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Multi-objective optimization and parametric analysis of energy system designs for the Albano university campus in Stockholm

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Abstract

In this study, a multi-objective optimization approach is applied to the energy system design of the Albano university campus in Stockholm. The greenhouse gas emissions, the life cycle cost and the net exergy deficit of the campus are minimized, while the nearly zero energy requirements are respected. Four optimal solutions are identified based on those under equal importance, environment-oriented, economy-oriented, and exergy-oriented scenarios. The energy components of the four scenarios are analyzed and compared. A parametric analysis is conducted to investigate the impact of the variations in a number of economic, environmental and technical parameters on the composition of the optimal solution.

Keywords: nearly zero energy; nearly zero exergy; multi-objective optimization; parametric analysis

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1. Introduction

As the largest energy consuming sector in the world, buildings account for 35% of global final energy use and are responsible for approximately 17% of energy-related CO2 emission$_s$ [1]. With the rising requirement for living standards, these numbers are expected to continue growing in the future. On the other hand, under the pressure of aggravating energy-related environmental challenges, many countries have launched regulations on building energy

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performance. The EU Energy Performance of Buildings Directive (EPBD) stipulates that all new buildings must be nearly zero energy buildings (nZEB) by the end of year 2020 [2]. A nearly zero energy building is one that has a very high energy performance and whose energy demand is to a large extent satisfied by renewable energy sources from on-site or nearby [3]. Researchers have conducted a large number of studies to find cost-optimal solutions for nZEB, from both the building side and the energy system side. The finding that it is quite difficult to achieve nZEB status at the individual building level has motivated researchers to investigate the solutions of nZEB at the district level; that is, a nearly zero energy district (nZED) [4].

In addition to nZEB/nZED, another important aspect is mitigation of the environmental impact. The EU 20-20-20 targets aim to cut 20% greenhouse gas (GHG) emissions by 2020 compared with 1990 levels. Therefore, environmental performance must be considered along with the energy performance when designing district energy systems. The concept of energy quality has recently attracted researchers' attention. Energy quality, in the context of the built environment, is expressed as exergy, which is a thermodynamic concept that measures the maximum useful work potential of a given amount of energy that a system can use by interacting with a given reference state. Kilkis [5] introduced Rational Exergy Management Model (REMM) to look into the potential to curb avoidable CO_2 emissions in the built environment. REMM links the exergy efficiency to the avoidable CO_2 emissions. High exergy efficiency indicates a high level of match between demand and supply and implies low avoidable CO_2 emissions. Lu et al. [6] proposed an energy quality management approach for building clusters and districts and integrated exergy efficiency as an objective into their district energy system design optimization framework [6]. Similar to nZEB, the concept of nearly zero exergy buildings (nZEXB) is put forth and further expanded to nearly zero exergy districts (nZEXD) [7, 8]. A nearly zero exergy building/district manages its demand and supply, seeking to equate the delivered exergy from the grid with the surplus exergy exported to the grid [9]. It should be noted that a nZEB (nZED) might not necessarily be a nZEXB (nZEXD) due to the different exergy levels in the exchanges, as some studies have noted [10].

Apart from the concerns for energy, exergy, and emissions, stakeholders are also cost-sensitive, which means that in achieving these objectives the designed energy system must be cost efficient. The life cycle cost (LCC), which comprises the investment cost, operational cost, maintenance cost, and possibly disposal cost, has been widely adopted as an indicator to evaluate energy systems in recent studies [11]. All of the above-mentioned aspects mentioned above must be taken into account when designing an optimal district energy system. In most cases, however, these aspects contradict each other. This necessitates a multi-objective optimization approach that is capable of simultaneously optimizing two or more objectives and presents a series of optimal solutions in the form of Pareto fronts. Pareto fronts show the tradeoff between different objectives and enable stakeholders to make compromise between objectives. In the present paper, we employed a genetic algorithm (GA) based multi-objective optimization approach to find the optimal energy solutions for a sustainable district – the Albano university campus in Stockholm. GA well suits the need for district energy system designs, which often involve two or more objectives, both continuous and discrete design variables, non-linear functions, and non-concave search domains [12]. GA has a number of variants that are capable of multi-objective optimization. We employed the Pareto archive NSGA-II algorithm due to its fast convergence. The optimizer used in this study is MOBO, a multi-objective building optimization software, developed by Palonen et al. [13].

