KTH Architecture and the Built Environment

Optimal Design of District Energy Systems: a Multi-Objective Approach

CONG WANG

Licentiate Thesis
Stockholm, Sweden 2016

TRITA-IES 2016:05
ISSN 0284-141X
ISBN 978-91-7729-129-9

KTH School of ABE
SE-100 44 Stockholm
SWEDEN

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges till offentlig granskning för avläggande av teknologie licentiatexamen i Installation- och Energisystem 2016-10-14 klockan 14:00 i sal M108, Kungl Tekniska högskolan, Brinellvägen 23, Stockholm, Sweden.

Abstract

The aim of this thesis is to develop a holistic approach to the optimal design of energy systems for building clusters or districts. The emerging Albano university campus, which is planned to be a vivid example of sustainable urban development, is used as a case study through collaboration with the property owners, Akademiska Hus and Svenska Bostäder. The design addresses aspects of energy performance, environmental performance, economic performance, and exergy performance of the energy system. A multi-objective optimization approach is applied to minimize objectives such as non-renewable primary energy consumptions, the greenhouse gas emissions, the life cycle cost, and the net exergy deficit. These objectives reflect both practical requirements and research interest. The optimization results are presented in the form of Pareto fronts, through which decision-makers can understand the options and limitations more clearly and ultimately make better and more informed decisions. Sensitivity analyses show that solutions could be sensitive to certain system parameters. To overcome this, a robust design optimization method is also developed and employed to find robust optimal solutions, which are less sensitive to the variation of system parameters.

The influence of different preferences for objectives on the selection of optimal solutions is examined. Energy components of the selected solutions under different preference scenarios are analyzed, which illustrates the advantages and disadvantages of certain energy conversion technologies in the pursuit of various objectives. As optimal solutions depend on the system parameters, a parametric analysis is also conducted to investigate how the composition of optimal solutions varies to the changes of certain parameters.

In virtue of the Rational Exergy Management Model (REMM), the planned buildings on the Albano campus are further compared to the existing buildings on KTH campus, based on energy and exergy analysis. Four proposed alternative energy supply scenarios as well as the present case are analyzed. REMM shows that the proposed scenarios have better levels of match between supply and demand of exergy and result in lower avoidable CO_2 emissions, which promise cleaner energy structures.

Keywords: multi-objective optimization, robust design optimization, district energy system, parametric analysis, exergy

Preface

The major sponsor for the research for this thesis was the Swedish Energy Agency (Energimyndigheten). Co-sponsors were Akademiska Hus AB, iNEX Internationell Exergi AB, EQUA Simulation AB, Folkhem Bostäder AB, Humlegården Fastigheter AB, NCC Construction Sverige AB, SP Sveriges Tekniska Forskningsir, White Arkitekter AB, and WSP Sverige AB.

The work presented in this thesis was carried out between November 2014 and August 2016 at the Division of Building Service and Energy Systems in the Department of Civil and Architectural Engineering at the Royal Institute of Technology (KTH), Stockholm, Sweden.

Firstly of all, I would like to express my deepest gratitude towards my supervisor, Professor Ivo Martinac for his ample guidance and patient support. He always encouraged me to overcome difficulties in the pursuit of my research. Our valuable discussions always inspired and enlightened me. Professor Martinac also gave me a large degree of freedom in doing my research, which I very much appreciate.

Also, I am sincerely grateful to my co-supervisor, Dr. Siir Kilkis, for her consistent support and valuable input to my work. I also want to thank my co-supervisors, Dr. Genku Kayo, Dr. Dietrich Schmidt, and Dr. Kari Alanne, for their helpful suggestions and comments.

Last, I would like to thank all my colleagues at the Division of Building Service and Energy Systems. Without them, my life in the past two years would not have been so joyful and fruitful.

Stockholm, August 2016

Cong Wang

Publications

This licentiate thesis is based upon the following four papers:

Paper I. Wang, C., Martinac, I. & Magny, A. (2016). Multi-Objective Optimization of Energy System Designs for the Albano University Campus in Stockholm. In *iiSBE Forum of Young Researchers in Sustainable Building 201*6, 21 June, 2016, Prague, Czech Republic.

Paper II. Wang, C., Martinac, I. & Magny, A. (2015). Multi-Objective Robust Optimization of Energy Systems for a Sustainable District in Stockholm. In *14th International Conference of the IBPSA*, 7–9 Dec 2015, Hyderabad, India.

Paper III. Wang, C., Kilkis, S., Tjernström, J., Nyblom, J., & Martinac, I. Multi-Objective Optimization and Parametric Analysis of Energy System Designs for the Albano University Campus in Stockholm. Accepted for the proceedings of *International High-Performance Built Environment Conference* (iHBE), 17–18 Nov 2016, Sydney, Australia, to be published in Elsevier's Procedia Engineering Journal.

Paper IV. Kilkis, S., Wang, C., Björk, F., & Martinac, I. Cleaner Energy Supply Structures for Campus Building Clusters. Submitted to *Journal of Cleaner Production*, March 2016.

Contents

Chapter 1

Introduction

1.1 Background

Buildings are the largest energy consuming sector in the world; they accounts for nearly 35% of global primary energy use and are responsible for approximately 17% of CO_2 emissions [1]. In the European Union (EU), 40% of primary energy use and 36% of CO_2 emissions are attributed to the building sector [2]. Population growth, increasing levels of indoor activities, and rising requirement for comfort have meant that the energy demand of the building sector is expected to ascend in the future. On the other hand, under the pressure of rapid depletion of fossil fuels and the ever-aggravating energy-related environmental challenges, many political entities have implemented regulations regarding building energy efficiency. For instance, the new recast of the European Energy Performance of Buildings Directive (EPBD) released by the EU in 2010 stipulates that all newly constructed buildings within the EU must reach the nearly zero energy level by the end of the year 2020 [3]. The EPBD defined a nearly zero energy building (nZEB) as one that has a very high energy performance and an energy demand that is satisfied to a large extent by renewable energy sources from on-site or nearby [4]. Sweden's national goal is to reduce energy use in the building sector by 20% by 2020 and by 50% by 2050 [5, 6]. Researchers have conducted a large number of studies to improve the building energy efficiency. However, finding cost-optimal solutions for nZEB is a challenging task that requires intensive measures taken from both the demand side (the building) and the supply side (the energy system). In addition, some studies have noted that it is quite difficult to achieve the nearly zero energy status at the individual building level, which motivates researchers to seek the potential solutions of nZEB for a group of buildings or building clusters, where on-site renewable sources can be used to a large extent [7]. This extends the concept of a nearly zero energy building to a nearly zero energy district (nZED).

CO_2 and other greenhouse gases emitted into the atmosphere from a range of human activities are the major cause of global warming. The atmospheric concentration of greenhouse gases has been steadily rising over the last few decades and constitutes one of the foremost global environment problems. The last decade has witnessed the warmest world since reliable records of global mean temperature began 150 years ago [5]. Thus, the mitigation of the greenhouse gas (GHG) emissions is another important issue in addition to the energy performance that requires action by countries and international collaboration. In order to meet its climate and energy targets for the year 2020, the EU launched the so called "20-20-20" targets in 2007. These targets aim to reduce the greenhouse gas emissions by 20% relative to 1990 levels, achieve a 20% improvement in energy efficiency, and increase the share of energy from renewables to 20% [8]. Two years after being set, these targets were enacted in legislation in 2009. Despite the fact that Sweden accounts for only 0.2% of global emission, the country has chosen to taken more initiative than many other countries in tackling issues regarding energy and climate change [9]. Sweden's national aim is to reduce the greenhouse gas emissions by 40% compared with 1990 levels by 2020 [6, 9]. The Swedish Parliament also envisions Sweden as a zero-net-GHG-emissions country by 2050 [5, 9]. Consequently, in parallel to fulfilling the nearly zero energy requirements, the reduction of greenhouse gas emissions must also be considered when designing the district energy system.

The concept of energy quality has attracted researchers' attention in recent years. Energy quality, also known as exergy in the context of the built environment, is a thermal dynamic concept that measures the maximum useful work potential of a given amount of energy that can be used by a system with a given reference state. Previous studies have focused mainly on the exergy analysis in single energy conversion technologies such as Photovoltaic (PV), solar thermal collectors, heat pumps and combined heat and power [10, 11]. These studies found that exergy efficiency is a key factor in evaluating the performance of energy conversion technologies. To the best of the author's knowledge, Kilkis initiated the overall exergy analysis on building energy systems [12]. Kilkis [13] developed a Rational Exergy Management Model (REMM) to investigate the possibility of curbing avoidable CO_2 emissions in the built environment. Exergy is destructed when a supply of a high quality energy source (such as electricity) is used to satisfy a demand of low quality energy (for instance, space heating). This type of energy quality mismatch wastes most of the available exergy and requires additional primary energy to be spent where the wasted exergy could have been utilized; this leads to additional CO_2 emissions that could have been avoided [13]. According to REMM, a better match between quality levels of demand and supply leads to lower avoidable CO_2 emissions. In this sense, exergy efficiency serves as an indicator of the avoidable CO_2 emissions. The International Energy Agency's (IEA) EBC Annex 37 collected worldwide knowledge and experience of low exergy heating and cooling for buildings and concluded that low exergy systems promote an appropriate use of energy in meeting the required building energy services [14]. Annex 49 continued the low exergy topic and included various energy demands in buildings, which consolidated the role of low exergy system in the built environment [15]. Moreover, the concept of low exergy was extended in ANNEX 49 to communities. Following Annex 49, Lu [16] developed an energy quality management approach for building clusters and districts, where exergy efficiency is integrated as one of the objectives into the energy system optimization framework. Inspired by nZEB, a new concept called 'net-zero exergy buildings' (nZEXB) was proposed [17]. A net-zero exergy building manages its demand and supply, seeking to balance the exergy delivered from the grid with the exergy exported to the grid over a certain period, typically one year. In a similar way, the scope of net-zero exergy was also extended to the district level, which put forth the concept of 'net-zero exergy districts' (nZEXD) [18, 19]. A net-zero exergy district is one that has a total annual sum of net-zero exergy exchange across the district boundary. As pointed out by some studies, an nZEB (nZED) might not necessarily be an nZEXB (nZEXD), due to different exergy levels in the exchanges [20]. Hence, the way in which energy quality is utilized and unnecessary exergy loss avoided should be considered in the design of district energy systems.

In addition to the concerns for energy, exergy, and emissions, human beings are cost-sensitive, which means that energy systems must be as cost-effective as possible. An energy system, over its life cycle, usually entails investment cost, operational cost, maintenance cost, and possibly disposal cost. Therefore, the life cycle cost (LCC) analysis, which has been widely employed in recent studies [21], is well suited to the evaluation of the economic performance of an energy system. The life cycle cost analysis takes into account costs related to all present and future activities. Costs that occur in the future are discounted based on the real interest rate. The life cycle cost analysis has also been developed in industry to assist project managers in decision making. Although there are some other commonly used measures, such as payback period and internal rate of return, minimum life cycle cost is the most straightforward way of measuring economic performance. These measures are consistent with each other if the same interest rate and length of period are used.

All of the above-mentioned aspects – high energy and exergy performance, low environmental impact and economic cost – constitute the comprehensive sustainability requirements. District planners must address all of these aspects when designing the energy system for a district. However, these aspects tend to contradict each other in most cases, which means that optimizing with respect to one aspect often results in unacceptable performance in the other aspects. Finding a single solution that simultaneously reaches an optimum in each aspect is rarely possible. For instance, increasing the share of energy from renewable sources helps lower the primary energy consumption and reduce the greenhouse gas emission, but usually involves a rising investment cost. What is reasonable is to identify a series of solutions that satisfy the performance requirements of each aspect at an acceptable level. This necessitates the employment of a multi-objective optimization approach that is capable of handling two or more objectives simultaneously. The results obtained from multi-objective optimization are presented in the form of a Pareto front. A Pareto front is a set of feasible solutions, each of which is Pareto-optimal in the sense that it cannot be improved in a single objective without worsening another one. The Pareto front shows the trade-off between different objectives and provides decision-makers with the opportunity to compare a large number of alternatives and make compromise between objectives. Multi-objective optimization has been widely used in building energy performance optimization [22], but has only recently been applied to the energy system designs, especially at a district level [16]. While a number of energy system modelling and optimization tools are commercially available for individual buildings, or for regional energy system planning, a user-friendly methodology and tool for energy system design at the district level is still lacking. Therefore, the present study develops a multi-objective optimization method for the district energy system design. The multi-objective approach has been proved to be a useful tool for district planners to design a district energy system that fulfills the sustainability requirements.

