# ANALYSIS OF THE ELECTRICITY DEMAND TREND IN HKSAR IN RELATION TO ENERGY EFFICIENCY OF COMMERCIAL BUILDINGS

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# ANALYSIS OF THE ELECTRICITY DEMAND TREND IN HKSAR IN RELATION TO ENERGY EFFICIENCY OF COMMERCIAL BUILDINGS

By

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# Abstract

Abstract of thesis entitled "Analysis of the Electricity Demand Trend in HKSAR in Relation to Energy Efficiency of Commercial Buildings" submitted by Lee Sung Kong for the degree of Master of Philosophy at The Hong Kong Polytechnic University in July 2002"

Energy required for cooling system in commercial buildings in a sub-tropical climate, as in Hong Kong, is substantial and costly for regular commercial operation. This thesis reports on an investigation of the electricity demand in Hong Kong in the short-run and long-run by studying the energy consumption sectors, the historical energy consumption, the macro economic factors and the energy efficiency measures in commercial buildings.

An initial multiple linear regression model is established, which gives a basic relation of the energy and the influencing economic parameters. Estimates of the future energy demand are made in this study using time series analysis. The co-integration approach is then adopted to examine the electricity consumption with macro economical factors and buildings development. Stationarity of the economic variables under time series analysis is achieved by differencing approach and verified via unit root test process. For the prediction of the long-run electricity demand, an error correction model is developed to overwrite the statistics inferences from the time series analysis. Changes of electricity load caused by building envelope designs, lighting intensity, fan and chiller efficiency are investigated by simulation using a reference commercial building and the building energy programme DOE-2.1E. Then the influence of building energy efficiency and growth of commercial building stock on the long-run electricity demand is determined by putting the simulated building energy requirement into the error correction regression model. The results will

contribute to the know-how of electricity supply and demand for the local economy and serve as a reference for energy planning and policy.

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I would like to express my sincere gratitude to my parents for their support and encouragement during many years of my study.

# DECLARATION

The research described in this thesis is the original work of the author except where otherwise specified or where acknowledgements are made by reference. The work was carried out at The Hong Kong Polytechnic University, under the supervision of Dr. K. T. Chan. The work has not been submitted for another degree or award of other academic or professional institution.

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# Table of Contents

# List of Tables

# List of Figures

**Chapter 7**

# Abbreviation and Notation

**Abbreviation:**

| | |
|---|---|
| ARMA | Autoregressive moving average model |
| CAV | Constant air volume |
| COP | Coefficient of performance |
| ESMD | Electrical and Mechanical Services Department, HKSAR |
| HKSAR | Hong Kong Special Administration Region |
| VAR | Vector autoregressive model |
| VAV | Variable air volume |

**Notation:**

| | |
|---|---|
| **A** | N x N matrix of coefficiencts |
| $P_t$ | Average price of two electricity suppliers (China Light & Power Co. Ltd. & Hong Kong Electric Co. Ltd.) |
| CPI | Composite consumer price 89/90 |
| $C_t$ | Commercial buildings in meter square at present time |
| $D_t$ | Domestic buildings in meter square at present time |
| $E_t$ | Electricity demand in terajoule |
| $ed_t$ | Autoregressive function of energy demand at present time |
| $ed_{t-1}$ | First order autoregressive function of energy demand |
| FP | Fuel price in Hong Kong |
| GE | Government expenditure and equity investment |
| $IN_t$ | Industrial buildings in meter square at present time |
| I | Lag term of $Z_t$ |
| $I(d)$ | Integrated of order $d$ times |
| POP | Population of Hong Kong |
| $Q$ | Residual sum of squares |
| $R_t$ | Real gross domestic product in Hong Kong dollar at present time |
| r | Cointegrating rank |

| | |
|---|---|
| TED | Energy consumption for multiple regression model |
| TUGO/TUSG | Units of public owned and saleable estates |
| $U_t$ | Independent variable to standard regression model |
| VAR | Single vector autoregressive equation |
| VOT | Volume of trade |
| VONC | Volume of non-commercial building |
| $\chi_t$ | Vector or (p × 1) vector of non-stationary variable |
| $\Delta w_t$ | $w_t - w_{t-1}$ |
| $\Delta x_t$ | $x_t - x_{t-1}$ |
| $\Delta y_t$ | $y_t - y_{t-1}$ |
| $Y$ | Energy demand |
| $Z_t$ | Components of the vector $\chi_t$ |
| $\hat{Y}$ | Estimated of energy demand |
| α | Cointegrating vector / coefficient of independent variable |
| $\beta$ | Constant term of multiple regression model |
| $\beta_1$ | estimate parameter of coefficient to $C_t$ |
| $\beta_2$ | estimate parameter of coefficient to $D_t$ |
| $\beta_3$ | estimate parameter of coefficient to $I_t$ |
| $\beta_4$ | estimate parameter of coefficient to $A_t$ |
| $\beta_5$ | estimate parameter of coefficient to R |
| $\varepsilon_t$ | Error term of the multiple regression model |
| μ | Constant |
| $\hat{\lambda}_i$ | Canonical correlations |
| $\lambda_{trace}, \lambda_{\max}$ | Test statistics for the number of cointegrating vectors |
| σ | (p × 1) vector of constant terms of vector of autoregressive model |
| $\Pi_k$ | (p × p) coefficient matrices |
| $\Gamma_k$ | Coefficient of change of vector of non-stationary variable |

# Chapter 1

# Introduction

## 1.1 The need of studying the energy demand trend

Hong Kong is an international financial trading and service center in the world. Its economy has risen rapidly for the last 20 years. To meet with the demand from the business sector, many commercial buildings have been built in recent years, and the amount will be over 10 million $m^2$ floor area at the end of 2002. Energy demand in Hong Kong recorded dramatic increases in the period from 1970 to 2000 and especially at the beginning of 1980's. This high energy demand is due to the existence of many high-rise buildings that are air-conditioned to provide the occupants with a comfortable work environment. In particular, the energy consumption of the commercial building sector has been increasing at an even faster rate than the overall economic growth. In 1998, Hong Kong had a total electricity consumption of 125,447 terajoules (TJ), of which the commercial sector accounted for 59%. After a slight drop in 1999, the total electricity consumption increased to 130,675 terajoules (TJ) in 2000, and 62% was by the commercial sector (Census and Statistics Department, 2000). The data indicate a very interesting issue of energy supply and demand. Among the electricity consumption in the commercial buildings, the operation of air conditioning systems consumes more than 60% of its total electricity consumption. This is about 11.5% of the final energy requirement in Hong Kong, which is much more significant compared with the 6.1% (IEA 1991) final consumption for commercial space heating and cooling in the member counties of IEA (International Energy Agency). If we have more information on the pattern of electricity consumption by the commercial sector, the related study is very useful to energy saving issue. On the other hand, owing to the movement of the manufacturing processes to Mainland China since late 1980', there was an obvious drop in the energy consumption by the industrial sector. According to the information from the Hong Kong Census and Statistics Department, the development of total floor area of industrial buildings dropped to 21,830,000 square meters in 1998 and the development of new industrial buildings stopped after that period of time. Therefore, energy use for the commercial activities becomes a larger portion of electricity demand in the city. In recent years, a list of energy saving procedures and standards of electronic appliances has been issued by the government. For building energy design, the Energy Advisory Committee introduced a comprehensive set of Building Energy Codes of Practice (BEC) to include lighting, air-conditioning, electrical installations, and lifts and escalators in buildings. The recommendation in BEC provides a minimum standard to construct an acceptable energy efficiency building design. The aim of BEC is to arouse public awareness of energy efficiency and environmental improvement in building designs, to encourage estate developers to build more energy efficient new buildings and to benefit the global environments. Understanding the energy consumption trend of commercial buildings can predict the energy demand and find out the significance of energy saving measure on cost control and environmental protection. This study focuses on the major social and economic factors, the envelope construction of commercial buildings and the influential system parameters that affect energy consumption. The results of building energy simulation with DOE-2E program provide a framework of studying energy efficiency of commercial buildings. Using statistical package with advance statistical analysis, the prediction of energy demand and analysis of the long-run effect of energy saving measures in the commercial sector can be forecasted by energy prediction models.

## 1.2 Summary of the research objectives and work undertaken

The objectives of this study and the approach in developing a macro electricity demand model are outlined in this section. Published forecast by Chan and Lee (1998) based on a multiple linear regression model built on economic and building data illustrated the influence of building energy on the macro energy demand in Hong Kong. Recently, there were many research works done by other researchers. Examples include Bentzen and Engsted (1993) in estimated short-run and long-run Danish energy demand elasticity; Bentzen (1994) in analysis of Danish gasoline demand; Masih and Masih (1996) in analysis of energy consumption in relation to real income; Arsenault, et. al. (1995) in analysis of energy demand of Quebec, Canada; Silk and Joutz (1997) in analysis of short-run and long-run elasticities in US residential electricity demand. They suggested that the adjustments made by error corrections mechanism to the model-based forecasts would usually result in improved forecast accuracy. In this thesis the error correction method is employed to calculate the long-run forecast of electricity demand. The study of the electricity demand trend in relation to energy efficiency of commercial buildings is based on the relationships between the time series data, the development of estimated econometric model and the mechanics of forecasting technique.

Research in energy economics and related disciplines is becoming more quantitative. Therefore, econometrics model is used in energy forecast with the influences of macro-level economic factors. The sources of economic data using in this study are compiled from publishes of Hong Kong Census and Statistics

Department. In recent applied literatures, alternative modelling strategies of 'general to specific' method by Engle-Granger procedure (1987) and dynamic ordinary least square (Stock and Watson 1983, 1993) are modernised to use in forecast models. For accuracy of long run estimation in electricity demand, the unit root tests of Engle and Granger (1987) and the maximum likelihood estimation of Johansen and Juselius (1990) are used to analyse the long-run demand characteristics. Similar calculations are undertaken in this study. Attention is also paid to the analysis of the forecasting properties of the estimated electricity model. Cointegration and error-correction modelling are applied to study the adjustment mechanisms and structure changes in the modelling of electricity forecast. Finally, a long-run electricity error-correction model is established to estimate the electricity demand in the future and to detect the systematic bias based on the estimated values of the explanatory variables. In particular, the influence by the stock and growth of buildings (HK Rating and Valuation Department, 1999) on the growth of energy demand is assessed. The objectives are summarized as follows:

a) To study the influences of leading economics factors on the total electricity demand trend in Hong Kong.
b) To investigate the influences of envelope construction and other energy saving measures in commercial buildings on total electricity consumption under the characteristics of local climate.
c) To investigate the cointegration relation among the time series of independent economic variables in the long run electricity demand.
d) To develop an error correction mechanism and apply it to derive an equation for estimating the long run electricity demand.

