MULTI-OBJECTIVE OPTIMIZATION OF ENERGY SYSTEM DESIGNS FOR THE ALBANO UNIVERSITY CAMPUS IN STOCKHOLM

Cong WANG, Ivo MARTINAC, Alessandro MAGNY

Royal Institute of Technology, Stockholm, Sweden, congwang@kth.se

Abstract

In this paper, a multi-objective optimization approach based on genetic algorithm is applied to the energy system design of a sustainable district – the new Albano university campus in Stockholm. The study aims to help district planners find optimal energy solutions that have good energy, environmental and economic performances. Three objectives are minimized: the non-renewable primary energy consumption, the greenhouse gas emissions, and the levelized life cycle cost. A wide range of energy conversion technologies and energy sources including both renewables and non-renewables have been modeled. The potential to recover waste heat from greywater and a prospective IT/Data center is analyzed. The energy system is modelled in steady-state and simulated in an hourly resolution with renewable energy production determined at real time. The optimization results are presented in the form of Pareto fronts, which helps district planners understand more clearly the trade-off between conflicting objectives and make more informed decisions.

Keywords: multi-objective optimization, district energy system, nearly zero energy

1 Introduction

According to the World Business Council, building sectors currently account for nearly 40% of the world primary energy consumption [1]. With the rising living standard, this number is expected to continue to increase in the future. On the other hand, due to the accelerating depletion of fossil fuels and consequent environmental challenges, most of political entities have launched energy saving regulations. In Europe, the new recast of the European Energy Performance of Buildings Directive (EPBD) regulates that all newly constructed buildings in the European Union (EU) should be nearly zero energy by the end of the year 2020 [2, 3].

A nearly zero energy building (nZEB) is defined as a building that has a very high energy performance and where energy demand is to a large extent covered by renewable energy sources [4]. A large number of studies have been carried out from both the demand side (buildings) and the supply side (energy systems), trying to find cost-optimal solutions of nZEB. It is found to be difficult to achieve nearly zero energy at the individual building level and instead some researchers point out the potential solutions of nZEB for a group of buildings, extending nZEB to the district level [5]. In addition to finding cost-optimal solutions for nearly zero energy, another key aspect is to minimize the environmental burdens. The EU 20-20-20 targets call for a 20 percent reduction in greenhouse gas (GHG) emissions by 2020 relative to 1990 levels. Thus district planners often have to ponder both economic
and environmental performance. It is important to analyze various alternative solutions and offer district planners a large number of possibilities, in order for them to make better and more informed decisions.

A multi-objective optimization approach is able to simultaneously optimize two or more conflicting objectives and provide users with an infinite number of solutions – called Pareto optimal solutions. It thus well suits the design of a district energy system, in which economic and environmental objectives often conflict each other and decision makers need to compare different alternatives. This paper applies a genetic algorithm (GA) based multi-objective optimization approach to the energy system design of a sustainable district – the Albano university campus in Stockholm. Inspired by the concepts from evolutionary biology such as inheritance, mutation, crossover and selection, GAs generate a population of candidate solutions in each iteration based on the fitness of solutions from the previous iteration. Such a process is repeated until a predefined number of generations are reached or convergence criteria are fulfilled [6]. GAs are suitable for such complex multi-objective optimization problems as district energy system designs which involve both continuous and discrete variables, non-linear functions and non-convex search domains [7].

The application of genetic algorithms to building and energy related researches is still growing. Genetic algorithms have been used for instance in finding optimal building design alternatives or optimizing HVAC systems [8]. Several variants of genetic algorithms are available to handle multi-objective optimization. Specifically, the Pareto archive NSGA-II algorithm is applied in this study, which has been reported to have good convergence [9]. The optimization tool used in this study is MOBO, a multi-objective building optimization software, developed by Aalto University [10].