Energy system designs, like many real-world design problems, are subject to uncertainties. Uncertainties might arise from various sources and emerge in different stages of the design process. Specifically, uncertainties in the design of energy systems can come from inaccuracy in energy demand estimation, manufacturing errors, and deviation from optimal operation of energy conversion technologies, unpredictability of renewable energy production due to the intrinsic stochasticity of weather conditions, varying economic parameters, etc. Despite the success of existing studies that have resolved district energy system designs, they all share a major limitation in that they rely on deterministic approaches, assuming all system parameters are perfectly known and suffer no variability. These models optimize energy systems under the most likely conditions and assume that, if any, small deviations would occur from the predicted solutions under presumed conditions. Although uncertain variables are most likely to be confined within a small and acceptable range, they might still have a great influence on the outcome. Slight deviations in design variables and other system parameters might possibly lead to great deviations in objective values. Therefore, the desirable optimal solutions should be robust enough to withstand small deviations of inputs and constraints. In many cases, the robust optimum may not coincide with the global optimum. Figure 1.1 adapted from Ref. [23] illustrates the concepts of deterministic optimal and robust optimal for a single objective optimization problem with only one design variable, where x is the design variable and $f(x)$ is the objective function.

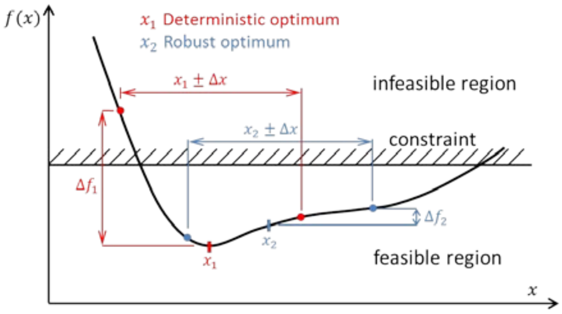


Figure 1.1: Illustration of a robust optimal solution (adapted from Ref. [23])

Based on Figure 1.1, a deterministic approach would conclude that x_1 is superior to x_2 and is the global optimum, as it gives the lowest objective function value. However, if uncertainty is assumed to exist in the design variable, x_2 will be preferred, as it implies a less risky attitude than x_1. A slight variation that occurs to the deterministic optimum x_1 leads to a significant degradation of the objective performance and, in the worst case, even causes a violation of the constraint. Solution x_2, by contrast, suffers from only a slight performance deterioration. This raises the need for an approach of optimization under uncertainty or robust design optimization. Thus, in this study, a multi-objective robust design optimization approach is developed and applied to the design of the district energy system.

The robust optimization in this study is preceded by a sensitivity analysis on the deterministic optimal solutions, which identifies the economic and technical parameters to which the objective values are most vulnerable. However, the sensitivity analysis fails to tell whether an optimal solution itself remains optimal under the variation of certain system parameters, and if not, how much the new optimal solution is different from the old one. Therefore, a parametric analysis is also necessary to examine how the composition of optimal solutions varies to the changes of some parameters.

Through collaboration with the property owners, Akademiska Hus and Svenska Bostäder, the emerging Albano university campus, is used as a case study in this thesis.

1.2 Outline

The thesis is composed of four major parts (Chapters 3-6), which correspond to the four publications (Papers I-IV), preceded by an introduction (Chapter 1) and a methodology chapter (Chapter 2), and followed by conclusions and future work (Chapter 7). The chapters are organized as follows.

Chapter 1 serves as an introduction to the background of the study, where the rationale, purpose, and approach of the research are briefly described. The thesis is outlined, with each chapter summarized.

Chapter 2 elaborates the methodology adopted in this study, as well as an introduction to the Albano university campus and the stakeholders’ goals regarding sustainability. The available renewable energy sources and energy saving potentials on-site Albano are explored in this chapter. The energy system, composed of energy sources, energy conversion technologies and energy use, is modelled. The design variables, objective functions, and constraints are defined.

Chapter 3 conducts the deterministic multi-objective optimization of the energy system for Albano. Three objectives are minimized: the non-renewable primary energy consumption, the greenhouse gas emissions, and the life cycle cost. In order to investigate the effect of certain technologies on the solutions, the optimization is resolved for four scenarios, which are pre-defined based on the employment of certain technologies.

Chapter 4 applies the multi-objective robust design optimization approach to the energy system design of Albano. Only the environmental performance and economic performance are optimized, whereas the non-renewable primary energy consumption is handled as a constraint in order to respect the nearly zero energy requirements. A sensitivity analysis is used to find the most sensitive parameters, which are assumed to be uncertain in the robust optimization.

Chapter 5 carries out a parametric analysis, following the deterministic multi-objective optimization, where the exergy performance, along with the environmental and economic performance is optimized. To reflect stakeholders’ various preferences for the three objectives, the equal importance, environment-oriented, economy-oriented, and exergy-oriented solutions are identified and compared. How the variation in certain parameters affects the composition of the equal importance solution is investigated through the parametric analysis.

Chapter 6 compares the planned buildings on the Albano campus with the existing buildings on the KTH campus from the energy and exergy perspectives. In addition to the present case, four alternative energy supply scenarios involving a number of ‘best practice’ technologies are proposed, which have a higher share of renewable energy and lead to a cleaner energy supply structure. The exergy performance of the four scenarios, as well as the present energy supply structure, is analyzed by applying the Rational Exergy Management Model. Comparisons are made across the four proposed scenarios and with the present case.

Chapter 7 summarizes the knowledge and experience obtained from the four publications and concludes the thesis. This chapter also indicates the limitations that lie in the present research and elaborates the points that need to be further explored in future research.

Chapter 2

Methodology

2.1 The Albano Campus

Albano is an area in the northern part of Stockholm, which used to be an industrial site during the 20th century. The City of Stockholm is now planning to build Albano as a modern and sustainable university campus. As Albano is located between the Royal Institute of Technology, Stockholm University, and the Karolinska Institute, the campus will be used jointly by the three universities. With a total floor area of 150 000 m^2, the campus consists of two types of buildings: educational buildings for lectures, offices, and laboratories; and residential buildings for students and visiting scholars. Upon completion, the campus is expected to hold more than 15 000 students, teachers, and other inhabitants. The stakeholders plan to build the campus in a sustainable, ecological, and economical way in order to take advantage of the best available technologies and make the campus an example of sustainable urban development. The owner of the educational buildings, Akademiska Hus, has strong environmental objectives, both regarding energy use in existing buildings – the energy use should be halved from 2000 to 2025 – and that new buildings should be nZEB. The campus should use as little supplied energy as possible and the energy supplied should be produced locally as much as possible. The owner of the residential buildings, Svenska Bostäder, which is wholly owned by the City of Stockholm, is one of the largest housing companies in Sweden. Figure 2.1 presents an aerial view of the future Albano campus. Figure 2.2 provides the visual representation of Albano buildings.

Figure 2.1: An aerial view of future Albano (source: Ref. [24])

Figure 2.2: Visual representation of future Albano Buildings (source: Ref. [24])

As a future development project, limited information is available regarding the construction details and energy usage. Assumptions have been made in order to estimate the building energy use. Building performance tools, IDA ICE and VIP-Energy, are employed to simulate the dynamic heating and cooling load of one representative educational building and one representative residential building, respectively. The other buildings are assumed to have the same load profile as the representative buildings, since buildings of each type share similar properties. The load profiles of each type of buildings are aggregated to obtain the total energy load profile of the campus as a whole. All of the load profiles are given on an hourly basis, which is required by the energy system simulation and optimization.

The space heating and cooling load profiles for educational buildings are calculated using IDA ICE on Building 2 (Hus 2). The assumptions are made in the model regarding the average U-value of the building envelope including walls, roofs and windows. The results have been normalized over the floor area of Hus 2, and then multiplied by the total floor area of the educational buildings.

No cooling is needed for residential buildings. The heating load profile is calculated using VIP-Energy on Building 6b (Hus 6b). The total heating load profile of residential buildings is obtained in the same way as for educational buildings.

The total heating and cooling demand profiles for the entire Albano campus are obtained by summing the two types of buildings.

A measurement of hourly domestic hot water consumption was carried out by Svenska Bostäder on a typical student housing apartment located at Värtavägen 60. The pattern of specific domestic hot water use for residential buildings is then assumed to be the same as the building under measurement, with the annual amount adjusted to the living density. For educational buildings, the property owner (Akademiska Hus) suggests the annual amount of energy use for domestic hot water and the hourly profile is assumed by the author. The profile of domestic hot water use of the entire Albano campus is obtained by aggregating the profiles of each type of buildings.

The electricity for HVAC use is given by building energy performance calculation along with heating and cooling load. The electricity for non-HVAC use is suggested by Akademiska Hus and Svenska Bostäder.

2.2 Energy System Modelling

2.2.1 Energy Sources and Conversion Technologies

A complete district energy system is composed of three parts: energy sources, energy conversion technologies, and energy use.

To cover the energy used by the building systems, a large set of technical solutions are taken into consideration. The energy sources available on-site Albano are solar energy that can be used for solar thermal collectors (TC) and photovoltaic (PV) panels; thermal energy from ambient heat sources via heat pumps; wind; and biogas produced from on-site anaerobic digestion. Besides the energy sources available on-site, the following delivered energy sources from outside Albano are considered. District heating and cooling networks that exist in Stockholm are included as a possible energy source. A natural gas distribution network is also passing by Albano and could be used for heating and electricity production via Combined Heat and Power (CHP). Biofuels such as biogas, wood, and pellets, are largely used in Sweden. Therefore, they are included as the possible energy sources available for Albano. Finally, the connection to the national electricity grid is also considered.

Energy use for domestic hot water production used to be a minor part in total energy use of a building. However, given that numerous measures have been taken to save the energy use for space heating, the heat use for domestic hot water has become increasingly significant. The heat demand for domestic hot water production in residential buildings on Albano is larger than that for spacing heating. Therefore, the potential to recover heat from greywater is worth considering. A number of studies have investigated the economic and technical efficiencies of heat recovery from greywater. Amo and López studied the drain water heat recovery in a residential building located in Gävle with 23 apartments and 48 residents [25]. They reported that with a centralized heat exchanger to pre-heat the cold water, as much as 23% heat is saved for domestic hot water production. Following the same methodology as in Ref [25], a 23% reduction in heat demand is assumed in this study if greywater heat recovery is employed in the energy system design.

An IT/data center is expected to be placed on the Albano campus. Based on the experiences from the present computer center on KTH campus, the new IT/data center is supposed to provide waste heat at the power of 1.7 MW. It is worth considering utilizing this large amount of waste heat when designing the energy system. The temperature level of the waste heat from the IT/data center is about 35–40 °C [26], which is not high enough for domestic hot water production. Therefore, an additional heat pump is required to raise the temperature level.

In summary, the available energy sources for the Albano area include:

- Solar energy
- Wind energy
- Ground source thermal energy
- Recovered waste heat from greywater
- Recovered waste heat from IT/data center
- Delivered energy (wood, pellets, natural gas, biogas, district heating/cooling, and grid electricity).

Energy conversion technologies are selected based on the above-mentioned energy sources and the energy requirements of the buildings. Focus is put on the technologies that are already commercialized or have been widely used. Promising technologies that are still in the research phase are not considered. To simplify the model and optimization process, energy storage technologies have not been included in the model, but will be integrated into the model in future work. The selected technologies in the model are listed below:

- Ground source heat pump (GSHP)
- On-site wind turbines, i.e. several small scale wind turbines (WO)
- Combined Heat and Power (CHP), either MCFC or a reciprocating engine (RE)
- Absorption chiller (AC)
- Electric chiller (EC)
- Solar cells (PV)
- Solar thermal collectors (TC)
- Biomass boiler (BB), burning either pellets or woods
- District heating (DH)
- District cooling (DC)
- Electricity grid (EG)

2.2.2 Design Variables, Objective Functions, and Constraints

Design variables are selected based on energy conversion technologies adopted in the energy system. The model can accommodate both continuous and discrete or binary design variables. Continuous design variables represent the size of energy conversion technologies, whereas discrete or binary design variables denote the number or existence of energy conversion technologies. The optimization process finds the set of design variables that minimizes the defined objective functions. The ranges or acceptable values of design variables are given based on the availability of corresponding technologies, the capacity of the district, and the load of buildings. Constraints can be imposed on the design variables. In Paper I-III, for instance, the sum of installed area of PV and solar thermal collectors is limited by the constraint according to the maximum available roof area.

The nZEB requirements restrict the non-renewable primary energy (NRPE) consumption. The non-renewable primary energy consumption ($E_{P,nren}$) is defined in line with REHVA nZEB technical definition [4], by Equation (2.1) below,

$$E_{P,nren} = \sum_i E_{del,i} * f_{del,nren,i} - \sum_i E_{ex,i} * f_{ex,nren,i} \tag{2.1}$$

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 greenhouse gas emissions are 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 the non-renewable primary energy consumption, following Equation (2.2) below,

$$m_{CO_2} = \sum_i E_{del,i} * K_{del,nren,i} - \sum_i E_{ex,i} * K_{ex,nren,i} \tag{2.2}$$

where $E_{del,n,i}$ and $E_{ex,n,i}$ are the same as in (1); $K_{del,nren,i}$ and $K_{ex,nren,i}$ are GHG emission factors for delivered and exported energy, respectively, which convert the amount of energy consumed to the amount of equivalent CO_2 emitted with the unit $kgCO_2/kWh$. In the present study, only electricity could be exported to the grid. Thus, the corresponding GHG emission factor is assumed to compensate the grid mix.