The heat transfer and thermal performance of various envelope constructions are studied using the building energy simulation tool DOE-2.1E. Forecast of the electricity demand by commercial buildings having energy effective envelope or energy intensive envelope is determined from the projected volume of new commercial buildings (expressed in $m^2$ floor area) and the results of building energy simulation (express in $kWh/m^2$ floor area). Finally, an error correction model is developed under the Johansen and Juselius procedure for long run accuracy adjustment.

Energy required for cooling in commercial buildings in a sub-tropical climate like Hong Kong is substantial. The electricity consumption of commercial buildings will therefore be a significant portion of the total electricity demand. This project aims to evaluate the impact of energy efficiency and the growth in the stock of commercial buildings on the future electricity demand in Hong Kong. It attempts to combine the technical study of energy efficiency of commercial buildings with the statistical forecast of electricity demand.

There is lack of energy demand forecast in Hong Kong. Many researchers in North America and Europe have studied the volatility of energy demand with the economic parameters. Though much work has been done on the macro supply and demand of energy, investigators rarely include building developments and energy saving measures as parameters in the demand trend analysis.

This thesis addresses the change of building energy requirement and its influence on the energy demand trend. The study has two parts, namely the development of an electricity demand forecast model at macro level in relation to the economy, and the analysis of the implication of energy-related system design parameters on electricity requirement. In the first part, the economic factors and the types and volumes of new buildings are investigated for electricity demand forecast by regression and error correction modeling. In the second part, alternative design options for building envelope construction and various energy-related system design parameters are studied at micro level by thermal system simulation with the aid of a building energy simulation program. The changes of energy requirement resulting from the building envelope options and system design parameters are then coupled to the electricity demand forecast given by the econometrics model.

The outcomes of the research will enhance knowledge of the influence of economic growth, building envelope designs and energy-related system parameters in commercial buildings on the total electricity demand. As commercial buildings in Hong Kong are voluminous and the commercial sector accounts for over 60% of the total electricity supply by the two local power companies, the objectives of this study will constitute a contribution to the understanding of energy supply and demand for the local economy. The predication of electricity demand trend can be utilized for formulation of energy policy, targets for new and existing commercial buildings, planning for power supply capacity, evaluating the impact of energy cost on the economy and serving as a reference for energy planning and policy.

## 1.3 Outline of the thesis

This thesis comprises eight chapters. In this chapter an introduction of the need of studying the energy demand trend is given. The need of forecasting electricity demand of commercial buildings in Hong Kong is explained and the objectives of this research works are established. An overview of the research work and the outline of the thesis are given in this chapter.

Chapter 2 outlines the electricity demand and supply in Hong Kong. Data of historical final energy and electricity consumption are presented. Electricity sources and electricity consumption sectors are identified and various building stocks used in the regression model are calculated. The influence of building energy use on the total electricity demand is explained.

Chapter 3 identifies uses of multiple regression model in the energy analysis with related energy economics and influencing variables. It reports on the basic form of energy multiple regression model and the calculation of short-run and long-run energy elasticity.

Chapter 4 reviews the DOE-2.1E energy simulation program to alternative methodologies of building energy simulation. Building energy efficiency parameters which relate to the local codes of practice for energy efficiency are investigated using a representative commercial building for modeling and parametric analysis. The changes of energy requirement in a representative building, which may be energy saving or extra energy demand resulting from various building envelope designs and energy-related system parameters, are assessed.

Chapter 5 presents the results of energy demand using linear multiple regression model. The results include statistical trend of economic factors, electricity demand model and final energy demand trend. Future energy demand with influence of commercial building envelope designs is investigated.

Chapter 6 introduces the time series approach to deal with energy economics data in the model. Cointegrating relation of economics time series is studied. Test for sationary of time series factor is discussed. In the estimation of long run electricity demand, error correcting method is applied and the error correction model is generated in this chapter.

Chapter 7 reports the results of using cointegration and error correction model in energy regression analysis. Autoregression model of energy economics data is studied. Result of long-run electricity demand is rectified by the method of error correction modeling. The estimation of long-run electricity demand by incorporating the simulated energy requirement of commercial buildings with energy effective features as well as energy intensive features into the electricity demand model is studied.

Chapter 8 summaries the application of statistical energy model in energy forecast in Hong Kong. Significance of using error correcting approach and recommendation of future work in energy forecasting is discussed in this chapter.

## Chapter 2

# Energy Supply and Demand

### 2.1 Energy sources and historical electricity consumption

Energy supply in Hong Kong is entirely from external sources. Energy, in term of product like oil and coal, is imported from other Asia and mid-east countries. Most of oil products are imported from Republic of Singapore and the cost of oil products are affected by external environment and import countries' policy. The major energy product in Hong Kong, such as gas and electricity, is somehow produced through transformation processes from imported fossil fuel. Electricity is the major form of energy usage in commercial, domestic and industrial sectors. Different energy use sectors require different forms of energy product and can be categorized into various forms as coal, oil, electricity and gas. Transportation and aviation need gasoline and diesel oil. Industries need natural gas and electricity for machinery operation. Home appliances and commercial operation need supply of electricity. As we know, Hong Kong economy relies on commercial goods and services heavily. The commercial services economy provide a market situation for property developers to build many commercial offices. In evidence, commercial offices become a large portion of building development besides residential building. Hence, electricity consumption of commercial operation is one of major energy usage in Hong Kong. Study of active and passive energy use of commercial buildings is important to understand energy consumption of the commercial sector. The result of the study can estimate energy demand in long term and benefit to long-term energy policy in Hong Kong.

Collating with energy statistics published by Hong Kong Census and Statistics Department, the quantity of retained imports of motor gasoline increased between year of 1989 and 1996 but decreased from year of 1997. This is because automobile is luxury product and it is very elastic to income of people. After 1997, Hong Kong economy has been slow down, and then the luxury products and other high expenses entertainment have been decreased. The quantity of retained imports of fuel oil was decreased in 1990 and 1997 sharply, and a significant increase was noted in 1992. The imports remained at a high level in 1989 and 1999. This is because retained imports of aviation gasoline and kerosene, gas, diesel oil and naphtha have been remained in high demand due to growth of economy in the period. The quantity of retained imports of natural gas increased since 1995 substantially and remained at a high level since 1997. This is because the Hong Kong government encourages the use of natural gas in industrial sector and public transport instead of motor gasoline. The related figures are shown in Figure 2.1 to Figure 2.6. Also with growth of economy, the list prices of all products increased except aviation gasoline 100 and fuel oil, which remained unchanged, compared with the year 1998.