2 Methodology

2.1 Case description

The Albano university campus, located between Royal Institute of Technology (KTH), Stockholm University, and Karolinska Institute, is to be constructed in the next years. With a total floor area of 150 000 m², the campus consists of two types of buildings: lecture buildings and residential buildings. The planners expect Albano to be a sample of sustainable urban development, aiming to achieve the best energy and environmental performances. As a future development project, information regarding the detailed energy use is limited. With some assumptions made about the construction, building performance tools such as IDA ICE and VIP Energy are employed to simulate the dynamic energy demand of one representative lecture building and one representative residential building respectively. As buildings in each type have similar functions, it is further assumed that they have the same specific energy use profiles. The specific energy use for each type of buildings is given in Tab. 1. The total energy use profiles are then obtained by aggregating the profiles of two types of buildings. Tab. 2 summarizes the yearly energy use of the buildings in each type and as a whole. The work of defining Swedish nZEB is still going on by the Swedish Energy Agency and the National Board of Housing, Building and Planning, who have been collecting suggestions, comments and experiences. One reference can be taken is the most recent edition of the Swedish building code – BBR 22, which requires that building specific delivered energy use should not be above 70 kWh/m² for commercial buildings and 80 kWh/m² for residential buildings [11]. These two values apply to the region where Stockholm is located.
### Tab. 1  Specific energy use of Albano

<table>
<thead>
<tr>
<th>Building</th>
<th>Space Heating [kWh/m²]</th>
<th>Hot Water [kWh/m²]</th>
<th>Space Cooling [kWh/m²]</th>
<th>Electricity [kWh/m²]</th>
<th>Total Floor Area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Educational</td>
<td>26</td>
<td>5</td>
<td>10</td>
<td>14</td>
<td>100 000</td>
</tr>
<tr>
<td>Residential</td>
<td>36</td>
<td>43</td>
<td>0</td>
<td>19</td>
<td>50 000</td>
</tr>
</tbody>
</table>

### Tab. 2  Total energy use of Albano

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Educational</td>
<td>2600</td>
<td>500</td>
<td>1000</td>
<td>1400</td>
</tr>
<tr>
<td>Residential</td>
<td>1800</td>
<td>2150</td>
<td>0</td>
<td>950</td>
</tr>
<tr>
<td>Total</td>
<td>4400</td>
<td>2650</td>
<td>1000</td>
<td>2350</td>
</tr>
</tbody>
</table>

### 2.2  Energy system

#### 2.2.1  System modelling and definition

The district energy system is modelled as composed of three parts: delivered energy sources, energy conversion technologies, and energy use. Seven delivered energy sources are assumed to be available: electricity from the grid (EG), natural gas, biogas, biomass (pellets and wood chips), district heating (DH) and district cooling (DC). Seven energy conversion technologies are available on-site: Combined Heat and Power (CHP), using either a molten carbonate fuel cell (MCFC) or a reciprocating engine (RE), biomass boiler (BB), ground source heat pump (GSHP), absorption chiller (AC), on-site small-scale wind turbines (WO) including both building-mounted and stand-alone wind turbines, Photovoltaics (PV) and solar thermal collector (TC). These energy conversion technologies along with delivered energy sources are used to satisfy the four types of energy demand on the campus: electricity ($E_{us,E}$), space heating ($E_{us,H}$), domestic hot water use ($E_{us,HW}$), and cooling ($E_{us,C}$). Fig. 1 presents the sketch of the energy system, illustrating energy fluxes from energy sources to energy use through different types of conversion technologies.

The non-renewable primary energy (NRPE) consumption is calculated in accordance with REHVA nZEB technical definition [4], defined as below,

$$E_{P,nren} = \sum_i E_{det,i} * f_{det,nren,i} - \sum_i E_{ex,i} * f_{ex,nren,i}$$  \hspace{1cm} (1)

where $i$ denotes the $i$-th energy carrier at the on-site boundary; $E_{det,i}$ and $E_{ex,i}$ are the annual delivered and exported energy respectively; $f_{det,nren,i}$ and $f_{ex,nren,i}$ are the corresponding non-renewable primary energy factors for delivered and exported energy respectively.