The life cycle cost, which covers the investment cost, operation and maintenance (O&M) cost, and the revenue from selling the electricity to the grid, is employed to evaluate the economic performance of the energy system. The disposal or recycling cost is omitted. The life cycle cost is expressed as annually interest rate leveraged cost, calculated as,

$$\overline{LCC} = \sum_s C_{inv,s} * A_s + \sum_s C_{O\&M,s} + \sum_i E_{del,n,i} * P_{buy,i} - \sum_i E_{ex,n,i} * P_{sell,i} \tag{2.3}$$

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.

A net-zero exergy district attempts to equate the exergy delivered to the district with the exergy exported from the district. In order to see the possibility of achieving the net-zero exergy status, the net exergy deficit (E_x) is calculated in a similar way to the non-renewable primary energy consumption, following Equation (2.4) below,

$$E_x = \sum_i E_{del,i} * F_{del,nren,i} - \sum_i E_{ex,i} * F_{ex,nren,i} \tag{2.4}$$

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, which is always less than or equal to one. The Carnot factor of electricity is one, as electricity is of the highest quality. The Carnot factor of fuels is often defined as,

$$F = 1 - T_{ref}/T_{resource} \tag{2.5}$$

where T_{ref} is the temperature of the reference state and $T_{resource}$ is flame temperature of the fuel. In the present study, the ground temperature is used as the reference, as the ground is the ultimate sink that absorbs the seasonal swings in outdoor ambient temperature. An equilibrium temperature is often found at the depth of 9.1 meters under the ground for a given location [27]. The ground temperature at equilibrium of the Stockholm region where Albano is located is 281.5 K [28], which is adopted in the calculation of Carnot factors.

The energy production from renewable energy sources by PV, solar thermal collectors, and wind turbines is determined by real weather conditions. In the model, the power output of these technologies is simulated based on the input weather profiles on an hourly basis. The energy demand and supply must be balanced at each hour. Consequently, the intrinsic intermittency of renewable energy production demands that the designed energy system has sufficient capacity to fill the gap when the renewable energy production is low. The loss of power supply probability (LPSP) serves as a measure of the insufficiency of an energy system. LPSP is calculated as the ratio of the number of failure hours to the total number of hours in a year [29],

$$LPSP = \frac{\sum_{t=1}^{t=N} hour(P_{supply} < P_{demand})}{N} \tag{2.6}$$

where N is the total number of hours in a year; P_{supply} and P_{demand} are supplied and demanded power, respectively. A positive value of LPSP indicates the percentage of the failure in an entire year.

The first three papers (Paper I-III) apply multi-objective optimization to the energy system design for Albano. The greenhouse gas emissions and the life cycle cost are objectives that are minimized in all three papers. The non-renewable primary energy consumption is minimized in Paper I, but is handled as a constraint in Paper II and III. The net exergy deficit serves as an objective only in Paper III. LPSP is adopted as a constraint and kept at zero in all three papers.

2.3 Multi-Objective Optimization

2.3.1 Deterministic Optimization

Multi-objective optimization involves more than one objective function to be optimized simultaneously. As an area of multiple criteria decision making, multi-objective optimization is well suited to the energy system design, in which a number of aspects – such as energy, environmental impact, and economy – need to be addressed. Genetic algorithms are popular approaches to solving a multi-objective optimization problem, which allow computation of an approximation of the entire Pareto front. As a class of heuristic methods, genetic algorithms mimic the natural selection process, approximating the optimal solutions through a converging set of solutions (referred to as population). Having adopted concepts from evolutionary biology, such as inheritance, mutation, crossover and selection, genetic algorithms generate a population of candidates in each iteration (referred to as generation) based on the fitness of solutions from the previous iteration. This process is repeated until the maximum number of generations is reached or the convergence criteria are fulfilled. Genetic algorithms suit the need for district energy system designs, which often involve both continuous and discrete variables, non-linear functions, and non-concave search space. The non-dominated sorting genetic algorithm-II (NSGA-II) [30] has become one of the standard approaches to solving a multi-objective optimization problem. This study employs one of the variants of NSGA-II: Pareto archive NSGA-II (aNSGA-II). The optimization tool used is MOBO, a multi-objective building optimization software that has aNSGA-II built in [31].

All the objective functions are calculated by an in-house MATLAB script that models and simulates the energy system. MOBO firstly creates a population of design variables, which are fed to MALAB. The MATLAB script analyzes the energy balance over an entire year on an hourly basis and computes the objective functions and constraints. Based on the fitness of objective values and constraints, MOBO creates a new population. Such a process is repeated until the pre-defined number of generations is reached. The algorithm parameters, such as crossover probability, mutation probability, population size, and number of generations, are fine tuned to guarantee the convergence.

2.3.2 Robust Optimization

Optimization under uncertainty is rooted in structural and aerospace engineering [23] and has recently been introduced to the building energy performance community. Several studies have focused on uncertainties in building parameters, energy load, system capacities and energy prices. Hopfe et al. [32] proposed a Kriging meta-model based robust multi-criteria design optimization approach for building designs. A building located in the Netherlands was employed as a case study with uncertainties imposed on the five most sensitive input parameters, which were perturbed with a Monte Carlo sampling of 201 samples. The resulting Pareto solutions showed much more robustness than the deterministic ones. Shi et al. [33] studied the techno-economic performance of an autonomous PV-wind hybrid power system by means of constraint multi-objective genetic algorithm and Monte-Carlo simulation. A robust optimal system configuration that is insensitive to design variable variations was achieved. Rezvan et al. [34] optimized the capacity of distributed energy conversion technologies under uncertainties in load demand, where uncertainties were formulated by assuming three different load scenarios with different probabilities of occurrence. Moradi et al. [35] considered uncertainties in delivered energy prices as well as in energy demand, and applied a fuzzy programming approach to the capacity optimization of CHP and boilers.

Major approaches that address uncertainty in robust optimization include fuzzy programming, min-max regret analysis, sampling-based approaches etc. Monte Carlo simulation (MCS) methods are a widely used class of sampling-based methods that obtain the statistical features of output by performing repeated sampling and computation. As MCS methods treat the deterministic simulation model as a black box, a deterministic mode can be easily extended to robust optimization without extra modification. Conventional MCS methods require a large number of samples due to the random sampling technique, which results in a high computational intensity. To overcome this, Latin Hypercube Sampling (LHS) is employed. LHS divides each uncertain parameter into a number of equally probable intervals and selects a sample point within each interval. In this way, LHS reduces the number of samples without losing the sampling accuracy [36].

The selected uncertain variables are perturbed by LHS to generate samples. A uniform distribution and no correlations between uncertain variables are assumed.

The formulation of the robust optimization approach used in this study is given below:

$$\begin{cases} find \quad \boldsymbol{X} \\ min \quad \tilde{f}_i\,(\boldsymbol{X},\boldsymbol{p}) = k\mu_{f_i}(\boldsymbol{X},\boldsymbol{p}) + (1-k)\sigma_{f_i}(\boldsymbol{X},\boldsymbol{p}) \\ s.t. \quad g_j(\boldsymbol{X},\boldsymbol{p}) \le 0 \end{cases} \tag{2.7}$$

where $\boldsymbol{X}$ denotes design variables, and $\boldsymbol{p}$ represents system parameters, $\tilde{f}_i$ is the i-th effective objective function representing the weighted sum of the mean μ_{f_i} and the standard deviation σ_{f_i} of the i-th original objective values of the LHS samples, with k denoting the weighting factor, and g_j is the j-th constraint. Both design variables $\boldsymbol{X}$ and system parameters $\boldsymbol{p}$ can be uncertain, which are sampled based upon the specified distribution pattern.

Chapter 3

Results – Part I Deterministic Optimization

This chapter is based on Paper I. The main purposes of this chapter are

- To see how the proposed multi-objective optimization approach can be applied to assist the planners in the energy system design;
- To shed light on the trade-off between energy performance, environmental performance, and economic performance;
- To examine the effect of certain technologies on the energy, environmental, and economic performances of the energy system.

3.1 Description

Seven delivered energy sources are used in the system: electricity from the grid (EG), natural gas, biogas, biomass (pellets and wood chips), district heating (DH), and district cooling (DC). Correspondingly, seven energy conversion technologies are integrated: Combined Heat and Power (CHP) using 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). Fig. 1 in Paper I presents the energy system, illustrating energy fluxes from energy sources to energy use through different types of conversion technologies. Based on the selected energy conversion technologies, 14 design variables are employed in the optimization; seven of these are continuous and the other seven are discrete or binary. Tab. 3 in Paper I presents the names, types, and ranges or acceptable values of the 14 design variables.

Due to the high living density, the energy used for domestic hot water production constitutes a significant part of the total heat demand in residential buildings. There is great potential to recover heat from waste water. Thus, the heat recovery from waste water in residential buildings is investigated and integrated into the optimization framework. In addition, An IT/data center is planned to be located in one of the educational buildings. There would be a considerable amount of waste heat available from the IT/data center, which is also taken into account as an on-site energy source in this study.

The non-renewable primary energy consumption, greenhouse gas emissions, and the life cycle cost are minimized, with the loss of power supply probability kept zero as a constraint. In order to provide the stakeholders with a larger set of solutions, the optimization is solved for four different scenarios, as defined below:

Scenario I. All technologies as presented in Fig. 1 in Paper I.

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.

3.2 Results

The optimal solutions are presented in Figure 3.1 and Figure 3.2 in the form of Pareto fronts. For each scenario, the figures present the tradeoff between the non-renewable primary energy consumption and the life cycle cost, and between the greenhouse gas emissions and the life cycle cost.

The alternative case that uses only district heating and cooling, with electricity supplied solely by the grid and without any form of heat recovery, is taken as the reference case for comparison. This reference case is also plotted in Figure 3.1and Figure 3.2, referred to as DHDC.

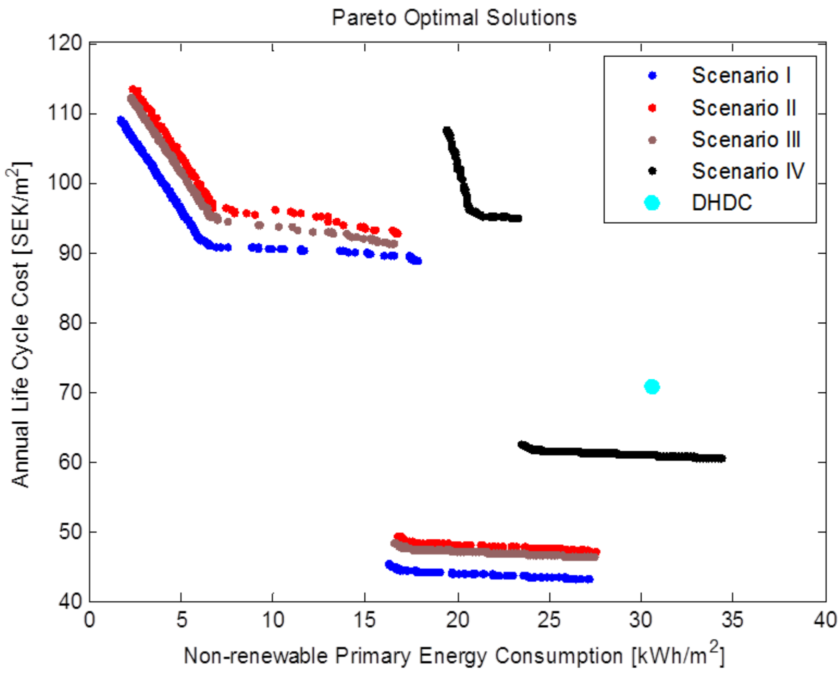


Figure 3.1: Pareto-optimal solutions that trade off LCC and NRPE consumption (Paper I)

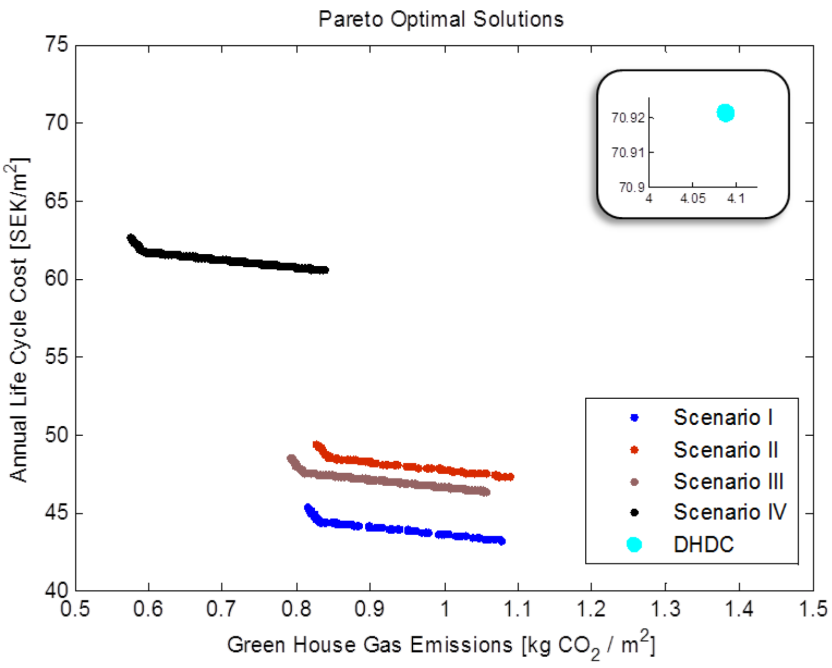


Figure 3.2: Pareto-optimal solutions that trade off LCC and GHG emissions (Paper I)

3.3 Discussion

The Pareto fronts of all four scenarios in Figure 3.1 consist of two pieces: the lower cost piece and the higher cost piece. The discontinuity is due to the appearance of CHP in the higher pieces of the Pareto fronts. CHP is much more costly than a biomass boiler (BB) that appears in the lower cost piece. However, CHP does not appear in the Pareto fronts in Figure 3.2. This is because CHP burns natural gas or biogas, which tends to lead to high costs and high emissions. Solar thermal collectors are never preferred to a biomass boiler in any scenario, due to the large mismatch between heat production and heat demand. Most heat production takes place in summer, whereas most heat demand takes place in winter.