Like many real-world design problems, energy system designs are susceptible to uncertainties. System parameters are either not precisely known or vary significantly over time. A sensitivity analysis conducted in the previous study [14] showed that optimal solutions could be sensitive to some parameters. Although the previous study sheds light on how the objective values of a given optimal solution vary to the changes in economic and technical parameters, it fails to tell whether the optimal solution itself remains optimal or not and if not, how much the new optimal solution is different from the old one. Therefore, the optimization in the paper is followed by a detailed parametric analysis to examine the way that the composition of the optimal solution varies to the changes of some parameters.

2. Methodology

2.1. Case description

The Albano university campus is located in the northern part of Stockholm, sitting amid three universities: the Royal Institute of Technology, Stockholm University, and the Karolinska Institute. The campus will have a total floor area of 150, 000 m^2 and consists of two types of buildings: lecture buildings and residential buildings. The campus will be used jointly by the three universities and is expected to host more than 15, 000 students and teachers. The owner of the lecture buildings on the Albano campus, Akademiska Hus, has strong environmental objectives, both regarding energy use in existing buildings – the energy use should be halved from year 2000 to 2025 – and that new buildings should be nZEB. Furthermore, the CO_2 footprint from operating the buildings should be eliminated. The campus should use as little supplied energy as possible and the energy supplied should be produced locally as much as possible. The construction of the campus is ongoing and limited information is available at this early stage. Consequently, assumptions have been made in order to calculate the energy consumption of buildings. The building energy performance tools, IDA ICE and VIP Energy, are used to simulate the dynamic energy load of one representative lecture building and one representative residential building, respectively. Since buildings of each type have similar properties, it is assumed that they also have the same energy use profiles. The profiles of each building type are then aggregated to obtain the total energy use profile of the campus. Table 1 shows the yearly total energy consumption and peak power load of four types of energy use.

Table 1. Annual energy consumption and peak power load of the Albano campus.

	Heating	**Domestic Hot Water**	**Cooling**	**Electricity**
Power [kW]	1750	750	2400	450
Energy [MWh]	3600	2150	1000	2200

2.2. Energy system modelling and definition

The district energy system is composed of three parts: delivered energy sources, energy conversion technologies, and energy use. Three delivered energy sources are available on-site the Albano campus: electricity from the grid (EG), district heating (DH), and biogas (BG). Eight energy conversion technologies are modeled: combined heat and power (CHP) including a molten carbonate fuel cell (MCFC) and a reciprocating engine (RE), ground source heat pump with a borehole field (GSHP), electric chiller (EC), absorption chiller (AC), on-site small-scale wind turbines (WO), Photovoltaics (PV), and solar thermal collectors (TC). All renewable energy production is on-site, which means that the on-site boundary and nearby boundary coincide. These energy conversion technologies and delivered energy sources together with on-site renewable energies satisfy four types of energy use: electricity ($E_{\mathrm{us,E}}$), space heating ($E_{\mathrm{us,H}}$), domestic hot water ($E_{\mathrm{us,HW}}$), and space cooling ($E_{\mathrm{us,C}}$). Figure 1 presents the energy system modelling, with energy flows directed from energy sources to energy services through conversion technologies.

The nZEB requirement imposes a restriction on the non-renewable primary energy (NRPE) consumption. NRPE consumption ($E_{P,nren}$) is defined in accordance with REHVA nZEB technical definition [3], by Equation 1 below,

$$E_{P,nren} = \sum_i E_{del,i} * f_{del,nren,i} - \sum_i E_{ex,i} * f_{ex,nren,i} \tag{1}$$

where i denotes the i-th energy carrier; $E_{del,i}$ and $E_{ex,i}$ are the annual delivered and exported energy, respectively; $f_{del,nren,i}$ and $f_{ex,nren,i}$ are the NRPE factors for delivered and exported energy, respectively.

The environmental impact is indicated by the greenhouse gas emissions, measured by annual $\mathrm{CO_2}$-equivalent emissions during the operation of the energy system. The $\mathrm{CO_2}$-equivalent emissions (m_{CO_2}) are calculated in consistence with the definition of NRPE consumption, following Equation 2 below,

$$m_{CO_2} = \sum_i E_{del,i} * K_{del,nren,i} - \sum_i E_{ex,i} * K_{ex,nren,i} \tag{2}$$

where $E_{del,n,i}$ and $E_{ex,n,i}$ are the same as above; $K_{del,nren,i}$ and $K_{ex,nren,i}$ are GHG emission factors for delivered and exported energy, respectively. As only electricity is exported to the grid, the corresponding GHG emission factor is assumed to compensate the grid mix.