The greenhouse gas emissions are expressed by the annual CO$_2$ equivalent emissions during the operation of the energy system, defined in consistence with the non-renewable primary energy consumption calculation,

$$m_{CO_2} = \sum_i E_{det,i} * K_{det,nren,i} - \sum_i E_{ex,i} * K_{ex,nren,i}$$  \hspace{1cm} (2)

where $E_{det,i}$ and $E_{ex,i}$ are the same as in (1); $K_{det,nren,i}$ and $K_{ex,nren,i}$ are CO$_2$ equivalent emission factors for delivered and exported energy respectively with the unit kg CO$_2$/kWh, which convert the amount of consumed energy to the amount of emitted CO$_2$ equivalents. As only electricity is exported to the electricity grid in this study, the corresponding emission factor is assumed to compensate the electricity grid mix.
The levelized life cycle cost covers the investment cost, operation and maintenance (O&M) cost, delivered energy cost, and compensation from selling electricity to the grid, over the entire life time. The disposal and recycling cost is not taken into account. The life cycle cost is expressed as annually interest rate levelized cost, calculated following the equation below,

\[
LC\bar{C} = \sum_s C_{inv,s} \cdot A_s + \sum_s C_{O&M,s} + \sum_i E_{del,n,i} \cdot P_{buy,i} - \sum_i E_{ex,n,i} \cdot P_{sell,i}
\]

where \( s \) stands for the \( s \)-th energy conversion technology, \( i \) stands for the \( i \)-th energy carrier, \( C_{inv,s} \) for the investment cost, \( C_{O&M,s} \) for O&M cost, \( P_{buy,i} \) is the purchased price of energy carrier \( i \), and \( P_{sell,i} \) is the selling price of energy carrier \( i \). The selling electricity price to the grid is assumed the same as purchased price from the grid. \( A_s \) represents the annuity factor for levelizing the cost of the \( s \)-th technology. It is further assumed that the real interest rate, inflation rate and fuel prices all keep constant during the entire life time.
The power produced from renewable energy sources depends strongly on the weather conditions. In this study, the renewable energy production is determined by the real weather conditions. Correspondingly, the simulation of energy system is carried out on an hourly basis, where the demand and supply balance is analyzed in each hour. The loss of power supply probability (LPSP) is introduced here to measure the sufficiency of the energy system in meeting the energy demand at real time. LPSP is calculated as the ratio of failure time to the whole time length [12]:

\[
LPSP = \frac{\sum_{t=1}^{N} \text{hour}(P_{\text{supply}} < P_{\text{demand}})}{N}
\]

(4)

The positive values of LPSP indicate the percentage of the time in a year when the energy system fails to sufficiently meet the energy demand.

2.2.2 Renewable energy sources

The solar and wind energy are available as renewable energy sources on-site Albano. Buildings on Albano have a total roof area of 34 200 m², and with a ground coverage ratio 20%, 6900 m² is assumed to be the maximum available effective area for solar devices, as some roof space is also dedicated to human activities and other equipment installation (e.g. wind turbines). With 6900 m² effective installation, PV can produce approximately 1000 MWh electricity annually. Small-scale wind turbines are considered to take advantage of wind energy. The possibilities of installing both building-mounted and stand-alone wind turbines are analysed in this study. The estimated maximum number of wind turbines installed on-site Albano is 16 and 12 for building-mounted and stand-alone respectively. With the wind profile on Albano, it is estimated to produce about 70 MWh electricity each year.