In Scenario I, the minimum cost solution consists only of a biomass boiler (BB) that supplies heat and district cooling (DC) that supplies cold. There are no PV or wind turbines in this solution. As the PV area gradually grows from zero, NRPE consumption and GHG emissions diminish as the cost rises. When PV reaches its maximum, wind turbines begin to appear. The number of wind turbines increases until they reach their maximum. The Pareto front presented in Figure 3.2 and the lower piece of the Pareto front presented in Figure 3.1 are then ended. If a further reduction in NRPE consumption is wanted, CHP appears, generating both electricity and heat. CHP, together with a biomass boiler, supplies the heat, forming the higher cost piece of Pareto front in Figure 3.1.

In Scenario II, no district heating or cooling is employed. As a result, the cold must be supplied by means of ground source cooling using boreholes, which leads to a higher investment cost and shifts the Pareto front upwards. The Pareto front of Scenario III shifts downwards and leftwards in comparison with Scenario II, which implies that heat recovery from greywater may not only reduce NRPE consumption and GHG emissions, but can be profitable as well. Scenario IV employs a 1.7 MW heat pump in order to take advantage of the low temperature heat from the IT/data center. The Pareto fronts are shifted upwards by the high investment cost of the heat pump. The Pareto front in Figure 3.2 also moves towards the left, implying a significant reduction in GHG emissions. The reason why the Pareto front in Figure 3.1 moves towards the right is that the heat pump is driven by electricity that has a larger NRPE factor than biomass used by a boiler.

Chapter 4

Results – Part II Robust Optimization

This chapter is based on Paper II. The main purposes of this chapter are

- To identify the system parameters which the solutions might be sensitive to through a sensitivity analysis;
- To apply a multi-objective robust optimization approach to find the robust optimal solutions for the energy system design.

4.1 Description

Three delivered energy sources are utilized: electricity from the grid (EG), biogas and biomass (wood pellets). Seven energy conversion technologies are employed in the model: biogas CHP, biomass boiler (BB), ground source heat pumps (GSHP), absorption chiller (AC), on-site wind turbines (WO), PV and solar thermal collector (TC). Figure 2 in Paper II presents the modelled energy system, with energy fluxes directed from energy sources to energy use through conversion technologies. Seven continuous, two discrete, and one binary design variables are employed in the optimization. Table 2 in Paper II presents the design variables as well as their ranges or acceptable values.

The greenhouse gas emissions and the life cycle cost are the two objectives to be minimized. The non-renewable primary energy (NRPE) consumption is handled as a constraint, along with the loss of power supply probability that is kept at zero in the optimization. The EPBD stipulates that the NRPE consumption should not exceed a control point. However, EPBD leaves it up to each member state to determine the value of this control point. As the process of defining Swedish nZEB is still ongoing, the value of 70 kWh/m^2 is adopted in this chapter, which reflects the Swedish Building Code (BBR).

First, the deterministic Pareto-optimal solutions are obtained. Then a sensitivity analysis is conducted for two representative solutions: the best environmental performance solution and the best economic performance solution. The sensitivities of these two solutions to certain system parameters are examined. The most sensitive parameters are identified, which are assumed to be uncertain in the subsequent robust optimization. Finally, the robust Pareto-optimal solutions are achieved under the robust optimization framework.

4.2 Results

Figure 4.1 presents the deterministic Pareto-optimal solutions. A biomass boiler (BB) and ground source heat pump (GSHP) combine to supply heat for space heating and domestic hot water use. Electricity is supplied collaboratively by the grid (EG), wind turbines (WO), and PV. The cooling demand is satisfied solely by GSHP. The best economic performance solution has a levelized life cycle cost of 90 SEK/m^2 a year and an annual GHG emission of 1.43 kg CO_2/m^2. In contrast, the best environmental performance solution reduces the emissions to 1.26 kg CO_2/m^2 a year but at the cost of 98 SEK/m^2. Intermediate solutions start to curb GHG emissions from the best economic performance by gradually replacing GSHP with BB and by installing more PV to limit the net non-renewable primary energy consumption.

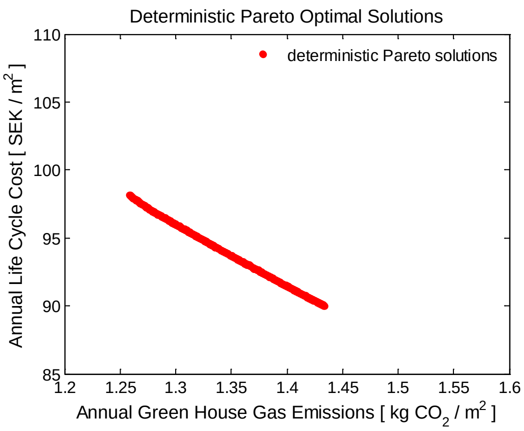


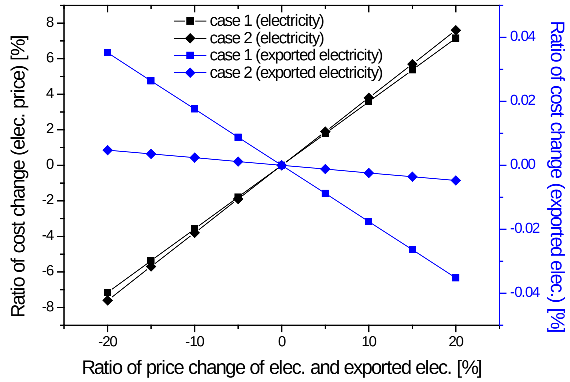
Figure 4.1: Deterministic Pareto-optimal solutions (Paper II)

Figure 4.2 presents the results of the sensitivity analysis. The best environmental performance solution is marked as case 1 and the best economic performance solution is marked as case 2.

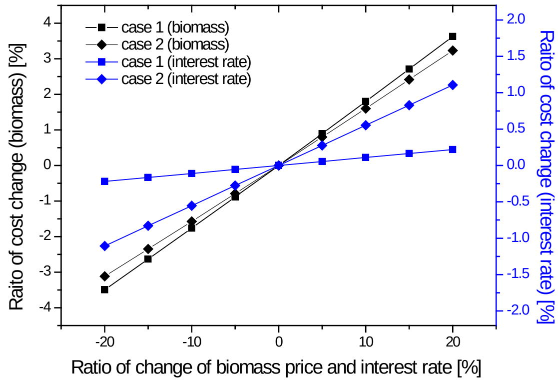
Figure 4.2 (a) and (b) show the sensitivities of case 1 and case 2 to four economic cost parameters: the electricity price, biomass price, the real interest rate, and the price of exported electricity. As expected, the life cycle cost varies linearly with the changes of energy prices and interest rates. The electricity price is found to be the most sensitive economic parameter, due to the large portion of delivered electricity cost in the life cycle cost.

Figure 4.2 (c) presents under different efficiencies of GSHP and BB respectively. The slight performance deterioration of GSHP causes a significant growth in the NRPE consumption. The influence of BB's efficiency on the NRPE consumption is small due to the low non-renewable primary energy factor of wood pellets. However, it is still probable that the constraint is violated.

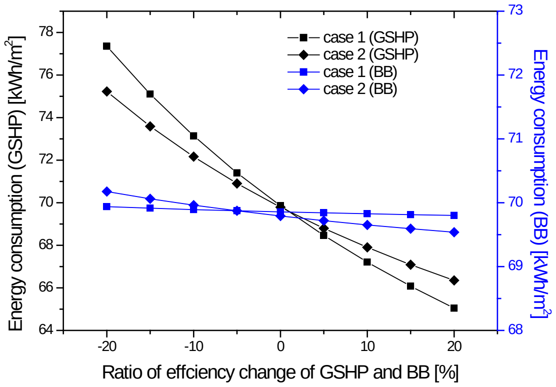
The size of energy conversion technologies are design variables that are optimized. However, the realized size may not be exactly equal to the desired size, due to various uncertainties that occur in the manufacturing process, power generation process, and aging process. Figure 4.2 (d) presents the effect of such a deviation on the loss of power supply probability. As observed from the figure, a realized size that is smaller than designed leads to the failure of the energy system to meet the energy demand.



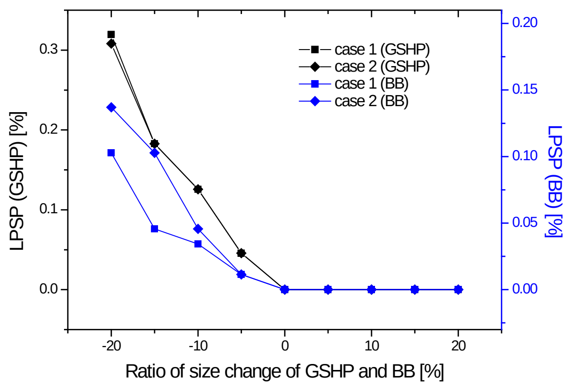
(a) LCC – Electricity price



(b) LCC – Biomass price and interest rate



(c) NRPE – Efficiency of GSHP and BB



(d) LPSP – Size of GSHP and BB

Figure 4.2: Sensitivity of LCC, NRPE, and LPSP to selected parameters (Paper II)

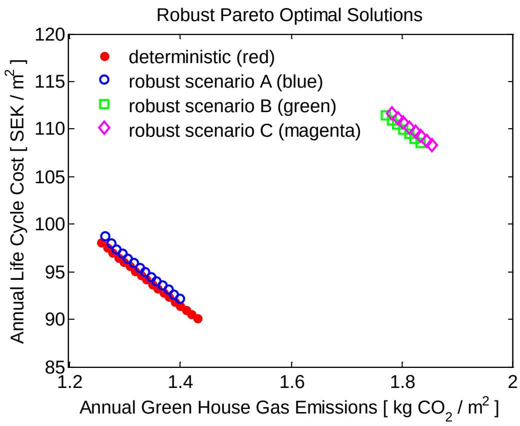


Figure 4.3: Robust Pareto-optimal solutions (Paper II)

Eight parameters are assumed to be subject to uncertainty in the robust optimization, including two economic parameters and six technical parameters. The two economic parameters are electricity price and biogas price. The six technical parameters are the size and efficiency of each of the three energy conversion technologies: GSHP, BB, and CHP. Three scenarios are defined based on the uncertainty range and different weighting factors, as presented in Table 3 in Paper II. The Pareto-optimal solutions under the setup of the three defined scenarios are presented in Figure 4.3, along with the previous deterministic results for comparison.

4.3 Discussion

The robust Pareto fronts shift away from the deterministic one, upwards and towards the right, which means that the robust optimal solutions are less optimal than deterministic ones. This is logical, as the loss in performance is compensated for by the increase in robustness. The more robustness wanted in the energy system, the more compromise has to be made on the optimality of the objectives. A significant jump is observed from robust scenario A to robust scenario B, as the uncertainty range of technical parameters increases from 5% in scenario A to 10% in scenario B. This is because CHP, together with an absorption chiller (AC), must be employed to guarantee the sufficiency of cooing power in scenario B, where GSHP alone fails to meet the cooling demand due to its uncertain size. The difference between the results of scenarios B and C is small, which indicates a marginal impact of the weighting factor on the robust optimal solutions.

An additional sensitivity analysis is conducted in the same way as the previous one on the best environmental performance solutions of each robust scenario. The results are presented and compared in Figure 9 in Paper II. Cases 3, 4, and 5 are the best environmental performance solutions of scenarios A, B, and C, respectively. The analysis proves that the robust optimal solutions do have more robustness and higher reliabilities than deterministic ones, especially under uncertain technical parameters.

