Modeling urban energy flows at macro and district levels – towards a sustainable urban metabolism

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Abstract

The urban sustainability is a growing importance in the built environment research. Urban areas play a key role in planning for sustainable city development. Urbanization has implications for future energy systems and energy-related emissions. The new built environment requires systems that are cost-efficient and have more efficient utilization of energy with a low environmental impact. This can be analyzed and designed with efficient tools for current and future energy systems. The objectives of this dissertation are to examine and analyze the metabolic flows of urban areas, and to develop a methodology for optimization of energy systems and services for the urban district. The dissertation is comprised of two phases and eight appended publications.

In the first phase of this dissertation, the research is emphasized on an in-depth understanding of the complex dynamics of energy utilization in large urban areas. An integrated approach applied in this phase includes the energetic urban metabolism, the long-term energy systems modeling using the Long-range Energy Alternative Planning (LEAP) system, and the Multi-Criteria Decision-Making (MCDM) approach. The urban metabolism approach has been employed to analyze the urban energy flows at macro level. The LEAP model and MCDM approach have been used to develop and evaluate energy scenarios in both demand and supply sides.

In the second phase, the research recognizes the lack of tools that applicable for district energy systems analysis. This phase concentrates on the important role of the district level in urban energy systems. Research methods include the Multi-Objective Optimization using Genetic Algorithms, the carbon budget approach, and the case study method. Research in the second phase is mainly focused on the development of tool for energy systems and services at the district level.

Keywords: Building clusters; Built environment; Energy modeling; Energy systems; Multi-objective optimization; Urban metabolism

Preface

This dissertation was carried out into two parts. The first part was completed at the Department of Energy Technology (EGI) at KTH under the supervision of Professor Ivo Martinac. Research at EGI focused on the development of energetic urban metabolism based on input-output analysis and energy systems modeling using the Long-range Energy Alternative Planning System (LEAP) model. Some parts of the research were collaborated with the Stockholm Environment Institute–U.S. Center, Technical University of Denmark and Osaka University, Japan.

The research in second part was carried out at the Division of Building Service and Energy Systems at KTH and Faculty of Engineering, Dhurakij Pundit University, Bangkok, Thailand. The work was under the supervision of Professor Ivo Martinac. The important research partner in this part was Akademiska Hus. Special thanks are owned to Jerker Nyblom, Environmental Coordinator of Akademiska Hus AB, Region Stockholm. In addition, the second part of this dissertation had various opportunities to collaborate with the VTT Technical Research Centre of Finland, the Global Carbon Project–Tsukuba International Office, National Institute for Environmental Studies, Japan, and Department of Infrastructure Engineering, The University of Melbourne, Australia.

I express my deepest gratitude to my supervisor, Professor Ivo Martinac for his never ending support. Your encouragement and coaching have been highly important to me, especially during difficult times during the study. I would like to thank colleagues at Department of Civil and Architectural Engineering for their helpfulness and friendliness. I am deeply grateful to my parents and lovely sister for unlimited love and support to achieve my goal. Special thanks to Thip-arphorn Pol-art who came to encourage me and shared the good times during the final stage of this dissertation.

Stockholm, November 2015
Aumnad Phdungsilp

List of appended publications

This doctoral dissertation consists of a compilation of the following publications. These are referred to in the text by their Roman numerals.

Publication I

Phdungsilp Aumnad (2006). "Energy Analysis for Sustainable Mega-Cities." Licentiate of Engineering Thesis, Department of Energy Technology, KTH Royal Institute of Technology, Stockholm, Sweden.

Publication II

Kennedy Christopher, Steinberger Julia, Gasson Barrie, Hansen Yvonne, Hillman Timothy, Havránek Miroslav, Pataki Diane, **Phdungsilp Aumnad**, Ramaswami Anu, Mendez Gara (2009). "Greenhouse gas emissions from global cities." Environmental Science & Technology, 43, pp. 7297–7302.

Publication III

Kennedy Christopher, Steinberger Julia, Gasson Barrie, Hansen Yvonne, Hillman Timothy, Havránek Miroslav, Pataki Diane, **Phdungsilp Aumnad**, Ramaswami Anu, Mendez Gara (2010). "Methodology for inventorying greenhouse gas emissions from global cities." Energy Policy, 38(9), pp. 4828–4837.

Publication IV

Phdungsilp Aumnad and Martinac Ivo (2013). "A Proposal of Urban District Carbon Budgets for Sustainable Urban Development Projects." In: Hakansson et al. (Eds.), Sustainability in Energy and Buildings, Smart Innovation, Systems and Technology 22, Springer-Verlag, Berlin.

Publication V

Phdungsilp Aumnad and Martinac Ivo (2015). "Distributed energy resource systems towards carbon-neutral urban development: A review and application." Accepted for publication in International Journal of Energy and Environment.

Publication VI

Magny Alessandro, Martinac Ivo, **Phdungsilp Aumnad** (2014). "Optimization of energy supply systems for a sustainable district in Stockholm using genetic algorithms." In: Proceedings of the 2014 World Sustainable Building Conference, Barcelona, Spain.

Publication VII

Phdungsilp Aumnad, Martinac Ivo, Magny Alessandro (2015). "Energy system and service optimization for building clusters of new urban development: Applying multi-objective genetic algorithms." Submitted to Sustainable Energy Technologies and Assessments, Elsevier.

Publication VIII

Phdungsilp Aumnad, Martinac Ivo, Ngo Tuan (2013). "A framework for integrated energy systems, infrastructure, and services optimization with visualization and simulation platform for low-carbon precincts." In: Proceedings of the International Symposium for Next Generation Infrastructure, Wollongong, Australia.

Author's contribution to the publications

Publication I

The author was responsible for most aspects of the publication. This publication focuses on two methodologies: (i) the urban metabolism based on input-output analysis, and (ii) modeling long-term energy flows in city. The results of the work presented in the Licentiate of Engineering Thesis.

Publication II

The author was responsible for data collection and empirical findings in the case of Bangkok, while other co-authors were responsible for other cities. The planning and writing of the publication were made together.

Publication III

The author was involved in the discussion leading to the methodology for inventorying greenhouse gas emissions from cities presented in this publication. Main materials were extracted from the work in publication I. Author also contributed to some part of the literature review and checked the findings and consistency for the case of Bangkok.

Publication IV

The author was responsible for initiating, executing and writing the publication. The second author provided advice, comments and suggestions.

Publication V

The author was responsible for initiating, executing and writing the publication. The second author provided advice, comments and suggestions.

Publication VI

The author was responsible for data collecting and calculating the energy use. The planning and writing of the publication were made together.

Publication VII

The author was responsible for almost aspects of the publication and performed part of the calculation and analysis. The work was partly developed together with co-authors.

Publication VIII

The author was responsible for initiating, research design, executing and writing the paper. The second and third authors provided advice, comments and suggestions.

Other publications not included in this dissertation

Phdungsilp Aumnad, Wuttipornpun Teeradej (2013). "Analyses of the decarbonizing Thailand's energy system toward low-carbon futures." Renewable and Sustainable Energy Reviews, 24, pp. 187–197.

Janthana Kunchornrat, **Phdungsilp Aumnad** (2012). "Multi-level governance of low-carbon energy systems in Thailand." Energies, 5(3), pp. 531–544.

Phdungsilp Aumnad (2011). "Futures studies' backcasting method used for strategic sustainable city planning." Futures, 43, pp. 707–714.

Contents

1. Introduction

In modern urbanization, the concept of sustainable urban development has emerged as an influential phenomenon observed on many levels. The significance of sustainable urban development in the context of cities has been well documented (Rydin, 2010; UN-Habitat, 2011; Fenton et al., 2015). Urban areas play a key role in planning for sustainable city development, and urbanization has implications for future energy systems and energy-related emissions. In addition, more floor space in both residential and commercial buildings will be needed, particularly in emerging economies and developing countries, which will determine urban sustainability for decades.

Urban sustainability is a growing concern in energy and climate research. While urban areas are sources of emissions, they also are part of the solution. Many efforts are now underway to reduce energy use and energy-related CO_2 emissions from urban areas. New tools, such as the Greenhouse Gas (GHG) Emissions Standard for Cities, Urban Risk Assessment, and the Global City Indicator, are being launched to manage cities' efficient use of resources and related emissions. New financial options, such as Green Bonds and Emissions Trading Systems, are also being implemented (Phdungsilp and Martinac, 2013). However, the research on links between urban areas and GHG emissions is relatively limited. There is a growing number of studies have assessed the urban energy use and energy-related emissions but these assessments are based on different approaches and different scales of application.

1.1. Background

Cities account for a large share of energy resources and also provide opportunities for energy management at various scales from individual buildings, districts, urban areas, and entire cities. Urban districts can be a testing ground for new solutions. Future urban development should be planned to utilize local energy sources and maximize the use of renewable energy resources. Traditional analysis of urban energy use highlights direct energy use of end-user sectors in an urban system (Kaneko et al., 2003; Dhakal, 2009; Zhang et al., 2014). However, urban systems are highly complex and integrated. The building sector not only uses energy directly, but also indirectly in the intermediate inputs produced by other sectors. To ignore the linkage between direct and indirect energy usages would be to underestimate the amount of city-level energy use.

In addition, many initiatives and efforts have been taken to reduce energy use and to increase energy efficiency in individual buildings, such as the development of a net-zero energy building. The concept undoubtedly generates sustainable building, but not within the urban context. Urban districts and building clusters are the point of analysis in many studies. Recently, the focus on energy analysis and sustainability of the built environment has expanded from single buildings into the district and urban levels, apart from the city level (Haapio, 2012; Hedman et al., 2014).

Against this background, analysis of energy systems and services at the urban district level would be an effective means of transforming cities to increase efficient use of resources and reduce related emissions. This dissertation merges work on urban metabolism, energy systems analysis, and energy system and service optimization at the district level to provide different perspectives on the development of urban energy systems. The three approaches dovetail at various points and provide complementary perspectives on urban energy systems.

1.2. Objectives and research questions

The overall goal of this dissertation is to examine the metabolic flows of urban areas and to analyze the energy systems and services in the urban district. The study utilizes both theoretical and methodological tools and modeling for a case study. The dissertation is divided into two main thematic areas: urban energetic metabolism and the optimizing energy systems and services. The specific objectives are:

- To identify and analyze the urban energy flows and energy-related emissions; and
- To develop a methodology for optimization and design of energy systems and services for the urban district.

The research is expected to understand the energetic urban metabolism flows, and to bridge the gap between macro and building levels in term of methods and tools for energy services and systems analysis. To achieve the objectives, a set of research questions have been identified.

Research question I: How multi-disciplinary research fields have been applied to analyze the urban energy flows? What tools can be employed for urban energy planning? The questions are guiding for **Publication I**.

Research question II: The importance of urban areas in addressing energy and environmental issues makes significant contribution to develop strategies for climate change mitigation. Thus, the second set of questions is: How and why cities' emissions differ? How can robust and transparent emission inventory be developed? The questions are guiding for **Publication II** and **III**.

Research question III: A significant CO_2 emission reductions can be implemented in urban areas. Urban sustainability is growing importance area in energy and climate change research. Thus, the third set of questions is: What methods can be applied to allocate emission restrictions into urban areas? What kind of energy technologies can be applied to achieve carbon-neutral urban development? The questions are guiding for **Publication IV** and **V**.

Research question IV: There are a number of methods and tools for analyzing, designing and planning for energy systems at national, city and building levels. However, there is a lack of method and tool for district level. Thus, the fourth set of questions: How can efficient tool for designing energy systems be developed? What is the future work in this research area? The questions are guiding for **Publication VI**, **VII** and **VIII**.

1.3. Method

The dissertation was employed a mixed-method approach of both quantitative and qualitative measures. Figure 1.1 provides an overview of the research methods and corresponding publications. This dissertation had two phases. The first phase emphasized the theoretical research, which resulted in **Publication I**. The research tools included the Long-range Energy Alternative Planning System (LEAP) model, GHG inventory, and energetic urban metabolism based on input-output (IO) analysis. The study applied these three methods in a case study of the city of Bangkok.

Research on energy systems and services at the urban or district level is a growing area in literature. However, methods and tools that applicable for urban/district energy systems analysis are still limited. In the second phase of this dissertation, it concentrated on the important role of the district level in urban energy planning and the application of energy systems modeling in a real development project. Research methods in this phase included the carbon budget approach and multi-objective optimization using genetic algorithms (MOO GAs), and also the case study method. This phase was carried out in collaboration with academia and industry.

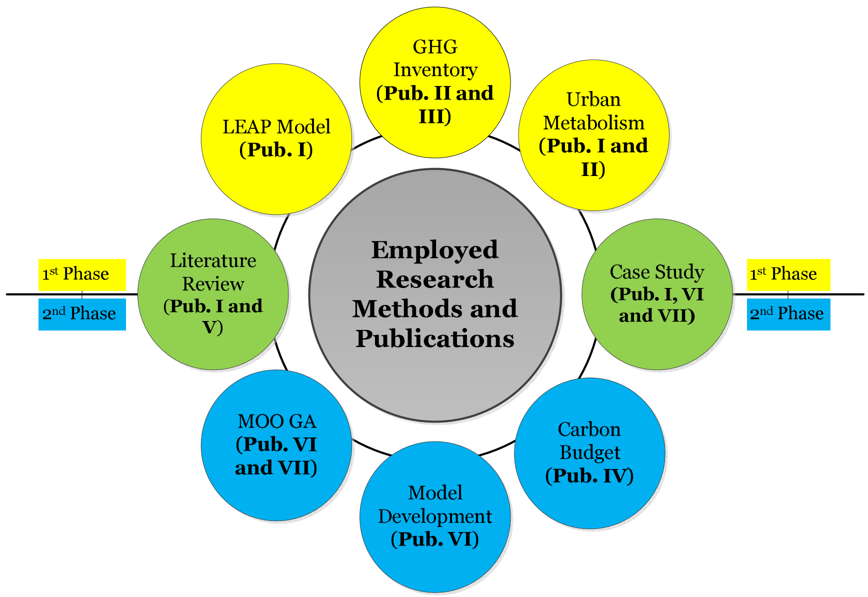


Figure 1.1 Overview of the employed research methods

1.4. Outline of the dissertation

The dissertation is divided into four sections, and seven chapters, as shown in Figure 1.2. Section one comprises Chapter 1, which begins with an introduction, background, and objectives of the research. This chapter also presents the employed research methods and corresponding publications of the dissertation.

Section two (Chapters 2 and 3) describes the theoretical framework and methodologies. Chapter 2 presents the urban metabolism, energy use in the built environment, and urbanization and carbon emissions. In addition, this chapter discusses the analyses at the district level regarding bridging the gap between research at urban and building levels. Chapter 3 presents the methods and techniques in urban energy systems planning and analysis.

Section three (Chapter 4) presents the application of system analysis as applied to urban and district energy systems and presents the findings from the two approaches. Section four (Chapters 5 and 6) includes the conclusions and recommendations for future work.

Chapter 7 presents the summary of publications in the research.

