Multi-objective Optimization of Solar System Sizing in Households with Common Heat Sources

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Abstract. According to following worldwide trend to decrease energy and environmental performance of the building sector, the utilization of renewable energy sources represents a key toward sustainable buildings. The aim of this paper is to introduce an optimization methodology for solar system sizing (photovoltaics and solar thermal collectors) with using a multi-objective optimization for single family house with space heating, domestic hot water preparation and user/appliances electricity consideration. Optimization is based on three objectives: non-renewable primary energy, carbon emissions and total costs. Optimization procedure is performed by interconnection of simulation tool TRNSYS and MATLAB with using genetic algorithm. In TRNSYS, four different heat sources (electric heater, natural gas boiler, wooden fuel boiler and air source heat pump) combined with photovoltaic and solar thermal system have been modelled. Presented case study provides results of optimization for given family house.

1. Introduction
In the energy sector, the emphasis is placed on reducing energy consumption and mitigating climate change. The European Parliament and the Council of the European Union have determined a European Directive [1] which refers to the reduction of the energy performance of buildings and introduces the concept of nearly zero energy buildings (nZEB), where significant part of consumption should be covered by renewable energy sources. The Europe 2020 strategy challenges member states to meet the targets in 2020, which are 20 % reduction of greenhouse gas emissions compared to year 1990, to obtain 20 % renewable energy in final energy consumption and to increase energy efficiency by 20 % at least. Targets are also set for 2030 and 2050. The European Union is on good way to meet these objectives, at least for 2020.

In the last years, multi-objective optimization procedures became into one of the main challenges of the building sector. These procedures can be divided into three tasks including optimization of building envelope only [2][3], design optimization of building energy systems only [4][5][6][7] and design optimization of both building envelope and energy systems [8][9][10]. It was investigated that building regulations which depend mainly on building envelope requirements do not guarantee the best environmental and economical solutions [11]. The study was aiming to achieve low-emission cost-effective thermal-comfort solutions for modern buildings with using multi-objective optimization and genetic algorithm. The paper [12] presented methodology for finding the optimal size of the main components for a solar thermal system with using particle swarm optimization. The results were comparable to those obtained with the more common genetic algorithm. Maximizing of solar fraction...
was chosen as objective. Next authors [13] performed a coordinated optimal design method as computation cost-effective method for stand-alone and grid-connected zero/low energy buildings and their energy systems on the basis of multi-stage design optimization methods, to effectively consider the interactions between building envelope and energy system design optimizations. The proposed method had essential advantage particularly when the numbers of design variables are large. A comparison of single-objective and multi-objective optimization methods for renewable energy system optimization has been made [14] with using genetic algorithm based on Hong Kong Zero Carbon Building as case study. Total costs, carbon emissions and grid interaction index were chosen as objectives. The paper [15] proposed a methodology, aimed to optimize the design of the mix of renewable energy systems for the integration of building energy demand in terms of energy uses for space heating/cooling, domestic hot water and electric devices with using genetic algorithm and primary energy and costs as objectives.

In this paper, the methodology of multi-objective optimization of solar systems sizing for common type of household systems is described. For optimization purposes genetic algorithm has been applied [16].

Case study was performed for four types commonly used heat sources (electric heater, natural gas boiler, wooden fuel boiler and air source heat pump) for covering space heating, hot water preparation and user/appliances electricity demand together with implementation of photovoltaic system and solar thermal system. Optimization is used to find an optimal solar system sizing with combination of heat source selection under three given objectives: non-renewable primary energy, carbon emissions and total costs for 15 years.

2. Methodology

Multi-objective optimization was performed by cooperation of simulation tool TRNSYS and MATLAB environment. Interconnection of both tools is based on change (overwrite) of TRNSYS input text file for TRNSYS simulation by MATLAB environment. TRNSYS tool then performs simulation of predefined system with hourly time step. This process is then repeated under certain conditions. Time step of one hour has been used because it is at least needed for solar thermal system simulation and sufficient enough for PV system/user electricity demand simulation compared to the shorter time steps [17].

