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Energy Analysis for Sustainable Mega-Cities

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Licentiate Thesis

School of Industrial Engineering and Management
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ABSTRACT

Cities throughout Asia have experienced unprecedented economic development over the past decades. In many cases this has contributed to their rapid and uncontrolled growth, which has resulted in a multiplicity of problems, including rapid population increase, enhanced environmental pollution, collapsing traffic systems, dysfunctional waste management, and rapid increases in the consumption of energy, water and other resources. The significant energy use in cities is not very well perceived in Asian countries. Although a number of studies into energy consumption across various sectors have been conducted, most are from the national point of view. Energy demand analysis is not considered important at the level of the city. The thesis is focused on the dynamics of energy utilization in Asian mega-cities, and ultimately aims at providing strategies for maximizing the use of renewable energy in large urban systems.

The study aims at providing an in-depth understanding of the complex dynamics of energy utilization in urban mega-centers. An initial general analysis is complemented by a detailed study of the current situation and future outlook for the city of Bangkok, Thailand. An integrated approach applied to the study includes identification of the parameters that affect the utilization of energy in mega-cities and a detailed analysis of energy flows and their various subsystems, including commercial, industrial, residential and that of transportation. The study investigates and evaluates the energy models most commonly used for analyzing and simulating energy utilization. Its purpose is to provide a user-friendly tool suitable for decision-makers in developing an energy model for large cities. In addition, a Multi-Criteria Decision-Making (MCDM) process has been developed to assess whether or not the energy systems meet the sustainability criteria.

A metabolic approach has been employed to analyze the energy flow and utilization in selected Asian mega-cities, including Bangkok, Beijing, Shanghai, and Tokyo. The approach is applied to measure the majority of indirect energy flows or the energy embodied in the flows of goods and services involving the residents of those cities. Since the function of cities is to serve the lives of the residents, indirect energy consumption could be regarded as being of equal importance as that of direct energy use. The essence of embodied energy is that an indirect reflection upon behavior following direct energy consumption. It can illustrate how a city relies on the outside, for example other cities, countries, etc. and provides some interesting information that cannot be easily drawn from the direct energy demand. The study reveals that the indirect energy demand is more significant than the direct energy demand in Bangkok, Shanghai, and Tokyo, while direct energy demand is greater than the indirect energy demand in Beijing. This can be explained by the fact that Bangkok, Shanghai, and Tokyo have a greater reliance upon the outside in terms of energy demand.

The Long-range Energy Alternative Planning (LEAP) system has been selected to perform Bangkok energy modeling. 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 is examined. Different policies can be grouped by the sectors analyzed. The only supply-side policy considered meets an existing target of having 10% of electricity generated from renewable sources. The study period for the model started in 2005 and ends in 2025, with the year 2000 taken as the base year. The proposed scenarios were evaluated using the MCDM approach to rate their sustainability. Team members found that this method provided a methodology to help decision-makers to systematically identify management objectives and priorities.

Keywords: Asian mega-cities; energy demand; metabolism of cities; energy modeling; sustainable energy; energy planning; renewable energy; Multi-Criteria Decision-Making

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IV. Phdungsilp A., *Bangkok energy modelling for the promotion of sustainable city energy development*, Manuscript submitted to Energy Policy.

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1. INTRODUCTION

1.1. Background of the thesis

Cities have been considered as the centers of cultural, social and technological innovation, economic development, inventions and their applications, and also the political power of a particular country. After the industrial revolution, urban areas in different parts of the world grew rapidly due to their increased populations. The most important growth of urban areas is the formation of so-called mega-cities or the city of human settlements of about or above 10 million inhabitants. These cities are the magnets for people, functions, organizations, and the structuring of the country and the world around their social and economic dynamics. They always interact on local and global levels. Therefore, the impact of mega-cities on the natural environment is being felt far beyond their geographic boundaries.

Mega-cities are not considered to be just cities of a large size. They have a strong internal coherence. They are not a juxtaposition of different areas. Most often they are fundamentally one single area. They consist of a complex unit of production for consumption, a large labor market, a specific system of power and extreme social and cultural differentiation. Functions and activities performed within their territories are spatially interconnected. Their territories are used daily by millions of people within its boundaries. As for the rest of the country, it increasingly becomes the hinterland for the functions and power that emerge from mega-cities (Castells 1993).

The previous decade has seen Asia become the key region in need of environmental protection. The region has become increasingly vulnerable to environmental damage and ecological disasters caused by rapid urbanization, population growth, and the expansion of industrial activities. As a result of the growing urban population and its increased levels of consumption (i.e. energy, water, and other resources), negative effects have been brought upon the environment.

A significant increase in the consumption of energy and other resources as well as the contribution of Greenhouse Gas (GHG) emissions is expected to take place in cities within Asia, especially in mega-cities. These cities that have rapidly expanding populations are enjoying higher living standards and more material affluence than people in rural areas and smaller cities. The problems mega-cities face today will be similar to those that smaller cities face in the future. Therefore their actions may provide models for other cities (IGES 2004). Hence, a study of mega-cites may provide a good basis for governments to create comprehensive action strategies to promote sustainable development. However, the strategies will differ from city to city and no single universal strategy will work in all situations.

Cities in rapidly industrialized regions of Asia face many tasks related to economic and environmental issues. So far, the energy use and emissions are not well understood. Urban authorities are largely not aware of the multiple benefits of energy management and carbon dioxide (CO_2) reduction. The literature has shown that there has been limited research on the management of energy within the cities. The studies were not considered important at the city level until recently, and most energy related decisions were made at the national level (IGES 2004). Due to growing concerns about climate change, efforts are being made to understand the use of energy at the city level in greater detail. It is important to integrate energy analysis with urban development. The efforts should be directed towards supporting cities in understanding the problem and identifying possible measures for implementation. The priority for a systematic approach is an analysis of the energy flow into the city, the driving forces behind energy use, and associated policy measures. In this regard, it is imperative to establish a comprehensive study at the city level and to prepare appropriate measures for responding to specific local needs and conditions.

An appropriate response to a city's energy and environmental problems requires an analysis of past and present situations, formulation and implementation of remedial measures, development and transfer of technologies and enhancement of human capacity. Although, at the national as well as at the city level, authorities wish to learn from a sensible practical model in order to improve their local development, there has been little progress due to the limited exchange of well-analyzed information. There is a need for the relevant analysis of experiences, successes, and failures in urban energy use from different cities, providing a systematically arranged policy that is truly useful for national and city authorities in developing their policies, plans, and programs (IGES 2004). In order to provide relevant information for policy-makers at different levels of government and agency, information gained from the studies should be properly analyzed and should provide examples of policy alternatives or demonstrate policy guidelines for effective measures that are generally applicable.

1.2. Sustainability and mega-cities

The term mega-city was created by the United Nations in mid-1980 in a study addressing issues generated by rapid urbanization and a growing population as experienced by cities. The common issues relating to urban energy use include transportation, building and housing, public health and safety, and an increase in the standard of living. Therefore, the development of mega-cities and their effects upon future human society cannot be neglected.

In 1800 only 3% of the world's population lived in cities later in 2000 more than half of the world's population lived in urban areas. Big cities are growing at unprecedented rates and sizes. UN projections show that by the year 2015 there will be 36 mega-cities and 23 of them in Asia alone (UNPF 1997). UN data shows that mega-cities are growing faster than any other size of city (Salas 1986; UN 1995). In the past 30 years the urban population in developing countries has tripled, and projections suggest that the urban growth will continue into the next century. Urban areas in Asia, Africa, and Latin America are growing at an average rate of one million people per week (UNDP 1995; 1996).

In the process of urbanization, the urban concentration has been shifting from industrialised nations to developing ones. Table 1.1 shows the top ten largest cities in 1950, 2000, and 2015. Today the world has 22 mega-cities, and 18 are in developing countries, mostly in Asia and Latin America. Estimation was predicted that from 1950 to 2050 the urban population in the Third World countries will increase almost 16 times from under 200 million to 3,150 million people (UN 1985; 1995; 2002). So far, most of the discussion regarding mega-cities has focused on their problems such as air pollution, modes of transport, etc. rather than on seeing the city as a large consumer of energy, natural resources, goods and services, for example Girardet 1996; Rogers 1997; Moavenzadeh et al. 2002.

The concept of sustainable development has been applied to the so-called sustainable city. However, this concept is difficult to define precisely because it refers to process rather than to end-point. Cities can vary in their definitions and classifications depending on the issues being considered. In fact, there are several terms that apply to a city, most often they refer to conceptual, physical and administrative boundaries, including urban area, rural area, municipality, metropolitan, city, etc. In some cities the buffer zone, such as sub-urban/peer-urban, can be included within the definition.

Furthermore, to analyze the city it cannot be looked at as a single and self-contained. A city requires a flow of natural resources, services, people, information, etc. for its different stages of development. These flows are often uncontrollable and in many cases have benefits but in others problems such as local pollution, traffic congestion, and waste water (SEI 2003).

Table 1.1. Ten largest cities in the world in 1950, 2000, and 2015 (UN 2002).

	Population (millions)
1950	
New York, USA	12.3
London, England	8.7
Tokyo, Japan	6.9
Paris, France	5.4
Moscow, Russia	5.4
Shanghai, China	5.3
Essen, Germany	5.3
Buenos Aires, Argentina	5.0
Chicago, USA	4.9
Calcutta, India	4.4
2000	
Tokyo, Japan	26.4
Mexico City, Mexico	18.4
Bombay, India	18.0
Sao Paulo, Brazil	17.8
New York, USA	16.6
Lagos, Nigeria	13.4
Los Angeles, USA	13.1
Calcutta, India	12.9
Shanghai, China	12.9
Buenos Aires, Argentina	12.6
2015	
Tokyo, Japan	26.4
Bombay, India	26.1
Lagos, Nigeria	23.2
Dhaka, Bangladesh	21.1
Sao Paulo, Brazil	20.4
Karachi, Pakistan	19.2
Mexico City, Mexico	19.2
New York, USA	17.4
Jakarta, Indonesia	17.3
Calcutta, India	17.3

In general, sustainable development is defined as a constraint upon present consumption in order to ensure that future generations will inherit a resource base (or a set of opportunities) that is no less than the inheritance of the previous generation. Moavenzadeh et al. (2002) argued that sustainability concerns issues of both technology and equity. However, there are many more definitions. The following section gives an overview of how sustainable cities are defined by different organizations in different geographical regions.

In Sweden, the Swedish Research Council for Environment, Agricultural Science and Spatial Planning (Formas) defines the sustainable city as a society in which economic development, social welfare and cohesion are united with a healthy environment. The society satisfies its current needs without jeopardizing the ability of coming generations to satisfy theirs (Formas

2004). This vision is formulated in a governmental paper, which is based on the Brundtland report.

The Regional Environmental Center for Central and Eastern Europe (REC) refers to the sustainable city as one that aims to ensure adequate availability of resources, (re-) utilization, social comfort, equity, economic development and prosperity for future generations (REC 2003). They have also provided a list of some important issues that must be taken into consideration, including minimizing urban sprawl, use of renewable or recyclable resources, minimizing material output and its ecological effects, democracy, etc.

The URBAN 21 Conference in Berlin developed the definition of a sustainable city. They defined sustainable urban development as improving the quality of life in a city, including ecological, cultural, political, institutional, social and economic components without leaving a burden on future generations (URBAN 21).

The concept of sustainable cities was defined by Development Alternatives in India in response to the conditions in India. They said that a sustainable city means one that is able to provide basic needs for the populace along with the necessary infrastructures of civic amenities, health and medical care, housing, education, transportation, employment, good governance, etc. It should take care of the population's needs, all sections of society without discrimination (Development Alternatives, India 2003).

In South America Fundacion Ambiente y Recursos Naturales (FARN) which is a non-profit organization in Argentina whose mission is to promote sustainable development. FARN defines a sustainable city as a city that integrates environmental dimensions into the social and economic sectors in order to meet the needs of present generations without compromising those of the future. Thus, a sustainable city requires institutions and systems that can facilitate public participation in decision-making regarding the use and management of the environment (FARN 2003).

The Sustainable Cities Programme which is a joint facility of the United Nations Centre for Human Settlements (UN-Habitat) and the United Nations Environment Programme (UNEP), has defined a sustainable city as a city where achievements in social, economic, and physical development are made to last. A sustainable city has a lasting supply of the natural resources on which its development depends, (the use of a sustainable yield) and a lasting security from environmental hazards which may threaten development (although allowing for acceptable risk). The planning and management for a sustainable city development requires agreements and coordinated action by a variety of public, private, and popular sector involvement at the individual, community, city, and national level (UNDP 2003).

In general, sustainability is a much more subjective concept. It refers to a set of social goals like improving the welfare system and the quality of the environment, increasing individual freedoms, having a more even distribution of wealth, and improving the health and education systems. Sustainability is not only concerned with the continuing ability to increase income through economic growth, but also the ability to achieve other more qualitative goals. Cities can be seen as focal points for achieving sustainability. They offer many opportunities. From an energy point of view, the energy efficiency of cities both in transport and building sectors has great potential. The provision of many services is easier and more efficient in an urban area. Theoretically and technically it is possible to have very effective transport system without cars (Register 1987; Richards 1990; Girardet 1996; Roelefs 1996; Rogers 1997; Roseland 1997).

The challenge of achieving the goal of a sustainable city is not a technological problem, but it will need a change in politics, economics, and social relations, as well as an integration of these aspects into the system (Hopwood 2001). The sustainable city includes an integrated system of co-ordination and cross-sector work between agencies, and developmental activities related to a holistic approach in its design and management. So far, policies attempting to adopt the concepts of sustainability within a city have not gone far enough into the root of the issue. To achieve this it would require dramatic changes in the governmental process of decision-making concerning both social and economic policy.

Mega-cities already represent extreme or more intense manifestations of the urbanization profile. However, mega-cities will continue to grow, both in their size and in their attractiveness as a location for the lives and functions of a populace. The goal of achieving sustainability is worth striving for and will require a continuation of the present small steps, as well as the incorporation of large strides.

1.3. Investigation of Asian mega-cities

If the 20th century was the century of urban sprawl, then the 21st century will be the century of mega-cities. Asian mega-cities are at the center of the region's economic growth and development. They are growing rapidly, not only in terms of population but also in terms of economy and industry. Throughout Asia there is an increasing concentration of urban growth in large cities. The reasons for this concentration include: the effects of large sale economies and forces of agglomeration, wider opportunities for employment, the effect of the global economy, and the relatively greater availability of social, health and cultural services. Much of this growth is taking place in areas around the built-up city as a mixture of residential, industrial, and commercial developments spread over the surrounding areas. Bangkok is a good example of this.

In the year 2000, about 30% of the population in the Asian region lived in cities. There are contradictions in the rate of growing urbanization. Japan was the first rapidly urbanize and was followed by South Korea. During the 1960s over 79% of the population in these countries lived in urban areas. In Southeast Asian countries urbanization started slowly but has grown faster since the 1970s. The South Asian region, including Bangladesh, India, Nepal, and Pakistan, has experienced a gradual rise in urbanization. The growth rate of the population has been intensive in some major cities such as Mumbai, Calcutta, Dhaka, and Karachi. Since 1960 the urban populations have been rising at a rate of approximately 3 to 5% annually (World Bank 2003).

Asia now has more major cities than any other region in the world. Table 1.2 shows the distribution of larger cities in Asia compared with the world's total. China and India, the most highly populated countries, have the largest number of major cities.

Table 1.2. Population in Asian urban agglomerations of more than 3 and 5 million inhabitants in 1990 (World Bank 2003; UN-HABITAT 2001).

	More than 5 million		More than 3 million	
	Number of cities	Population (Mill.)	Number of cities	Population (Mill.)
China	4	36.11	8	50.91
India	4	37.27	7	49.17
Indonesia	1	9.42	2	12.42
Japan	2	31.01	2	31.01
Korea	1	11.33	2	16.08
Pakistan	1	7.67	2	11.75
Philippines	1	8.40	1	8.40
Thailand	1	7.16	1	7.16
Vietnam	-	-	1	3.17
Sub Total	15	148.37	27	190.08
Others	20	190.29	42	268.37
World Total	35	338.66	69	458.45

Due to limited research and data on Asian mega-cities, this thesis considers a few selected cities i.e., Bangkok, Beijing, Shanghai, and Tokyo. Analysis of these cities can be used to generate wider perspectives on other cities in Asia. Table 1.3 summarizes the investigation of Bangkok, Beijing, Shanghai, and Tokyo, respectively. These cities share the characteristics of having a high population density and of being the most important cities in their respective countries. They differ in terms of a number of factors such as their levels of income and development, forms of governance and institutional capacities.

Table 1.3. Summary of selected Asian mega-cities investigation.

Cities	Bangkok	Beijing	Shanghai	Tokyo
Status	A combination of a modern and a historical city. Suffers from unplanned transportation systems and an undeveloped mass transport network. Large consumer of air-conditioning.	Rapidly transforming with a growing population, many new buildings, and increasing automobile traffic. Following Tokyo's model for transport but with a phase-lag.	The richest mega-city in China. Rapidly developing. New business facilities, increasing automobile traffic.	Most developed mega-city in Asia. A modern urban infrastructure, a well-organized mass transport system, and a number of new energy-saving technologies.
Modal split of passenger transportation	Majority of travel by private cars and buses. Since 1998, the mass transit system i.e. Skytrain, subway, was developed.	Rapidly rising number of cars' shared since 1990. Increasing in the number of buses.	Majority of motorized transportation by bus. Highest level of non-motorized travel.	Majority of travel by rail and subway. Bus is insignificant.
Fuel structure	Oil, electricity, and gas dominated.	Heavily, coal dominated.	Heavily, coal dominated.	Oil, electricity, and gas dominated.
Energy efficiency of major technologies	Moderate to high	Low	Low	High

1.4. The research questions and conceptual model

Cities throughout Asia have experienced an unprecedented economic development over the past decades. In many cases, this has contributed to their rapid and uncontrolled growth, and has resulted in multiple problems, which include rapid population increase, enhanced environmental pollution, collapsing traffic systems, dysfunctional waste management, as well as a rapid increase in the consumption of energy, water, and other resources.

Considering sustainable development in relation to sustainable cities, as mentioned earlier, different interpretations and various aspects have been defined. However, they do not give a clear definition that can be easily implemented in practice. This thesis focuses on energy use in Asian mega-cities, and sustainability is interpreted as a future where the energy system is based upon renewable resources and energy efficiency. The energy system is characterized by both sides those of supply and demand.

The study focuses on the dynamics of energy utilization in Asian mega-cities, and ultimately aims at providing strategies for maximizing the use of renewable energy in large urban systems. The study aims at providing an in-depth understanding of the complex dynamics of energy utilization in urban mega-centers. An initial general analysis will be complemented by a detailed study of the current situation and a future outlook for the city of Bangkok, Thailand.

At present there is a lot of research and development regarding energy systems and sustainable cities. The problem is, however, that much of the research is not done in a holistic manner. Research institutions, development agencies, and organizations address each issue individually in a singular way. For instance, agencies involved with the building sector focus on certain technologies, while others deal with pollution, transportation, environment, or social issues. An integrated approach seeks to incorporate all the important aspects into a holistic synthesis. In this approach, all of the different criteria will be focused on simultaneously and tradedoff against each other in order to optimize the overall efficiency of the design.

Figure 1.1 shows the research concept model. The study begins with understanding energy flow in Asian mega-cities, and reviews studies from international research teams to quantify the energy demand and supply in selected Asian mega-cities, including Bangkok, Tokyo, Shanghai, and Beijing. At this stage, the major drivers affecting the energy demand in the process of dynamic structural changes are also identified. A city's metabolism has been studied to distinguish the direct and indirect energy consumption by using Input-Output (IO) analysis. The research into metabolism aims to understand the physical flows into, within, and out of the cities. Direct and indirect energy demand can be a proxy to emphasize how cities rely upon the outside in terms of energy demand.

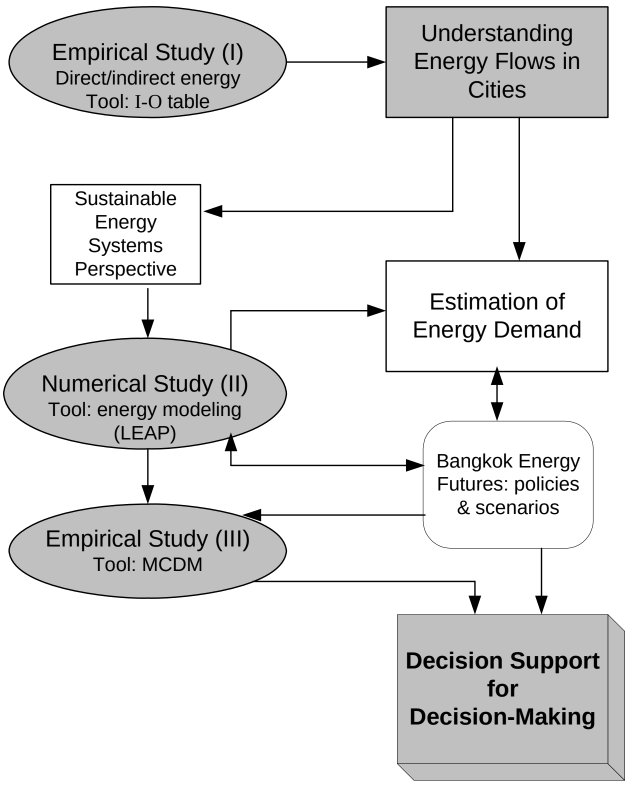

Figure 1.1. Research conceptual model.

The second stage is to estimate the energy demand in various sub-sectors (Bangkok case study); the Long-range Energy Alternatives Planning (LEAP) system has been used to estimate energy demand, as well as to analyze energy scenarios in Bangkok. The backcasting approach is applied to create the city's energy scenarios to give an image of future energy systems. According to Dreborg (1996), backcasting means that the development of scenarios is dictated by starting in the future. Backcasting is used to develop images of the future where the result describes a possible and desirable future for sustainable energy systems in city. This method has been applied in a number of energy future studies, particularly in the study of complex long-term sustainability problems.

The last stage is the Multi-Criteria Decision-Making (MCDM) method, which has been developed in order to evaluate the city's energy scenarios. The intent of MCDM is to improve the quality of decisions that involve multiple criteria by making the options more explicit, rational, and efficient.

1.5. Research approach and thesis structure

The following study items are included within the thesis:

- Identification of the parameters that affect the utilization of energy in mega-cities.
- Detailed analysis of the energy flows in mega-cities and their various sub-systems, including the transportation, industrial, residential, and commercial sectors.
- Evaluation of the energy models most commonly used for analyzing and simulating energy utilization.
- Analysis of the potential for renewable energy utilization.
- Development of strategies for renewable energy use.
- Development of a tool for decision-making.
- Case study: city of Bangkok, Thailand.

In regards to the study items, the following methodologies are employed:

- A review of the studies from international research groups and clarification of the work in each group, in order to find what kind of aspects within sustainable cities they are working on.
- Cooperation with other organizations, including the Stockholm Environmental Institute (SEI), Sweden, the Institute for Global Environmental Strategies (IGES), Japan, for data sharing and methodology development; and the System Analysis Laboratory, Helsinki University of Technology, Finland, for the application of MCDM.
- A comprehensive analysis of data and methodology development from literature, as well as research institutes to quantify the energy supply and demand, as well as the drivers affecting energy consumption.
- The collection of energy and economic data at national and city levels. Also a collection of complementary data from various research reports. This is crucial for energy modeling because in order to construct a model it is a question of what kind of data is available.
- An investigation into the city's metabolism and a survey of the methods used for calculation to analyze the relationship between the activity levels of major urban sectors and energy demand.
- Development of energy modeling for Bangkok is done in cooperation with the Energy Research Centre at the University of Cape Town, South Africa.
- The surveying and development of a method for multi-criteria evaluation used within energy planning.
- The application of all methods to the case study.

This thesis is organized into two parts, a study of the literature, followed by a development of the methodologies and the application of the methodologies to the case study. The aim of the first part is to present an overview of a selection of Asian mega-cities and the relationships between sustainable development and mega-cities focusing on energy utilization. The second part discusses the development of methodologies, including the metabolism of cities, energy modeling and MCDM. The objective is to find the tools for a holistic approach and then to use them to analyze and build a city's energy scenarios and policies. The overall goal of this study is to identify the characteristics of Asian mega-cities within the perspective of energy utilization and to develop a user-friendly tool of an integrated approach for the cities' decision-makers.

Chapter 1 discusses the background to the thesis and the relationship between sustainable development and mega-cities. The research approach and conceptual model is explained. Selected Asian mega-cities are investigated.

Chapter 2 examines the understanding of energy flows in a large urban system, of the surveying of international frameworks of cities and of sustainability. Factors driving energy consumption and the metabolism of a city are described. A review of cities' metabolisms is identified and described.

In Chapter 3 the estimation of energy demand, both direct and indirect, is calculated and described. A comparative study on the analysis of the embodied energy of selected Asian mega-cities is discussed, as well as a survey of the energy modeling that is widely used in energy planning.

Chapter 4 deals with the multi-criteria decision-making (MCDM) in the assessment of the sustainability of energy systems within the city. It starts with a review of MCDM in energy planning and the development of a method for multi-criteria evaluation to be used with energy systems.

Chapter 5 shows the testing of methods, including embodied energy analysis, energy modeling and MCDM in the city of Bangkok as a case study.

Chapter 6 includes conclusions and future work based upon the case study.

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2. UNDERSTANDING ENERGY USE IN CITIES

2.1. Energy, cities, and sustainable development

Sustainable urban development is closely linked to patterns of energy use and urbanization. Today, almost 75% of the population in industrialized countries lives in urbanized areas. The number of people living in urban areas is rapidly increasing worldwide. In 1950, about 30% of the world's population lived in urban areas. The figure has increased to 47% in 2000 and is expected to reach 60% by 2030 (IGES 2004). Cities contribute towards promoting both local and global sustainability. They are centers of high living standards and they consume large amounts of energy, materials, and other resources, which lead to the over utilization of limited natural resources and large increasing volumes of GHG.

However, urban situations differ between continents, regions, countries, and even within the same country. Sustainable energy systems are poised to meet growing energy demands, while simultaneously addressing energy poverty, energy security, and environmental improvement. An estimate shows that trillions of dollars will be invested worldwide within the next two decades in order to develop and upgrade global energy systems, with nearly 1 trillion dollars per year required in developing countries. But investments in sustainable energy systems are still a small fraction of the total investment in the energy sector that continues to rely on fossil fuels (CEG 2004). The creation of sustainable energy systems is intimately linked to environmental issues. In addition to the misery and suffering associated with the affects of ill health, fossil fuels damage the economy, leading to direct costs and losses in productivity.

As one of the key drivers in economic development and a main source of environmental problems, energy is an essential component of a society. It transforms materials and labor into useful goods and services. There is a strong relationship between the quantity of energy used by a country and the size of its economy. However, this relationship is not necessarily linear in form, so with the right policies may be able to decrease the amount of energy needed in order to produce the Gross Domestic Product (GDP). For example, China has shown that it is possible to achieve economic growth without a corresponding jump in GHG emissions. Its CO_2 emissions fell by 6-14% between 1996 and 1999, while its economy grew by 22-27%. In contrast with the U.S. situation, the CO_2 emissions during the same period increased by approximately 5% (CESA 2004). Energy is a complex element of sustainable development policies and the connection between energy and other issues, such as the social aspects, becomes even more complex.

From the thermodynamics point of view, the availability of energy resources can easily determine, for instance, how much food is grown and cooked or how a living space is heated or cooled. Moreover, the quality of energy is as crucial as its quantity. Solid, liquid, and gaseous fuels vary in their ability to provide energy services depending on their applications and end-use devices. Coal can be a higher quality energy resource than wood, while oil has a higher quality than coal, and electricity has a higher quality than solid, liquid, or gaseous fuels.

Within an urban settlement there is an increasing acceptance amongst engineers and specialists from other disciplines that current modes of human existence are unsustainable in terms of environmental, social, and economic perspectives. There are many indicators to support this view such as global climate change, resource depletion, droughts, floods, local pollution, deterioration in the quality of life, etc. Therefore, it is a challenge to build a sustainable society by focusing on urban settlements. To study sustainable urban development, we may consider it as inputs and outputs of than urban system, including its energy use, the recycling, treatment and disposal of its waste as well as its manpower and knowledge. More specifically, a model can consider the energy and environmental impacts of the commercial, transportation, industrial and residential sectors. Details of an inputs and outputs analysis will be described within the study of a city's metabolism.

2.1.1. Energy and urbanization

It is well recognized that the bulk of the world's energy consumption is within cities, and much of the rest is used for producing and transporting goods and people to and from cities. It is thus crucial to develop strategies for the use of sustainable energy. The major factors influencing energy use in cities include patterns of urban settlement, transportation systems, incomes and lifestyles, the energy efficiency of technologies, industrial processes, building technologies, climate and methods of waste disposal. Some factors, such as income and lifestyle changes, are particularly significant in Asian mega-cities e.g., Bangkok, Beijing, and Shanghai. Significant changes in energy use can be achieved by a combination of energy efficiency and more efficient energy supply systems. There are many good examples, particularly from Scandinavian countries, of how energy efficiency combined with efficient supply systems can dramatically reduce urban energy use.

From 2000 to 2030, virtually all population growth is expected to occur in urban areas and mostly in less developed regions of the world (UN 2002). Figure 2.1 shows the growth of urban agglomerations in selected mega-cities. New York and London are typical mega-cities in more developed countries that developed in the 1800s and early 1900s, reached their current size in the middle of the last century, and have since experienced slow growth or decline. Mega-cities in some developing countries, such as Mexico City, grew rapidly between 1950 and 1980, and are growing more slowly now. Many Asian and African mega-cities, such as Lagos and Bombay, are experiencing very rapid growth and are projected to continue at this pace.

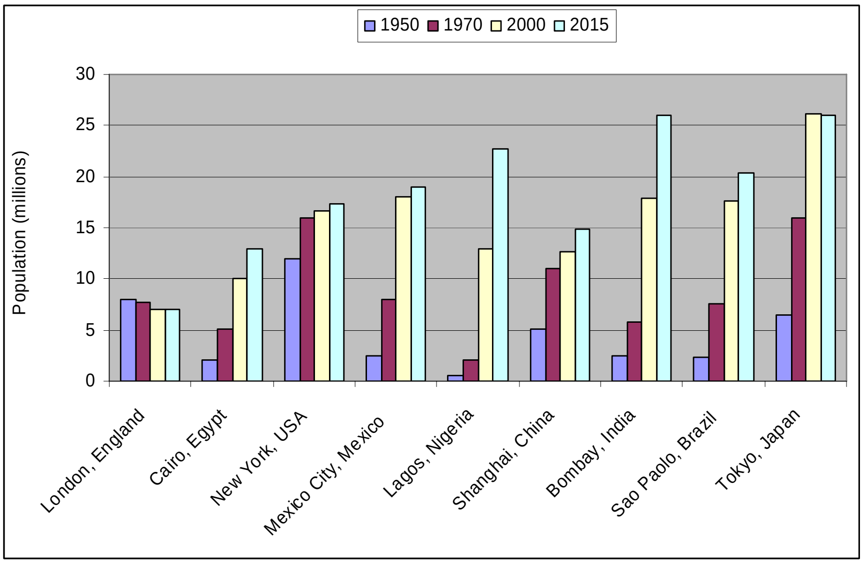


Figure 2.1. Growth of urban agglomerations in selected mega-cities in 1950-2015 (UN 2002).

The potential for urban growth in Asia is tremendous. It is estimated that the population increase of cities in developing countries will be from 37% to over 54% by 2030 (UN 2002). This means that 2.6 billion people will live in Asian cities. The number will exceed twice the current population of China and represent 53% of the world urban population by 2030 (ECOASIA 2001). Predictions show that in 2015 there will be 358 cities worldwide with a population of over a million people, of them 153 are expected to be in Asia (UN-HABITAT 2001). The sustainability of these cities will have enormous implications.

Cities are one of the key element contributions towards global sustainability. A high population density and massive consumption open up several options to effectively utilize natural resources and promote efficient urban infra-structural development. For example, compact settlement and a high population density in a city may reduce per capita the infrastructure and distribution costs and open up opportunities for economies of a large scale. This can be seen in Hong Kong, which is a very densely populated city. Thus, cities can greatly facilitate the implementation of measures, which reduce energy use and stress upon the environment. Cities and their energy consumption bring two major environmental issues to the forefront for policy-makers. The first is the massive consumption of energy and materials that affects natural systems and, ultimately, areas and peoples outside the boundaries of cities and even the next generation of residents. The second is the exposure of a large and concentrated urban population to worsening air, water, and waste pollution.

2.1.2. Determinants of energy use in cities

Energy has long played a central role in the development and function of the economy. It is an essential input for economic activities. Reliance on energy will obviously continue to grow with increase in populations and improvements in the standards of living, especially in cities. History has shown that increased mechanization and energy use brings its own burdens upon the environment.

As regards urbanization, it is no doubt that energy has no conflict with it in regards to the population pattern and type of infrastructure. Cities open up many opportunities for the efficient utilization of energy. European and North American cities stand in contrast to Asian cities, which tend to be more dense and expansive. European cities are likely to be less dense and typically have more efficient transportation and energy distribution systems. North American cities are of a low density and sprawl over large areas, thus requiring large amounts of energy to run the transportation and distribution systems; their public transportation is cost ineffective.

Energy use concerns are not only related to availability or to use but also to implications, which follow the energy use. Fossil fuel produces local air pollutants, GHG, and waste. If pollutant concentrations reach an unacceptable level then there are serious problems concerning human health and the environment. The efficient utilization of energy and the use of renewable resources are the keys to conserving conventional energy resources, as well as to reducing the levels of air pollutants such as nitrogen oxide (NO_x), sulfur dioxide (SO_x), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PMs). The following sub-sections describe several key factors that determine the nature of energy use in cities.

2.1.2.1. Pattern of urban settlements

The compactness of urban settlements influences the energy demand in regards to transportation and for other energy utilization areas such as district heating and cooling for space conditioning. Another factor related to urban planning is the urban spatial structure and functions. They all affect energy use as they influence the demand for the mobility of the urban dwellers. Mixed land use, for example residential and industrial or residential and commercial, results in a different energy use. Urban zoning policy and the relocation of industry from city centers to peri-urban areas in some Asian cities significantly influence travel demand and, thus, energy use. Similarly, the patterns of energy use in commercial or service cities are different from those in industrial cities.

2.1.2.2. Income level and lifestyle

As mentioned earlier, mega-cities are the engines for the economic growth of a region or even country. Castells (1993) argued that mega-cities will continue to grow both in their size and attractiveness for the location of the functions and lifestyles of people because they are the centers of economic, technological, and social dynamism. They actually are the development engines of their own countries. Mega-cities are the connecting points of a network on which everybody relies on in the new economy.

It is often difficult for policy-makers to constrain increasing energy consumption, especially in rapidly industrializing cities such as Bangkok, Kuala Lumpur, and Shanghai. Studies on the relationship between income and energy use at the national level have clearly demonstrated that there is a strong correlation between per capita energy consumption and GDP. It is generally accepted that energy use per capita increases with income, but at some point it may decrease (IGES 2004). A higher income is associated with a better lifestyle and more consumption, which affects energy use within and beyond the borders of cities. Consumption-oriented lifestyles are associated with the greater utilization of natural resources, as well as the greater energy use needed to produce goods and materials; consequently, they create more GHG emissions. This relationship is important in the sustainability debate as it seeks to provide welfare and equity along all scales.

2.1.2.3. Energy efficiency technologies

Energy efficiency is defined as the energy needed to produce a unit of energy service. Since energy demand is for service purposes, energy efficiency can directly improve or worsen energy consumption. Energy technologies dominate consumption within a city, including the automobile along with household and commercial appliances used for lighting, heating, cooling, and cooking. Improving energy efficiency is a function both of the technology itself and of the patterns of energy utilization.

There is significant untapped potential for improving energy efficiency in almost all energy applications. Improving energy efficiency is often highly profitable, but there are still some barriers that remain. Technological improvements will only be effective if there is a commitment by society to limit the total throughput of matters and energy at a sustainable level (Huesemann 2003). The very first step towards sustainability would be a public discussion of complicated and controversial value-laden issues. However, citizens are most likely led to believe that technological solutions alone will be sufficient to guarantee sustainability. The use of new technologies in the city can make everyday life easier and deliver better social and cultural services than there ever was before.

2.1.2.4. Industrial processes

These issues are related to energy efficiency technologies; however, separating the discussion aims to give an overview of disaggregated sectors, including the transportation and building sectors. More details about energy demand in different sectors will be discussed in Chapter 3 (energy system models and energy demand analysis).

The energy efficiency of all industrial production processes affects the energy use in the city too. Asian mega-cities are rapidly relocating their primary industries either to peri-urban areas or to areas outside the cities' borders, leaving cities increasingly dominated by the tertiary sector. Small and medium-sized enterprises (SMEs), however, remain prevalent in many Asian cities and pose a big challenge for energy planners. The role of local policy-makers in this area is limited in South and Southeast Asia (IGES 2004). Another relevant issue is the type of industry there is within the considered city. For example, heavy industries and car manufacturing industries consume more energy than electronic and agricultural industries.

2.1.2.5. Transportation systems

The energy consumed by the transport sector is influenced by its systems. Transportation systems are very important, for mobility is a key aspect of urban life. Historically, cities have moved from non-motorized to rail-based and then gradually to automobile-dominated transportation.

Energy utilization within the transport sector depends upon a number of factors. For example, the infrastructure for rail and road networks, the mass transportation systems, the share of public and private travel demands, the role of alternative fuel vehicles, and the share of small-occupancy vehicles such as two-wheelers as used in Bangkok, Jakarta, Delhi, etc. (IGES 2004). Increasingly, cars dominate transportation due to rising incomes, an increased social status through car ownership, and inefficient public transportation systems. These trends seem to be typical problems in Asian cities.

Improper transportation systems threaten energy security and result in the increase of local air pollution and GHG emissions. Traffic congestion reduces the quality of life in the city and wastes time as well as energy. This problem is often found in big cities in South and Southeast Asia. The design, placement, and density of buildings in an urban environment also have a great influence upon the consequent transportation patterns.

2.1.2.6. Building technologies and climate

The technologies in the building sector, for example air-conditioning, district heating and cooling systems, insulation systems, and other energy management building systems, have a significant effect on the use of energy. Energy services, including space conditioning and lighting, are the most dominant form of energy use in the building sector and depend directly upon floor spaces, whose use depends on a number of factors such as real estate market prices, business culture and socio-cultural factors.

The climate characteristics of the cities (cool, temperate, hot-arid and hot-humid) have greatly influenced energy use in building as well. Hot and cold climate conditions directly affect energy use due to the greater demand for space conditioning. North Asian cities, such as Beijing, require more energy than cities of more temperate climates. Buildings in Southeast Asian cities require space cooling all year round. Cities in East Asia, such as Tokyo and Seoul, suffer from urban heat island and require both heating and cooling. The literature has shown that the heat island effect may be beneficial to relatively cooler cities because of the reduction of their heating demand in winter. However, the penalty in summer has far exceeded the winter gains in cities, which experience hot and humid summers (EC 2000).

2.1.3. Urban effects on energy use

This section reviews some of the central aspects of major urban environment in relation to their energy use. A city changes its landscape from the ecosystem and therefore is consequent to the change in the relationship between biological and physical aspects of the environment. City dwellers are exposed to more kinds of toxic chemicals in higher concentrations and to more human-produced noise, heat, and particles than are their rural neighbors. According to Akbari et al. (1992), there are four basic environmental goals for a city, namely, reducing energy use, reducing and removing pollutants, helping to create a pleasing environment and aiding biological conservation. The following sub-sections describe all the common urban influences the use of energy has in Asian cities.

2.1.3.1. Urban heat island

An urban heat island is a phenomenon in which the core urban temperature is higher than the land surrounding it. Studies show a direct correlation between the density and population of a city and the intensity of the heat island effect. Higher urban temperatures increase the demand for electricity, which is needed for cooling, which in turn leads to an increase in the production of CO_2 and other pollutants if the electricity is fossil fuel based. The urban heat island is not a problem in cities situated at high altitudes, since the effect enables a reduction in the demand for heating. This could be true in winter, but studies have shown that these benefits are far out-weighed by costs incurred during summer (Landberg 1981; EC 2000). Heat island effects have been reported in dense and highly urbanized cities all around the world. The urban heat environment is worsening mostly in Asian mega-cities regardless of the stages of development or income levels. For example, Bangkok, Shanghai, and Tokyo are becoming warmer and warmer every day.

Man-made changes to the urban environment are the source of the urban heat island phenomenon. The radiation balance within the urban system is disrupted as surfaces absorb long-wave radiation and are unable to radiate it back out. An increase in anthropogenic heat discharge, a decrease in surface evaporation, changes in the thermal characteristics of urban surfaces, an increase in traffic and air pollution, together with the reduction in airflow and humidity caused by the sheltering effect of buildings, are the major factors behind these changes (EC 2000). Mega-cities are characterized by having a population of a high density and a high level of energy consumption per capita. The energy demand is fulfilled through electricity and the combustion of fossil fuels, which ultimately discharge heat into the urban atmosphere.

Direct heat discharge sources are usually categorized as stationary or mobile. The single greatest source of stationary heat discharge from buildings comes from air-conditioning units. These units are very densely concentrated throughout cities, for example in the inner Bangkok area. Some waste incineration plants and industries located in cities, such as in Tokyo, release heat directly into the urban environment.

The most important mobile source of heat is automobiles. In city centers and high traffic zones, the concentration of this discharged heat is increased by congestion and fuel inefficient vehicles, of which Bangkok is a good example. A closer look at a mid-size urban city reveals that only 13% of the total energy input into transportation is converted into useful work. The rest is dissipated as heat into the environment of the city (Moavenzadeh et al. 2002).

Rapid urbanization and population growth in mega-cities has resulted in the build-up of massive infrastructures and dense settlements. With the development of the urbanized world vegetated land surfaces are converted into concrete and asphalt. A change in the nature of surfaces has primarily affected solar reflectivity, so-called albedo. This parameter is different from normal reflectivity in the sense that reflectivity might only account for visual bands, whereas albedo accounts for all the incoming radiation to a surface. Asphalt roads, concrete pavements and corrugated roofs, which form the major part of dense cities, have a low value of albedo. For instance, asphalt has 0.05-0.20, and concrete has 0.10-0.35 (Bretz et al. 1998). Low albedo surfaces absorb significant proportions of solar radiation and contribute to the worsening of the urban heat environment.

In addition, loss of vegetation inhibits the evapotranspiration process, in which plants use heat from the air to evaporate water from their leaves. This process enables vegetation to act as a heat sink. Changes in wind patterns have also exacerbated the urban heat problem. The formation of an urban canopy changes the wind pattern, preventing wind from entering and blowing heat away from ground surfaces, and traps heat inside the canopy. The cumulative effects of the above factors make the urban environment hotter than surrounding areas.

2.1.3.2. Air pollution

Air pollution is a persistent and pervasive urban environmental problem that imposes significant health and economic costs. The impacts of the urban system on the air can be added to the problem of the urban heat island, as mentioned earlier. Asian mega-cities, such as Bangkok and Beijing, experience similar and serious air pollution problems. In addition, the number of cities with very poor air quality continues to grow, including many cities in developing countries.

The main pollutants reducing air quality are SO_x, PM, NO_x, CO_2, O_3, lead, heavy metals, and volatile organic compounds (VOCs). The sources of pollution are urban transport, the generation of electricity and heat from non-renewable energy resources, and industrial activities. Air pollution may be worsened by the local topography, wind direction and weather conditions. Many cities around the world have undergone and continue to undergo rapid growth. Yet, in the absence of adequate environmental management measures in many cities, this growth is happening at a considerable and often increasing cost. More people, more industry, and more motor vehicles produce ever-worsening air pollution, an already serious environmental threat in many cities.