The economic performance of the energy system is evaluated by the life cycle cost, which takes into account the investment cost, operation and maintenance (O&M) cost, and the revenue from selling the electricity to the grid. The disposal or recycling cost is omitted in this study. The life cycle cost is expressed as annually interest rate leveraged cost, calculated as,

$$\overline{LCC} = \sum_s C_{inv,s} * A_s + \sum_s C_{O\&M,s} + \sum_i E_{del,n,i} * P_{buy,i} - \sum_i E_{ex,n,i} * P_{sell,i} \tag{3}$$

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; A_s represents the annuity factor for levelizing the cost of the s-th technology. The price sold to the grid is assumed to be the same as purchased from the grid.

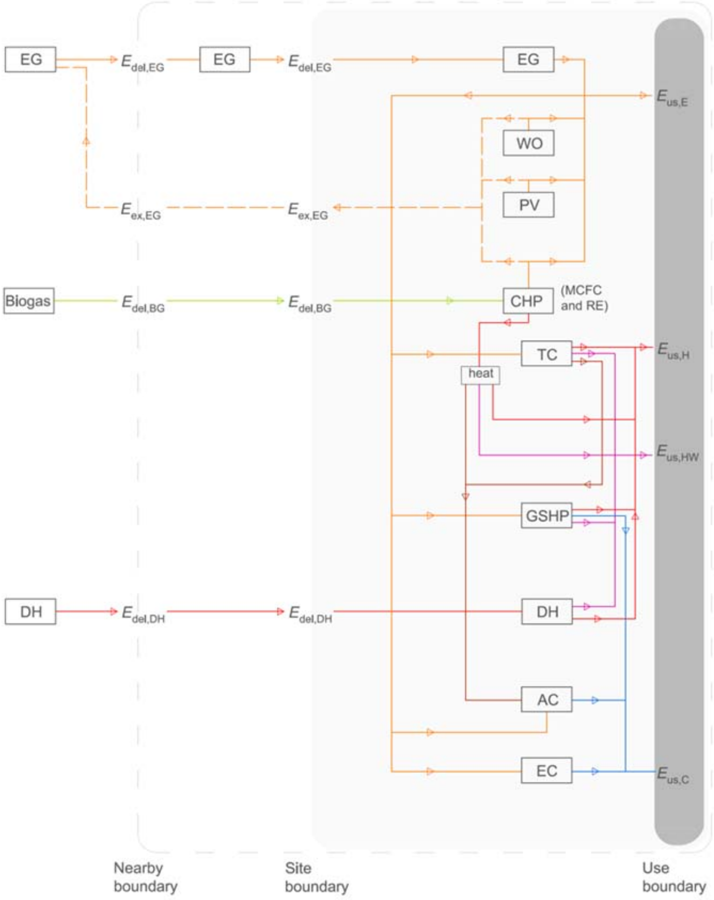


Fig. 1. A sketch of energy system modelling with energy sources, conversion technologies and energy flux.

A nearly zero exergy district seeks to balance the exergy delivered to the district with the exergy exported from the district. In order to see how Albano can achieve a nearly zero exergy status, the net exergy deficit (E_x) is calculated in a similar way to the NRPE consumption, following the formula below,

$$E_x = \sum_i E_{del,i} * F_{del,nren,i} - \sum_i E_{ex,i} * F_{ex,nren,i} \tag{4}$$

where $F_{del,nren,i}$ and $F_{ex,nren,i}$ are the Carnot factor of the delivered energy and exported energy respectively. The Carnot factor measures the quality of a specific type of energy. The Carnot factor of fuels is often defined as $F = 1 - T_{ref}/T_{resource}$, where T_{ref} is the reference temperature and $T_{resource}$ is flame temperature of fuel. The Carnot factor of electricity is one, as electricity is of the highest quality. The Carnot factor of district heating is set as 0.71, calculated based on the shares of energy sources in the district heating power plant [15].