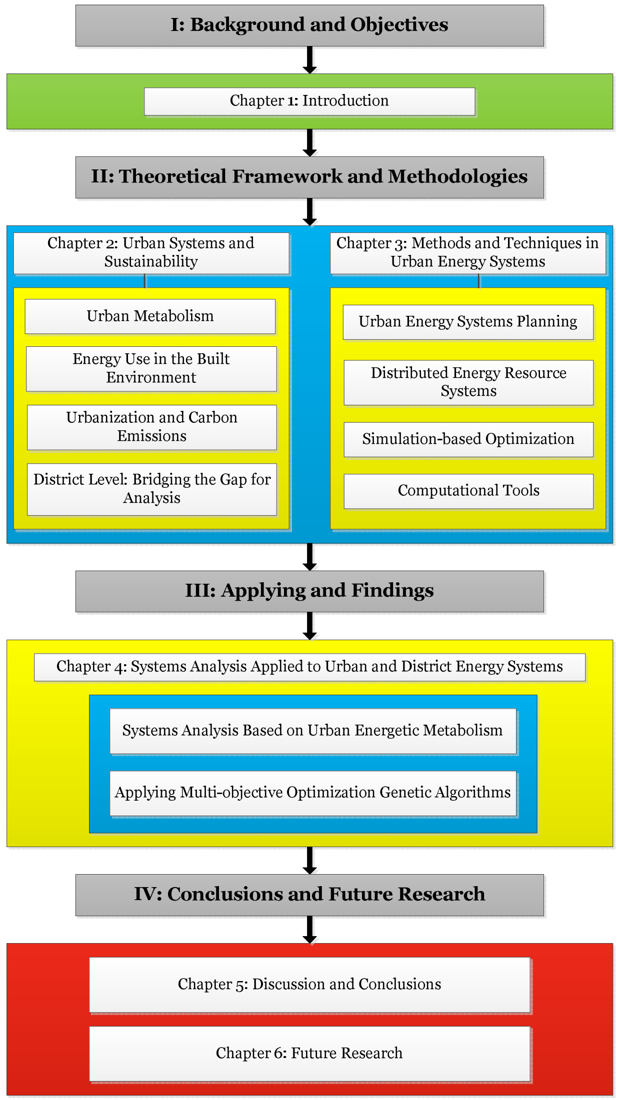


Figure 1.2 Layout of the dissertation

2. Urban Systems and Sustainability

2.1. Urban metabolism

The urban metabolism approach has become an important tool for the analysis of urban systems in various aspects, such as urban energy and material flows. The concept of urban metabolism describes the energy and material exchanges between nature and society. Urban metabolism has been identified as a promising approach to quantify energy and other resource uses in modern societal systems. In addition, urban metabolism offers a framework for quantifying, analyzing, and influencing urban form, function, process, and sustainability. Wolman (1965) was a pioneer researcher who used the urban metabolism concept to quantify the flows of energy and materials into and out of a hypothetical American city of one million people. He considered the city as analogous to an ecosystem, and described how energy and materials flowed into the system, similar to the way in which organisms in an ecosystem consume resources. As a consequence, the system creates products and generates wastes. The study was further developed by Douglas (1983), who described the equations to measure the energy, water, and material balances. Girardet (1990) proposed a cyclical urban metabolic model from his finding that a linear sequence from a city's input of resources to its generation of products and wastes did not accurately emulate how real organisms influence Earth's life-support system. Newman et al. (1996) studied the trends of per capita resource input and waste metabolism in Sydney. This study was another pioneer work in linking urban metabolism to livability and sustainability analysis. However, the study had the limitation of dealing with only a descriptive level and not delving into the social and political drivers of urban form and levels of flows. A combined model of urban metabolism with social factors was developed to expand the scope of urban metabolism to include human factors, such as employment rate and education (Newman, 1999).

Urban systems have a large impact on the environment outside the system. Various researchers have applied the concept of urban metabolism to analyses of cities (see **Publication I, II and III**). The early studies of urban metabolism as applied to actual cities were conducted in the 1970s, and included Tokyo (Hanya and Ambe, 1976) and Hong Kong (Newcombe et al., 1978). These researchers considered cities as similar to biological organisms, which use energy and resource inputs, transform them to do work, and produce waste. They used urban metabolism to understand urban trajectories of resource use, waste production, and associated environmental impact (Pincelt et al., 2012). Urban metabolism provides a systematic framework to examine the interactions of natural-human systems and a basis for analyzing sustainability implications (Kennedy et al., 2007; Barles, 2007; Pincetl et al., 2012). Research on urban metabolism, therefore, focuses on the sources and consumption of resources, and on their cycling within the system. In early urban metabolism research, Wolman (1965) developed a linear model of urban metabolism that included input and output processes. Next, Girardet (1990) proposed a cyclical process of urban metabolism, based on the black box model in which the inner details of each component of the system are unknown. Zhang et al. (2009) tried to improve the limitations of the black box model by proposing a network process. They proposed descriptions of metabolic processes based on insights from studies of biological metabolism and theory of complex urban ecosystems. The approach enabled an analysis of the metabolic processes of input, transformation, cycling, and output of energy and materials from a top-down perspective. Figure 2.1 presents the evolution of urban metabolism models.

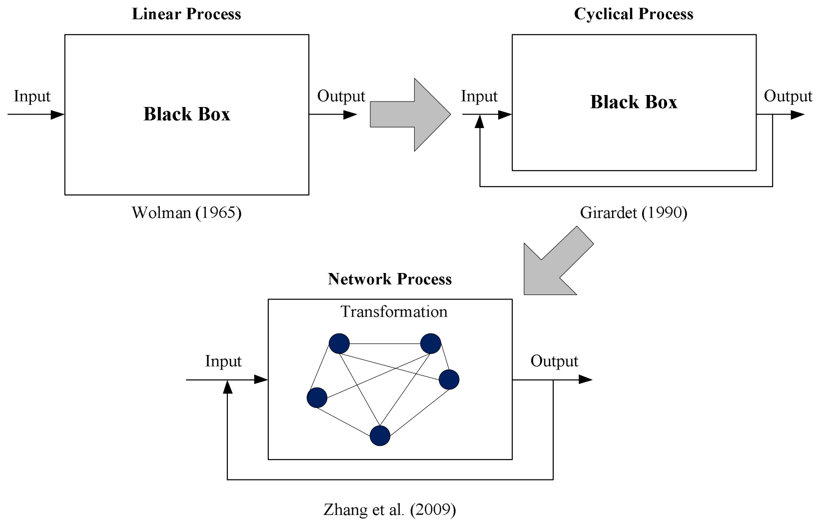


Figure 2.1 The evolution of urban metabolism models (Adapted from Zhang, 2013).

Because quantification of urban metabolism in all flows is complex, some researchers have focused on the metabolism of a single flow such as energy metabolism (see **Publication I and II**). Haberl (1997) pioneered the work on energy metabolism, and subsequently established an energy metabolic method (Haberl, 2001a; 2001b). The method has been used to study the modernization of socio-economic systems around the world, including Southeast Asia (Haberl, 2001b); the United States and 15 countries in the European Union (Haberl et al., 2006); the Czech Republic (Kuskova et al., 2008); and the cities of Prague (Fikar and Havránek, 2009), Vienna (Krausmann, 2011), and Xiamen (Zhao, 2012). In addition, engineers, urban planners, and system ecologists have used the urban metabolism model, although urban policy makers have been slow to use it to aid decision-making.

Sustainability requires a comprehensive assessment of environmental, social, and economic perspectives. Sustainability has been applied to several sectors at different scales, and in the establishment of building environmental assessment methods in different countries, such as LEED (US), BREEAM (UK), CASBEE (Japan), and EcoEffect (Sweden). Within the concept of urban metabolism, sustainability problems arise within the energy and material relationships between the built environment and nature. Urban metabolism can complement the requirements and address some aspects of sustainability, such as energy use and efficiency. Therefore, integration of urban metabolism in the planning process can apply to a variety of urban development projects. Pincetl et al. (2012) expanded the concept of urban metabolism to a systems approach for influencing urban sustainability, and concluded that urban metabolism analysis requires a political, ecological, and theoretical framework.

2.1.1. Urban metabolism assessment methods

In literature, the quantification of urban metabolism has evolved into two distinct approaches: the energy-material flux approach and the “emergy” method (Odum, 1996; Sahely et al., 2003; Barles, 2009; Huang et al., 2006; Pincetl et al., 2012). The first approach, which is closely associated with engineering, incorporates material flow analysis (MFA) to assess energy and material flows through the urban system. It also accounts for the energy used to transform raw materials and resources into material goods to meet demands, and the associated waste flows. A recently developed method joins life-cycle assessment (LCA) to urban metabolism, to capture the direct and indirect material flows of cities beyond their boundaries. LCA offers a tool for quantifying the materials of urban metabolism (Pincetl et al., 2012).

The energy-material flux approach dominates the methodology in urban metabolism. It involves quantification and tracking energy and mass flows in standard units (for example, joules, tons, kilograms). Several studies have used the energy-material flux urban metabolism framework to analyze different urban areas and system components. These studies have illuminated a variety of phenomena in cities around the word (Kennedy, 2010).

The second approach for quantification of urban metabolism is based on the concept of "emergy," in which all measures are normalized to a standard unit based on solar energy (Odum, 1996). Emergy draws underlines cities' fundamental dependence on ecological processes that are possible only because of solar energy. Emergy measures energy flow in nature and humans to generate products and ecological services. The method emphasizes standard units of energy, materials, nutrients, and waste flows in biophysical systems (solar emergy joules: SEJ); however, it is difficult to express all the processes in common units (Huang and Chen, 2009; Pincetl et al., 2012). The emergy method's complexity limits its use, and therefore, the energy-material flux method is more common in urban metabolism. A comparison of the urban metabolism methods is shown in Table 2.1.

Most urban metabolism studies use aggregated data at the city or regional level to provide a snapshot of energy and resource use. However, many cities have no disaggregated data. The challenge to make urban metabolism more useful is to find a way to attribute the flows to end-uses and the places where they generate outputs within cities. In addition, urban metabolism should be integrated with a city's political, economic, demographic, and geographic factors. Because of the complexity of quantifying urban metabolism and the lack of available data, the concept typically is used to focus on a single flow, thereby permitting a more profound understanding of that flow. Therefore, this dissertation focuses on energy metabolism (see **Publication I, II and III**).

Table 2.1 Comparison of the main urban metabolism assessment methods

Method	Strengths	Weaknesses
Material flow analysis	It is based on accounting approach which can be used for quantification of inputs and outputs of numerous commodities. Can be used to derive aggregated indicators for sustainability.	Does not include the important role of energy flows. Requires data about materials extraction and use which is not often available at the urban scale.
Emergy analysis	The method ensures that all the flows are accounted for the difference in the quality of the energy and materials. It permits an integrated evaluation of the status of urban development and identifying the causes of degradation of the urban system.	It is difficult to interpret the results. Appropriate energy transformation rates must be determined for all flows.
Input-output analysis	Economic sectors are included with energy and material flow analysis, which allows linkage to life cycle assessment. Helping to understanding and identification of the actors in urban systems.	The combination of energy and material flows with input-output tables is difficult on urban scale due to limited availability of data on the flows. Data have to obtain from the provincial or country level to quantify the goods and services. The result remains a rough estimation.

Table 2.1 (continued)

Method	Strengths	Weaknesses
Ecological dynamics	Analyzes the operation and evolution trends of urban system in chronological order. Combines the economy and nature to simulate the evolutionary trend of the urban system.	It is difficult to quantify the unifying flow processes for multiple ecological elements. Previous studies have focused mostly on the metabolic processes for a single element.
Ecological network analysis	Enables quantitative simulation of the structure and functional relationships among components of the urban system.	The lack of flows among networks in a socio-economic system makes it difficult to refine the sectors of the network. The analyses require large amounts of quality data.
Process analysis	Provides detailed analysis of urban resource use and associated environmental impacts.	Requires large quantities of data and time-consuming calculation. Results may be precise for a given study area.

Source: Pincetl et al., 2012; Zhang, 2013.

2.2. Energy use in the built environment

2.2.1. Building scale

The concept of sustainability is applied through the built environment by looking at the contribution of CO_2 emissions, which can be used as a proxy for energy use. The building sector is responsible for approximately 40 percent of global primary energy use and is a major contributor of GHG emissions; therefore, specific attention is required to reduce energy use and CO_2 emissions. Furthermore, final energy use is projected to increase 20 and 44 percent from 2009 to 2035 for climate mitigation and business-as-usual scenarios, respectively (Anderson et al., 2015). In addition, if embodied energy and embodied emissions are used to determine the full impact of the built environment, the figures increase significantly. Consequently, the built environment is the dominant driver of global energy use and GHG emissions.

Both technical and behavioral factors affect energy use in a building. From a technical perspective, the factors in building energy include the building form, the thermal properties of the materials, the thermal performance of the entire building, and the operating systems (such as HVAC systems). The energy balance of the building can be represented mathematically in the following equations.

$$Q_{loads} = Q_{\text{int}} + Q_{conv,\text{int}} + Q_{\text{inf}} + \Delta E_{air} \quad \text{Eq. (2.1)}$$

$$q_{tsol} + q_{asol} + q_{lw} + q_{conv} - q_{cond} = 0 \quad \text{Eq. (2.2)}$$

In Eq. (2.1), Q_{loads} is the building heating or cooling loads; Q_{int} is the internal heat gains from lighting, people, and equipment; $Q_{conv,\text{int}}$ is the convection heat transfer between zones; Q_{inf} is the heat transfer due to infiltration; and ΔE_{air} is the change of energy stored in the zone. Eq. (2.2) represents the energy balance for building exterior, where q_{tsol} is the solar radiation transmission, q_{asol} is the absorbed solar radiation, q_{lw} is the net long wave radiation flux, q_{conv} is the convection heat flux exchanged with outside air, and q_{cond} is the conduction heat flux into the wall. Several building energy performance simulations have been developed, based on the principle of energy balance, such as IDA ICE, EnergyPlus, TRANSYS, DOE2.1E. These sophisticated energy simulation programs are capable of modeling the building systems in detail and analyzing building energy performance. Technical solutions make it possible to improve building energy efficiency and reduce environmental impact. However, these solutions must be integrated with human behaviors to maximize their potential.

Behavioral aspects of energy use in a building include users' awareness, quality of energy usage, and change of equipment. Occupants react differently according to their personal characteristics. Energy-related occupant behavior depends on actions and activities performed in buildings to provide good indoor environmental quality, particularly thermal comfort. Analyzing occupants' interactions with the building systems can help to understand behaviors associated with energy use. A number of studies have focused on how behaviors impact building energy use. Some studies utilized methodologies (modeling approaches) or techniques (monitoring and visualization) to analyze total real building energy use and to investigate the factors that influence occupant behavior in buildings (e.g., IEA Annex 66).

The energy associated with a building can be classified into operational energy and embodied energy. Operational energy comprises the energy use of building, such as HVAC system, electrical load, and water heating. Operational energy represents the dominant share of global energy use by buildings. Embodied energy is the impact from the production of materials, transportation to the construction site, and the construction process. According to Anderson et al. (2015), the operational phase dominates the primary energy of a building at more than 80 percent compared to the embodied phase (about 10 to 15 percent) in a building's lifecycle. Figure 2.2 presents the primary energy use in operational phase and embodied phase in building's lifespan.

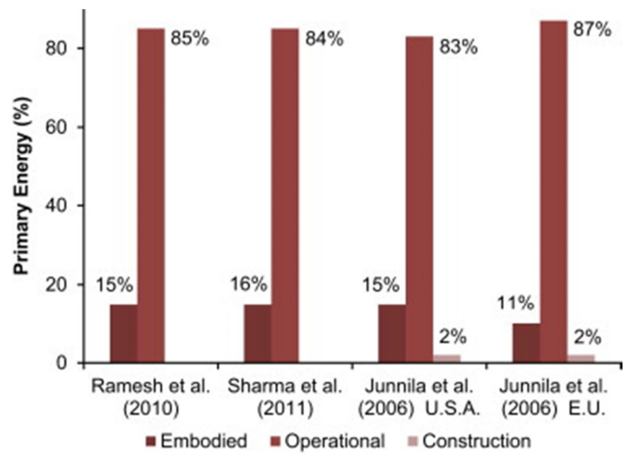


Figure 2.2 Comparative life-cycle operational energy and life-cycle embodied energy

Many efforts have been pursued to decrease the use of energy in buildings on several levels. Large studies and implementing programs related to building energy use have been launched in both developed and developing nations. In developing countries (such as China, India, and Thailand), most studies have focused on the areas of energy efficiency improvements and low-energy buildings, while in developed countries, efforts have moved toward nearly zero energy buildings. The European Union has established the "nearly zero energy building" under the recast of the EU Directive on Energy Performance of Buildings (EPBD) as the target within 2018 for all publicly owned buildings, and within 2020 for all new buildings (EU, 2010). In terms of the analysis methods, there are several proven methodologies at the building scale. The common analysis methods include building energy modeling, statistical modeling, life-cycle assessment (LCA), process-based LCA, economic input-output LCA, and hybrid LCA.