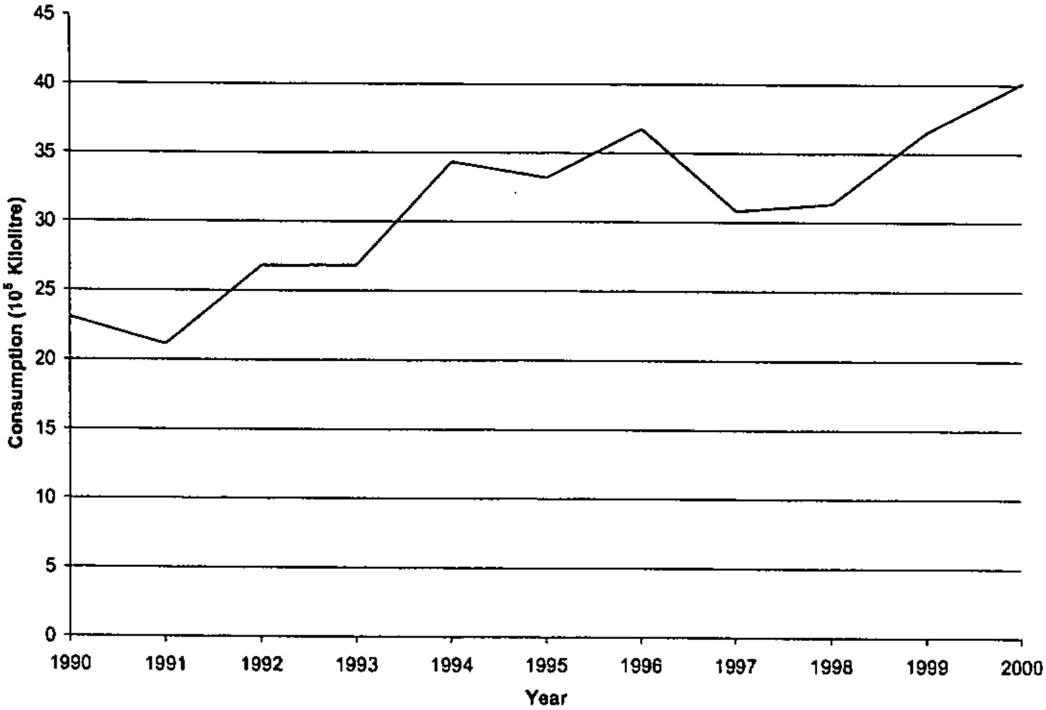



Figure 2.1 Consumption of aviation gasoline and kerosene from 1990 - 2000

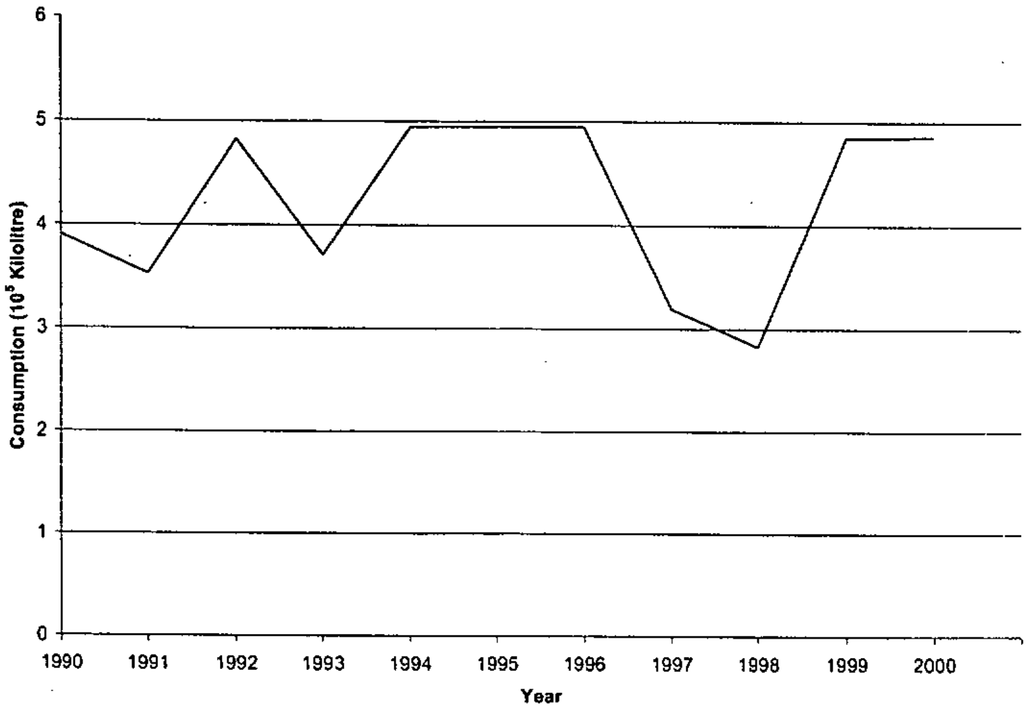



Figure 2.2 Consumption of motor gasoline from 1990 - 2000

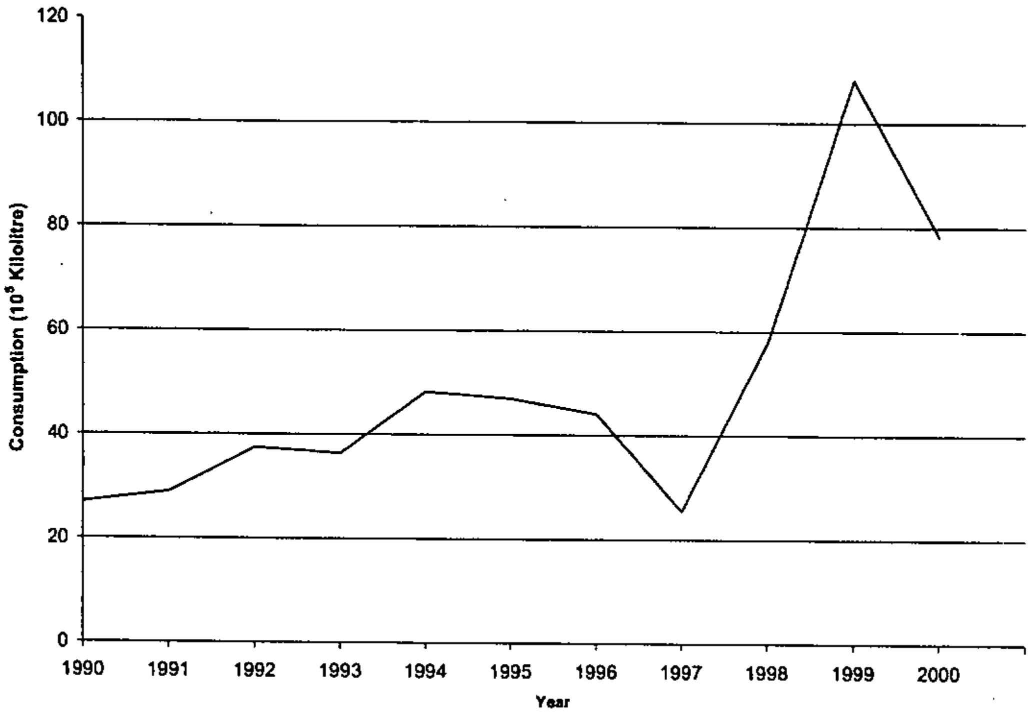



Figure 2.3 Consumption of gas diesel from 1990 – 2000

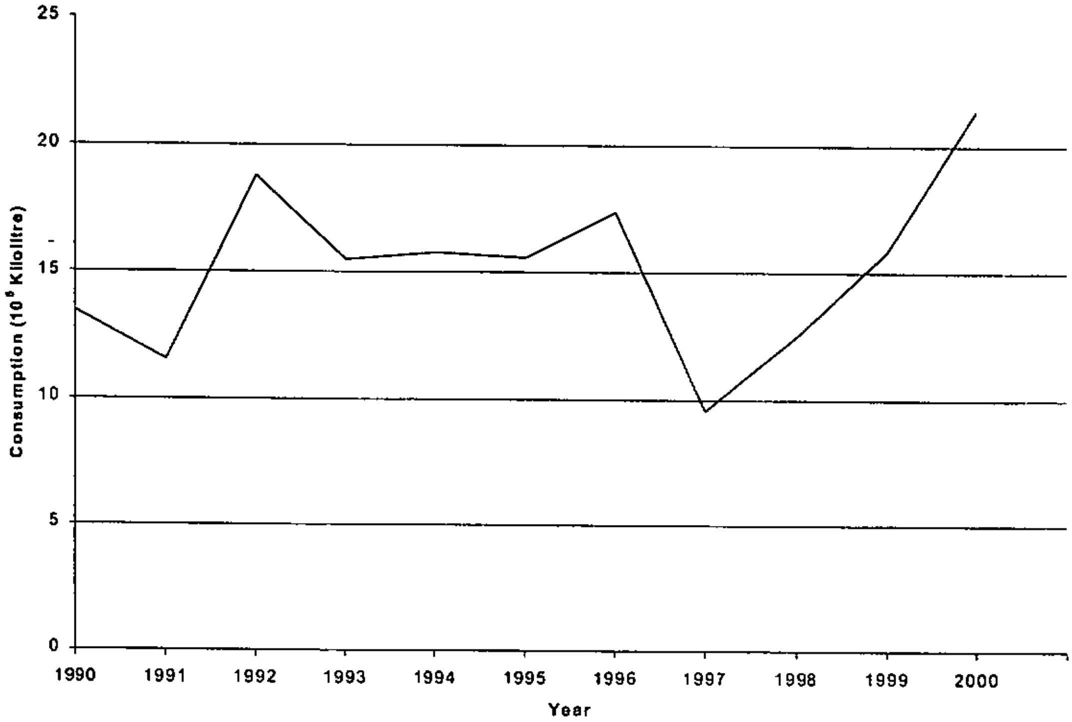



Figure 2.4 Consumption of fuel oil from 1990 - 2000

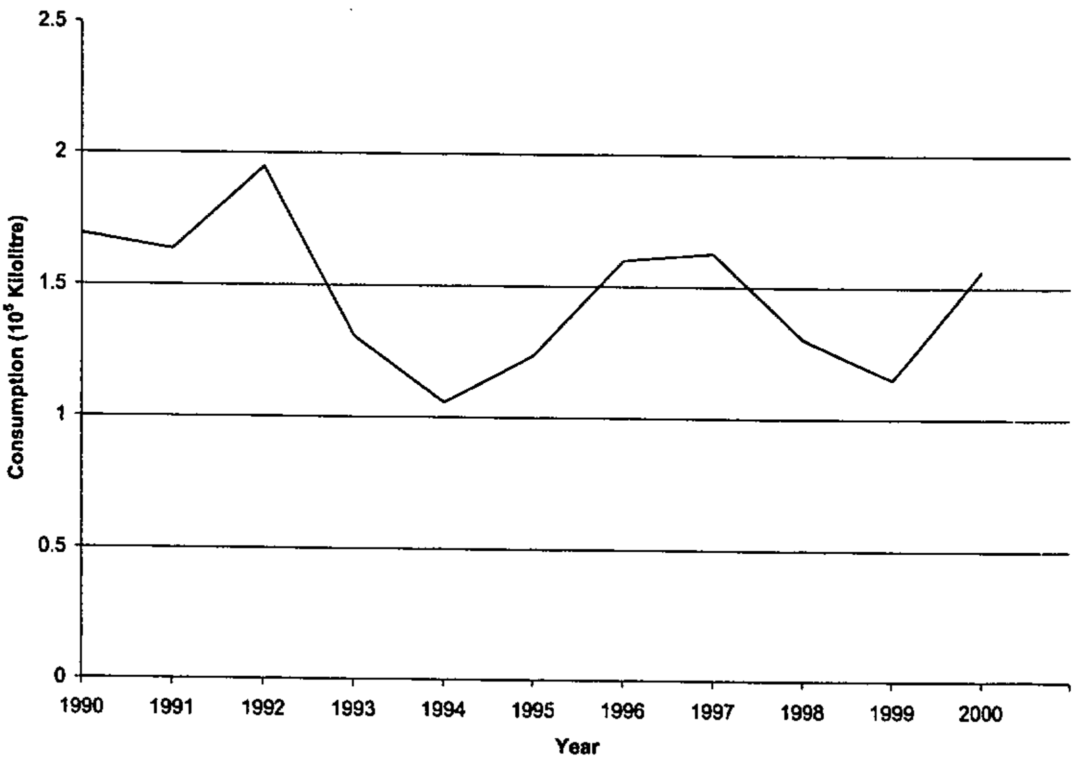



Figure 2.5 Consumption of LPG from 1990 - 2000

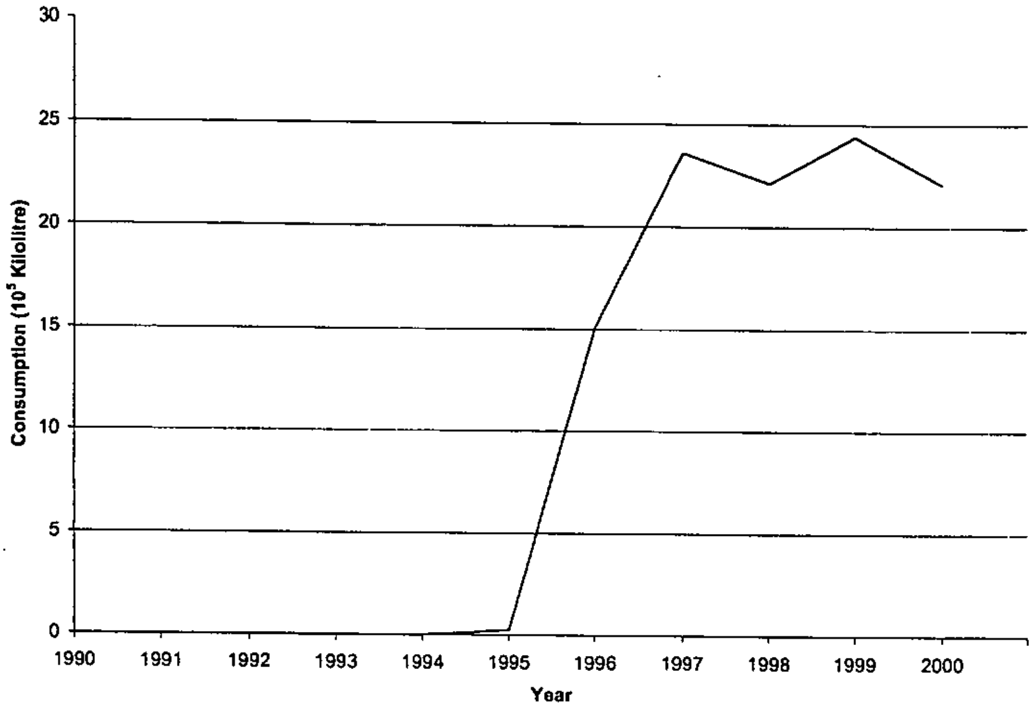



Figure 2.6 Consumption of natural gas from 1990 - 2000

Before we start to study the final energy demand in Hong Kong, two terms using in energy requirement are explained. 'Final energy requirements' refers to the amount of energy consumed by final users for all users for all energy purposes. For example, heating, cooking and machinery operation. For final energy users, electricity and gasoline are the most common energy products. 'Primary energy requirements' refers to overall energy consumption within a geographic territory including requirements for energy transformations. There are indigenous energy sources and imported energy commodities consumed within Hong Kong. The difference of these two requirements is that the energy used or lost in the energy transformation and the distribution process. According to the energy statistics published of 'Hong Kong Census and Statistics Department 1999', the total local electricity consumption in 1999 dropped slightly when compared with 1998. Since 1980, commercial user is the largest electricity user category, while domestic users and industry users are second and third respectively. Hence, my study is emphasized on electricity demand of commercial sector. The situation reflected the business structure of Hong Kong economy with manufacturing being the major business before 1980. The situation has changed since 1982. Electricity consumption of industrial users dropped while domestic users' category increased in that year. At that time, many factories were moved to Mainland China due to various economic reasons. Between 1989 and 1999, the consumption of commercial users increased from 48% to 61% and that of domestic users from 21% to 25%. In the same period, the consumption of industrial users decreased from 31% to 14%. Final energy use was around 220,000 terajoules in year 1989 and increased to 464,000 terajoules in year 1999. There was a 110% increase in the last ten years. This research study concentrates on analyzing electricity consumption in the past and forecast of future use of commercial building with impact of building energy effect by statistics modeling.

## 2.2 Energy supply and demand in HKSAR

There are two local electricity suppliers and the charges of commercial tariffs by the two suppliers are similar. The final electricity demand is 125,000 terajoules and this was about 55% higher when compared to 80,000 terajoules in 1989. The average increase was about 5% per year since 1989. For electricity demand in Hong Kong, the historical trend from year 1972 to year 2000 is shown in Figure 2.7. In 1997, commercial buildings consumed more than 55% of total electricity and the rest was shared by residential and industrial buildings in the percentage of 30% and 15% respectively. The estimated total electricity demand in 2003 will reach 147,000 terajoules, of which 90,000 terajoules would be consumed by the commercial sector. The predicted growth rate of electricity demand in commercial and residential buildings is around 4.4% and 5% growth rate respectively. The total electricity demand for these two sectors will reach 86000 and 40000 terajoules in year 2003. For the industrial sector, the electricity demand has decreased for the last 3 years. The reason is that the manufacturing industries have strategically moved to other Asia counties for better budget control and business opportunities. Electricity demand of the industrial sector will decrease to 18000 terajoules in year 2003, but the total electricity demand is increasing.

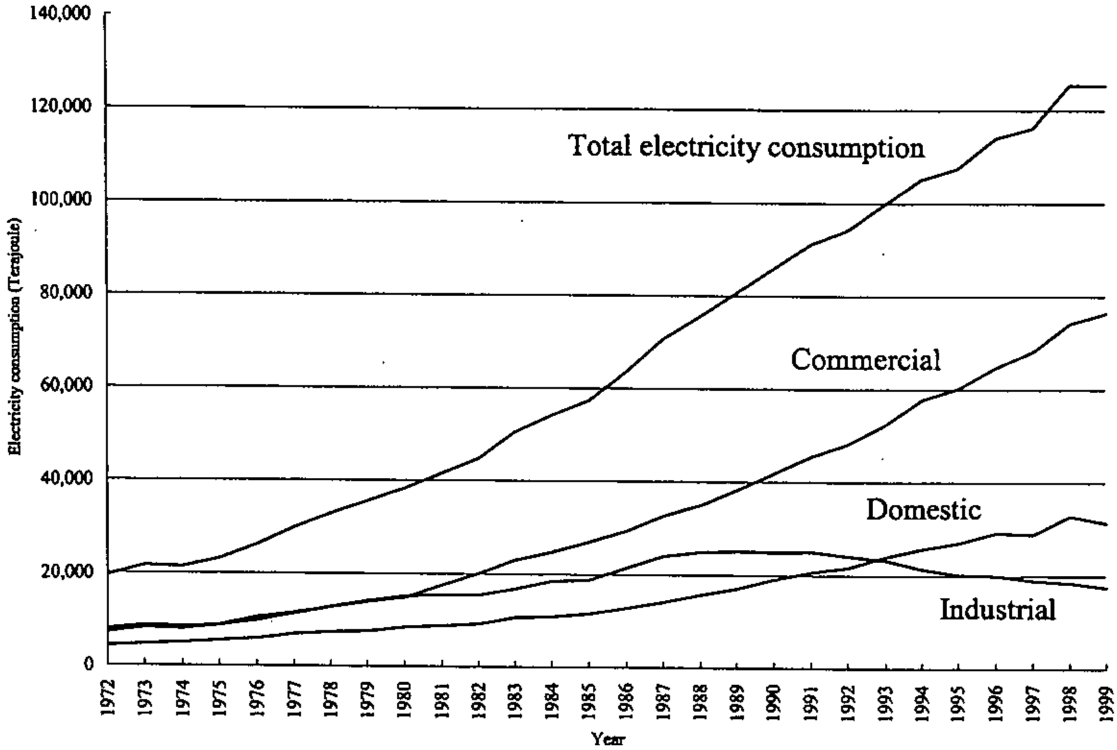



Figure 2.7 Electricity consumption of commercial, Domestic and Industrial sectors from 1972 to 1999, (Hong Kong Energy Statistics Annual Report 1998-2000)

## 2.3 Energy consumption sectors

To understand the influences of economics factors on the energy demand trend, the following major economics indicators shown in table 1 have been studied.