Chapter 5

Results – Part III Optimization and Parametric Analysis

This chapter is based on Paper III. The main purposes of this chapter are

- To determine the role that the concept of nZEXD plays in the design of energy systems;
- To investigate the impact of stakeholders' preferences on selection of optimal solutions;
- To find out how the composition of optimal solutions vary to the changes of certain system parameters through a parametric analysis.

5.1 Description

Electricity from the grid (EG), district heating (DH), and biogas (BG) are the three delivered energy sources that are utilized. Eight energy conversion technologies are employed in the model: Combined Heat and Power (CHP) including MCFC and RE; ground source heat pump (GSHP); electric chiller (EC); absorption chiller (AC); on-site small-scale wind turbines (WO); PV; and solar thermal collectors (TC). Fig. 1 in Paper III presents the sketch of the energy system modelling, illustrating the energy flows from energy sources to energy use through conversion technologies. The optimization employs eight design variables that are all continuous, representing the corresponding eight energy conversion technologies.

Three objectives are minimized: the greenhouse gas emissions, the life cycle cost, and the net exergy deficit. The non-renewable primary energy consumption and the loss of power supply probability are constrained. The control point for the non-renewable primary energy consumption is 40 kWh/m^2, which is stricter than used in the preceding chapter.

The Pareto-optimal solutions from deterministic multi-objective optimization are first obtained, which sheds light on the options that decision-makers potentially have. Four scenarios are defined by weighting each objective in four different ways, in order to reflect decision-makers' various preferences for the three objectives. The four scenarios are the equal importance, environment-oriented, economy-oriented, and exergy-oriented scenarios. The optimal solution under each scenario is identified and their compositions are analyzed. Finally, a parametric analysis is conducted on the equal importance scenario in order to determine how the composition of the optimal solution varies to the changes of certain system parameters.

5.2 Results

The Pareto front is presented in Figure 5.1, with each dot representing a Pareto-optimal solution. The dot is colored by the net exergy deficit, the value of which can be read from the color bar. Figure 5.1shows a clear trade-off between GHG emissions and the life cycle cost. It also shows that low net exergy deficit can only be achieved in the medium range of GHG emissions and the life cycle cost, which implies that the pursuit in economic or environmental performance deteriorates the net exergy performance from a net-zero exergy point of view.

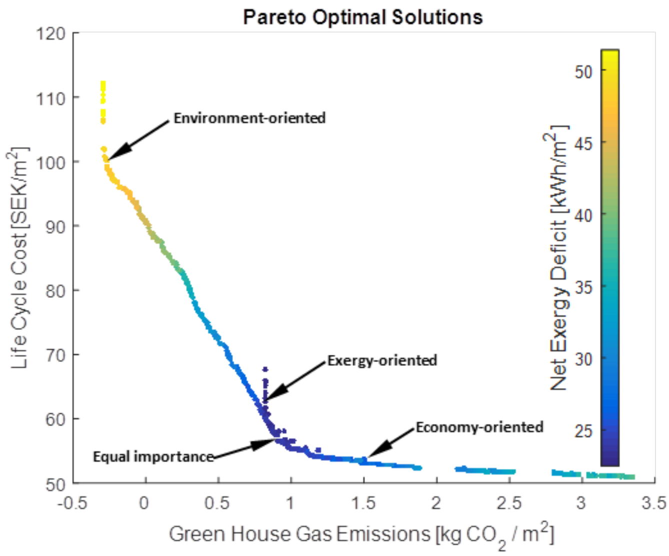


Figure 5.1: Pareto-optimal solutions from multi-objective optimization (Paper III)

The solution with district heating (DH) providing heat and electric chillers providing cold is taken as a reference case. In order to measure the performance improvement achieved by the optimization, all Pareto-optimal solutions are compared with the reference case through the following ratios, which are defined as:

- 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 above-defined ratios:

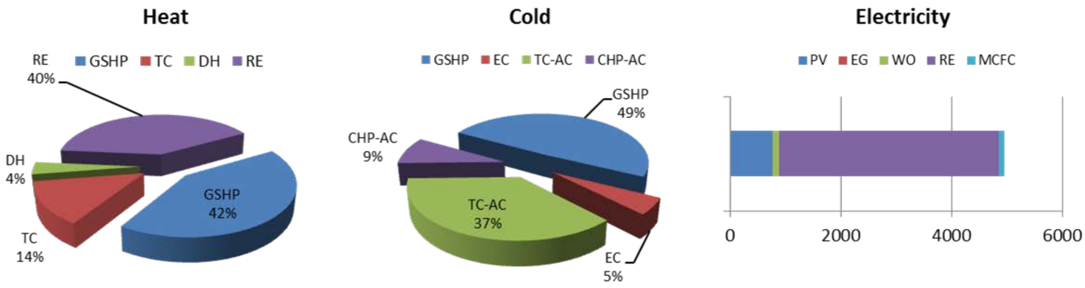
$$IR = \omega_1 * ER + \omega_2 * CR + \omega_3 * E_xR.$$

In response to stakeholders' various preferences for different objectives, four sets of weight combinations are defined, deriving four scenarios:

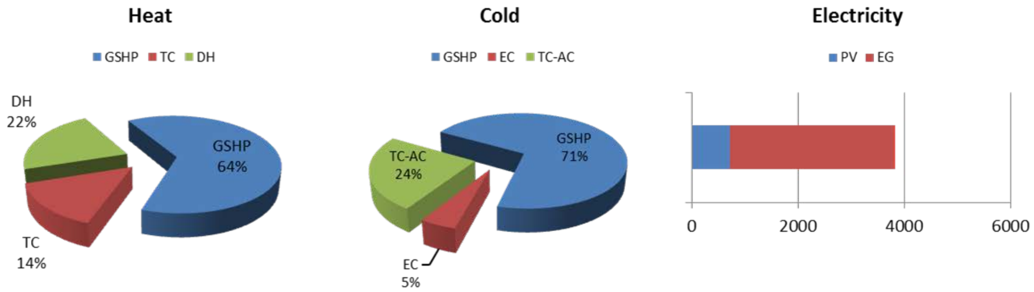
- Equal importance scenario: $\omega_1 = \omega_2 = \omega_3 = 1/3$
- Environment-oriented scenario: $\omega_1 = 0.8;\ \omega_2 = \omega_3 = 0.1$
- Economy-oriented scenario: $\omega_2 = 0.8;\ \omega_1 = \omega_3 = 0.1$
- Exergy-oriented scenario: $\omega_3 = 0.8;\ \omega_1 = \omega_2 = 0.1$

The optimal solution under each scenario is identified and marked on Figure 5.1. The components of heat (including both space heating and domestic hot water), cold, and electricity are analyzed in Figure 5.2 for each scenario, respectively.

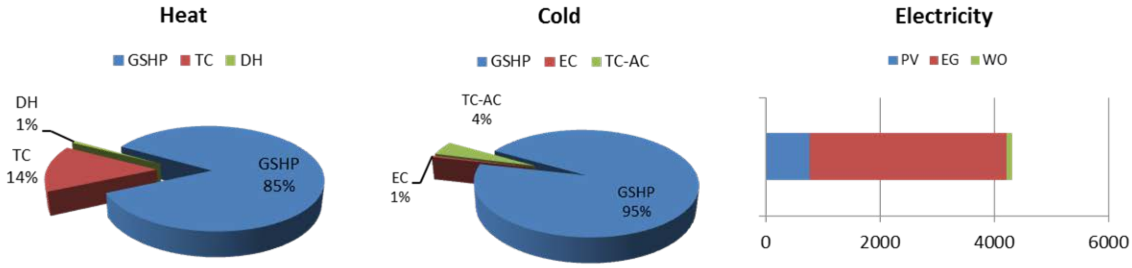
One technical parameter and one environmental parameter, along with four economic parameters, are fed into the parametric analysis. The results are given in Figure 5.3.



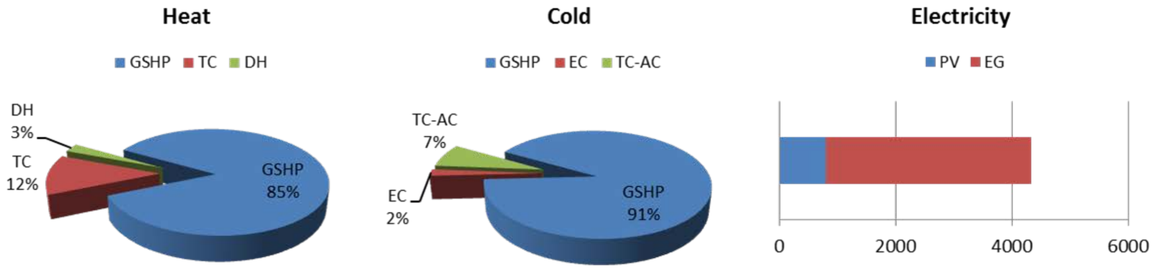
(a) Energy component analysis of the optimal solutions under the equal importance scenario



(b) Energy component analysis of the optimal solutions under the environment-oriented scenario

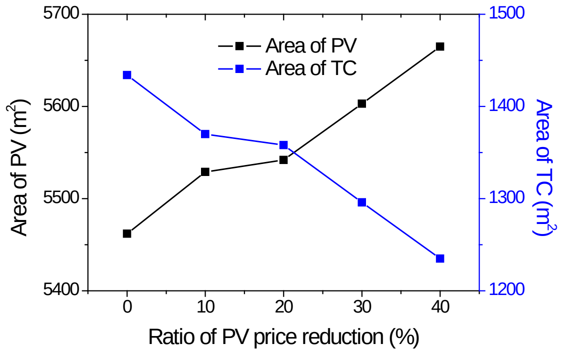


(c) Energy component analysis of the optimal solutions under the economy-oriented scenario

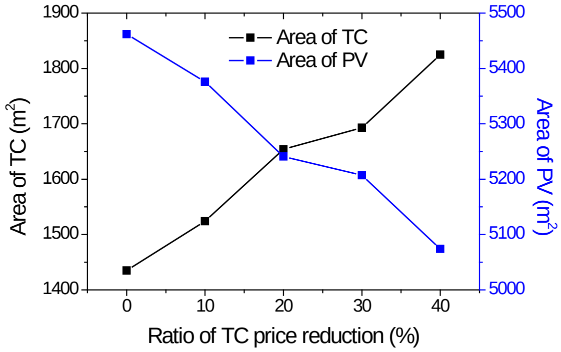


(d) Energy component analysis of the optimal solutions under the exergy-oriented scenario

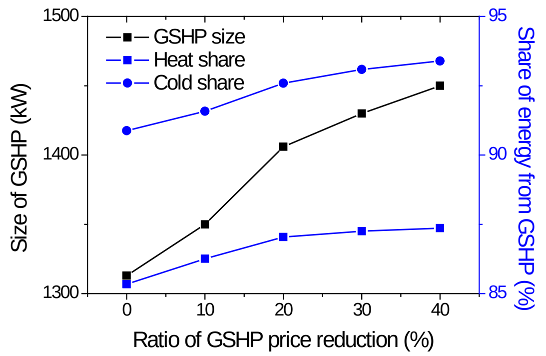
Figure 5.2: Energy component analysis of optimal solutions under four scenarios (Paper III)



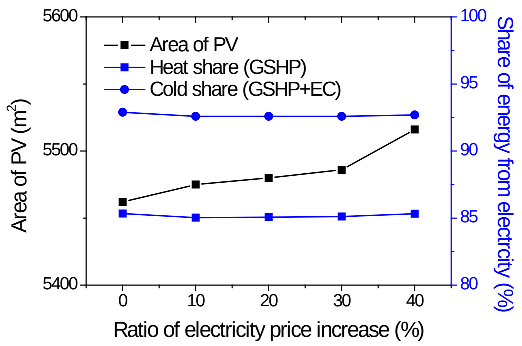
(a) Reduction of PV price



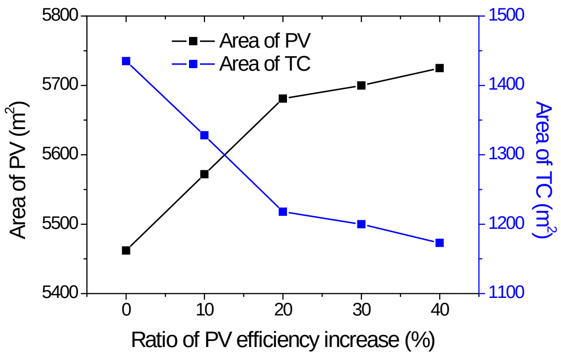
(b) Reduction of TC price



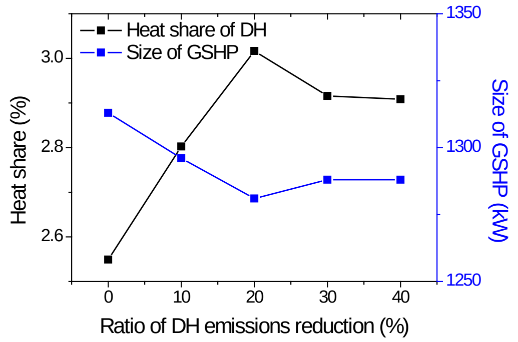
(c) Reduction of GHSP price



(d) Electricity price increase



(e) PV efficiency increase



(f) District heating emission reduction

Figure 5.3: Parametric analysis of economic and technical parameters: (a) PV; (b) TC; (c) GSHP; (d) Electricity; (e) PV efficiency; (f) DH emission; (Paper III)

5.3 Discussion

Figure 5.2 shows that GSHP plays the most significant role in heat and cold production in 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 the different scenarios. Solar absorption chilling (TC-AC) is the second-largest component of cold production after GSHP and becomes especially important in the 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.