The grave consequences of air pollution for public health are measured not only in terms of human sickness and death, but also in terms of a loss in productivity and missed educational and other human developmental opportunities. It is because of these health costs, productivity losses and degradation of air quality that the city's economic growth and contribution to national development is hindered. In addition, air pollution imposes significant additional operating costs on businesses, industries, households and public services. Likewise, it accelerates the deterioration of buildings and historic monuments, and a reputation for bad air pollution certainly deters investments from outside the city. Apart from its local urban effects, air pollution has a profound regional and global impact as well. Urban air pollution is a major contributor to the problems of ozone layer depletion, global warming and climate change. To meet these challenges at a global level it is required that urban air pollution be controlled and reduced.

The technical aspects of urban air pollution are reasonably well understood and the necessary technologies are generally available. Urban populations are aware of the nature of the air pollution from which they suffer and are increasingly unwilling to let it worsen (WHO 1996). In many cities, both the attitudes of the populace and of the official have changed and there is a growing political commitment to the need for change. To convert these more favorable conditions into actual improvements in air quality there is a need to create a management system, an urban air quality system, which would be capable of addressing the complex issues. In addition, the system should ensure the formulation and implementation of realistic and effective strategies, as well as action plans that will systematically address the short and long-term causes of urban air pollution and help the city achieve a sustainable growth path.

2.1.3.3. Microclimate

Cities convert land from its natural state in order to accommodate buildings, houses, roads and other infrastructures. This tends to modify the albedo, hydrologic and wind patterns, which in turn affects the microclimate. These affect the microclimate of the building in relation to comfort as well as that of the energy use in buildings for heating, cooling and lighting. Wind velocities in the city are generally lower than in the surrounding countryside, which is due to buildings obstructing the flow of air. The wind affects temperature, rate of evaporative cooling and plant transpiration, and is thus an important factor at a microclimatic level. Built-up areas with tall buildings may lead to complex air movements through a combination of wind channeling and resistance. This often results in wind turbulence in some areas and concentrated pollution where there are wind shadows.

As regards thermal comfort, moderate air movement has a cooling effect and is usually desirable because it helps disperse local atmospheric pollutants. Air movement also helps to remove heat from the human body's surface, although increasing wind velocities can significantly reduce thermal comfort. Therefore, the planner should consider how wind direction and wind velocity will affect existing and proposed buildings, especially when designing high-rise buildings that are popular in East and Southeast Asian mega-cities.

Vegetation is the most obvious and easiest way to improve the urban environment with respect to air movement. Trees help in a number of ways: they reduce wind speed, which is undesirable, but the net effect depends upon the location and the type of tree. However, the effect of vegetation in the urban environment depends upon its proportion compared to the whole area of the city. In a dense and highly built-up city, the area available for vegetation is limited and its effect on the heat environment could be minimal. Also, its effectiveness depends on the conditions of the local climate, whether it is hot and dry or hot and humid.

2.1.3.4. Transport and road traffic

Transport and traffic congestion has a significant effect upon the quality of the urban environment, the quality of life, time and energy consumption. Private cars, trucks, and other motor vehicles dominate most Asian cities. It is estimated that a private vehicle typically consumes more than twice of the energy per passenger-kilometer than a train, and almost four times that of a bus (Whitelegg 1993). The energy, as well as pollution, implications of an urban layout that does not maximize the potential of public transport are likely to be very significant.

A study has shown that cities of a high density, for example Hong Kong, have far lower transport energy demands per capita than low density cities. On average, when comparing 10 major cities in the U.S. with 12 European cities, the latter are five times as dense but the U.S. cities consume 3.6 times as much transport energy per capita (Newman & Kenworthy 1989). The conclusion often drawn from such data is that dense cities are low energy cities in terms of energy demand for the transport sector. In the absence of an effective integrated public transport system, increasing the density will inevitably increase traffic and pollution. The challenge is to anticipate and implement public transport systems before the increases in population density to ensure that the increasing existing and future inhabitants use public transport instead of private cars and thus shift the balance away from the car (Steemers 2003).

In Asia, many cities have implemented measures at different stages, ranging from end-of-pipe interventions to more upstream measures. The measures vary from command and control to those that are market based. Cities often focus on how to organize transport demands into a better modal structure, a step requiring the integration of urban planning and land-use policies together with transportation and environmental planning. Policy-makers are concerned about the share of private transportation both in meeting demand and in its contribution to pollutant concentrations. End-of-pipe approaches, such as setting emission standards, improving fuel quality, and implementing vehicle technology interventions, are limited to vehicles and their increased use. While such measures are necessary they are not sufficient. A long-term solution to the environmental and congestion problems of urban transportation introduced in Asian cities requires additional steps.

Solutions to urban transportation issues are to a great extent linked with the city and transportation planning. Asian cities lack proper city planning and the growth of urban centers has been haphazard. Factors influencing urban transportation vary from country to country depending on its economic situation. Population growth and urbanization, as well as inadequate infrastructures are considered to be the major determinants of transportation problems in Asian urban areas. There has been a considerable increase of motorization in almost all of the countries in Asia with the few exceptions being in Central Asian cities (World Bank 2004). For example, in Bangkok the number of vehicles grew more than sevenfold between 1970 and 1990, whereas in Beijing it was a threefold increase between 1991 and 2000. Similar trends in growth occurred in Jakarta and Kuala Lumpur (Ramanathan 2000).

Congestion is the common mark of motorization in most growing Asian cities such as Bangkok, Delhi, Jakarta, Manila, and Seoul. They are particularly congested with weekday peak-hour traffic speeds reported to be on average 10 km per hour or less. One estimate puts the average travel time for commuters in Asia at 42 minutes. This number can be much higher as in the case of Bangkok, where the average is estimated to be about 60 minutes (UN-HABITAT 2001; World Bank 2004). A study on Bangkok estimated that the direct economic costs of congestion could be as high as US$3.71 billion annually. A recent World Bank study estimated that a 10% reduction in peak-hour trips in Bangkok would provide benefits of about US$400 million annually (UN 2001).

2.1.3.5. Food supply

Food supply is an important issue regarding urban management and sustainable development. It may not be directly effected by energy use but it can be considered as being influenced by air pollution and GHG emissions from the energy sector. A sustainable city should be self sufficient both in terms of energy and food supplies. Also taking food production into consideration is a crucial factor for life in the city.

Shanghai can be cited as an example of how mega-cities can be organized in terms of food production. In the Shanghai region two factors have contributed to its recent increased food production. One is the transfer of the control of the production, distribution and marketing of food from many diverse operating units to the Shanghai municipal government. The other is the modernization of farming achieved by the means of mechanization, electrification, water-conservancy work, and the large-scale provision of modern inputs. Spatially, two zones are distinguished as being for the purpose of urban agriculture. The suburbs near to the inner zone immediately surrounding the built-up area are devoted to year-round vegetable production and the outlying suburbs are where coarse and hardy crops are grown. Thus, Shanghai is totally self-sufficient in regards to vegetables, most grains, and significant proportions of pork, poultry, and other foods (Yeung 2000).

In other cities, the trend of increased food production is offset by the accelerating loss of suburban farmland. In Beijing, the vegetable land of 607,000 hectares in 1949 dwindled to 427,000 hectares in 1980, a 30% loss, which resulted from the state taking land from nearby suburbs for new housing and factories (Smil 1984). Similarly, Bangkok has lost suburban farmland due to real estate development and increase of industrial areas.

2.1.4. International frameworks for cities and sustainable development

Recent global summits, including the United Nations Conference on Environment and Development (1992), the United Nations Conference on Population and Development (1994), the World Summit for Social Development (1995), and the Second United Nations Conference on Human Settlements (1996), have placed health and human development on the political agenda. These initiatives have achieved a global consensus on issues of development that emphasize policy integration, and participation and action at all levels, especially at the local level. This section reviews some key international initiatives that are relevant to cities and sustainable development.

The review of different frameworks can provide an insight into the path to sustainability particularly at the level of the city. At present Asian mega-cities are reliant upon fossil fuels mainly for transportation and the generation of electricity. As a consequence the local as well as global environments are unsustainable and new strategies need to be considered. Different initiatives have shown their attempts to improve such sustainability. However, there is no single solution for every city. This is due to the fact that different cities have different conditions. From the energy point of view, more sustainable energy systems in the city should inevitably include the increased use of renewable energy, energy efficiency in all economic sectors, efficient public transportation, and ultimately a steady reduction of the dependence on fossil fuels as well as the introduction of cleaner fuels. In addition, social sustainability requires that the residents have access to appropriate, affordable, healthy and safe energy services.

2.1.4.1. Agenda 21

The United Nations program of action on sustainable development is a detailed plan of initiatives that has greatly influenced thinking and action on all levels. It emphasizes the importance of local action. Agenda 21 (UN 1993) addressed all major areas of development, especially emphasizing the environment but also considering international cooperation, poverty, human health and population. It indicates several key aspects of social development, including equal rights, empowerment and education. Agenda 21 devotes one chapter to the role of local authorities and identifies local governments as one of the main partners in its implementation. About two thirds of the recommendations have implications for cities. Planning, local capacity building, community and inter-sector involvement and information are highlighted as processes for implementation. Several guides to Agenda 21 have been produced, some specifically for local governments (UN 1993; WHO 1997).

However, Agenda 21 does not contain a specific chapter on energy issues but it has some aspects to do with energy in relation to environment and development and has been addressed in Chapter 9 of Agenda 21. This chapter is emphasis on the protection of the atmosphere, which includes four program areas, improving the scientific basis for decision-making, promoting sustainable development, preventing stratospheric ozone and preventing trans-boundary atmospheric pollution (UN 1993).

Agenda 21 forms the basis of action for many sectors and levels of government, and the key role of local governments is clearly highlighted. While the role of energy in sustainable development is addressed in several chapters dealing with human health, promoting sustainable human settlements, the protection of the atmosphere, transportation, industry, agriculture and technology. Energy issues and strategies were not comprehensively dealt with within Agenda 21.

2.1.4.2. Second United Nations Conference on Human Settlements

The Second United Nations Conference on Human Settlements (UN-HABITAT 1996) was held in Istanbul on 3-14 June 1996. The main objective was to make the world's cities, towns, and villages healthy, safe, equitable and sustainable. Other objectives included: placing urbanization and urban-rural relationships at the top of national and international development agendas; promoting new policies and strategies for managing urbanization and housing development; and helping to improve community environments and highlight needs and opportunities for investment into infrastructures and services. The Habitat Agenda comprises a Statement of Principles and Commitments and a global plan of action adopted at the conference. The Agenda addresses key challenges facing the world's towns and cities over the next two decades, with a special focus on remedial action from 1996 to 2000. The growth of urban agglomerations also provides a challenge for the future, especially when such urbanization is accompanied by increased social polarization, poverty and unemployment.

2.1.4.3. The European Sustainable Cities & Towns Campaign

The European Sustainable Cities & Towns Campaign (EC 1994) has arisen from Agenda 21 and the European Commission’s fifth action program on the environment. The Campaign forms part of the Sustainable Cities Project, the overall cooperation between the Campaign, the European Commission’s Expert Group on the Urban Environment, and the Commission’s Directorate-General for Environment, Nuclear Safety and Civil Protection. The objective of the Campaign is to promote development towards sustainability through Local Agenda 21 processes by strengthening partnerships among all actors within the local community, as well as cooperation between local authorities.

The Aalborg Charter was adopted at the first European Conference on Sustainable Cities & Towns in Aalborg, Denmark in 1994. The charter initiated the campaign and proposed a number of stages in preparing a local action plan. More than 200 local authorities have signed the charter, committing them to producing a local action plan for sustainable development. The campaign has initiated a number of activities through the collaboration of networks to support and encourage these cities. The activities included the development and publication of guidance for local planning, training courses, seminars, networking and databases on good practices.

The second phase of the campaign (1996-1998) was the implementation of the Lisbon Action Plan adopted at the Second European Conference on Sustainable Cities & Towns in Lisbon, Portugal in 1996. The action plan focuses on how to implement the principles laid down in the Aalborg Charter and how to start and conduct a Local Agenda 21 process, and provides practical steps on how to plan the implementation of local plans for sustainability.

2.1.4.4. The WHO Healthy Cities Project

The Healthy Cities Project (WHO 1996) started in 1987 and designated 35 cities as European project cities. The first phase of the project, from 1987 to 1992, emphasized advocacy, and by tackling the political and institutional barriers to change, laid the foundation for successful work towards health for all. The strategic objectives of the second phase (1993-1998) included speeding up the adoption of policy at a city level, strengthening national and sub-national support systems, and building strategic links with other sectors and organizations that influence urban development. Comprehensive city health plans were setting explicit targets and tackling challenges such as equity and sustainable development while establishing mechanisms to promote accountability for health.

2.1.4.5. The Sustainable Cities Programme

The Sustainable Cities Programme (SCP 1999) is a global program of the United Nations Centre for Human Settlements (UN-HABITAT) and the United Nations Environment Programme (UNEP). It is the leading technical cooperation program in the field of urban environmental planning and management, and is the principal activity of the United Nations system for operational sustainable urban development, and thus contributing to the implementation of the globally-agreed Agenda 21 and Habitat Agenda. The SCP is currently active in the following places:

- Africa: Accra (Ghana), Dakar (Senegal), Dar es Salaam (Tanzania), Ibadan (Nigeria), Lusaka (Zambia), Maputo (Mozambique), Moshi (Tanzania), Nampulo (Mozambique), Zanzibar (Tanzania);
- Asia: Colombo (Sri Lanka), Madras (India), Cagayan de Oro, Tagbilaran, and Lipa (Philippines), Shenyang (China), Wuhan (China);
- Middle East: Ismailia (Egypt), Tunis (Tunisia);
- Latin America: Concepcion (Chile); and
- Central & Eastern Europe: Katowice (Poland), Moscow (Russia), St. Petersburg (Russia).

2.1.4.6. Kitakyushu Initiative

The Kitakyushu Initiative Network (IGES 2004; 2005) was formed (as of April 2005) from members from 61 cities in 18 countries in the Asia-Pacific region. It is forecasted that by 2015 two-thirds of the mega-cities in the world will be in the Asia-Pacific region. It is thus essential for cities to join together to help each other and tackle environmental issues. The Network is playing an important role in fostering the capacity building of local environmental staff through conducting pilot projects and sharing lessons learned among the member cities in order to improve the quality of the environment. This initiative was adopted in 2000 at the Ministerial Conference on Environment and Development in Asia and the Pacific (MCED), which is one of the most important official meetings in the Asia-Pacific region for environment and development.

In the year 2004 the countries of the Asia-Pacific reviewed their activities towards sustainable development. During its network meeting, the Kitakyushu Initiative adopted the Kitakyushu Initiative Action Plan for future activities (2005-2010). The action plan included concrete activities to help member cities reduce and manage solid waste, improve air quality, promote urban environmental planning, conserve and improve water quality, build management capacities particularly through the use of Information Communication Technology (ICT), and increase energy conservation. Member cities' lack of capacity and appropriate technology as well as difficulties of procuring financial resources, were noted.

Cooperation for capacity-building, financing, technology transfer, and institutional strengthening were identified as possible mechanisms to address these challenges. The Network has also proposed the outline of eight functions as follows:

- Assistance in the preparing and implementing of integrated and sustainable urban development plans and strategies with quantitative indicators.
- Periodical monitoring of implementation and progress in terms of quantitative indicators.
- Promotion of information exchange and sharing of experiences among participating local governments.
- Provision of a platform for the transfer of technology and know-how packages, good practices and a successful municipal/regional model for sustainable development.
- Links, catalysation, and facilitation of internal and external financial support for international cooperation initiatives to network local authorities.
- Facilitation of capacity-building activities for environmental administration staff in participating local governments.
- Promotion of environmental education program in inter-city cooperation such as student exchanges.
- Encouragement of private enterprises to participate in infrastructural development and environmental quality enhancement program.

2.1.4.7. The International Solar Cities Initiative

The International Solar Cities Initiative (ISCI 2004) is a new organization for sustainable action in urban energy management worldwide. It is a partnership between concerned cities and researchers involved in climate research, renewable energy and urban design. The emphasis is on total-city energy planning, based on a universal per capita emissions target for atmospheric sustainability by 2050. All ISCI cities will use the same per capita target. This target will be consistent with the Intergovernmental Panel on Climate Change (IPCC) and 2050 population estimation data. It is initially set to two tons of CO_2-equivalent in GHGs per head, which is consistent with a 2050 global target of 450 parts per million by volume of CO_2-equivalent. ISCI pathfinder cities will provide other cities with much needed practical examples of cost-effective, sustainable energy planning that can achieve these goals.

The ISCI project has not focused on small-scale isolated demonstrations or expensive, but ineffective, public relations projects. The goal of the initiative is to support energy and climate policies by stimulating the interest of cities into becoming benchmark cities that commit themselves to ambitious emission reduction goals. ISCI will support this goal by:

- Developing recommended agreed targets for emissions reduction by 2050.
- Encouraging participant cities to use backcasting planning from the 2050 target to assess the appropriateness of interim targets and projects.
- Providing a forum for the exchange of scientific and technical knowledge, developed by high-level experts in the field of renewable energy and cooperating urban planners, through journals, electronic media and conferences.
- Creating international technical standards for baseline studies, and a scientifically acceptable modeling framework for the unbiased comparison of different technical and policy measures.
- Assisting the development of regional and international projects and educational programs that implement renewable energy and energy efficiency.
- Assisting member cities in the coordination of global emission targets with other social, economic, and environmental goals.

- Encouraging cities to participate in new business opportunities created through the use of advanced emissions reduction techniques.

2.1.4.8. The International Council for Local Environmental Initiative

The International Council for Local Environmental Initiatives (ICLEI 2006) was founded by local governments at the United Nations Headquarters in New York in 1990. ICLEI's mission is to build and serve a worldwide movement of local governments to achieve tangible improvements in global sustainability with a special focus on environmental conditions through accumulative local actions. Recently, over 475 local governments have joined the association. ICLEI is an open association and the vision is as:

- A growing association of local governments dedicated to sustainable development.
- A high-energy, flexible movement of local governments working together in networks to improve performance supported by campaigns, programs and strategic alliances.
- An effective sustainability and environmental agency demonstrating creativity and excellence both in developing cutting-edge solutions and in program design and execution.

ICLEI develops and runs a range of campaigns and program that address local sustainability issues. It offers the opportunities of joining pilot projects and receiving support and guidance for implementation. ICLEI’s selected priority program areas include building sustainable communities and cities, protecting common global interests, and involvement in governance and sustainability management.

2.2. Factors driving energy consumption

Modern forms of energy empower human beings in countless ways by reducing drudgery, increasing productivity, transforming food, providing illumination and transportation, powering industrial processes, conditioning space for households and buildings, facilitating electronic communications and computer operations, etc. Patterns of energy use vary dramatically, in ways that reflect and intensify social and economic inequities. However, the prevalent pattern and profile of energy use today raises important questions about the links between energy and the economy, environmental protection, society and security. In the previous sections some of the physical determinants of energy used in the cities, as well as impacts, were outlined. At the city level, similar to the national level, there is a need to understand the mechanisms of the driving forces behind energy consumption. A sound understanding of these factors is essential to follow the energy use patterns and trends. The following sub-sections describe the factors that drive energy consumption in the city.

2.2.1. Urban demographic changes

There is no question as to whether or not population and the sizes and numbers of households affect energy use in the city. Tokyo’s population has been stable since the early 1970s. Beijing and Shanghai’s populations have been growing, especially since 1980, but less rapidly than other similar cities in Southeast Asia. Much of this growth is attributable to migrant populations. Changes in the political boundaries such as there have been in Beijing have often resulted in drastic population changes (IGES 2004).

The number of households is obviously increasing primarily due to the rapidly decreasing size of the average household. The population of Shanghai is greater than that of Tokyo, but has fewer households. The number of households could be a more important determinant of energy use than population.

Another important aspect of demographic change is the difference between the daytime population and that of the night-time. Tokyo attracts a significant number of commuters who are not counted among the resident population. One-third of the total workforce commutes from surrounding cities and prefectures utilizing its well-developed railways and subways. The ratio of the daytime to night-time population increased from 1.15 in 1975 to 1.25 in 1999 in Tokyo, and stabilized after 1990 (TMG 2000; IGES 2004). Bangkok has a similar trend to Tokyo, during the morning and evening people travel from outer Bangkok Metropolitan Area (BMA) and outlying cities to inner BMA for their work and schooling. Another issue concerns the immigrants, who live in Bangkok but are not registered as residents this makes Bangkok more complex and difficult to predict. In Beijing and Shanghai the situation is in contrast with Tokyo and Bangkok (Yoon & Araki 2002).

2.2.2. Patterns of urbanization

Patterns of urbanization, such as urban population density, the structure of urban functions, urban geography, and land use patterns, are important determinants of energy use in a city. These basics have to meet the fundamental needs of the growing urban population and its quality of life while using natural resources in a sustainable way. For example, a compact city may have lower per capita energy consumption due to its compact infrastructure and lower per capita building floor space, both traits that reduce energy consumption. In Japan, the per capita energy consumption in dense urban areas is lower than that in non-urban areas. Developed countries exhibit a similar relationship. In contrast, cities in China and Thailand report the opposite trend, which is that city residents use more energy (Ichinose et al. 1993; Harasawa 2002). This can be explained by the income gap between urban and rural areas in Japan, where density has a clear influence on per capita energy use. In contrast, in China and Thailand, as well as other developing countries the effect of the significant income gap surpasses that of density for commercial energy uses and the effect of density is often not seen.

Corresponding to the IGES (2004) report, the energy and CO_2 performances in terms of a cumulative index of economy and per capita energy/emission of Tokyo are better than those of Beijing and Shanghai, this is partly due to the density effect. This density effect is especially significant in the central business districts of cities. This is because large cities in China, such as Beijing, have a combination of urban and rural settlements. The traditional urban structure of Tokyo is a central core; it plans to adopt a multi-core urban form that might have significant implications for energy use. It is also characterized by mixed land use. In Beijing and Shanghai, urban zoning for industrial and other activities has become common practice in the last few decades. The exact implications for energy use in regards to the relocating of industries from residential areas to designated industrial zones are difficult to quantify. Although, such measures in the residential areas of Shanghai and Beijing have resulted in reductions in the concentration of air pollutants (Stubbs & Clarke 1996).

In Bangkok, the inner city districts are densely populated and the land has already been utilized to near saturation point. Land use patterns in this area include commercial ventures, residential quarters, government offices, education establishments and temples. Intensification of the land usage is characterized by vertical developments in the form of high-rise buildings for offices and dwellings. Therefore, in this area only the middle and high-income groups can afford to live where a good infrastructure is available, which is significant for energy use.

According to contemporary models of a sustainable city, three city models are currently debated: the compact city, the decentralized concentration and the short cycles city (Frey 2004). Their supporters suggest that all of these cities are models for sustainable urban development.

2.2.2.1. The compact city

Generally, a compact city refers to a city with a high-density population. Supporters of the compact city suggest that it has urban qualities not provided by sprawling cities. They say that it is efficient in terms of the distribution of human activities and in its optimal use of its infrastructure and viable public transport and non car-based transport systems. There is the preservation of valuable land and energy through dense development, good access to workplaces, services, facilities and a reduced need to travel. A high quality of life, a safe and vibrant environment, and support for businesses and services as a result of the concentration of activities within in urban quarters. There are reduced levels of pollution, as a result of reduced car usage. There is also potential for socio-cultural vitality and diversity, and many options for a wide range of activities, social amenities, and cultural facilities (Frey 1999; Girardet 2001; Lloy-Jones 2004).

2.2.2.2. The decentralized concentration

Supporters of the decentralized concentration or the polycentric city model stress that the process of a diffusion of people and urban activities has not simply led to urban sprawl but to the emergence of new more polycentric patterns of urban development with a greater specialization of functions between centers and a growing significance on networks of cities (Breheny 1992; van der Valk & Faludi 1992; Knights 1996; Frey 2004; Lloyd-Jones 2004).

An urban structure with compact and dense settlements and centers away from the principal center and conurbation is seen as a realistic compromise between compaction and dispersal. This group also argues that the compact city has a number of serious deficiencies. For example, its negative impact on the countryside and the economic development of rural communities, increased congestion and pollution, reduced amenity space and privacy, and increased social segregation due to high-priced housing in the city's core and suburbs (Frey 2004; Lloy-Jones 2004).

2.2.2.3. The short cycle city

This model is a further development of decentralized concentration through the inclusion of ecological and environmental principles. It is associated with the environmental thrusts of Local Agenda 21 and an emphasis on achieving local environmental sustainability through more efficient local use of natural resources and recycling, greater local autonomy, and smaller ecological footprints (Barton et al. 1995; Lloyd-Jones 2004).

In structural terms this model responds to the existing nature of today's sprawling cities and can be adapted and implemented in various urban forms like dense city cores and new green field development. This model aims to increase the quantity, quality and accessibility of green spaces in the city. To enlarge and integrate the green structures (for example, through green networks and the landscaping of the public realm), giving additional possibilities for recreation and leisure, and having an intentional ecological impact on the microclimate of the city and reducing the impact of pollution (Frey 2004).

2.2.3. Income growth and social change

It is well recognized that rapidly industrialized countries as well as those in economic transition like China and Thailand yield high economic growth. Tokyo experienced sustained economic growth from the early 1960s until it went into recession in the early 1990s. Double-digit growth in Beijing and Shanghai has continued since 1990 (IGES 2004). The financial collapse in Thailand during 1997-1998 had obvious implications for Bangkok, but Thailand has regained growth rates of the GDP at approximately 5% per year since 2001 (DEDP 2000). Economic growth in the city has led to an increase in income, which in turn affects the lifestyles of residents. For they can afford to consume more material goods, follow fashions, and pursue leisure activities. Hence, they use more energy. Figure 2.2 shows the trend in GDP per capita in China (not including Hong Kong and Macao), India, Japan, Korea, Malaysia, Singapore and Thailand.

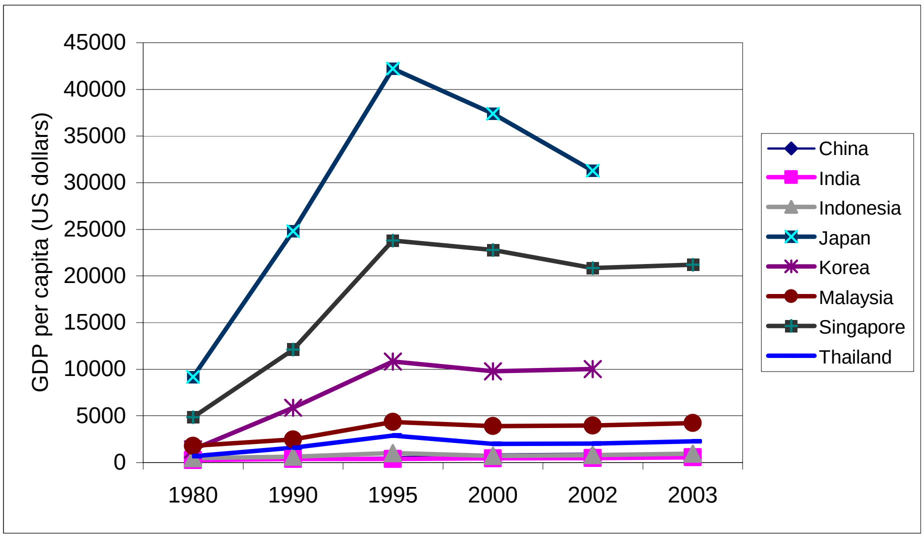


Figure 2.2. Trend in GDP per capita in selected Asian countries (IGES 2004).

Currently the studies in public and political concern about energy and its impacts are increasing. In fact, efforts to empirically examine, theorize, and model the dynamics and consequences of societal energy use have been pursued for more than 20 years. But understanding energy consumption is far from being a straightforward matter (IGES 2004). It is obvious that energy flows are produced and shaped by human actions. This consumption occurs via a complex of fuel flows, energy technologies and regulatory systems. The flow is determined by a fairly complex interplay of socio-cultural, geographic, technological and institutional factors (Stern 1993).

The social sciences have produced fairly good pieces of work on the role of energy and energy technology in society e.g., Cottrell 1955, Mazur & Rosa 1974, White 1975, Adams 1975, Duncan 1978, Buttel 1979, Humphrey & Buttel 1982 and Olsen 1991. A large amount of literature also focuses on the connections between social status and consumption, including the construction of status via the stylized consumption of food, clothing, music, language, automobiles, housing and appliances (Ewen 1976 & 1988; Cowan 1989; Featherstone 1990 & 1991; Gartman 1991).

The interdisciplinary literature that is directly concerned with the consumption of energy suggests that social structure and cultural practice are indeed central to the structuring of energy consumption. The significant differences in energy use are observed between income groups, across the stages of a life-cycle and among ethnic subcultures (Lutzenhiser 1992; Lutzenhiser & Hackett 1993).

According to the study on socio-technical household energy consumption by Lutzenhiser (1997), using the data from a major survey of housing, energy use and household technology in northern California. This data showed considerable variation in the energy consumption across sample households, with distinct differences in consumption by sub-groups defined on the basis of both social stages e.g., life-cycle, wealth, ethnicity, and also technical stages e.g., age, type, size of housing and types of appliances. A series of multivariate models were estimated and these socio-technical models offer a good match in accordance with the data. They suggested that both the behavior of social groups and their material conditions contribute to the structuring of consumption in a variety of ways. A second-stage analysis using regression estimates and subgroup characteristics showed that various combinations of behavior, housing and technology were responsible for shaping consumption quite differently across social groups. Rates of energy input and pollution were also found to be socially variable.

From the study mentioned above it can be concluded that the social system is a primary determinant of energy consumption. In a system of status-graded lifestyles, volumes of energy flow provide rough measures of social standing. The poor being excluded from all but the most modest forms of consumption, while middle class consumption is centered largely on housing and technologies, and the wealthy are empowered in a variety of ways by high levels of energy flow.

2.2.4. Structure of economic activities

From the city point of view the volume of the Gross Regional Product (GRP) and energy demand have a direct co-relation since economies heavily rely on energy sources. In Tokyo, the growing population, high population density, noise and environmental problems related to primary industries are forcing industries to relocate away from city centers to the outskirts and peri-urban areas. Therefore, Tokyo is dominated by service industries and is becoming a commercial city. The share of the tertiary sector in total value added has risen from 67% in 1980 to 78% in 1997 (Dhakal & Kaneko 2002). There are similar trends in other cities in China, Japan, Korea and Thailand that are following Tokyo's pattern.

In Bangkok, a gradual shift from primary industries to tertiary and commercial activities has followed the Tokyo model. The primary industries have been moved from the inner Bangkok area to the city's outskirts, but there are still many SMEs in the city center. In contrast, Beijing and Shanghai are industrial cities. As a result, the industrial sector is expected to play a major role in energy demand in Beijing and Shanghai.

A study by the Asian Development Bank indicated that the high income countries show strong co-relations between the fall in agricultural employment, generally declining rates of manufacturing and industrial employment, and a strong growth in employment within the service sector. The middle-income countries show a more mixed pattern with declines in agricultural employment countered by a variable increase in the manufacturing and service industries. The low-income countries remain dominated by agriculture with little growth in manufacturing but significant growth in the service sector. Within these co-relations there is clear evidence of the increasing importance of the macro-economy of mega-cities (Prabhavalkar 2002).

2.2.5. Lifestyle and the level of consumption

Lifestyle and the level of consumption regarding goods and services are significant factors that can either increase or decrease energy consumption in the residential sector. A number of determinants, particularly the scale and intensity of cooking, lighting, electrical appliances and space conditioning devices, influence the use of energy in a household. Consumption can be viewed as the motor propelling an economy in that the producers will fabricate only the goods and services that consumers want to buy. Most environmental degradation can be traced to the extraction of energy resources and other materials with their transformation to produce (both directly and indirectly) the goods and services valued by consumers (Duchin 1997). The patterns of goods consumption could alter, which can alleviate the pressures on energy utilization.

The lifestyle and consumption level can be concerned with individuals. An individual's behavior is tightly linked to his or her employment. In fact, the income earned has to cover the costs for purchased goods and services. Consumption behavior is also related to other people's employment and consumption. A household generally comprises of one or more paid workers. At least a portion of the income they earn is pooled, based on various kinds of negotiations to pay for both common purchases and financially dependent individuals. A household's lifestyle refers to the jointly determined work and consumption practices of its members (IGES 2004). A society often believes that its quality of life generally increases with higher consumption levels. In other words, the higher the consumption of goods and services is the better the quality of life is. This belief has to change.

Lifestyles are reflected by consumption patterns, but they also encompass other elements such as time, social identity, education, employment, family status and cohort. When looking at the entire life of a person or a household, time and budget constraints become relevant variables that can be addressed. It is also a more appropriate level in which to understand social dynamics and wealth accumulation. Cohort effects can then be evaluated and related back to individual issues (Schipper et al. 1989; Jalas 2002; Perrels 2002).

In most developing Asian countries, significant economic and lifestyle changes have been taking place. For instance, the Chinese have continued to require a larger quantity and better quality of energy. People directly consume energy for lighting, cooking and other daily uses. But they also aspire to a higher quality of life by purchasing fashionable goods and services. All of these products and services obviously consume energy during their production processes. On the other hand, they also indirectly consume energy through the act of purchasing these products.

In the U.S., the Empowerment Institute (EI 2005) claims that their Sustainable Lifestyle Campaign, which is working for over 30,000 people in the U.S., has achieved the following average resource savings per year. Namely, 35-51% less garbage sent into the waste stream, 25-34% less water used, 9-17% less energy used, 16-20% less fuel used for transportation and US$ 227-389 saved through the more efficient use of resources. However, it is not clear how representative and reproducible these numbers are.

Recently UNEP has suggested using the life functions of nutrition, mobility, housing, clothing, health, and education as a way to organize its work on Sustainable Consumption and Production (UNEP 2002). These functions can be seen as components of lifestyles. Moreover, the counterparts to these functions are products and services. This is a useful manner of organizing the analysis of sustainable consumption issues. The discussion about sustainable consumption suggests focusing more on the following factors: the available infrastructure, the nature of the energy system, the properties of products and services available, and through habits, social expectations and long-term decisions, which shape the long-term development of society (Hertwich 2003).

2.3. The metabolism of a city

As a city is a dynamic system it is therefore important to understand trends in energy use over time. Like the human body, a city can be characterized by its metabolism, where energy and materials are used as input and waste as output. The metabolism approach is a powerful metaphor for the illustration of the processes that mobilize and control the flows of energy and materials through a city. Understanding how a city works as an ecological system will help take control of the vital links between human actions and the quality of the environment. Hence, the knowledge of human-induced energy and material flows with comparison to those of natural flows is a major step towards the design of sustainable development schemes.

2.3.1. City as an ecosystem

The impact of cities upon the environment has not always been the same. Cities in developed countries have largely overcome their traditional environmental problems such as waste water removal, sanitation, water supply, indoor air pollution, etc. Thus the attention has turned to their impact on ecosystems further away as well as those that are larger in scale. Cities in the developing world are more concerned with other issues. Challenges for urban development in developing countries have been divided into two categories: inefficient modes of resource use (for example, in the water or energy supply) and a limited capacity for the absorption of pollution and flooding. Brandon & Ramankutty (1993) classify the key urban environmental challenges in the Asian region as water pollution, air pollution, solid waste management and inappropriate land use.

A study of urban energy and environmental problems requires an interdisciplinary approach, which in turn requires an interdisciplinary language. One interesting approach is the system theory as applied to ecology (Odum 1989). At the heart of the system theory is the definition of a system in terms of its boundary, the flows across the boundary and the links within the boundary. Changes in the status of the system depend on positive feedback, which enlarge or otherwise enhance the system, and negative feedback, which reduce it. At the global scale, environmental change is studied as a set of bio-geochemical cycles, following such key elements as water, carbon, nitrogen, sulfur, phosphorous and the other nutrients on which plants and animals depend (Munn 1986; Lovelock 1991; Nisbet 1991). The rate at which a particular particle moves through a cycle may be measured through the study of environmental pathways, which show how much time a particle may stay in various environmental media (Mackay 1991). One aspect of this study, of interest to plant and animal health, is the tendency for harmful residues to accumulate in flora and fauna, a process known as bio-accumulation. On a global scale, this accumulation occurs in sinks such as the atmosphere, the ocean, or the vegetal mass of plants and trees.

So far, the language sounds more or less biological, but it can easily be transformed into something more familiar to the engineers. As mentioned earlier, an ecosystem is a biotic assemblage of plants, animals, and microbes, taken together with their physico-chemical environment. In an ecosystem the biological cycle of materials is maintained by three groups, which are producers, consumers and decomposers as shown in Figure 2.3. The producers are plants and some bacteria capable of producing their own food photosynthetically or by chemical synthesis. The consumers are animals that obtain their energy and protein directly by grazing, feeding on other animals, or both. The decomposers are fungi and bacteria, which decompose the organic matter of producers and consumers into inorganic substances that then can be reused as food by the producers. They are the recyclers of the biosphere. Nature is capable of sustaining the producer-consumer-decomposer cycle indefinitely, with the sun as the energy source. The smallest such entity that is self-sufficient is an ecosystem (Ayres & Simonis 1994).

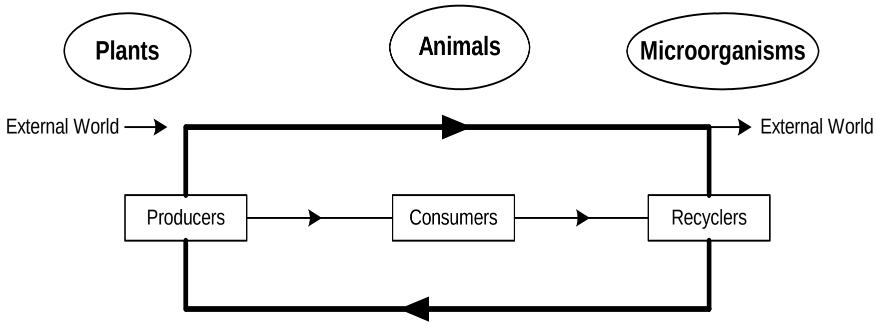


Figure 2.3. The movement of chemicals and materials through the natural ecosystem (adapted from Ayres & Simonis 1994).

Functionally, human activities that perturb the natural environment can also be divided into three similar components (Figure 2.4). This human-induced system is called an anthroposystem. Productive activities include energy production (fossil fuels), manufacturing (non-fuel minerals) and growing food. The consumers are humans and their domestic animals. Decomposing or recycling activities include treatment of waste water and the recycling of metals. However, whereas an ecosystem relies on its decomposers for a complete recycling of its elements, the system created by human activity lacks such efficient decomposers and recyclers. As such, manufactured materials that are no longer needed and the by-products of industrial activity are disposed of within the physical environment. The process of adding unwanted material to the environment is called pollution. The waste products are taken by the atmosphere and the hydrosphere, and delivered into the biological and geochemical receptors. In this sense, the anthroposystem is a system more open to the engineering point of view (Ayres & Simonis 1994).

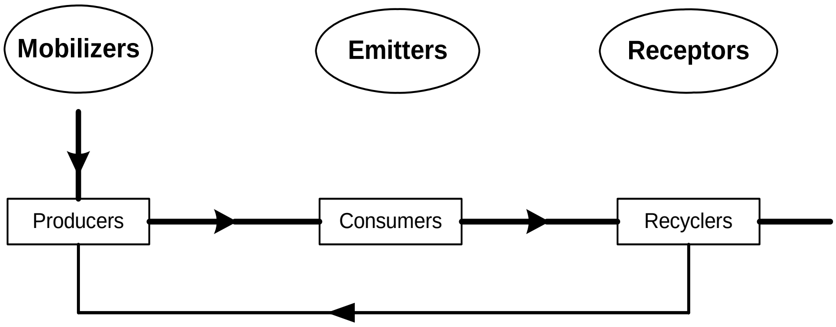


Figure 2.4. The movement of chemicals and materials through a system resulting from human activity (adapted from Ayres & Simonis 1994).

The above models provide a convenient framework for comparing an ecosystem to an anthroposystem. The flow of material in both systems is illustrated quantitatively by the arrows in the figures. In an ecosystem most of the material is transferred from the producers (plants) to the recyclers (bacteria); only a small fraction is passed through the consumers to the recyclers. The decomposers (recyclers) return most of the material to the producers for reuse. In the anthroposystem the flow from the producers to the recyclers is small or even non-existent, since it would be pointless to produce (mobilize) material and immediately recycle it without a consumer within the loop. In this system, much of the mobilized material is transferred to the rest of the external environment by the producer or by the consumer. Hence, it is an open system with recycling accounting for only a small fraction of the mobilized matter.

In an ecosystem, recycling and sustained development (evolution) is facilitated by the close physical proximity and functional matching between producers and consumers. The physical proximity of producers, consumers, and recyclers in an ecosystem (e.g., plants, animals, and bacteria) assures that very little energy is required for the physical transport of matter between the plant and its symbiotic bacterial population. Also, the physical proximity allows a reasonably fast mutual adjustment if there is a perturbation in the system. In the anthroposystem, on the other hand, the consumers play a more significant role. There is usually a significant physical displacement between the producer and the consumer. According to this it is the amount of energy required to transfer the matter back to the producer or to a recycler. This physical separation of consumers, producers, and recyclers appears to be a major difference between the ecosystem and the anthroposystem. It can be noted that the anthroposystems differ from ecosystems mainly in that they lack efficient material recyclers that allow sustainable development (Ayres & Simonis 1994).

All of the flows mentioned by the model also occur within a city. The city can be viewed as an organism with a metabolism that can be studied. Metabolic studies can provide the basis for discussions on the desirability of changes within the type or scale of a city's metabolism, and how such changes might be best accomplished. Graedel (1995) argued that to study a city as organisms and ecosystems, and to devise ways to evaluate their environmental performance could benefit society in three fundamental ways namely, by maintaining human systems, by maintaining environmental systems and then by redesigning human systems.

2.3.2. Review of the metabolism of a city

As the center of population and human activity, a city is also the center of the flow of materials. A city gathers resources of all kinds from near and far. For example, Bangkok receives steel and copper from Sweden, porcelain from China, cars from Japan, fashionable goods from France and Italy, and machines from the U.S. Some of this material, such as the steel in buildings, is retained for long periods of time. Other material is transformed within a short time and its residues discarded. Though waste is seldom disposed of within the urban area itself, it generally moves a much shorter distance than the distance from which their progenitors were acquired. Cities are great at attracting but weak at dispersing. The metabolism of a city is a relatively new area of study, and one where much more data needs to be gathered before meaningful results can be derived (Ayres & Simonis 1994; Newman 1999; Sahely et al. 2003; Kennedy et al. 2005).