Table 2.1 Description of energy consumption sectors in Hong Kong for general regression modeling

1. Composite consumer price 89/90
2. Fuel price in Hong Kong
3. Gross domestic product at constant price of 89/90
4. Government expenditure and equity investment
5. Volume of trade
6. Average Price of electricity of China Light & Power Co. Ltd. & Hong Kong Electric Co. Ltd.
7. Population
8. Units of public owned and saleable estates
9. Total floor area of commercial, industrial & private residential building

There are nine various economical related variables to be studied in our models to explain the electricity and final energy demand trend. Explanation of the ordinary energy consumption factors for general multiple regression model in chapter 6 is as follows: Fuel price is calculated in dollar per megajoule. Total Government Expenditure and Equity Investments are recorded from the account of Actual Expenditure, i.e. General Revenue Account and Funds. This item is calculated as operating expenditure plus capital expenditure plus all funds from government investments. Total trade is total amount of import of trade plus domestic exports of trade plus re-export of trade in million dollars. The general tariffs for electricity of the two suppliers, China Light & Power Co. Ltd. (CLP) and Hong Kong Electric Co. Ltd. (HEC) are included. Population has been measured. Units of public owned and saleable estates are considered as a separate variable to be studied in the general energy model in Chapter 3. Gross domestic product (GDP) is a measure of the total value of production of all resident producing units of a country or territory in a specific period, before deducting allowance for consumption of fixed capital. Real GDP has been used in our regression model which is calculated as the sum of private consumption expenditure, government consumption expenditure, gross domestic fixed capital formation, changes in inventories, and nets of goods and services. The Consumer Price Index (CPI) is an important economic indicator that measures changes in the price level of consumer goods and services generally purchased by households and is an important indicator of inflation affecting consumer behaviors.

## 2.4 Building stock

The energy consumption of building sector is categorized into three subsectors as domestic, commercial and industrial. Volume of the properties is referred to the Hong Kong Property Review compiled by Rating and Valuation Department. The total floor areas of commercial building include private office and government owned office building. The total floor areas of residential building include private residential building, government owned domestic buildings, urban improvement, flat-for-sale, sandwich class housing schemes and public rental estates from Housing Authority and Housing Society. The industrial sector includes private flatted factories, private specialized factories and private storage. All property data are captured from issues since 1972. Many factors affect the volume and time-table of building development, and changes are inevitable in the following years. Therefore, revisions were made and released in subsequent issues. This study has been worked to the best for assuring collection of all figures. The stock of private domestic units collected from the issues includes basically all independent dwelling with an exclusive cooking area, bathroom and washroom. The number do not include some of the more traditional village houses, quarters held by the People's Liberation Army, quarters attached to premises of utility companies, dormitories, quarters held by the Hospital Authority, hotels and hostels. In year 2000, supply of new residential units dropped by 27%. The completions of 25,800 units were slightly below the annual production of 27,000 units for the 10 years period ending 1999. Completions of all private residential units in the year of 2001 and 2002 are forecast to increase moderately to 28,000 units and 30,000 units respectively. For the commercial sector, volume of commercial buildings in this study includes all private offices and government owned office buildings. Overall commercial buildings completions in 2000 were less than 1999. The total completion was 159,900m$^2$ in year 2000. Forecast completions for 2001 and 2002 are still below the average supply in the past ten years.

