solution, the research team first considered the impact factors associated with the PV (photovoltaic) system [63,64], which are very similar to those of the STE system, except that modules are used in the PV system whereas solar collectors are used in the STE system [65,66]. Toward this end, the study established a database of several impact factors based on previous studies (see Table S1) and the Korea Public Institution and Geographical Information [63–71]. As shown in Table S2, the