The results reveal 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 might be considered from an economic point of view as it is more cost-effective than GSHP. Biogas CHP is not desirable unless environmental performance is strongly emphasized, as it is very cost-prohibitive. EC is never favored and is used as a backup technology to cover the peak cooling load. It appears that different objective preferences do not significantly impact renewable energy production from solar sources such as TC and PV.

As shown in Figure 5.3 (a) and (b), the installed area of PV and TC increases steadily as they drop in price. As PV increases, TC drops, and vice versa. TC also seems to be more sensitive to price reduction than PV. Figure 5.3(c) shows that 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, probably because the size of GSHP is almost reaching a critical point. Figure 5.3(d) reveals that the increase of electricity price modestly promotes the use of PV. The share of electricity heating (GSHP) and cooling (GSHP and EC) has proved to be quite stable to the variation of electricity price. Figure 5.3 (e) shows that a slight improvement of PV efficiency effectively promotes the use of PV. However, as the efficiency improvement continues from 20% to 40%, the promotion slows down. As Figure 5.3 (f) shows, DH emission reduction has had an inconsistent effect on the energy system configuration. DH reaches its largest share in heat supply, at around 20% emission reduction. As the emission is further reduced, the share of DH drops and tends to stabilize.

Chapter 6

Results – Part IV Cleaner Energy Supply Structures

This chapter is based on Paper IV. In this chapter, through the Rational Exergy Management Model:

- The Albano campus buildings and KTH campus buildings are analyzed and compared on energy and exergy values;
- Four energy supply scenarios are proposed as options toward a cleaner energy supply structure;
- The best level of match between supply and demand is found to reduce the avoidable CO_2 emissions to 0.02 kg/kWh.

6.1 Description

The Rational Exergy Management Model (REMM) was initially developed by Kilkis in 2011 in her doctoral dissertation [13]. It has since been successfully applied to the energy and exergy analysis of buildings [18] and later extended to the analysis of districts [37] and cities [38].

A complete REMM analysis consists of the following four steps:

Step 1: Modelling the exergy demand of buildings

Step 2: Modelling the exergy supply based on the resource supply

Step 3: Modelling the level of match and the compound CO_2 emissions

Step 4: Considering scenarios to curb CO_2 emissions through better exergy matches

Exergy supply can be divided into two parts: the part used to meet the exergy demand and the part that is irreversibly destroyed, as indicated in Equation (6.1).

$$\varepsilon_{sup} = \varepsilon_{dem} + \varepsilon_{dst} \tag{6.1}$$

or re-arranged, $$\varepsilon_{dem} = \varepsilon_{sup} - \varepsilon_{dst} \quad (6.2)$$

The exergy demand or supply is calculated as the corresponding energy supply or demand multiplied by a Carnot factor. The Carnot factor for space heating and cooling is defined based on the temperature difference between the reference temperature and the desired indoor air temperature, whereas the Carnot factor for exergy supply depends on the temperature difference made by the energy resource with the reference temperature. Equation (6.3) indicates the means of calculating exergy demand and supply,

$$\varepsilon = (1 - \frac{T_{ex}}{T_{ref}}) \times E \quad (6.3)$$

where T_{ex} is the desired indoor temperature for demand or the temperature of energy resource for supply, and T_{ref} is the reference temperature. The ground temperature at a depth of 9.1 m is taken as the reference. In Stockholm, the value is 281.5 K.

The level of exergy match is given by the parameter Ψ_{Ri} , which is the ratio of the exergy demand to the exergy supply, as defined in Equation (6.4)

$$\Psi_{Ri} = \varepsilon_{dem}/\varepsilon_{sup} \quad (6.4)$$

or re-arranged, $$\Psi_{Ri} = 1 - \varepsilon_{dst}/\varepsilon_{sup} \quad (6.5)$$

The level of match is linked to the avoidable CO_2 emissions by Equation (6.6)

$$\sum CO_{2i} = (\frac{c_i}{\eta} + \frac{c_j}{\eta}(1 - \overline{\Psi}_{Ri})) \times E_T \quad (6.6)$$

where c_i and c_j are the net calorific value of the CO_2 emissions content of the energy resource at the building level and the energy system level, respectively; η is the energy efficiency of the final end use energy E_T.

A cluster of eight buildings on KTH campus is selected for the analysis. These eight buildings are supposed to have broad representativeness, as they contain offices, lecture rooms, laboratories, a library, a restaurant and an IT/data center. The energy use data for the eight buildings are collected on a monthly basis and then summed to get the annual data. Due to the availability of data for domestic hot water use, only energy use for spacing heating, cooling and electricity are analyzed.

The KTH campus and the Albano campus share the same district heating and cooling network, which is one of the largest heating and cooling systems in Europe. The power plant currently consists of two CHP units (KVV6 and KVV1), two seawater-based heat pumps, electric boilers, and peak load boilers. The two existing CHP units burn coal and biofuels. A new biofuel-based CHP unit (KVV8) is to be commissioned in the near future, when the share of renewable energy will increase to more than 70%. The two existing CHP units and the two heat pumps dominate the district heating supply, with the remaining need covered by peak load boilers and electric boilers. The two heat pumps together have a 100% share in district cooling.

One efficient way to improve the level of exergy match is to use low temperature heating and high temperature cooling. A conventional heating system usually has the supply temperature of water between 75 °C and 85 °C, whereas a low-temperature heating system supplies water at a temperature below 55 °C. In the case of a high-temperature cooling, the supply temperature of water is between 16 and 20 °C, in contrast to 6 °C in current district cooling network.

An aquifer thermal energy storage (ATES) system is one of the most promising technologies that should be considered to serve the Albano campus. The Stockholm region has experience in using ATES. The Arlanda Airport of Stockholm is using the world's largest ATES system to heat the air and melt the snow in winter and to provide comfort cooling in summer.

Another option to increase the share of renewable energy and make a cleaner energy supply structure is to take advantage of solar energy. Apart from conventional solar thermal collectors, photovoltaic thermal hybrid solar collectors (PVT) combine a PV module that converts sunlight into electricity with a solar thermal collector that removes heat from the PV module. The capture of both electricity and heat makes PVT more energy- and exergy-efficient than PV or solar thermal collectors alone. Four of the eight selected KTH campus buildings have been found to have available roof area to accommodate PVT.

6.2 Results

Table 6.1 presents the averaged energy use of buildings in the KTH campus cluster based on functions. These KTH campus buildings fall mainly into two categories. Buildings that include laboratories are categorized into one group (faculty buildings), whereas buildings that only have offices and lecture rooms are categorized into another group (office buildings). The library, restaurant and the IT/data center are not further categorized in the analysis.

Table 6.1: Averaged energy use in KTH campus cluster (Paper IV)

Building Function	*Specific Energy Profile* (kWh/m^2/year)			Total Floor Area (m^2)
	E_H	E_C	E_L	A_T
• Faculty (Incl. Labs)	140.4	20.6	116.7	24,776
• Office, Lecture, Departments	83.8	17.9	49.0	14,393

Table 6.2 presents the energy saving that Albano lecture buildings (referred to as educational buildings in Chapter 2) have achieved compared with the office building category of the KTH cluster. The comparison is made at the total energy level as well as the component level; that is, space heating, cooling, and electricity. The planned lecture buildings on Albano have saved 58% of total energy use, including 73% of space heating, 55% of cooling, and 35% of electricity, compared with the existing KTH office buildings. This is consistent with the goal of making Albano a nearly zero energy district.

Table 6.2: Energy savings factors for Albano and KTH buildings (Paper IV)

Compared Buildings		*Energy Savings Factor*			
Albano	KTH	E_H	E_C	E_L	E_s
• Lecture	• Office	0.73	0.55	0.35	0.58

Based on the averaged energy use presented in Table 6.1, the averaged exergy consumption of each building cluster is obtained following Equation (6.3). Table 6.3 compares the average exergy consumption of office buildings in the KTH campus cluster and lecture buildings in the Albano cluster. Unsurprisingly, the same exergy saving is achieved as energy saving for spacing heating, cooling, and electricity, since the present energy system design for Albano does not employ any low temperature heating or high temperature cooling, which means that the Carnot factors are the same. However, the Albano lecture buildings have saved 45% of total exergy consumption compared with KTH office buildings, which is lower than the energy saving due to the relative lower weighting of thermal energy components in total exergy than in total energy.

Table 6.3: Exergy savings factor for Albano and KTH buildings (Paper IV)

Compared Buildings		*Exergy Savings Factor*			
Albano	KTH	ε_H	ε_C	ε_L	ε_s
• Lecture	• Office	0.73	0.55	0.35	0.45

Figure 6.1 presents the values of exergy components for the technologies in the present case and for the possible options that could be used in the alternative scenarios. The blue, green, and red columns indicate the value of exergy supply (ε_{sup}), the value of exergy demand (ε_{dem}), and the value exergy destroyed (ε_{dst}), respectively. All the exergy values are based on unit energy, which actually corresponds to the Carnot factors that cause the difference between energy and exergy values. The purple diamonds denote the parameter Ψ_{Ri}, which measures the level of exergy match between supply and demand. Readers are referred to Ref [13] for the details of calculating the exergy values for CHP, PVT, ATES, and heat pumps.

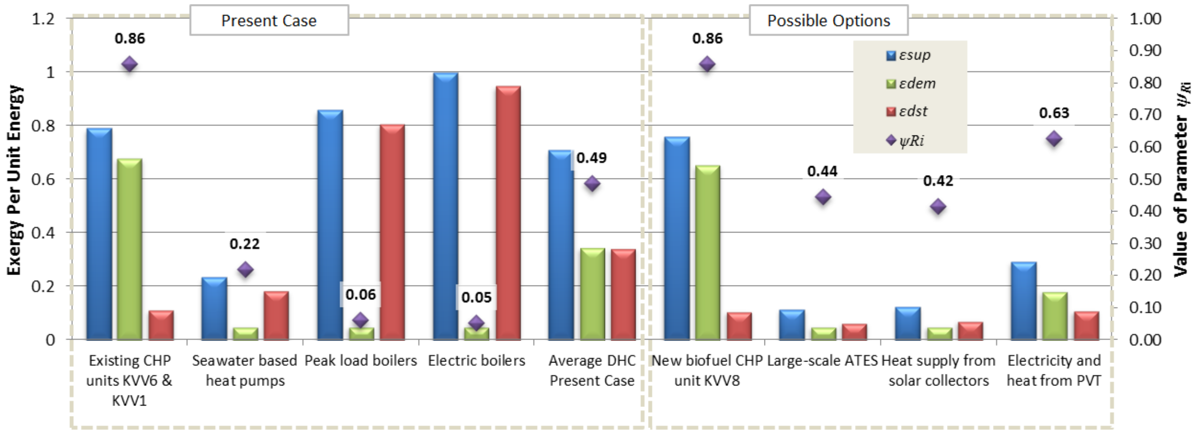


Figure 6.1: Exergy component values for present technologies and future options (Paper IV)

Although it is difficult to tell from Figure 6.1, the new biofuel CHP unit has a lower exergy supply and results in a slightly higher level of match, due to the exclusion of coal, which is one of the sources of the existing CHP units. The highest exergy destruction and lowest level of match take place in peak load boilers and electric boilers. The CHP units and PVT have the best level of exergy match among all the technologies. Based on the share of each technology in the present district heating and cooling network, the averaged level of exergy match is 0.49 for the present case, which leads to 0.06 kg/kWh of avoidable CO_2 emissions. In order to improve the level of match and reduce the avoidable CO_2 emissions, four scenarios of future district heating structures are proposed based on the above-mentioned technologies.