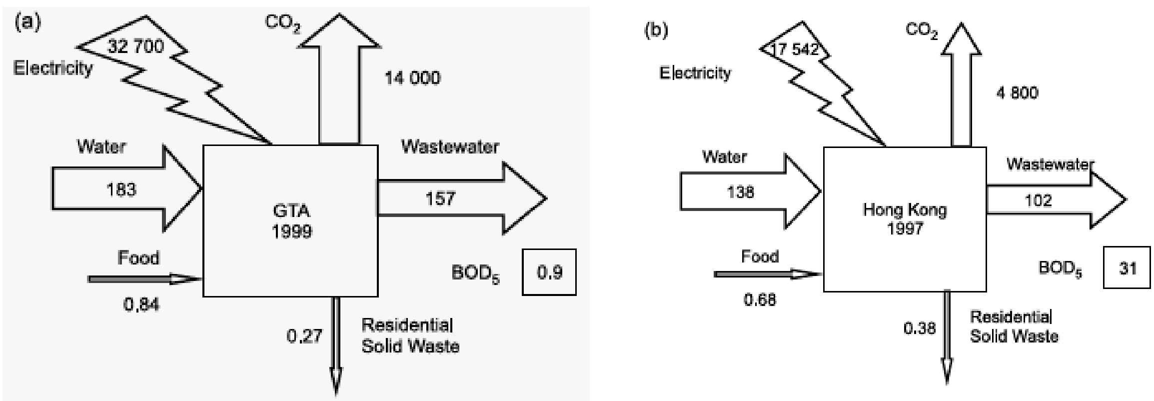
The concept of urban metabolism was first developed by Wolman (1965). He viewed the urban environment as an ecosystem and began measuring its metabolic activities. This was in the time when air and water quality was deteriorating rapidly in many American cities. Wolman used the national usage rates of water, food and fuel with the production rates of sewage, waste and air pollutants to derive per capita inflow and outflow the rates for a hypothetical American city of one million people (White 1994). Wolman's top-down approach to determining material flow, even with the omission of some inputs such as infrastructure materials, electricity and other durable goods helped to focus attention on the system-wide impacts of the consumption of goods and the generation of wastes within the urban environment (Decker et al. 2000).

One of the earliest and most comprehensive studies was that of Brussels, Belgium by ecologists Duvigneaud and Denaeyer-Desmet in 1977, which included quantification of urban biomass and even organic discharges from cats and dogs (Kennedy et al. 2005). The urban metabolism approach to studying cities continued as part of the UNESCO Man and Biosphere Project (MAB) in the early 1980s. A significant contribution was made by Newcombe et al. (1978), who studied the metabolic processes of Hong Kong. Using the previous mass balance studies, the Hong Kong study took the urban metabolism model a step further and characterized the physical indicators of the flows through the city and the social variables that affected the human population such as employment, health, mortality and satisfaction (White 1994). The study was well ahead of its time in promoting the need for a more sustainable urban environment.

The pioneering work of Newcombe et al. (1978) has since been updated by Warren-Rhodes & Koenig (2001). The combination of these studies is powerful in scope, as trends in the urban metabolic fluxes between 1971 and 1997 could be quantified and closely analyzed. In its transition from a manufacturing center to a service-based economy, and the addition of more than three million people since 1971, it seems that Hong Kong paid a high environmental price for its continued and unrelenting growth. Per capita food, water and materials consumption had surged by 20, 40, and 149%, respectively, since 1971. In addition, total air emissions, carbon dioxide outputs, municipal solid wastes, and sewage discharges had risen by 30, 250, 245, and 153%, respectively (Warren-Rhodes & Koenig 2001).

Newman et al. (1996) highlighted the use of metabolism analyses as part of a state of the environment (SOE) report for Australia. The study compared the metabolic flows for Sydney between 1970 and 1990. Apart from a few air quality parameters, there was a disconcerting upward trend in per capita resource inputs and waste outputs over the study period.

A recent study performed by Sahely et al. (2003) estimated the urban metabolism of the Greater Toronto Area (GTA) and also made an attempt at comparing the urban metabolism of a few cities worldwide. The most noticeable feature of the GTA metabolism is that the inputs had generally increased at higher rates than the outputs for the years of study (1987 and 1999). The inputs of water and electricity had increased marginally less than the rates of population growth (25.6%), and estimated inputs for food and gasoline had increased by marginally greater percentages than the population. With the exception of CO_2 emissions, the measured output parameters are grew slower than the population; residential solid waste and wastewater volumes had actually decreased in absolute terms over the 12 year period from 1987 to 1999. The study also compared the GTA with Sydney and Hong Kong. Unfortunately, these studies were conducted for different study years, and in many cases the results are not directly comparable (Sahely et al. 2003). However, to give an overview of the metabolism of the GTA and Hong Kong, Figure 2.5 shows a systems flow diagram comparing selected flows for the GTA in 1999 and for Hong Kong in 1997.



(a) the GTA 1999 (b) Hong Kong 1997

Figure 2.5. Comparison of urban metabolisms: (a) the GTA 1999, and (b) Hong Kong 1997 (compiled from Sahely et al. 2003).

In Figure 2.5, food, water, wastewater and residential solid waste are expressed in tons per capita, CO_2 and BOD_5 in kg per capita, and electricity in MJ per capita. This type of diagram is commonly used in material flow analysis and can be used as a communication tool to convey information to policy-makers as well as to the public.

Studies of full urban metabolism models with trend analysis are few and far between (Sahely et al. 2003). There are other studies of the metabolism of other cities, including those of Tokyo, Vienna, Greater London and a part of the Swiss Lowlands (Hanya & Ambe 1976; Baccini 1987; Hendriks et al. 2000; CIWS 2002). Not all studies have quantified urban metabolisms as a complete model some of them examine only one perspective. For instance, Bohle (1994) considers the urban food systems in developing countries. While a few studies have focused on quantifying the embodied energy in cities (Zucchetto 1975; Huang 1998), other studies have broadly included fluxes of nutrients and materials and the urban hydrologic cycle.

From the review of the literature, it can be seen that the model of urban metabolism has been used by engineers (e.g., civil engineers and mechanical engineers), urban planners and system ecologists. Interestingly, a thermodynamic approach to urban metabolism models has been put forward by system ecologists (Odum 1996). This approach quantifies the flows of embodied energy, which is defined as the total amount of energy needed directly and indirectly to make any goods or services (Bakshi 2000). Indices and ratios based on embodied flows can be calculated and used to evaluate different types of systems (Ulgiati & Brown 1998). This concept is adapted in this thesis; thus, the study will be focused upon embodied energy rather than a study of full urban metabolism.

2.3.3. Evaluating urban metabolism methodologies

The metabolism of a city can be analyzed in terms of four fundamental cycles, energy, material, water and nutrients. Differences in the cycles may be expected between cities due to age, stage of development and cultural factors. Other differences, particularly in the energy cycle, may be associated with climate or urban density. The detailed methodological steps of urban metabolism are outlined in the pioneering work of Baccini & Brunner (1991) and for other studies see Hendriks et al. 2000, Warren-Rhodes & Koening 2001. The major steps can be concluded as follows: (1) definition of goals and the research questions of the study, (2) system description, (3) data acquisition, (4) material balances, and (5) interpretation.

The material balances mentioned in step 4 are common to engineers. In fact, mass flow analysis has been practiced by engineers for a long time, but emphasis is usually placed on the flow of a particular substance and not on entire systems (Baccini & Brunner 1991). Since mass is not destroyed in the system. The total inputs into a process equal the total outputs plus stock increases. This basic principle holds for urban metabolism models as well. The main obstacle is obtaining sufficient data to quantify all of the relevant inputs and outputs. The following mass and energy balance equations were originally put forward by Douglas (1983) for use in urban metabolism studies (Alberti 1996):

(1) Surface urban energy balance

$$Q_S + Q_F + Q_I = Q_L + Q_G + Q_E \qquad \text{Eq. (2.1)}$$

where Q_S is the rate of the arrival of radiant energy from the sun, Q_F is the rate of the generation of heat due to combustion and dissipation in machinery, Q_I is the rate of the heat arrival from the Earth's interior, Q_L is the rate of loss of heat by evapotranspiration, Q_G is the rate of loss of heat by conduction to soil, building, roads, etc., and Q_E is the rate of the loss of heat radiation.

(2) Urban water balance

$$P + D + A + W = E + R_S + S \qquad \text{Eq. (2.2)}$$

where P is the precipitation, D is the dew and hoar frost, A is the water released from anthropogenic resources, W is the piped water, E is the evaporation, R_S is the natural and piped surface, and the subsurface flow out of the city, and S is the change in water storage within the urban fabric.

(3) Urban material budget

$$M_s = M_o + W_f + W_a + M_c + M_t \qquad \text{Eq. (2.3)}$$

where M_s is the quantity of materials supplied to the city, M_o is the materials exported from the city, W_f is the solid and liquid waste materials, W_a is the atmospheric pollutants discharged from the use of materials, M_c is the material converted through heat production or other processes, and M_t is the net addition of materials to the urban fabric and stock.

Although the equations 2.1-2.3 outline the major inputs and outputs of an urban region from a theoretical standpoint they do not necessarily set up a system that can be efficiently analyzed with the available data. For example, the surface urban energy equation does not separate man-made energy inputs from natural inputs. In addition, energy fluxes related to a loss of heat are quite difficult to quantify. They may not be so relevant to analysts. Also, they would be difficult to communicate to policy-makers and stakeholders (Sahely et al. 2003).

Nevertheless, the idea from the ecologists (Odum 1996), who put forward the thermodynamic approach to urban metabolism, as mentioned earlier, in addition to the important idea being, that the interactions between nature and society on which each socio-economic system depends constitute its relation to the natural environment, is an understanding of society as a socially organized and thermodynamically open system that has been termed anthropogenic, social and industrial metabolism (Baccini & Brunner 1991; Fischer-Kowalki & Haberl 1993; Ayres & Simonis 1994; Kate et al. 2001). A number of operational tools have been developed to analyze urban metabolism. The following section gives a brief introduction to the concepts of the well-known analytical frameworks, including Input-Output analysis (IO-analysis), material flow analysis (MFA), life cycle analysis (LCA) and ecological footprint.

2.3.3.1. Input-Output analysis

The Input-Output analysis (IO-analysis) is an analytical framework created by Nobel Prize laureate (economics) Wassily Leontief in the late 1930s (Leontief 1936, 1941, 1970) and was originally designed to analyze the interdependence of industries in an economy. Today the compilation of IO-tables is a standard in national accounting statistics in almost all countries in the world and IO-methods are routinely applied in economic analyses. Since the late 1960s, IO-analysis was extended to address economy-environment relationships, focusing predominantly on energy use and pollution (Cumberland 1966; Ayres & Kneese 1969; Leonteif 1970; Griffin 1976; Bullard & Herendeen 1977; Proops 1977; Duchin et al. 1994; Duchin 1998).

In principle, a standard IO-model is used to calculate gross output and factor inputs required to satisfy a given final demand. Alternatively, IO-tables represent: (1) the flows of commodities and services between the industries of an economy in an inter-industry flow table, (2) the deliveries of commodities and services from the producing sectors to final demand sectors in a final demand table, and (3) the requirements of primary factors of production in a factor input or value added table. The variables in the IO-tables may be measured in physical units such as pieces, tons, joules, in monetary units, or in a mixture of both.

The advantage of measuring the flows of commodities in physical units as compared to monetary units lies in the fact that physical units explicitly represent the quantity of the flows, whereas a measurement in monetary units always combines quantity and unit prices (Duchin 2004). The convention of national accounting, however, is to measure the variables in monetary units, whereas IO-tables in physical units are available only for a small number of countries and points in time. Therefore, national statistical offices routinely provide monetary IO-tables. For instance in Thailand, the National Economic and Social Development Board (NESDB) produces IO-tables every five years.

To determine resource use, as well as environmental pressures associated with additional vectors of resource use, energy inputs are needed. Usually, these tables use in a form of a unit of final energy demand. It can be seen that the IO-tables represent the material flow data of a society and together with the energy consumption data, the energy metabolism can be calculated. Hence, from a conceptual point of view, it is clear that the metabolism model can be adequately understood only if both material and energy are considered.

2.3.3.2. Material flow analysis

This method is an environmental accounting approach aimed at the quantification of metabolism. It is applicable to various geographic and institutional scales (Hendriks et al. 2000; Grunbuhel et al. 2003; Brunner & Rechberger 2004). MFA at the national level, so-called economy-wide MFA, is probably the most advanced in terms of methodological standardization and indicator development, but unavailable and uncommon in most developing countries as compared to IO-tables. The economy-wide MFAs are consistent compilations of the annual overall material throughput of national economies, expressing all flows in tons per year (Eurostat 2001).

The MFA was reinvented in the 1990s as a consequence of the growing importance of the notion of sustainable development. In recent years, methods for economy-wide material flow accounting have been harmonized and a large number of material flow studies for both industrial and some developing countries have been published to date (Eurostat 2001; Haas et al. 2005). MFA makes use of the mass balance principle known as inputs equal outputs plus stock increase. This requires a sufficiently precise definition of the physical boundaries of a given economic system and a comprehensive coverage of the inputs, outputs and stock changes (Fischer-Kowalski 1998; Eurostat 2001). For the purpose of material flow analysis, highly aggregated indicators are derived from MFA. The convention is to aggregate all solid materials i.e., biomass, gross ores, industrial and construction minerals, fossil fuels and the physical volume of traded commodities that cross the defined boundary of a system, but not water and air because the socio-economic throughput of these materials exceeds that of all others by order of magnitude (Eurostat 2001).

Overall, these indicators are intended to represent a proxy for aggregated environmental pressure comparable to aggregated energy use. However, for the purpose of evaluating environmental pressures associated to a city's metabolism, MFA cannot be used directly as it does not specify the material requirements of final demand categories. Therefore, an additional step in the empirical analysis is needed, one that makes use of other methods such as NAMEA (National Accounting Matrix Including Environmental Accounts) in combination with IO-analysis (Eurostat 2001; Haas et al. 2005).

2.3.3.3. Life cycle assessment

LCA is a tool that assesses the impacts of product systems and services, accounting for the resources used during the production, distribution, use and disposal of a product (ISO 1997). LCA has developed from the analysis of cumulative or embodied energy demand (Boustead & Hancock 1979; Casler & Wilbur 1984). It uses physical process analysis sometimes in combination with monetary IO-analysis. LCA consists of three distinct analytical steps: (1) the determination of processes involved in the life-cycle of a product, (2) the determination of environmental pressure such as resource use produced in each of those processes and (3) the assessment of environmental impacts and aggregation as impact indicators. The ISO 14040 standard for LCA defines the first two steps as inventory analysis and the third step as impact assessment (ISO 1997). ISO defines two additional procedural steps, goal and scope definition (i.e., planning the LCA) and interpretation (i.e., discussion and conclusion). LCA can be seen as constructing a causal link between production processes, associated environmental stress and the produced products (Haas et al. 2005).

The causal link can be constructed in different ways (Baumann & Tillman 2004):

(1) One can divide all of the existing emissions by the total number of products produced over a period. This is the more common, attribution mode, which attributes responsibility for the existing emissions evenly across the produced products.

(2) One can ask what happens when an additional product is produced. This marginal perspective is relevant, for example, when looking at the production of electricity, where the existing base load of coal or hydropower stations has significantly different emissions from the newly built gas or wind power plants.

LCA practice today can build on the cumulative effort of data collection. Standard LCA software already existing includes databases for many basic materials and a number of important commodities. More extensive databases, such as EcoInvent, are available for purchase. Some industry associations have produced their own data. SimaPro, the most widely used software tool now also contains data from IO-analysis, so that hybrid assessments can be constructed. The data represents conditions in industrialized countries. Data from developing and emerging countries, however, is still lacking. Hence, there is a lack of data especially on a number of agricultural products and manufactured products, and also, the available data may be biased (Haas et al. 2005).

2.3.3.4. Ecological footprint

The original ecological footprint was conceived as a simple and elegant method for comparing the sustainability of resource use among different populations (Rees 1992). The consumption of these populations is converted into a single index: the land area that would be needed to sustain that population indefinitely. This area is then compared to the actual area of productive land that the given population inhabits, and the degree of un-sustainability is calculated as the difference between the available and the required land. Unsustainable populations are simply populations with a higher ecological footprint than available land.

Consumption is divided into 5 categories: food, housing, transportation, consumer goods and services. Land is divided into 8 categories: energy land, degraded or built land, gardens, crop land, pastures, managed forests and land of limited availability. The ecological footprint is calculated by compiling a matrix in which a land area is allocated to each consumption category. In order to calculate the per-capita ecological footprint, all land areas are added up, and then divided by the population, giving a result in hectares per capita.

A number of researchers have criticized the method as it was originally proposed, for example Ayres 2000, Moffatt 2000, Opschoor 2000, van Kooten & Bulte 2000. The criticisms largely refer to ecological footprints as being an oversimplification of the complex task of measuring the sustainability of consumption, leading to the comparisons of populations becoming meaningless or the result of a single population being significantly underestimated. In addition, the aggregated form of the final ecological footprint makes it difficult to understand the specific reasons for the un-sustainability of the consumption of a given population, and to formulate appropriate policy responses (Rapport 2000). In response to the problems, the concept has undergone significant modification. The development of and debate about the method are continuing.

2.3.4. Strengths, weakness, and extending of the metabolism modeling

The study of urban metabolism can be used as part of a national environmental report, for example the study by Newman et al. (1996). One of the strengths of the urban metabolism model is that it provides parameters that meet the criteria for good sustainability indicators. The model is scientifically based on the principles of the conservation of energy and mass. In addition, Hendriks et al. (2000) highlighted that urban metabolism is a useful tool for early recognition, as urban metabolism does not rely on signals of environmental stress but rather highlights potential future problems by demonstrating changes in flows and stocks of the region. Urban metabolism can also increase the effectiveness of policy making by forcing decision-makers to consider the whole system and setting priorities accordingly.

The major limitation of the approach of urban metabolism is the availability and accuracy of data at the city level, especially in developing counties where most data is at the national level. Even in developed countries information is quite scattered and needs to be synthesized. Decker et al. (2000) provided a comprehensive review of available data, highlighted data gaps, and emphasized the need for more interdisciplinary research and integrative data analysis. A further limitation has been a tendency for the framework to focus on the biophysical environment with less emphasis on the social and economic issues.

The tool would be more useful to policy-makers and decision-makers if it incorporated socio-economic considerations. Newman (1999) stated that it is possible to define the goal of sustainability in a city as the reduction of the city's use of natural resources and the production of waste while simultaneously improving its livability. Thus, it can fit better into the capacities of the local, regional and global ecosystems. He also proposed an extended metabolism model as shown in Figure 2.6, which includes livability measures such as indicators of health, employment, income, education, housing, leisure, accessibility, urban design quality and community.

The extended metabolism model (Figure 2.6) indicates how the basic concept of metabolism can be extended to include the dynamics of settlements and the livability of those settlements so that the economic and social aspects of sustainability are integrated with the environmental. In this model, it is possible to specify the physical and biological processes of converting resources into useful products and wastes. It is based on the laws of thermodynamics, which shows that anything that comes into a biological system must pass through it and that the amount of waste is therefore dependent on the amount of resources required. This model becomes more of a human eco-system approach. Sustainability of a city is thus not only the reduction of metabolic flows i.e., resource inputs and waste outputs, it must also be about increasing human livability, including social amenities and health.

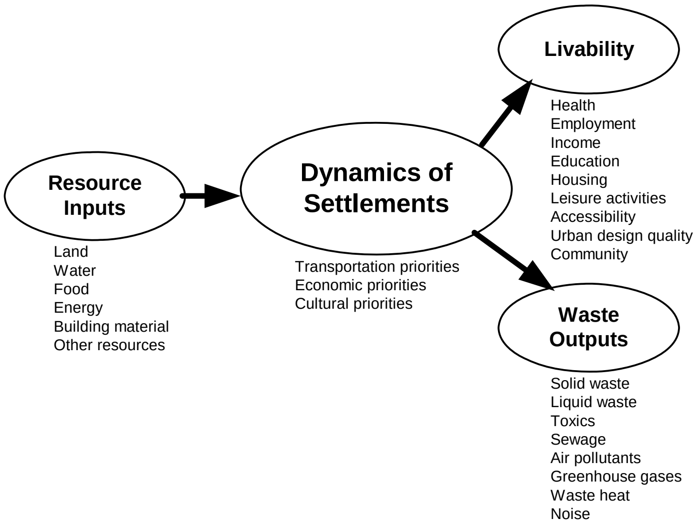


Figure 2.6. The extended metabolism model of the city (adapted from Newman 1999).

The extended metabolism model can be applied to a range of levels and to a range of different human activities. For example, the industrialists can examine the input of resources and the output of waste while measuring their usual economic parameters and other matters such as worker health and safety. A household can make an assessment of their metabolic flows and livability, and together make attempts to do better with both. An urban planner can be assessed in regards to sustainability using this model to demonstrate projects. Businesses can use the model to design sustainability plans. Also, a city can make comparisons by analyzing indicators for resource use, waste, and livability in other cities (Newman 1999).

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3. ENERGY SYSTEM MODELS AND ENERGY DEMAND ANALYSIS

The significance of energy use in cities is not very well understood, especially in Asian countries. Although a number of studies on energy consumption from various sectors (transport, industry, residential and commercial) have been conducted, most are from a national point of view. Energy demand is not considered important at the city level. Also, when analyzing energy or other social and economic systems, there are a number of factors that need to be taken into account. Computer models can help humans as a useful tool in analysis. This chapter deals with energy modeling as a tool designed to help with analyzing the energy situations, particularly at the city level. It is followed by the embodied energy analysis in selected Asian mega-cities. This analysis is based on the concept of urban metabolism as described in chapter 2.

3.1. Modeling the energy system

When analyzing energy or other social and economic systems, it is common to use computer models due to the factors that need to be considered such as time, modularity and transparency of structure, the level of complexity, the level of technological detail, etc. The purpose of integrated energy modeling is to inform discussions and decision-makers in a coherent manner and to develop insights into energy systems for reasons such as marketing services. It is important to look at the bigger picture in terms of such modeling. Basically, the models are not constructed for the sake of modeling itself rather they are tools designed to help with the analysis of some real life situations (Alfstad 2005). A model is created for a distinct purpose and it is supposed to be applied to a particular problem. There is a wide range of options and techniques available to energy analysts. The following sections describe the classification of energy system models, as well as selected well-known models used throughout the world. According to Sterman (1991) has summarized the benefits of models as:

- They are explicit. Assumptions that go into a model can be stated in written documentation and be subject to review. For complex systems, skilled professionals from various professions can critically assess the data that has been used.
- Computer models do not make logical errors. Computer models infallibly compute the logical consequences of the modeler's assumptions.
- They are comprehensive. The models can be all-inclusive and are able to relate a great number of factors simultaneously.

In order to decide on the use of one specific model, it is important to explain the differences between model structure, data, and the modeling method. A model is a simplified abstraction of a real technical energy system. The structure of the model is defined by processes and the energy and material flows between the processes. Some models can also distinguish different regions and economic sectors. A model needs technical and economic data to describe processes and flows. It also needs a set of mathematical equations to describe the behavior of the system.

The main consideration of a selected model is the method because the model can be a simulation or an optimization. Simulation is better suited to energy demand analyses or explorative analyses, while optimization is especially suited to calculate least-cost strategies under certain boundary conditions. As a general rule, simulation is easier to understand and to apply. The interpretation of the results is straightforward. Conversely, optimization is more complex and it takes more time to get meaningful results. Interpretation of results and error detection requires considerable experience. The results are sometimes unexpected, but give new insights into the system's behavior (IEA 2000; Alfstad 2005). Other considerations for the selection of a model are the possible time horizon, limitations on the number of possible processes and flows allowed by the modeler, cost and hardware requirement of the software, and the necessary engineering skills and computer literacy of users (IEA 2000).

3.1.1. Classification of energy system models

Models are built for various purposes and consequently have different characteristics and applications. They are classified according to the model category, although many models contain elements of several types and cannot unambiguously be said to belong to only one such category (Alfstad 2005). The most fundamental distinction is related to the driver of the system. In a Top-Down model, the functional details of the system are derived from aggregated macro-economic parameters such as labor, capital, interest rate, etc. In contrast, in a Bottom-Up model the driver is energy service demand and the results are produced by the structure of a detailed system of technologies. A Bottom-Up model is thus rich in technological detail, and aggregated values are based on a projection of the energy service demand and the properties of these technologies. They are mostly used in evaluation of the impacts of technology choices. In general, the available techniques to classify the energy models fall into four broad categories, ranging from economy-wide Top-Down models to disaggregated detailed Bottom-Up models (Harnish et al. 2002; Howells et al. 2002). The following section describes the basic distinctions of four different models: simulation model, optimization model, general equilibrium model, and input-output model, respectively. Table 3.1 summarizes the characteristics of the different approaches to energy modeling.

3.1.1.1. The simulation model

This model is a mimic of real systems. It has zero degree of freedom. Therefore, the solution is directly predetermined by the user. The purpose of the simulation may be foresight (predicting how systems might behave in the future under a particular set of assumed conditions) or policy design (designing new strategies for decision-making and evaluating their effect on the behavior of the systems). In other words, simulation models are a “what if” tool. They calculate what would happen under given assumptions of consumption forecasts and policies. Such a model, however, allows the user to explore different hypotheses via scenarios, and typically capture the area of interest at a macro-economic level. These models are used to investigate technologically-oriented measures where macro-economic interactions (i.e., effects of price) are less important. Simulation models have two main components, firstly, a representation of the problem being studied and secondly, a set of decision-making rules (Howells et al. 2002; Alfstad 2005).

A particular type of simulation model is achieved through accounting models. These models set up an accounting balance for the flow of energy through an economy for each given time period, usually one year. They are like assets that have equal liabilities in a financial balance sheet; supply needs to equal consumption in an energy balance. It can be explained mathematically by equation 3.1:

$$P + I - X - DS = L + C_f + C_{ne} \quad \text{Eq. (3.1)}$$

where P is total indigenous production, I is imports, X is exports, DS is stock changes, L is losses and own consumption within the energy sector, C_f is total end use, and C_{ne} is non-energy consumption.

3.1.1.2. The optimization model

This model uses technology databases containing detailed information on the intended area of application and the relevant cost aspects involved. It is also designed to determine how to make the best of a given situation. The optimization model has a goal or an objective represented by a function usually referred to as an objective function, which is to be maximized according to the alternatives given and the constraints imposed. Although this kind of model is flexible, a high level of detail often needs to be incorporated into the model for the simulation to be realistic. This requires information such as load curves and technological requirement profiles, which are not always easy to acquire. A model of this nature usually implements a form of linear programming, and tries to find an optimal solution subject to a range of constraints. The model is usually applied when considering technology-related economic research questions (Howells et al. 2002; Alfstad 2005).

The optimization model is prescriptive rather than descriptive and tells the user how to create the best situation for a related predefined goal. As opposed to the accounting model, the optimization model has several degrees of freedom. Therefore, there may be more than one feasible solution to the problem. In terms of forecasting and predicting actual behavior, one should be very careful when applying the optimization model. The output of this model should be seen as the best way of accomplishing a goal, rather than as a prediction. So, instead of being a “what if” tool, it is a “how to” tool. For instance, if the goal is to minimize cost, then users should use the optimization model. The optimization model is most useful when the situation of the problem is to choose the best from a set of well-defined options.

Furthermore, a model can be static, quasi-dynamic or dynamic. A static model generates a solution to a problem at a single point in time, neglecting any temporal development. Quasi-dynamic and dynamic models analyze the system over longer periods of time. In quasi-dynamic modeling the system is optimized for one period at a time, with the solution for one period forming the starting point for the solution of the next period. In a fully dynamic model the solutions for all periods are calculated simultaneously and an optimum for the entire time horizon is found.

3.1.1.3. The general equilibrium model

The general equilibrium model has a strong theoretical basis of market equilibrium, and adopts a micro-economic view of consumer and producer behavior. Demand elasticity is introduced and users specify a demand curve rather than a single value for the demand. Based on the analysis, the demand level can change in response to price changes. The production function used and the supported elasticities play a well-defined role in determining the results. The empirical foundation, however, is weak, and it is often questionable as to whether or not the scenarios captured are realistically represented. This type of model focuses on macro-economic research questions of national, multi-national and global significance (Howells et al. 2002; Alfstad 2005).

3.1.1.4. The input-output model

The input-output model (IO-model) is based on macro-economic interaction matrices, energy balances and labor market statistics. An IO-model is an accounting system showing economic transaction. Activities are explained against the backdrop of sectoral development, energy carrier consumption and emissions development. It is useful in analyzing the economic relationship of links among major sectors of an economy. Using IO-analysis, it is possible to project output requirements that must be met by the economic sectors, given a change in output in the energy sector of the economy. IO-model is an equilibrium model in that it assumes no surplus production or consumption. It is also a static model so that it is difficult to incorporate changing conditions into a model of this type, especially if the simulation period is over a long term. It is rather a snap-shot of the economy at one point in time. This type of model focuses on the formulation of macro-economic and sectoral research questions (Howells et al. 2002; Karkacier & Goktolga 2005).

As described above, there are several types of models pursuing different objectives, such as demand sectors analyses, minimizing goods and services costs, measuring pollutant emissions, etc. Furthermore, the modeling procedure must be iterated with respect to new issues arising from the decision framework and from the analysis of intermediate results. Such an iterative procedure must be set up to regularly update the model database, to analyze and compare different development scenarios, and to perform a sensitivity analysis that allows the users to identify the key-parameters of the case studies and to point out the effect of their variables. Table 3.2 summarizes a number of well-known and user-friendly models for energy system analysis. They are built upon different approaches e.g., simulation or optimization, and different objectives such as comprehensive and sub-system analyses.

Table 3.1. Energy model characteristics (Howells et al. 2002).

	General equilibrium model	Input-output model	Optimization model	Simulation model
Timeframe	Medium to long term	Short to medium term	Short to long term	Short to long term
Focus	Micro-economic	Macro-economic	Technology energy system with cost structure	Technology system with specific general conditions and barriers
Calibration	Usually one reference year	Usually many years	One reference year	One reference year
Critical factors	Nesting structure, elasticities	Quality of historical time series	Additional conditions (bounds)	Quality of tech. and economic
Level of detail of the energy systems	Low	Low	High	Partially high
System boundaries	Entire economy	Entire economy	Energy system	Energy system
Flexibility in terms of a sectoral question formulation	High	High	Limited	Low
Interaction and feedback with the entire economy	Considered	Considered	Not implicit, only with coupling	Not considered
Classical question formulation	Macro-economic effects of environment-economic instruments	Sectoral effects on environmentally economic instruments	Cost-effectiveness analysis	Identification of priorities for a mix of technological measures
Price-quantity-relations	Implicit	Implicit	Considered	Only in part, not implicitly considered
Rationality and market balances	In principle assumed	Not relevant	Implicit for future decision-making	Independent
Development of reference scenarios	Endogenous	Dependent on level of endogenisation, usually considered endogenous	Plausible expert assumptions	With considerable exogenous guidelines
Technology and technological development	For the most part, combined together to single or few tech.	Aggregated at the level of interacting structures	As separate tech. and explicit estimations of each future develop.	As separate tech. and explicit estimation of each future develop.
Model generator	-	-	Mostly yes	Mostly no
Strengths	Closed theoretical structure	Broad empirical foundation, sectoral disaggregation of ind. sectors	Applicable to tech. total sys., flexible application possibilities	Also usable without targeted entities for optimization
Weaknesses	Small empirical basis, often low level of sectoral differentiation	Statistical theoretical background, founded solely upon historical analyses, extensive model preparation and maintenance	Implicitly rational optimization decisions, strongly influenced by bounds	Economic influences underrepresented, based considerably on the quality of expert knowledge
Theoretical foundation	Neo-classical	Historical analysis of macro-economic interaction matrix	Optimization with regard to tech.-economic criteria	Primarily tech. determinism of energy systems
Implementation of the modelling	Decisions corresponding to nesting and elasticities	Econometric estimation of the interconnections of the matrix	Technological database with optimization algorithms	Technological database, expert knowledge
Flexibility in terms of technically detailed questions	Low	Low	High, dependent upon the level of detail of the tech. database	High for limited complexity
Flexibility in terms of the scope of reference	Medium	Fundamentally possible, low for existing models	High	Possible
Dynamics	Model inherent	Implemented in different degrees	Explicit via specific technologies	Explicit via specific technologies
Modelling supply and production	Function of production with nesting and elasticities	Interlacing structure via modelling	Endogenous	Scenarios
Modelling demand and consumption	Demand elasticities	Endogenous, in part also exogenous	In part, exogenous via scenarios, in part connected to economic	On the basis of scenarios, coming out of economic growth

Table 3.2. A summary of models used in energy-environmental planning (partially extracted from IEA 2000).

Model name	Origin	Type of model	Other information
BALANCE	IAEA, US-DOE[1]	Energy supply and energy system model	A model for the simulation of energy supply, belongs to the ENPEP family
CO2DB	IIASA[2]	Energy information system	CO_2 database
DECPAC/ DECADES	IAEA[3]	Energy information system	Database and technology chain analysis
EFOM-ENV	EU[4]	Energy supply and energy system model	Energy Flow Optimization model
EM	World Bank, GTZ[5]	Model for life-cycle assessment of power systems	Environmental Manual: a simulation model
ENERPLAN	UNDTCD[6]	Modular planning instrument	It couples a macro-economic model with a simulation model of energy sectors
ENPEP	IAEA, US-DOE	Modular planning instrument	Energy and Power Evaluation Program
ETA-MACRO	EPRI[7]	Energy-economic model	Energy Technology Assessment, a dynamic model which couples the macro-economic MACRO with the aggregated energy system model ETA
GEM-E3, E3ME	EU	Energy-economic model	Computable General Equilibrium Model for studying economy-energy-environment interactions
GLOBAL 2100, GREEN, 12RT	OECD[8]	Energy-economic model	Dynamic models based on energy technology assessment with 5 world regions
HOVA	PROFU[9]	Model for the analysis of energy conservation potential	An Excel-based with database model
LEAP	SEI-Boston[10]	Modular planning instrument	Long-Range Energy Alternatives Planning, a simulation model with environmental database
MADE	IKE[11]	Model for the analysis of energy demand	Model for the Analysis of Energy Demand, a module of the ENPEP planning tool
MARKAL	ETSAP[12], IEA	Energy supply and energy system model	MARKet ALlocation model with an user support system
MARKAL-MACRO	BNL[13]	Energy-economic model	Linked models for energy-economy analysis
MARTES	PROFU	District heating model	A simulation model for district heating production
MEDEE	IEJE[14]	Model for the analysis of energy demand	Modèle d`Evaluation de la Demand En Energie, a bottom-up model
MESAP	IER[15]	Modular planning instrument	Modular Energy System Analysis and Planning
MESSAGE	IIASA	Energy supply and energy system model	Optimization Model for Energy Supply Systems and Their General Environmental Impact
MIDAS	EU	Energy supply and energy system model	A modular simulation model
MODEST	IKP[16]	Energy system optimization model	Minimization of capital and operation costs of energy supply and demand side management
NEWAGE	IER	Energy-economic model	Quasi-dynamic model with an hybrid representation (bottom-up and top-down) of the technologies of the industry sector
PLANET	IER	Energy supply and energy system model	Long-term energy system simulation

[1]USA Department of Energy
[2]International Institute for Applied Systems Analysis, Laxenburg, Austria
[3]International Atomic Energy Agency
[4]European Union
[5]Gesellschaft für Technische Zusammenarbeit mbH, Germany
[6]United Nations, Department of Technical Co-operation for Development
[7]Electric Power Research Institute, Palo Alto, California, USA
[8]Organization for Economic Co-operation and Development, Paris, France
[9]Projektinriktad Forskning och utveckling-PROFU, Göteborg, Sweden
[10]Stockholm Environment Institute-Boston, USA
[11]Institut für Kernenergetik und Energiesysteme, University of Stuttgart, Germany
[12]Energy Technology System Analysis Project
[13]Brookhaven National Laboratory
[14]Institut Economique et Juridique d'Energie, France
[15]Institut für Energiewirtschaft und Rationelle Energianwendung, University of Stuttgart, Germany
[16]IKP Energy System Institute of Technology, Linköping, Sweden

Table 3.2. (continued) A summary of models used in energy-environmental planning (partially extracted from IEA 2000).

Model name	Origin	Type of model	Other information
POLES	EU	Energy supply and energy system model	Prospective Outlook on Long-term Energy Systems, a simulation model
PRIMES	EU	Energy-economic model	A computable Price-Driven Partial Equilibrium Model of the Energy System and Markets for Europe
SAFIRE	EU	Technology assessment model	Strategic Assessment Framework for the Implementation of Rational Energy, a simulation model for heat and power supply at the local and regional level for European countries
SESAM	Aal-U[17]	Modular planning instrument	The Sustainable Energy Systems Analysis Model for energy systems planning at local and regional scale
TEESE	TERI[18]	Modular planning instrument	TERI Energy Economy Simulation and Evaluation model
TIMES	ETSAP[19], IEA	Energy supply and energy system model	The Integrated MARKAL-EFOM System, an optimization model that produces least-cost solutions. It is intended to replace MARKAL which has its origin in the late 1970 and no longer meets modern requirements and possibilities of up-to-date software engineering
WASP	IAEA, US-DOE	Electricity supply model	Wien Automatic System Planning, an optimization model

[17]Aalborg University, Denmark
[18]Tata Energy Research Institute, India
[19]Energy Technology Systems Analysis Programme, Italy

3.1.2. The selected model in this thesis

As mentioned earlier, data about energy in developing countries, especially at the city level is quite sparse. Most of the data is from the national point of view. For example, in Bangkok the detailed breakdown of energy demand cannot be drawn from the statistical data, which is primarily at the national level. The amount of data recorded in Bangkok is usually restricted to the total consumption of the various energy forms e.g., diesel oil, gasoline, and electricity (Phdungsilp 2005). One of the primary objectives of this study is to provide a user-friendly tool for decision-makers, especially at the city level, to perform demand and supply analysis, develop forecasts and perform impact assessments. There is a wide range of options and techniques available to energy analysts who wish to use such models. Several models have been developed and used in recent years for energy planning. They vary from econometric models using linear programming to techno-economic models that analyze sectoral energy consumption at a detailed level. In this study, the LEAP model has been used to simulate the current energy situation for a given area and to develop forecasts for the future under certain assumptions.

The LEAP model was developed by the Stockholm Environment Institute (SEI-Boston) in 1997, when SEI-Boston joined forces with five leading international energy research and training institutions to create a new software tool for integrated energy and environmental analysis. For more detail of LEAP development see SEI-Boston 1995 and Heaps 2004.

LEAP is a general purpose energy modeling tool that can be used for a wide variety of tasks ranging from the preparation of energy balances and energy forecasts to policy analyses. It is a scenario-based energy-environment model. Its scenarios are based on the comprehensive accounting of how energy is consumed, converted and produced in a given region or economy under a range of alternative assumptions about population, economic development, technology, price and so on. Scenarios are developed by asking “what if” questions. For instance what if the population growth slows down? What if transportation systems are improved, What if renewable energy technologies are introduced? With its flexible data structures, LEAP allows for analysis as rich in technological specification and end-use detail as the user chooses (Heap 2004).

Important advantages of LEAP are its flexibility and ease-of-use, which allow decision-makers to move rapidly from policy ideas to policy analysis without having to resort to using a more complex model. LEAP is designed as a powerful decision support system (DSS) with extensive data management and reporting capabilities to support this requirement. More than 200 government agencies, NGOs, and academic organizations have used LEAP for a variety of tasks, including energy forecasting, GHG mitigation analysis and integrated energy planning (Heaps 2004). Analyses have been conducted for different spatial levels, including large cities, states and countries. It can be seen that LEAP is probably one of the best models for this study since it allows for a transparent arrangement of data and various flexible scenarios and energy system configurations can be developed. This model is useful in both developed and developing counties, even if data at the city level is not readily available.

3.1.3. LEAP model framework

LEAP is an accounting tool that balances production and consumption of energy in an energy system model. It is not a model of a particular energy system, but rather a tool that can be used to create models of different energy systems. It supports a wide range of methodologies, including simple trend projections, econometric forecasts, end-use analyses and engineering-based simulations or a combination of these techniques. LEAP is deterministic, in the sense that all of the outcomes are specified by the user. As such, it is a tool that calculates the implications of a set of assumptions and tells the user what would happen if these were true. Scenario analysis is at the heart of using LEAP, and LEAP provides a wide range of tools for quickly constructing, evaluating and comparing alternative policy scenarios in terms of their energy requirements, their social costs and benefits, as well as their environmental impacts.

Based on the assumptions provided by the user, LEAP balances energy flow equations, thereby identifying energy transformation and primary energy supply requirements. The requirements are back-calculated from a set of final energy demands, which form the fixed side of the first set of the equations in the accounting process. The entire system can be included within the model and the level of detail is decided by the user.

The central concept of LEAP is an end-use driven scenario analysis. Additionally, the model includes the technology and environmental database (TED), which provides extensive information on the technical characteristics, costs and environmental impacts of a wide range of energy technologies. The LEAP framework mainly contains five modules: energy demand, transformation, resource analysis, cost-benefit analysis and non-energy sector effects (SEI-Boston 1995; Heap 2004). Figure 3.1 shows the overview of the LEAP model calculation flows. The following sections give a brief description of different modules of LEAP.

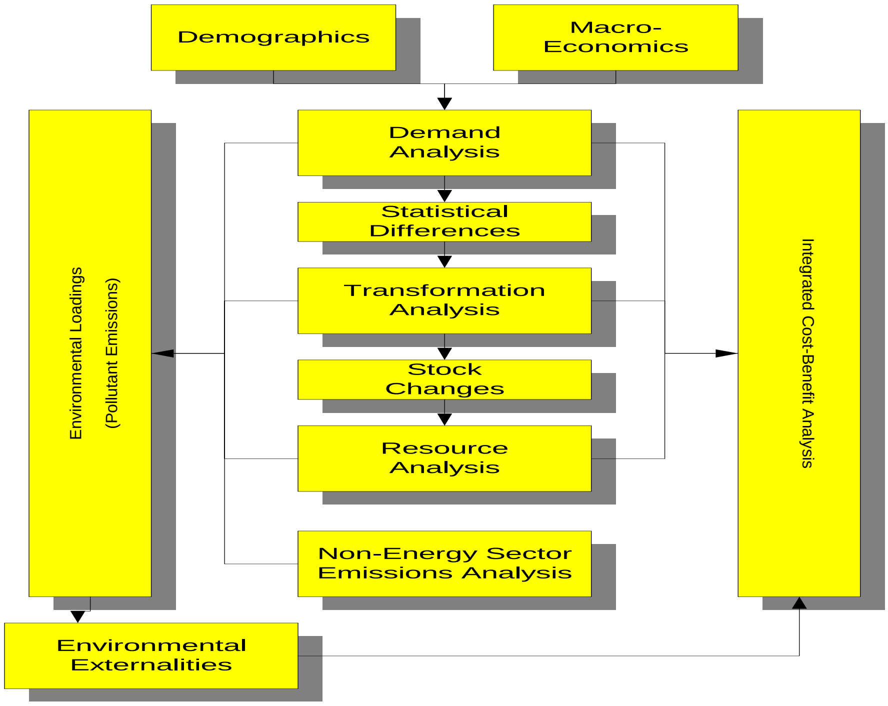
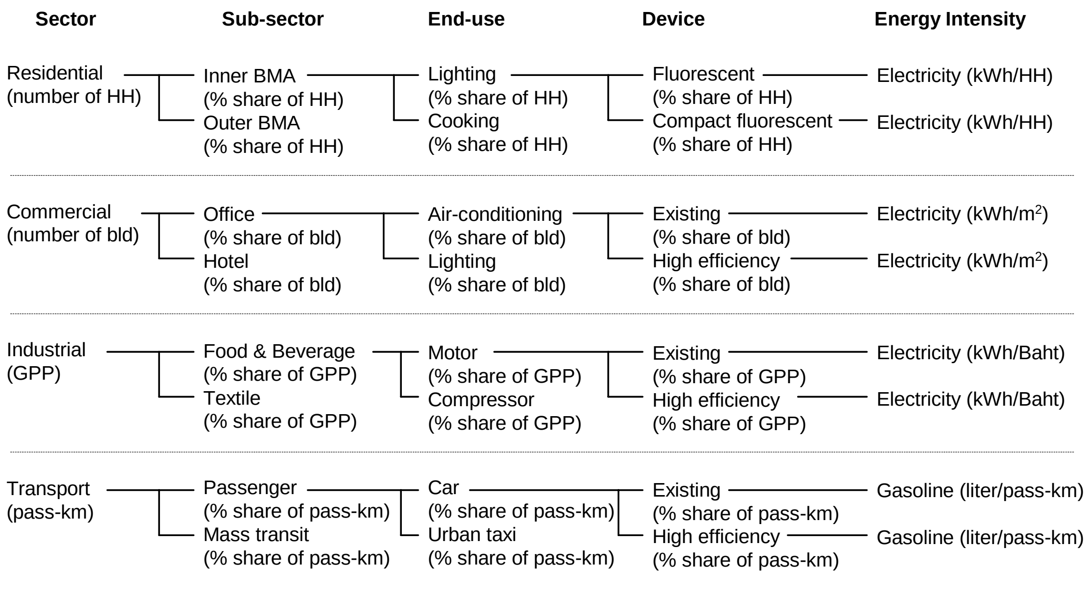


Figure 3.1. LEAP calculation flows (adapted from Heaps 2002).