Development of the private flatted factories for manufacturing purposes decreased in the last ten years. There was almost no new private flatted factory in last two years. New type of industrial/office buildings is proposed in these few years to cater for the accommodation needs of different business activities within the same site or building. The operation of new industrial/office buildings is good for clean industrial, general office and commercial uses. More flexibility is given to users regarding the scope of permitted uses. The completion of industrial/office developments was 37,100 $m^2$ in 2000 and this was a slight reduction comparing with year 1999. Forecast figures by Rating and Valuation Department indicate further decrease in constructions of industrial buildings in future due to low demand in the market.

## 2.5 Influence of building energy use on total energy demand

Residential and commercial buildings use majority of electricity consumption in Hong Kong. Most of the residential units are high rise, and air-conditioning window-units are widely used especially in the season from May to November. On the other hand, commercial buildings are also high rise, and they are enclosed and centrally air-conditioned throughout the year. However, effective energy use in building services has been encouraged by the Government policy. For example, Government Property Agency (1990) and Energy Efficiency Advisory Committee (1993). To understand the utilization of building energy, particularly on the cooling load resulted from the external heat gains through the building envelopes in air-conditioned commercial buildings. An Overall Thermal

Transfer Value (OTTV) is used to evaluate the design on the thermal performance of the building envelope (Chan, 1996).

The reference commercial building taken in this study for energy simulations is based on the investigation of Chan 1996. Different thermal performance of building envelopes and cooling energy requirements are dependent on variety of envelope constructions. For example, curtain wall designs are common, but their constructions vary from light-weight to massive, from reflective to absorptive, insulated or non-insulated, with single or double glazing, and vary in the glazing areas. These commercial buildings are subjected to cooling requirement throughout most of the year. The electricity consumption for operation of the air conditioning system accounts for about 60% of their total consumption. The cooling load is particularly dependent on the construction of the building envelope and the weather conditions. Not much attention has been paid to designing and operating for energy efficiency in buildings in Hong Kong. Heat gain through the building envelope may account for about 20% of the chiller load for a typical office building Hong Kong. Therefore, control of the thermal performance of the building envelope is an important factor to achieve energy save in commercial building especially in subtropical region. However, attentions of work practice and general awareness should also be kept in mind. The magnitude of the energy save due to envelope may vary. It depends on the construction of the envelope, the thermal and physical properties of the constituent layers in individual building. A cooling criteria limiting the amount of heat gain through the building fabric and reducing the energy consumption for cooling was initiated by the Government. In the view that the OTTV approach does not address systematic performance and has limitation on many aspects, e.g.

utilization of daylighting, an alternative approach of normalized energy consumption and performance line are advocated to be used as the measures of building energy control.

Owing to awareness of designing and operating for energy efficiency in commercial building, minimum requirements, specific design parameters, control criteria for air-conditioning installations and minimum coefficient of performance for air-conditioning equipment are proposed by the Energy Efficiency Committee. Codes of practice to set out energy efficiency requirements for power distribution and utilization in buildings, minimum allowable luminous efficacy for different lamp types and maximum lighting power density of a particular space are prepared for construction references. Measures and design options of building envelopes and systems for energy efficiency in relation to the legislative codes of practice are studied. Through the simulation by DOE-2E, results of the effectiveness of design schemes on energy, the growth of energy demand from commercial property development and the range of building energy requirement from minimal to good design practices can be derived. Various building energy consumptions are obtained by adopting different building energy parameters. Hence, different level of electricity consumption is generated. The resulting final energy requirement can be determined based on the different level of electricity usage in the society.

## Chapter 3

# Energy Regression Model

### 3.1 Energy economics and influencing variables

To study energy demand with influencing economic variables, indices of leading indicators in macroeconomics model are used. An indicator is any variable informative about another variable of interest. The outcome of leading indicator is known in advance of a related variable that is desired to forecast. A Composite Leading Index, called CLI, is a combination of such variables. There has been a recent revival of interest in using CLI of economic activity in forecasting the state of the economy. Those research works were done by Inter alia, Artis, Bladen-Hovell, Osborn, Smith and Zhang (1995), Diebold and Rudebusch (1989, 1991a, 1991b), Koch and Rasche (1988), Lahiri and Moore (1991), Neftci (1991), Parigi and Schlitzer (1995), Samuelson (1987), Stock and Watson (1989, 1992), Weller (1979) and Zarnowitz and Braun (1992). The studies were involved in perceived forecasting failures by macro econometric systems. CLI was treated as a reference to the issue and database of the energy model to be developed in this project.

The basis for the evaluation of indicators in forecasting is an integration of cointegrated parameters subject to shift in effect of changing economy. Assume the energy model is an integrated dynamic system, information losses may arise from ignoring cointegration between economic variables and energy demand variable and the forecast model is inefficient. In this study, Johansen and Juselius test procedure is discussed and is employed to study the long run relationship in the energy model. One of the reasons is that the Johansen and Juselius procedure does not assume the existence of at most a single cointegrating vector. It tests for the number of cointegrating relationship among the variables within the study model. There have been several studies about the relationship between macroeconomic variables and the resource related variables on the other side (Harvie and Hoa, 1993). Some of the literatures emphasize on modeling approach, such as deriving income elasticity energy demand for developing counties by gathering counties data (Zilberfarb and Adams 1981), estimating energy demand for a selection of developing counties (Dunkerley, 1982), modeling multivariate simultaneous approach of energy demand for Thai (Hoa, 1992), estimating short run and long run Danish energy demand elasticities (Bentzen and Engsted, 1993) and analyzing of Danish gasoline demand (Bentzen, 1994). In those recent applied literatures, unidirectional causality relation has been detected to appear between economic growth and energy consumption.

This thesis reports the long run and cointegrated relationship of economic factors to the energy demand function. The analysis includes two parts of studies, the final energy consumption and the electricity consumption. For macro analysis of energy demand function, factors affecting energy consumption have been studied as the relation of energy consumption with composite consumer price 89/90, fuel price in Hong Kong, gross domestic product at constant price of 89/90, government expenditure and equity investment, volume of trade, average price of electricity of the two power companies, population, residential units of public owned and saleable estates and total area of commercial, industrial and private residential building. For electricity demand function, analysis includes quantifying the relationship of electricity demand with relevant economics and non-economic variables such as national income, population, price of electricity and different building energy sectors. Much effort has been put into the access of information and its preparation. In the recent applied literatures, existences of long run relationship have been detected by various econometrics testing procedure. Then, we are going to investigate how electricity consumption changes against different economic variables with a time series in trend stationary base. Regression analysis of electricity consumption is applied to develop time series forecast model and the test procedure and application of the model is explained in Chapter 7.

### 3.2 Use of multiple regression in the energy analysis

Analysis of the energy demand should include the measures of the economic variables mentioned in section 3.1. The advantage of using regression analysis is that it is able to include many independent variables in a mathematical expression. The model can incorporate the effect of changes in related independent variables mentioned in chapter 2. The regression model with economic independent factors in our study can be described as an econometric modeling.

Econometric models of different levels of complexity can be formulated to estimate long term and short term elasticity coefficients with respect to each variable. In this thesis, the econometric models incorporate the effects of changes in population, structure of building development, pattern of industrial growth, change of electricity price in Hong Kong, etc. The coefficient of parameter of the economic independent variable is able to explain the degree of effect of the variable to energy demand. With the analysis of building energy demand, the variables of building sectors are calculated as total gross floor area in $m^2$ in every year. Trial and error approach is needed in the selection of explanatory variables. Time lag and functional forms' format are also involved in developing the energy model. With the use of multiple regression analysis, a number of economics and building services related variables are included. Various elasticity coefficients of variables are calculated under the analysis of regression model. F-test is used to test the overall significance of the whole regression model and t-test is used to test hypothesis about the coefficient parameter of every economic factor in the energy model individually. The time series approach of forecasting electricity demand is discussed in Chapter 7. Also, the statistical significance of parameters under econometric estimation is influenced by problem of multicollinearity and serial correlation.

The analysis of various factors affecting energy consumption and economic growth in Hong Kong may involve the process of simultaneous equations. Causal relation between energy consumption and economic activity is difficult to determine and its related studies are not included here. Energy economic factor chosen in the research is in term of energy use in commercial, residential and industrial buildings. The estimated electricity consumption includes all energy uses in those buildings. Elasticity of every single economic related variable is calculated in the model with data measured in natural logarithms. The price variable chosen to use in analyzing effect of price to energy demand is taken to be the price of electricity supply of two suppliers. The parameters of this model could be estimated using time-series extracted from presses of Hong Kong Census and Statistic Department. In double log specifications, the logs of the dependent and independent variables are linked via a linear equation in which all parameters appear in a linear form. Each parameter in double log form shows the percentage change in the dependent energy variable with respect to the percentage change in any one of the independent economic variables under consideration. In econometric analysis such an economic parameter is called the 'elasticity'. When we look at the elasticity of one independent economic variable in the multiple regression model, we assume all other independent economic variables are kept constant.

Artificial neural network is an alternative framework for making energy forecast (Masumi, 1996). An example is the Elman network (Elamn, 1990) incorporating time series analysis to establish the forecasting model for building energy demand. A study on Chongqing's building energy forecast using neural network was reported by Yang and Wu (2002).

Two dominant approaches can be used to analyse time series. One is called spectral analysis, in which the key assumption is that any non-trending time series can be decomposed into a certain number of cyclical patterns (Priestley, 1981). Another approach emphasizes on time-domain analysis, where the autocorrelation function is employed in the analysis. Many time series analysis models have been used in econometric studies such as autoregressive integrated moving average modeling and autoregressive modeling by Box and Jenkins (1970). Further, the harmonic regression or the Fourier analysis of a time series, which is a method applicable to time series that are periodic in nature, is a decomposition of the series into a sum of sinusoidal components by the method of least squares regression on one or more sinusoids (Cooley and Tukey, 1965). In this thesis, the cointegration approach of analysis of non-linear time series is adopted for the study of macroscopic energy demand.