Table 6.4: Summary of the shares of the technological options (Paper IV)

Scenario Options (Supply Side)	*Shares of the Options in the DH Grid*				
	Present Case	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*
Existing CHP units KVV6 & KVV1	0.47	0.47	0.47	0.37	0.27
Seawater based heat pumps	0.21	0.21	0.21	0.21	0.21
Peak load boilers	0.19	0.19	0.00	0.00	0.00
Electric boilers	0.13	0.00	0.00	0.00	0.00
New biofuel CHP unit KVV8	0.00	0.13	0.32	0.32	0.32
Large-scale ATES (Summer/Winter)	0.00	0.00	0.00	0.10	0.15
Heat supply from solar collectors	0.00	0.00	0.00	0.00	0.02
Electricity and heat from PVT	0.00	0.00	0.00	0.00	0.03

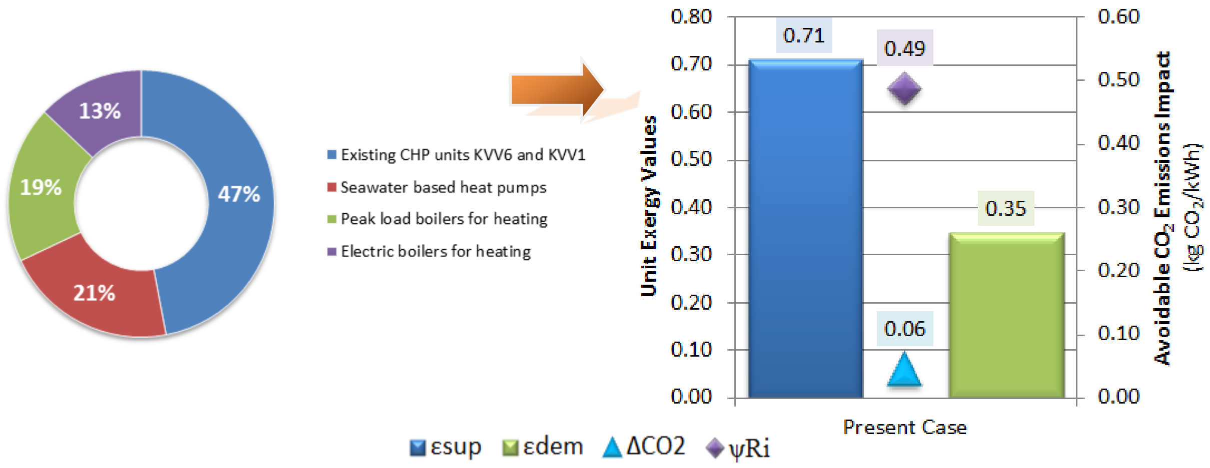
Table 6.4 defines the four proposed scenarios, where the share of each technology in each scenario, as well as in the present case is given. In future energy supply structures, the electric boilers and peak load boilers that have the worst exergy performance are replaced by the new biofuel CHP unit. The share of existing CHP units is also gradually lowered with the gap covered by large-scale ATES and PVT.

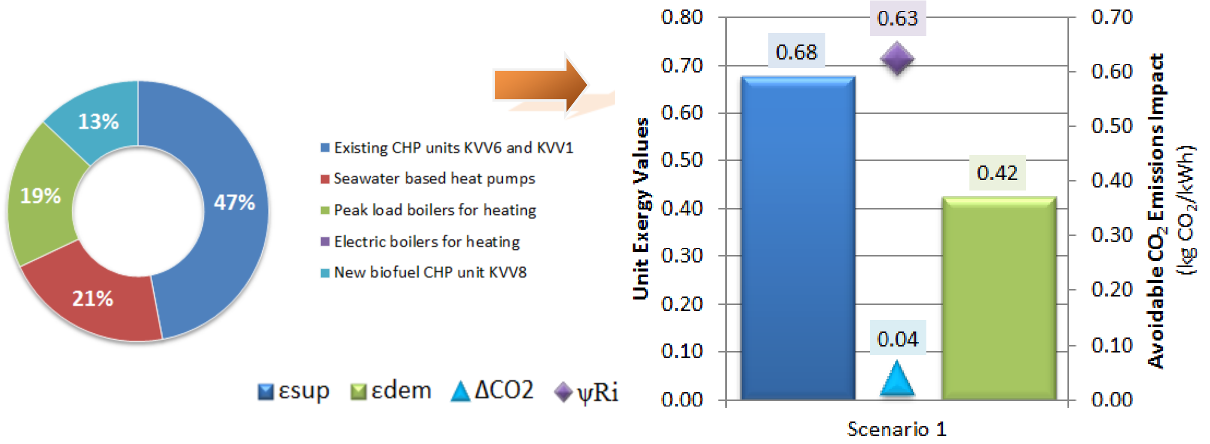
In Scenario 1, the new biofuel CHP unit replaces electric boilers in the present case. Electric boilers lead to the greatest amount of exergy destruction, as the highest exergy resource – electricity – is used to satisfy the low exergy demand of space heating. In the present case, the level of match between exergy supply and demand is 0.49. This change on the supply structure of district heating improves the level of match between exergy supply and demand to 0.63, which reduces the avoidable CO_2 emissions to 0.04 kg/kWh.

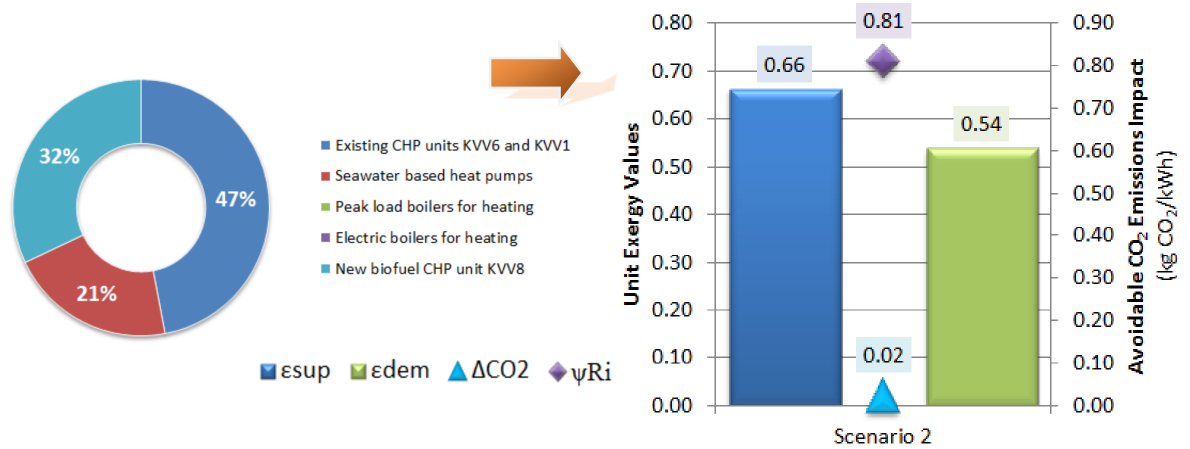
In Scenario 2, high exergy destruction technologies are further eliminated. The peak load boilers, which are the second worst in the present case in terms of exergy match, are removed. The gap is covered by the increased share of the new biofuel CHP unit. The level of exergy match rises to 0.81 and the avoidable CO_2 emissions further drop to 0.02 kg/kWh.

In Scenario 3, the share of the two existing CHP units is lowered by 10%, from 47% in the present case to 37%. The 10% reduction is covered by the newly introduced large-scale ATES. With ATES partly replacing the existing CHP units, both exergy supply and demand are lowered. The exergy supply is reduced to 0.60 per unit energy and exergy demand, due to demand reduction of electricity caused by the lower share of CHP, is lowered to 0.48 per unit energy. Accordingly, the level of match between exergy demand and supply becomes 0.80, while the avoidable CO_2 emissions remain at 0.02 kg/kWh. ATES facilitate the use of low temperature heating and high temperature cooling, which leads to a lower exergy demand of buildings in both the KTH campus cluster and Albano campus cluster.

In Scenario 4, the share of existing CHP units are further lowered by 10% from 37% in Scenario 3 to 27%. Accordingly, the share of large-scale ATES is increased to cover 15% of heat, together with the introduction of solar thermal collectors that account for 2% of heat and PVT that provides for 3%. The exergy supply continues to be reduced to 0.53 per unit energy, while the exergy demand further drops to 0.42. Accordingly, the level of exergy match becomes 0.78, which leads to 0.03 kg/kWh avoidable CO_2 emissions. Based on the values of exergy match and avoidable CO_2 emission, Scenario 4 seems to have a slightly lower performance than Scenario 2 and 3. However, solar thermal collectors and PVT, as on-site distributed renewable energy conversion technologies, help improve the energy and exergy self-efficiency of building clusters, which makes Albano campus and KTH campus get closer to the (nearly) net-zero energy/exergy targets.







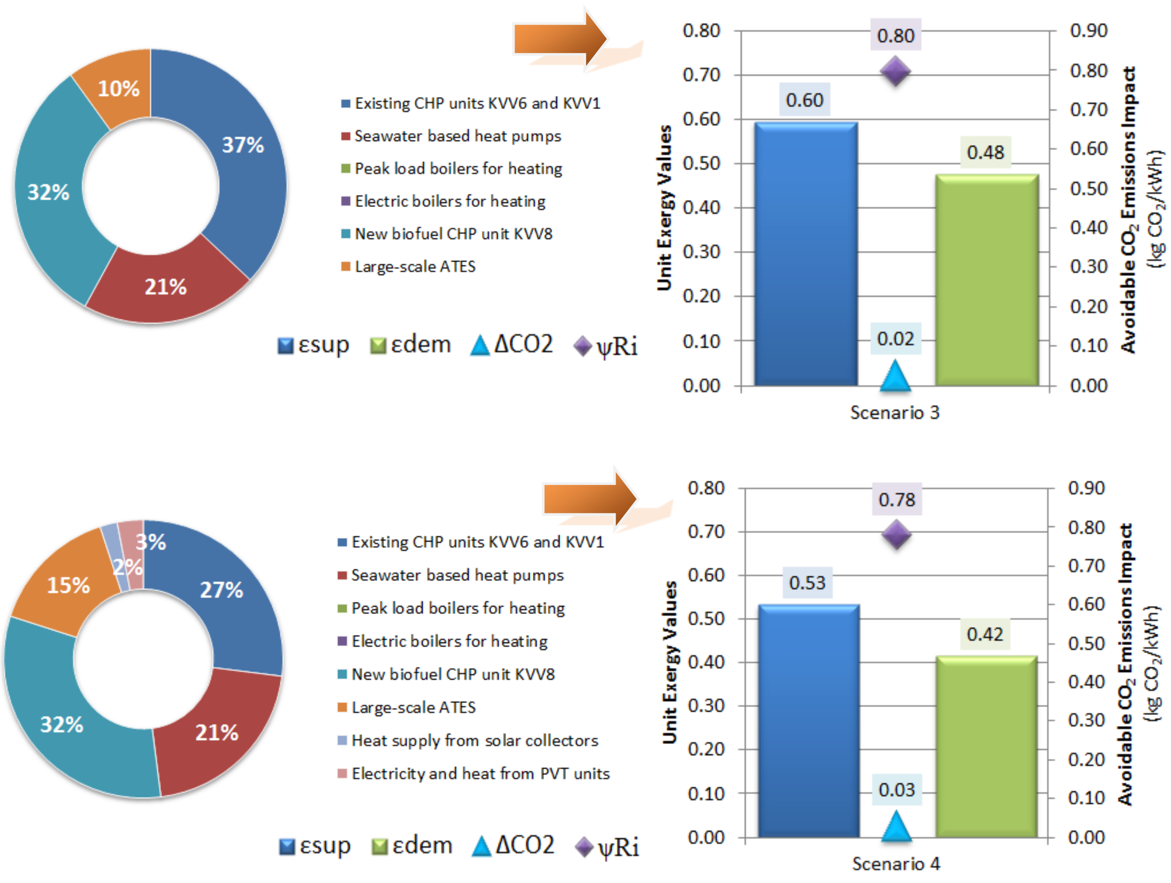


Figure 6.2: Shares in the energy system and exergy profile of four scenarios (from [39])

6.3 Discussion

The comparisons of energy and exergy consumption are made between the planned buildings on the Albano campus and the existing buildings on the KTH campus. The planned buildings on Albano have achieved significant energy and exergy savings compared to the KTH campus buildings, which is consistent with the property owners' goal of making Albano a vivid example of sustainable urban development.

From the energy supply side, it is also important to improve the level of exergy match and reduce the avoidable CO_2 emissions in the energy system. The present case results in a relatively low level of exergy match and high avoidable CO_2 emissions impact, as it employs electric boilers and peak load boilers, which have the worst exergy match, as well as coal as part of the fuel of the CHP units . Accordingly, four scenarios are proposed that represent future energy supply structures, where low exergy performance technologies are replaced by such high performance options as a biofuel CHP unit, large-scale ATES, solar thermal collectors, and PVT. These options contribute to a better exergy match and a cleaner energy supply structure.

Apart from being used as a reference in evaluating future alternatives to improve energy and exergy performance of the two building clusters, the results of the research work can also be used by the property owners or decision-makers to guide them in advancing the sustainable use of energy in building clusters on campuses.

Chapter 7

Conclusions and Future Work

7.1 Conclusion

This thesis presents a summary of the efforts made by the author since November 2014 to develop a holistic approach to the optimal design of a district energy system. In collaboration with the property owners, the author applied the approach to the new Albano university campus, seeking to make it fulfil the comprehensive requirements of sustainability and become an example of sustainable urban development.

The approach aims to find the best energy system solutions that could make a building cluster or a district have good energy, environmental, economic, and exergy performances. The energy performance is indicated by the non-renewable primary energy consumption, the environmental performance by the greenhouse gas emissions, the economic performance by the life cycle cost, and the exergy performance by the net exergy deficit. The selection of these objectives reflects both prospective legislative requirements and stakeholders' key concerns as well as the research interest of academia.