2.2.3 Heat recovery from greywater

The energy use for producing domestic hot water used to be a minor part in the total energy use of a building. As numerous measures have been taken to save the energy use for space heating, however, the energy used for heating water has become increasingly significant. The heat demand for domestic hot water production in residential buildings on Albano is 43 kWh/m², which is bigger than 36 kWh/m² for spacing heating, accounting for 44% of the total building energy use. Therefore, there is a potential to recover the heat from greywater, which could save both energy and economic cost. A number of studies have been conducted to investigate the economic and technical efficiencies of heat recovery from greywater. Amo and López (2015) studied the drain water heat recovery in a residential building located in Gävle with 23 apartments and 48 residents [13]. With a centralized heat exchanger to pre-heat the cold water, up to 23.16 MWh heat has been saved annually, corresponding to 23% reduction in heat demand.

The total domestic hot water use in residential buildings on Albano is 40 000 m³, which leads to approximately a heating energy use of 2150 MWh. Following the same methodology as in Ref [13], a 23% reduction in heating energy demand is assumed in this study if greywater heat recovery is taken into account in the energy system design.

2.2.4 Heat recovery from an IT/Data center

According to the district planners, an IT/Data center is expected to be placed on the Albano campus. Based on the experiences from the current computer center on KTH campus, the new IT/Data center is supposed to provide waste heat at the power of 1.7 MW. The amount of heat provided over a year will then be 15000 MWh. It is worth considering utilizing this large
amount of waste heat when designing the energy system. At the power rate of 1.7 MW, however, the waste heat from the IT/Data center alone is not able to cover the peak heat load of Albano. It therefore has to be used along with other energy conversion technologies. The temperature level of the waste heat from the IT/Data center is about 35-40 °C [14], which is not high enough for domestic hot water generation and even for ordinary space heating. Thus, an additional heat pump is required to raise the temperature level up to 60 °C. As the waste heat is available on-site, it does not count for the delivered primary energy consumption.

2.3 Design variables, objectives and constraints

Tab. 3 Design variables used in the study

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Unit</th>
<th>Variable type</th>
<th>Value or range [min, max]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground source heat pump</td>
<td>kW_{th}</td>
<td>Continuous</td>
<td>[0, 3500]</td>
</tr>
<tr>
<td>Area of PV</td>
<td>m²</td>
<td>Continuous</td>
<td>[0, 6900]</td>
</tr>
<tr>
<td>Area of solar thermal collectors</td>
<td>m²</td>
<td>Continuous</td>
<td>[0, 6900]</td>
</tr>
<tr>
<td>Biomass boiler</td>
<td>kW_{th}</td>
<td>Continuous</td>
<td>[100, 3500]</td>
</tr>
<tr>
<td>Reciprocating engines</td>
<td>kW_{el}</td>
<td>Continuous</td>
<td>[10, 3000]</td>
</tr>
<tr>
<td>Molten carbonate fuel cell</td>
<td>kW_{el}</td>
<td>Continuous</td>
<td>[240, 350]</td>
</tr>
<tr>
<td>Absorption chiller</td>
<td>kW_{c}</td>
<td>Continuous</td>
<td>[100, 3000]</td>
</tr>
<tr>
<td>Existence of absorption chiller</td>
<td>Binary</td>
<td></td>
<td>[0, 1]</td>
</tr>
<tr>
<td>Existence of anaerobic digester</td>
<td>Binary</td>
<td></td>
<td>[0, 1]</td>
</tr>
<tr>
<td>Number of building-mounted on-site wind turbines</td>
<td>Discrete</td>
<td></td>
<td>[0, 1, 2, ..., 15, 16]</td>
</tr>
<tr>
<td>Number of stand-alone on-site wind turbines</td>
<td>Discrete</td>
<td></td>
<td>[0, 1, 2, ..., 11, 12]</td>
</tr>
<tr>
<td>CHP type:</td>
<td>Discrete</td>
<td></td>
<td>[0, 1, 2]</td>
</tr>
<tr>
<td>0 is no CHP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 is reciprocating engine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 is molten carbonate fuel cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHP fuel type:</td>
<td>Discrete</td>
<td></td>
<td>[1, 2]</td>
</tr>
<tr>
<td>1 is natural gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 is biogas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass boiler:</td>
<td>Discrete</td>
<td></td>
<td>[0, 1, 2]</td>
</tr>
<tr>
<td>0 is no biomass boiler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 is pellet boiler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 is wood residue boiler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limit</td>
<td>m²</td>
<td>≤</td>
<td>6900</td>
</tr>
</tbody>
</table>