### 3.3 Basic form of energy multiple regression model

The function of energy multiple regression model is to conduct a forecast estimation of energy demand by ordinary least square method based on previous statistical data. The steps in constructing and using the model are stated as follows:

1. The form of the probabilistic model is hypothesized.
2. The model coefficients are estimated using the method of least square.
3. The probability distribution of error is verified and variance is estimated.
4. The utility of the model is checked.

Many statistical packages, e.g., Shazam, SAS, SPSS, can perform the hypothesis test, model outcome and forecast estimation for the users. The whole process starting from data entry to result analysis is being simple to all users. In this thesis, SPSS 9 is used to performed regression analysis. In the later time, that package has been upgraded to SPSS 10 for higher performance. Both versions are designed to operate in Windows environment. Shazam 8.0 is chosen to perform advanced statistics analysis in our model development like Dickey-Fuller test and cointegration analysis in later time. The program was written by Kenneth J. White and Diana Whistler in early 90' released by Department of Economics at University of British Columbia. To begin with our regression analysis of energy model, the general multiple regression model is introduced and the format is written as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots + \beta_k X_k + \varepsilon \qquad (3.1)$$

where $\beta_k$ = coefficient parameter of $X_k$,

$\varepsilon$ = the error term

$\beta_0$ = constant term of the model

$X_{1,2\ldots\ldots,k}$ = Independent variables of the model

$Y$ = Dependent variable of the model

When we start to develop a multiple regression model, a set of assumption has to be made to avoid bias of estimation. The assumptions for the linear energy multiple regression model are as follows:

1. At any given combination of values of $X_1, X_2, \ldots\ldots, X_k$, the population of potential error term value has a mean equal to 0.
2. By constant variance assumption, any given combination of values of $X_1, X_2, \ldots\ldots, X_k$, the population of potential error term values has a variance that does not depend upon the combination of values of $X_1, X_2, \ldots\ldots, X_k$. That is, the different populations of potential error term values corresponding to different combinations of values of $X_1, X_2, \ldots\ldots, X_k$ have equal variances. The constant variance is written as $\delta^2$.
3. By normality assumption, any given combination of values of $X_1, X_2, \ldots\ldots, X_k$ the population of potential error term values has a normal distribution.
4. By independence assumption, any one value of the error term $\varepsilon_t$ is statistically independent of any other value of $\varepsilon_t$. That is, the value of the error term $\varepsilon_t$ corresponding to an observed value of variable energy demand is statistically independent of the error term corresponding to any other observed value of variable of energy demand.

Based on model (3.1), our general econometric model of electricity demand has been developed accordingly. The independent variables are categorized into commercial sector, domestic sector, industrial sector, real gross domestic product and average electricity price of Hong Kong electricity supply companies. These types of statistical data can explain an important consideration of energy demand with the influence of economic growth.

The function of electricity demand is written as follows:

$E_t = [C_t, D_t, IN_t, R_t, P_t]$

where $E_t$ = electricity demand in terajoule

$C_t$ = commercial buildings, in $m^2$

$D_t$ = domestic buildings, in $m^2$

$IN_t$ = industrial buildings, in $m^2$

$R_t$ = real gross domestic product in Hong Kong dollar

$P_t$ = the average electricity price of Hong Kong electricity supply companies in dollar per joule

Hence, our general electricity demand function can be expressed in multiple regression model (3.2):

$$E_t = \beta_0 + \beta_1 C_t + \beta_2 D_t + \beta_3 IN_t + \beta_4 P_t + \beta_5 R_t + \varepsilon_t \qquad (3.2)$$

where $\beta_0$ = constant

$\beta_1$ = estimate parameter of coefficient to $C_t$

$\beta_2$ = estimate parameter of coefficient to $D_t$

$\beta_3$ = estimate parameter of coefficient to $IN_t$

$\beta_4$ = estimate parameter of coefficient to $P_t$

$\beta_5$ = estimate parameter of coefficient to $R_t$

$\varepsilon_t$ = error term of the model

subscript $t$ = year of time

As for the historical data of economic, I have analyzed a group of economic data such as composite consumer price 89/90 (CPI), fuel price (FP), real gross domestic product (R), government expenditure and equity investment (GE), volume of trade (VOT), average price of electricity of the two power companies

(P), population (POP), number of units of public owned and saleable estates (TUGO/TUSG), volume of non-commercial building (VONC) and total floor area of commercial, industrial and private residential building (C/IN/D). All variables are in logarithmic scales. In the general multiple regression analysis stated in chapter 5, the effect of the group of economic data on electricity and final energy demand is discussed. Adoption of those economic variables in this study is based on the information from the published Economic Prospects and Economic Background (Hong Kong Census and Statistics department, annual publication). Recently, studies have confirmed the existence of cointegrating long-run relationship among energy consumption, real income and price in energy dependent industrializing counties (Samimi 1995 and Masih and Masih 1997). Those studies reported the influence of macro-economic variables to energy demand trend. Therefore, an improved energy regression equation is established and presented in chapter 6. The series of macro-economic variables using in the error correction model have been extended to cover a longer period and some variables are removed. In the error correction model, I have analyzed the variables of real gross domestic product, price of electricity and restructured the building development into three variables as of commercial, industrial and residential building stock (Dahl and Sterner 1990, Ramanathan 1999). The error correction model can give the estimation of the elasticity of electricity demand to electricity price and the estimation of change of electricity demand by the change of building stocks. Variable of real gross domestic product was chosen, as it was an important indicator of the total worth of production in an economic entity. In particular, the use of the commercial building stock as one of the independent variables in the model is emphasized, as the commercial sector is the largest single end user of electricity in Hong Kong.

The behavior of linearity of the related statistical data is important to formation of energy regression model. Observation is one of the methods to check the linearity of the statistical data. Alternatively, we can use the function of Scatterplot Matrix to review the distribution of the data. The diagram of Scatterplot Matrix using SPSS is shown in Figure 2.8, where positive correlation and linear relations of all variables are ascertained.

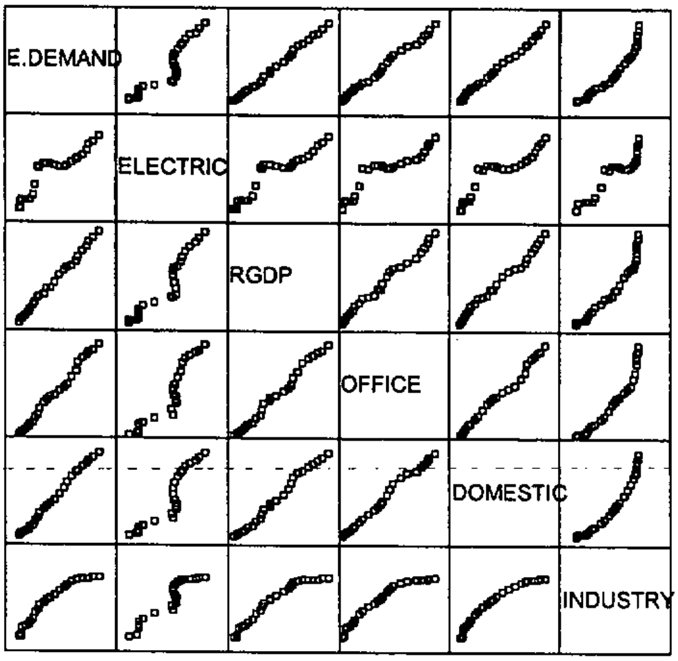



Figure 3.1 Linear relationships among the variables by Scatterplot Matrix

However, the observations of the statistical data of energy economics used in our regression model are linear over last 20 years. Hence, observations to the figures are sufficient to determine whether the data sets are in linear trend. According to the assumption of linear regression model, at any given combination of values of $C_t$, $D_t$, $IN_t$, $P_t$, $R_t$, the population of potential error term values is normally distributed with mean 0 and a variance $\sigma^2$, i.e. $\varepsilon = [0, \sigma]$, that does not depend on the combination of values of $C_t, D_t, IN_t, P_t, R_t$ .The energy model indicates that at any given combination of values of $C_t, D_t, IN_t, P_t, R_t$ , the variation of energy variables is caused by and same as the variation in the $\varepsilon_t$ value. Therefore, at any given combination of values of $C_t, D_t, IN_t, P_t, R_t$, the population of variable that can be observed is normally distributed with mean of following expression:

$$\beta_0 + \beta_1 C_t + \beta_2 D_t + \beta_3 IN_t + \beta_4 P_t + \beta_5 R_t \tag{3.3}$$

and a variance $\delta^2$ that does not depend on the combination of values of $C_t, D_t, IN_t, P_t, R_t$. Moreover, the independence of the variance indicates that there are no patterns in the error term values when the time series data are utilized in this energy regression study. The related statistical data for carrying multiple regression analysis has been identified and the results of study are reported in Chapter 5. Forecast of energy demand is responsive to the energy economic variables in the model. The parameter of $\beta_1$ represents the increase in energy demand that is associated with 1 percentage increase in the stock of commercial buildings when the rest of other independent variables do not change. Actual energy consumption can be compared to predict energy demand though the calculation with the model. The predicted outcome of energy demand in future is presented in chapter 5.