Due to the intrinsic intermittence of renewable energy production, the capacity of the designed energy system should be large enough to fill the gap when renewable energy production is low. The energy system is simulated on an hourly basis and employs the loss of power supply probability (LPSP) as an indicator to monitor the sufficiency of the energy system in satisfying the energy demand [14]. LPSP is calculated as the ratio of the number of failure hours to the total number of hours in a year, with a positive value indicating the percentage of failure time in a year.

2.3. Design variable, objectives and constraints

The optimization consists of eight continuous design variables that represent the size of energy conversion technologies. Table 2 presents the design variables and their ranges. One constraint is imposed on the design variables to limit the total area of PV and solar thermal collectors based on the maximum available roof area.

To achieve a nearly zero energy status, the NRPE consumption is adopted as the second constraint. According to EPBD, the NRPE consumption of buildings should not exceed a control point. However, EPBD does not specify value. Instead, EPBD leaves it up to each member state to determine this control point. The Swedish control point for nZEB is not available yet, as the work of defining Swedish nZEB is still going on by the Swedish Energy Agency and the National Board of Housing, Building and Planning. In this study, we set the control point as 40 kWh/m^2. The value of LPSP is kept zero during the optimization, as the third constraint, which ensures that the energy demand is always fully met by the designed energy system at any time in a year.

The GHG emissions, the life cycle cost, and the net exergy deficit are set as the three objectives to be minimized.

Table 2. Design variables employed in the optimization

Design Variable	**Unit**	**Type**	**Value [min max]**
Area of PV	m^2	Continuous	[0, 6900]
Area of solar thermal collector	m^2	Continuous	[0, 6900]
Ground source heat pump	kW$_{th}$	Continuous	[0, 2400]
Electric chiller	kW$_{th}$	Continuous	[0, 2400]
Absorption chiller	kW$_{th}$	Continuous	[0, 2400]
Reciprocating engines	kW$_{el}$	Continuous	[0, 300]
Molten carbonate fuel cell	kW$_{el}$	Continuous	[0, 300]
Wind turbines	kW$_{el}$	Continuous	[0, 150]
Limit			
Sum of PV and solar thermal collector	m^2	Equal or less than	6900

3. Results and Analysis

The optimal solutions from multi-objective optimization are first presented in the form of a Pareto front, which shed light on the options that decision makers can potentially have. As decision makers may have different preference for the three objectives, we defined four scenarios by weighting each objective differently. The four scenarios are the equal importance, environment-oriented, economy-oriented, and exergy-oriented scenarios. The corresponding optimal solution under each scenario is identified, with its composition further analyzed. Finally, a parametric analysis is carried out on the optimal solution under the equal importance scenario, in order to investigate how the variations of certain parameters influence the optimal solutions.

3.1. Pareto-optimal solutions

The dot is colored by the net exergy deficit as defined in Equation 4, whose value can be read from the color bar beside. Each solution is Pareto-optimal, in the sense that the performance in one objective (such as GHG emissions) cannot be improved without losing performance in other objectives (for example, life cycle cost or net exergy deficit). The objective values of all such solutions constitute the Pareto front. A clear tradeoff can be observed between GHG emissions and the life cycle cost. The result reveals at least how much economic performance stakeholders have to sacrifice in return for a better environmental performance. The figure also shows that low net exergy deficit solutions mostly lie in the medium range of the cost and the emissions. This means that from a net-zero-exergy point of view the pursuit in either economic or environmental performance will deteriorate the net exergy performance.

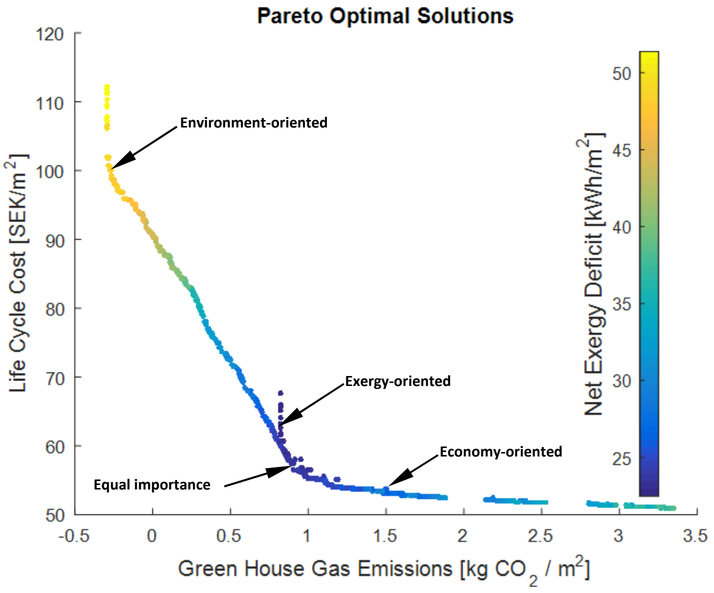


Fig. 2. Pareto optimal solutions from multi-objective optimization.