3.1.3.1. Demand module

Demand analysis is disaggregated in a hierarchical tree structure of levels. It can range from highly disaggregated end-use oriented structures to highly aggregated analyses. Typically, a structure would consist of sectors: households, industry, transport and agriculture, each of which might be broken down into different sub-sectors, end-uses and fuel-using devices. Users can adapt the structure of the data to their purposes based on the availability of data, the types of analyses they want to conduct and unit preference. It is also possible to create different levels of disaggregation in each sector (Heaps 2002). Figure 3.2 illustrates the example of the tree structure in the energy demand module. This example shows a typical approach to disaggregated demand data structure in four levels representing sectors, sub-sectors, end-uses and devices. In the energy demand module the energy intensity values, along with the type of fuel used in each device, are required to estimate the energy requirements at sector, sub-sector and end-use levels.



Notes: HH stands for household, BMA stands for Bangkok Metropolitan Area, bld stands for building, and GPP stands for Gross Provincial Product.

Figure 3.2. Example of the tree structure in the energy demand module.

Similarly, the module offers a choice of methodologies that can be applied to the energy demand analysis:

- Activity level analysis, which consists of either final energy demand analysis or useful energy demand analysis, in which energy consumption is calculated as the product of an activity level and an annual energy intensity.
- Stock analysis, in which energy consumption is calculated by analyzing the current and projected future stocks of energy-using devices with the annual energy intensity of each device.
- Transport analysis, in which energy consumption is calculated as the product of the number of vehicles, the annual average mileage (i.e., distance traveled per vehicle), and the fuel economy of the vehicles (e.g., liters per km).

In fact, users can mix and match these different methodologies within each set of data. For example, useful energy analysis can be applied to the analysis of industrial and commercial heating, while final energy analysis can be employed for all other sectors. In each case, demand calculations are based on a disaggregated accounting for the various measures of social and economic activity such as the number of households, vehicle-km, tons of industrial production, commercial value added, etc. These activity levels are multiplied by the energy intensities of each activity. In addition, the emission factors of different pollutants in the TED module are linked to the device level to appraise the environmental emission from energy utilization during the planned horizon. TED contains emission factors for hundreds of energy consuming and energy producing technologies, including the default emission factors suggested by the Intergovernmental Panel on Climate Change (IPCC).

In the demand module, LEAP requires data for the base year at least (and any for future years). Then, using the functions, such as interpolation, extrapolation and growth rate method, the future energy demand and emissions are estimated for the other years.

3.1.3.2. Transformation module

Before being used, the primary energy has to be transformed through secondary energy into final energy. In a transformation analysis, the processes with their efficiencies and losses are incorporated within the model, in order to calculate the total amount of primary energy that is required to produce the final energy demand. This module simulates the conversion and transportation of forms of energy from the point of extraction of the primary resources and imported fuels all the way through to the point of final consumption. The different levels of complexity within the transformation processes can be distinguished from the simple to the more complex processes with multiple inputs, outputs and efficiencies (Heaps 2002).

The general structure of transformation modules is shown in Figure 3.3. A module is a branch representing an energy conversion sector such as the generation of electricity, oil refining, district heating, transmission, distribution, etc. Each module contains a number of processes that represent the individual technologies, which convert energy from one form to another or transmit or distribute energy. Each module has one or more output fuels; the module's processes are dispatched to try and meet any of the requirements for its output fuels.

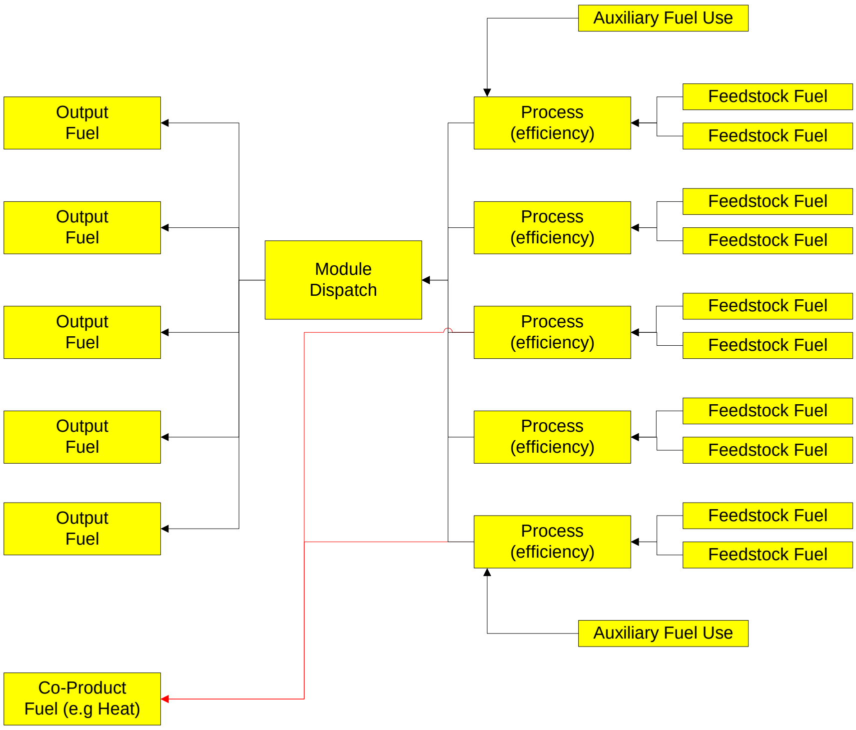


Figure 3.3. The general structure of transformation modules (adapted from Heaps 2002).

The transformation calculations are driven by the results of the demand analysis. Similar to the demand module, alternative scenarios can be used to represent different future transformation configurations, reflecting alternative assumptions about policies and technologies. This feature is useful when implementing renewable energy supply policies, for instance, the target of having 15% of electricity generated from renewable energy sources by 2025.

3.1.3.3. Resource analysis

The resource analysis is used for entering data on the availability of primary resources, including fossil and renewable resources, as well as information on the costs of indigenous production and imports, and exports of both primary resources and secondary fuels. Resource branches are always sub-divided into two categories: primary resources and secondary fuels. Fossil fuel resources require the total available reserve of the resource, while renewable energy resources require only that which is available from the resource.The availability of each resource is specified for the area as a whole. Resource availability can build up from a more disaggregated analysis, in which the total availability is sub-divided by region or some other type of classification. In terms of renewable resources analysis, this approach is useful for keeping track of resources such as biomass. It provides a comprehensive framework for the whole of the energy flow from resources (biomass) through conversion to end-use consumption (Heaps 2002).

An example of the structure for resource analysis is given in Figure 3.4 as a wood resources structure in the biomass model. Similar to demand analysis, the study area is divided into sub-areas, zones and land use types. The area is divided into two regions: Northern and Central, and both regions have two zones: forest and non-forest, each with respective land use types. For all land use types the acreage, the productivity (i.e., standing stock and average annual yield of wood or crop productivity) and the access fraction has to be specified. The access fraction represents the maximum fraction of annual yields and stock that can be used for energy purposes.

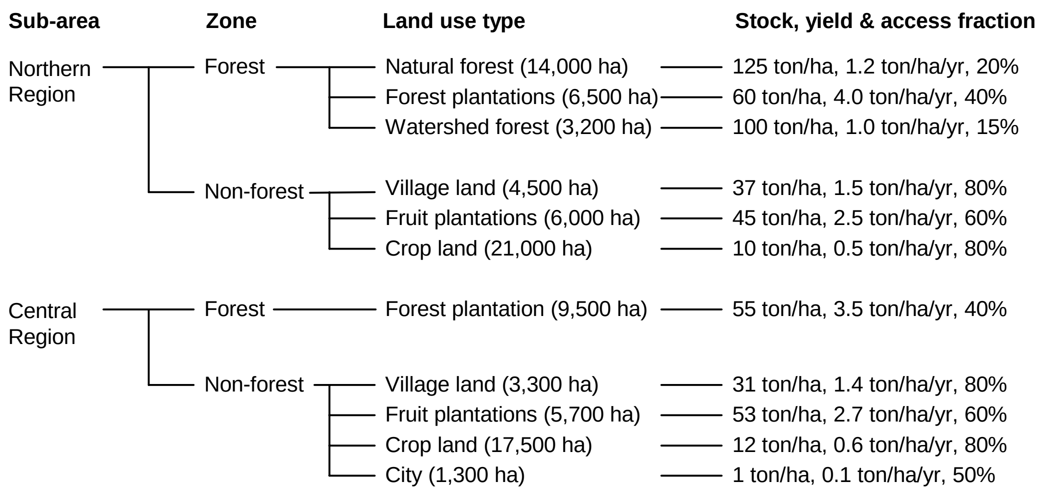


Figure 3.4. Example of a wood resources structure (adapted from SEI 1995).

3.1.3.4. Cost-benefit analysis

LEAP can perform integrated social cost-benefit analysis on the scenarios created. The cost-benefit analysis calculates the costs within each part of the energy system: the capital and operating maintenance costs of the purchase and use of the technologies in the demand and transformation system; the costs of extracting primary resources and importing fuels, and the benefits from exporting fuels. In addition, it allows examination of the environmental externalities by assigning costs to the emission of pollutants and any other direct social and environmental impacts of the energy system.

Cost-benefit analysis is based on the social costs of resources, not the final prices of the energy in respect to the consumer. It centers on the costs to society of a given set of actions. It does not take the perspective of a particular consumer or producer. Social costs and prices need to be the same. For example, electricity prices may differ from the costs of producing electricity, due to subsidies, transfer payments and market distortions.

In the LEAP model, the cost-benefit analysis is not intended to provide an analysis of financial viability. Instead, it helps identify a range of socially acceptable policy scenarios. Users specify a costing boundary e.g., a whole system including resource costs or a partial system and the costs of the fuels delivered to a module. Figure 3.5 shows the specifying limited boundary in different modules. Cost-benefit analysis calculates the Net Present Value (NPV) of the differences in costs between scenarios. NPV sums all costs in all years of the study discounted to a common base year (SEI-Boston 2005).

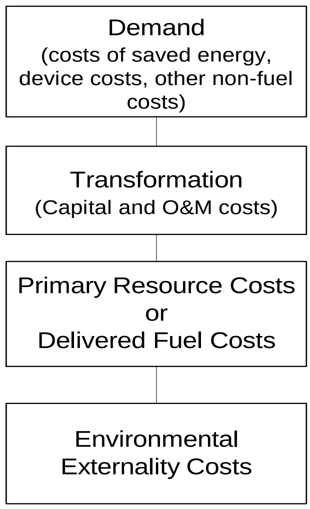


Figure 3.5. An example of a costing boundary in cost-benefit analysis (adapted from SEI-Boston 2005).

3.1.3.5. Non-energy sector effects

LEAP also has an option to create inventories and scenarios for non-energy related effects. Typically, this feature is used for inventories and scenarios of GHG emissions and as a complement to the analysis of energy sector emissions and mitigation measures such as cement processing emissions, landfill emissions, etc.

Unlike an energy demand analysis in which total effects are calculated as the consumption of the energy as product and an emission factor, in the non-energy sector users specify total annual effect loadings. Users also have the ability to analyze any number of different emission scenarios.

3.2. Estimation of urban energy use

Typically the estimation of energy demand is performed centrally. Energy production is normally accomplished in large sized facilities, which are intended to provide energy for large areas and for a long time horizon. Centralized planning goes together with a macroscopic view of an energy system. Energy representations are still highly aggregated and do not examine possible variations within the spatial distribution of the energy demand and of the energy supply sources. Since one of the objectives of this thesis is to try to integrate the maximum use of renewable energy at the city level, a much more detailed approach to energy demand needs to be developed in order to effectively integrate renewable energy into an urban energy system. In addition, the need for a city perspective within an urban energy system is intended to identify the most advantageous technologies in order to maximize economic benefits and minimize environmental damage. This section presents an overview of energy use in cities i.e., the estimation of useful energy demand, final energy consumption and demand forecasting. Considering useful energy the benefits are twofold: it will provide opportunities to integrate renewable energy into an urban energy system; and it will be useful for further study, e.g., optimization modeling such as MARKAL, which requires useful energy demand as the primary driver in the model.

3.2.1. Energy demand estimation

In many countries the detailed breakdown of the city's energy demand cannot be drawn from national statistics, this is particularly so in developing countries. The amount of data recorded at the city level is usually restricted to the total consumption of the various energy forms. Therefore, it is useful to develop a Bottom-Up approach in order to attain the required degree of detail. In this study the detailed disaggregated energy demand will be further used to illustrate the final energy demand, as well as to calculate indirect energy consumption.

The rationale behind the Bottom-Up approach is that there is no need for electricity, fuel, oil, gasoline, etc. What is needed are energy services for accomplishing various activities which are undertaken in each sector. This service is provided by means of an end-use device e.g., boiler, engine, etc., which transforms fuels, electricity or other energy forms into useful energy (Finon & Lapillone 1983). Such an approach not only provides the basis for establishing energy balances but also allows for a better approximation of the likely penetration of renewable technologies in end-use activities such as solar collectors for water heating (Sarafidis et al. 1999). However, energy services are immaterial services for the procurement of what energy is actually used for; for example, the transportation of a person or goods from A to B or the provision of air-conditioned rooms or a well-lit work place, etc. Useful energy can be defined as the energy equivalent to the work actually performed in the process of providing energy services. For example, the amount of heat released by a heating system in a room that is to be kept at a desired temperature, the drive-power actually applied to accelerate a vehicle or the light emitted by a lamp. Useful energy can be calculated from data on final energy use by multiplying the amount of final energy used for a certain appliance or process by the efficiency of this appliance or process.

Usually, the estimation of energy demand is at first common disaggregation demand and distinct end-use activities, as shown in Table 3.3. For each end-use activity energy requirements are estimated by means of technical models relating present or future energy demand to a number of known or predictable key parameters. These parameters can be classified by the following categories: (a) structural characteristics such as population, type, number and magnitude of dwellings, (b) natural characteristics such as climatic conditions and their seasonal variations, (c) technological characteristics such as the type and efficiency of the end-use devices, (d) behaviour characteristics such as lifestyle and mode of technologies used (NTUA 1996; Sarafidis et al. 1999). The procedures for estimating the useful energy demand as shown in Table 3.3 can be explained as follows (Stoll 1989):

- Space heating method: used for estimating energy needs for space heating within the building sector. It relies on a simplified model of the thermal heat balance of dwellings. Heat losses are calculated by a set of equations, which represent heat losses through the building shell and air infiltration. The key parameters used in the estimation procedure are the number and characteristics of buildings.
- Appliance saturation method: used for estimating energy needs for air-conditioning and other electrical appliances. The key parameters for the implementation of this method are the number of households and the stock of appliances (saturation level per type of appliance; technical characteristics, mode of usage).
- Floor space method: used principally for the electricity uses of the tertiary sector. It is similar to the appliance saturation method, except that end-use activities are defined on the basis of the building's cross-sectional area. Electricity needs (e.g., for lighting, air-conditioning, etc.) are expressed on a per unit of area basis. The estimation in the agricultural sector can be based on cultivation areas instead of building areas.
- Thermophysical law: is particularly used for water heating. The key parameters used are population data and other users of hot water such as numbers of tourists, water consumption per capita, and comfort standards (temperature of hot water).
- Statistical records of energy data: some statistical data for fuels and electricity consumption are usually available at the city level (e.g., the transportation and industrial sector), so that energy demand can be drawn directly from statistical records.

However, the estimation of energy demand always depends on how much detailed primary data can be obtained from statistical records, and if so, does the data available match the objective. The useful energy demand established through LEAP is based upon the projections of relevant drivers such as population growth, GDP growth, number of passengers-kilometers, number of buildings, etc.

Table 3.3. Energy demand disaggregation and the estimation methods (compiled from Sarafidis et al. 1999; Howells et al. 2002).

Demand sectors	End-use activities	Service	Method
Residential	Cooking	Useful energy	Appliance saturation
	Space heating	Useful energy	Floor space or appliance saturation or space heating
	Water heating	Useful energy	Thermophysical law or floor space
	Lighting	Useful energy	Floor space or appliance saturation
	Air-conditioning	Useful energy	Appliance saturation
	Others	Useful energy	Appliance saturation
Public	Space heating	Useful energy	Floor space
	Water heating	Useful energy	Floor space
	Air-conditioning	Useful energy	Floor space
	Lighting	Useful energy	Floor space and/or base year data
Commercial	High temperature process heat	Useful energy	Thermophysical law or appliance saturation
	Water heating	Useful energy	Thermophysical law or floor space
	Lighting	Useful energy	Floor space
	HVAC	Useful energy	Floor space or appliance saturation
	Refrigeration	Useful energy	Appliance saturation
	Other	Useful energy	Appliance saturation
Industry (and agriculture)	Thermal uses	Useful energy	Base year data or appliance saturation
	Electric uses	Useful energy	Base year data or appliance saturation
Transport	Land passenger	Land pass-km	Base year data
	Air passenger	Air pass-km	Base year data
	Land freight transport	Land ton-km	Base year data

In the transport sector, various modes of transport, such as petrol cars, diesel trucks or electric trains, convert fuel into an energy service. It is more useful to consider this service rather than the useful energy. The conversion ratio between the fuel and the service delivered is therefore referred to as intensity, rather than efficiency (Howells et al. 2002). The services delivered in the transport sector are passenger-kilometer and ton-kilometer for the passenger and freight sectors, respectively.

Hence, the final energy consumption can be estimated from the useful energy demand of the technical models compiled, with the fuels available for providing the energy required, the share of the various conversion technologies used in each activity, and the efficiency of each technology.

$$EC_{i,j} = \sum_{k=1}^{n} \frac{E_j p_{i,j,k}}{e_{i,j,k}}$$ Eq. (3.2)

where EC is the energy consumption, E is useful energy demand, p is share of technologies, e is the efficiency of technologies, i is fuel, j is end-use activity, and k is technology.

The energy demand is estimated for a base year for which all the data needed for calculating useful energy demand and final energy consumption are available. It is necessary to compare the resulting aggregated figures of consumption with existing statistical records in order to check the consistency of the modeling. This calibration procedure provides a safe basis for the energy modeling and allows for more reliable future estimates.

Energy demand forecasting typically starts by estimating for the examined time horizon the values of considered key parameters included within the technical models, as well as the expected changes in the shares of the conversion technologies and in their efficiencies. In the transportation sector for example the modal shift from private cars to mass transport is frequently considered.

3.2.2. Representing an urban energy system

For the purpose of illustrating the modeling process, the energy system can be visualized by simulating the flow of energy in various forms (energy carriers) from the source of supply through the transformation systems to the demand devices, which satisfy end-use demands. In this study a Reference Energy System (RES) type of representation was chosen. RES is a format for the graphical display of energy balances. It was first developed at Brookhaven National Laboratory (BNL), USA. It has been used for energy assessments and energy policy and planning studies throughout the world. It is a way of representing the activities and relationships of an energy system. RES describes the flow of energy from the sources to the final uses. It shows all flows of energy from the primary energy supply through central conversion and different forms of distribution, and then onto its final use within different sectors. Additionally, the RES usually contains useful information on energy demand and even energy services. A principle physical flow of a RES is presented in Figure 3.6. However, RES is not a geographical representation of the energy system. RES representation, facilitates the learning process for people who are involved in planning, since it clearly shows how different parts of the energy system interact with each other (Kanpal 1998; IEA 2000).

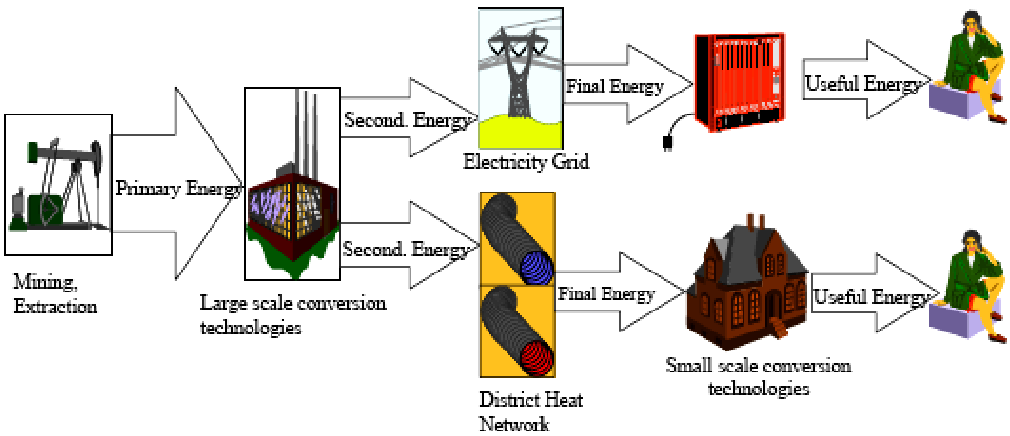


Figure 3.6. A physical representation of the RES (adapted from IEA 2000).

Through RES it is possible to see how energy flows and how energy conversion technologies influence the fuel-technology chains in an energy system. This overall perspective is particularly important when one evaluates the demand side, energy conservation technologies (i.e., the balance between supply and conservation measures) or the cost-efficiency of a proposed investment to control emissions. While the RES is a graphical representation of energy flows within an energy system, an energy balance contains the values of all energy flows. These can be included in the graphical form or be presented in separate tables. In fact, RES may contain more conversion levels like distribution, end use technologies and useful energy demands, which are not normally included in an energy balance table. It is preferred that RES it is built-up according to certain practical recommendations (IEA 2000):

- Sources and primary energy supply: the RES begins at the far left of the diagram with the input flows of energy e.g., oil, natural gas, coal, petrol and imported electricity.
- Processes: next follows the processes that modify the fuels e.g., oil refining and the preparation of pellets from the biomass.
- Conversion technologies: next the flow of energy enters the large energy conversion technologies e.g., electricity production plants, district heating and cooling plants, and combined heating and power plants.
- Distribution systems: large scale conversion is followed by distribution systems for the different energy forms e.g., electricity, district heating and cooling, and natural gas.
- End-use technologies: the next step is the small-scale energy conversion technologies e.g., oil fired boiler for multi-family houses, solar heating systems for single family houses, electrical appliances, petrol fuelled cars; and small scale combined heating and power plants. All of these technologies are supplied by final energy sources.
- Useful energy demand: the energy that is needed for different kinds of applications e.g., space heating and cooling, lighting and cooking.

Figure 3.7 shows an example of part of the RES in an energy system. In addition to the conventional energy balance and the RES, there is another representation tool that is used frequently: the Sankey diagram. In the Sankey diagram the flows of energy from input of energy to final use is illustrated by lines of different width, where the width is proportional to the size of the energy flow. This gives an immediate feeling of the relative importance of the energy flows. The energy system must often be more simplified than the RES, in order to fit all flows into one diagram. The RES representation will generally be the basis for further analyses. For presentation purposes, it could very well be supplemented by energy balances or Sankey diagrams. Another way is to use it in conjunction with optimizing models such as MARKAL. RES can be used to show different aspects of the energy system. It can also cover the total energy system but in order to make this possible the RES should be somewhat simplified. Otherwise, it will be too large and complicated for practical use (IEA 2000).

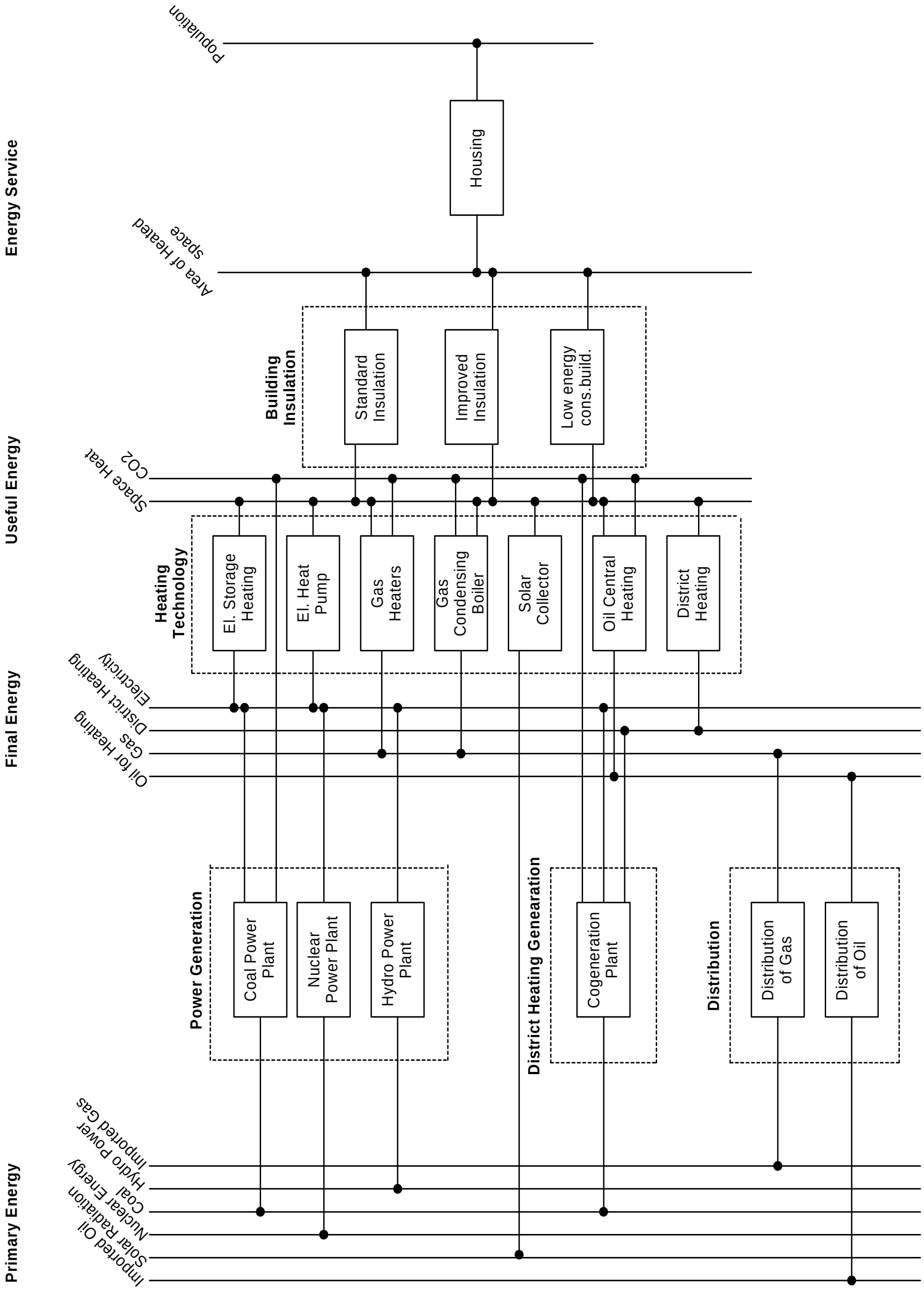


Figure 3.7. Example of part of the RES (redrawn from IEA 2000).

3.3. Direct and indirect energy demand analysis

There has been limited research at the level of the city and most studies consider direct or end-user energy consumption. The local effects on resource use in cities also need to be better understood. Since the function of a city is to serve the lives of their residents, indirect energy use in city or energy embodied in the consumption of goods and services by its residents can be regarded as being as important as direct energy use (Phdungsilp 2005). However, physical models of a city are extremely complex and have difficulty in dealing with boundary issues i.e., indirect resource requirements. The urban metabolism approach, as described earlier, can be used in order to obtain a comprehensive energy breakdown.

In this study, the concept of urban metabolism has been applied to analyze the energy demand (direct and indirect) at the level of the city. The concept of metabolism implies the processes of physical exchange or energy and material flows between human societies and their natural environment, as well as the internal energy and material flows of human societies (Ayres & Simonis 1994; Fischer & Huttler 1998). From the perspective of the metabolism concept, two types of problems can be addressed: resource scarcity on the input side and emission on the output side. It is obvious that the metabolism of a city can only be clarified if both the energy and material flows are considered. This thesis is not intended to study full urban metabolism, but rather focus on analyzing the energy flow within a city. In order to do so, the concept of embodied energy is employed. Embodied energy analysis has been used by several authors to distinguish between the indirect energy use for the production of goods and the direct energy use (van Engelenburg et al., 1994; Subak 1995; Coley & Goodliffe 1997; Phdungsilp 2005). Indirect energy use can also imply the economic dependency of the city upon the outer regions and especially highlight the environmental load displacement upon outer regions. Additionally, the ratio of direct energy use or indirect energy use can also provide information about economic structural change within the city. Furthermore, it can be used to determine the associated environmental impacts and to predict some of the consequences of social and technological development.

Indirect energy consumption can illustrate how a city relies upon the outside. Certainly, the direct energy demand can be taken as an indicator of how a city relies upon factors from the outside. However, as energy demand is a proxy indicator, indirect energy demand may provide some very interesting information that cannot easily be drawn from direct energy demand (Kaneko et al. 2003).

- A material-related indicator can clarify the dependency upon outside factors. The direct energy demand of each sector, as a pure energy-related indicator, can give little information about material reliance outside of the city. But this indicator can contribute to this query in some sense.
- Indirect energy demand is directly related to the characteristics of the sectors themselves, which can easily clarify the sectoral differences and characteristics in terms of energy or material. Consequently, implications regarding the industry structure transition can be drawn.
- Since indirect energy demand is a reflection of the industrial structure of the city, a comparison among cities at different stages of development can indicate how the evolution of industry influences the energy reliance of the city.
- Indirect energy demand illustrates how a city relies upon the outside or is relied upon by the outside. This indicator serves to clarify the role of the city in the sense of energy consumption beyond the geographical scope of the city.

This section will firstly propose a method to account for indirect energy consumption based upon the concept of urban metabolism, which provides a framework for understanding the interactions between economics and urban energy use, and then uses this method for the estimation of the embodied energy analysis. Finally, it also makes an attempt to compare direct and indirect energy demand of selected Asian mega-cities based upon the available data.

3.3.1. Model for indirect energy consumption based on embodied energy analysis

To simulate the direct and indirect energy flows within the metabolism perspective, the concept of embodied energy is employed in this research. The term embodied energy use means the total amount of energy needed directly or indirectly to make any product or service (Bakshi 2000). According to the laws of thermodynamics, the metabolism model implies that anything that comes into a system (city) must pass through it and that the amount of waste is therefore dependent on the amount of resources required. Without violating laws there should be an energy balance for each production sector within the system. This is simply demonstrated in Figure 3.8.

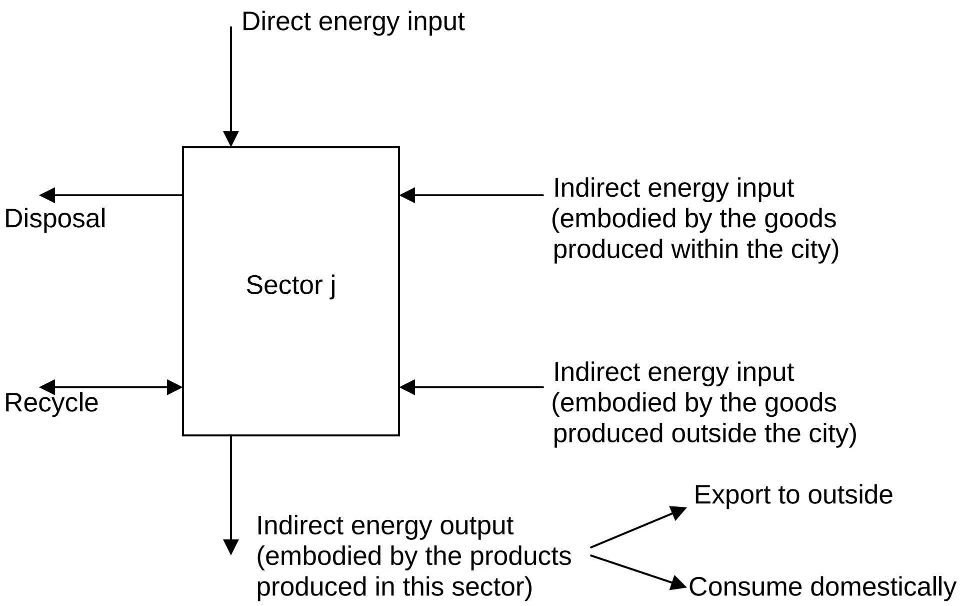


Figure 3.8. Energy balance for sector j on a city scale (adapted from Kaneko et al. 2003).

Due to the limited data of the disposal and recycle parts, this study neglects these two parts, implying that there is no material recycling or disposal by the sectors. The basic closed embodied energy model can therefore be expressed in Eq. 3.3 as follows:

$$E_j + \sum_{i=1}^{n} \varepsilon_i x_{ij} = \varepsilon_j X_j \qquad \text{Eq. (3.3)}$$

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 city, x_{ij} is the goods and services flow from sector i to sector j within that city, ε_j is the embodied energy per unit production of sector j within the city, and X_j is the gross production of sector j.

Solving the Eq. 3.3 for ε can be expressed in matrix form. The embodied intensity or embodied energy per unit production of each sector can therefore be calculated as Eq. 3.4:

$$\varepsilon = E * (X - x)^{-1} \qquad \text{Eq. (3.4)}$$

where $(X\text{-}x)^{-1}$ is referring to $(I\text{-}A)^{-1}$, Leontief's Inverse Matrix - a fundamental matrix of an Input-Output (IO)-analysis that identifies any ripple effects among economic sectors. Detailed IO-analysis is looked at in the next section.

As mentioned earlier, Equations (3.3) and (3.4) represent a closed system. However, cities are open systems that exchange goods and services with other cities and countries. For a city level analysis, the establishment of appropriate boundary conditions can be problematic. Specifically, goods and services consumed within a city can be classified as : (a) local goods produced in the city, (b) goods imported from other areas of the country, and (c) goods imported from other countries. This makes it necessary to establish a model with not only boundaries between the city and the country, but also between the country and the rest of the world. Based on the available data it is difficult to calculate the embodied energy of goods imported from other countries. In this study, the embodied energy is assumed to be equal between imported goods from other areas in the country and imported goods from other countries if they are in the same sector, but different between local and imported goods. Therefore, this becomes a single-boundary model with only a boundary between locally produced goods and goods produced from outside of the city (Kaneko et al. 2003; Phdungsilp 2005). When distinguishing between local and imported goods, Eq. 3.3 can be changed as follows:

$$E_j + \sum_{i=1}^{n} \varepsilon_i x_{ij} + \sum_{i=1}^{n} \zeta_i \overline{x_{ij}} = \varepsilon_j X_j \qquad \text{Eq. (3.5)}$$

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.

In fact, the second term in Eq. 3.5 represents the embodied energy of intermediate-input local goods, and the third term represents the embodied energy of intermediate-input imported goods.

The model in Eq. 3.5 can be applied to a competitive-imports type IO-table that clearly distinguishes between local and imported goods, but not to a non-competitive-imports type IO-table that does not distinguish between local and imported goods. For example, city level IO-tables in Japan as well as in China are usually of the competitive-imports type and rarely of the non-competitive-imports type. 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 is:

$$E_j + \sum_{i=1}^{n} \varepsilon_i \gamma_j x_{ij} + \sum_{i=1}^{n} \zeta_i (1 - \gamma_j) x_{ij} = \varepsilon_j X_j \qquad \text{Eq. (3.6)}$$

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 a kind of indirect reflection on the behavior that follows after the consumption of direct energy. To emphasize the indirect energy consumption, meaning where the goods are finally consumed, the energy embodied in those goods should be accounted as a kind of indirect energy consumption or indirect energy demand. In terms of indirect energy consumption, the end-user should somehow take responsibility for the energy consumption and corresponding emissions.

3.3.2. Calculation method for embodied intensity based on Input-Output (IO) analysis

The IO-analysis technique is applied to recur the energy related economic activities. 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 on the assumption that goods are transferred in direct proportion to their monetary value. IO-tables have been applied to the analyses of environmental issues. More information and details on IO-theory can be found in articles by Leontief (1953), Duchin (1992), and Dixon (1996).

In principle, 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 of the general form shown in Table 3.4.

Table 3.4. Principle of an input-output (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		

As shown in Table 3.4, an IO-table consists of four main parts, including 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.

The transaction table is constructed to present the relationships among major sectors of an economy. Each producing sector within the economy has a certain amount of output, which may be used within the sector, sold as inputs to other producing sectors, or sold as final demand to the consumer. The transaction table of sectors can be written as a simultaneous set as follows:

$$
\begin{aligned}
x_{11} + x_{12} + x_{13} + Y_1 &= X_1 \\
x_{21} + x_{22} + x_{23} + Y_2 &= X_2 \\
x_{31} + x_{32} + x_{33} + Y_3 &= X_3
\end{aligned}
\qquad \text{Eq. (3.7)}
$$

Where x_{ij} is a sale from sector i (rows) to sector j (column), Y_i is a sale from sector i to final demand, and X_i is the total output of sector i.

Eq. (3.7) represents an example of three sectors within the economy, so that it explains the inter-industry relationship among sectors as $a_{ij} = x_{ij} / X_j$. This expression may be rearranged to $x_{ij} = a_{ij} X_j$, which is interpreted to mean that the level of sales from sector i to sector j depend upon the level of output in sector j.

The technical coefficients show the value of the input purchased from all sectors in the economy per monetary unit (e.g., Baht, SEK, Euro, etc.) of output in a particular sector. Technical coefficients can be derived by dividing all of the entries in each sector's column by the total output of that sector as shown in the following equation:

$$
\begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\qquad \text{Eq. (3.8)}
$$

Let x_{ij} symbolize the value of sales from sector i to sector j, and X_j the total output of sector j. Then the technical coefficient or input coefficient for each sector is calculated by using the following equation:

$$
a_{ij} = \frac{x_{ij}}{X_j} \qquad \text{Eq. (3.9)}
$$

Then, the Eq. (3.9) can be written as follows:

$$
x_{ij} = a_{ij} X_j \qquad \text{Eq. (3.10)}
$$

Substitution Eq. (3.10) into Eq. (3.7), rewrites the equations for the producing sectors as shown below:

$$
\begin{aligned}
a_{11}X_1 + a_{12}X_2 + a_{13}X_3 + Y_1 &= X_1 \\
a_{21}X_1 + a_{22}X_2 + a_{23}X_3 + Y_2 &= X_2 \\
a_{31}X_1 + a_{32}X_2 + a_{33}X_3 + Y_3 &= X_3
\end{aligned}
\qquad \text{Eq. (3.11)}
$$

Eq. (3.11) shows the interdependence of each sector on all of the others because it reveals that the level of output in any sector is dependent upon the level of output in other sectors, the input requirements of each sector, and the level of its final demand. Treating the final demand (Y_i) as exogenous to the sector, then:

$$
\begin{aligned}
X_1 - a_{11}X_1 - a_{12}X_2 - a_{13}X_3 &= Y_1 \\
-a_{21}X_1 + X_2 - a_{22}X_2 - a_{23}X_3 &= Y_2 \\
-a_{31}X_1 - a_{32}X_2 + X_3 - a_{33}X_3 &= Y_3
\end{aligned}
\qquad \text{Eq. (3.12)}
$$

or

$$\begin{aligned} (1-a_{11})X_1 - a_{12}X_2 - a_{13}X_3 &= Y_1 \\ -a_{21}X_1 + (1-a_{22})X_2 - a_{23}X_3 &= Y_2 \\ -a_{31}X_1 - a_{32}X_2 + (1-a_{33})X_3 &= Y_3 \end{aligned}$$ Eq. (3.13)

or matrix notation

$$\begin{bmatrix} (1-a_{11}) & -a_{12} & -a_{13} \\ -a_{21} & (1-a_{22}) & -a_{23} \\ -a_{31} & -a_{32} & (1-a_{33}) \end{bmatrix} * \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix}$$ Eq. (3.14)

or simply

$$A^* X = Y$$ Eq. (3.15)

In Eq. (3.15), X is the output matrix and A and Y are the coefficient matrix and the final demand matrix, respectively. The a_{ij} elements of the matrix (A^*) of Eq. (3.15) have the same values as the technical coefficients calculated from Eq. (3.9). Then, matrix A^* is the difference between two matrices, an identity matrix (I) minus the matrix of technical coefficients. Therefore, Eq. (3.15) can be written as:

$$(I - A)X = Y$$ Eq. (3.16)

where $(I - A)$ = A^*. The matrix $(I - A)$ is called the Leontief Matrix and then Eq. (3.16) may be rearranged as:

$$X = (I - A)^{-1} Y$$ Eq. (3.17)

Eq. (3.17) is the solution to the IO-model. The matrix $(I - A)^{-1}$ is so-called the Leontief's Inverse Matrix or simply the Inverse Matrix, and is a fundamental matrix for IO-analysis. It identifies any ripple effects among economic sectors. The elements of the inverse matrix measure the direct and indirect output levels from each sector of the economy necessary to satisfy the given levels of final demand.

It should be noted that there are two different types of prices in IO-tables: the market shipment price of the sector that has produced the relevant item, the so-called producer price, and the other called the purchaser price, which is based upon the sum of producer price, domestic transportation charges and trade margins. Most calculated embodied intensities are expressed on the basis of producer price (Nansai et al. 2002). An IO-table as described above is an accounting system that shows economic transaction, an application of the IO-technique can allow one to trace through an economy and the direct and indirect energy impact of changes in the final demand. According to IO-model, the embodied intensities can be obtained using producer prices in IO-tables, and others are obtained using purchaser prices. In this thesis, the embodied analysis is calculated on producer price, which is based on the factory gate value of a product. In the following section the calculation method of embodied intensities based on IO-tables is presented.

The treatment of imports in the IO-tables has a significant effect on the basic IO-model, regardless of whether it is based on producer price or purchaser price. If the environmental burdens (of energy use) related to the production of imported products are assumed to be identical to those of the very same domestic products, and are referred to the basic closed embodied energy model in Eq. (3.3), the total energy requirements generated by processes in sector j are the sum of the direct and indirect uses from intermediate demands that satisfy the following equation (Miller & Blair 1985; Nansai et al. 2002):

$$\varepsilon_1 x_{1,j} + \varepsilon_2 x_{2,j} + ... + \varepsilon_k x_{k,j} + ... + \varepsilon_n x_{n,j} + E_j = \varepsilon_j X_j \qquad \text{Eq. (3.18)}$$

where ε_j is the embodied intensity and indicates energy use in sector j, generated directly or indirectly per unit production (e.g., toe/million US$) producer price, $x_{i,j}$ is indicated input quantity from sector i into sector j (monetary unit), E_j is the direct energy use by activities in sector j (energy unit), and X_j is domestic production of sector j (monetary unit).

Dividing both sides of Eq. (3.18) by X_j, and using input coefficient or technical coefficient, a_{ij}, and direct energy use per unit production e_j gives Eq. (3.19):

$$a_{1,j}\varepsilon_1 + a_{2,j}\varepsilon_2 + ...a_{k,j}\varepsilon_k + ... + a_{n,j}\varepsilon_n + e_j = \varepsilon_j \qquad \text{Eq. (3.19)}$$

where $a_{i,j}$ equals to $x_{i,j}/X_j$, and e_j equals to E_j/X_j.