### 3.3.1 Long run and short run elasticity in energy demand function

To understand the degree of response of the energy demand function to the change of various economic factors, the concept of elasticity is employed and determined in our model. Elasticity is separated to long run and short run elasticity. Long run elasticity of the energy demand function determines the responses of the energy demand to the changes in the independent variables within long period of time. Long period is considered as 15 to 20 years. Short run elasticity determined the responses of the energy demand to the changes in the independent variables within 5 years. The degree of elasticity can be indicated in estimated multiple regression model. Let $\hat{Y}$ represents the estimation of the energy demand $Y$, then the estimated multiple regression model can be written as follows:

$$\hat{Y} = \beta_0 + \beta_1 C_t + \beta_2 D_t + \beta_3 IN_t + \beta_4 P_t + \beta_5 R_t \tag{3.4}$$

The elasticity of energy demand $\hat{Y}$ with respect to an independent variable $X_1$ is defined as:

$$\text{Elasticity of } \hat{Y} \text{ with respect to } X_1 = \frac{(d\hat{Y}/\hat{Y})}{(dX_1/X_1)} = \left(\frac{d\hat{Y}}{dX_1}\right)\left(\frac{X_1}{\hat{Y}}\right) \tag{3.5}$$

For a log-linear model,

$$\ln \hat{Y} = \beta_o + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \cdots + \beta_n \ln X_n \tag{3.6}$$

$$\Rightarrow \quad \hat{Y} = e^{\beta_o + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \cdots + \beta_n \ln X_n}$$

$$\frac{d\hat{Y}}{dX_1} = \beta_1 \left(\frac{1}{X_1}\right) e^{\beta_o + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \cdots + \beta_n \ln X_n} = \beta_1 \left(\frac{\hat{Y}}{X_1}\right)$$

$$\therefore \quad \text{Elasticity of } \hat{Y} \text{ with respect to } X_1 = \beta_1 \left(\frac{\hat{Y}}{X_1}\right)\left(\frac{X_1}{\hat{Y}}\right) = \beta_1$$

Hence, in the log-linear model, the elasticity of energy demand $\hat{Y}$ with respect to an independent variable $X_1$ is given by the slope coefficient $\beta_1$ in the model. It measures the percentage change in the energy demand $\hat{Y}$ for one percent change in $X_1$. Similarly, the coefficients $\beta_2$, $\beta_3$, $\cdots$ $\beta_n$ are the elasticity of energy demand with respect to the independent variables $X_2, X_3, \cdots X_n$ respectively.

The same concept can be applied to other regression analysis. It is a general measure of responsiveness that can be used to quantify many different relationships. The signs of $\beta_2$, $\beta_3$, $\cdots$ $\beta_n$ in model (3.6) indicate the short run influence of those economics variables on the energy demand. Positive sign means that there is a positive relationship between the dependent and independent variable. Negative sign indicates a reverse relation. From the economics point of view, if the coefficient is less than 1 in absolute value, the demand of energy is comparatively inelastic to the factor.

Long run elasticity is calculated as the short run elasticity divided by 1 minus the rest of other short run elasticity except itself. Alternatively, it is determined by the error correction model of time series econometric analysis (Hendry et al., 1984) and (Hendry, 1995). In the econometric theory (Johansen and Juselius, 1990), it is suggested that the long run relationship of energy demand and its independent factors, for example $Y$ and $C$, will grow in the same rate and the equilibrium will be in constant. The equilibrium is calculated as $(Y - C)$. The long run elasticity is detected from the long run coefficient of parameter in the error correction model (ECM). The study of error correction model is started as follows:

$$y_t = \beta_0 + \beta_1 x_t + \beta_2 x_{t-1} + \beta_3 y_{t-1} + \varepsilon \tag{3.7}$$

where $x_{t-1}$ and $y_{t-1}$ represent the values at one year time lag of the statistical data of the variable itself. The second step is to apply the differences to the general form and the representation is written as follow:

$$\Delta y_t = \beta_0 + \beta_1 \Delta x_t + (\beta_3 - 1)(y_{t-1} - x_{t-1}) + \varepsilon_t \tag{3.8}$$

The model (3.8) is the result of subtracting $y_{t-1}$ from each side, adding and subtracting both $\beta_1 x_{t-1}$ and $(\beta_3 - 1)\, x_{t-1}$ on the right hand side of the model (3.7).

The last error term is an error correction term of disequilibrium. $\beta_1 \Delta x_t$ term is indicated as an equilibrium response in the error correction model. Detail of derivation of model (3.8) is:

Step (1) $y_t = \beta_0 + \beta_1 x_t + \beta_2 x_{t-1} + \beta_3 y_{t-1} + \varepsilon$ (3.7)

Step (2) Add and subtract both $\beta_1 x_{t-1}$ and $(\beta_3 - 1)\, x_{t-1}$ on the right hand side of the model (3.7) and also subtract $y_{t-1}$ from each side:

$$y_t - y_{t-1} = \beta_0 + \beta_1 x_t + \beta_2 x_{t-1} + \beta_3 y_{t-1} + \varepsilon + \beta_1 x_{t-1} + (\beta_3 - 1)x_{t-1} - \beta_1 x_{t-1}$$
$$- (\beta_3 - 1)x_{t-1} - y_{t-1}$$

Step (3) $\Delta y_t = \beta_0 + \beta_1 \Delta x_t + (\beta_3 - 1)(y_{t-1} - x_{t-1}) + \varepsilon_t$

According to the example of the formulation of error correction model, the long run elasticity is generated by calculation of $\frac{(\beta_1 + \beta_2)}{(1 - \beta_3)}$, i.e., let $y_t = y_{t-1}$ and $x_t = x_{t-1}$, and solve for $y_t$ (Wickens and Breusch, 1988).

The application of ECM in this analysis is chosen by the typical formulation postulated by economic theory for energy demand function. The detail application of ECM to our electricity demand function is discussed in chapter 7 where the long run elasticity of energy demand with respect to the economical variables is determined. The error term is assumed to be white-noise and normally and identically distributed. Estimation of normal multiple energy regression model will provide approximate long-run elasticity. The data used in ECM analysis are annual ranging from 1972 to 1998 in Hong Kong. The data were obtained from historical annual statistics reports issued by the Hong Kong Census and Statistics Department.

## Chapter 4

# Building Energy

### 4.1 Methodologies of building energy simulation

The study of building energy, application of building envelope design and evaluation of space cooling system are simulated by energy simulation program. Building energy programs at the late 1960s (e.g. Sando 1970) focused on sizing heating and cooling plant using simple assumptions for the building envelope losses and gains. New design strategies were developed in US and UK at the late 1970s. For purpose of receiving more accurate energy simulation output, many new generations of building energy analysis program have been designed and improved. Generally, there are four major calculation techniques like regression equations, lumped parameter, response function and finite volume heat balance, being used for estimating building heat flow and energy usage (Chan 1996). Two approaches to model the systems are introduced, menu-based and component-based (Hanby 1987). In the menu-based simulation program, e.g., the US Department of Energy's DOE-2E (LBL 1980), a comprehensive menu of systems and options is available, but making the program large and relatively less efficient. The second approach is component-based or called modular, e.g., TRNSYS, a transient system simulation program (Solar Energy Laboratory 1990) in which component can be chosen from a menu to synthesize tailor-made HVAC systems, making the program compact and flexible. Menu-based simulation program, DOE-2E, is adapted to work on the simulation in our building energy simulation. According to a survey of 64 commercial buildings in Hong Kong (Chan 1996), the construction characteristics of high-rise commercial buildings in Hong Kong were identified and a reference building was developed as the basis for simulation. The reference building is 40-storey high with building parameters representing the average of those that could be expected among the new buildings and the existing ones in Hong Kong. It is taken to be the reference for comparison of the thermal performance of the building envelope designs, energy requirement of air conditioning systems and parametric analysis.

## 4.2 Review of the DOE-2.1E program

The most sophisticated of those programs mentioned in section 5.1 were detailed simulation programs which were capable of predicting the hour by hour variations of heat fluxes, internal temperature and energy usage in response to internal load patterns, plant schedules, system operation characteristics and weather conditions for multi-zone buildings. The simulation programs are worked out by solving the physical equations governing transient heat transfer through conduction, convection, infiltration, ventilation and radiation. Energy simulation program, DOE-2E, is based on the time domain approach. The latest version of DOE-2.1E was released in 1994 with enhancements in the modeling of window properties. Additional HVAC system modules have been added in DOE-2.1E and its micro version can be run in Windows platform. The use of DOE-2E will enable the analysis of energy consumption in buildings through simulation of hour-by-hour performance of the HVAC system for each of the 8760 hours in a year.

Detailed studies of the heating and cooling load in conjunction with the system design and plant performance will be useful in understanding the energy saving potential in building energy design. Usually the energy consumption of a building is determined by its shape, orientation, materials and construction of the envelope, window-to-wall ratio, ambient conditions, use of the building, type of systems, required internal conditions, systems control strategy and equipment operation. DOE-2.1E has been employed to use as a standard building energy simulation (ASHRAE 1989). The simulation output of DOE-2E provides meaningful numbers for efficient building energy requirements. LOADS, SYSTEMS, PLANTS and ECONOMICS are the four simulators in input file to be created for the program's operation model and hierarchy of building energy simulation is determined as thermal boundaries, spaces, zone, secondary systems, primary plants and economics in sequence. The program permits the user to input the instructions in English by the function of Building Description Language (LBL 1989) and provides very detailed analysis of component heat losses or gains, and the evaluation of design alternatives. Tests of accuracy and verification of DOE-2 were conducted in various researches in The Hong Kong Polytechnic University, for example, use of building energy by in-situ measurements and computer modeling (Chow and Fong 1996), evaluation of DOE-2 (Chow, Chan and Leung 1992), and analysis of thermal performance of building envelopes and energy calculation (Chan, 1996).

### 4.3 Reference commercial building for energy simulation

Majority of commercial buildings in Hong Kong are high rise. Two types of common constructions are found in Hong Kong, the old design is with concrete frame and load-bearing external wall, and the latest one is with steel or concrete frame plus non load-bearing external wall. While concrete wall structures with ceramic tile finish or stucco finish are typical for older buildings, curtain walls are common for commercial buildings since late 1970s. These buildings vary in the types of fenestration, window-to-wall ratio, materials of opaque wall, with or without insulation, and light or heavy weight construction. A 40-storey square building with construction characteristics representing the average of the buildings surveyed (Chan, 1996) is taken to be the reference for comparison of the energy requirement of buildings having various envelope and system characteristics. Annual cooling energy consumption of the buildings were calculated based on identical internal characteristics and cooled with same air conditioning system for 2860 hours in a year to maintain indoor temperature of $24^0$C. This reference building used in the simulation analysis has a total floor area of 1296 $m^2$ at each level, of which 1071 $m^2$ is air-conditioned. It is intended to resemble the real construction of typical high rise office buildings found locally, having the building parameters at about the 50% reviewed from 40 studied buildings in order to represent the average of those that could be expected among the likely new buildings and existing ones. The total external wall area (both opaque and glazed) of the whole building is 18432 $m^2$. It is a curtain wall building with spandrel wall construction of 25 mm granite panel, backed with an inner layer of heavy-weight concrete (Chan, 1996). The U-value of the opaque wall is 2.34 $Wm^{-2}K^{-1}$ and the wall mass is 312.4 $kgm^{-2}$ which is a usual medium weight construction. The window-to-wall ratio is 0.5 which is most common for curtain wall buildings. Single-glazed reflective glass with shading coefficient of 0.45 is used.