2.2.2. Urban scale

When analyzing energy use, there are similarities and differences between the building and the urban scales. The similarities are related to the methodological development for energy analysis, because several methodologies are applicable at various scales. The main difference between the building and the urban scales is the analysis boundaries. The urban scale can be ranked from a small city to a mega-city, depending on the definition used in the study. Energy use in cities is widely discussed in **Publication I**. The topics include the determinants of energy use in cities, urban effects on energy use, international frameworks for cities and sustainable development, factors driving urban energy use, and estimation of urban energy use.

Energy use at the urban level is related to the influence of urban form, urban density, transportation infrastructure, and consumption pattern. Studies on the influence of urban form have found that households in urban centers have lower CO_2 emissions than suburban locations, and these CO_2 emissions are strongly based on socio-demographic factors (Glaeser and Kahn, 2010; Wiedenhofer et al., 2013; Anderson et al., 2015). Similar to the building level, energy use at the urban level can either direct or indirect (embodied energy in goods and services). Figure 2.3 presents a comparative study on the direct and indirect energy use in selected Asian mega-cities. The indirect energy use was estimated based on the input-output technique and embodied energy analysis. Detailed calculation of the indirect energy is described in **Publication I**. The indirect energy use is more significant than direct energy use in Bangkok, Shanghai, and Tokyo. For Beijing, the direct energy is greater than the indirect energy. This can be explained by the fact that Bangkok, Shanghai, and Tokyo have a great reliance upon the outside in terms of energy demand, while Beijing is more self-sufficient. The ratio of direct energy to indirect energy demand also provides information about economic structural changes.

Assessment methodologies for urban scale energy use are similar to the methods used at the building scale. The methods for urban level energy analysis are LCA, input-output LCA, hybrid LCA, urban metabolism, agent-based simulation, complex systems approach, econometric model, and building stock model. The LCA-based approach is a dominant method for urban energy analysis (Anderson et al., 2015). During the past decades, several sophisticated energy systems models have been developed and applied to several urban areas, cities, and countries, for example LEAP, MARKAL/TIMES, EnergyPLAN, and HOMER. The evolution of energy systems models is discussed in **Publication I**.

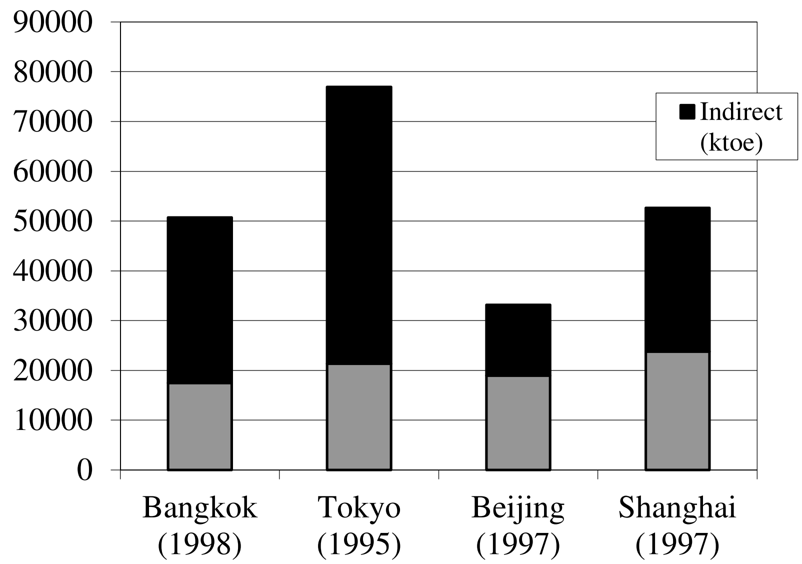


Figure 2.3 Direct and indirect energy in selected Asian mega-cities (Based on calculation of case studies in **Publication I**)

2.3. Urbanization and carbon emissions

The world's population is now over 50 percent urban, and cities make an important contribution to CO_2 emissions. Urban sustainability is realized through optimal resource utilization and the ability to minimize emissions. Urbanization has both positive and negative impacts and plays a significant role in the interaction between urban areas and global climate change. Urban areas are the centers of consumption and depend on high levels of energy and material flows. These flows represent impacts on different scales ranging from local to regional to global. On the other hand, the economies of scale associated with the high population density and concentration of economic activity contribute to significant economic growth. Previous studies (such as Newman, 1999; Newman et al., 2009; Moore et al., 2013) confirmed that urban areas are an appropriate focus for research to address sustainability issues and to find feasible ways to reduce environmental impacts.

Publication II describes an attempt to quantify GHG emissions from 10 global cities, while the methodology for quantification is discussed in **Publication III**. A central concept of quantifying emissions is based on urban metabolism. The carbon emissions are determined for seven components or urban inventories, including electricity, heating and industrial fuels, industrial processes, ground transportation, aviation, marine, and waste. Emissions are calculated for the 10 cities (or metropolitan regions), with populations from 432,000 to 9,519,000, and are compared in per capita terms (Figure 2.4).

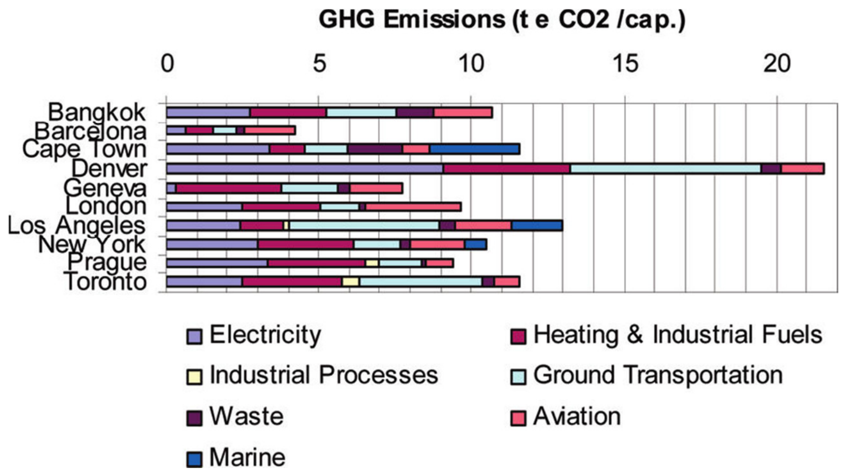


Figure 2.4 Direct GHG emissions in 10 global cities
(Based on **Publication II**)

In addition, many governments have recognized the role of urban areas in resource efficiency and climate change mitigation, and are developing strategies to reduce their emissions. Consequently, some jurisdictions have established emission targets, as shown in Figure 2.5 (see **Publication IV**).

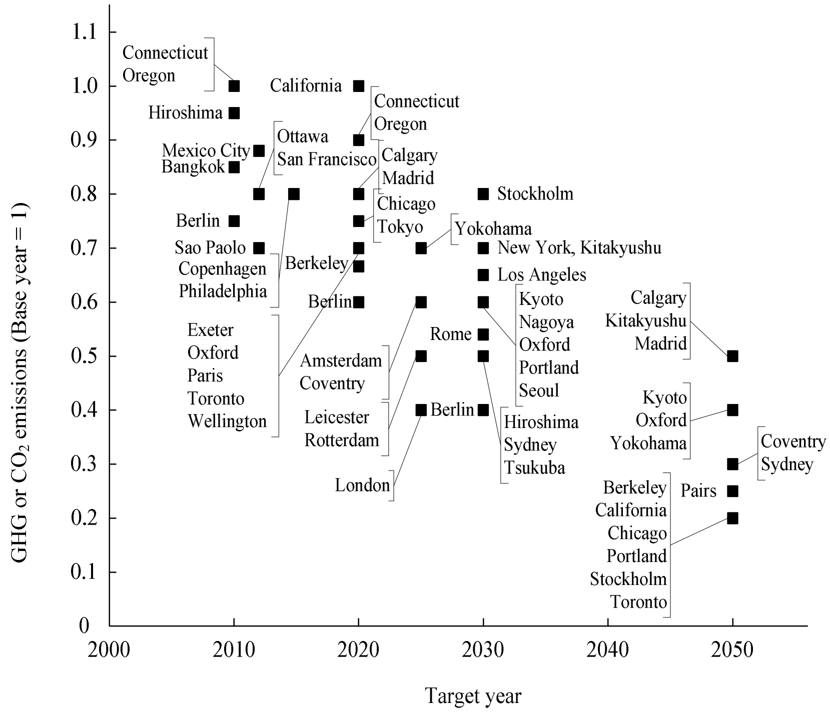


Figure 2.5 Emission targets of the cities across the world (Based on **Publication IV**)

2.4. District level: Bridging the gap between urban and building scale

Generally, research on energy use in the built environment is divided between the building and urban scales. This division is useful for investigations with clearly defined boundaries and methods to be applied. However, analysis at the urban scale may not take into consideration new construction or development projects within its boundary. Construction tends to occur within existing urban cities; therefore, construction of new buildings or building clusters must be considered within the context of an existing city. At the building level, the analysis usually treats the building as a stand-alone object, but this approach misses opportunities of energy sharing or energy exchange within nearby buildings. The scale-specific analysis might fail to measure the environmental impact in the built environment through the omission of analyses of the interactions between individual buildings and the urban context (Anderson et al., 2015). In addition, existing tools (such as, energy models) at the urban or building scale may be appropriate for district level. Therefore, analysis of energy use at the district level attempts to bridge the gap between the building and urban scales.

Having identified a research gap and its potential consequence, the dissertation developed a methodology for district scale in **Publication V and VII**. District-level energy planning is an important part of a city energy development strategy. It assists in optimizing the energy infrastructure and improving the overall efficiency of energy systems. An analysis of energy systems at the district level also plays a crucial role in achieving the city's emission target, as mentioned in the previous section, through increasing utilization of renewable and sustainable energy. In fact, some researchers are aware of this research gap. For example, Yamaguchi et al. (2007), and Yamaguchi and Shimoda (2010) proposed a simulation modeling approach for energy use in the business district of Osaka, Japan. Some researchers have studied district-scale energy models based on system design studies (Weber at al., 2006; Ren and Gao, 2010; Bourdic and Salat, 2012), and energy efficiency rating of districts (Hedman et al., 2014). Recently, Anderson et al. (2015) mentioned that additional methodological developments are required to bridge the gap between the building and urban scales. This statement was confirmed in the study by Huang et al. (2015), in which the challenges for small-scale district energy planning still remain in terms of the analysis method and modeling tool. An analysis of district energy system can support a city's energy management and forecast a future urban energy system.

3. Methods and Techniques in Urban Energy Systems

This chapter describes the main methods and techniques applied to analyze urban energy systems, and research methods employed in this dissertation. Specific details of research methods and tools are presented in **Publication I, III, IV, VI, and VII**.

3.1. Urban energy systems planning and analysis

Urban energy systems are an important part of cities. Without reliable energy carriers, daily operations within the city would not be possible. According to Keirstead and Shah (2013), there are two perspectives for analyzing urban energy systems. The first is to look at cities as physical systems that can be analyzed using theory of thermodynamics or systems analysis. The second uses a set of socio-technical theories to deal with the ways in which technologies and people co-evolve. Energy planning usually consists of various activities, such as analysis of end-uses, demand and supply management, and simulation and optimization covering certain aspects of the energy system. Energy planning involves finding a set of energy sources and energy conversion devices to meet the energy requirements in an optimal manner. A recent trend is for energy planning to occur in parallel to the rise of the city as a key player in implementation of energy policies and measures. Traditional energy planning is based on the supply side, whereas urban energy planning emphasizes the demand side (see Figure 3.1 for a comparison). An analysis of energy systems at the urban level is important because many decisions are made at this level where there is a closer connection between decision makers and the public. Urban energy planning takes into account available energy sources and energy demand in a region. This implies that the assessment of energy demand, supply, and its intervention in the energy system is appropriate for the local context. There have been various planning approaches and guidelines for urban energy planning, such as Community Energy Planning (Huang et al., 2015), Decentralized Energy Planning (Hiremath et al., 2007), Low-Carbon City Planning (Gomi et al., 2010; Chen and Zhu, 2013), BREEAM Communities (BRE, 2011), LEED-ND (USGBC, 2011), and CASBEE (IBEC, 2007).

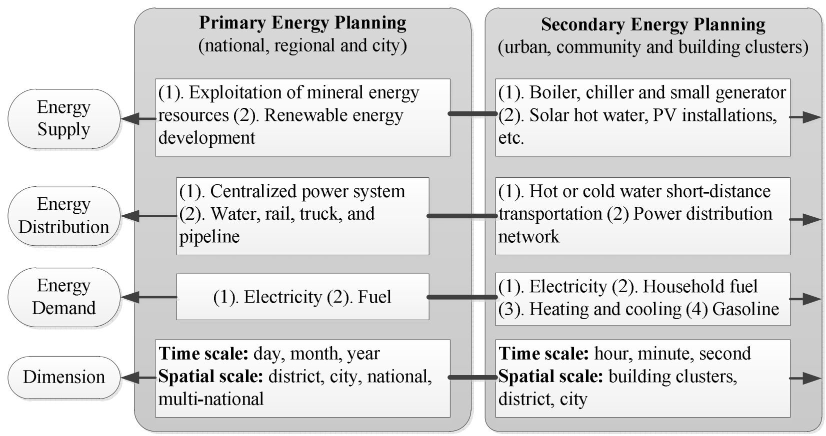


Figure 3.1 Comparison between traditional energy planning and urban energy planning (Adapted from: Huang et al., 2015)

As discussed in many academic articles, urban metabolism can be integrated into the process of energy planning (Kennedy et al., 2011; Kostevšek et al., 2013). Kostevšek et al. (2013) confirmed that urban metabolism is applicable in energy planning, and showed that the metabolism approach represents the groundwork for energy planning. In **Publication I**, the study proposed using urban metabolism as a tool for urban energy analysis. This approach was used for to analyze detailed energy situations in a case study of Bangkok, Thailand, and is also useful for GHG emission accounting. While urban metabolism works well to quantify energy flows in the current situation, the core issue of energy planning is to solve the contradiction between the current and future energy supply and demand. This calls up a limitation of the metabolism approach. Therefore, the study used the long-term energy-planning model (Long-range Energy Alternative Planning: LEAP) to project energy demand in the Bangkok case study and to develop a model to forecast energy demand in that city up to 2025. The study developed two scenarios for energy planning: a business-as-usual (BAU) scenario and an alternative scenario. The former followed the current trends of parameters without policy interventions, and the alternative analyzed the effect of policies and interventions on energy use and GHG emissions.

Based on the urban metabolism concept, the study developed and tested the robust and transparent GHG inventory procedure **(Publication III)**. This research was a comparative study of GHG emissions from 10 global cities, and the paper describes the methodology and presents new data of these cities' urban metabolism. The methodology and data were used to quantify the emissions for components of electricity, heating and industrial fuels, ground transportation fuels, aviation and marine fuels, industrial processes, and waste. To accommodate the effects of spatial and lifecycle boundaries, three measures of overall emissions were used:

(i) physical emissions within the boundary of the city;
(ii) single process emissions form end-use activities associated with the city's metabolism; and;
(iii) extended life-cycle emissions associated with the city's metabolism.