Expressing these with vector and matrix for sector j = 1 to n gives Eq. (3.20) as follows:

$$(\varepsilon_1 \quad \varepsilon_2 ... \quad \varepsilon_n)\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1,n} \\ a_{21} & a_{22} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{pmatrix} + (e_1 \quad e_2 \quad ... \quad e_n) = (\varepsilon_1 \quad \varepsilon_2 ... \quad \varepsilon_n)$$

Eq. (3.20)

Then, expressing Eq. (3.20) with embodied intensity vector ε, direct energy use per unit production e, and input coefficient matrix A in Eq. (3.21), (3.22), and (3.23), respectively, gives Eq. (3.24) as shown below:

$$\varepsilon = (\varepsilon_1 \quad \varepsilon_2 \quad \cdots \quad \varepsilon_n) \qquad \text{Eq. (3.21)}$$

$$e = (e_1 \quad e_2 \quad \cdots \quad e_n) \qquad \text{Eq. (3.22)}$$

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1,n} \\ a_{21} & a_{22} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{pmatrix} \qquad \text{Eq. (3.23)}$$

$$\varepsilon * A + e = \varepsilon \qquad \text{Eq. (3.24)}$$

Solving this equation for ε provides Eq. (3.25), which gives embodied intensity.

$$\varepsilon = e * (I - A)^{-1} \qquad \text{Eq. (3.25)}$$

This method is now widely used, since it is difficult to make accurate estimates of energy uses for imported products. As described above, $(I - A)^{-1}$ refers to Leontief's Inverse Matrix, where I is the identity matrix. However, the above method involves calculating the energy use for only domestic production activities and excludes inputs from imported products. Conversely, the following method of calculating involves imported products.

Import coefficient m_i that represents percentages of imported products with respect to intermediate demand and domestic final demand in sector i is defined as the following equation (Miller & Blair 1985; Nansai et al. 2002; Kaneko et al. 2003):

$$m_i = \frac{M_i}{\sum_{j=1}^{n} a_{i,j} X_j + F_i} \qquad \text{Eq. (3.26)}$$

where M_i is the imports in sector i, n is number of sectors, and F_i is domestic final demand.

Subtracting the energy use for imported products from Eq. (3.19) gives Eq. (3.27):

$$a_{1,j}\varepsilon_1 + a_{2,j}\varepsilon_2 + \cdots + a_{k,j}\varepsilon_k + \cdots a_{n,j}\varepsilon_n - (a_{1,j}m_1\varepsilon_1 + a_{2,j}m_2\varepsilon_2 + \cdots a_{k,j}m_k\varepsilon_k + \cdots + a_{n,j}m_n\varepsilon_n) + e_j = \varepsilon_j \qquad \text{Eq. (3.27)}$$

Then, expressing import coefficient m_i using diagonal matrix M gives the following equation:

$$A * \varepsilon - M * A * \varepsilon + e = \varepsilon \qquad \text{Eq. (3.28)}$$

Solving Eq. (3.28) for ε gives the embodied intensity for domestic producer goods equation (Eq. 3.29) as shown below, which gives an accurate value for the actual burdens domestically generated.

$$\varepsilon = e\{I - (I - M)A\}^{-1} \qquad \text{Eq. (3.29)}$$

The data from IO-tables comprises a useful data source for calculating embodied energy, which is the energy required to provide a product both directly and indirectly through all the processes upstream i.e., traceable backwards from the finished product to the consideration of raw materials. In particular, these data are very significant since all products and services are covered. However, it should be recognized that there are limitations to the application of data from IO-tables. For example, in the Thai IO-tables all commodities and services are classified into a very limited 180 categories, as compared to Japanese IO-tables, which are classified into 400 categories (Nansai et al. 2002; NESDB 2003). Therefore, one category contains many different products. Individual sectors are provided for typical materials, including steel, glass, resin and paper; but a large number of different manufacturers produce these materials and they consist of an immense number of different types and qualities. Therefore, IO-analysis provides only an average value. When it comes to more highly processed products, such as machinery, a large number of different types of products are lumped together in one sector. Typically, the electric household machines and equipment sector include a wide range of products such as microwave ovens, air-conditioners, washing machines, refrigerators and vacuum cleaners. In this case, it is obvious that multiplying the price of each product by the intensity per price in this sector will provide a rough estimation.

One increasingly used approach to overcome these problems with IO-analysis is to use a method that combines the process analysis method and IO-analysis called the hybrid method. According to Bullard et al. (1978) and Lave et al. (1995), they have classified methods for embodied analysis into three groups: (a) IO-analysis, (b) process analysis, and (c) hybrid analysis. Process analysis methods are generally the most accurate, but they are often incomplete due to the amount of detail required for the evaluation of the main production process and of the complexity of associated upstream processes. IO-analysis, while comprehensive, is subject to various errors. For example, it does not differentiate between different production processes. Hybrid analysis combines both of these methods with the aim of reducing errors that are typically found among both. However, previous hybrid analysis methods have tended to be somewhat limited by either of the methods on which they are based. Details of hybrid analysis can be found in Treloar 1997, Treloar et al. 2000; 2001.

3.3.3. Comparative study on indirect energy use of selected Asian mega-cities

There are many studies of energy use and related emissions on a national level that have been published; conversely, at the city level there are very few such studies. City-scale studies that cover urban sectors comprehensively are still at the methodological stage of development. Such analyses typically focus on the urban energy of specific cities, most of which are outside of Asia. Furthermore, most of the interest was confined to the improvement of energy efficiency or the reduction in the use of fossil fuels. Obviously, studies on indirect energy consumption in cities are rare in Asia, as well as the rest of the world (ICLEI 1997; McEvoy et al. 1997; Kates et al. 1998; Baldasano et al. 1999; Newman 1999; Bennett & Newborough 2001; IGES 2004; Kennedy et al. 2005). It should be noted that when considering energy consumption as well as environmental protection measures at the city level the production, consumption and other activities of cities are closely linked with those of other cities and countries. City-level measures should always be considered from the viewpoint of interdependence between the factors within the city and those outside of it. The main problem area to be considered is the indirect energy consumption, or the embodied energy in goods and services that are imported from outside of the city. For instance, if a city does not produce goods but consumes goods from the outside, the direct energy consumption in the city is small. Even when the apparent environmental load in the city is small, the actual environmental load outside of the city may be large. Therefore, it cannot be concluded that the policies of a city with low direct energy consumption are favorable to the global environment.

As regards energy consumption statistics at the city level, some of the city's administration has provided this kind of data; however, it is difficult to interpret variations in the indirect energy consumption from the statistics released to the general public. This section presents a comparative study upon the indirect energy consumption of selected Asian mega-cities, including Bangkok, Beijing, Shanghai and Tokyo. The indirect energy use in those targeted cities has been estimated using the same methodology (IO-table and embodied energy analysis) as described in the earlier section. The studies on Beijing, Shanghai and Tokyo were extracted from Urban Energy Use and Greenhouse Gas Emissions in Asian Mega-Cities: Policies for A Sustainable Future (IGES 2004), while the Bangkok case is compiled from one of the author’s papers (see Phdungsilp 2005). A detailed estimation of indirect energy consumption in Bangkok will be described in chapter 5. Unfortunately, all of these studies were conducted for different study years, and in many cases the results are not directly comparable, given data gaps and assumptions made by the analysts. However, some interesting comparisons with caveats can be made.

The consumption of large amounts of goods and services by cities has an indirect effect upon places outside of the cities where the manufacturing and resource extraction take place. On a global scale, it does not matter where environmental loading originates: cities should be judged by their contributions to the total environmental load. A city does not only consume goods and services, it also supplies them in the form of exports. The relationship between the direct and indirect energy consumption for which a city is responsible differs from city to city depending upon its scale of industrialization and type of industries. Therefore, the emissions for which a city is responsible are those which are emitted as a result of direct emissions plus the net value of emissions embodied in material goods that are consumed in a city after subtracting exported material goods. Figure 3.9 shows the proportion of the direct and indirect energy consumption in selected Asian mega-cities.

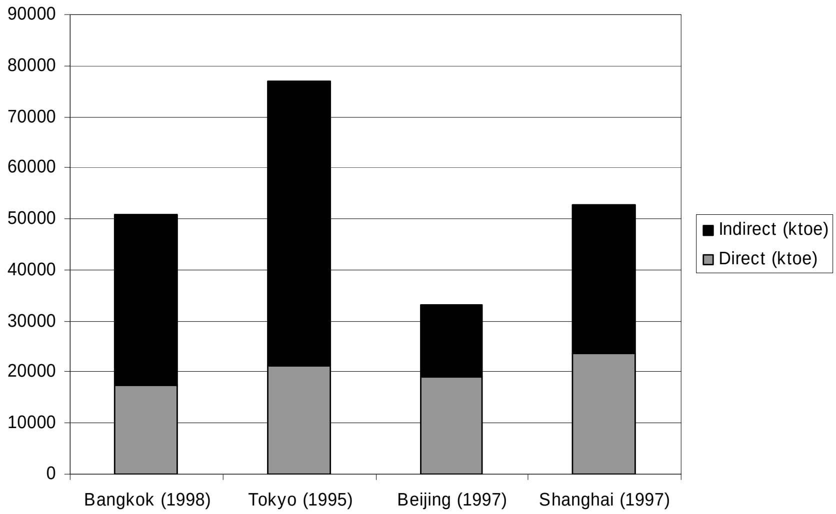


Figure 3.9. Direct and indirect energy consumption of selected Asian mega-cities (compiled from IGES 2004; Phdungsilp 2005).

According to the Figure 3.9, indirect energy consumption is more significant than direct energy demand in Bangkok, Shanghai and Tokyo. During 1990-1995, the total amount of energy demand within Tokyo decreased by 6.34%, while indirect energy demand decreased by 10.74% and direct energy demand increased by 9.36%. During 1992-1997 the total amount of energy demand of Shanghai increased by about 1.66%, among which the direct energy demand increased by 25.37% and the indirect energy demand decreased by 11.94%. For the Beijing case, the direct energy demand is greater than the indirect energy demand. During the period 1992-1995, the total amount of energy demand increased by 25.77%, among which the direct energy demand increased by 33.57% and simultaneously the indirect energy demand increased by 14.89% (IGES 2004). These differences 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.

Indirect energy uses can identify the degree to which the economic dependency of the city is upon the outer regions and especially it can highlight the environmental load displacement of the highly developed mega-cities to the outer regions. Additionally, the ratio of direct energy to indirect energy demand can also provide information about economic structural changes within the city.

Apart from indirect emissions responsibility, the indirect energy consumption can be addressed from other viewpoints, including that of waste management and the creation of a material-cycle society, which is found in an advanced form in Europe. These can reduce emissions as well as the consumption of natural resources.

The lack of quantitative and qualitative information at the city level poses a problem in regards to the Asian context. The obstacles that stand in the way of a comparative analysis include the incomparability of information, problems in defining data and differences in the methods used to organize information and data. It can be seen that scientific as well as energy analysts need to create consistent information.

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4. MULTI-CRITERIA DECISION-MAKING FOR THE SUSTAINABILITY ASSESSMENT OF ENERGY SYSTEMS

Tradeoffs among conflicting objectives lie at the heart of much energy planning. Engineers, economists, policy-makers and government agencies have many objectives, goals, criteria, attribute or performance indices they use to judge possible courses of action. The problem is that it is frustratingly rare that all of these desiderata can be met or maximized by a single alternative. Instead, some options will be good according to some criteria whereas other alternatives will do better against differing criteria. Choosing one of the alternatives over the others means that the priorities must have been set in such a way that accomplishing some goals would sacrifice others. Setting priorities is hard for an individual to do, and even more difficult when there are many people involved in a decision-making process, each with their own values and perspectives. Confronting a decision consists of understanding how well different options might perform based on the given objectives (Hobbs & Meier 2000). In the energy sector, tradeoffs are particularly evident because of the large environmental, social and economic costs frequently involved in providing reliable and convenient energy supplies.

The main purpose of this chapter is to introduce a systematic approach to examining tradeoffs and expressing value judgments that can yield critical insights, facilitate constructive discussion among conflicting interests, and effectively build a consensus. Multi-Criteria Decision-Making (MCDM) is presented through actual application, illustrating how it can help bring insight into problems and facilitate agreement among a range of stakeholders. This thesis emphasizes the use of this technique in dealing with sustainable energy systems (i.e. the evaluation of scenarios). The reviews of the literature show that MCDM techniques are gaining popularity within sustainable energy management. These techniques provide solutions to problems that involve conflicting and multiple objectives.

4.1. Overview of multi-criteria decision-making

It is well known from psychological research that the human brain can at any one time consider only a limited amount of information. The very nature of multiple criteria problems is that there is much information of a complex and conflicting nature, often reflecting differing viewpoints and often changing with time. One of the principal aims of MCDM methods is to help decision-makers organize and synthesize such information in a way that leads them to feel comfortable about making a decision. Belton (1990) stated that the context in which MCDM is useful does not fit into the traditional optimization paradigm of operational research. The concept of an optimum does not exist; there is no such thing as a “right answer”. The aim of MCDM methods is to help decision-makers learn about the problems they face, to learn about their own and other parties' value systems, to learn about organizational values and objectives by exploring them within the context of the problem, which can guide them through a process of learning, understanding, information processing, assessing, and defining of the problem and its circumstances.

MCDM method can provide solutions to increasingly complex energy problems. Traditional single criteria decision-making is normally aimed at the maximization of benefits with a minimization of costs. These methods provide a better understanding of the inherent features within decision-making problems, promote the role of the participants in the decision-making processes, facilitate compromise and collective decisions, and provide a good platform in which understanding the perception of the model and analysis in a realistic scenario can take place. These methods help to improve the quality of decisions by making them more explicit, rational and efficient. They deal with the process of making decisions in the presence of multiple objectives. A decision-maker is required to choose among quantifiable or non-quantifiable and multiple criteria. The objectives are usually conflicting, and therefore, the solution is highly dependent upon the preferences of the decision-maker and therefore must be a compromise. In most cases, different groups of decision-makers are involved within the process. Each group brings different criteria and points of view, which must be resolved within a framework of understanding and mutual compromise. Many applications of MCDM to energy engineering can be found within the literature (e.g., Afgan et al. 1998, Afgan & Carvalho 2000, Afgan et al. 2000a, Hobbs & Meier 2000, Afgan & Carvalho 2002, Phdungsilp & Martinac 2004). In addition, the applications include areas such as integrated manufacturing systems, evaluation of technology investment, water, and agriculture management (e.g., Putrus 1990, Boucher & McStravic 1991, Ozelkan & Duckstein 1996, Raju & Pillai 1999). Based on the intention of MCDM methods, Hobbs & Meier (2000) concluded that these methods have six basic functions that support the overall goal:

1. To structure the decision process. The MCDM approach helps analysts and decision-makers think systematically about a problem by providing a logical framework for defining the alternatives, comparing their performance on important objectives, and to consider different viewpoints.
2. To display tradeoffs among criteria. An example of a tradeoff is "a decrease of 10,000 tons in SO_2 emissions would require a cost increase of US$ 2,000,000." Such displays aim to help planners, regulators, and the public understand the relative advantages and disadvantages of alternatives. Two common approaches include X-Y plots, where individual points represent the performance of alternatives upon two objectives, and value paths in which a series of vertical bars or scales represent the degree of achievement for each criterion. A single alternative is represented as a path that connects points upon those scales.
3. To help people reflect upon, articulate, and apply value judgments concerning acceptable tradeoffs, resulting in recommendations concerning alternatives. Recommendations can be of several types: choosing the best single option, constructing a portfolio consisting of several options, defining two or more alternative strategies representing different viewpoints, and screening out undesirable options. The objective is to help people understand the implications of their value judgments and to inspire confidence in the soundness of the decision without being unnecessarily difficult.
4. To help people make more consistent and rational evaluations concerning risk and uncertainty. Psychological studies show that people have difficulty being consistent in decisions concerning which risks are acceptable. Some MCDM methods attempt to measure decision-makers' attitudes towards risk using utility functions, and then use those functions to evaluate the alternatives.
5. To facilitate negotiation. MCDM methods accomplish this in two ways: firstly, by quantifying and communicating the priorities held by different stakeholders, and secondly, by moving the discussion away from alternatives and towards fundamental objectives and tradeoffs among those objectives. A focus on values facilitates negotiation because it encourages people to think about their common interests and avoids the defensive discussions that often result from each stakeholder anchoring on a preferred alternative. Understanding whether differences of opinion arise from disagreements over facts or over values is difficult in emotionally charged debates over issues such as nuclear power, but is critical to making progress in negotiations. A discussion of values can also help define new alternatives that better satisfy group objectives.
6. To document how decisions are made. By detailing how each of the steps of MCDM analysis has been applied, an agency or firm can communicate the basis of its decision to stakeholders. Indeed, some of the first applications of formal MCDM methods by the US Government required agencies to document the rationale for the decisions within environmental impact statements.

MCDM is a branch of a general class of operations research models that deal with the problems of decision-making under the presence of a number of decision criteria. According to Climaco (1997), this class can be further divided into Multi-Objective Decision-Making (MODM) and Multi-Attribute Decision-Making (MADM). There are several methods in each of the above categories. Priority based, outranking, distance based and mixed methods are also applied to various problems. Each method has its own characteristics and the methods can also be classified as deterministic, stochastic and fuzzy. There may be combinations of the above methods, depending upon the number of decision-makers the methods can be classified as single or group decision-making methods. Decision-making under uncertainty and decision support systems are also prominent decision-making techniques (Gal & Hanne 1999).

These methodologies share common characteristics of conflict among criteria, incomparable units, and difficulties in the selection of alternatives. The best alternative is usually selected by making comparisons between the different alternatives in respect to each attribute. The overview of the multi-criteria decision process is shown in Figure. 4.1. The different weighting methods are described in the following sub-sections.

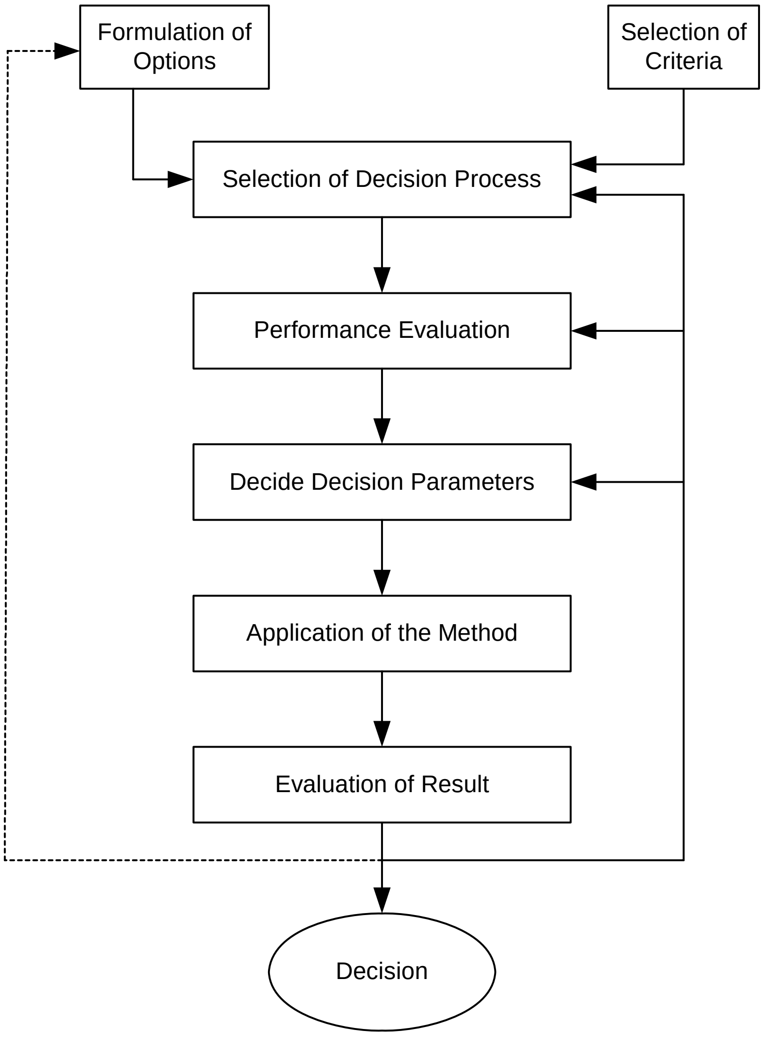

Figure 4.1. Multi-criteria decision process (adapted from Pohekar & Ramachandran 2004).

4.1.1. Weighted sum method (WSM)

The weighted sum method (WSM) is the most commonly used approach, especially in single dimensional problems. If there are M alternatives and N criteria then the best alternative is the one that satisfies the following expression (Solnes 2003):

$$A^*_{WSM} = Max \sum_{i}^{j} a_{ij} w_j \ \ for \quad i = 1,2,3...M \qquad \text{Eq. (4.1)}$$

where A^*_{WSM} is the WSM score of the best alternative, N is the number of decision criteria, a_{ij} is the actual value of the ith alternative in terms of the jth criterion, and w_j is the weight of importance of the jth criterion.

The total value of each alternative is equal to the sum of the products. Difficulty with this method emerges when it is applied to mutli-dimensional decision-making problems. In combining different dimensions, and consequently different units, the additive utility assumption is violated.

4.1.2. Weighted product method (WPM)

The weight product method (WPM) is very similar to WSM. The main difference is that instead of addition in the model there is a multiplication. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In general, in order to compare the alternatives A_K and A_L the following product is obtained (Chang & Yeh 2001):

$$R(A_K / A_L) = \sum_{j=1}^{N} (a_{kj} / a_{Lj})^{w_j} \qquad \text{Eq. (4.2)}$$

where N is the number of criteria, a_{kj} is the actual value of the ith alternative in terms of jth criterion. If $R(A_K / A_L)$ is greater than one, then alternative A_K is more desirable than alternative A_L (in the maximization case). The best alternative is the one that is better than or at least equal to all the other alternatives.

4.1.3. Analytical hierarchy process (AHP)

Analytical Hierarchy Process (AHP) has been developed by Saaty (1980; 1992). The essence of the process is the decomposition of a complex problem into a hierarchy with a goal or objective at the top of the hierarchy, criteria and sub-criteria at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy. Elements at a given hierarchical level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The verbal terms of Saaty's fundamental scale of 1-9 are used to assess the intensity of preference between the two elements. The value of 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly, and 9 extremely more important. The values of 2, 4, 6, and 8 are allotted to indicate compromise values of importance. The ratio scale and the use of verbal comparisons are used for weighting of quantifiable and non-quantifiable elements. The method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives is obtained. The entries of a final weight coefficients vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy. A decision-maker may use this vector in accordance with his particular needs and interests. To elicit pair-wise comparisons performed at a given level, a matrix A is created in turn by putting the result of pair-wise comparison of element i with element j into the position a_{ij} as below:

$$A = \begin{bmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ a_{n1} & a_{n2} & . & a_{nn} \end{bmatrix} \qquad \text{Eq. (4.3)}$$

After obtaining the weight vector, it is then multiplied with the weight coefficient of the element at a higher level (that was used as criterion for pair-wise comparisons). The procedure is repeated upwards for each level, until the top of the hierarchy is reached. The overall weight coefficient, with respect to the goal for each decision alternative is then obtained. The alternative with the highest weight coefficient value should be taken as the best alternative. One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision-maker's inconsistency and randomly generated index. This index is important for the decision-maker to assure that his/her judgments were consistent and that the final decision is made well. The inconsistency index should be lower than 0.10. Although a higher value of inconsistency index requires re-evaluation of pair-wise comparisons, decisions obtained in such cases could also be taken to be the best alternative (Pohekar & Ramachandran 2004).

4.1.4. Preference ranking organization method for enrichment evaluation (PROMETHEE)

This method uses the outranking principle to rank the alternatives, combined with the ease of use and decreased complexity. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. Brans et al. (1986) have offered six generalized criteria functions for reference, namely usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion. The method uses preference function $P_j(a,b)$, which is a function of the difference d_j between two alternatives for any criterion j; i.e., $d_j = f(a,j) - f(b,j)$, where $f(a,j)$ and $f(b,j)$ are values of two alternatives a and b for criterion j. The indifference and preference thresholds q' and p' are also defined depending upon the type of criterion function. Two alternatives are indifferent for criterion j as long as d_j does not exceed the indifference threshold q'. If d_j becomes greater than p', there is a strict preference. Multi-criteria preference index $\pi(a,b)$, a weighted average of the preference functions $P_j(a,b)$ for all the criteria, is defined as follows:

$$\pi(a,b) = \frac{\sum_{j=1}^{J} w_j P_j(a,b)}{\sum_{j=1}^{J} w_j} \qquad \text{Eq. (4.4)}$$

$$\Phi^+(a) = \sum_A \pi(a,b) \qquad \text{Eq. (4.5)}$$

$$\Phi^{-}(a) = \sum_{A} \pi(b,a) \quad \text{Eq. (4.6)}$$

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a) \quad \text{Eq. (4.7)}$$

where w_j is the weight assigned to the criterion j, $\Phi^{+}(a)$ is the outranking index of a in the alternative set A, $\Phi^{-}(a)$ is the outranked index of a in the alternative set A, and $\Phi(a)$ is the net ranking of a in the alternative set A. The value having the maximum $\Phi(a)$ is considered to be the best.

a outranks b if $\Phi(a) > \Phi(b)$, a is different to b if $\Phi(a) = \Phi(b)$ Eq. (4.8)

4.1.5. The elimination and choice translating reality (ELECTRE)

This method is capable of handling discrete criteria that is both quantitative and qualitative in nature and provides a complete ordering of the alternatives. The problem is to be formulated so that it chooses alternatives that are preferred over most of the criteria but that do not cause an unacceptable level of discontent for any of the criteria. The concordance, discordance indices and threshold values are used in this technique. Based on these indices, graphs for strong and weak relationships are developed. These graphs are used in an iterative procedure to obtain the ranking of alternative (Pohekar & Ramachandran 2004). This index is defined in the range (0-1), provides a judgment about the degree of credibility of each of the outranking relations, and represents a test to verify the performance of each alternative. The index of global concordance C_{ik} represents the amount of evidence to support the concordance among all criteria, under the hypothesis that A_i outranks A_k. It is defined as:

$$C_{ik} = \sum_{j=1}^{m} W_j c_j (A_i A_k) / \sum_{j=1}^{m} W_j \quad \text{Eq. (4.9)}$$

where W_j is the weight associated with jth criteria.

The ELECTRE method yields a whole system of binary outranking relations between the alternatives. Because the system is not necessarily complete, the ELECTRE method is sometimes unable to identify the preferred alternative. It only produces a core of leading alternatives. This method has a clearer view of alternatives by eliminating less favorable ones, especially convenient while encountering a few criteria with a large number of alternatives in a decision-making problems (Goicoechea et al. 1982; Pohekar & Ramachandran 2004).

4.1.6. The technique for order preference by similarity to ideal solutions (TOPSIS)

This method was developed by Huang & Yoon (1981) as an alternative to ELECTRE. The basic concept of this method is that the selected alternative should have the shortest distance from the negative ideal solution in a geometrical sense. The method assumes that each attribute has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions. Thus, the preference order of alternatives is yielded through comparing the Euclidean distances. A decision matrix of M alternatives and N criteria is formulated first. The normalized decision matrix and the construction of the weighted decision matrix is carried out. This is followed by the ideal and negative-ideal solutions. For the benefit criteria the decision-makers want to have the maximum value among the alternatives and for cost criteria they want minimum values amongst alternatives. This is followed by a separation measure and a calculating of the relative closeness to the ideal solution. The best alternative is the one that has the shortest distance to the ideal solution and the longest distance to the negative ideal solution (Pohekar & Ramachandran 2004).

4.1.7. Compromise programming (CP)

Compromise programming (CP) defines the best solution as the one within a set of efficient solutions whose point is the closest to an ideal point. The aim is to obtain a solution that is as close as possible to the ideal. The distance measure used in CP is the family of L_p-metrics and is given as (Zeleny 1982):

$$L_p(a) = \sum_{j=1}^{j} w_j^p \left| f_j^* - f(a) \right| / \left| M_j - m_j \right| \qquad \text{Eq. (4.10)}$$

where $L_p(a)$ is the L_p metric for alternatives a, $f(a)$ is the value of criterion j for alternative a, M_j is the maximum (ideal) value of criterion j in set A, m_j is the minimum (anti-ideal) value of criterion j in set A, f_j^* is the ideal value of criterion j, w_j is the weight of the criterion j, and p is the parameter reflecting the attitude of the decision-maker with respect to compensation between deviations. For $p = 1$, all deviation from f_j^* are taken into account in direct proportion to their magnitudes, meaning that there is full (weighted) compensation between deviations.

4.1.8. Multi-attribute utility theory (MAUT)

Multi-Attribute Utility Theory (MAUT) takes into consideration the decision-maker’s preferences in the form of the utility function, which is defined over a set of attributes. The utility value can be determined by the determination of single attribute utility functions followed by a verification of the preferential and utility independent conditions and the derivation of multi-attribute utility functions. The utility functions can be either additively separable or multiplicatively separable with respect to single attribute utility. The multiplicative form of equation for the utility value is defined as (Keeny & Raiffa 1976):

$$1 + ku(x_1, x_2, \ldots x_n) = \prod_{j=1}^{n} (1 + kk_j u_j(x_j)) \qquad \text{Eq. (4.11)}$$

where j is the index of attribute, k is overall scaling constant (greater than or equal to -1), k_j is the scaling constant for attribute j, u(.) is the overall utility function operator, and u_j(.) is the utility function operator for each attribute j.

4.2. Developing of multi-criteria decision-making in energy systems assessment

The MCDM has been applied in several energy-related areas: renewable energy planning, energy resource allocation, building energy management, transportation energy management, energy planning, electric utility planning, and others. These areas have common features of the minimization of cost benefit rations, high degrees of uncertainties in the formulation of the problems, incommensurable units, and the need to handle socio-economic aspects in planning.

Renewable energy planning and energy resource allocation refer to the compilation of feasible energy plans and the dissemination of various renewable energy options. The key factors applicable are investment planning, energy capacity expansion planning, and the evaluation of alternative energies. Building energy management refers to design, selection, installation and building energy management options within a multi-criteria environment. The application normally deals with quantitative issues. Transportation system applications include the evaluation of alternative strategies for pollution control, the elimination of old polluting vehicles, and choosing between private and public transport, etc. The key features of transportation applications are of a high concern for reasons of a socio-economic nature. Project planning refers to site selection, technology selection and decision-making support in renewable energy harnessing projects. Miscellaneous applications include desalination plant selection, solid waste management, etc.

It can be observed from the literature surveyed and a review of application of MCDM to sustainable energy planning by Pohekar & Ramachandran (2004) that AHP is the most popular method for prioritizing the alternatives, followed by PROMETHEE and ELECTRE. According to the aim of this thesis which is to provide a user-friendly tool for aiding energy planners as well as policy-makers regarding policy interventions in regards to energy modeling. The following section describes a technique used for sustainability assessment of energy scenarios based upon the MCDM approach, which enables individual as well as group decision-making to select an appropriate mix of energy technologies or intervention policies.

4.2.1. A framework of the multi-criteria decision-making process

The purpose of the MCDM method is to produce the means by which decision teams as well as energy planners are better able to understand and handle a holistic approach. It is a tool for organizing information required for decision-making. A framework of the MCDM method, corresponding to the evaluation of energy scenarios, can be seen as two main phases.

In the first phase, the participants or the decision team decide on the criteria they want to use and determine their relative importance. Since there are usually quite a lot of criteria to consider, it is suggested that the criteria is organized into five to eight main criteria, each with several sub-criteria (Andresen 2000). This is the first step and should be done at the beginning before there are scenario designs to be considered. In this thesis the main criteria, as well as sub-criteria, were selected from several studies (see Afgan et al. 2000b, Hobbs & Meier 2000, Afgan & Carvalho 2002, Phdungsilp & Martinac 2004, Cavallaro & Ciraolo 2005). In this phase, the scales can also be established that will be used later in scoring the various criteria. Both qualitative and quantitative values can be incorporated within the method.

In the second phase, the group uses the method to judge the relative merits of the energy scenarios (alternatives). This is done by determining scores for each scenario for each criterion, using the measuring scales defined in the first phase. The scores can be aggregated into several overview presentations. For example, a single score for each scenario, a star diagram for each scenario that shows its score graphically, and a bar chart for each scenario which gives more detail about the weighted results.

For practical reasons it is recommended that the team designates one of its members to be responsible for organizing the information and following the steps. This person becomes the resident MCDM expert. Other members of the team do not need to become familiar with the mechanics of aggregating the information and running the MCDM calculation, which can be done by various MCDM software applications; but they do need to understand the principles involved so that they develop faith in the method.

In general, the proposed method can be conducted in a user-friendly seven-step procedure. The first three being carried out in phase one, while the last four are carried out in phase two:

- Step 1: selecting the main criteria and sub-criteria.
- Step 2: developing measurement scales for the sub-criteria.
- Step 3: generating energy scenarios.
- Step 4: weighting the main criteria and sub-criteria.
- Step 5: predicting the performance of the scenarios.
- Step 6: aggregating the scores.
- Step 7: analyzing the results and making decisions.

It should be noted that during this process, criteria may be added, removed, or reformulated, which may require the team to go back and redo a part or all of the procedure several times. This should be considered a useful outcome, for it indicates that the discussion and analysis of the problem and the objectives has produced a deeper understanding within the decision team.

Also, it is important to remember that the primary goal of this method is not to provide definitive answers, but to enhance the ability of all participants to comprehend the problem at hand.

4.2.2. Selected main criteria and sub-criteria

It is important to specify the objective first and then select the main criteria and sub-criteria, respectively. In this thesis, the objective is to propose sustainable energy systems; therefore, the main criteria and sub-criteria have been selected from a set of sustainability indicators for energy system assessment as presented in various studies.

The criteria for the energy system assessment have to reflect three main aspects, namely environmental, economic and social. Some criteria or sub-criteria can be quantifiable such as annual resource use. Others can be qualitative such as integration in the urban context. As any other complex system, the energy system is defined by the constraints that reflect its function, technology, geography, property and capacity.

In order to cope with the complexity of sustainability related issues for different systems the criteria have to reflect the wholeness of the system, as well as the interaction of its subsystems. Consequently, criteria have to measure the intensity of the interactions among the different elements in the system and its environment. In this view, there is a need for the criteria sets to be related to the interaction processes that allow an assessment of the complex relationship within the system. This implies that the complexity of criteria is defined reflecting links among the internal parameters and external parameters of the system.

In this study, the main criteria for the sustainability assessment are: resource use, environmental loading, financial and economic, social, and practical. In this respect, the design criteria and sub-criteria used are shown in Table 4.1, while Figure 4.2 shows the overall structure of criteria use.

Table 4.1. The design main criteria and sub-criteria.

Main criteria	Sub-criteria
Resource use	Resource depletion
	Annual electricity
	Annual fuels
Environmental loading	Annual CO_2 emissions
	Annual SO_2 emissions
	Annual NO_x emissions
Financial and economic	Construction cost
	Annual operation cost
	Annual maintenance cost
	Market maturity
Social	Job creation
	Public acceptable
	Human health impacts
	Integration in urban context
Practical (political)	Compatibility with political, legislative and administrative situation
	Data availability adequate
	Consistence with local technical and economic (maintainability)

The number of main criteria and sub-criteria must be considered carefully. If there is a large amount of criteria, the problem may be difficult to handle, and one may lose the overview. Also, with a large number of criteria, the importance weights end up small, and thus the meaningfulness of the weights is less acute. Alternatively, if there are only a small number of criteria, it may lead to an oversimplification of the real world (Andresen 2000).

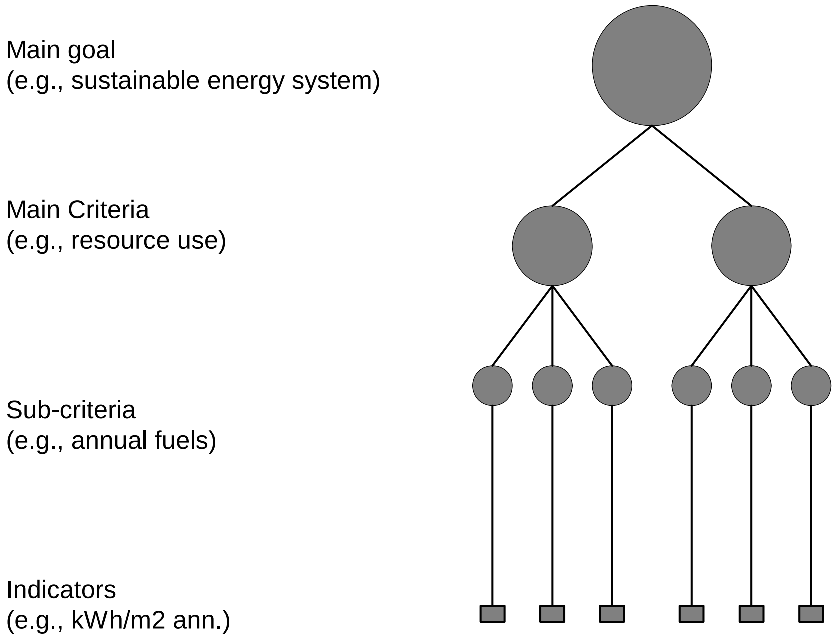

Figure 4.2. The overall structure of criteria and sub-criteria use.

The number of criteria may affect the value balance of the hierarchy. The greater the level of detail pertaining to an objective, possibly reflected in the number of sub-criteria, the more likely it is that it will be attributed a high level of importance. Miller's theory (Miller 1956) suggested that it may be wise to limit the number of main and sub-criteria to approximately seven. Miller claimed that seven plus or minus two represents the greatest amount of information that an observer can give about an object on the basis of an absolute judgment. This theory is widely accepted within the behavioral sciences.

4.2.3. Generating energy scenarios

The energy scenarios (alternatives) depend upon each individual case since it is basically a craft; little formal guidance can be given for this task. In this thesis, the energy demand is organized into four sectors: residential, commercial and building, industry, and transport. In addition, the supply-side is taken into consideration as well. A detailed analysis will be discussed in the case study in chapter 5.

One of the ultimate goals of the thesis is to promote the maximum use of renewable energy within a large urban area. Therefore, individual policies (scenarios) have been created for various sectors to support this objective. For example, in the residential sector, scenarios simulate the impacts of solar water heaters, passive design, daylighting applications, and photovoltaic installations in households. The policy question addresses the implications of, what if the policies are implemented according to the assumptions stated in this section.

It is important to consider constraints to implementation in the selection of policies, because the analysis of policies will provide a useful input into the city's energy modeling. It may thus be useful to categorize the policies into main groups and sub-groups, according to the purpose and the individual sectors.

4.2.4. Performance prediction

The performance prediction is done in accordance with the developed scales for the sub-criteria. A scale for each sub-criterion is necessary to be able to measure the performance of individual scenarios. A measurement scale is a way to convert a value into a score. A value can be a number or a phrase, depending on whether the criterion is quantitative or qualitative.

Quantitative values are used for criteria that can be measured directly with numbers, such as annual energy use, carbon emissions, etc. Qualitative values are words or phrases that can be used to characterize how well a scheme rates against a particular criteria where the rating is more a matter of judgment, not normally subject to quantification. These are quality issues, such as public acceptance or integration into an urban context. Some criteria can be characterized in either a qualitative or quantitative way.

All criteria are ultimately converted to a qualitative scale. For example in the 4-to-10 scale, the upper and lower ends have particular meanings. The upper end, a score of 10, means that the scenario rates as “excellent”. To be more exact, the 10 means that the scenario is the “best reasonable attainable” with regard to the particular criteria. The lower end, a score of 4, means that it is just marginally possible to construct such an energy system.

The next step is to create a measurement scale for each of the main criteria, indicating the assessment of the merit of achieving particular scores. In this study, the main criteria are evaluated by using a questionnaire on a 4-to-10 scale or by simply saying that a bigger number is better. Table 4.2 illustrates the example of a measurement scale for annual electricity use.

Table 4.2. Example of measurement scale for annual electricity use.

Score	Judgment	Annual electricity use (kWh/m^2)
10	Excellent	80
9	Good to Excellent	100
8	Good	120
7	Fair to Good	140
6	Fair	160
5	Acceptable to Fair	190
4	Marginally acceptable	250

However, the process of creating measurement scales should generate much discussion. It will often come to light that the same words have different meanings for different individuals. Scaling the objectives of a problem in this manner not only helps the team arrive at uniformity of measurement scales, but is also a way to define the general nature and context of the problem. This process also involves the collective participation of the entire team and allows each team member to express his or her own values and expertise to the group as a whole.

Regarding the levels of the predicted performance of the proposed scenarios, with respect to the criteria, are determined. The performance prediction can be done based on computer simulation (energy modeling), databases, rules of thumb, experience or expert judgment. It is best if the scoring for the performances is decided upon by the whole team.

4.2.5. Weighting of criteria and aggregating scores

The main criteria weights reflect the central priorities of the project. The weights chosen will be critical in comparing alternative schemes. There are different ways of eliciting weights. The grading method works with the weights directly. The criteria weights are determined on a 10-point scale similar to the one used for scoring the performances. The decision team expresses the importance of criteria in grades on the scale 10, 9, 8, and so on down to 4. The most important criterion receives a grade of 10. All other criteria are compared to this e.g., if a criterion is felt to be somewhat less important than the most important one, it receives a grade of 8.

Another method is a complex mathematical technique, The so-called AHP as mentioned in section 4.1.3. Furthermore, there is a range of software available that can implement the MCDM model. In this thesis, the computer program Web-HIPRE (HIerarchical PREference analysis on the World Wide Web) has been used in this process. The Web-HIPRE has been developed by the Systems Analysis Laboratory at the Helsinki University of Technology, Finland. Since it is a web-based software, it can be accessed from anywhere in the world and provides a common platform for individual and group decision support (Hämäläinen 2000). Detailed information will be given in the next section.

Andresen (2000) suggested that in order to present the overall performance of an energy scenario a so-called "star diagram" is a useful tool to graph the weights. In this diagram it is possible to show multiple dimensions; thus, all individual performance measures can be gathered into one picture. Each finger (see Figure 4.3) represents the scale for one criterion. The performance on each criterion is plotted on each finger. The center of the star usually designates the lowest/worst performance, or the minimum score of 4, for each criterion. The outer unit polygon represents the maximum score of 10 for each criterion.

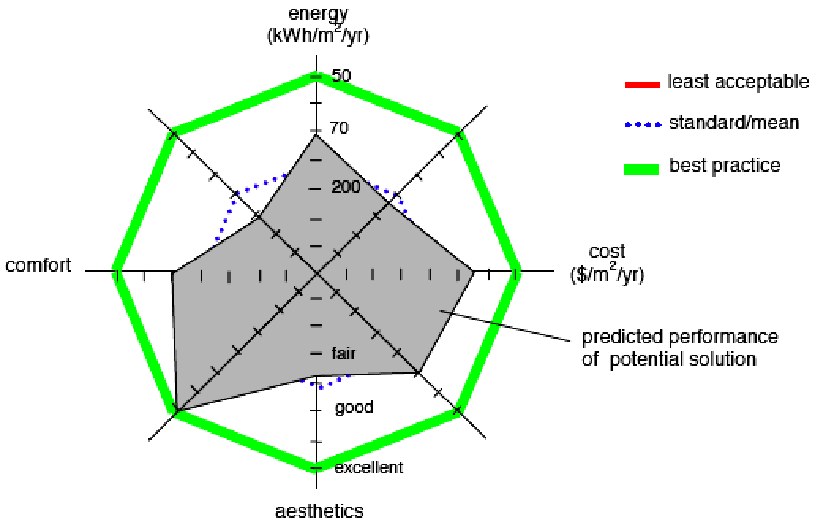

Figure 4.3. An example of a star diagram with indicated individual criteria scores and reference scores (adapted from Andresen 2000).