Software MATLAB was used for optimization process thanks to its optimization toolbox. For the purpose of this paper genetic algorithm (type NSGA II) was used. Genetic algorithm is one of the mostly used multi-objective optimization algorithm [18]. Software TRNSYS was used to build simulation models representing common technical systems in single family houses with different heat sources and solar systems. These pre-defined models were used for dynamic simulations (calculation time step 1 hour) of overall energy consumption in building and evaluation of defined objectives.

Space heating need of already designed building was calculated in TRNBUILD environment based on building description. Heating need for DHW preparation was calculated in TRNSYS with respect to the modified load profile of water heaters [19] – type L. Modification of L profile was to delete consumption during the day when occupants are not at home, but with keeping the same daily consumption. Simulation models built in TRNSYS take also into account the user electricity profile, which is in most cases neglected because of lack of data on realistic loads. User electricity demand includes electricity for household appliances and lighting. On the other hand, due to rather different behaviour of household occupants, the load profile of user energy cannot be easily standardized. Variability of the load profile (during the year, throughout the day) has a significant effect on the assessment of the utilization of the PV system production, especially for buildings without electric heat source. To include the user electricity demand in simulations, a generator of a realistic load profile for given household has been developed. The original tool [20] was modified with permission of the authors and used for the following case study. Modified load profile generator creates the annual user electricity load profile with one-minute time-step based on number of occupants, active occupancy and given group of household appliances including artificial lighting. Appliances operation is based on active occupancy in household and probability of use. Solar irradiance data are used to determine artificial lighting needs.
The optimization target is to minimize defined objectives: specific non-renewable primary energy consumption [kWh/m².a], specific CO₂ emissions [kgCO₂/m².a] and total costs for 15 years. Total costs consist of initial investment cost and operational costs during 15 years. Length of operational costs 15 years is chosen due to technical system lifetime. Results are represented by Pareto fronts. Pareto front occurs, when no objective can be improved without sacrificing at least one other objective. Based on Pareto front obtained, multi-criteria decision making can be done. Optimal choice depends on boundary conditions given by decision maker. An example of boundary condition can be minimum total costs with no respect to the environmental, minimum environmental impact demanded by statutes with no respect to the total costs or boundary conditions demanded by donation programs for refurbishment, etc.

2.1. Objectives
Three objectives were defined: non-renewable primary energy (nPE) as indicator of energy performance, CO₂ emissions (CO₂) as climate change indicator and total costs (COSTS) as economic indicator. The objectives represent contradictory environmental and economic issues of renewable energy sources application. Calculation of individual objective is based on the specific values determined for individual energy carriers (conversion factors of non-renewable primary energy, CO₂ emission factors and energy prices/investment costs) and their calculated energy consumption. These factors were taken from Czech decrees, [21] for nPE and [22] for CO₂. Factors are determined by the type of fuel. Energy carriers as fossil fuels have approximately same value worldwide for each carrier (e.g. natural gas combustion in Europe is similar as in Asia). Difference occurs when electricity is used as energy carrier. However, each country has different energy mix, which implies a different representation of energy carriers involved in electricity production. Higher use of renewable resources reduces these factors. The energy mix with political influence has a considerable influence on these factors for electricity.

2.2. Framework
The framework consists of three parts. At first part, the different TRNSYS models with different heat sources in households (with solar system) were created with assuming that the building envelope is already properly designed from the thermal and energy view. Subsequently, the design parameters are chosen. It depends on the user which parameters of the technical system he wants to optimize. In this paper, sizing of solar systems was chosen as design parameters – area of photovoltaic panels [m²] and area of solar thermal collectors [m²]. Solar system parameters as PV cell efficiency, solar thermal efficiency curve, technology, solar DHW tank and other manufacturer data are specified in the model. Second part is used for control TRNSYS by MATLAB. Based on the design parameters selection in the first part, the selected design parameters in text input file of TRNSYS are overwritten to parameters readable and searchable by MATLAB. Last third part represents whole optimization which is processed in MATLAB. In this part it is necessary to define ranges of design variables. This range definition should be based on practical knowledge of common values.
In the optimization process it necessary to set the parameters of the genetic algorithm at which conditions the optimum will be found. Parameters of the genetic algorithm are e.g. number of genes, population size, maximum number of generations, etc. The optimization process loads the control part (second part) to start the optimization process. Based on the obtained outputs (results), inputs are methodically generated (optimized). The result of the optimization is to render the Pareto front including continuous results during the optimization.