The first measure was predominantly composed of emissions from fossil fuel combustion within the city boundaries. The second measure included all emissions from electricity use and waste disposal, and the direct emissions from fuel loaded at airports and harbors. The third measure was GHG emission factors for the lifecycle of fuels, rather than for direct emissions. This work makes several contributions to the quantification of energy use and energy-related GHG emissions for cities.

The methodology developed in this paper allows to use for energy planning and analysis of urban areas.

Following the fundamental idea from **Publication III**, the work discusses an alternative approach for urban energy planning in **Publication IV**. The study developed a proposal of carbon budget approach for urban development projects focusing on the urban district level. To reduce the flows of urban metabolism as well as emissions, it is important to facilitate the integration of technical and policy innovations into urban systems. Urban districts can be a testing ground for new solutions. Urban areas are assigned an emission budget and must keep local emissions (such as building and transport) within this figure. This paper presents five alternative carbon budget allocation methods: (i) allowance auctioning; (ii) equal share approach; (iii) per capita approach; (iv) economic approach; and (v) consumption-based approach. The urban carbon budgets can be used for energy planning when urban districts are the points of action. Urban district carbon budgets can complement a city's efforts to reduce its metabolic flows and planning for energy infrastructures. A growing number of cities around the world have taken action and launched initiatives to reduce their emissions. Some cities have already adapted the concept of carbon budgets under different targets and base years. According to Salon et al. (2010), local government is responsible for deciding which strategies to use to reduce local emissions and for implementing them. The carbon budget approach would provide a framework to target the emissions. The carbon budget approach not only serves as a framework for climate change mitigation, it also provides the fundamentals for energy planning and analysis.

3.2. Distributed energy resource systems

The environmental concerns of urban development lead to finding cleaner energy conversion and more efficient energy use. Local generation of heat and power and the use of renewable energy resources are promising options to provide a clean and efficient energy supply (Alarcon-Rodriguez et al., 2010). Technological innovations allow the shift from centralized energy systems to smaller and distributed systems. Thus, it is possible to use available resources and technologies in the local area. A new trend in energy systems planning is toward distributed energy systems because they are more efficient, reliable, and environmentally friendly than traditional energy systems (Pepermans et al., 2005; Alanne and Saari, 2006; Carley, 2009; Akorede et al., 2010). **Publication V** reviews the distributed energy resource (DER) system and discusses the recent developments in DER systems in an urban context and their application for carbon-neutral urban development in a case study. DER, which is an integrated and decentralized energy system, can refer to small decentralized power generating technologies that can be combined with energy management and storage systems and located close to the point at which the energy is converted to energy services. DER can be either electric-only (for example, solar PV, wind, small hydro), thermal-only, combined heat and power (CHP), or energy storage of both thermal energy and electricity (Herrera, 2002; Alarcon-Rodriguez et al., 2010; Kumar et al., 2011).

In the literature, works related to DER systems encompass a set of generation technologies, modeling techniques and planning tools, and application domains. The majority of literature focuses on modeling studies, followed by relevant concept, supply technology, energy systems design, and policy assessment (**Publication V**). Table 3.1 presents a cluster analysis of the relevant publications related to DER studies. Modeling studies are the largest group within the data set in the analysis, and consist of several modeling techniques, such as accounting, optimization, and simulation. Optimization is not always about finding the best solution, but may concern the exploration of alternatives. The relevant concept in relation to DER includes regional energy clustering, integrated energy systems, energy hubs, micro-grid, and the exergy approach. The energy systems design studies consider either a building or building clusters, district scale, and specific sites. The works in this cluster typically investigate the pattern of energy services and the combination of equipment and operation to meet energy requirements. This cluster is often interrelated with the modeling study cluster. The studies within supply technology cluster are focused on renewable energy technologies, CHP systems, energy storage technologies, decentralized energy systems, and demand-side and supply-side matching. The policy assessment cluster focuses on environmental and economic performance, and how energy performance might be shaped by policy interventions. The studies were conducted at different spatial scales, from individual buildings to a city level.

Table 3.1 Cluster analysis of reviewed papers (From author's survey of state-of-the-art DER systems referred to in **Publication V**)

Cluster	Scale	Number of publications
Relevant concept	Building, Building Cluster, City, Community, and District	22
Supply technology	Building, City, and District	11
Modeling study	Building, Building Cluster, City, Community, District, and Municipality	39
Energy systems design	Building, Building cluster Regional, and City	15
Policy assessment	Building, City, District, and Municipality	10

DER systems offer a promising opportunity for urban district development by developing more affordable small-scale energy resource portfolios. In terms of energy carriers, electricity dominates the medium of exchange and heat also plays an important role. Biofuels and hydrogen are expected to contribute to energy exchanges in DER systems. The main advantage of DER systems is the reduction of primary energy because the systems are installed close to or inside the end-users' facility, which results in energy savings and lower transmission losses. Another advantage is low CO_2 emissions since DER technologies usually use renewable energy sources or clean energy sources, rather than fossil fuels. DER systems are also able to provide cost-effective energy services to users. Figure 3.2 presents the technologies that can configure DER systems.

The environmental impact of energy conversion processes is widely discussed among academics and practitioners. To date, the global primary energy source of the conventional power plants is fossil fuels. In the literature, there are four major environmental benefits related to the adoption of DER technologies: (i) promoting higher energy efficiencies; (ii) reducing CO_2 emissions; (iii) minimizing the health risks; and (iv) conserving more natural resources (Akorede et al., 2010). These benefits are in line with the findings in **Publication V**; most of the reviewed publications recognize that environmental benefits drive adoption of DER systems.

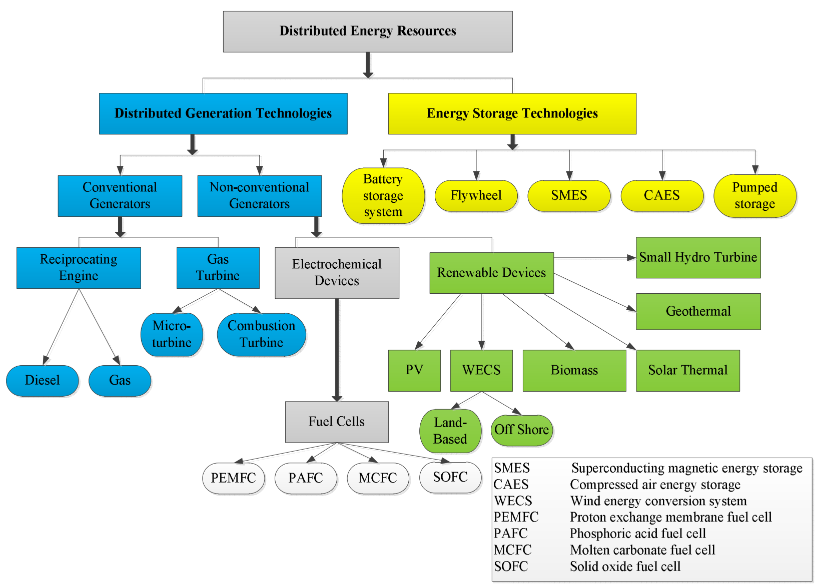


Figure 3.2 DER technologies
(Adapted from Akorede et al., 2010)

3.3. Simulation-based optimization in energy systems

As reported in **Publication V,** new modeling techniques have been proposed for energy systems analyses in recent years, and one of the most powerful is multi-objective optimization based on genetic algorithms (GAs). Computational simulation, which allows energy use to be quantified, involves energy flows modeling based on the building's geometry, materials, and HVAC systems. The design of energy systems is not straightforward, but must take into consideration both technology configuration and the energy performance of buildings. An energy systems design must achieve high levels of performance for the lowest possible cost, which is similar to the design of high-performance buildings. Also, many physical processes can lead to conflicting objectives. The design space of possible solutions is very large (Evins, 2013). Energy systems design is a classical constraint of optimization. In the literature, linear programming (LP) and non-linear programming (NLP) are commonly used to solve this problem. Because it is difficult to find a global optimum solution for this type of optimization problem, and there are a large number of possible combinations, many approximation algorithms have been developed to attain near optimum solutions (Huang et al., 2015).

Simulation-based optimization generally tries to describe the dynamic behavior of technologies and systems. It usually employs numerical techniques to find the best solution in an energy system, based on the selected technical, environmental, or economic objective to be minimized or maximized. However, optimization does not necessarily mean finding the global optimal solution(s) to a problem due to the nature of optimization problem (Baños et al., 2011). Computers may be used in various ways to optimize engineering designs, and Evins (2013) and Nguyen et al. (2014) provided details of common optimization algorithms used for building-related optimization and simulation-based optimization methods applied to building performance analysis. All are heuristic methods, including direct search (such as Pattern Search, LP and NLP), evolutionary algorithms (such as GAs, Evolutionary Programming, Covariance Matrix Adaptation Evolutionary Strategy, and Differential Evolution), and algorithms that mimic other natural processes (such as Particle Swarm Optimization, Ant Colony Optimization, Simulated Annealing, and Harmony Search). Figure 3.3 depicts the trend of optimization algorithms found in the literature related to building optimization problems. This knowledge facilitates the optimization study in this dissertation because there is limited literature on simulation-based optimization in energy systems at the district/urban level.

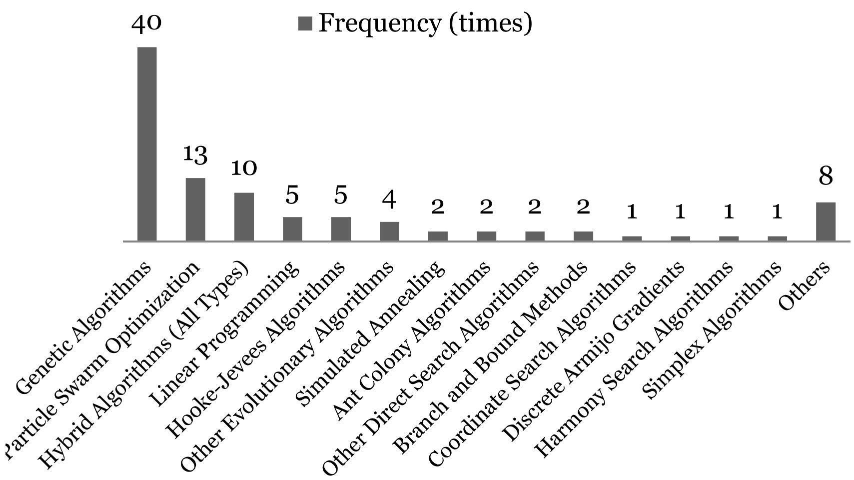


Figure 3.3 The frequency of use of different optimization algorithms in building optimization studies (Adapted from Nguyen et al., 2014)

Traditionally, energy systems analysis aims to find the least costly solution, but in recent years, there has been a growing need to incorporate sustainability concerns in energy systems planning. As a result, use of multi-criteria approaches has increased. The design of energy systems is a multi-objective optimization problem in nature. The problem also includes non-linear and non-convex objectives and constraints with discrete and integer variables. As mentioned earlier, optimization involves finding a set of design parameters that minimizes or maximizes objective function(s) subject to a group of constraints. However, engineering problems frequently require a solution to conflicting objectives. Multi-objective optimization (MOO) is a means to address conflicting objective functions. MOO produces a set of solutions by varying the impact of each objective function in the global optimum. A generic representation of the optimization problem can be expressed as:

$$\min F(x) = \min\left(\left[f_1(x), f_2(x), \ldots f_m(x)\right]\right) \quad \text{Eq. (3.1)}$$

Subject to

$$x \in \Omega \quad \text{Eq. (3.2)}$$

$$g_j\left(x\right) = 0, \qquad j = 1, 2 \ldots p \quad \text{Eq. (3.3)}$$

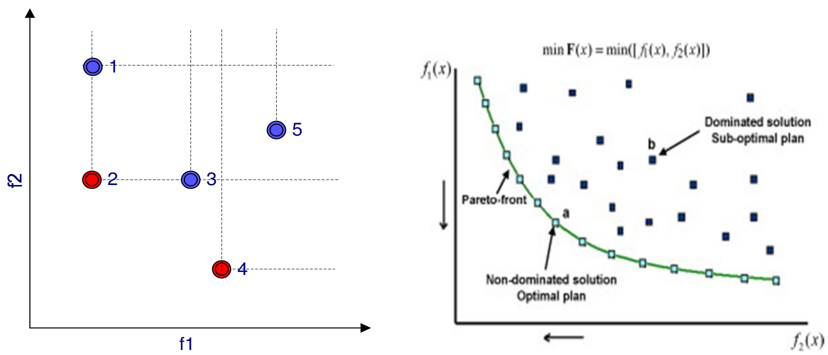
$$h_k\left(x\right) \leq 0, \qquad k = 1, 2 \ldots q \quad \text{Eq. (3.4)}$$

where $F_{(x)}$ is a vector of m objective functions $f_i(x)$. For a single-objective problem, $m = 1$. All objectives are expressed as minimization. A maximization objective can be formulated by minimizing the negative of the objective function as $\min - f_i(x)$, where x is the decision vector, such as technology types, sizes, and locations that includes a set of n decision variables $\left[x_1, x_2, x_3, \ldots, x_n\right]$. Ω is the decision domain defined by the possible values that the decision variables can take or the search space. The optimization problem is bounded by equality constraints $\left(g_j\right)$ and inequality constraints $\left(h_k\right)$.

The MOO problems involve either the minimization or maximization of several mathematical functions to find a set of optimal design solutions. A problem with conflicting objectives has no single solution, but a set of optimal solutions. The solution to a MOO problem is not a unique element, but a set of solutions, each of which satisfies the objectives at an acceptable level without being dominated by any other solution. In a MOO problem, the concept of "dominance" is used to determine if one solution is better than another (Deb, 2001; Alarcon-Rodriguez et al., 2010). The concept of dominance can be exemplified in a two objective minimization examples, s shown in Figure 3.4a. The dominance relationships are as follows: Solution 2 dominates solution 1, 3, and 5; solution 3 dominates only solution 5; and solution 4 dominates only solution 5. Solution 2 and 4 are non-dominated; that is, no solution dominates them. Even if solution 2 is equal in one objective to solution 1 and 3, it still dominates them. In Figure 3.4b, a solution "a" is said to dominate a solution "b" if the following two conditions are true:

- "a" is no worse than "b" in all objectives and
- "a" is better than "b" at least one objective.

In this case "b" is said to be dominated by "a", or "a" is said to be non-dominated by "b". The non-domination relationship determines the concept of Pareto optimality. A solution is said to be Pareto optimal if it is not dominated by any other solution in the solution space. A Pareto optimal solution cannot be improved in one objective without losing in another one. The set of non-dominated solutions is referred to as the Pareto optimal set. For a given Pareto optimal set, the corresponding objective function values in the objective space are called the Pareto front. The goal of multi-objective optimization is to identify solutions in the Pareto optimal set; however, identifying the entire Pareto optimal set, for many cases, is practically impossible. Therefore, a practical approach is to investigate a set of solutions that represent the Pareto optimal set (Deb, 2001; Konak et al., 2006).



(a) (b)

Figure 3.4 Pareto front for two objective functions
Source: Alarcon-Rodriguez, 2009; Alarcon-Rodriguez et al., 2010

There is no single method for efficiently solving all optimization problems; instead, a number of methods exist, known as mathematical programming methods, which usually are available in the form of mathematical programming algorithms. The energy systems planning problems actually have multiple-objectives, such as minimize cost, maximize performance, and so on. A solution to a multi-objective problem is to investigate a set of solutions that satisfies the objectives at an acceptable level without being dominated by any other solution (Konak et al., 2006). MOO problems have been proposed to be solved suitably using Evolutionary Algorithms (EA), which use a population-based approach in the search procedure (Deb, 2001). There are two general approaches to solve MOO problems. The first is to combine the individual objective functions into a single composite function. A single object can be determined with methods such as weighted sum method and utility theory. The second approach is based on the use of heuristic optimization techniques, such as EA, to determine an entire Pareto optimal solution set (Alarcon-Rodriguez et al., 2010). Finding the final solution (one optimal solution) for a MOO problem can involve a decision-making process.