3.2. Evaluation

In order to evaluate the obtained optimal solutions, the solution with district heating (DH) providing heat and electric chillers providing cold is considered as a reference solution. All Pareto solutions are compared to this reference solution. The reference solution entails GHG emissions of 4.0 kg CO_2/m^2, a levelized life cycle cost of 52 SEK/m^2, and a net exergy deficit of 44 kWh/ m^2. To measure the improvement achieved by the optimization, the Pareto-optimal solutions are compared with the reference solution with the following ratios defined:

- GHG emissions reduction ratio: $ER = 1 - GHG/GHG_{ref}$
- Life cycle cost saving ratio: $CR = 1 - LCC/LCC_{ref}$
- Net exergy deficit cut ratio: $E_xR = 1 - nE_xD/nE_xD_{ref}$

where GHG, LCC, and nE_xD denote the GHG emissions, the levelized life cycle cost and the net exergy deficit respectively; the subscript ref indicates the reference case. Thus, the overall improvement ratio (IR) is defined as the weighted sum of the ratios above: $IR = \omega_1 * ER + \omega_2 * CR + \omega_3 * E_xR$.

To reflect stakeholders' preferences for the different objectives, four types of weight combinations are defined, deriving four scenarios:

- Equal importance scenario: $\omega_1 = \omega_2 = \omega_3 = 1/3$.
- Environment-oriented scenario: $\omega_1 = 0.8;\ \omega_2 = \omega_3 = 0.1$.
- Economy-oriented scenario: $\omega_2 = 0.8;\ \omega_1 = \omega_3 = 0.1$.
- Exergy-oriented scenario: $\omega_3 = 0.8;\ \omega_1 = \omega_2 = 0.1$.

The optimal solution under each scenario is further identified and marked on Figure 2. The component analysis of heat (including both space heating and domestic hot water), cold, and electricity is presented in Figure 3-6, for each scenario, respectively. The electricity use is different across scenarios, as electricity is also used to drive the thermal energy conversion technologies in addition to satisfying the campus electricity demand.

As shown in the figures, GSHP plays the most significant role in heat and cold production in all scenarios. GSHP reaches the highest share (85%) for heat in the equal importance and exergy-oriented solutions, whereas the highest share of GSHP for cold (95%) occurs in the exergy-oriented solution. The environment-oriented scenario realizes the smallest share of GSHP in both heat and cold among all scenarios. DH accounts for a small share for heat in all scenarios except in the economy-oriented scenario, where DH provides 22% of total heat. TC has a relatively stable share for heat across different scenarios. Solar absorption chilling (TC-AC) is the second largest component of cold production after GSHP and becomes especially important in economy-oriented and environment-oriented scenarios. EC forms a significantly small portion of cold production in all scenarios. CHP (RE and MCFC) only appear in the environment-oriented scenario, where RE makes the largest contribution for electricity and the second largest for heat. In this scenario, almost no electricity is purchased from the gird, whereas EG is the major component in the other three scenarios. PV produces a similar amount of electricity in four scenarios, which implies that PV installation is not significantly affected by the objective preferences. WT is only needed in the exergy-oriented scenario and is responsible for a negligible fraction of electricity production, probably due to the low wind speed on Albano.

The results illustrate that GSHP is most promising in producing heat and cold in terms of overall performance. DH is mostly used to cover the peak heating load, but it is worth considering from an economic point of view as it is more cost-effective than GSHP. Biogas CHP is cost prohibitive and is not desirable unless environmental performance is strongly emphasized. EC is never favored and can be viewed as a backup technology to cover the peak cooling load. It seems that different objective preferences do not have a significant impact on renewable energy production from solar sources (such as TC and PV).

3.3. Parametric analysis

Optimal solutions depend on the various parameters employed in the energy system modelling. Some parameters are, however, subject to uncertainties or vary over time. Therefore, a parametric analysis is conducted in this subsection to examine the impact of varying parameters on the composition of optimal solutions. The parametric analysis focuses on three types of parameters: economic, environmental, and technical parameters. Due to limited resources, we have only investigated the impact on the optimal solution under the equal importance scenario.