Design variables are selected based upon the availability of energy sources and energy conversion technologies, which can be continuous, discrete or binary. Tab. 3 presents the 14 design variables that are employed in the system design, seven of which are continuous representing the size of energy conversion technologies, whereas the other seven are discrete or binary denoting the existence or the number of energy conversion technologies.

The non-renewable primary energy consumption, the greenhouse gas emissions, and the levelized life cycle cost are the three objectives, which are minimized in the optimization.
One constraint is to limit the total installed area of solar thermal collectors and PV panels. LPSP is employed as the second constraint, which is kept zero in the optimization, ensuring that energy demand is sufficiently satisfied in every hour by the designed system.

3 Results

In order to provide district planners with a larger set of solutions, it is beneficial to find suboptimal solutions, where some technologies have been excluded in the system design. The optimization problem is thus solved for four different scenarios defined as follows:

Scenario I. All technologies as listed in Fig. 1;
Scenario II. Based on Scenario I, but no district heating/cooling;
Scenario III. Based on Scenario II, with heat recovery from greywater;
Scenario IV. Based on Scenario III, with heat recovery from an IT/Data center.

The Pareto optimal solutions are presented in Fig. 2 and Fig. 3. For each scenario, the figures present the tradeoff between the non-renewable primary energy consumption and the levelized life cycle cost, and between GHG emissions and the levelized life cycle cost. Each dot in the figures represents a possible solution for the energy system, which is optimal in the sense that it cannot be improved in one objective (e.g. GHG emissions) without losing performance in another one (e.g. life cycle cost). The objective values of all such optimal solutions constitute the Pareto front as shown in each figure.

The solution that consists of district heating and cooling only, with electricity supplied solely by the grid and without any form of heat recovery, is taken as the reference case. This solution is plotted in Fig. 2 and Fig. 3, referred to as DHDC. In this case, the NRPE consumption amounts to 30.7 kWh/m², the GHG emissions to 4.1 kg CO₂/m², and the levelized life cycle cost to 70.9 SEK/m².

The Pareto front of the tradeoff between the NRPE consumption and the levelized life-cycle cost in all four scenarios consists of two pieces: the lower cost piece and the higher cost piece. The discontinuity that lies in the cost is due to the appearance of CHP in the higher piece of the Pareto front. CHP is much more costly than biomass boiler (BB) that appears in the lower cost piece. With the introduction of CHP into the system, the high investment cost makes the levelized life-cycle cost jump. It is noteworthy that CHP does not appear in the Pareto front of the tradeoff between GHG emissions and levelized life-cycle cost. This is because CHP burns natural gas or biogas, which tends to cause a high cost and high emissions. Solar thermal collectors do not appear as Pareto optimal solutions in any scenarios. This is due to the big mismatch between heat production and heat demand. The most of heat production takes place in summer time, whereas most of heat demand takes place in winter time. As a result, solar thermal collectors contribute little to the energy production and fail to compete against PV.

In Scenario I, the minimum cost solution consists of a biomass boiler (BB). The cold is supplied by district cooling (DC). In this solution, both the PV installation area and the number of wind turbines (WT) are zero. As PV installation area gradually increases from zero, NRPE consumption and GHG emissions diminish with the cost rising. When PV reaches the maximum installation, wind turbines begin to appear. The number of wind turbines increases until reaching the full installation, accounting for the left end of the Pareto front in Fig. 3 and of the lower piece of Pareto front in Fig. 2. If a further reduction of non-renewable primary energy consumption is wanted, CHP appears, generating both electricity and heat. If the electricity produced is more than needed, it will be exported to the grid. CHP
together with a biomass boiler supplies the heat for the entire Albano, forming the higher cost piece of Pareto front in Fig. 2.