However, there is a limit to the number of dimensions that can be presented without making the graphics look too cluttered. According to Miller's theory (Miller 1956), a maximum of nine fingers is probably the limit. Therefore, only the main criteria should be plotted in the star diagram. The sub-criteria may be indicated below the main criterion.

4.3. The Web-HIPRE decision-support software

Web-HIPRE is Internet software for multi-criteria decision analysis based on the well-known decision support software HIPRE 3+ (Hämäläinen & Lauri 1995). Web-HIPRE provides implementations of AHP and multi-attribute value theory (MAVT) to support the different phases of decision analysis, prioritization and analysis of the results. Individual models can be integrated into a group model via the Internet. In general, Web-HIPRE includes decision-making, group collaboration and computer support.

Web-HIPRE is a Java-applet and can be accessed from any location with a Java-enabled web-browser (e.g., Internet Explorer and Netscape) connected to the Internet. When using Web-HIPRE, the browser loads the applet in its local memory, from where it is operated. When the browser is closed, no files remain on the user's computer. An essential feature is the possibility of defining links to other Internet addresses. These links can refer to graphical or any other forms such as sound or video to describe the criteria or alternatives, which can improve the quality of decision support dramatically.

The methods used in Web-HIPRE are based on the AHP and on MAVT. In the area of MAVT, it supports direct weighting, Simple Multi-Attribute Rating Technique, SMART (Edwards 1977; von Winterfeldt & Edwards 1986; Edwards & Barron 1994), SWING (von Winterfeldt & Edwards 1986) and the rank based SMARTER technique (Edwards & Barron 1994). Figure 4.4 presents the hierarchy of the residential case for evaluating the energy scenarios. In the hierarchy window, different weighting or rating methods can be used in the local subtrees, and the selected methods are shown by abbreviations including: DR = Direct, SM = SMART, SW = SWING, SR = SMARTER, PW = AHP (Pair-wise Comparisons), and VF = Value Functions.

Basically, the method of SWING weighting is to elicit weights for the criteria. This is based on comparisons of differences: how does the swing from 0 to 100 on one preference scale compare to the 0 to 100 swing on another scale? Regarding SMART, it has undergone one important change and one potentially useful extension. The change was the introduction of the swing-weights procedure for weight assessment to replace the one originally recommended. Thus, SMART became SMARTS (SMART with Swings). Edwards & Barron (1994) have also developed a way of implementing SMARTS that is less demanding in regards to the information input requirements from the decision-maker. This procedure is named SMARTER (SMART Exploiting Ranks).

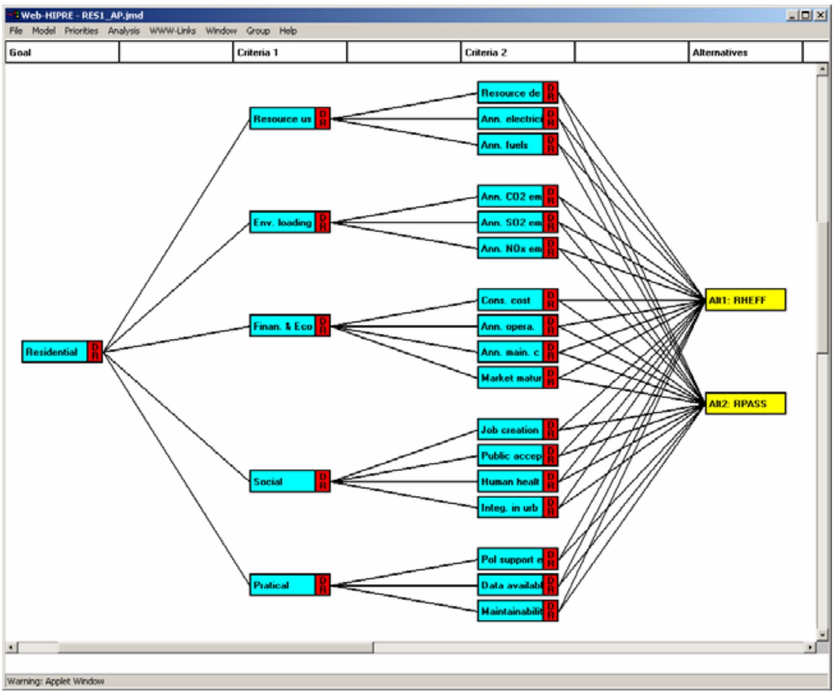

Figure 4.4. An example of value tree window of the residential case (extracted from Web-HIPRE, www.hipre.hut.fi).

4.3.1. The analytic hierarchy process method

Besides the original form of AHP, Web-HIPRE also supports a continuous preference scale. Preferences can be given, for example graphically with the slider or numerically by typing a value (Figure 4.5). When all the pair-wise comparisons have been given, elicited weights for each attribute are shown by numbers and bar-graphs.

Verbal statements can also be used to define preferences by choosing an appropriate expression from the list. Web-HIPRE uses the original mapping from words to ratios, which is: equal preference = 1, moderate preference = 3, strong preference = 5, very strong preference = 7, and extreme preference = 9 (Saaty 1980). However, it has been shown that the use of the 9/9 – 9/1 scale (Ma & Zheng 1991) or the balanced scale (Salo & Hämäläinen 1997) gives a better equivalency to verbal expressions (Pöyhonen et al. 1997). These variant scales can be used by selecting the corresponding rations from the continuous scale.

However, the original consistency ratio (CR) of AHP (Saaty 1980) is not applicable with the general scales. When using different discretions of a scale or a continuous scale, a scale-invariant consistency measure should be used. In Web-HIPRE the consistency measure (CM) is used (Salo & Hämäläinen 1997). It is derived by transforming the inconsistent replies into an extended set of feasible preference statements, and using the properties of this set to measure the inconsistency of the pair-wise comparison matrix.

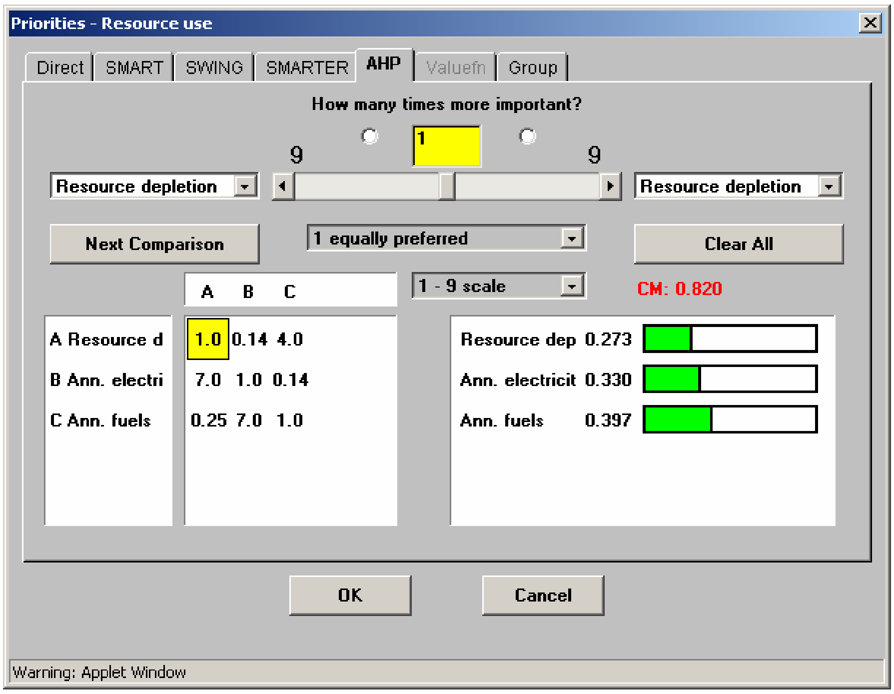

Figure 4.5. An example of the AHP weighting window (extracted from Web-HIPRE, www.hipre.hut.fi).

In CM, inconsistent replies are transformed into a non-empty set of feasible preferences and the properties of this set can be used to measure the inconsistency of the original matrix. More precisely, the consistency measure is defined as (Salo 1993):

$$CM = \frac{2}{n(n-1)} \sum_{i \rangle j} \frac{\bar{r}(i,j) - \underline{r}(i,j)}{(1+\bar{r}(i,j))(1+\underline{r}(i,j))} \qquad \text{Eq. (4.12)}$$

where $\bar{r}(i,j)$, $\max_k a(i,k)a(k,j)$ stands for the extended bound of the comparison matrix a(i,j) or the element in the i[th] row and the j[th] column, and $\underline{r}(i,j)$ is the inverse of $\bar{r}(i,j)$.

Thus, the consistency measure is an indicator of the size of this extended region formed by the set of local preferences such that $w_i \le \bar{r}(i,j) w_j$ for all $i,j \in \{1,...,n\}$. This measure increases with the inconsistency of the elements of the pair-wise comparisons matrix.

4.3.2. The multi-attribute value theory method

In Multi-Attribute Value Theory (MAVT) the problem is structured into a hierarchical form similar to AHP. The objective is to obtain general value scores for each alternative. The value scores are composed of the ratings or the alternatives with respect to each attribute and of the weights of the attributes. By using an additive value function, the overall value score of an alternative x is (Mustajoki & Hämäläinen 1999):

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \qquad \text{Eq. (4.13)}$$

where $v_i(x_i)$ is the component value of an attribute rating x_i and w_i is the weight associated with an attribute i. The component value functions $v_i(\cdot)$ and the weight w_i get values between 0 and 1, and the weights are normalized to sum up to one. The weight w_i indicates the relative importance of the event of an attribute i changing from its worst level to its best level compared to the corresponding changes on the other attributes.

In MAVT the weights of the attributes can be given directly, or some sophisticated methods like SMART, SWING or SMARTER can be used. On the lowest level, value scores can be given directly or, for example value functions can be used to transform the ratings of the alternatives into the value scores.

4.3.3. Combined use of the methods

A unique feature of Web-HIPRE is the possibility to use different weighting methods within the same hierarchy. Thus, under each element of the hierarchy the decision-maker can select the most suitable method. Users can apply different methods, but only one of them is active. All of the prioritizations made by the other methods are stored, which makes the comparison of different weighting methods easy.

AHP and MAVT methods can be combined freely in criteria weighting. In respect to the alternatives, AHP weights can be converted to the compatible 0-1 value scale by setting the lowest priority weight to zero, the highest priority weight to one, and scaling the intermediate weights proportionally to this scale (Dyer 1990). More precisely, the converted weight w_{ci} for the alternative is (Mustajoki & Hämäläinen 1999):

$$w_{ci} = \frac{w_i - w_{\min}}{w_{\max} - w_{\min}} \qquad \text{Eq. (4.14)}$$

where $w_{\max} = \max(w_1, ..., w_n)$ and $w_{\min} = \min(w_1, ..., w_n)$ are the original maximum and minimum AHP weights. These converted AHP weights can now be treated as value scores. Alternatively, value scores can be normalized to sum up to one in order to make them compatible with the AHP weights.

4.3.4. Group decision-making

There are different ways of approaching multi-attribute preference aggregation and combination in group-decision-making. In methods allowing incomplete information, such as preference programming (Salo & Hämäläinen 1995), PAIR (Salo & Hämäläinen 1992a), and PRIME (Salo & Hämäläinen 1992b), it is possible to define intervals for the weight ratios instead of exact number estimates. The intervals can be interpreted to denote the decision-maker's preferential uncertainty. Interval models can also be used in group-decision-making by forming intervals so that they include the opinions of all the members (see e.g., Hämäläinen & Pöyhönen 1996). As the local weights are presented as intervals, the overall priorities are also intervals.

Another way to combine individual models is to use a direct aggregation method. In MAVT, the weighted sum of individual values can be taken to get the group values, but generally this requires the explicit comparison of interpersonal preferences. The AHP literature proposes two aggregation methods: the geometric mean method (Aczel & Saaty 1983) and the weighted arithmetic mean method (Dyer & Forman 1992). The weighted arithmetic mean method satisfies the commonly accepted axioms for social choice except for the independence of irrelevant alternatives, which is also violated by AHP itself (Ramanathan & Ganesh 1994). However, it again requires the explicit weighting of group members.

In Web-HIPRE, individual weights can be aggregated into a group model within the weighted arithmetic mean method. This naturally includes the weighted sum of MAVT as a special case. In the group hierarchy each decision-maker is graphically represented by an element, which actually presents the whole hierarchy of the individual decision-maker. The composite group priorities are generated as a weighted sum of individual priorities, which are obtained from the individual models. This feature is very useful for decision-making in regards to energy for many stakeholders should be involved in the decision process. Then, the outcome of these group member elements is the overall score for the alternatives. One should note that, if necessary, the individual members can work in an asynchronous distributed mode i.e., in different locations and at different times.

4.3.5. Analyzing the results

In Web-HIPRE, the composite priorities (i.e., the overall scores for the alternatives) are shown both by numerical values and by bar graphs (see Figure 4.6). Bars can be divided into segments in different ways indicating the relative importance of the criteria and sub-criteria. Any criterion can be chosen as the goal. Then, Web-HIPRE calculates the composite priorities from the sub-hierarchy under a selected goal element.

For group decision-making, the overall weights in the group model are represented similarly as in an individual model. The bar graphs can be divided according to the relative importance of the decision-makers.

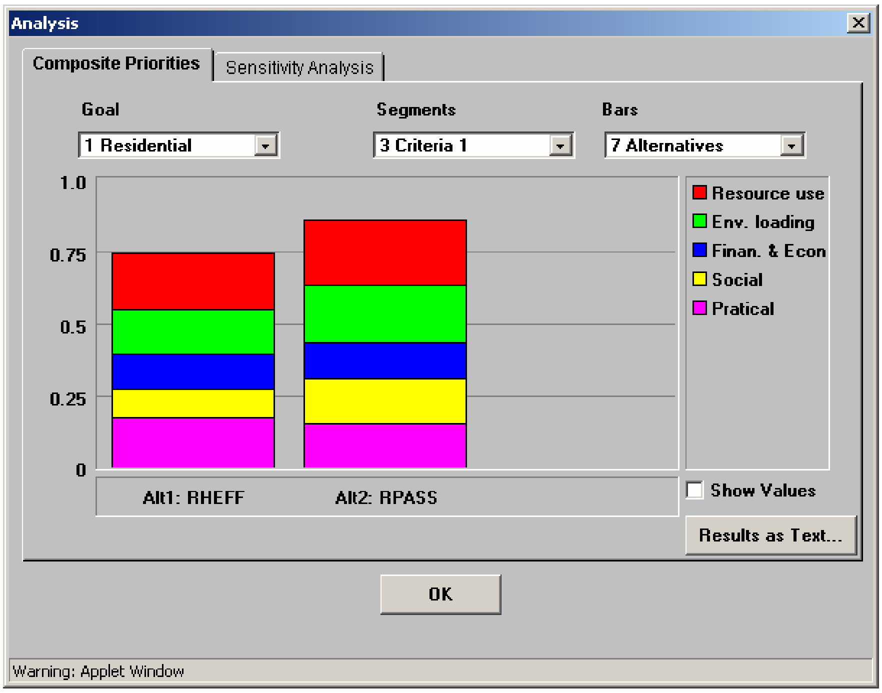

Figure 4.6. An example of the overall values of the alternatives (extracted from Web-HIPRE, www.hipre.hut.fi).

The main advantage of MCDM is that it provides a systematic way of assessing the importance of criteria. In addition, MCDM is an attempt to measure the preferences of a diverse group of people. The MCDM approach can be considered as an alternative to considering only a handful of predefined plans. Most applications in energy planning have emphasized the minimization of cost. However, in the MCDM method the environmental and other non-cost objectives can be added to such models in order to allow the planner to generate many alternatives representing a range of tradeoffs.

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5. CASE STUDY: CITY OF BANGKOK, THAILAND

This case study is built upon developing methodologies, including indirect energy consumption based on embodied energy analysis, energy modeling, and multi-criteria decision-making, as described in the previous chapters.

5.1. Analysis of the energy situation

Over the past two decades, the economic development in Thailand along with relevant policies have transformed the country from an agricultural-based economy into a semi-industrialized economy. Consequently, energy consumption has rapidly increased. However, due to the limited data at the city level especially from disaggregated sectors, the energy analysis is somehow described from both national and city perspectives.

5.1.1. Energy organization in Thailand

The energy sector is undergoing a period of restructuring and privatization. The Thai electric utilities and petroleum industries, which have historically been state-controlled monopolies, are currently being restructured. Previously, all energy related organizations operated under a decentralized structure, each divided into separated ministries and departments. This decentralization was caused by various things, among which, were differing objectives and varying circumstances. Certain organizations, such as the Metropolitan Electricity Authority (MEA) and the Provincial Electricity Authority (PEA), were established as public utility service providers to local towns. Therefore, they were assigned under the Ministry of Interior. Some organizations were established at a time when there were no authorities assigned to manage and control energy production. They were assigned under the Office of the Prime Minister, such as the Electricity Generating Authority of Thailand (EGAT).

In 1986, the government took into consideration the necessity of aligning policies and supervising the decentralized organizations in order for them to work towards same goal. As a result, the Prime Minister's Direction 1992 (B.E. 2535) was issued, establishing the National Energy Policy Office (NEPO) to assume such responsibility as a department under the Office of the Prime Minister. NEPO was chaired by the Prime Minister, and consisted of ministers from related ministries as board members. The Board's Secretary-General acted as both member and secretary to the Board. The Board had the authority to make decisions, establish policies for the cabinet, and assign government agencies or state enterprises to implement plans and projects.

There were energy related agencies allocated in over 20 units across nine ministries. This hindered the overall operation and caused differing policies and legislation governing each agency. The government attempted to unify these various independent units in order to help facilitate energy management. In November 2001, the Bureau of Energy was established. Subsequently, in January 2002, the Bureau of Energy became the Ministry of Energy. A comparatively small-sized ministry consisting of six departments: The Office of the Ministry, The Energy Policy and Planning Office, The Department of Mineral Fuels, The Office of the Permanent Secretary, The Department of Alternative Energy Development and Efficiency, and The Department of Energy Business (MOEN 2005).

5.1.2. Energy supply and demand analysis in Thailand

Thailand is endowed with diverse energy resources. Natural gas and low-grade lignite have the greatest potential, while crude oil, condensate and hydro are available to some extent. Natural gas is proving to be the country's prime energy resource. From 2000 to 2004, it contributed about 57% of the domestic production of primary energy and about 31% of the total primary energy supply. Total natural gas reserves approximated were 33,516 Billion Cubic Feet (BCF) as of 2004, of which 96% are found offshore and 11,911 BCF are proven reserves. Lignite is one of the main indigenous resources. In 2004, total lignite reserves were estimated at about 2,870 million tons and almost 60% of them are found in the northern region. Crude oil and condensate account for a small amount of the domestic reserves. The total estimation of oil reserves is 516 million bbl and the condensate is approximately 903 million bbl (DEDE 2004).

Among the domestic production of primary energy, hydro and other renewable energy resources make a great contribution to the energy system. In 2004, Hydro, geothermal, solar cell and wind power accounted for 4% of the total production of commercial energy. Biomass, including fuel wood, paddy husk, bagasse, agricultural waste, garbage and biogas contributed to 30% of the country’s primary energy production.

However, in terms of total primary energy supply, Thailand relies on imported energy, which accounts for half of the country's total energy supply. Most of the imported energy is crude oil, which accounts for about 70% of the total energy imported and is followed by coal, petroleum products, hydro and charcoal, respectively. Figure 5.1 shows a comparison of total primary energy supply and the domestic production of primary energy. The comparisons include commercial energy, new and renewable energy, and other energy such as black liquor.

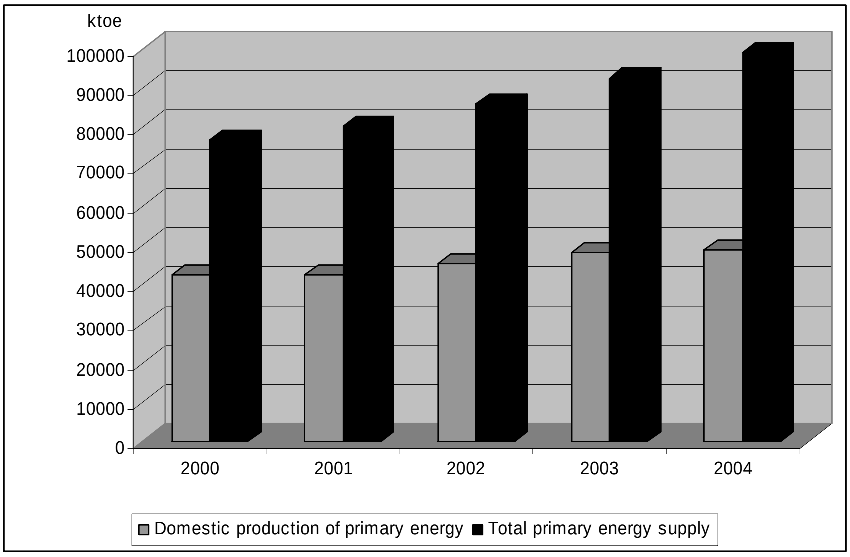


Figure 5.1. Comparison of total primary energy supply and domestic production of primary energy (Data source: DEDE 2004).

Regarding the energy demand, the economic growth rate over the period 1987-1996 was about 10% annually, and the energy demand has grown by an average of 11% annually (DEDP 2000). During the period 1997-2000, due to the economic crisis in Southeast Asia, the average annual GDP growth rate was about 1.2% and the energy demand growth rate was 0.8% annually. The annual final energy demand growth rate was approximately 6% during 2000 and 2004, caused by the recovery of the economic situation. These relations can be explained in a form of energy intensity, which is an index to show the relationship between energy consumption and a value added. As shown in Figure 5.2 the energy intensity is expressed in ktoe per thousand Baht at 1988 constant prices. Energy intensity increased from 15.9 ktoe/thousand Baht in 2000 to 16.4 ktoe/thousand Baht in 2004.

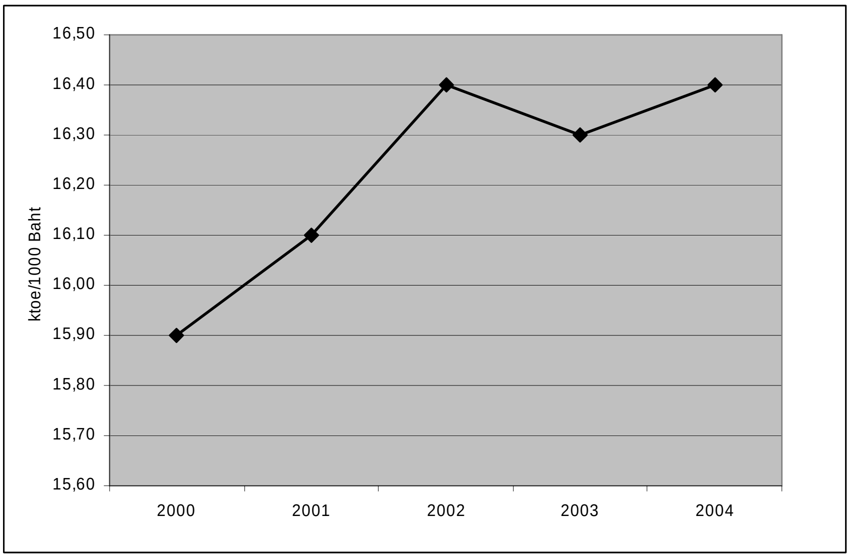


Figure 5.2. Energy intensity in Thai economy during 2000-2004 (Data source: DEDE 2004).

Typically, the final energy demand in Thailand is disaggregated into four sectors: agriculture, industry, residential and commercial, and transport. In the past ten years, transportation has been the largest consumer of final energy consumption, followed by industry, residential and commercial, and agriculture sectors, respectively. Figure 5.3 shows the final energy consumption in Thailand by sectors during the period 2000-2004. In 2004, the total final energy consumption of both commercial and renewable energy was 60,269 ktoe; of this, the commercial energy accounted for 84.2%. Petroleum products consisted of 64% of the total commercial energy consumption, while biomass was the main source of renewable energy utilization.

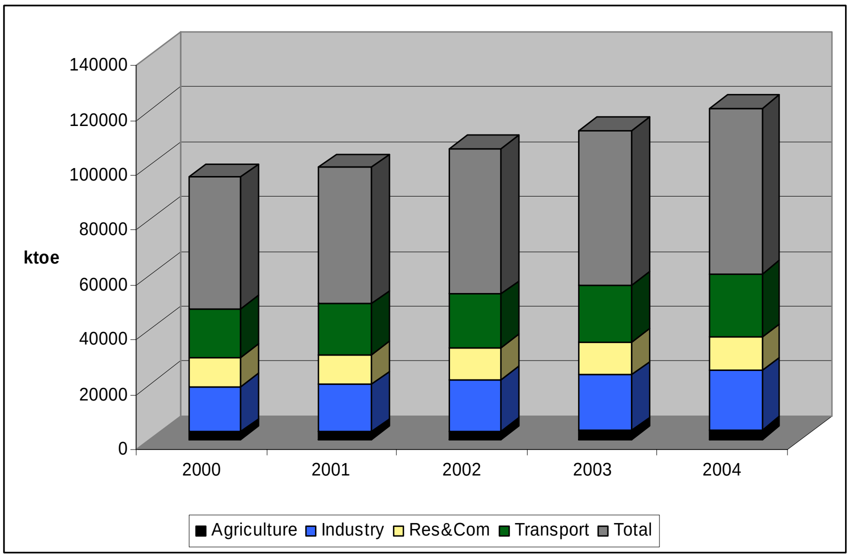


Figure 5.3. Final energy consumption by sectors in Thailand (Data source: DEDE 2004).

5.1.3. Energy use pattern in Bangkok

As mentioned above, the typical energy analysis is disaggregated into four sectors; therefore, the energy use pattern in Bangkok is described in the same manner. In Bangkok, the consumption of energy is dominated by electricity and petroleum products. The proportion of each energy requirement depends upon the energy services within each sector. Figure 5.4 shows an estimation of energy consumption by sectors in Bangkok.

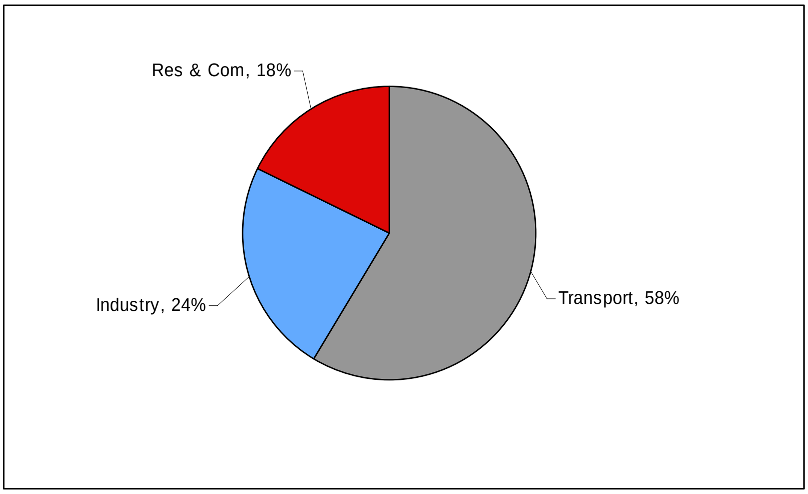


Figure 5.4. Estimation of energy consumption by sectors in Bangkok (estimated by LEAP model).

The transport sector accounts for half of the energy consumption in Bangkok. The petroleum products consumed in this sector are mainly comprised of diesel, gasoline, and liquefied petroleum gas (LPG). A small fraction of electricity is used by sky trains and sub-ways. The sky train and sub-way have been in operation since 2000 and 2004, respectively. Road transport takes the biggest proportion. According to the vehicles registered under the Motor Vehicle Act, motorcycles account for almost 40%, passenger cars approximately 30%, vans and pickups share about 15%, and the rest is contributed by microbus, motor-tricycle, urban taxi, fixed route taxi, fixed route bus, bus for hire, private bus and others.

The industry sector can be broadly divided into two categories: manufacturing and construction. Manufacturing consists of food and beverages, textiles, wood products, paper, rubber, chemical and petroleum industries, non-metallic, basic metal, and other manufacturing. The energy demand basically consumes electricity and non-electricity. The major purpose of the electricity consumption is for the electric equipment such as motors and pumps. Also, space conditioning shares a big proportion due to the structure of the manufacturing industry, which is required to control temperatures in their processes, for instance car assembly, electronic equipment, etc. Non-electricity utilization is for thermal purposes in boilers and furnaces.

The residential and commercial sector mainly consumes electricity for the purposes of air-conditioning and lighting. The non-electricity demand is primarily for cooking devices such as LPG cooking stoves. The economic development of the Thai economy brings Bangkok into being an industrialized and service-oriented city. The Bangkok Metropolitan Area (BMA) urbanization pattern can be divided into inner BMA and outer BMA. The inner BMA is built up of temples, government offices, educational institutions, commercial offices, and two to four story row houses that serve for commercial retail as well as living quarters. The outer BMA was traditionally cultivated land; however, economic development and immigration have transformed this area into residential and industrial estates.

A small amount of energy consumed in the agriculture sector accounts for approximately 0.05% of the total energy consumption in Bangkok. The energy consumed is based on non-electricity, comprising almost entirely of diesel. However, the zones for agricultural purposes have been transformed and have other purposes such as for households and offices. Moreover, land prices are increasing and this causes agricultural activities in Bangkok to become less significant in terms of energy consumption.

5.2. Direct and indirect energy consumption

Theoretical IO-analysis and embodied energy analysis has been described in Chapter 3. As it is greatly data-intensive, data collection has been the central issue, for a model structure that can be analyzed is largely dependent upon the data available. The models need detailed accounts of the flow of energies and materials for each sector. The material flow data is extracted from the Thai IO-tables. The data available makes it difficult to collect the energy flows from each sector in Bangkok. To avoid this problem, the LEAP model is used to calculate the energy demand in Bangkok.

5.2.1. Data specification

5.2.1.1 Input-output tables

The IO-tables of Thailand have been compiled every five years since 1970. An IO-table records a matrix of goods and transactions of services among the sectors of a certain region within a certain period of time, normally a duration of one year. The values of domestic production as well as the input components (for goods and services) of the individual sector may be inferred from the figures, as illustrated in the sectors column of the IO-table. Moreover, the amount of domestic production sales, as well as the import of the respective goods and service sectors demanded, may be inferred from the sector row within the tables.

In this study, the IO-tables of Thailand from 1998 (NESDB 2003) were used to estimate the embodied energy. Due to unavailable data, the IO-table of Bangkok has been transformed to be based upon the national level. The IO-table for the basic sector classification consists of 180 sectors. For analysis, several intermediate sectors in the national IO-table were consolidated to convert the matrix into 16 sectors such as food manufacturing, textile industry, trade, services, etc., according to the economic structure of Bangkok. The IO-coefficient is estimated from the national IO-table and converted into the city level (Bangkok) by the Cross-Industry Location Quotient Method (CIQ). For more details of this method see Schaffer (1976). Other relevant data was collected from various statistics and materials for the estimation of gross consumption.

5.2.1.2 Energy demand data

Compared with the material flow data, the energy consumption data to detail each sector is much more difficult to obtain; the detailed breakdown of energy demand in Bangkok cannot be drawn from statistical data. The amount of data recorded in Bangkok is usually restricted to the total consumption of the various energy forms e.g., diesel oil, gasoline and electricity. In order to overcome this obstacle and to obtain the required data, the LEAP model has been used to estimate the energy demand within the various sectors corresponding to the IO-tables (Phdungsilp 2005). The estimated breakdown of direct energy consumption in Bangkok from 1998 is shown in Table 5.1.

Since the central concept of the LEAP model is based on end-use analysis, the energy demand is first disaggregated into various economic activities corresponding to the consolidated IO-table. The energy intensity values in each device are collected from both local and international studies. Other input parameters are related to a number of known or predictable data. These parameters can then be classified into the following categories: (a) structural characteristics e.g., GDP, population, number of dwellings, etc. (b) technological characteristics e.g., the type and efficiency of the end-use devices, and (c) behavioral characteristics e.g., mode of technologies used.

5.2.2. Direct and indirect energy consumption in Bangkok

The estimated breakdown of direct and indirect energy demand in Bangkok for the year 1998 is presented in Table 5.1. It shows that the transport sector consumed the majority of energy in Bangkok. This aspect was consistent with the country's consumption. From the national point of view, between 1991 and 2000 transportation was the largest consumer of energy with a growth rate of 5.8% within the total energy consumption. It accounted for approximately 40% of the total energy demand in Thailand.

The indirect energy demands of Bangkok were estimated and compared with the direct energy demands. Table 5.1 shows the comparison between the estimated breakdown between direct and indirect energy demands in Bangkok for 1998. The total direct and indirect energy demand is shown in Figure 5.5. It should be noted that household consumption is only accounted in the direct energy demand due to its direct payment from residents and to avoid double counting within the calculation. According to Figure 5.5, indirect energy demand is more significant than direct energy demand in Bangkok. This can be explained by the fact that Bangkok has a great reliance upon the outside in terms of energy demand.

Table 5.1. Comparison estimated breakdown direct and indirect energy demand in Bangkok in 1998.

Sectors	Direct energy demand (ktoe)	Indirect energy demand (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 industries	46.00	388.19
Non-metallic products	351.53	419.78
Metal, metal product & machinery	75.89	283.48
Other manufacturing	37.70	55.68
Public utilities	1,613.47	2,194.04
Construction	112.75	137.31
Trade	1,404.49	5,348.49
Transportation and communication	10,242.18	13,043.12
Services	2,285.47	10,528.69
Consumption of households	834.00	-
Total	17,498.96	33,234.56

An interesting finding from the estimated direct and indirect energy demand is the deviation in the service and trade sectors. The indirect energy consumption in these sectors is about five times higher than the direct energy consumption. Therefore, measures (e.g., sustainable consumption) attempting to reduce the consumption of goods and services would show a great reduction in energy consumption. However, this point needs further research to examine the affect.

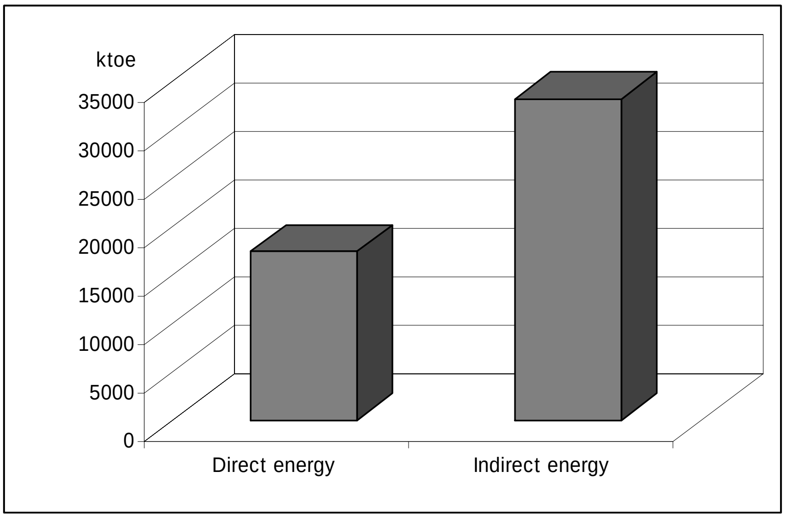


Figure 5.5. The estimated total direct and indirect energy demand in Bangkok for 1998.

The essence of the embodied energy analysis is an indirect reflection on the behavior that follows after the direct energy consumption. Indirect energy consumption illustrates how a city relies upon the outside. Certainly, the direct energy demand can be taken as an indicator on how a city relies upon factors from the outside. However, indirect energy demand can provide additional information for further studies as well as policy measures.

5.3. Bangkok energy modeling

The aim of this section is to develop some scenarios for Bangkok's energy future. The simulation model (LEAP) has been used to simulate how energy might develop in Bangkok over the twenty-five years from 2000 to 2025. The planning period starts in 2005 and ends in 2025, with 2000 being taken as the base year. These developments are driven not only by the nature of the energy sector itself, but also by broader factors, notably population and economic growth, and other factors that vary with each sector. A range of policy interventions have been selected, and how these would change energy development in Bangkok is examined and compared to a reference case. Interventions were evaluated by various criteria, including implementation costs, technical feasibility, environmental priority, and political will. This method will be explained in the MCDM to evaluated policies session. Different policies can be grouped by their sectors: commercial, industrial, residential and transportation, respectively. These scenarios should be understood as a series of "what if" questions, as described earlier.

5.3.1. Model of energy demand and supply

The model of the energy demand for the different sectors is formulated and structured upon the framework of the LEAP mode. The historical data were collected from several reports of the governmental and non-governmental agencies, which include the Ministry of Energy (MOE), the Department of Energy Development and Promotion (DEDP), the recently named Department of Alternative Energy Development and Efficiency (DEDE), the Metropolitan Electricity Authority (MEA), the National Economic and Social Development Board (NESDB), the Bangkok Metropolitan Administration (BMA), the National Statistical Office (NSO), the Bank of Thailand (BOT), the Mass Rapid Transit Authority of Thailand (MRTA), the Bangkok Mass Transit System (BTS), and others.

As mentioned earlier, a detailed breakdown of the energy demand in Bangkok cannot be had from statistical data (which is primarily data of the various energy forms). Also, there has not been any research carried out on city energy modeling in Thailand (Phdungsilp 2005). Therefore, this study is probably the first study of energy modeling at a city level in Thailand. It also makes an attempt to analyze the policies of intervention. Due to the sparse availability of data, the greatest challenge in constructing the energy modeling is to set up a system that can be efficiently analyzed.

5.3.1.1. Commercial sector

In this thesis, the assumption concerning commercial buildings is based upon "Designated Buildings" in different sub-sectors. This is due to the difficulty of obtaining the number of buildings in Bangkok. In 1992, the Royal Thai Government promulgated an Energy Conservation Promotion Act (ECP Act) and these buildings covered by the Act were entitled "Designated Buildings", defined as those that are not royal buildings or palaces, embassies or consulates, offices of international organizations, any that are established by an agreement between Thai and foreign governments, ancient places, temples or buildings for religious purposes, along with the buildings that meet the following conditions (NEPO 1999):

- A building or buildings under the same address that are allowed by any energy distributor to install an electricity metering device, or to install one or more transformers whose combined capacity is 1,000 kW or 1,175 kVA and above.

- A building or buildings under the same address that consume commercial energy, including electricity and steam as of January 1 to December 31 of the previous year, in total volume energy of $20*10^6$ MJ or more of electrical energy equivalent.

Figure 5.6 summarizes the status of Bangkok's commercial sector in the year 2000, the base year of the energy model. According to DEDP, the designated buildings are divided into six categories: office, hotel, hospital, department store, academic institute and miscellaneous. There are about 881 designated buildings situated in Bangkok (AIT 2002).

The energy demand estimation in commercial buildings is made up of six building types and three end-uses, including HVAC systems, lighting and others. The consumption is formulated as a function of the number of buildings, proportion of energy services (HVAC, lighting, and others), device efficiency and the energy intensity on a building basis for each end-use.

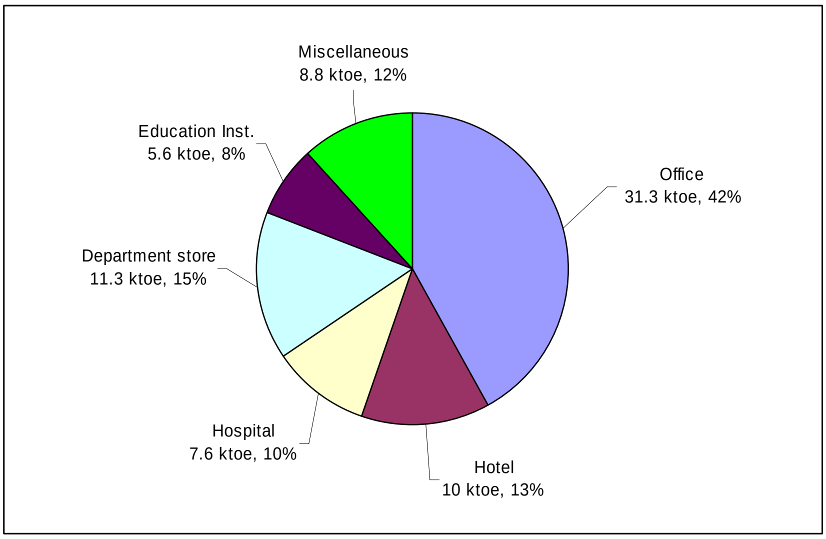


Figure 5.6. Total commercial energy used by building types in 2000 (AIT 2002).

The projected number of designated buildings is shown in Table 5.2. It is also assumed that during the study period, the office growth rate will be 2% per year during the years 2000 to 2015 and will drop down to 1.5% per year from 2016 to 2025. With hotels, the growth rate will be 1.5% per year during the years from 2000 to 2015 and drop to 1% per year from 2016 to 2025. The growth for hospitals is assumed to be constant throughout the planned period. The department store growth rate from 2000 to 2015 is assumed to be 1% per year and then drops to 0.5% per year from 2016 to 2025. With academic institutions it is assumed that the growth rate will be 1% per year from 2000 to 2010. With the miscellaneous category a growth rate of 1.5% per year is assumed to be constant from 2000 to 2025.

Table 5.2. The number of projected designated buildings in Bangkok (compiled from AIT 2002).

Sub-sector	2000	2005	2010	2015	2020	2025
Office	425	469	518	572	616	664
Hotel	99	107	115	124	130	137
Hospital	66	66	66	66	66	66
Department store	117	123	129	136	139	143
Academic institution	65	68	72	72	72	72
Miscellaneous	109	117	126	136	147	158
Total	881	950	1,026	1,106	1,170	1,240

The end-use considered is electricity, and the proportions of energy services and the breakdown of the annual energy consumption are derived from AIT (2002) and Chirarattananon & Taweekun (2003). They are also assumed to be constant for the planned period. These parameters are presented in Table 5.3.

Table 5.3. Average breakdown of annual energy consumption and percentage share of energy services per building (compiled from AIT 2002 and Chirarattananon & Taweekun 2003).

	Office	Hotel	Hospital	Department store	Academic Inst.	Misc.
A/C system (kWh)	1,345,612	1,702,305	1,893,502	1,857,109	1,345,612	1,345,612
Average % share	52	66	65	43	66	60
Lighting (kWh)	433,918	193,210	491,777	541,034	433,918	433,918
Average % share	20	20	17	25	15	20
Others (kWh)	246,807	62,499	104,530	592,969	246,807	246,807
Average % share	28	14	18	32	19	20

5.3.1.2. Industry sector

The industry sector can be broadly classified as nine manufacturing sub-sectors, including food and beverages, textile, wood and furniture, paper, chemical, non-metallic, basic metal, fabricated metal, and others (unspecified), according to DEDP and NSO. The model calculates the energy demand as a function of gross provincial product (GPP), and as a proportion of utilized energy, device efficiency and useful energy intensity. Figure 5.7 summarizes the status of Bangkok's industry sector in 2000.