A wide range of energy conversion technologies and energy sources including both renewables and non-renewables has been modelled. These technologies include district heating and cooling, ground source heat pump, CHP, biomass boiler, solar thermal collectors, PV, wind turbines, etc. The on-site renewable energy sources such as solar, wind and ground source thermal energy as well as delivered energy sources including grid electricity, natural gas, biogas, biomass, and district heating/cooling are assumed to be available. The potential of heat recovery from low temperature sources – for instance, from greywater and a planned IT/data center – is explored. Genetic algorithm-based multi-objective optimization is applied to find the best combination of these technologies. The above-mentioned aspects are all respected in the optimization: they are either optimized or handled as constraints. The optimization results are presented in the form of Pareto fronts, which consist of a set of Pareto-optimal solutions. The Pareto fronts clearly show the trade-off between various objectives, which give decision-makers an overview of the energy system design and help them understand the options and limitations that they face. In order for decision-makers to determine final solutions, objectives are weighted in four different ways, in response to decision-makers' various preferences. Energy components of the best solutions selected under different preferences are analyzed. The results of the analysis show that some technologies are better suited to the pursuit of performance in one aspect than others. The ground source heat pump has been shown to have the best overall performance. Energy production from solar sources through PV and solar thermal collectors has proved to be less sensitive to the preference differences.

Sensitivity analyses have shown that optimal solutions might be sensitive to uncertainties that exist in certain system parameters and design variables, which can cause violation of constrains or result in a loss of system reliability. Therefore, in addition to the deterministic optimization approach, a robust design optimization approach is developed and employed to obtain the robust optimal solutions. Robust optimal solutions sacrifice the optimality of objectives in return for more robustness in the system. The system reliability is guaranteed with a robust optimal solution, when uncertainties occur in technical parameters such as the deterioration of efficiency or degraded size of energy conversation technologies. However, the results also show that the higher the amount of robustness that is wanted in the system, the more compromises that must be made on the optimality of objectives.

The composition of optimal solutions depends strongly on the system parameters. When certain parameters are perturbed, the newly obtained optimal solutions are most likely to be different from the old ones. A parametric analysis is conducted to investigate how the composition of optimal solutions varies to the changes of certain parameters. The results show that in general the share of one energy conversion technology increase as its price drops. However, the price reduction of some technologies is more effective for promoting its use than that of other technologies. The use of ground source heat pump providing heat and cold seems to be stable to the electricity price growth. It is also observed that the impact of parameters variation on the composition of optimal solutions is not linear and could be even non-monotonic in some cases.

Finally, a comparative study is conducted between the buildings on the Albano campus and the existing buildings on KTH campus from both energy and exergy perspectives. The planned Albano buildings will achieve significant energy and exergy saving over the KTH buildings, which is inherent in the concept of a better use of energy and exergy in the built environment. For both building clusters, it is important from the energy supply side to consider means to implement a cleaner energy supply structure. The Rational Exergy Management Model is employed to analyze the level of match between exergy supply and exergy demand and the avoidable CO_2 emissions on the present case and four proposed scenarios. Based on the analysis results, scenarios that involve low shares of heat from boilers and high shares of heat or electricity from biofuel CHP, large-scale ATES, solar thermal collectors and PVT realize the high levels of exergy match. These alternative technologies reduce the waste of exergy and lead to a more efficient and cleaner energy supply structure.

The studies presented in the thesis constitute a holistic approach to the optimal design of energy systems for building clusters or districts. The research shows that it is advisable to achieve the nearly- or net-zero status at the district level from energy, exergy, environment, and economic perspectives. The local renewable energy resources can be utilized to the best extent at the district level. In addition, there might be low temperature waste heat available on the district and, if utilized properly, the waste heat can make a significant contribution to the energy supply and correspondingly reduces the delivered energy use. The successful application of this approach to the Albano university campus proves that it is a useful tool for the energy system design in future urban development. However, this thesis has certain limitations. The Albano project is still at an early stage and limited information is available. Consequently, assumptions and approximations made about the building designs, energy load, and economic and technical parameters can be very rough. As the author has not been involved in the architectural design and has had limited access to high quality information regarding building designs, the research has focused only on the energy supply side, which means that buildings are treated as a black box with energy loads assumed as given. In future studies, the author will seek to intervene in the building designs, and make efforts from the demand side as well as from the supply side.

7.2 Future Work

In the present study, the non-renewable primary energy consumption and the greenhouse gas emissions during operation measure the energy performance and the environmental performance of energy systems, respectively. However, the embodied energy use and the life cycle greenhouse gas emissions, which take into account the energy and emissions incurred during the manufacturing process of energy conversion technologies, could be better indicators for determining the effectiveness of energy-saving and emission-curbing. Thus, these two indicators will be integrated into the optimization framework in future studies.

A complete energy system is composed of energy sources, energy conversion technologies, and energy use. However, as pointed out in the previous section, the present study focuses on the supply side, which only optimizes energy conversion technologies and corresponding energy sources. Instead of treating buildings as a black box, future work will optimize the energy system from both supply and demand side. Building design parameters will be introduced into the optimization framework and will be optimized together with energy conversion technology parameters.

For the sake of simplicity, energy storage technologies are not included as available options in the present study. Although the ground source heat pump can be used for energy storage, the present study assumes a constant COP without considering the underground temperature variation. In future work, the response of the ground and the performance of the heat pump will be modelled and integrated into optimization. Future studies will also include other thermal storage technologies, such as phase-change materials.

The parametric analysis in the present study is a local analysis, conducted by varying only one parameter at one time while keeping other parameters fixed. A global analysis procedure will be developed in future work to address the synergistic effects of these parameters.

The present study treats the Albano campus as a whole. However, there are two property owners of the buildings, as well as three universities and the municipality, involved in this urban development project. Future work will investigate how energy systems and services at a district level can be handled on market terms, with a focus on innovative forms of cooperation and business models between stakeholders.

Bibliography

[1] International Energy Agency (2013). *Transition to Sustainable Buildings – Strategies and Opportunities to 2050*, IEA, Paris.

[2] Buildings – European Commission (2016, August 1). Retrieved from https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

[3] EPBD (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), *Official Journal of the European Union* (18.06.10).

[4] Kurnitski, J., (2013). nZEB technical definition and system boundaries for nearly zero energy buildings. REHVA Federation of European Heating, Ventilation and Air Conditioning Associations, pp. 4–16, 2013. Brussels, Belgium.

[5] Sweden's Environmental Objectives – An Introduction (2016, August 1). Retrieved from http://www.miljomal.se/sv/Environmental-Objectives-Portal/

[6] Vägen till ett energieffektivare Sverige, SOU 2008:110 (2016, August 1). Retrieved from http://www.regeringen.se/rattsdokument/statens-offentliga-utredningar/2008/11/sou-2008110/

[7] Kayo, G., Hasan, A., & Siren, K. (2014). Energy sharing and matching in different combinations of buildings, CHP capacities and operation strategy. *Energy and Buildings, 82*, 685–695.

[8] 2020 Climate & Energy Package – European Commission (2016, August 1). Retrieved from http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm

[9] Sweden Tackles Climate Change (2016, August 1). Retrieved from https://sweden.se/nature/sweden-tackles-climate-change/

[10] Hepbasli, A. (2010). A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs). *Energy Conversion and Management*, *51* (10), 2041–2061.

[11] Koroneos, C., Spachos, T., & Moussiopoulos, N. (2003). Exergy analysis of renewable energy sources. *Renewable Energy, 28* (2), 295–310.

[12] Kilkis, S. (2007). A Rational Exergy Management Model for Curbing Building CO_2 Emissions. *Transactions – American Society of Heating Refrigerating And Air Conditioning Engineers*, *113* (2), 113.

[13] Kilkis, S., (2011). *A Rational Exergy Management Model to Curb CO_2 Emissions in the Exergy-Aware Built Environments of the Future*. (Doctoral dissertation). Royal Institute of Technology, Stockholm, Sweden.

[14] EBC Annex 37 – Low Exergy Systems for Heating and Cooling (2016, August 1). Retrieved from http://www.iea-ebc.org/projects/completed-projects/ebc-annex-37/

[15] ECBCS Annex 49 – Low Exergy Systems for High-Performance Buildings and Communities (2016, August 1). Retrieved from http://www.annex49.info/background.html

[16] Lu, H., Alanne, K., & Martinac, I. (2014). Energy quality management for building clusters and districts (BCDs) through multi-objective optimization. *Energy Conversion and Management, 79*, 525–533.

[17] Kilkis, S. (2008). Optimization of Heat Pump Applications for Net-Zero Exergy Buildings. In *9th IEA Heat Pump Conference*, 20-22 May 2008, Zürich, Switzerland.

[18] Kilkis, S., (2012). A net-zero building application and its role in exergy-aware local energy strategies for sustainability. *Energy Conversion and Management 63,* 208–217.

[19] Lu, H., Yu, Z., Alanne, K., Zhang, L., Fan, L., Xu, X. & Martinac, I. (2014). Transition path towards hybrid systems in China: Obtaining net-zero exergy district using a multi-objective optimization method. *Energy and Buildings, 85*, 524–535.

[20] Kilkis, S. (2010). Net-Zero Energy or Net-Zero Exergy Buildings for a Sustainable Built Environment? In *10th REHVA World Congress CLIMA*, 9–12 May 2010, Antalya, Turkey.

[21] Leckner, M. & Zmeureanu, R. (2011). Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. *Applied Energy, 88* (1), 232–241.

[22] Nguyen, A. T., Reiter, S., & Rigo, P. (2014). A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy, 113,* 1043–1058.

[23] Yao, W., Chen, X., Luo, W., van Tooren, M., & Guo, J. (2011). Review of uncertainty-based multidisciplinary design optimization methods for aerospace vehicles. *Progress in Aerospace Sciences, 47* (6), 450–479.

[24] City of Stockholm (2016, August 1), Retrieved from http://bygg.stockholm.se/Alla-projekt/Albano/

[25] Gavilán del Amo, A., & Alonso Lopez, A. (2015). *Drain water heat recovery in a residential building*. (Master's thesis), University of Gävle, Gävle, Sweden.

[26] Svensson, G., & Söderberg, J. (2012). A Heat Re-Use System for the Cray XE6 and Future Systems at PDC, KTH. *Cray User Group Final Proceedings: Greengineering the Future. Cray User Group*.

[27] Kavanaugh, S. P., & Rafferty, K. D. (1997). *Ground-source heat pumps: Design of geothermal systems for commercial and institutional buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[28] Carlson, S. W., & Thornton, J. W. (2002). Development of equivalent full load heating and cooling hours for GCHPs. *ASHRAE Transactions*, *108* (2), 88–98.

[29] Yang, H. X., Lu, L., & Burnett, J. (2003). Weather data and probability analysis of hybrid photovoltaic–wind power generation systems in Hong Kong. *Renewable Energy*, *28* (11), 1813–1824.

[30] Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. A. M. T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, *6* (2), 182–197.

[31] Palonen, M., Hamdy, M., & Hasan, A. (2013, August). MOBO a new software for multi-objective building performance optimization. In *Proceedings of the 13th International Conference of the IBPSA* (pp. 2567–2574).

[32] Hopfe, C. J., Emmerich, M. T., Marijt, R., & Hensen, J. (2012). Robust multi-criteria design optimisation in building design. *Proceedings of Building Simulation and Optimization, Loughborough, UK*, 118–125.

[33] Shi, J. H., Zhong, Z. D., Zhu, X. J., & Cao, G. Y. (2008). Robust design and optimization for autonomous PV-wind hybrid power systems. *Journal of Zhejiang University Science A*, *9* (3), 401–409.

[34] Rezvan, A. T., Gharneh, N. S., & Gharehpetian, G. B. (2012). Robust optimization of distributed generation investment in buildings. *Energy*, *48* (1), 455–463.

[35] Moradi, M. H., Hajinazari, M., Jamasb, S., & Paripour, M. (2013). An energy management system (EMS) strategy for combined heat and power (CHP) systems based on a hybrid optimization method employing fuzzy programming. *Energy*, *49*, 86–101.

[36] Helton, J. C., & Davis, F. J. (2003). Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. *Reliability Engineering & System Safety*, *81* (1), 23–69.

[37] Kılkış, Ş. (2014). Energy system analysis of a pilot net-zero exergy district. *Energy Conversion and Management*, *87*, 1077–1092.

[38] Kılkış, Ş. (2012). Green cities and compound metrics using exergy analysis. Encyclopedia of Energy Engineering and Technology. Taylor and Francis, New York.

[39] Kilkis, S., Wang, C. Björk, F. & Martinac, I. (2015). Building Clusters on University Campuses and Surrounding Urban Areas: Pilot Sites for a Sustainable Built Environment in Stockholm. In *10th Conference on Sustainable Development of Energy, Water and Environment Systems* (SDEWES), 27 Sep–2 Oct 2015, Dubrovnik, Croatia.