**Fig. 2** Pareto optimal solutions that trade off LCC and NRPE consumption

**Fig. 3** Pareto optimal solutions that trade off LCC and GHG emissions
In Scenario II, no district heating or cooling is wanted. As a result, the cold has to be supplied by means of ground source cooling using boreholes. It leads to a higher investment cost and shifts upwards the Pareto front. The Pareto front of Scenario III shifts downwards and leftwards from Scenario II, which means that the heat recovery from greywater does not only save NRPE consumption and GHG emissions, but can be profitable as well. Scenario IV takes advantage of the waste heat from the IT/Data center and employs a 1.7 MW heat pump to raise the temperature. As a heat pump is costly, the Pareto front shifts upwards accordingly. The Pareto front in Fig. 3 moves towards the left quite much, implying a significant reduction in GHG emissions. It might be seemingly surprising that the Pareto front in Fig. 2 shifts rightwards interpreted as a higher NRPE consumption than without the heat recovery. This is because the heat pump consumes electricity that has a higher non-renewable primary energy factor than biomass.

4 Conclusion

In this paper, a genetic algorithm based multi-objective optimization approach has been developed and successfully applied to the energy system design of a district – the new Albano university campus. The purpose of this study is to assist district planners in finding an optimal energy system solution that cannot only fulfil the nearly zero energy requirements but also have good economic and environmental performances. The optimization approach simultaneously minimizes the non-renewable primary energy consumption, the greenhouse gas emissions, and the levelized life cycle cost. Instead of defining weights for different objectives, this approach presents optimal solutions directly in the form of Pareto fronts, which more clearly illustrates the trade-off between conflicting objectives. The methodology presented can help district planners explore the possibilities that an energy system can achieve and makes it easier for decision-makers to reach a compromise between economic and environmental performances. Put simply, decision-makers can just pick up a solution point from the Pareto front based on their preference over different objectives. On-site renewable energy sources including solar energy, wind energy and ground source thermal energy are explored in the study. Energy saving potentials such as heat recovery from greywater and from an IT/Data centre are investigated. In order for district planners to better understand the influence of certain technologies on the trade-off relations between objectives, the optimization problem has been solved for various scenarios and a series of Pareto fronts are presented for comparison.

Some interesting findings from the optimization results might be useful for district planners or other decision-makers. The heat recovery from greywater applied to high living density residential buildings has the potential to save a considerable amount of energy and GHG emissions. If there is free heat available from for instance an IT/Data center, it is strongly recommended to take advantage of it to reduce the emissions. In the case of Albano, small-scale on-site wind turbines produce a limited amount of electricity, due to the low wind speed on Albano. In contrast, PV can produce a larger amount of electricity at a lower cost than do wind turbines. If a budget limit exists for local electricity production technologies, PV is preferred to wind turbines.

In future studies, more objectives will be added into the optimization framework. The total exergy efficiency of the system, for instance, is to be maximized. Exergy is a measure of energy quality. High exergy efficiency usually indicates highly efficient use of energy sources. A sensitivity analysis will be carried out to examine the system robustness and find the most influential parameters. The optimal energy system designs might change completely if some
sensitive parameters are varied only moderately. Energy storage devices (e.g. batteries, water tanks, underground storage, etc.) are not considered in the current study, which can be expected to have significant impact on the optimal solutions by allowing the energy production of certain technologies, for instance, solar thermal collectors, to better match the energy demand. Energy storage will therefore be modelled and integrated into optimization in future studies. One of the limitations of this study lies in the assumptions and approximations made about the energy load, costs, and efficiencies of energy conversion technologies. As the Albano project develops, more detailed information will become available. Future studies will then be conducted with updated parameters.

References