As shown in Figure 3.3, GAs are a popular and suitable method to solve optimization problems. The application of GAs to building and energy-related issues is a growing field of research. GAs able to simultaneously search different regions of a solution space and to find a diverse set of solutions. GAs have been the most popular heuristic approach to multi-objective design and optimization problems (Konak et al., 2006). Detailed accounts of the development of MOO based on the GA approach can be found in Srinivas and Deb (1994), Coello-Coello (2000), Jones et al. (2002), Deb et al. (2002), Xiujuan and Zhongke (2004), Konak et al. (2006), Coello-Coello (2006), Alarcon-Rodriguez et al. ,(2010), Baños et al. (2011), and Evins (2013). Therefore, **Publication VI** developed the MOO GA for designing energy supply systems for the Albano district in Stockholm, Sweden. The description of the MOO model is discussed in **Publication VII**. The solution strategy for a case study is based on four steps, as shown in Figure 3.5. The optimization is performed using the optimizer software coupled to the objective function calculation. Matlab is used for calculating the objective functions and MOBO (Multi-Objective Building Optimization) is used for optimization. The computational optimization tool is discussed in section 3.4.

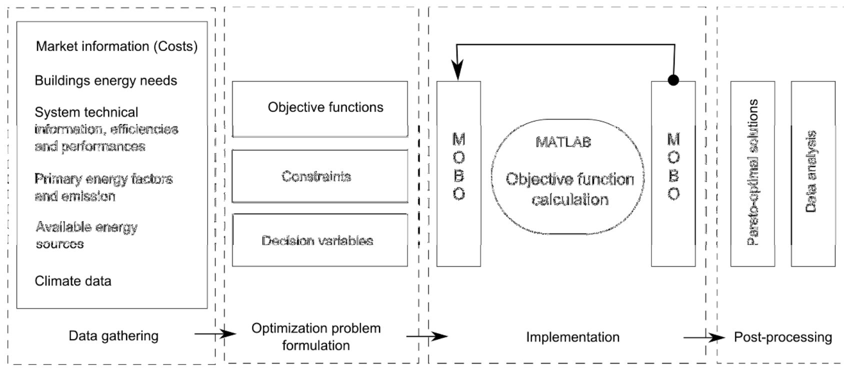


Figure 3.5 Solution strategy for solving a MOO problem in the case study (Developed for the Albano case study in **Publication VI** and extended to use in **Publication VII**)

According to Figure 3.5 (for details see **Publication VI** and **VII**), the MOO model was developed to minimize three objective functions: the non-renewable primary energy, the operational CO_2 emissions, and the levelized lifecycle cost. The available energy technologies are represented in the MOO model as decision variables or design parameters.

3.4. Computational tools for urban energy systems

Generally, a building performance optimization problem can be performed using building energy simulation software and optimization solvers. The building energy simulation models the energy use profiles and then generic optimization software is applied. However, most existing building simulation software was developed for a building scale only, and its application is limited to building clusters or district scale, as discussed in **Publication VII**. Most studies in building optimization couple a building simulation program with an optimization engine may consist of one or several optimization algorithms (Attia, 2012; Nguyen et al., 2014). Figure 3.6 shows the typical methodology of a building simulation-based optimization process.

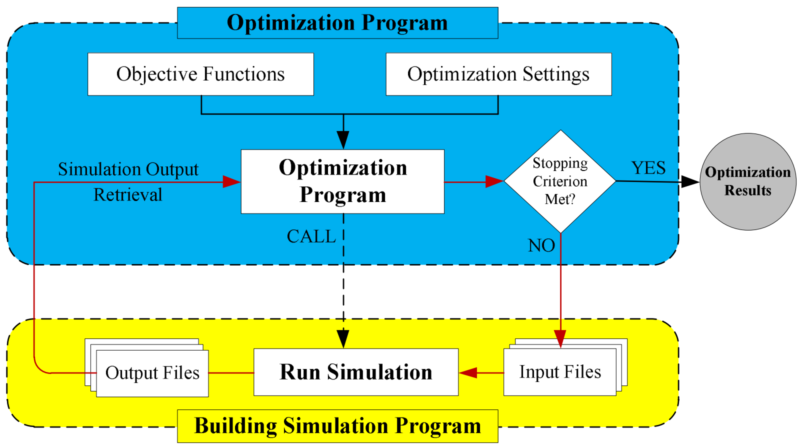


Figure 3.6 The coupling between building energy simulation and optimization software (Adapted from Nguyen et al., 2014)

The efficient analysis of a complex system, such as energy systems, requires an approach that can overcome difficulties in modeling real phenomena, while maintaining computational transparency, reliability, and interoperability across the analysis. A numbers of computational tools are available for building performance analysis. According to Manfren et al. (2011), the most common way to calculate load profiles of buildings is to use simulation tools like EnergyPlus or TRNSYS. In a study on simulation-based optimization methods applied to analyses of building energy performance, Nguyen et al. (2014) confirmed that the majority of building simulation programs use EnergyPlus and TRNSYS, and the tools used most often in building optimization are GenOpt and MatLab optimization toolboxes. For the urban, city, and national scales, several comprehensive reviews of tools for energy system planning and analysis can be found in the literature (for example, Connolly et al., 2010; Mendes et al., 2011; Manfren et al., 2011; Keirstead et al., 2012; Huang et al., 2015). Table 3.2 summarizes the frequently used computational tools of energy analyses at different scales, based on a survey of the research.

Although many computer tools and models are available for building energy performance analyses, renewable and energy systems designs, and optimization, challenges remain for building clusters or for the district level. The tools should help in the formulation of different design strategies and in the analysis of energy, environmental, and economic of energy systems.

Accounting tools are designed for estimation of parameters and the calculation of quantities of energy. They are usually a spreadsheet-based platform for evaluation of an energy project. Some tools can account for the whole energy chain in a given region. Simulation tools developed to describe the dynamic behavior of technologies and systems employ numerical techniques to perform transient analysis. Optimization tools are developed to find the best solution based on selected objectives. MOO techniques offer a promising tool with potential to account for several conflicting objectives simultaneously (Manfren et al., 2011).

Table 3.2 Summary of the frequently used computational tools of energy analyses at different scales (alphabetically)

Tool	Description	Scale of application
DOE-2	Building energy performance simulation software	Building
EnergyPlus	Building energy performance simulation software	Building
EnergyPLAN	Hour-by-hour simulation of energy systems tool	City, country and region
ESP-r	Building energy performance simulation software	Building
IDA-ICE	Building energy performance simulation software	Building
LEAP	Accounting tool based with scenario-based energy modeling tool with capability for optimization.	City, country and region

Table 3.2 (continued)

Tool	Description	Scale of application
HOMER	Simulation and optimization model for distributed generation systems	Urban and city
TRNSYS	Transient system simulation program enable to simulate whole building energy use	Building
GenOpt	Generic optimization solver software	Building
MARKAL/ TIMES	Energy optimization model	City, country and region
Matlab	Generic optimization tool	Building and urban
MOBO	Optimization engine	No limitation in its applicability
RETScreen	Accounting tool enables to evaluate renewable energy technology implementation	Urban, city and country

Compiled from Manfren et al., 2011; Evins, 2013; Palonen et al., 2013; Machairas et al., 2014; Nguyen et al., 2014; Huang et al., 2015.

4. Systems Analysis Applied to Urban and District Energy Systems

Overall, this dissertation is based on a systems analysis approach; therefore, this chapter discusses the systems analysis and presents the findings from such an approach as applied to urban and district energy systems. Applying a systems approach provides an opportunity to get a holistic picture of the effects of change. A number of models and assessment tools have emerged from a system-based approach, for example simulation model, optimization model, material flow analysis, life-cycle inventory, and sustainable assessment (Chang, 2011). The methodologies developed in **Publication I**, **II, III, IV,** and **VII** drew upon the principles of systems analysis, and in particular, this dissertation deals with the input-output analysis (IO analysis), life-cycle inventory, and multi-objective optimization model.

4.1. Systems analysis based on urban energetic metabolism

To quantify energy and resource use and supply in modern urban systems, the concept of urban metabolism (as described in the previous chapter) offers a promising framework to understand the interconnection of complex systems. However, each urban system has its own characteristics, including the mix of resource use and geographic and economic structures. In **Publication I**, the fundamental tool applied was based on Leontief's IO analysis (Leontief, 1986), a method of systematically quantifying the interrelationships among the various sectors of a system. IO analysis is based on information concerning the input and output states of the system and can be applied at various levels, from a single economic enterprise to a country. IO analysis is often applied to energy study because it can account for both direct and indirect energy (Ziębik et al., 2005). Ziębik and Hoinka (2013) applied the method to an energy analysis of complex buildings, and Zhang et al. (2014) used IO analysis to calculate the energy flows for urban energy consumption in the city of Beijing.

The study focused on urban energetic metabolism rather than a full urban metabolism because of data available. The work applied IO analysis to a case study of Bangkok to account for direct and indirect energy use. The direct energy use represents energy flows between sectors, whereas indirect energy use represents energy use in the production and transfer to intermediate products. Indirect energy can also imply the economic dependency of the city upon outer regions, and especially can highlight the environmental load displacement on those regions. Figure 4.1 illustrates the direct and indirect flows of energy among the sectors of an urban energetic metabolism. For the calculation, the study employed the concept of embodied energy. Several authors have used embodied energy analysis to distinguish between indirect energy use for the production of goods and direct energy use (Phdungsilp, 2006). The ratio of direct and indirect energy use can provide information about economic structural change within the urban metabolism. It also can be used to determine associated environmental impacts and to predict some consequences of social and technological development.

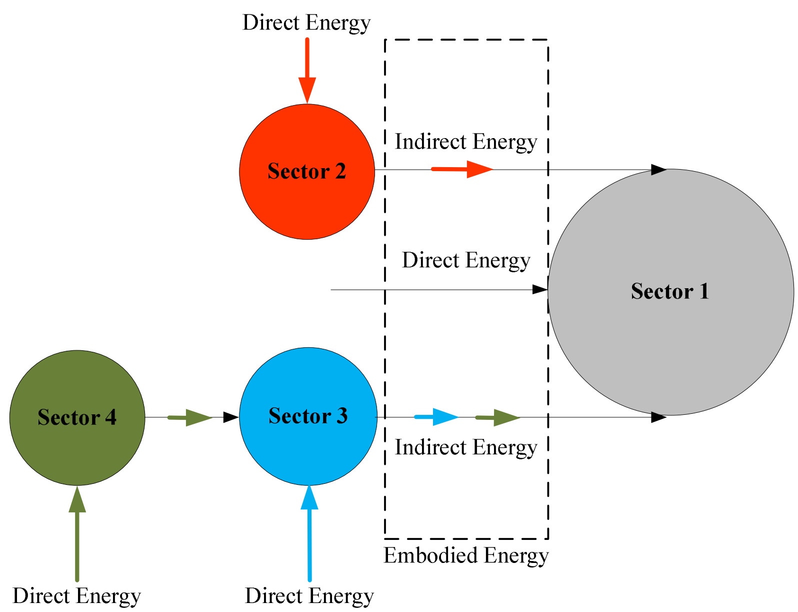


Figure 4.1 Direct and indirect energy flows among the sectors (Adapted from: Zhang et al., 2014)

Obviously, direct energy use can indicate how a city or an urban area relies upon factors from the outside; however, as energy demand is a proxy indicator, indirect energy use provides some very interesting information that cannot easily be drawn from direct energy use (Kaneko et al., 2003). Indirect energy use can illustrate how a city or an urban area relies upon the outside its physical boundary. The embodied energy analysis is use to simulate the direct and indirect energy flows within the metabolism perspective. The term "embodied energy use" means the total amount of energy needed directly or indirectly to make any product or service (Bakshi, 2000). Within the laws of thermodynamics, the urban energetic metabolism model implies that anything that comes into an urban system must pass through it, and therefore, the amount of waste depends on the resources required. Figure 4.2 presents an energy balance for a production sector within an urban system.

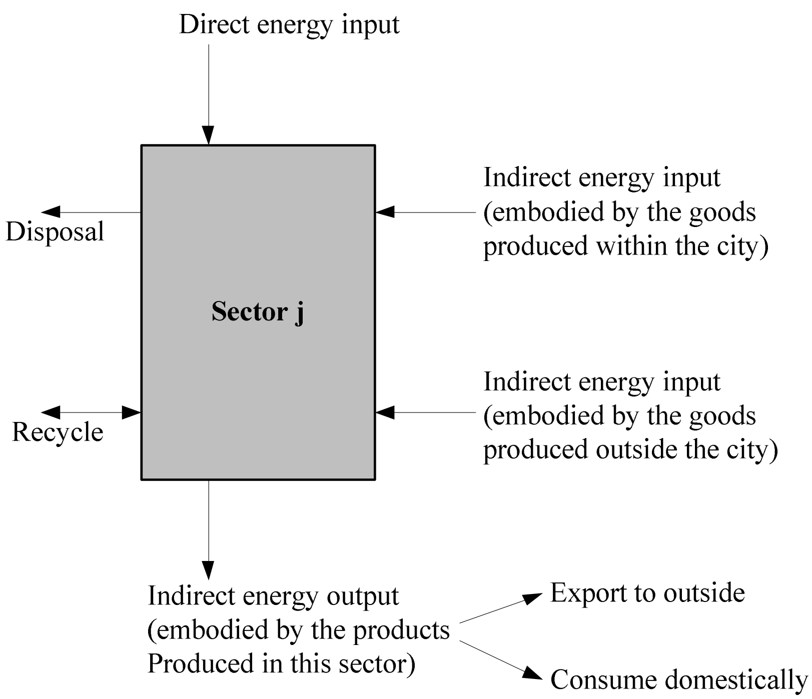


Figure 4.2 Energy balance for sector "j" on an urban scale
(Based on an energy balance for each production sector within the system in **Publication I**)

An IO model is useful in analyzing the economic relationship of links among the major sectors of an economy. This model is a static model or a snap-shot of the economy at a fixed point in time. In IO tables, exchanges of goods and services among industrial sectors are presented in matrix form. Most of the tables actually available are specified in currency units. Energy and resource flows among industries can be analyzed based on the assumption that goods are transferred in direct proportion to their monetary value. A standard static IO model is used to calculate the gross output and factor inputs required to satisfy a given final demand. Alternatively, final demand can be deduced for a given gross output. In most cases, an IO model is based on an IO table similar to that shown in Table 4.1.

An IO table consists of four main parts: transaction table (x_{ij}), value added (V_j), final demand (Y_i), and total output (X_j). Similarly, this kind of model has three basic tables: the transaction table, technical coefficients, and the interdependence coefficients matrix.

Table 4.1 Principle of an IO table

Sectors j i	Intermediate demand or intermediate transaction				Final demand (Y_i)	Total output (X_i)
	1	2	...	n		
1	x_{11}	x_{12}	...	x_{1n}	Y_1	X_1
2	x_{21}	x_{22}	...	x_{1n}	Y_2	X_2
3	x_{31}	x_{32}	...	x_{3n}	Y_3	X_3
:	:	:	...	:	:	:
n	x_{n1}	x_{n2}	...	x_{nn}	Y_n	X_n
Value added	V_1	V_2	...	V_n		
Total output	X_1	X_2	...	X_n		

Because data was limited regarding disposal and recycling in my case study of Bangkok, the model omits these two parts, implying that there is no material recycling or disposal by the sectors. The embodied energy analysis using the IO table is described extensively in **Publication I**, and only the most important parts of this methodology are summarized here. The basic embodied energy model can be expressed as:

$$E_j + \sum_{i=1}^{n} \varepsilon_i x_{ij} = \varepsilon_j X_j \qquad \text{Eq. (4.1)}$$

where E_j is the direct energy input into sector j, ε_i is the embodied energy per unit production of sector i within the urban or city, x_{ij} is the goods or services flow from sector i to sector j within that system, ε_j is the embodied energy per unit production of sector j within the system, and X_j is the gross production of sector j.