The energy prices and cost of energy conversion technologies have varied significantly over time. For instance, the turnkey price of PV in the Swedish market halved over the years from 2011 to 2014 [16]. Herein the prices of PV, solar thermal collectors, and ground source heat pump are assumed to decrease, whereas the electricity price is assumed to increase in the following years. The results are presented in Figure 7. Figures 7 (a) and (b) show that the installed area of PV and TC increases steadily as they drop in price. As both are limited by total available roof area, they crowd each other out. It is also observed that the installation of TC is more sensitive to its own price reduction than that of PV. Figure 7 (c) illustrates how the cost reduction encourages the utilization of GSHP. GSHP’s share in heat and cold production grows only slightly as the GSHP price declines. The upward convex trend indicates a diminishing marginal effect of price reduction, which might imply that the size of GSHP is almost reaching a critical point. Figure 7 (d) reveals how the rising electricity price affects PV installation and the share of electricity heating and cooling (GSHP and EC). The increase of electricity price modestly promotes the use of PV. The share of electricity heating and cooling has proved to be quite stable to the variation of electricity price.

It can be expected that the energy performance of PV will continue to improve in the next few years. Thus, the parametric analysis is also conducted on this technical parameter – PV efficiency. The local district heating company is taking action to increase the share of renewable energy. The actions include installing a new biofuel CHP plant, which echoes the Stockholm city’s ambition to become a fossil fuel free city by 2050 [17]. Therefore, the influence of districting heat emission reduction on the optimal solution is examined through the parametric analysis, with the results shown in Figure 8. Figure 8 (a) shows that a slight improvement of PV efficiency is effective in promoting the use of PV. As the efficiency continues to improve from 20% to 40%, however, the promotion slows down. Unlike other parameters, DH emission reduction has been shown to have an inconsistent impact on the energy system configuration. DH reaches its largest share in heat supply (3%) when the emission is reduced by 20%. As the emission is further reduced, DH's share drops and then shows a tendency to stabilize.

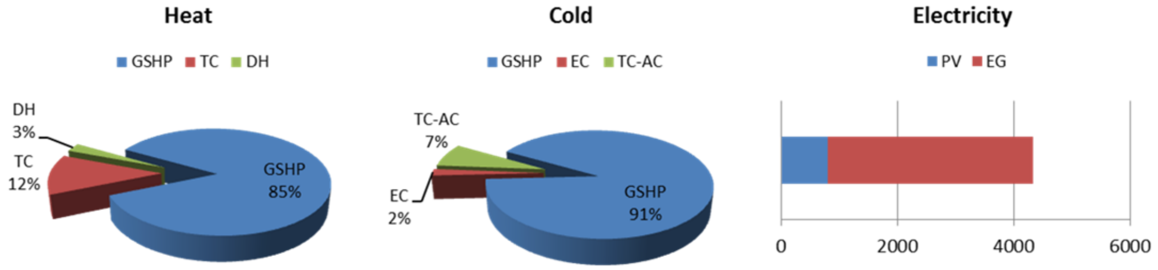


Fig. 3. Energy components analysis of the optimal solution under the equal importance scenario.

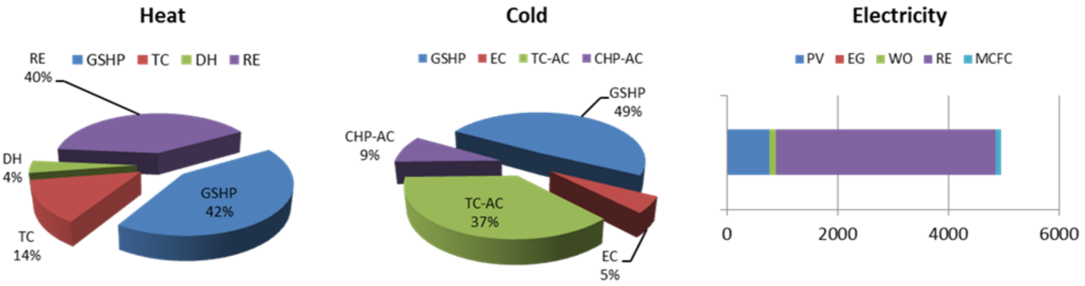


Fig. 4. Energy components analysis of the optimal solution under the environment-oriented scenario.