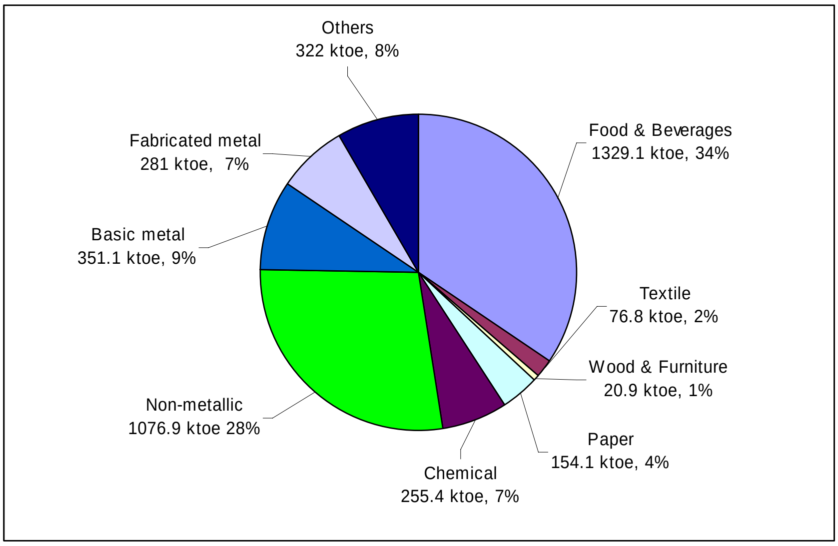


Figure 5.7. Energy consumption of industrial sub-sectors in 2000.

Data of GPP is taken from the NESDB and is used to project the future GPP by using the average annual growth rate of 3%. The proportions of GPP in the industrial sub-sectors are assumed to be constant for the duration of the time horizon. The proportion of energy utilized at end-use and device levels are derived from the energy consumption in the year 2000 (DEDP 2000). It is also assumed to be constant throughout the study period. The proportion of energy utilization in industrial sub-sectors is shown in Table 5.4.

Table 5.4. Proportion of energy utilization in industrial sub-sectors (DEDP 2000).

Fuel types	Proportion of energy utilization (%)								
	Food	Textile	Wood	Paper	Chemical	Non-metallic	Basic metal	Fabricated metal	Others
Natural gas	1.00	-	-	-	18.93	18.17	-	21.41	-
LPG[a]	0.82	1.00	0.86	3.20	3.52	0.76	3.36	2.49	6.01
Kerosene	0.01	0.07	0.02	0.04	0.07	0.05	0.09	0.40	1.32
Gasoline	0.03	0.21	0.24	0.11	0.11	0.18	0.07	0.37	2.47
Diesel	2.60	1.25	10.61	2.48	2.59	1.32	4.06	1.74	13.28
Fuel oil	10.16	42.24	10.85	29.54	12.26	7.49	26.07	6.60	70.35
Electricity	10.71	28.38	69.35	18.54	27.59	10.47	41.10	66.99	2.00
Imported coal	-	-	-	-	25.33	24.66	9.11	-	-
Coke	-	-	-	-	-	-	16.14	-	-
Anthracite	-	-	-	-	5.09	-	-	-	-
Lignite	0.93	6.85	-	46.09	-	32.56	-	-	4.57
Fuel wood	9.12	-	8.07	-	4.51	3.97	-	-	-
Rice husk	12.80	-	-	-	-	0.37	-	-	-
Bagasse	51.82	-	-	-	-	-	-	-	-

[a]LPG stands for Liquefied Petroleum Gas

The average device efficiencies are taken from the energy audit reports of King Mongkut's University of Technology Thonburi (KMUTT), Thailand. The average useful energy intensity in each sub-sector is presented in Table 5.5. However, it is too difficult to classify different types of devices with a specific energy because of the variety of devices and also the limitation of data within the industrial sector. It is assumed that each type of energy in each sub-sector is used as a specific device. The useful energy intensity is estimated by the following equation:

$$UEI_j = \sum_t \frac{(EnU_{i,j} * \eta_{i,j})}{GPP_j}$$ Eq. (5.1)

where UEI_j is the useful energy intensity in the industrial sub-sector j (ktoe/10^6 Baht), $EnU_{i,j}$ is the energy type i utilized in the industrial sub-sector j (ktoe), $\eta_{i,j}$ is the device efficiency using fuel type i utilized in the industrial sub-sector j, and GPP_j is Gross Provincial Products of the industrial sub-sector j, (10^6 Baht).

Table 5.5. Average useful energy intensities in industrial sub-sectors (Tanatvanit et al. 2003).

Industrial sub-sectors	Average useful energy intensity (ktoe/10^6 Baht)
Food and beverages	0.0213388
Textile	0.0052836
Wood and furniture	0.0100809
Paper	0.0185502
Chemical	0.0094627
Non-metallic	0.0216113
Basic metal	0.0338194
Fabricated metal	0.0225538
Others	0.0155091

5.3.1.3. Government sector

There is limited data in this sector; therefore, only street lighting in Bangkok is counted. However, large government buildings are subject to the requirements of the ECP Act, so they are considered in the commercial sector. The annual street lighting consumption data is obtained from the Bangkok Metropolitan Administration (BMA) and the Metropolitan Electricity Authority (MEA). Energy demand is calculated from the parameter of activity and fuel intensity per unit of activity.

5.3.1.4. Residential sector

The household sector in Bangkok is divided into two areas: the inner BMA and outer BMA. Figure 5.8 presents the status of Bangkok's residential sector in the year 2000. The number of households is formulated as a function of the population and the size of households as the following:

$$H_t = \frac{P_t}{S_t}$$ Eq. (5.2)

where H_t is the number of households in year t, P_t is the number of the populace in year t, and S_t is the size of the household in year t.

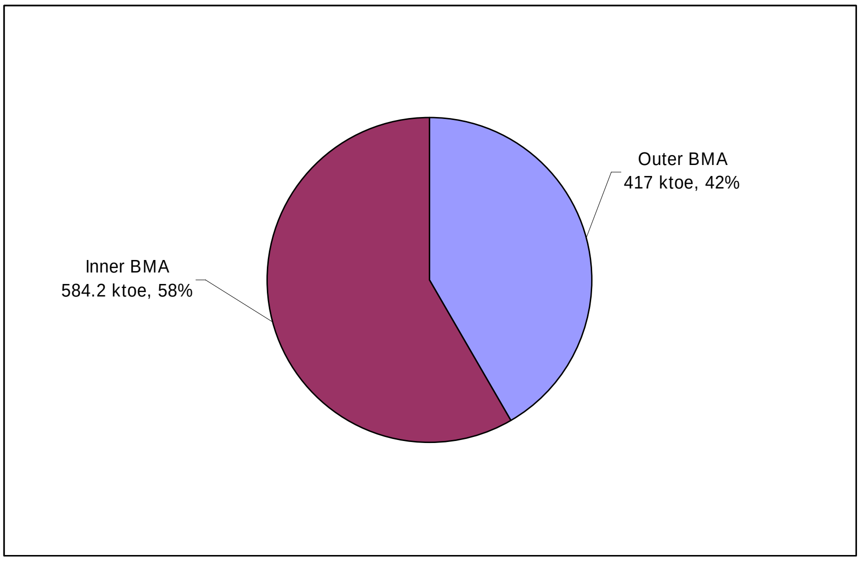


Figure 5.8. Energy consumption of residential sector in 2000.

The size of the household of the projected population is estimated by using the log-limit model (Tanatvanit et al. 2003). The lower limit of household size applied in this study is three persons per household. The estimated number of households in Bangkok is shown in Table 5.6.

The end-uses are organized into six categories, including cooking, lighting, space conditioning (air-conditioning and fan), refrigeration, water heating, and others (iron, TV, radio, etc.). The proportion of end-use devices is disaggregated into existing appliances and high efficiency appliances, which are either in use or are likely to be introduced in the near future. The energy intensity of each appliance can be formulated as a function of the number of appliances, capacity of appliances, and the average usage hours. The average number of appliances per household and usage hours per day is obtained from statistical data and reports of the DEDP. The average capacity of conventional and high efficiency appliances is taken from the public documents of the DEDE and market surveys, as shown in Table 5.7. The average intensity of each end-use appliance can be estimated by the following equation:

$$EI_i = hr_i * Cap_i * No_i \quad \text{Eq. (5.3)}$$

where EI_i is the energy intensity of appliances, (kWh/year.HH), hr_i is the usage hours per year of end-use device i, (h/year), Cap_i is the average capacity of end-use device i, (kW), No_i is the average number of end-use devices i per household (unit/HH), and HH is the household.

Table 5.6. The number of projected households in Bangkok Metropolitan (compiled from Tanatvanit et al. 2003).

Year	Inner Bangkok	Outer Bangkok
2000	1,516,503	1,393,477
2005	1,577,693	1,484,572
2010	1,617,235	1,627,772
2015	1,646,505	1,802,086
2020	1,669,754	2,006,319
2025	1,688,121	2,028,389

Table 5.7. Energy intensity of the appliances used in the residential sector (DEDP 1997; Tanatvanit et al. 2003).

Type of appliance	Inner Bangkok	Outer Bangkok
Non-electricity appliance		
(toe/HH.yr)	0	0.04089
1 Wood stove	0	0.10098
2 Charcoal stove	0.05364	0.08046
3 LPG stove	0.05191[a]	0.07787[a]
Electricity appliance (kWh/HH.yr)		
1 Electric cooking stove	192.00	192.00
2 Rice cooker	106.20	106.20
3 Incandescent lamp	34.56	34.56
4 Fluorescent lamp	272.16	272.16
5 Compact fluorescent lamp	5.76	5.76
6 Refrigerator	311.11	311.11
	260.14[a]	260.14[a]
7 Air-conditioner	3,999.24	2,488.42
	3,423.17[a]	2,129.97[a]
8 Fan	414.14	376.49
	392.04[a]	356.40[a]
9 Iron	144.00	144.00
10 Clothes washer	113.47	113.47
11 Water heater	462.00	462.00
12 VDO	3.60	3.60
13 Television	84.35	84.35
14 Radio	5.94	5.94

[a]Figures are the average energy intensity of efficient appliances.

Energy consumption of a given technology is calculated as the number of households in each area, the saturation of the end-use within the household, the technology share of the end-use, the efficiency of the end-use, and the unit energy consumption of the given technology. Total energy consumption is the sum of the different technology categories.

5.3.1.5. Transport sector

In the transport sector, only road transport is considered due to its high proportion of the total consumed energy in the transport sector and the available data. Passenger travel includes the vehicle types of car, microbus and pickup, van and pickup, motor-tricycle, urban taxi, fixed route taxi, motor-tricycle taxi, motorcycle, fixed route bus, bus for hire, private bus, non-fixed route truck, private truck, tractor, mass transit system, and others. Figure 5.9

summarizes the status of Bangkok's transport sector by vehicle types for the year 2000. It is shown that in the transport sector almost all the energy is in passenger travel. There was a small amount of energy (electricity) used by the BTS or the sky train, which was in operation in the year 2000.

Typically, the energy demand for transportation is estimated by using the volume of traffic in terms of vehicle-kilometer. The projected number of vehicles is multiplied with the average distance per year to appraise the vehicle-kilometers per year. The energy demand is formulated as a function of the number of vehicles, average distance, proportion of vehicle types, and fuel economy or fuel efficiency of vehicle. In the LEAP model, total passenger-travel demand is expressed in terms of passenger-kilometers (pass-km). Therefore, total travel demand can be estimated as follows:

$$TD_t = \sum V_{i,t} * D_t * LF_i \qquad \text{Eq. (5.4)}$$

where TD_t is the total travel demand in year t expressed in pass-km, $V_{i,t}$ is the number of vehicles i registered in year t, D_t is the average distance of vehicle i (km), and LF_i is the load factor of vehicle i or the average number of occupants (passenger/vehicle).

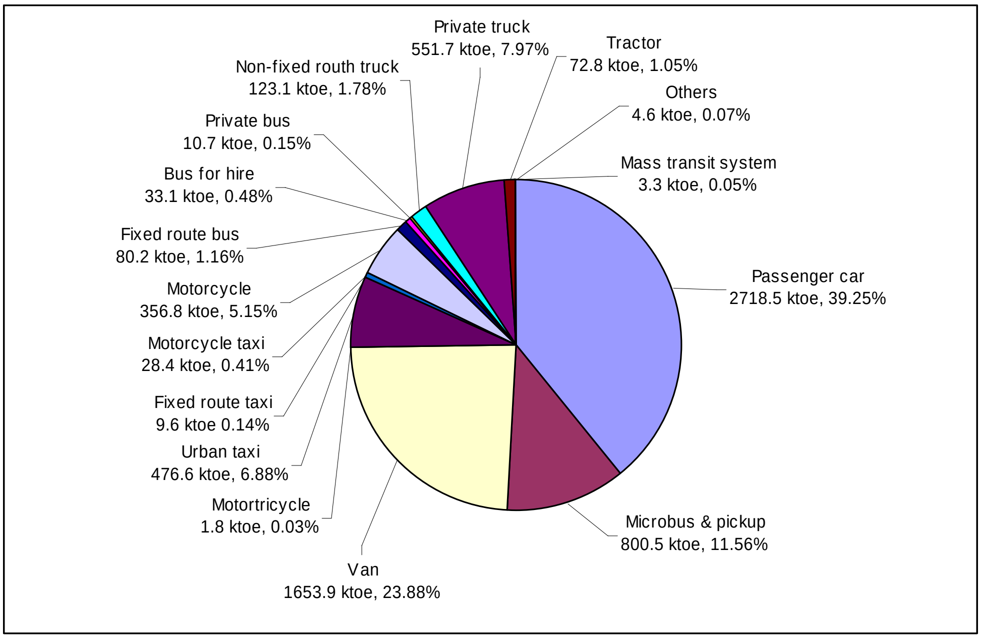


Figure 5.9. Energy consumption of transport sector by vehicle types in 2000.

The population per vehicle tends to decrease when a country develops. The estimation of the number of vehicles from the person-per-vehicle point of view should be of a lower limit of car ownership to be incorporated into the estimated number of vehicles (Tinakorn & Sussangkarn 1996). The estimation can be done with the log-limit equation where the limit is incorporated into the GDP and the population. The number of vehicles can be estimated by the following equation:

$$V_{i,t} = e^{(a_i + b_i * GDP_t + c_i * POP_t)} + LV_i \qquad \text{Eq. (5.5)}$$

where a_i, b_i and c_i are the coefficients in the model of the vehicle i, GDP_t is the Gross Domestic Product in the year t, POP_t is the number of the populace in the year t, and LV_i

is the lower limit of vehicle type i. The lower limits of each vehicle are used in this thesis, a comparison of model-based forecasting, and the actual number of registered vehicles in the year 2000 are presented in Tables 5.8 and 5.9, respectively.

The travel demand for road transportation is estimated on the basis of Eqs. (5.4) and (5.5), shown in Table 5.10. In the LEAP model, sub-sector and end-use levels, the shares of total passenger travel demand, and the different vehicles are estimated on the basis of Eq. (5.4). Each vehicle is disaggregated into existing technologies and alternative technologies or fuels. The energy intensity of vehicle technologies under device levels are calculated on the basis of fuel economy and occupancy, and re expressed in terms of liters per pass-km (l/pass-km) as follows:

$$EIV_i = \frac{1}{(FE_i * LF_i)} \qquad \text{Eq. (5.6)}$$

where EIV_i is the energy intensity of vehicle i (l/pass-km) and FE_i is the fuel economy of vehicle i expressed in vehicle-kilometer per litre (veh-km/l). The estimated energy intensity of the vehicle type is presented in Table 5.11. In a mass transit system the estimation of transport demand is based upon the load factor, average distance and operating hours, which are taken from MRTA 2005 and BTS 2005.

Hence, the energy demand in the transport sector is calculated as a function of the number of vehicles, average distance, proportion of vehicle types and the fuel economy or fuel efficiency of vehicle.

5.3.1.6. Model of electricity generation

Most of the analysis in this study is focused upon the demand-side, but the demand has to be met by the supply-side, which is transformation in the LEAP model. Electricity generation is included in the transformation module. Apart from ensuring that the energy system balances, there are two major environmental issue concerns: emission of GHGs contributing to global climate change and local air pollution. This characteristic allows the analysis of both problems.

Electricity generation calculations depend upon demand sector calculations. This sector specifies the technology attributes, merit order, and annual system load curve shape of electricity generation sector (SEI-Boston 2005). Actual electricity generation in any given model year depends on the level of electricity consumption generated by the five demand sectors and the level of imports (national grid). The model structure characterizes the generation sector, and then based on the level of electricity required to meet the annual demand requirements, it dispatches technologies to generate the needed electricity.

The electricity generation modeled in the Bangkok energy modeling is significant in examining the annual magnitude and composition of power generation. The Bangkok model offers a simple and transparent framework for exploring both the magnitude and the composition of the generation of electricity for the duration of the study period. This feature is useful for the implementation of the generation of electricity from renewable energy sources.

Table 5.8. Lower limits of persons per vehicle.

Vehicle types	Actual no. of persons per vehicle in 2000	Other studies		This study
	Bangkok	Study A[a]	Study B[b]	Bangkok
1. Passenger car	5	3	3	3
2. Microbus and pickup	15	3	100	10
3. Van and pickup	8	3	3	3
4. Motortricycle	6,279	-	-	5,000
5. Urban taxi	88	-	50	50
6. Fixed route taxi	694	-	-	600
7. Motortricycle taxi	767	-	-	700
8. Motorcycle	3	3	3	3
9. Fixed route bus	369	200	400	350
10. Bus for hire	816	200	1,000	200
11. Private bus	1,500	200	8,000	1,000
12. Non-fixed route truck	140	20	200	100
13. Private truck	71	20	100	50
14. Tractor	277	50	-	100
15. Small rural bus	0	300	-	-
16. Others	664	-	-	400

[a]Study A is obtained from Tinakorn & Sussangkarn 1996.
[b]Study B is obtained from Tanatvanit et al. 2003.

Table 5.9. Comparison of model-based forecast and actual number of registered vehicle in 2000 (extracted from Tanatvanit et al. 2003).

Vehicle types	Bangkok		Whole country	
	Actual	Forecast	Actual	Forecast
1. Passenger car	1,240,985	1,351,213	2,111,163	2,159,181
2. Microbus and pickup	295,527	357,465	554,242	573,696
3. Van and pickup	737,476	774,165	3,209,525	3,237,258
4. Motortricycle	1,076	893	4,879	4,009
5. Urban taxi	64,321	65,576	66,449	67,732
6. Fixed route taxi	8,187	8,195	8,779	8,862
7. Motortricycle taxi	7,403	7,401	47,227	47,155
8. Motorcycle	1,964,850	1,825,945	13,816,560	13,555,846
9. Fixed route bus	15,379	14,601	73,255	71,295
10. Bus for hire	6,961	7,268	18,746	19,590
11. Private bus	3,788	3,664	8,919	7,745
12. Non-fixed route truck	40,442	37,402	83,453	83,453
13. Private truck	79,721	75,857	569,067	564,365
14. Tractor	20,518	20,235	111,302	111,920
15. Others	8,553	8,513	99,294	97,132

Table 5.10. Estimated travel demand for road transportation in Bangkok (partially extracted from Tanatvanit et al. 2003).

Vehicle types	Estimated travel demand (10^6 pass-km)		
	2000	2010	2020
1. Passenger car	19,402	28,528	30,980
2. Microbus and pickup	6,190	9,542	11,137
3. Van and pickup	12,750	28,100	33,784
4. Motortricycle	16	13	12
5. Urban taxi	3,961	6,065	7,085
6. Fixed route taxi	158	140	110
7. Motortricycle taxi	244	241	235
8. Motorcycle	11,057	10,947	11,262
9. Fixed route bus	972	999	1,049
10. Bus for hire	383	581	747
11. Private bus	125	74	33
12. Non-fixed route truck	1,258	1,621	1,821
13. Private truck	4,877	5,768	6,317
14. Tractor	592	966	1,341
15. Others	80	118	136
16. Mass transit system	684	11,700	11,700

Table 5.11. Fuel economy of the automotive technologies by fuel types in Bangkok Metropolitan Area (Chanchaona et al. 1997).

Vehicle types	Average fuel economy (l/km)		
	Gasoline	Diesel	LPG
1. Passenger car	0.085690	0.080257	-
2. Microbus and pickup	0.081235	0.072202	-
3. Van and pickup	0.080515	0.073260	-
4. Motortricycle	0.083333	-	0.071429
5. Urban taxi	0.085690	-	0.085985
6. Fixed route taxi	0.076923	-	-
7. Motortricycle taxi	0.080000	-	0.087184
8. Motorcycle	0.040750	-	-
9. Fixed route bus	-	0.091659	-
10. Bus for hire	-	0.095877	-
11. Private bus	-	0.095420	-
12. Non-fixed route truck	-	0.108696	-
13. Private truck	-	0.125628	-
14. Tractor	-	0.136612	-
15. Others	-	0.063492	-

5.3.2. Energy policies and scenarios

The LEAP model is implemented in four sectors, commercial building, industrial, residential and transport, to illustrate the effects of alternative strategies on energy utilization and emissions. Furthermore, the supply-side policy considered meets a target of 10% electricity generation from renewable resources in a Bangkok energy system by 2025.

Individual policies have been created for the sectors (except the government sector), then combined in sectoral combinations, and finally brought together in an all policy scenario. For example, in the residential sector policies simulating the promotion of high efficiency appliances, passive design, and daylighting application are outlined separately. Residential policies are in turn combined with commercial, industrial and transport policies. Examining these policies together avoids double counting in the energy system. The policy question addresses the implications of what if a policy was implemented according to the assumptions stated? The question is "what if the energy policy in Bangkok changed the development path away from business-as-usual?" – what would the policy impacts be?

The study focuses on three key implications, including energy savings, local pollutants, and the avoidance of GHG emissions. It should be noted that local pollutants are analyzed at source, for instance where the combustion of the fuel leading to the pollution occurs. The air pollution problem in Bangkok exemplifies this problem, with local transport emissions in particular contributing to poor air quality.

The approach taken with global pollution is different. Emissions of GHGs (notably CO_2) contribute to global climate change, and it does not matter where the emissions occur. Most of the GHG emissions are due to the use of fossil fuels and actually occur at power stations. However, LEAP allows these emissions to be analyzed either at the source or to be attributed to the demand sector.

5.3.2.1. Business-as-usual scenario

The reference case in LEAP represents a base case without policy interventions. It is often referred to as the "business-as-usual" (BAU) scenario. In other words, it is a projection of what would happen in the absence of any specific energy policies and strategies.

The BAU scenario is constructed upon the current trends of parameters in each sector and assumed to be continuously increasing. The commercial sector is assumed to grow with the number of buildings. The industry grows with the GPP in the manufacturing sector at 3% annually. The government sector is assumed to be constant during the study period. The residential sector will grow by the number of households in each area. It is also assumed that the present efficiency of any appliances and technologies, and the pattern of energy utilization for different appliances and technologies, is unchanged in the future. The transport sector is assumed to grow with the estimated travel demand and number of vehicles.

5.3.2.2. Alternative policies and interventions

Alternative scenarios aim to illustrate the effect of policies and interventions on energy utilization and emissions. As mentioned earlier, the study focuses on energy savings, local pollutants and the avoidance of GHG emissions. Therefore, the selection of policies and interventions to be explored in LEAP was based upon those three factors. In addition, the use of renewable energy technologies is of interest in the Bangkok energy model. A total of sixteen policies have been selected for simulation. Table 5.12 summarizes the policies and interventions within the modeling.

Table 5.12. Description of energy policies and interventions for sustainable energy development in Bangkok.

	Policy or measure	Description
Residential (R)	Promoting high efficiency appliances (RHEFF: Res. High Eff. Appliances)	Conventional refrigerators, air-conditioners, and fans are replaced by high efficiency ones by 2025.
	Passive design and daylighting application (RPASS: Res. Passive design & daylighting)	New households in outer the Bangkok Metropolitan Area (BMA) will be built on passive design and improve lighting by daylighting application, consequently reducing cooling load (10%) and energy consumption for lighting (10%), starting 2005.
Commercial building (C)	Efficient HVAC system (CHAVC: Com. HVAC)	Improving efficiency of HVAC 10% by 2005 in every building type.
	Utilization of daylighting in lighting system (CDAY: Com. Daylighting)	Utilization of daylighting can improve the lighting systems. Assume 5% savings in lighting by 2005 and increasing this to 10% in 2010, and 15% in 2020, respectively.
	Behavioural change in HVAC and lighting systems (CBEH: Com. Behavioural change)	10% savings in HVAC systems by 2025, and 10% savings in lighting systems by 2025, driven by changes in user behaviour.
Industry (I)	Energy efficiency (IEFF: Ind. High Efficiency 10%)	Increasing industrial energy efficiency target of 10% by 2010. The improvements are from lighting, compressed air, motors, as well as improved boiler and steam system efficiency.
	Switching to natural gas (ING: Ind. NG Switching)	The Thai government has the policy to promote the use of natural gas (NG), which is a domestic resource and the country's major source of energy. Thermal energy supplied by non-renewable resources, LPG and electricity in industries switches fuels to NG by 2010.
Transport (T)	Introducing NGV to gasoline and diesel vehicles (TNGV: Tran. NGV)	Introducing NGV to gasoline and diesel vehicles: passenger car, microbus & passenger pickup, van & pickup, fixed routed taxi, fixed route bus, bus for hire, private bus, non-fixed route truck, private truck, and other. Penetration rates are about 5% by 2005, rising to 10% in 2010 and 20% in 2025.
	Switching to gasohol in gasoline vehicles (TGSH: Tran. Gasohol)	Thai government has a policy to switch all gasoline vehicles to gasohol (gasoline + ethanol) starting in 2007. This measure will be applied to passenger car, microbus & passenger pickup, van & pickup, motortricycle, urban taxi, fixed routed taxi, motortricycle taxi, and motorcycle.
	Introducing biodiesel in diesel vehicles (TBID: Tran. Biodiesel)	Biodiesel grows to a market share of 20% by 2025. This measure will be applied to all diesel vehicles.
	Modal shift from private passenger to mass transit systems (TSHIF: Tran. Modal shift).	Increasing the share of mass transit of 40% by 2015, rising to 60% by 2025. Considering for Passenger car, microbus & pickup, van & pickup, and urban taxi
Supply-Side	A target of 10% electricity generation from renewable resources by 2025. It is assumed that in order to meet the target electricity will generate from biogas PV will be installed in households and buildings, municipal solid waste, and solar thermal electricity.	
	Biogas Generation (BIO: Biogas generation)	Electricity produced from biogas. Assume 100 MW of plant with capacity factor of 0.7 by 2025.
	PV installed in households & buildings (PV: PV in Household and Building)	Assuming 500 MW of installed PV in households and buildings by 2025.
	Municipal Solid Waste (MSW: Municipal Solid Waste)	Assuming 120 MW of MSW plant will be installed by 2025.
	Solar Thermal Electricity (SOEE: Solar Thermal Electricity)	Assuming 400 MW of Solar Thermal Electricity plant by 2025.
	Renewable Electricity (EE: EE Renewable)	Including all scenarios from supple-side.

5.3.3. Results and discussion of the scenarios

5.3.3.1. The BAU scenario

The key drivers of the energy development and the assumptions used in the reference case or BAU scenario have already been described in section 5.3.2.1. The BAU scenario in the model shows that the total energy demand is estimated to be about 14,320 ktoe and 22,915 ktoe in 2005 and 2025, respectively. Table 5.13 shows the final energy demand for each sector. It can be seen that the transport sector, which focused only on road transportation, takes the biggest share of energy consumption in Bangkok. The energy demand is estimated at 8,692 ktoe in 2005 and 13,445 in 2025. Table 5.14 shows the energy demand for different fuels in the BAU scenario. It shows that diesel and gasoline are the major energy sources in Bangkok, which has an approximately 60% share of the total energy consumption. Detailed estimations of the energy demand for the different sectors under the BAU scenario are shown in Appendix A.

Table 5.13. Final energy demand by sectors in BAU scenario (ktoe).

Sectors	2005	2010	2015	2020	2025
Commercial	80.1	86.2	92.5	97.5	103
Industry	4,483.1	5,197.1	6,024.9	6,984.5	8,097
Government	12.3	12.3	12.3	12.3	12.3
Residential	1,052.3	1,110.3	1,173.7	1,243.9	1,257.6
Transport	8,692.6	10,507	11,195.5	11,884	13,445.3
Total	14,320.4	16,912.9	18,498.9	20,222.2	22,915.1

Table 5.14. The energy demand by fuel types in BAU scenario (ktoe).

Fuels	2005	2010	2015	2020	2025
Wood	208.4	241.4	279.7	324.1	375.1
Fuel oil	769.5	892.1	1,034.2	1,198.9	1,389.9
Natural gas	368	426.6	494.6	573.4	664.7
LPG	565.6	649.1	702.1	759.7	833.2
Kerosene	7.7	9	10.4	12	13.9
Gasoline	4,003.6	4,816.2	5,135	5,454.2	6,174.8
Electricity	1,799.4	2,036.4	2,248.7	2,489.6	2,720
Diesel	4,563.3	5,483.8	5,860.7	6,241.8	7,071.8
Coal	485.6	563	652.6	756.6	877.1
Lignite	526.3	610.1	707.3	819.9	950.5
Anthracite	15.1	17.5	20.3	23.5	27.2
Charcoal	7.5	8.2	9.1	10.1	10.2
Biomass	201.8	234	271.3	314.5	364.5
Bagasse	798.4	925.6	1,073	1,243.9	1,442.1
Total	14,320.4	16,912.9	18,498.9	20,222.2	22,915.1

5.3.3.2. Policies for the commercial sector

The main energy use in commercial buildings is electricity; therefore, the selected policies are intended to reduce electricity use by promoting high efficiency appliances, introducing the use of renewable energy technologies, as well as a behavioral change regarding the users. The energy savings that can be gained from implementing efficient HVAC systems and the utilization of daylighting as well as changing user behavior in commercial buildings are shown in Figure 5.10. The efficient HVAC systems policy shows the largest potential savings, while the user's behavioral policy shows a greater potential for reduction than the daylighting policy. The deviation of the daylighting policy to reference the case might seem small; however, the total savings in 2025 are estimated to be 16.2 GWh. The energy savings in commercial buildings are in the form of electricity. Reduced electricity consumption lowers demand and ultimately decreases the amount of CO_2 emissions from power plants. Figure 5.11 shows the avoided CO_2 emissions under different policies in the commercial sector.

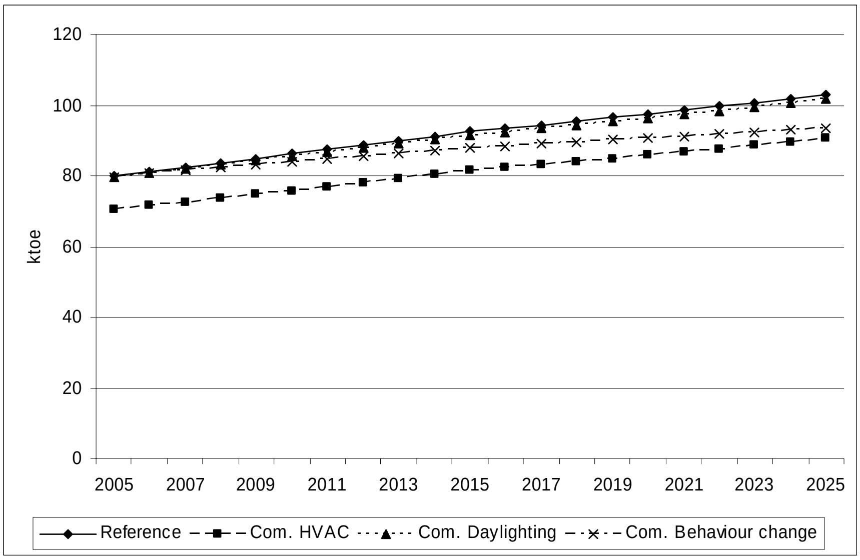


Figure 5.10. Energy savings in commercial buildings.

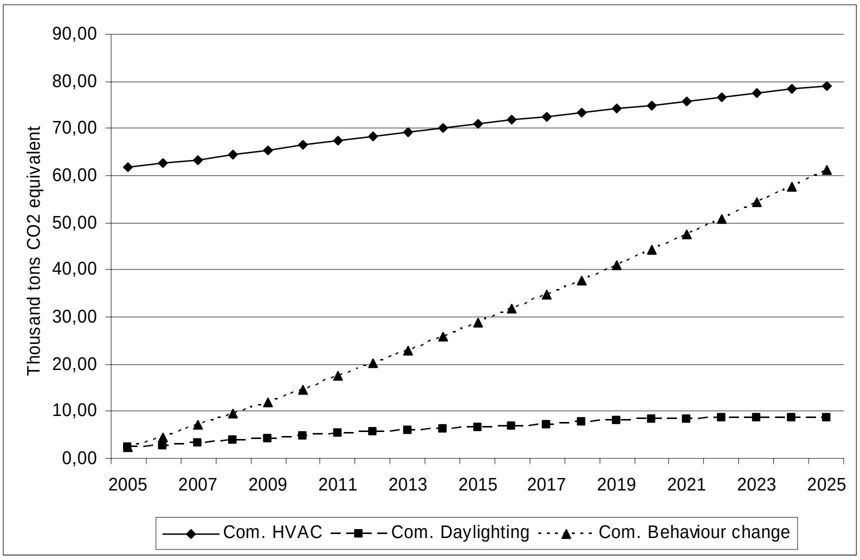


Figure 5.11. Avoided CO_2 emissions from commercial buildings.

5.3.3.3. Policies for the industrial sector

There are two scenarios in this sector. In the first scenario an increase in energy efficiency is assumed regarding industrial applications. The efficiency improvements occur in electrical devices as well as with suppliers of thermal heat. The improvements are likely to come from lighting, compressed air, motors, and improved boiler and steam system efficiency. The second scenario follows the Thai government to promote the use of natural gas. It is assumed that natural gas is available and a switch in the type of fuel used takes place within the thermal energy that is supplied by non-renewable resources.

In regards to the energy efficiency scenario, industry in Bangkok meets a 10% improvement in energy efficiency by 2010. The fuel switching scenario starts to take effect by 2010 as well. The reduction in the final energy demand in the industrial sector that occurs as a result of improved energy efficiency and fuel switching are shown in Figure 5.12. The potential energy savings in the energy efficiency scenario rises from 73.5 ktoe in 2005 to 736.1 ktoe in 2025, while the fuel switching scenario expects energy savings from 40.7 ktoe in 2005 to 441.1 ktoe in 2025. The reductions in CO_2 emissions from both scenarios are presented in Figure 5.13. It shows that the fuel switching scenario has great potential for reducing the amount of CO_2 emissions. Also, it will improve the level of the local air pollutants by reducing sulfur dioxide (SO_2). However, the main source of SO_2 in Bangkok comes from transportation, so this sector does not show the local pollutant reduction under both scenarios.

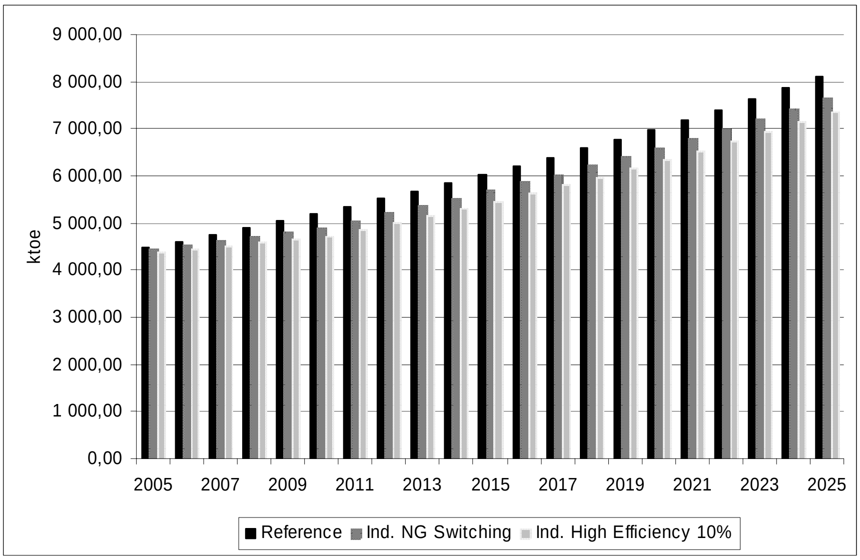


Figure 5.12. Final energy demand of the industrial sector under different scenarios.

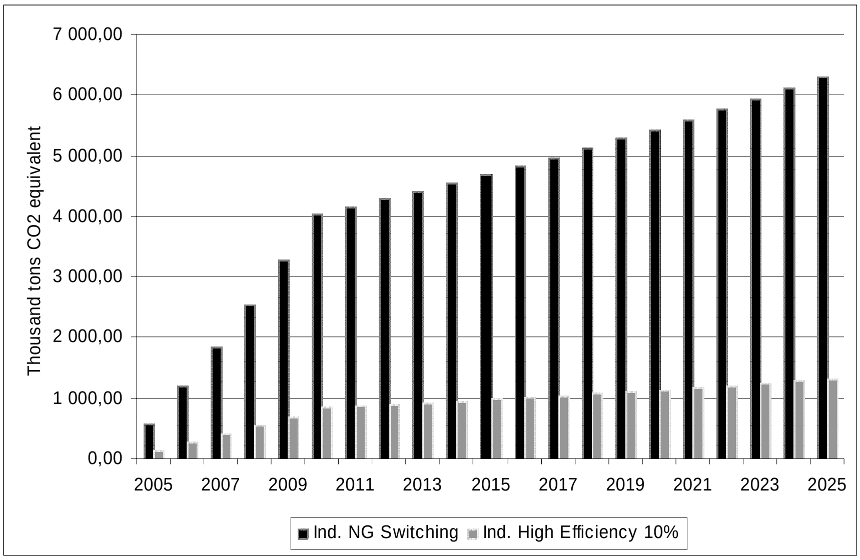


Figure 5.13. CO_2 reductions in the industrial under industrial policies.

5.3.3.4. Policies for the residential sector

Two scenarios have been examined in the residential sector, including the promotion of high efficiency appliances, passive design and daylighting scenarios. The fist scenario aims to simulate the effect of replacing conventional refrigerators, air-conditioners, and fans by high efficiency ones. The latter scenario assumes that the new households in the outer BMA will be built with passive design and improved lighting systems with daylighting application. These two scenarios will result in reduced electricity consumption as well as a reduction in CO_2.

The potential energy savings in the residential sector under both scenarios can be seen in Figure 5.14. The high efficiency appliances scenario shows a greater possibility of reducing the consumption of electricity than the passive design and daylighting scenario. The energy savings are expected to be 111 ktoe and 21.6 ktoe by 2025 under the high efficiency appliances, and the passive design and daylighting scenario, respectively. In the residential sector, the policies primarily reduce electricity consumption, and hence have an impact on CO_2 emissions. Figure 5.15 illustrates the avoided CO_2 emissions caused by residential policies. The reduction of CO_2 in the high efficiency appliances scenario is consistent with the potential for electricity savings. The amount of reduced CO_2 is expected to be 33.6 thousand tons CO_2 in 2005 and 721.3 thousand tons CO_2 in 2025. In the passive design and daylighting scenario, reduction in CO_2 is almost constant throughout the study period.

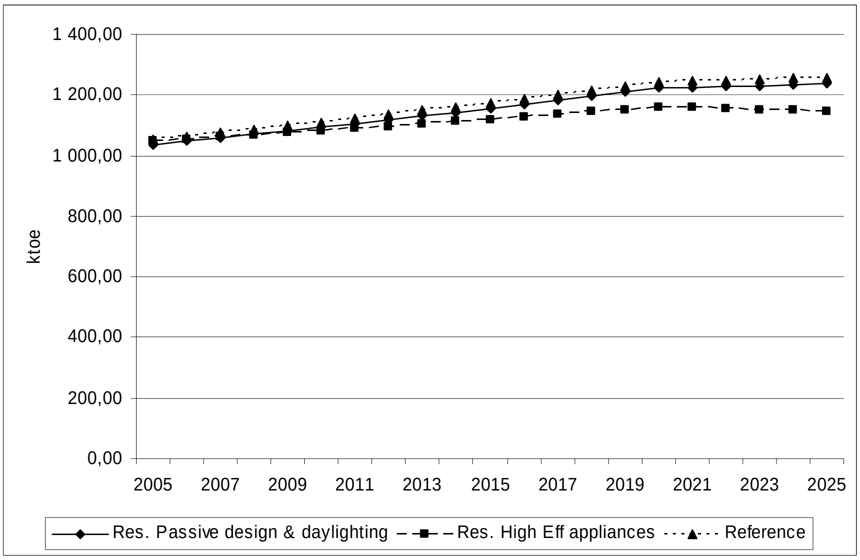


Figure 5.14. Trend of energy savings in residential sector.

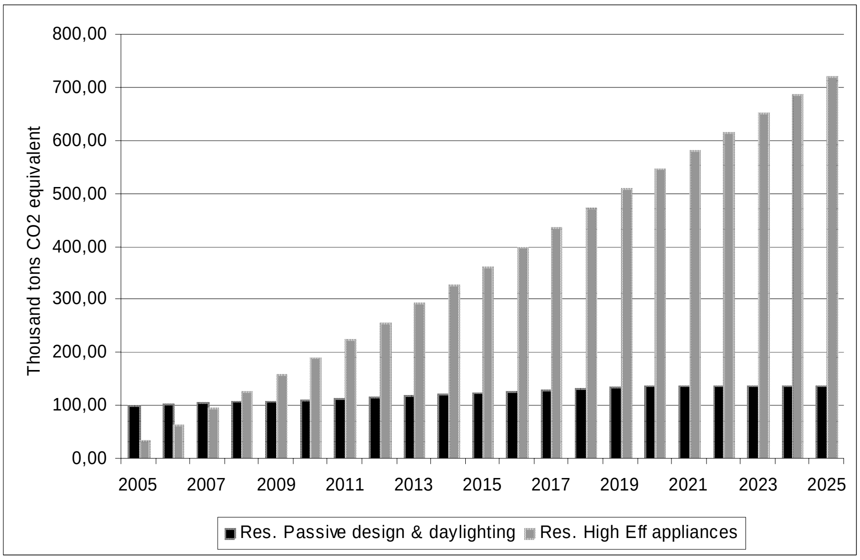


Figure 5.15. Avoided CO_2 emissions from residential policies.

5.3.3.5. Policies for the transport sector

As mentioned earlier, the transport energy policies focus on land-based transportation only. Air travel is not included in the model due to the difficulties in obtaining data and differentiating the energy use and environmental impacts within the boundaries of Bangkok, since most of the travel would be outside of the boundary. Air travel would have an influence on the more economic aspects rather than just the energy and environmental aspects.

Policy interventions in the Bangkok transport sector involve introducing cleaner fuel, such as introducing NGV, gasohol and biodiesel along with behavioral changes e.g., shifting transport modes from a private to a mass transit system. There are no energy savings for the introduction of cleaner fuel policies because it assumes that the cleaner fuels that replace existing fuels have the equivalent energy per liter. However, the introduction of cleaner fuel scenarios can decrease emissions and improve the level of local pollutants. The modal shift from a private transport system to a mass transit system results in large energy savings, as shown in Figure 5.16.

Due to the assumption in the modeling that the penetration rate of the introduction of cleaner fuels would be low, the reductions in the CO_2 emissions results change only a little compared to the reference case. Hence, only CO_2 reduction from the modal shift scenario is shown in Figure 5.17. Local emissions of (SO_2) are reduced in all transport scenarios over the time horizon, but they are more so within the modal shift policy. However, introducing the NGV policy has a very small change compared to the reference case. Figure 5.18 shows the overall reduction of local pollution regarding transport under the modal shift, gasohol and biodiesel scenarios. In the modal shift scenario, the reduced local pollutants show a significant decrease due to a shift to a much more efficient means of transport.