Then, solving Eq. 4.1 for ε can be expressed in matrix form. Therefore, the embodied intensity or embodied energy per unit production of each sector can be calculated as:

$$\varepsilon = E * (X - x)^{-1} \qquad \text{Eq. (4.2)}$$

where $(X\text{-}x)^{-1}$ is referred to as Leontief's Inverse Matrix, a fundamental matrix of an IO analysis that identifies any ripple effects among economic sectors. Equations (4.1) and (4.2) represent a closed system. However, cities or urban areas are open systems that exchange goods and services with other areas as well as countries. Based on available data, it was difficult to calculate the embodied energy of imported goods. For this study, it assumed the embodied energy to be equal between goods imported from other areas but within the country and those imported from other countries if those goods were in the same sector; however, the embodied energy was assumed to be different between local and imported goods if different sectors. Therefore, this becomes a single-boundary model with the only boundary between locally produced goods and goods produced from outside of the city (Kaneko et al. 2003; Phdungsilp 2006). When distinguishing between local and imported goods, Eq. 4.1 can be changed to:

$$E_j + \sum_{i=1}^{n} \varepsilon_i x_{ij} + \sum_{i=1}^{n} \zeta_i \overline{x_{ij}} = \varepsilon_j X_j \qquad \text{Eq. (4.3)}$$

where ζ_i is the embodied energy per unit production of imported goods, and $\overline{x_{ij}}$ is the flow of imported goods and services from sector i to sector j. The second term in Eq. 4.3 represents the embodied energy of local goods with intermediate input, and the third term represents the embodied energy of imported goods with intermediate input.

The model in Eq. 4.3 can be applied to a competitive imports IO table that clearly distinguishes between local and imported goods, but not to a noncompetitive imports IO table that does not make this distinction. Therefore, the degree of local self-sufficiency of each sector is used to distinguish between local and imported products (Kaneko et al. 2003). Then, the energy balance becomes:

$$E_j + \sum_{i=1}^{n} \varepsilon_i \gamma_j x_{ij} + \sum_{i=1}^{n} \zeta_i (1-\gamma_j) x_{ij} = \varepsilon_j X_j \quad \text{Eq. (4.4)}$$

where γ_j is the degree of self-sufficiency of product j, which can be expressed as $\gamma_i = X_j / (X_j + M_j)$ while M_j stands for the import of product j.

The essence of the embodied energy is an indirect reflection of the behavior that follows after the use of direct energy. To emphasize, indirect energy use means where the goods are finally consumed. The energy embodied in those goods should be considered as a kind of indirect energy demand. In this case, end-users should somehow take responsibility for the energy use and associated emissions.

As reported in **Publication I**, the direct and indirect energy demand in Bangkok was estimated using IO analysis. Because IO table at the city level was unavailable, the estimation was devised the IO table for Bangkok based on the national level. The IO tables for Thailand have been complied every five years since 1970. The estimation used the IO table for 1998 (NESDB, 2003) to calculate the embodied energy. The IO table for the basic sector classification consists of 180 sectors. For the Bangkok analysis, the study consolidated several intermediate sectors in the national IO table to convert the matrix into 16 sectors, according to Bangkok's economic structure. The study estimated the IO coefficient from the national IO table and converted it into a city level by the Cross-Industry Location Quotient Method (Schaffer, 1976). A detailed breakdown of energy use by sectors in Bangkok cannot be drawn from the statistical data. The amount of data recorded is usually restricted to the total use of the various energy carriers. To overcome this obstacle, the study used the LEAP model to estimate the energy use in various sectors, corresponding to Bangkok's IO table. The estimated breakdown of direct and indirect energy use in Bangkok is presented in Table 4.2.

Table 4.2 Comparison estimated breakdown of direct and indirect energy use in Bangkok in 1998. (Originally presented in **Publication I**)

Sector	Direct energy use (ktoe)	Indirect energy use (ktoe)
Agriculture	9.06	30.68
Food manufacturing	406.93	638.19
Textile industry	23.71	66.77
Saw mills & wood products	3.77	4.93
Paper industries & printing	52.01	95.21
Rubber, chemical & petroleum	46.00	388.19
Non-metallic products	351.53	419.78
Metal, metal product & machinery	75.89	283.48
Public utilities	1,613.47	2,194.04
Construction	112.75	137.31
Trade	1,404.49	5,348.49
Transport and communication	10,242.18	13,043.12
Services	2,285.47	10,528.69
Household consumption	834.00	-
Other manufacturing	37.70	55.68
Total	17,498.96	33,234.56

Through a study of urban metabolism, the primary aim is to understand how the components of urban GHG inventories contribute to urban GHG emissions (**Publication I**), and reported the methodology for this study in **Publication III**. The paper was determined the global warming potential, expressed in carbon dioxide equivalents (t e CO_2), for seven components or urban inventories. GHG emissions from electricity depend on the amount used and the GHG intensity of the supply. The emissions from electricity use for all types of end-use: residential, commercial, industrial, and transportation of the 10 cities were within a range of 0.35 to 3.31 t e CO_2/cap (Table 4.3). Emissions from seven of the 10 cities fell within the narrow range of 2.46 to 3.38 t e CO_2/cap. Toronto's high electricity use was mediated by low intensity, while Cape Town was mediated by high intensity.

Table 4.3 Electricity use, GHG intensity and emissions of the 10 cities (**Publication II**)

	Electricity use (GWh)	Per capita electricity (MWh/cap.)	GHG intensity (t e CO_2/GWh) Incl. line loss	GHG emissions (t e CO_2/cap)
Bangkok	28,500	5.04	550	2.77
Barcelona	7,479	4.66	143	0.67
Cape Town	12,209	3.49	969	3.38
Denver	6,659	11.49	792	9.10
Geneva	2,793	6.46	54	0.35
London	39,237	5.33	469	2.50
Los Angeles	63,919	6.71	368	2.46
New York City	49,567	6.07	497	3.01
Prague	5,506	4.66	710	3.31
Toronto	55,778	10.04	246	2.47

The use of fuels for heating and industry (excluding electricity) corresponded closely to heating degree days (using 18°C base temperature). It also excluded electricity used for heating. The linear fit in Figure 4.3 had a statistically significant (t stat = 4.28) and R^2 of 0.70. Bangkok was above the line, with zero heating degree days below 18°C. Its relatively high fuel consumption was primarily for industrial processes. Denver and Toronto had the greatest energy use at 73.5 and 58.9 GJ/cap., respectively, while Cape Town and Barcelona each used less than 16 GJ/cap. All three U.S. cities were above the best-fit line, perhaps due to larger house sizes or the quality of building envelopes. The GHG emissions for heating and industrial fuel use (Table 4.4) largely followed the same pattern as energy use.

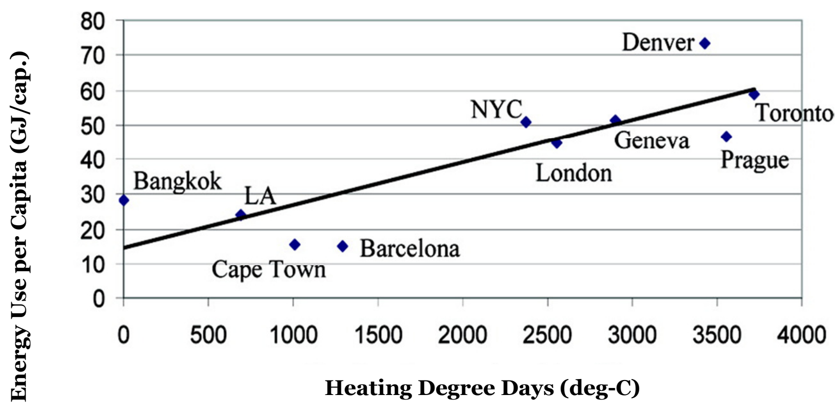


Figure 4.3 Energy use from heating and industrial fuels with heating degree day based on 18°C base temperature (**Publication I**)

The GHG emissions from ground transportation were calculated based on fuel sales data, vehicle-kilometer traveled, or by scaling from a regional level. These three sources were found to differ by less than 5 percent. Table 4.4 presents energy use and GHG emissions from heating and industrial processes and ground transportation. The analysis of the relationship between urban transport energy use and population density showed similar results to previous studies (e.g., Newman and Kenworthy, 1991 and Kenworthy et al., 2001). However, there was variation in GHG emissions between cities of similar densities. For example, Denver's ground transportation emissions were 2.26 t eCO_2/cap., higher than those of Toronto (Table 4.4). Some of this variation may be due to differences in vehicle fuel economy, quality of public transit, land-use planning, and government policy.

Table 4.4 Energy use and GHG emissions from heating and industrial processes and ground transportation (**Publication I**)

	Heating and industrial process		Ground transportation		
	Energy use (GJ/cap.)	GHG (t e CO_2/cap.)	Gasoline (ML)	Diesel (ML)	GHG (t e CO_2/cap.)
Bangkok	28.4	2.49	2,741	2,094	2.27
Barcelona	15.0	0.85	209	266	0.77
Cape Town	15.7	1.15	1,249	724	1.44
Denver	73.5	4.12	1,234	197	6.31
Geneva	51.3	3.45	260	51	1.85
London	44.9	2.58	1,797	1,238	1.22
Los Angeles	24.2	1.37	14,751	3,212	4.92
New York City	50.8	3.13	4,179	657	1.53
Prague	46.8	3.20	357	281	1.44
Toronto	58.9	3.30	6,691	2,011	4.05

By including emissions from air and marine travel, **Publication I** goes beyond the activities that occur in the cities and considers travel between urban centers that happens on a global scale. The paper reports the calculated emissions from combustion of fuels used by airplanes and ships at the cities' airports and harbors, although only airports within the city boundaries are included. The GHG emissions for air and marine generally reflect each city's gateway status. London has the highest emissions for air transportation at 3.12 t e CO_2/cap. The relatively high emissions for Geneva (1.72 t e CO_2/cap.) might reflect its role as an international organizational center.

The total end use emissions for the 10 cities ranged between 4.2 and 21.5 t e CO_2/cap. (Table 4.5). The values for end-use emissions are typical reported by municipal governments. The actual physical emissions that occurred within city boundaries were lower than the emissions attributable to end-use in cities. In most cases the GHG emissions associated with electricity used in cities occurred outside; the main exception was Barcelona, which has natural gas power plants within its borders. It is appropriate to attribute more than the within-boundary emissions to cities, as the consumption activities located in the cities cause emissions. If emissions are to be attributed to cities based on consumption activities, then a full lifecycle perspective should be taken. Beyond the GHGs emitted during the combustion of fossil fuels, there are emissions produced from the extraction, processing and transportation of these fuels to cities. Table 4.5 shows the impact of adding the upstream emissions for heating, industrial and all transportation fuels used for eight cities. The lifecycle emissions were between 7 percent and 24 percent higher than the direct emissions for the cities.

Table 4.5 Total GHG emissions within city measures (**Publication II**)

	Emissions within city (t e CO_2/cap.)	Emissions from end-use activities (t e CO2/cap.)	End-use emissions including lifecycle emissions for fuels (t e CO_2/cap.)
Bangkok	4.8	10.7	Not determined
Barcelona	2.4	4.2	4.6
Cape Town	Not determined	11.6	Not determined
Denver	Not determined	21.5	24.3
Geneva	7.4	7.8	8.7
London	Not determined	9.6	10.5
Los Angeles	Not determined	13.0	15.5
New York City	Not determined	10.5	12.2
Prague	4.3	9.4	10.1
Toronto	8.2	11.6	14.4

4.2. Applying multi-objective optimization genetic algorithms

A comprehensive literature review (**Publication V**) shows that multi-objective optimization genetic algorithms (MOO GAs) are a promising technique to solve multi-objective optimization problems in energy systems analysis. In fact, a large number of MOO techniques have been developed. Some techniques convert the problem to a one with a single objective, which is the classical approach to MOO. A limitation of this approach is that the solutions found are susceptible to the shape of the Pareto front and several runs of the optimization are required to find the Parato set (Deb, 2001; Deb et al., 2002; Coello-Coello, 2006). A new group of MOO techniques has been developed from several research communities, based on the principles of natural evolution. They are often referred to as Multi-objective Evolutionary Algorithms (MOEA). The main advantage is that they deal with multi-objective problems in an ideal way, without aggregating all objectives into a single measure of performance. They handle groups of possible solutions and are able to find several solutions of the Pareto set in a single run (Deb, 2001). They are a powerful method for solving problems with discrete and integer variables, such as energy systems design. The primary reason for using evolutionary algorithms for multi-objective optimization is their ability to deal with a set of possible solutions and finding Pareto optimal solutions.

Optimization is the task of finding a set of design parameters that minimizes or maximizes objective function(s) subject to a group of constraints. Situations with more than one objective are common when designing energy systems. Applying optimization problem to energy systems planning is the structured process of optimizing energy technology types, sizes and/or locations to achieve a set of objective(s) that are subject to a set of constraint(s). MOO addresses the issue of conflicting objective functions. The approach finds a set of solutions by varying the impact of each objective function in the global optimum. (See Chapter 3 for a generic representation of the optimization problem (Eq. (3.1)–(3.4)). However, engineering problems frequently require resolution of conflicting objectives, and MOO provides help solve the problem.

The optimization procedure produces a set of decision variables that allows the minimization or maximization of the objective functions. The decision variables x_i can be continuous, discrete or integer, depending on the nature of variables. The solution to MOO problem is to investigate a set of solutions, each of which satisfies the objectives at an acceptable level without dominating any other solution (Deb, 2001; Alarcon-Rodriguez et al, 2010). In a single optimization problem, a single best solution to a problem can be found, whereas MOO cannot lead to a single optimal solution because objective functions are often conflicting. For example, a decrease in one objective function value may lead to an increase in another one. The MOO process provides a set of optimal solutions, so-called Pareto optimal set. The mapping of the Pareto set in the criterion space results in a Pareto front or tradeoff surface. The Pareto points included in the Pareto optimal front are the points that are better in a tradeoff between different objectives (Daskin, 2010). The Pareto optimal points do best for at least one objective function and at least as good as the other design points in the feasible design space for all other objective functions (Collette and Siarry, 2003).

GAs belong to the category of EAs or nature-inspired search methods. GAs are a powerful tool for solving search and optimization problems based on the principle of genetics and evolution and have been the most popular heuristic approach to multi-objective design and optimization problems (Konak et al., 2006). GAs may use a population of chromosomes or individuals. Chromosomes are mode of discrete units called genes. Each gene controls one or more features of the chromosome. A chromosome corresponds to a unique solution in the solution space. GAs operate with a collection of chromosomes, a so-called population, which is normally randomly initialized. The first population consists of a number of trial solutions to the optimization problem, which are encoded into chromosomes. GAs use crossover and mutation operators to generate new solutions from existing ones. In crossover, typically two chromosomes (parents) are combined together to form new chromosomes, called offspring. The parents are selected from existing chromosomes in the population. The selection is based on fitness, so that offspring inherit good genes. The fitness of an individual is the value of an objective function for its phenotype. For calculating, the chromosome has to be encoded and the objective functions have to be evaluated. The crossover operator is applied iteratively until all pairs of chromosomes of the parents have been picked. The mutation operator provides a search element and introduces random changes into characteristics of chromosomes. This operator is applied to the offspring after crossover and at the gene level. According to Konak et al. (2006), the generic GAs procedure can be given as follows:

- Randomly generate solutions to form the first population and evaluate the fitness of a solution in the population;
- Crossover: generate an offspring population by choosing two solutions from the population based on the fitness values, and then using a crossover operator to generate offspring and add them to offspring population;
- Mutation: mutate each solution with a predefined mutation rate;
- Fitness assignment: evaluate and assign a fitness value to each solution based on objective function value;
- Selection: select solutions from offspring population based on their fitness; and
- If the stopping criterion is satisfied, terminate the search and return to the current population.