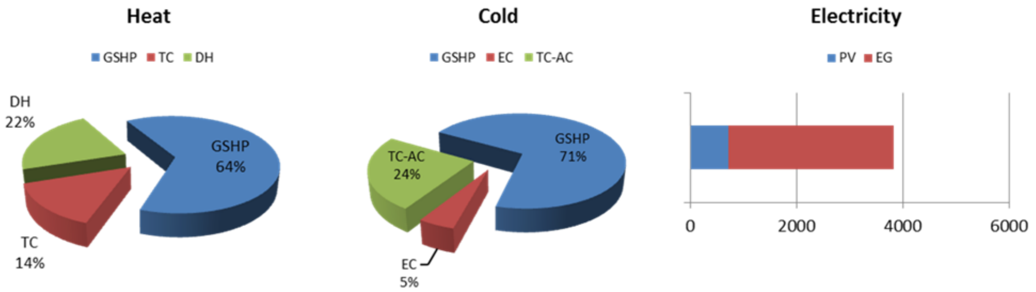


Fig. 5. Energy components analysis of the optimal solution under the economy-oriented scenario.

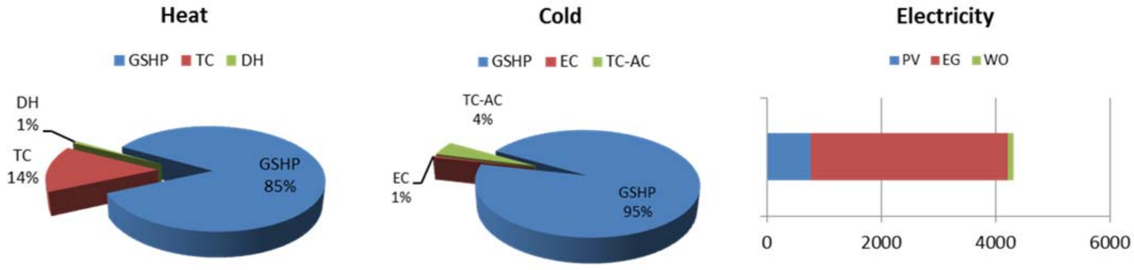
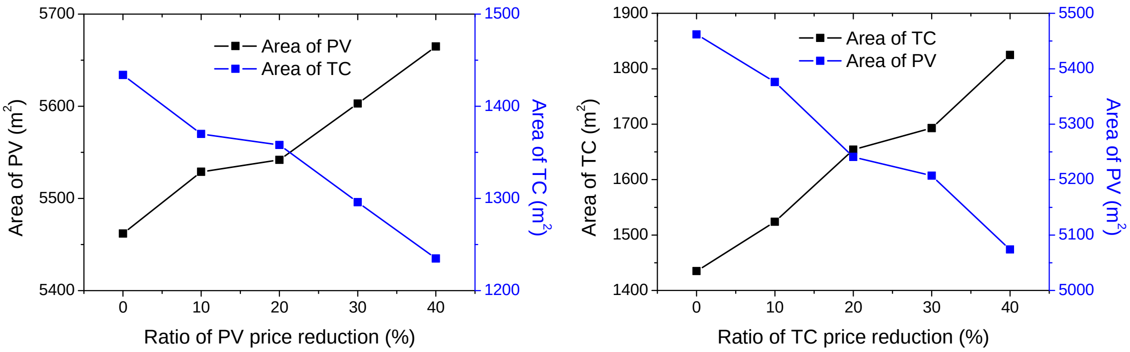
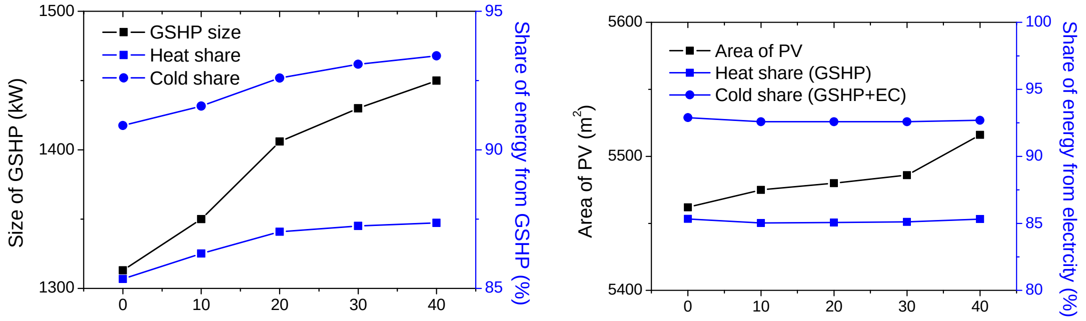


Fig. 6. Energy components analysis of the optimal solution under the exergy-oriented scenario.