3. Case study
Four different types of heat sources for space heating and DHW preparation were modelled in TRNSYS. Electric heater, natural gas boiler (condensing), wooden fuel boiler and air source heat pump were considered in the case study. Nine different combinations have been created in total (Table 1). Photovoltaic system without electric storage (grid on) has been considered for all cases. Solar thermal collectors were considered in several combinations (see Table 1).
Case study was performed for single family house with 4 occupants situated in Czech Republic. Modelled house has a floor area 150 m$^2$, sloped 30° roof area 170 m$^2$ (60 m$^2$ available for solar system installation), volume 450 m$^3$ and specific space heating demand 20 kWh/m$^2$.a. Daily hot water consumption is 160 litres per day. Household represents a typical family, where members are more out of household during the day. Defined active occupancy can be seen in Figure 1. User electricity demand has been considered 2500 kWh/a. Electricity load profile considered typical household appliances as refrigerator with freezer, iron, vacuum cleaner, hair dryer, personal computer, television (55”), oven, microwave, kettle, lighting, etc.  

![Active occupancy graph](image)

**Figure 1.** Active occupancy

**Table 1. Models combination**

| Space heating                  | DHW preparation                                      |
|-------------------------------|------------------------------------------------------|
| 1 Electric heaters (0.99)     | DHW tank with electric heater                        |
| 2 Electric heaters            | Solar DHW tank with electric heater + SOL            |
| 3 Natural gas boiler (0.93)   | DHW tank with electric heater                        |
| 4 Natural gas boiler          | DWH tank heated by gas boiler                        |
| 5 Natural gas boiler          | Combined solar DHW tank heated by gas boiler + SOL   |
| 6 Wooden fuel boiler (0.85)   | DHW tank with electric heater                        |
| 7 Wooden fuel boiler          | Combined solar DHW tank heated by wooden boiler + SOL|
| 8 Air source HP (3.2) + aux. electric heater (0.99) | DWH tank heated by heat pump (2.6)               |
| 9 Air source HP + aux. electric heater | Combined solar DHW tank heated by heat pump + SOL |

Heat output of heat sources is designed to be sufficient for all given combinations. In Table 1, bracket values are efficiencies of sources and they were kept constant except of air source heat pump (variable coefficient of performance COP with air temperature and temperature of heating water). Seasonal performance factor (SPF) of heat pump was 3.2 for space heating and 2.6 for DHW in base alternative. For cases without solar thermal system, DWH tank with constant volume 200 litres was considered. In combinations with solar thermal system, a specific volume of storage tank 50 litres per m$^2$ of collector area was used. Minimum volume of combined storage tank for solar systems (with 2 heat exchangers) was 530 litres.

For the case study, two design parameters were defined – area of photovoltaic panels and area of solar thermal collectors. Available roof area for solar system installation was 60 m$^2$ with direction to the south. Defined ranges of design variables were up to 30 m$^2$ for both installations with solar collectors and photovoltaic panels together. Area up to 60 m$^2$ for solar thermal collectors was not considered, because of excessive production which could not be utilized. For photovoltaic system only, range of photovoltaic array was up to 60 m$^2$. These parameters of genetic algorithm were used: population size 40, crossover fraction 0.65, mutation probability 0.1, maximum numbers of generations 50, Pareto front tolerance 0.001.

Calculation of indicators was based on factors and energy prices valid for Czech Republic (Table 2). While using heat pump (HP) or electricity heaters as heating source in household, the cheaper
electricity tariff has been considered for whole consumption. Parameters for electricity are distinguished for imported and exported energy. Caused negative value of objectives was due to approach based on overall balance (feed-in tariff). Considered investment costs were obtained from manufacturers (Table 3).