In **Publication VI** and **VII**, the MOO GAs were applied for the energy systems and services optimization for a sustainable district in Stockholm. New Albano was used as a case study, which is a planned new urban development area between KTH Royal Institute of Technology and Stockholm University, which serves as a living research laboratory for sustainable urban development in which different solutions can be tested. Albano aims to achieve a neutral balance in CO_2 emissions caused by the energy systems. Albano covers the development of approximately

150,000 m² of educational and research facilities (100,000 m²) and student and visiting scholar housing (50,000 m²). Figure 4.4 shows the overall planned layout of the Albano project. The contribution of this research is to develop a tool for modeling small-scale carbon-neutral energy systems and services for building clusters and urban districts. Only the first construction phase, consisting of five academic and five residential buildings for a total area of 100,000 m², was considered. The research study was conducted in collaboration with Akademiska Hus and Svenska Bostäder, both crucially involved in the development of the Albano project. The developer of the academic buildings is Akademiska Hus, while Svenska Bostäder is responsible for student apartments.

The optimization model used in this research focuses on the sizing and choice of the district energy system only. The design of the buildings was a given, and therefore, the optimization of the building parameters was not considered in this research. The area under analysis included two building clusters: lecture buildings and apartments. Buildings in each cluster have similar functions and were assumed to have similar energy use profiles. Table 4.6 presents the characteristics of the two building clusters.

Table 4.6 Characteristics of building clusters under analysis (**Publication VII**)

	No. of buildings	Floor area (m²)	Apartment	Owner
Lecture building	5	60,000	0	Akademiska Hus
Residential building	5	38,000	680	Svenska Bostäder
Total	10	98,000	680	

The building energy uses were obtained through energy simulation using IDA ICE or from measured data on similar projects. The energy use profiles obtained for the two building clusters were aggregated to obtain the total energy use for the Albano. Table 4.7 shows annual energy uses of the Albano area. The heating profile of the lecture buildings was derived from energy simulation software (IDA ICE). The results include annual ideal heater power and heating coil power, including distribution losses into the buildings. Building simulation also provided the hourly profile of air handling units cooling power. The demand for hot tap water of lecture building was relatively small; therefore, the profile of energy use was taken from the consulting company (ÅF). Electricity use for the lecture buildings was divided into non-HVAC electrical loads and auxiliary electricity for running HVAC equipment. Assumptions about equipment load with relative schedule were taken from Akademiska Hus. For residential buildings, the energy use profiles were obtained from comparative measured data or from typical Swedish values with consultation from Svenska Bostäder.

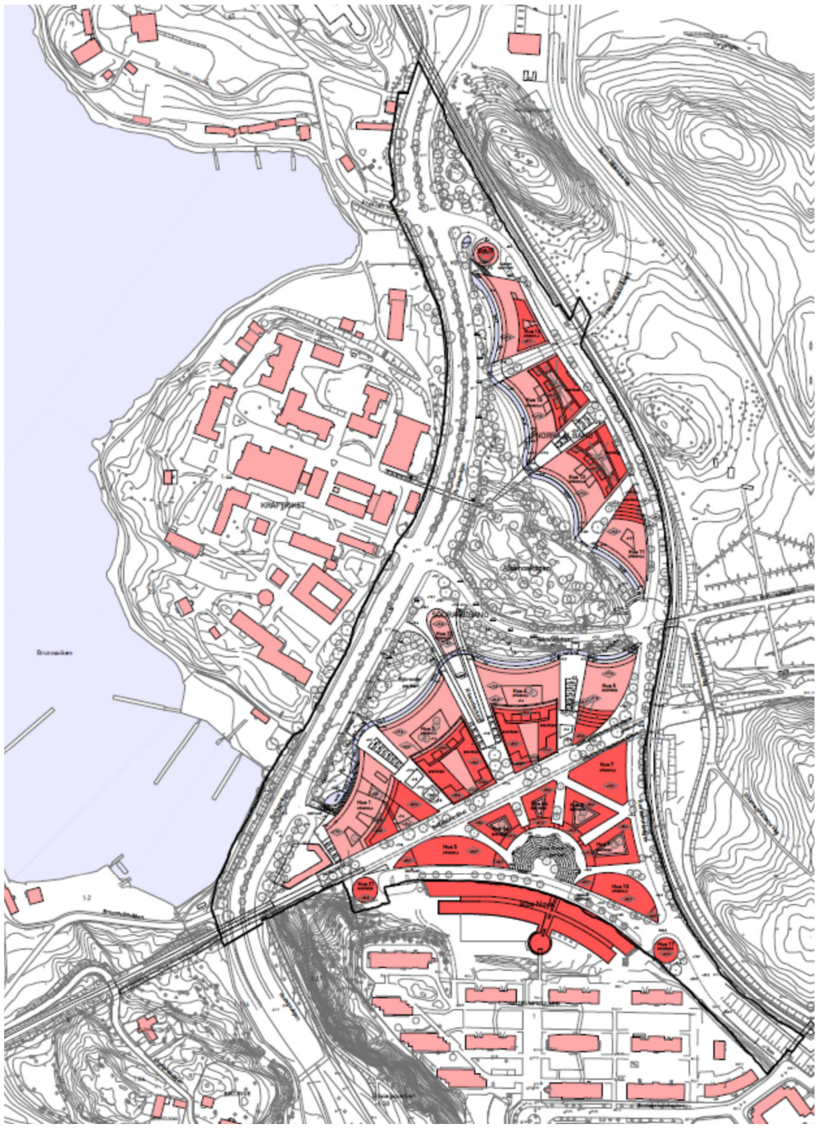


Figure 4.4 Plan layout of the Albano project

Table 4.7 Annual energy uses of the Albano area (**Publication VII**)

	Heating MWh	Hot tap water MWh	Cooling MWh	Electricity MWh	Total MWh
Lecture building	1,371	375	469	1,942	4,157
Residential building	736	812	0	1,945	3,493
Total	2,107	1,187	469	3,887	7,650

Data for economic calculations were gathered from Akademiska Hus, Svenska Bostäder, market analyses of the Swedish Energy Agency, and literature. The currency used was the Swedish Krona (SEK), and currencies used in other published studies were converted based on the yearly average exchange rate of their respective year. Data regarding efficiencies and operations of the energy systems were gathered from manufacturers, literature, and the consulting report. The available technologies were selected by considering the energy sources on the Albano site and the energy need of the buildings. The selection included both commercialized technologies and technologies in the early stage of commercialization. Promising technologies still in the research phases were not included. The available energy systems were represented in the MOO model as decision variables. The optimization resulted in a set of decision variables that allowed the minimization of the objective functions.

The ultimate goal of the study was to assist planners and decision-makers in designing energy systems to achieve carbon-neutral urban districts, while taking into account economic considerations. The three objective functions to be minimized were the non-renewable primary energy use $\left(E_{P,nren}\right)$, the operational global warming potential $\left(m_{CO_2}\right)$, and the levelized lifecycle costs $\left(\overline{LCC}\right)$. The main parameters used for calculating the objective functions are reported in **Publication VII**.

$$f_1 = E_{P,nren} = \sum_i (E_{del,n,i} f_{del,nren,i}) - \sum_i (E_{ex,n,i} f_{ex,nren,i}) \quad [kWh/y]$$

Eq. (4.5)

where i is the energy carriers at the nearby boundary; $E_{del,n,i}$ and $E_{ex,n,i}$ are the annual delivered and exported energy at the nearby boundary; and $f_{del,nren,i}$ and $f_{ex,nren,i}$ are the non-renewable primary energy factors for the delivered and exported of energy carrier i.

$$f_2 = m_{CO_2} = \sum_i \left(E_{del,n,i} K_{del,i}\right) - \sum_i \left(E_{ex,n,i} K_{ex,i}\right) \qquad \left[gCO_{2-eq}/y\right]$$

Eq. (4.6)

where K_i is the CO_2 emission factors for the energy carrier i in gCO_2-eq/kWh. The emission factors account for emissions only during the operation of the systems.

$$f_3 = \overline{LCC} = \sum_s C_{inv,s} A_{n,s} + \sum_s C_{O\&M,s} + \sum_i E_{del,n,i} C_{op,buy,i} - \sum_i E_{ex,n,i} C_{op,sell,i} \quad [SEK/y]$$

Eq. (4.7)

where s stands for the energy systems included in the energy supply configurations. $C_{inv,s}$ is the investment cost of the s-th system; $C_{O\&M,s}$ is the cost for operation and maintenance (without fuels); $C_{op,buy,i}$ and $C_{op,sell,i}$ are the cost factors for buying and selling the i-th energy carrier; and $A_{n,s}$ is the annuity factor for levelizing the costs of the s-th system under a lifetime n and a constant real discount rate i_r.

There were 16 decision variables (see Table 4.8). Available systems and delivered energy carriers were selected based on the energy sources that were on-site and nearby the case study location. The decision variables were both continuous, binary, and discrete variables.

For the Albano case study, two inequality constraints (g_1 and g_2) and two equality constraints (h_1 and h_2) were defined. The constraint functions were defined to limit the total surface of photovoltaic cells (A_{PV}) and thermal collectors (A_{TC}), based on the available roof areas, to limit the combined size of ground-source heat pump for space heating (S_{RGSHP}) and for domestic hot water production (S_{HWGSHP}), and setting to zero for district heating $(E_{del,n,DH})$ and district cooling $(E_{del,n,DC})$ when not required in the test cases. The inequality constraints were used to solve conflicts between on-site technologies, whereas the equality constraints represented the condition of annual delivered district heating and cooling. These constraint functions are expressed as:

$$h_1 = A_{PV} + A_{TC} - 1100 \leq 0 \qquad (m^2) \qquad \text{Eq. (4.8)}$$

$$h_2 = S_{RGSHP} + S_{HWGSHP} - 2 \leq 0 \qquad (MW) \qquad \text{Eq. (4.9)}$$

$$g_1 = E_{del,n,DH} = 0 \qquad (MWh) \qquad \text{Eq. (4.10)}$$

$$g_2 = E_{del,n,DC} = 0 \qquad (MWh) \qquad \text{Eq. (4.11)}$$

Table 4.8 Decision variables for the Albano case study (Based on **Publication VI** and **VII**)

Decision variable	Type	Range or acceptable values
Ground-source heat pump size for space heating and cooling (kW_{th})	Integer	[0,2000]
Ground-source heat pump size for hot water (kW_{th})	Integer	[0,2000]
Photovoltaic cells area (m^2)	Integer	[0,11000]
Solar thermal collectors area (m^2)	Integer	[0,11000]
Biomass boiler size (kW_{th})	Integer	[100,2000]
Reciprocating engine size (kW_{el})	Integer	[10,3000]
Molten carbonate fuel cell size (kWc)	Integer	[240,2800]
Absorption chiller size (kWc)	Integer	[100,2000]
Absorption chiller existence (-)	Binary	{0;1}
Anaerobic digester existence (-)	Binary	{0;1}
On-site wind turbine number (-)	Discrete	{0,1,2,3,4,5,6,7,8,9,10}
On-site wind turbine size (kW)	Discrete	{0.16; 0.49; 0.77; 0.8; 0.93; 2.2; 4; 13.1; 25.3; 30; 60}
Nearby wind turbine size (kW)	Discrete	{0; 150; 250; 500; 600; 601; 800; 1300; 1650; 2000}
CHP type [0: no CHP, 1: reciprocating engine, 2: molten carbonate fuel cell]	Discrete	{0; 1; 2}
CHP fuel type [1: natural gas, 2: biogas]	Discrete	{1; 2}
Biomass boiler fuel type [0: no boiler, 1: pellets, 2: wood residues]	Discrete	{0; 1; 2}

The solution strategy of the MOO GA was implemented using MOBO and Matlab environments. The optimization process was implemented on MOBO, while the objective function calculation was done using Matlab script. At each generation, MOBO creates a population assigning values to the decision variables. Then, for each individual, Matlab calculates the energy balance for a whole simulated year, using a steady-state method with an hourly resolution, and computes the objective function values. Based on these values, MOBO initiates the next generation. The algorithm used was a NSGA-II (An improved Non-dominated Sorting Genetic Algorithm-II). The GA parameters were crossover probability (0.80), mutation probability (0.015), number of generation (100), and population size (50). The optimization procedure resulted in a set of decision variables that allowed the minimization of the objective functions.

The main advantage in using MOBO instead of implementing the whole optimization procedure in a coding environment, such as MatLab, is that the user can take advantage of the user-friendly graphical interface and the built-in algorithms. In addition, the majority of algorithm parameters are predefined; therefore, users provide only a limited number of parameters while having access to the powerful functions of advanced engineering programming.

Following discussions with stakeholders (Akademiska Hus and Svenska Bostäder), the optimization problems were solved for four cases: (i) all technologies, (ii) no wind turbines, (iii) no district heating and cooling, and (iv) no district heating and cooling and no wind turbines. The Pareto fronts for the four cases are reported in **Publication VI** and **VII**. Figure 4.5 provides an example of the Pareto front of Case I. Table 4.9 presents an example of the selected results for the Case I (all technologies). Overall, the findings showed that significant CO_2 emission reductions and energy savings could potentially be achieved with an appropriate combination of energy sources. Promising solutions were PV, biomass, and wind turbines at nearby locations. Fuel cells fuelled with biogas appeared to be very promising technology to reach the energy balance in a cleaner way, but at high lifecycle costs. Reciprocating engines were optimal solutions only at small and medium sizes. Wood or pellet boilers of variable sizes appeared in almost all optimal cases, indicated that they could be used as a backup technology. Ground-source heat pumps performed better in lifecycle costs.