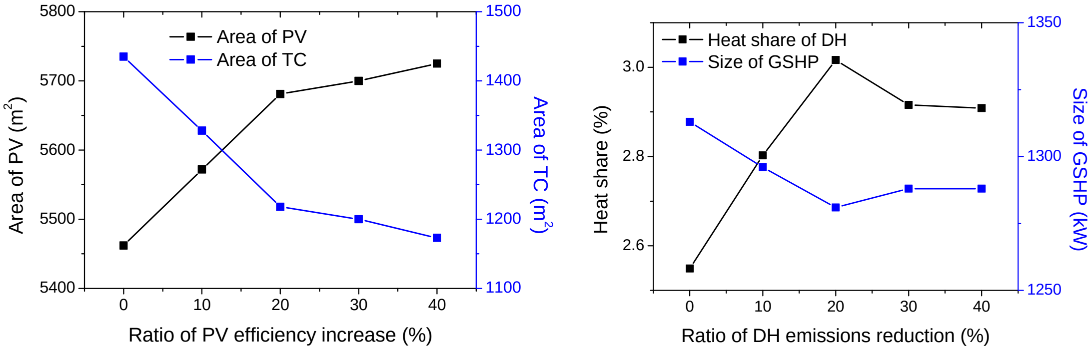


(a) Reduction of PV price (b) Reduction of TC price



(c) Reduction of GHSP price (d) Electricity price increase

Fig. 7. Parametric analysis of economic parameters: (a) PV; (b) TC; (c) GSHP; (d) Electricity



(a) PV efficiency increase (b) District heating emission reduction

Fig. 8. Parametric analysis of technical and environmental parameters: (a) PV efficiency; (b) DH emission

4. Conclusion

In this paper, a multi-objective optimization approach has been applied to the energy system design of the new Albano university campus in Stockholm. The optimization simultaneously minimizes three objectives: the greenhouse gas emissions, the life cycle cost, and the net exergy deficit. The nZEB requirement is handled as a constraint in the optimization on the non-renewable primary energy consumption. The results are presented in the form of a Pareto front, which is a combination of all Pareto-optimal solutions. The Pareto front can give stakeholders an overview of the design of the energy system that helps them more clearly understand the options and limitation that they face. In order for decision makers to select the solution from the Pareto font, the three objectives are weighted in four different ways, in response to the decision makers' preference for different objectives.

Correspondingly, four single optimal solutions are identified: an equal importance solution, an environment-oriented solution, an economy-oriented solution, and an exergy-oriented solution. The composition of these solutions is analyzed, which illustrates the difference in the measures taken in the pursuit of each objective. GSHP has shown the best overall performance in terms of meeting thermal energy demand. PV represents a significant and stable fraction of electricity production in all scenarios. District heating is much less costly than GSHP and might be favored from an economic point of view. Biogas CHP is generally not suggested unless zero emission is strongly prioritized. Like many real-world design problems, energy system design is also subject to uncertain parameters. Followed by a parametric analysis, a number of economic, environmental and technical parameters are selected, which are assumed to vary over time. Their impact on the equal importance solution is examined and presented. All the parameters have an influence on the composition of the equal importance optimal solution. The solution is more sensitive to some parameters than others. It is also observed that the influence in general is not linear and in some cases is not monotonic.

In future work, more parameters will be examined and the parametric analysis will be extended to the other three optimal solutions. It can be expected that the same parameter will exert different impacts on different optimal solutions. It should be noted that the parametric analysis in this study is a local analysis that does not consider the synergetic effect in the variation of parameters. Future studies will develop a new approach to address the influence from the variations of the entire set of parameters. In addition, as energy conversion technologies are developing rapidly, new and promising technologies will be integrated into the modelling and optimization framework. Energy storage technologies will also be introduced into the design; these are expected to significantly affect the optimal solutions by allowing a better match between supply and demand especially for renewable energy production.

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