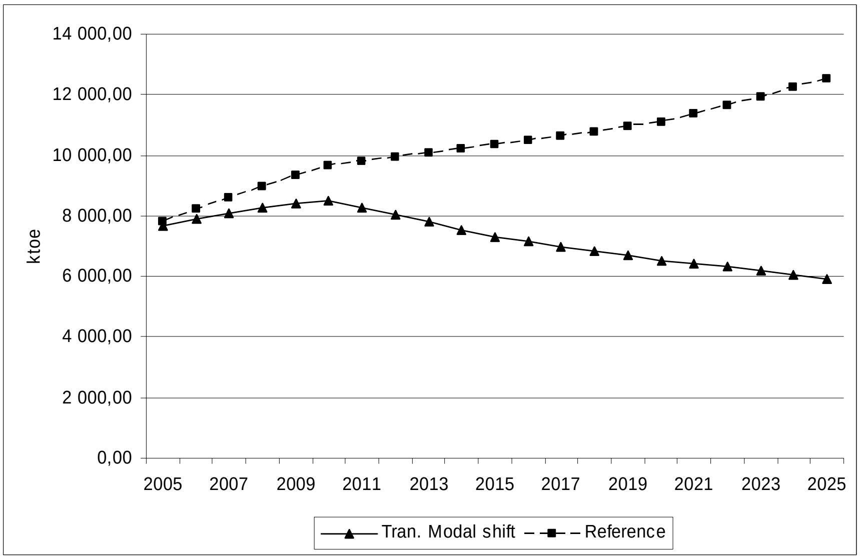


Figure 5.16. Trend of energy savings under the transport modal shift scenario.

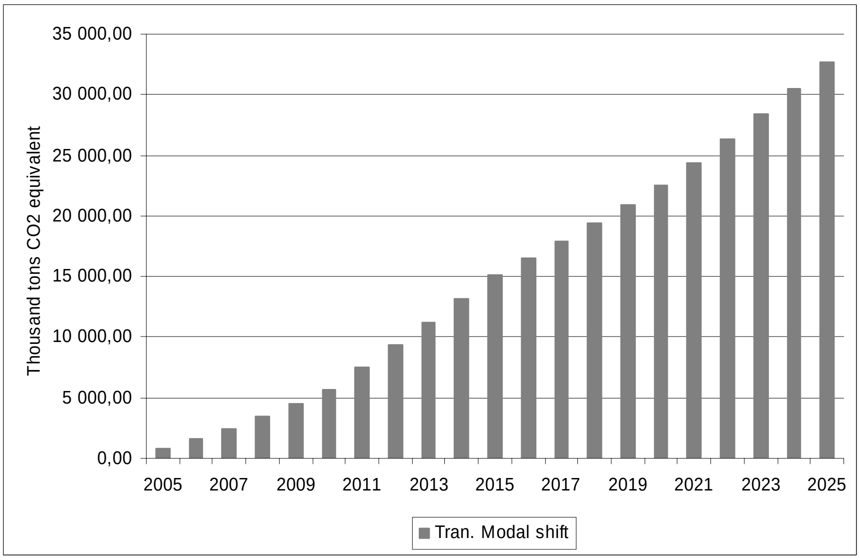


Figure 5.17. The transport CO_2 reductions under the modal shift scenario.

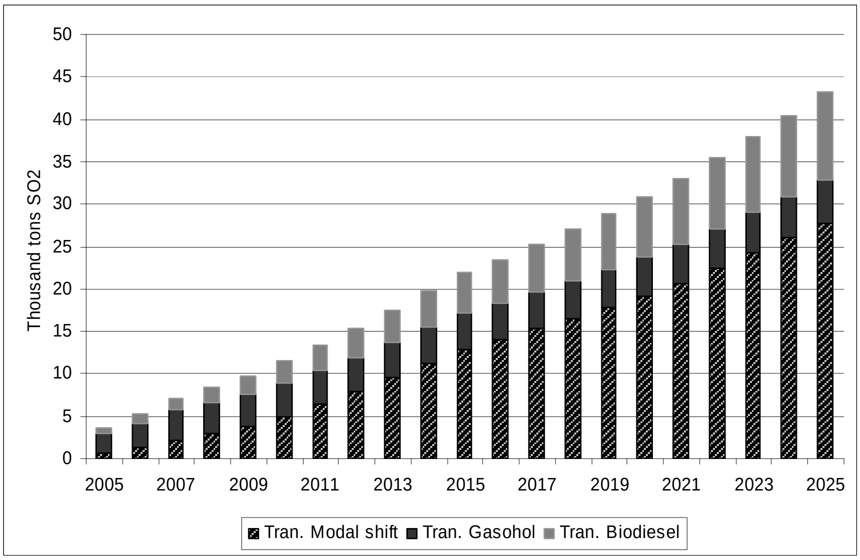


Figure 5.18. Local pollutant reduction in the transport sector.

5.3.3.6. Electricity generation from renewable energy technologies

The model is assumed to have a target of 10% concerning the electricity generated from renewable energy technologies by 2025. These requirements would be met by electricity being produced by biogas, PV installed in households and buildings, municipal solid waste (MSW) plants, and solar thermal electricity. In the model, process shares are set for individual policy, for example the PV installed has a process share of 3%, but most of the electricity is imported from the national grid. In the EE Renewable scenario (see Figure 5.19), it is assumed that all the scenarios where electricity generation is from renewable energy technologies are implemented together.

The results of the scenarios simulation show that the renewable electricity scenario has a significant reduction in CO_2 emissions. The expected CO_2 emissions would be 1,757 thousand tons CO_2-equivalent by 2025. Figure 5.19 shows the CO_2 reduction under different scenarios in the supply-side model. Among the different policies within the electricity generation scenario, the installation of PV in households and buildings shows the largest avoidance of CO_2 emissions, which would reach about 831 thousand tons CO_2-equivalent, while the solar thermal electricity, MSW, and biogas policies are expected to be, 671, 207, and 173 thousand tons CO_2-equivalent by 2025, respectively.

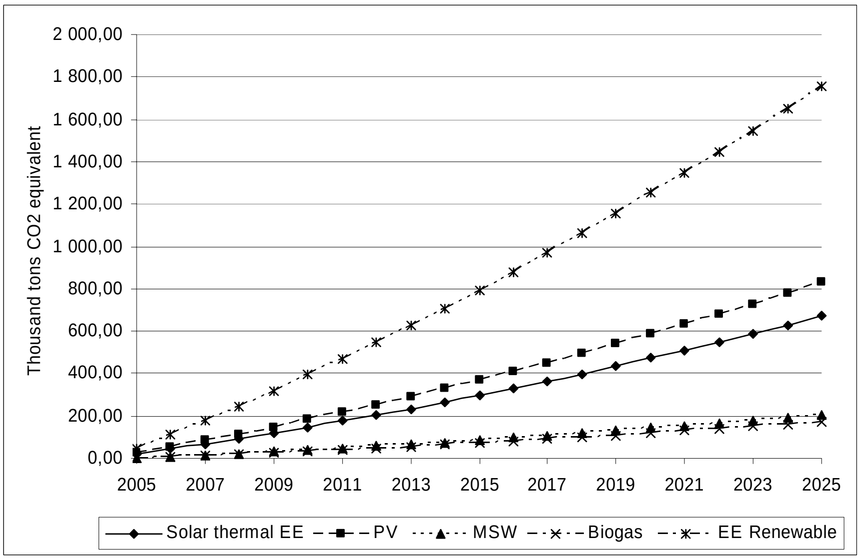


Figure 5.19. Avoided CO_2 emissions with renewable energy target.

The LEAP model represents a powerful tool for the analysis of energy planning with its associated environmental impacts. It can provide disaggregated energy demand in different sectors in particular areas. The Bangkok energy modeling examined in this study would be helpful to energy planners as well as to the city's administration in developing an energy plan, which regards sustainability.

Regarding the policy interventions in this study, they are considered with the broader policy goals of Bangkok in its effort to develop in a sustainable way. Some policies are consistent with government policies, some policies have cost savings, while others meet social or environmental goals. It is also important to consider whether or not policies can be implemented practically. All this balanced with some policies that would cause long-term change within Bangkok energy systems. Nevertheless, together this basket of policies could reduce local pollutants as well as help address global climate change. If all strategies on the demand side are simultaneously implemented the highest potential of energy savings in 2025 is expected to be 7,947 ktoe.

The modeling analysis outlines the implications of different policy scenarios. Because policies are not implemented as packages, the study provides analysis for each policy. However, the LEAP framework ensures that the total energy supply and demand match, avoiding the double-counting that sometimes occurs with policy-by-policy analysis (Winkler et al. 2005).

5.4. Energy decision with multi-criteria decision-making

MCDM and computer-based decision support systems can provide ways to systematically structure and analyze complex energy decision problems. The MCDM approach can help decision-makers organize and synthesize information in a way that leads them to feel comfortable about making a decision. With these systems, individuals can evaluate and compare policy alternatives (Mustajoki et al. 2004). The following section shows the results of the MCDM method as described in Chapter 4, along with a discussion of the scenarios evaluation and lessons learned from this approach.

Sustainability is an interdisciplinary task; therefore, teamwork between different but related disciplines makes it possible to face the challenge of solving the problem. In order to evaluate criteria and alternatives in this study, members of the group consisted of Ph.D. students at the Royal Institute of Technology, Stockholm, Sweden. Each member in the test group played the role of real members in a decision-making team, including politician, engineer, economist and environmentalist.

5.4.1. Weighting of criteria

The performance prediction for the alternatives was done using estimations based upon rules of thumb and the experience and knowledge of the team members. Computer simulation was carried out for the predicted energy demand. The criteria and sub-criteria were weighted directly. The weights were produced through individual opinion corresponding to their role-play. Data from members were entered into Web-HIPRE. The weighted main criteria are shown in Figure. 5.20. This chart shows the relative importance of weights for the criteria that were used in creating the total weighted scores for the different alternatives.

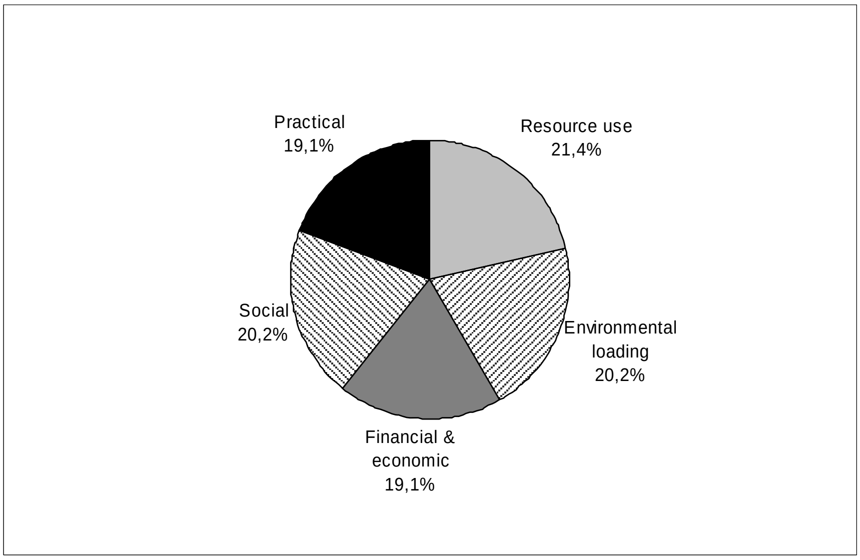


Figure 5.20. Results of main criteria weighting.

The residential sector was done with two policies: promoting high efficiency appliances (Alt1: RHEFF), and passive design and daylighting applications (Alt2: RPASS). Figure 5.21 shows the total weighted scores for the alternatives with the contributions of the different criteria indicated. Star diagrams showing the score for different policies in the residential sector are shown in Figure 5.22. A star diagram shows an overall picture of how well the alternative scores in regards to the different criteria. The center of the star represents the lowest point on the scale. Thus, the better the score, the more the star will be filled or shaded. Based on the figure and the star diagrams, the preliminary findings are: alternative 1 (Alt1: RHEFF) gets a total weighted score of 0.852 and alternative 2 (Alt2: RPASS) has a total score of 0.848. Both alternatives seem to get similar values. These alternatives have superior scores on resource use.

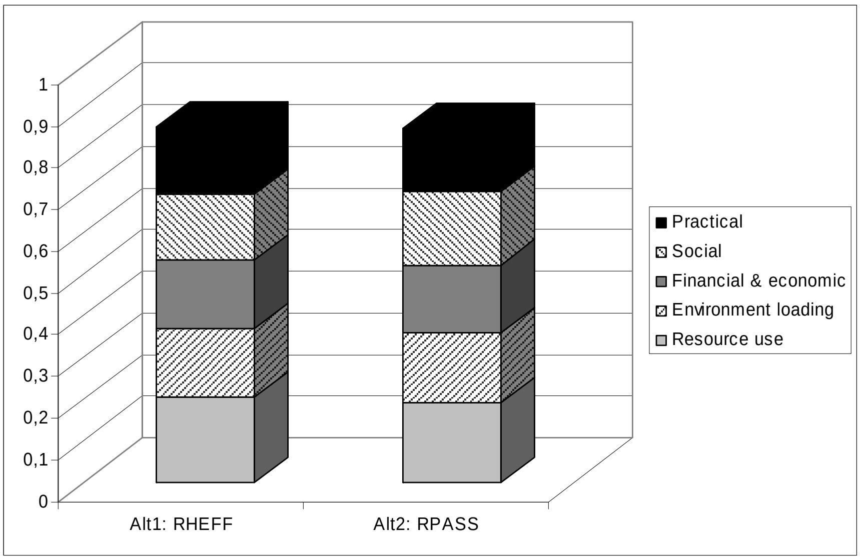


Figure 5.21. Total weighted scores for the alternatives in the residential sector.

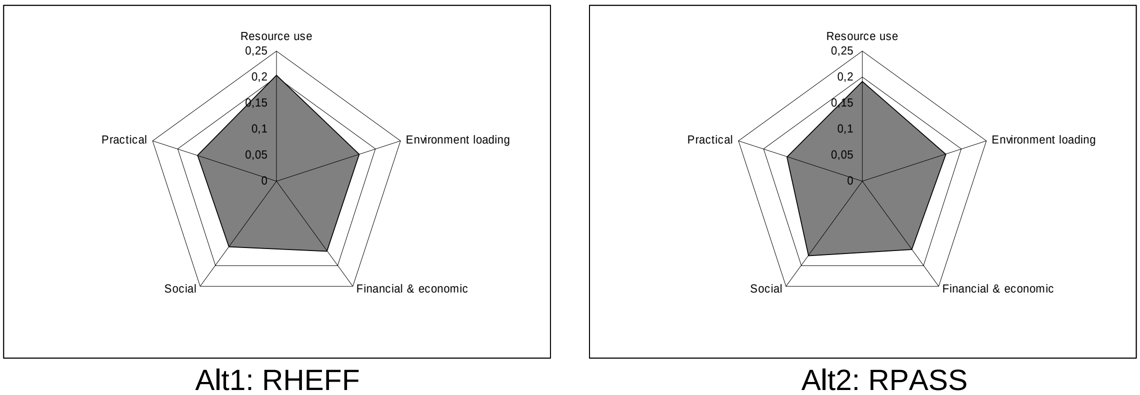


Figure 5.22. Star diagrams for residential energy policies.

The commercial sector consists of three policies: efficient HVAC system (Alt1: CHVAC), utilization of daylighting in lighting systems (Alt2: CDAY), and behavioral change in HVAC and lighting systems (Alt3: CBEH). Figures 5.23 and 5.24 show the total weighted scores for the alternatives and the star diagrams for the commercial energy policies. Alternative 2 (Alt2: CDAY) seems to be the best scheme with a total score of 0.801, while alternative 1 (Alt1: CHVAC) and alternative 3 (Alt3: CBEH) get approximately equal values of 0.797 and 0.762, respectively.

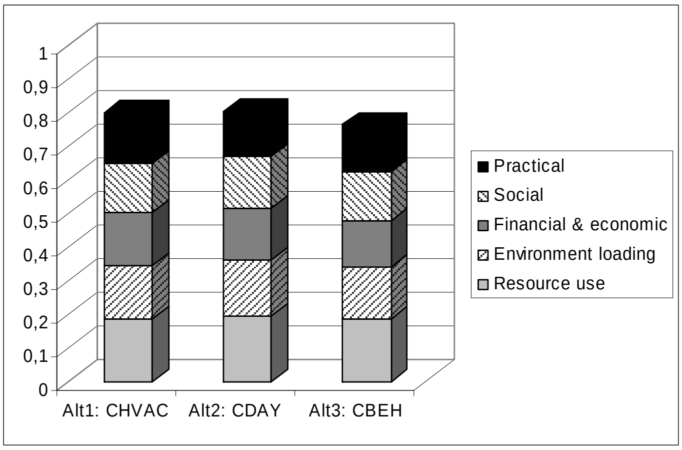
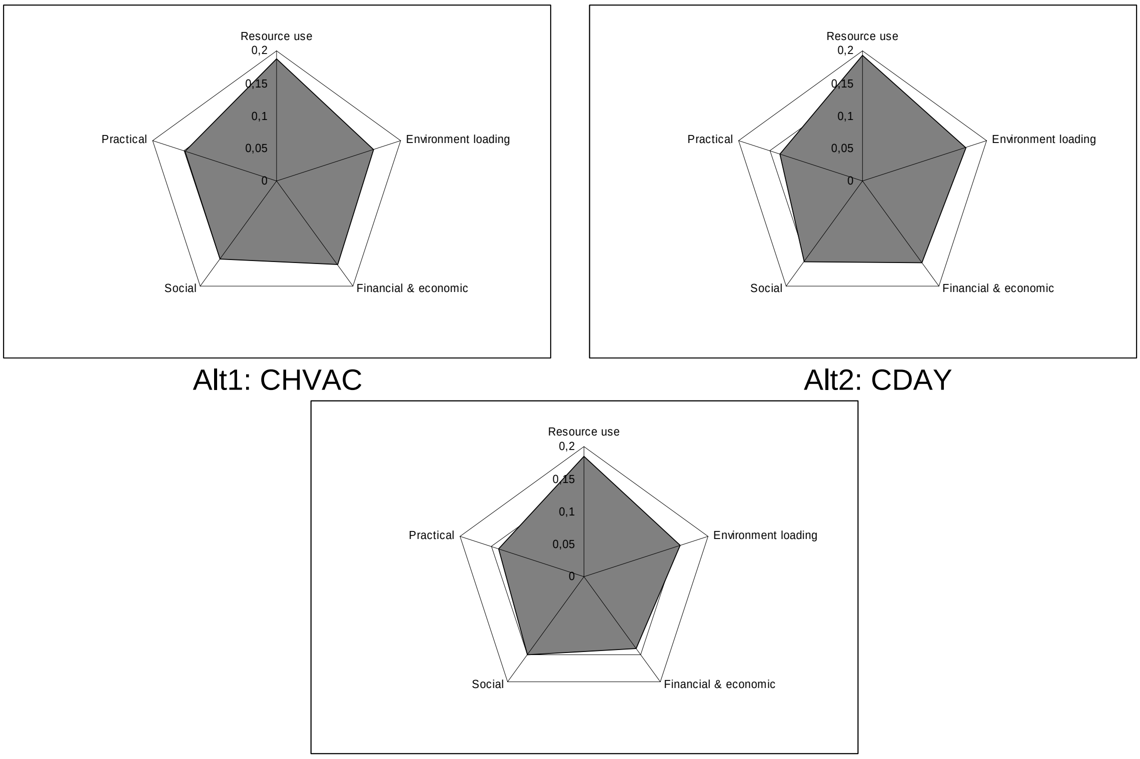


Figure 5.23. Total weighted scores for the alternatives in the commercial sector.



Alt3: CBEH

Figure 5.24. Star diagrams for commercial energy policies.

Two policies have been examined in the industrial sector. The total weighted scores of these alternatives are shown in Figure 5.25. The energy efficiency policy (Alt1: IEFF) receives a higher score (0.836), while the switching to natural gas (Alt2: ING) gets a total weighted score of 0.8. Star diagrams for industrial energy policies are shown in Figure 5.26. Alternative 1 (Alt1: IEFF) has a superior score on resource use and environment loading.

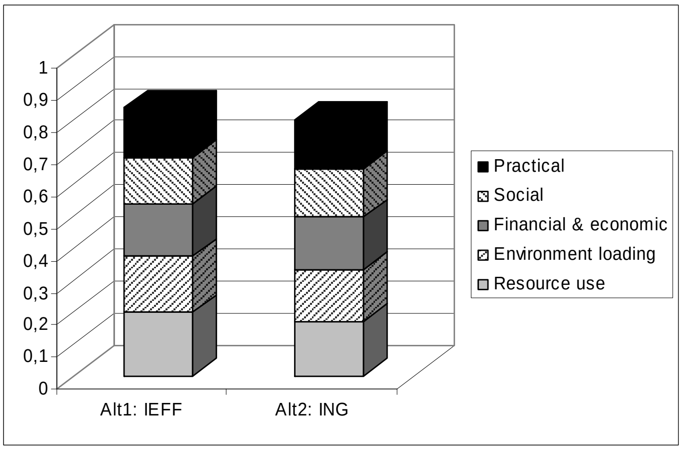


Figure 5.25. Total weighted scores for the alternatives in the industrial sector.

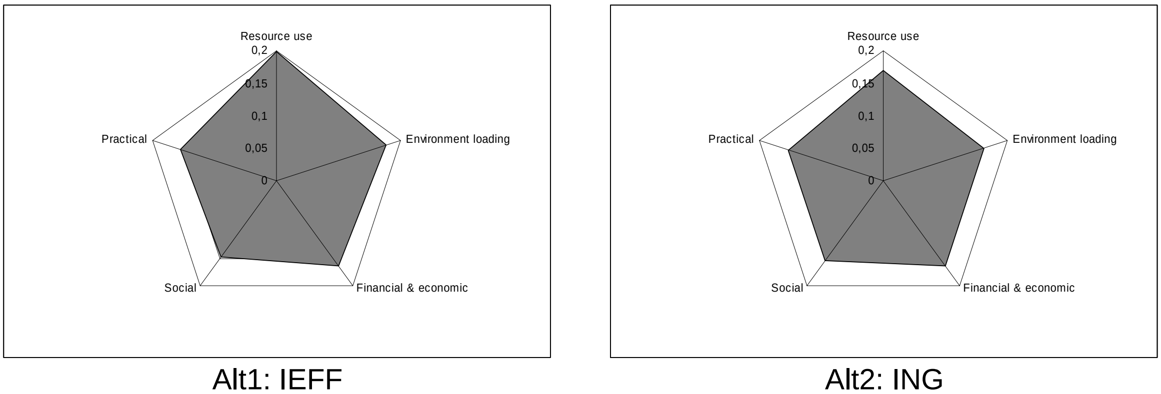


Figure 5.26. Star diagrams for the industrial energy policies.

The transport sector is comprised of four policy interventions; the evaluations of these policies are shown in Figure 5.27. Alternative 4 (Alt4: TSHIF), the modal shift from private passenger to mass transit system, receives the highest score of 0.876. It has a superior score on resource use, environment loading as well as on social aspects (see star diagrams in Figure 5.28). Introducing biodiesel policy (Alt3: TBID) gets a total weighted score of 0.802, while the introduction of NGV (Alt1: TNGV) and switching to gasohol (Alt2: TGSH) policies get approximately equal values of 0.773 and 0.775, respectively.

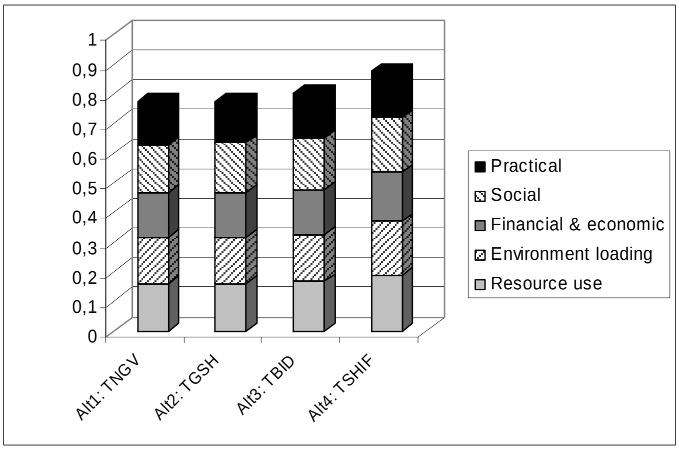


Figure 5.27. Total weighted scores for the alternatives in the transport sector.

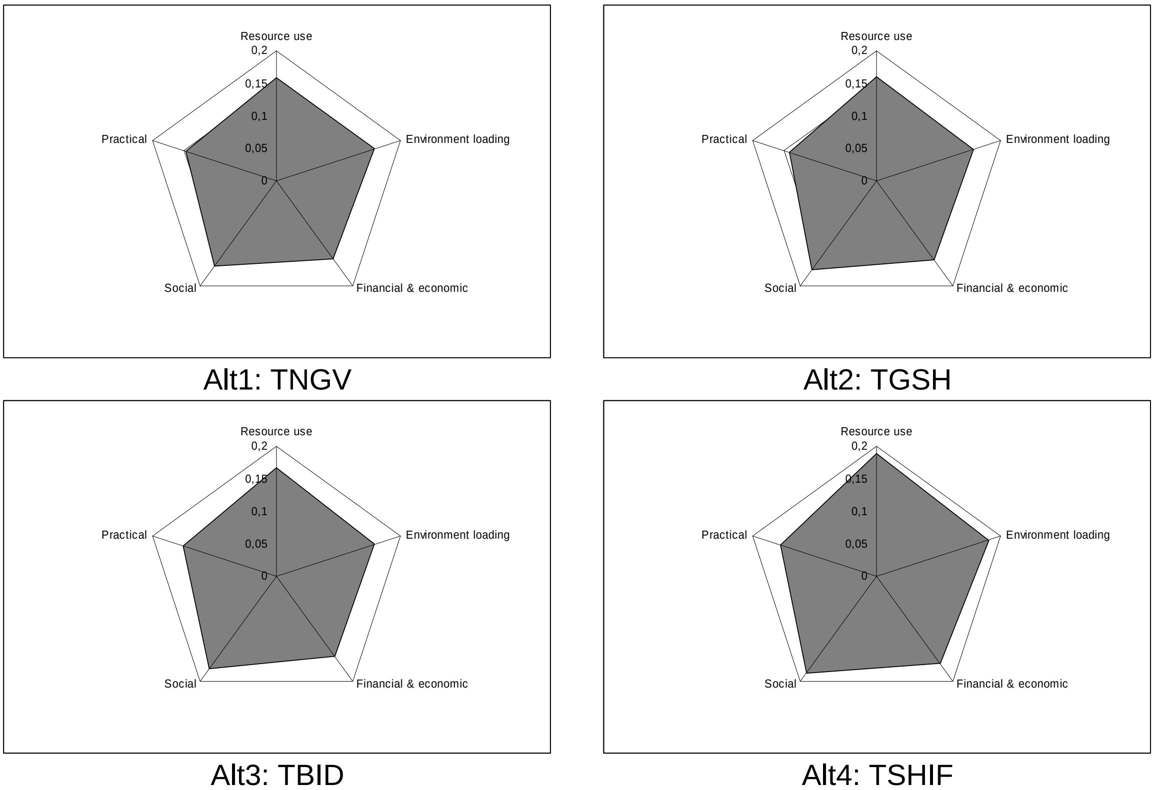


Figure 5.28. Star diagrams for the transportation energy policies.

A similar assessment was carried out for the supply-side. A star diagram for the target of 10% of the electricity being generated from renewable sources is shown in Figure 5.29. This alternative receives a total weighted score of 0.844, with the highest contribution to resource use (0.189) follow by environment loading (0.179), social (0.167), financial and economic (0.163), and practical (0.146), respectively.

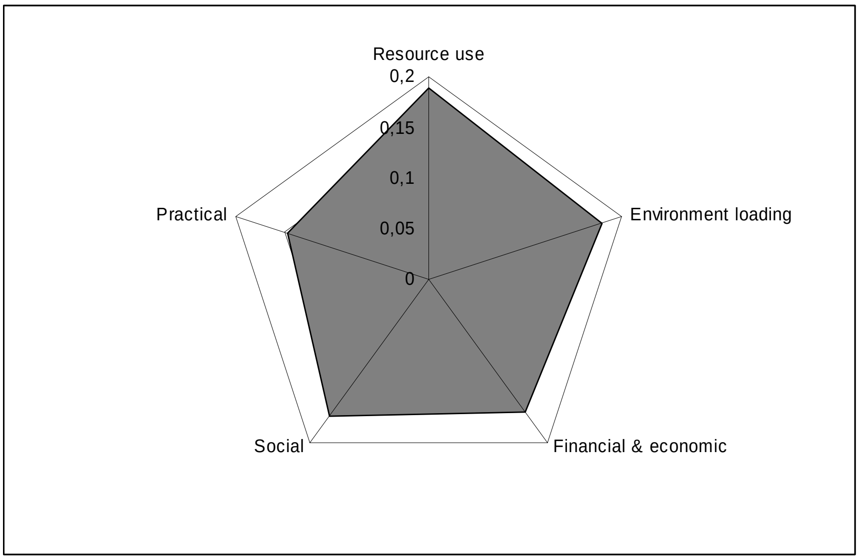


Figure 5.29. A star diagram for the alternative on the supply-side.

5.4.2. Lessons learned

Based on the evaluation of the exercises, the test group found that the hierarchical way of structuring the criteria was a useful tool in enabling them to have an overview, while simultaneously focusing on what is most important. The star diagrams were found to be valuable in comparing individual attribute performances across alternatives, but they could not be used to compare overall performances unless the weights were equaled. A star diagram is one of the useful formats in the evaluation. Such a diagram is produced for each scenario. By inspecting these diagrams, the team could get a quick understanding of the big picture. The diagram of the selected scenario might even make a good graphic to display in the energy system scenario, showing how it performs according to all relevant criteria. By visually inspecting these diagrams the team could attain an immediate perception of the overall situation.

In general, the MCDM method provides a methodology that helps decision-makers systematically identify management objectives and priorities and then to develop alternatives to achieve those objectives. It has proved to be a useful tool for decision-making regarding energy. Additionally, the test group felt that the approach was a useful way to document the results of the evaluations. They felt more comfortable that the best solution had been found when this structured approach was used. Furthermore, the method encourages team members to gain a deeper understanding of each other's field of expertise, for example the energy engineer learned more about politics and the environmentalist learned more about economics.

However, some members suggested that the method should incorporate uncertainty and risk analysis. This is due to the fact that the future costs and benefits that the alternatives may bring include degrees of uncertainty. For example, it is hard to predict exactly how energy prices will develop during the next 25 years. The ability to predict and evaluate the future consequences of alternatives may be crucial to the success of policy making. How then, should the uncertainties best be accounted for in the evaluation of the alternatives?

In the literature, some researchers argue that risky procedures are useful because they make the decision-maker think about the decision within the context of prevailing uncertainties, and therefore they can help to clarify preferences and values (Keeney 1980). This, however, may be adequately achieved through sensitivity analysis.

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6. CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

In this thesis an integrated approach to studying energy utilization in cities has been developed and applied. An integrated approach seeks to incorporate all significant aspects into a holistic synthesis. The study begins with understanding energy flows and analyses their flows by the urban metabolism method, and follows with the application of the proposed energy modeling and decision support in energy planning. These applications can be considered to be helpful tools for energy planners as well as city administrations to develop their energy plans in regard to sustainability issues.

The study describes a number of factors that influence energy use in cities. It shows that the major factors driving energy consumption include urban settlements, patterns of urbanization, income growth and social change, the structure of economic activities, and lifestyle. Income and lifestyle changes are particularly significant in Asian Mega-cities such as Bangkok, Beijing and Shanghai. Improvements in energy intensity due to positive technological change and higher productivity of energy have played an important role in reducing energy use. The improvement of fuel quality and fuel switching would also help to reduce energy consumption as well as emissions. Energy efficient technologies, industrial processes and building technologies have a significant effect upon energy use. The urban effects on energy use are also examined; the urban heat island is worsening in most Asian mega-cities and air pollution is affecting residents in terms of sickness, loss of productivity, and in other human development opportunities.

While direct energy consumption is discussed explicitly, the energy embedded in consumable goods and services are often neglected in the analysis of energy. The true energy use of a city needs to be clarified before alternative urban development paths are explored. This requires detailed analyses of the consumption activities of urban dwellers. The urban metabolism based upon embodied energy analysis can provide some sense of the size of the total energy consumption. IO-table analysis estimates of indirect energy demand show interesting results for Bangkok, Beijing, Shanghai and Tokyo. In Bangkok, Shanghai and Tokyo, indirect energy demands are more significant than direct energy demands. The volume of indirect energy demand in some Asian mega-cities, such as Bangkok and Tokyo, could be over two times that of the direct energy consumption.

To minimize the contributions of cities to national as well as global environmental change, reductions in only direct energy consumption are not enough. The consumption of large amounts of material goods by cities has an indirect effect on places outside cities where manufacturing and resource extraction take place. This is because cities do not only consume material goods but also supply them in the form of exports. The relationship between the direct and indirect energy consumption for which a city is responsible differs from city to city depending on its scale of industrialization and the type of industries. This provides the message that policy-makers should at least regard indirect energy consumption as an issue worthy of their attention.

The case study has confirmed that the LEAP model as a tool in energy planning can provide valuable insights into and to contribute to decision-making. Energy modeling can thus be an effective tool to assist policy-makers in evaluating different scenarios and their environmental consequences. In the study of Bangkok, the results reveal that the most significant energy savings are in the transport sector relative to the BAU scenario. The scenarios analysis shows that the implementation of modal shift from private passengers to mass transit systems has a great potential to reduce energy demand, CO_2 emissions, and improve the level of local air pollutants. This scenario has the potential of an energy saving of 6,614 ktoe in 2025. In the industrial sector, the improvement of energy efficiency has shown savings of 736 ktoe in 2025. The electricity savings under the promotion of the high efficiency appliances scenario in the residential sector and the potential of savings under the efficient HVAC systems scenario in commercial building are expected to be 111 ktoe and 12.3 ktoe in 2025, respectively. These energy savings are important to Bangkok, since it depends upon imports of both electricity and fuels. However, if all strategies on the demand-side are simultaneously implemented, the highest potential of energy savings in 2025 is expected to be 7,947 ktoe, while on the supply-side the renewable electricity scenario shows a significant reduction in CO_2 emissions. There would be a reduction of 1,757 thousand tons CO_2-equivalent by 2025.

The policy interventions are considered within the broader policy goals of Bangkok, and in an effort to develop in a sustainable manner some policies are consistent with government policies. Some policies are viable in terms of investment costs, social benefits, and the environment. The behavioral change in HVAC and the lighting systems in commercial buildings stand out as policies that have benefits from every angle. Bangkok has long suffered from the problem of traffic jams and high levels of air pollution. The modal shift policy within the transportation sector plays a key role in reducing both traffic problems and local air pollution. Hence, these scenarios should be implemented immediately.

As we have seen sustainability is an interdisciplinary question and it is cross-discipline teamwork that makes it possible to answer the question. The MCDM process has proved to be a powerful tool in energy decision-making. This system provides a methodology to help decision-makers systematically identify management objectives and priorities, and to develop alternatives to achieve those objectives. It has proved to be a useful tool in regards to the Bangkok case study. The method was applied in order to assess the outcome of the implementation of different policies within individual sectors; a similar assessment was also carried out for a supply-side target of 10% electricity being generated from renewable sources.

6.2. Future work

This study has been on an integrated approach, one that includes urban metabolism, energy modeling and an MCDM approach. Regarding the metabolism of a city, a full urban metabolism with respect to energy, materials, water, and nutrients should be quantified. There are practical reasons for understanding urban metabolism. The vitality of cities depends upon its spatial relationships with its surrounding and global resources. Metabolic processes that threaten the sustainability of cities are identified. Urban policy-makers should be encouraged to understand the urban metabolism of their cities. It is useful for them to know if they are using energy, water, materials and nutrients efficiently, and how this efficiency compares to other cities.

The metabolism approach to cities is considered a purely biological view, but cities are much more than a mechanism for processing resources and producing wastes: they are about creating human opportunity. Therefore, a basic metabolism concept should include a city's livability such as health, employment, income, education, leisure activities, etc. Therefore, this kind of study will involve the economic and social aspects of sustainability, together with the environmental aspect. This extended metabolism can be applied at a range of levels and to a range of different human activities, for instance city comparisons, industrial areas, demonstration of urban projects and individual businesses.

Further study in the LEAP model, however, should include cost comparison among policies as well as an energy supply mix in Bangkok. The cost savings would be an index for decision-makers to consider in choosing subsequent actions and policies to be implemented. The results in terms of cost savings, especially in the residential sector, can convince people to take action. The question of the energy supply mix is; how can Bangkok move away from its high dependence on petroleum products and still meet the demand? With this in mind, future work should be in developing renewable energy supply scenarios and strategies with a focus on fully renewable energy technologies.

The MCDM process provides a methodology to help decision-makers. The use of this decision aid can clarify the issues for individual decision-makers and provide a deeper understanding of the alternatives. The future perspective of energy decision-making with MCDM should include a sensitivity analysis. This could allow for the identification of the most robust solutions, which are less influenced by the weights attributed criteria. Also, it would be of interest to assess the role of the uncertainty value within the final preference scores in a more definite fashion.

Appendix 1. Estimated Bangkok energy demand by economic sectors under BAU scenario

Table A.1.1. Estimated energy demand in commercial sector.

Sector/sub-sector	Energy demand (ktoe)				
	2005	2010	2015	2020	2025
Commercial sector	80.1	86.2	92.5	97.5	103.0
Office	34.5	38.1	42.1	45.3	48.8
- Others	2.8	3.1	3.4	3.7	3.9
- Lighting	3.5	3.9	4.3	4.6	5.0
- HVAC	28.2	31.2	34.4	37.1	39.9
Hotel	10.7	11.6	12.5	13.1	13.8
- Others	0.1	0.1	0.1	0.1	0.1
- Lighting	0.4	0.4	0.4	0.4	0.5
- HVAC	10.3	11.1	12.0	12.6	13.2
Hospital	7.6	7.6	7.6	7.6	7.6
- Others	0.1	0.1	0.1	0.1	0.1
- Lighting	0.5	0.5	0.5	0.5	0.5
- HVAC	7.0	7.0	7.0	7.0	7.0
Department store	11.9	12.5	13.1	13.5	13.8
- Others	2.0	2.1	2.2	2.3	2.3
- Lighting	1.4	1.5	1.6	1.6	1.7
- HVAC	8.4	8.9	9.3	9.6	9.8
Academic institution	5.9	6.2	6.2	6.2	6.2
- Others	0.3	0.3	0.3	0.3	0.3
- Lighting	0.4	0.4	0.4	0.4	0.4
- HVAC	5.2	5.5	5.5	5.5	5.5
Miscellaneous	9.5	10.3	11.1	11.9	12.8
- Others	0.5	0.5	0.6	0.6	0.7
- Lighting	0.9	0.9	1.0	1.1	1.2
- HVAC	8.2	8.8	9.5	10.2	11.0

Table A.1.2. Estimated energy demand in industrial by sub-sectors.

Sector/sub-sector	Energy demand (ktoe)				
	2005	2010	2015	2020	2025
Industry	4,483.1	5,197.1	6,024.9	6,984.5	8,097.0
Food and beverages	1,540.8	1,786.2	2,070.7	2,400.5	2,782.8
Textile	89.0	103.2	119.6	138.7	160.8
Wood and furniture	24.3	28.1	32.6	37.8	43.8
Paper	178.6	207.0	240.0	278.2	322.6
Chemical	296.1	343.2	397.9	461.3	534.8
Non-metallic	1,248.4	1,447.2	1,677.7	1,944.9	2,254.7
Basic metal	407.0	471.8	547.0	634.1	735.1
Fabricated metal	325.7	377.6	437.7	507.4	588.3
Others	373.3	432.7	501.7	581.6	674.2

Table A.1.2. Estimated energy demand in industry sector by fuel types.

Sector	Energy demand (ktoe)				
	2005	2010	2015	2020	2025
Industry	4,483.1	5,197.1	6,024.9	6,984.5	8,097.0
Wood	205.4	238.1	276.0	320.0	371.0
Fuel oil	769.5	892.1	1,034.2	1,198.9	1,389.9
Natural gas	368.0	426.6	494.6	573.4	664.7
Liquefied Petroleum Gas (LPG)	83.6	96.9	112.3	130.2	150.9
Kerosene	7.7	9.0	10.4	12.0	13.9
Gasoline	14.2	16.4	19.1	22.1	25.6
Electricity	863.3	1,000.9	1,160.3	1,345.1	1,559.3
Diesel	144.1	167.0	193.6	224.5	260.2
Coal and coke	485.6	563.0	652.6	756.6	877.1
Lignite	526.3	610.1	707.3	819.9	950.5
Anthracite	15.1	17.5	20.3	23.5	27.2
Rice husk	201.8	234.0	271.3	314.5	364.5
Bagasse	798.4	925.6	1,073.0	1,243.9	1,442.1

Table A.1.3. Estimated energy demand in residential sector.

Sector/sub-sector	Energy demand (ktoe)				
	2005	2010	2015	2020	2025
Residential sector	1,052.3	1,110.3	1,173.7	1,243.9	1,257.6
Outer Bangkok Metropolitan Area					
- Water heating	5.9	6.5	7.2	8.0	8.1
- Space conditioning	164.8	180.7	200.1	222.6	225.1
- Refrigeration	29.2	32	35.4	39.4	39.9
- Lighting	39.9	43.8	48.5	53.9	54.5
- Cooking	164.3	180.2	199.5	222.0	224.5
- Others	40.4	44.3	49.0	54.6	55.2
Inner Bangkok Metropolitan Area					
- Water heating	6.3	6.4	6.5	6.6	6.7
- Space conditioning	356.6	365.4	372.0	377.4	381.5
- Refrigeration	38.7	39.7	40.4	41.0	41.4
- Lighting	42.4	43.4	44.2	44.8	45.3
- Cooking	121.0	124.0	126.2	128.0	129.4
- Others	42.9	43.9	44.7	45.4	45.9

Table A.1.4. Estimated energy demand in residential sector by fuel types.

Sector	Energy demand (ktoe)				
	2005	2010	2015	2020	2025
Residential sector	1,052.3	1,110.3	1,173.7	1,243.9	1,257.6
Wood	3.0	3.3	3.7	4.1	4.1
Liquefied Petroleum Gas (LPG)	204.1	217.8	233.4	251.0	253.8
Electricity	837.6	881.0	927.6	978.6	989.4
Charcoal	7.5	8.2	9.1	10.1	10.2

Table A.1.5. Estimated energy demand in transport sector.

Sector/sub-sector	Energy demand (ktoe)				
	2005	2010	2015	2020	2025
Transport sector	8,962.6	10,507.0	11,195.5	11,884.0	13,445.3
Passenger car	3,411.4	4,104.3	4,374.6	4,645.0	5,258.2
Microbus and pickup	1,004.6	1,208.6	1,288.2	1,367.9	1,548.4
Van and pickup	2,075.4	2,496.9	2,661.4	2,825.9	3,199.0
Motortricycle	2.2	2.7	2.8	3.0	3.4
Urban taxi	598.0	719.5	766.9	814.3	921.8
Fixed route taxi	12.1	14.6	15.5	16.5	18.6
Motortricyle taxi	35.7	42.9	45.7	48.6	55.0
Motorcycle	447.7	538.6	574.1	609.6	690.1
Fixed route bus	12.1	14.6	15.5	16.5	18.6
Bus for hire	41.5	49.9	53.2	56.5	63.9
Private bus	13.4	16.2	17.2	18.3	20.7
Non-fixed route truck	154.5	185.9	198.1	210.4	238.1
Private truck	692.3	832.9	887.7	942.6	1,067.0
Tractor	91.4	110.0	117.2	124.4	140.9
Others	5.7	6.9	7.4	7.8	8.9
Mass transit system	6.0	56.1	56.1	56.1	56.1

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