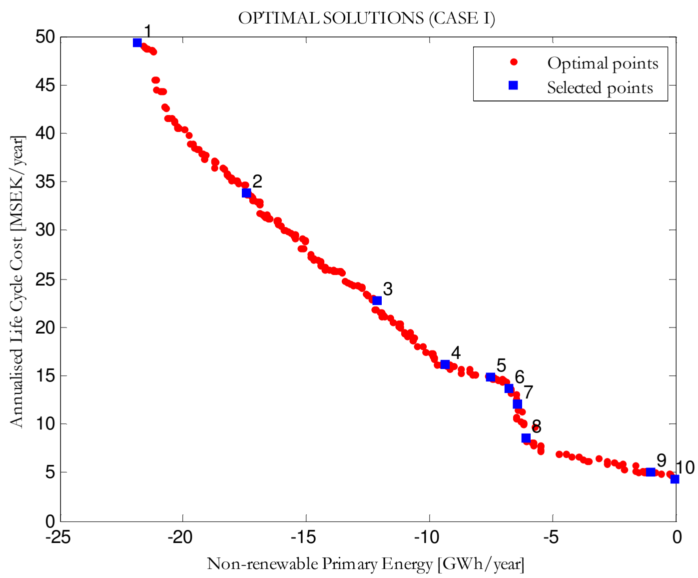


Figure 4.5 Pareto front of Case I and selected solutions (**Publication VII**)

Table 4.9 Selected results for Case I (**Publication VII**)

Albano – Case I: All technologies				
Solution	Unit	1	5	10
Non-renewable primary energy	MWh/y	-21853	-7491	-15
CO_2-eq emissions	t/y	-426	-132	4
Levelized lifecycle costs	MSEK/y	49	15	4
Heat Pump	kW_{th}	0	0	1001
Annual heating production	MWh/y	0	0	2064
Annual cooling production	MWh/y	0	0	443
Heat Pump (hot water)	kW_{th}	0	2	18
Annual hot water production	MWh	0	18	154
Solar Thermal	m^2	43	430	22
Annual production	MWh/y	17	100	9
Biomass Boiler	kW	388	1309	421
Annual production	MWh/y	7	1977	1067
Peak power	kW	158	1103	421
Fuel type	-	Pellets	Pellets	Pellets
CHP	-	Yes	Yes	No
CHP type	-	MC Fuel cell	MC Fuel cell	-
Size	kW_{el}	2269	240	-
Fuel type	-	Biogas	Biogas	-
Electricity generation	MWh/y	8850	2028	-
Heating generation	MWh/y	2090	67	-
Hot water production	MWh/y	1181	1133	-
Anaerobic Digester	-	No	No	-
Annual gas production	MWh/y	0	0	0
Absorption Chiller	kWc	1996	1918	-
Annual production	MWh/y	466	0	0
District Heating	MW_p	No	No	No
Annual delivered	MWh/y	0	0	0
District Cooling	MW_p	0	1	1
Annual delivered	MWh/y	4	470	27
Photovoltaic Area	m^2	10892	3129	1054
Annual generation	MWh/y	1331	382	129

Table 4.9 (continued)

Albano – Case I: All technologies				
Solution	Unit	1	5	10
Wind On-site	number *kW_p	10*60	10*60	4*0.77
Annual generation	MWh/y	699	699	2
Wind Nearby	number *kW_p	1*2000	1*2000	1*2000
Annual generation	MWh/y	4811	4811	4811
Delivered Biomass	MWh/y	8	2196	1186
Delivered Gas	MWh/y	18062	4140	0
Delivered Electricity	MWh/y	0	8	839
On-site and nearby electricity	MWh/y	15692	7921	4942
Exported electricity	MWh/y	11705	3988	908
O & M Cost	MSEK/y	4	3	1
Energy Cost	MSEK/y	28	7	1
Savings	MSEK/y	12	4	1
Initial Investment Cost	MSEK	215	98	47

5. Discussion and Conclusions

Urban areas are centers of consumption, innovation, education, employment, and commerce—the heart of the modern society. The study of 10 global cities has shown how and why GHG emissions differ in a wide variety of cities. Urban metabolism, a central concept in the scientific study of cities, helps to understand the flows of energy and materials. The implications of an urban metabolism study can improve resource use efficiency and climate change mitigation. This dissertation makes several contributions to the quantification of energy use and GHG emissions for cities. An inventory procedure based on the city's metabolism encourages cities to recognize the impact of urban activities on emissions.

Analyses of energy and energy-related emissions may explicitly discuss direct energy use, but neglect to consider the energy embedded in consumable goods and services. Even if energy use and energy-related emissions are measured, a typical approach is to encompass only the direct energy use within the urban area. However, primary production is generally located outside of cities, including goods manufacturing. The true energy use must be clarified before urban development paths are explored. Energetic urban metabolism, based on embodied energy analysis, provides a means to quantify both direct and indirect energy use.

Indirect energy use can identify the degree to which the city depends economically on the outer regions, and especially can highlight the city's environmental load displacement to the outer region. In this dissertation, the study used Bangkok as a case study in which to analyze direct and indirect energy use by 16 economic sectors. It was found that indirect energy use was more significant than direct energy use in Bangkok, which implies that city has a great reliance on the outside in terms of energy demand. The analysis based on urban metabolism demonstrated the complex energy flows in an urban area, which can be helpful for systematic policy making. The analysis also provides a holistic picture of urban energy use, and correspondingly, indicates that energy strategies should be based on such a systems approach.

Urban districts have become the point of energy analysis in recent years. In the second phase of this dissertation, the study examined the optimization of energy system and service for an urban district in Stockholm. Research focusing on optimization at the district level with a comprehensive assessment is still limited compared to other fields, such as building design. But there is a need to move beyond green buildings to a district scale. Traditionally, energy system and service optimization was considered a single-objective problem, in which the main concern was to minimize costs. However, the optimization problem in this dissertation had a wide range of technical and economic objectives, because energy systems design is in essence a multi-objective problem.

In a case study of Albano in Stockholm, the study applied MOO GAs to optimize the design of energy systems and services. A wide range of possible energy supply systems were included as design variables, such as wind turbine, solar thermal collector, solar PV, ground-source heat pump, fuel cells, biomass boiler, CHP, and district heating and cooling. Three objective functions were minimized: non-renewable primary energy, the annual operation GHG emissions, and the total levelized lifecycle costs. The optimization was implemented for four cases: (i) all technologies, (ii) no wind turbines, (iii) no district heating and cooling, and (iv) no district heating and cooling and no wind turbines. The findings showed that fuel cells appeared to be promising technologies to reach the energy balance in a cleaner way but at high lifecycle costs. Reciprocating engines were optimal solutions at small and medium sizes, and wood or pellet boiler of variable sizes appeared in almost all optimal cases. PV panels were often present at large scales. Ground-source heat pumps performed well in terms of lifecycle costs. District heating appeared in only a few optimal solutions, except to cover peak load. In addition, the findings provided understanding of the tradeoffs among the conflicting objectives and a selection of energy system alternatives.

The findings and implications of this dissertation contribute to the understanding of urban energetic metabolism and the development of tool for energy system and service optimization. The methodologies presented in this dissertation can be used to reduce the energy use and energy-related emissions in urban areas at both macro and district levels in other countries. This dissertation bridges the gaps on the view of the lack of research and method between urban and building scales with the focus on district scale. The study on the macro and district scales of urban areas is significant research area because urban areas are distinguished by various districts within their boundaries. Different districts have unique opportunities to design energy systems and provide energy services. This work can complement to the existing models and tools as a means to move towards low-carbon cities.

6. Future Research

This dissertation mainly utilized urban energetic metabolism and the MOO model. Important areas of future research are to investigate a full urban metabolism of a city, and to integrated a MOO model with visualization for better understanding and communicating.

Use of urban metabolism should be encouraged to quantify the metabolic flows at different scales from the district to the city level. Urban metabolism is useful for understanding how an urban area/city uses energy, water, material, and nutrients efficiently. The metabolism approach is basically a purely biological view, but urban areas are much more than a mechanism for processing resources and producing wastes. They also create human opportunities. Therefore, the extended urban metabolism should include the issues of livability, such as health, employment, income, education, and leisure activities. Future studies should involve the economic and social aspects of sustainability along with environmental sustainability. This extended metabolism can be applied as part of urban revitalization, transforming or changing areas in existing cities.

The MOO model for energy systems and services should be further developed. Further work should include the exergy analysis in the optimization model, which can lead to the analysis of energy quality management for more efficient energy use. Regarding the optimization tool, future studies should compare the performances and results of different optimization algorithms. Because MOO problems are complex, analysts must deal with a large quantity of data, especially in data post-processing, and the optimization outcomes are not easy to understand. The emerging research area, such as Big Data Engineering, may provide visualization and understanding of the variable correlation and tradeoff relationships between different objectives, as well as the ability to present findings in an easier and more understandable way.

Energy informatics can be enhanced to support communicating and benchmarking related to energy performance of urban areas both in the design and operational phases. Visualization increases the transparency of results and the understanding of interactions between users and energy systems. Computer-generated visualization is a powerful tool that enables engineers, developers and policy makers to better understand the implications of energy systems and services, explain a range of technological options, and analyze the effects of energy strategies. There is a need for a tool that offers holistic energy visualizing not only from the building perspective, but also at the urban district scale. As a future work, **Publication VIII** presents a conceptual framework for integrating energy systems, infrastructure, and services optimization with a visualization and simulation platform for low-carbon precincts. It describes the vision and architectural design for the integrated framework, which is expected to serve as a next-generation approach to managing energy services, carbon emissions, and efficient resource use in the built environment. The framework also will enhance understanding of urban energy systems and services and the analysis of energy competitions between resources and services.

7. Summaries of Appended Publications

Publication I: Energy Analysis for Sustainable Mega-Cities

The significant increase in the use of energy and other resources as well as the contribution of GHG emissions is expected to take place in cities within Asia, especially in mega-cities. This publication was focused on the dynamics of energy utilization in Asian mega-cities, and ultimately aimed at providing strategies for maximizing the use of renewable energy in large urban systems. The objective of the study was to provide an in-depth understanding of the complex energy systems in urban mega-centers. An initial analysis was complemented by a detailed study of the current situation and future outlook for the city of Bangkok, Thailand. An integrated approach applied to this study included identification of the parameters that affect the energy utilization in cities and a detail analysis of energy flows and their various subsystems. An urban metabolism approach was applied to analyze the energy flows in selected Asian mega-cities. The approach was employed to measure the majority of the energy embodied in the flows of goods and services of those cities. LEAP model was used to perform Bangkok's energy modeling. In addition, a Multi-Criteria Decision-Making (MCDM) approach has been developed to assess whether or not the energy systems meet the sustainability criteria. In a Bangkok case study, a range of policy interventions are selected and how these would change the energy development in Bangkok by the year 2025 was examined. Different policies can be grouped by the demand sectors. The only supply-side policy considered the target of having 10 percent of electricity generated from renewable sources. The proposed energy scenarios were evaluated using the MCDM approach to rate their sustainability.

Publication II: Greenhouse Gas Emissions from Global Cities

The world's population is now over 50 percent urban, and cities make an important contribution to national GHG emissions. Many cities are developing strategies to reduce their emissions. Cities may also learn by examining and adapting the strategies of other cities. However, it is necessary for cities to have reliable GHG inventories and to understand how and why their emissions differ. A central concept in the study of this paper is urban metabolism. The objective of this paper is to understand how and why urban GHG emissions differ. The global warming potential, expressed in carbon dioxide equivalents (t CO_2eq) was determined for seven components of urban inventories: electricity, heating and industrial fuels, industrial processes, ground transportation, aviation, marine, and waste. Emissions were calculated for ten cities (or metropolitan regions), which vary in population from 432,000 to 9,519,000; hence they are compared in per capita terms. Some are cities which have been the subject of urban metabolism studies: Los Angeles County, Greater Toronto, Geneva Canton, Greater Prague, and Cape Town. Others have had their urban energy use or GHG emissions previously quantified: Denver City and County, New York City, Greater London, Barcelona, and Bangkok. Results are first given of GHG emissions from end-use perspective, which include those that occur outside the boundaries of the cities such as from power generation, air and marine. In totaling the emissions for each city, two further measures are given: the emissions that only occur within the borders of the cities and a broader measure including upstream life-cycle emission for fuels used in the cities. The total end-use emissions for the ten cities range between 4.2 and 21.5 t CO_2eq/cap.

Publication III: Methodology for Inventorying Greenhouse Gas Emissions from Global Cities

As centers of wealth and creativity, with high population densities and economies of scale, cities play a significant role in tackling global climate change. Many cities have established GHG emission inventories using the simple pragmatic approach. However, there are several technical issues with GHG inventories for cities, for example lack of full life-cycle perspective, problem with defining spatial and temporal context, and issue of assigning emissions by political jurisdiction. This paper aimed to develop and test a more robust and transparent inventory procedure. The research was undertaken a comparative study of GHG emissions from a group of global cities. To accommodate the effects of spatial and life-cycle boundaries, three measures of overall emissions were used. These are: (i) physical emissions within the boundary of the city, (ii) single process emissions from end-use activities associated with the city's metabolism, and (iii) extended life-cycle emissions associated with the city's metabolism. This paper has made several contributions to the quantification of energy use and GHG emissions from cities. The findings has shown that life-cycle emissions are a more comprehensive measure of a city's contribution to global climate change than the within city emissions and direct emission measures.

Publication IV: A Proposal of Urban District Carbon Budgets for Sustainable Urban Development Project

Urban sustainability is growing importance in energy and climate research. Cities are responsible for as much as 80 percent of global GHG emissions, while they are also significantly impacted by climate change. Urban districts can be a testing ground for new solutions. Urban areas are often identified as sources of emissions; they are also part of the solution. Urban areas can be assigned an emission budget and keep local emissions within this figure. This paper describes a framework for carbon budgets with a focus on urban district level. The urban carbon budget is a mechanism for embedding long-term total emission restrictions into an urban economy. The objectives are to propose the concept of urban carbon budgets and to highlight the application to urban development projects. The paper proposed five alternative carbon budget allocation methods: (i) allowance auctioning, (ii) the equal share approach, (iii) the per capita approach, (iv) the economic approach, and (v) the consumption-based approach. The carbon budget approach can be an effective policy instrument for sustainable urban development projects.

Publication V: Distributed Energy Resource Systems towards Carbon-Neutral Urban Development: A Review and Application

The building sector consumes large amounts of energy resources, while also producing large quantities of waste and pollution. Buildings usually have a long life span, which means that its impacts on the environment are long and continuing. The distributed energy resource (DER) is often understood as an integrated and decentralized energy system. DER also refers to small decentralized power generating technologies that can be combined with energy management and energy storage systems, and located close to the point at which the energy is converted to energy services. DER systems offer a promising opportunity for sustainable urban/district development. This paper aims to explore how DER systems have been applied to urban/district development context. This work adds to the existing body of knowledge on the issue of local renewables and DER systems and the application in an on-going urban development project. This study differs from the previous studies in that it provides a comprehensive review of DER systems and attempts to classify areas of practice along with the application of DER systems in a case study.

Publication VI: Optimization of Energy Supply Systems for a Sustainable District in Stockholm using Genetic Algorithms

The energy systems design is the task of selecting a set of technologies for energy conversion and distribution to meet the energy demand. The design of a district energy system involves a search for solutions that achieve several objectives. The design objectives are often conflicting against each other. This kind of problem belongs to a class of multi-objective optimization (MOO) problems. MOO problems can be better solved by the optimization process using genetic algorithms (Gas). The aim of this paper is to apply MOO using Gas to find optimal combinations of energy systems at the district level. The solution strategy is based on four steps: (i) data gathering, (ii) optimization problem formulation, (iii) implementation, and (iv) data post-processing. The optimization has been solved for four cases: (i) all technologies, (ii) no wind turbines, (iii) no district heating and cooling, and (iv) no district heating and cooling and no wind turbines.

Publication VII: Energy System and Service Optimization for Building Clusters of New Urban Development: Applying Multi-objective Genetic Algorithms

The urban development has high impacts on resource uses and global carbon emissions. The future urban development should be planned to utilize local energy sources and maximize the use of renewable energy resources. Building clusters are a group of buildings with varied uses that constitute a functional unit or neighborhood district in terms of energy use and heat and power generation. There is a high potential of energy sharing between buildings in the cluster. This paper presents the development of the optimization model based on multi-objective optimization using genetic algorithms (MOGA) to find the optimal mix of technologies to cover the energy requirements at the building cluster level. The objective functions to be minimized are non-renewable primary energy use, emissions in the operational phase, and levelized life-cycle costs. The problem has 16 design variables. The optimization process was implemented on MOBO (Multi-Objective Building Performance Optimization), while the objective function was calculated using Matlab. The algorithm used is NSGA-II. The optimization model was applied to a case study (Albano), which is a planned new urban development area between KTH Royal Institute of Technology and Stockholm University. The case study has two building cluster: lecture building and residential buildings.

Publication VIII: A Framework for Integrated Energy Systems, Infrastructure, and Services Optimization with Visualization and Simulation Platform for Low-carbon Precincts

There is a growing interest in improving the energy performance of urban areas to reduce environmental impacts while maintaining economic competitive capacity and quality of life. The energy informatics can be enhanced to support decision-making, communication and benchmarking related to energy performance. This paper focuses on the development of an optimization tool and to visualize the findings in a 3D environment. The framework developed was based on techniques of three domains: building energy modeling, energy system and service optimization, and geographical information systems (GIS). This research is design to interface with the MUtopia simulation platform tool that supports the assessment of urban sustainability metrics at different scales. The integrated platform would offer a next generation approach to assist the design, analysis and evaluation of energy, carbon emissions and resource consumption in the built environment.

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