Table 2. Conversion, emission factors and energy prices

| Energy carrier                  | Non-renewable primary energy factor [-] | CO₂ emission factor [tCO₂/MWh] | Energy price [USD/kWh] |
|---------------------------------|----------------------------------------|-------------------------------|------------------------|
| Electricity                     | 3 / -3                                  | 1.01 / -1.01                 | 0.1708 / -0.0125       |
| Electricity (for HP)            | 3 / -3                                  | 1.01 / -1.01                 | 0.1042 / -0.0125       |
| Electricity (for electric heaters) | 3 / -3                                  | 1.01 / -1.01                 | 0.0833 / -0.0125       |
| Natural gas                    | 1.1                                     | 0.2                           | 0.0583                 |
| Wood                           | 0.1                                     | 0                             | 0.0529                 |

Table 3. Investment costs

| Energy source                      | Heating [USD] | DHW storage tank                                        |
|------------------------------------|---------------|----------------------------------------------------------|
| Electric heaters                   | 830           |                                                           |
| Gas boiler                         | 2 500         | Without SOL (200 litre): 420 USD                         |
| Wooden fuel boiler                 | 3 330         | With SOL, classic: included in SOL price                 |
| Air source HP                      | 10 400        | With SOL, combi: 3.12 USD per litre                      |
| Photovoltaic system (PV)           | 190 per m²    |                                                           |
| Solar thermal system (SOL)         | 830 per m²    |                                                           |

4. Results and discussion

Nine combinations with heat sources for space heating and DHW preparation with photovoltaic and solar thermal system have been processed through optimization. Optimization results were obtained as Pareto fronts for each combination. All of these Pareto fronts were composed into Figure 2 and Figure 3.

Based on Pareto fronts obtained, the lowest total costs combination was “2: Electric+Electric+SOL” with 15k USD considering installation of both solar systems with array 6 m² of photovoltaic panels (PV) and 1 m² of solar collector (SOL). The highest total costs (43k USD) combination was “9: HP+HP+SOL” with almost fully covered available roof area with both solar systems with arrays PV 29 m² and SOL 25 m². The lowest impact on non-renewable primary energy had combination “8: HP+HP” with fully covered available roof area with PV 60 m² and the highest impact had combination “1: Electric+Electric” without any solar system installation. Lowest CO₂ emissions had combination “4: Gas+Gas” with fully covered available roof area with PV 60 m² and the highest CO₂ emissions had “1: Electric+Electric” without solar system installation. Cases without any solar system installation (no PV, no SOL) are shown as last points of each heat sources (1,3,4,6,8) in the direction of increasing indicator (hatched points on the right). Considering these combinations without any solar system, electric heaters had the highest impact on non-renewable primary energy and CO₂ emissions with the lowest total costs. Total costs and CO₂ emissions of air source heat pump and gas boiler were similar, but heat pump had lower impact on primary energy than gas boiler. The highest total costs had wooden fuel boiler.
For decision making demonstration under given boundary conditions (see Table 2 and Table 3), limits were considered (dashed line in Figure 2, 3): maximum total costs 23k USD, zero non-renewable
primary energy and CO₂ emissions up to 20 kgCO₂/m².a. All objectives must be inside of boundary conditions - intersection solution. Selection of these limits show several optimal solutions which corresponds to: gas boiler with photovoltaic array only from 40 to 43 m² and heat pump with photovoltaic array only from 31 to 37 m².

Air source heat pump can have approximately the same CO₂ emissions impact as gas condensing boiler. Thus, an electrically driven heat pump does not have to be significantly more environmentally friendly than gas boiler for given emission factors (see Table 2). Neither point in the Pareto front represented an optimal solution where only a solar thermal system is installed. This was due to the high investment costs of solar collectors and low savings of selected indicators. Therefore, the installation of photovoltaic system had a significantly greater impact on minimizing the objectives than a solar system. Electric heater as heat source will never achieve zero non-renewable primary energy due to small roof area.

5. Conclusion

Universal methodology of multi-objective optimization was introduced based on dynamic simulation in TRNSYS with MATLAB cooperation. Three objectives following environmental and economic aspects were chosen – non-renewable primary energy, CO₂ emissions and total costs. The results reported in case study section have been based on simulation of nine combinations of commonly used heat sources in household with using renewable energy sources as photovoltaic system without electric storage (grid on) and solar thermal system. Multi-objective optimization was based on minimization of three objectives by solar system sizing and heating source selection. Results obtained from Pareto fronts shows contradictory environmental and economic issues of renewable energy sources application. Proposed methodology does not identify a unique optimal solution, which does not exist in a multi-objective optimization, but gives a chance to stakeholders to make the most proper decision according to his preferences. After decision making is possible to obtain one optimal solution.

6. References

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