Most of commercial buildings are air-conditioned with central refrigerating and air-conditioning plant. Heat rejection is typically by direct air-cooled, whereas large refrigeration capacity water-cooled plant in commercial buildings is uncommon because of lacking of fresh water. For those buildings close to the sea front, sea water cooling is a popular alternative due to its heat rejection effectiveness. For many years, fan coil unit systems have been commonly used in office buildings. In recent years, variable air volume (VAV) system started to be installed as standard design in new commercial buildings for the advantage of its part-load performance and less fan power consumption. Moreover, it is free from nuisance of water leakage to the occupants associated with water or air-water systems. Zone temperature of the reference building is controlled at 24 $^0$C for cooling and 21 $^0$C for heating using proportional thermostat with throttling range of 2 $^0$C. 22 $^0$C to 23 $^0$C is a deadband without heating and cooling provided. Heat is extracted from the space when the zone temperature is at or above 23 $^0$C, at that point the VAV box will be at the minimum position giving a minimum flow of 40% of the design flow rate. The zone damper will be at full open position providing maximum cooling when the zone temperature rises above 25 $^0$C. Heating water is available when there is heating requirement, though it is anticipated that office buildings generally have high internal heat gains and heating is only required occasionally even in the cool season. Air-cooled chillers plant and electric hot-water boiler are also included in the building and plant simulation.

The HVAC system for the reference building is generally operated in daytime only. The working hours are usually long because it is common to work overtime in Hong Kong. The cooling system of the reference building is scheduled to operate from 8:00a.m to 7:00p.m on weekdays, and from 8:00a.m. to 1:00p.m. on Saturdays but it is not operated on Sunday. Therefore, there are totally 3131 operation hours in a year. The occupancy density of the reference building is 7m$^2$ per person, which is generally adopted in the design of new local office buildings. This is high compared with the value of 25.6m$^2$ per person recommended in ASHRAE Standard 90.1 (ASHRAE 1999). The installed light intensity is taken to be 20 Wm$^{-2}$ that conforms to the local design practice and also commensurate with many energy standards, for example, ASHRAE standard 90.1 (1999). Amount of heat dissipation from office equipment has substantial changes over recent years due to office automation by use of electronic machines. Traditionally, equipment heat intensity of 5 $Wm^{-2}$ has been adapted to local design engineers. In a report of office equipment load factors analysis (Wilkins, et. al 1991), an average heat release rate of 19 $Wm^{-2}$, taking into account the use diversity, was concluded for an office having one personal computer for every worker and reasonable number of laser printers and copy machines. This is much higher than the traditionally assumed magnitude, whereas in ASHRAE Standard 90.1 (ASHRAE 1999) 8 $Wm^{-2}$ is recommended for offices. Taking into account the increasing use of electronic equipment in office, the ASHRAE recommendation and the results of local field survey, the equipment heat intensity is taken to be 12 $Wm^{-2}$ in the reference building.

## 4.4 Building energy efficiency parameters

Envelope constructions have large effect on the cooling energy requirement. OTTV is used as a criterion for building energy control to ensure energy effective envelope design. External weather is a major consideration of heat gain to envelope construction. Among the parameters of envelope construction, the window-to-wall ratio and the glass shading coefficient have much larger impact on the envelope heat gains than other parameters. The heat gain of envelope construction can be increased by more than four times due to increase of these two parameters within acceptable range. To investigate the total electricity consumption of the reference buildings, minimum requirements stipulated in the code of practice for energy efficiency, specific design parameters for air-conditioning installations and minimum coefficient of performance for chillers are studied in the simulations. Codes of practice to set out energy efficiency requirements for power distribution and utilization in buildings, minimum allowable luminous efficacy for lamp and maximum lighting power density of a particular space are studied. Two types of supply air systems are simulated. They are constant air volume (CAV) system and variable air volume (VAV) system.

The impacts of chiller efficiency, space cooling temperature, variable vs. constant air flow, fan efficiency and lighting intensity on the building energy requirement are studied. To compare the energy effectiveness of these parameters, the reference building described in section 4.3 is used as a based case. In this base case, cooling temperature is set at $24^0$C. Normal lighting power density is 20 $W/m^2$. Efficiency of supply fan and return system is 0.52 and 0.45, respectively. VAV system is used. Annual electricity consumption of commercial buildings is investigated by testing the alternative choices of those design parameters. Simulation is performed using DOE-2.1E. The results are summarized in Table 4.1.

For macroscopic control of lighting energy efficiency stipulated in the Code of Practice for Lighting Installations, the maximum allowable lighting power density for office is 25 $W/m^2$ which might occur if low efficacy lighting is used. The corresponding normalized annual electricity consumption is 223.4 $kWh/m^2$, which is 11.2% more than the base case. With high efficacy lighting, low lighting power density of 15 $W/m^2$ can readily be attained and the normalized electricity consumption is 179.5 $kWh/m^2$ which is 10.7% less than the base case.

One observation in local commercial buildings is that the air-conditioned space is often cold. This may be because of poor system control, or the temperature setpoint is too low. If the control works properly and the space cooling temperature is set to acceptable comfort level of 25$^0$C, annual total electricity consumption and consumption for HVAC only are 193.4 kWh/m$^2$ and 109.3 kWh/m$^2$, respectively. The total consumption is 3.7% less than the base case. If the cooling temperature is set to 22$^0$C, simulation result indicates 18.8% increase of the annual electricity consumption for HVAC.

Air cooled reciprocating chiller and water cooled centrifugal chiller are popular for using in commercial buildings in Hong Kong. The simulation results of energy differences for chillers with different heat rejection methods and coefficient of performance are shown in Table 4.1. In the base case, the type of chiller is air-cooled centrifugal, having COP of 2.94 at full load design condition. For small air cooled reciprocating air conditioning unit, the COP may be as low as 2.4, and it requires 20.5% more energy for HVAC than the base case. In term of energy efficiency, in spite of its low initial cost and flexibility, decentralized small air-conditioning units are not desirable. Alternatively, minimum coefficient of performance of 2.7 is stipulated in the Code of Practice for Energy Efficiency of Air Conditioning Installations for air cooled reciprocating chiller. For water cooled centrifugal chiller, coefficient of performance as high as 6.5 is achievable nowadays with product of latest technology. This will substantially reduce the cooling energy consumption. In this case, the annual total electricity consumption becomes 165.8 kWh/m$^2$, and the consumption for HVAC is reduced to 74 kWh/m$^2$ with 32% reduction compared to the base case. Further improvement can be attained by heat rejection using water cooling tower with variable speed fan.

Another key parameter affecting the building energy efficiency is the supply air volume flow and fan efficiency. The total fan power required for a constant air volume system (CAV), as stipulated in the Code of Practice for Energy Efficiency of Air Conditioning Installations (EMSD 1998), should not exceed 1.6W per L/s of supply air. If it is a variable air volume system (VAV), the total fan power should not exceed 2.2W per L/s of supply air at maximum flow design conditions. The maximum power allowed for VAV at design conditions is higher because the fan operation can be modulated with variable speed control or inlet guide vane control, giving smaller air volume flow and reduced fan power at part load conditions. The operating efficiency of the fan is another concern. In the base case, the air system is VAV with supply fan efficiency of 0.52 and return fan efficiency of 0.45 at design condition of maximum air flow, the total fan power is 1.96W per L/s which is better than the requirement of the Code of Practice for Energy Efficiency. However, if the air system in the base case is CAV, the total fan power of 1.96W per L/s is not acceptable, consuming fan energy of 32.1 kWh/m$^2$ floor area per year (equivalent to 61.3% increase of fan energy), and the fan efficiency has to be raised to about 0.6 in order to meet the code requirement of 1.6W per L/s supply air.

Parametric study can be conducted to give the extent of energy impact by the fan control and fan efficiency. An improved yet achievable fan efficiency is 0.75 at the design operating point, with variable speed control by frequency inverter for part load modulation. In this case, the normalized annual total electricity consumption is 187.3 kWh/m$^2$, the normalized fan energy is 10.4 kWh/m$^2$ which is 47.8% less than the base case, and the normalized electricity consumption for HVAC is 95.7 kWh/m$^2$ which is 12.4% less than the base case.

In conclusion, a combination of desirable system parameters for energy efficiency of commercial building is designed as a VAV system, fan system efficiency of 0.75 at design flow, variable speed control, space temperature of 24$^0$C, lighting intensity of 15 W/m$^2$ and using water cooled centrifugal chillers with nominal coefficient of performance equal to 6.5. The annual electricity consumption of this energy efficient building is 5769.7MWh (i.e., 134.7 kWh/m$^2$). If this efficient building is further enhanced with a desirable building envelope, with OTTV of 20.56W/m$^2$, annual electricity consumption will further drop 258.3MWh to 5511.4MWh (i.e., 128.7 kWh/m$^2$). This is equivalent to 35.9% improvement comparing to the base case. On the other hand, an energy inefficient building has been identified with undesirable system parameters including a CAV system, fan system efficiency of 0.52, space temperature of 23$^0$C, lighting intensity of 25W/m$^2$ and using air cooled reciprocating chillers with nominal coefficient of performance of 2.7. In combination with unsatisfactory building envelope design, where OTTV is equal to 38.3W/m$^2$, the simulated annul electricity consumption is as high as 263.5 kWh/m$^2$ which is 31.2% more than the base case.

## 4.5 Use of the simulation building energy in the energy regression model

The total floor area of commercial buildings has been projected by regression analysis in chapter 2. The forecast of total floor area of commercial buildings for next two decades is indicated in Figure 4.1. By linear projection, the total floor area of commercial buildings will reach 80 million m$^2$ in year 2025. With simulation output of electricity consumption by the defined energy efficient building, the estimation of the percentage change of the electricity demand by commercial buildings is indicated in Figure 4.2. It comes up to a decrease (i.e. energy saving) of 21% in year 2025 relative to the base case of all commercial buildings having average system design. On the other hand, the percentage increase of electricity demand by commercial buildings with undesirable system is also indicated in Figure 4.2. By year 2025, there will be an increase (i.e. energy wastage) of 19% if all new commercial buildings built after 2000 are energy inefficient.

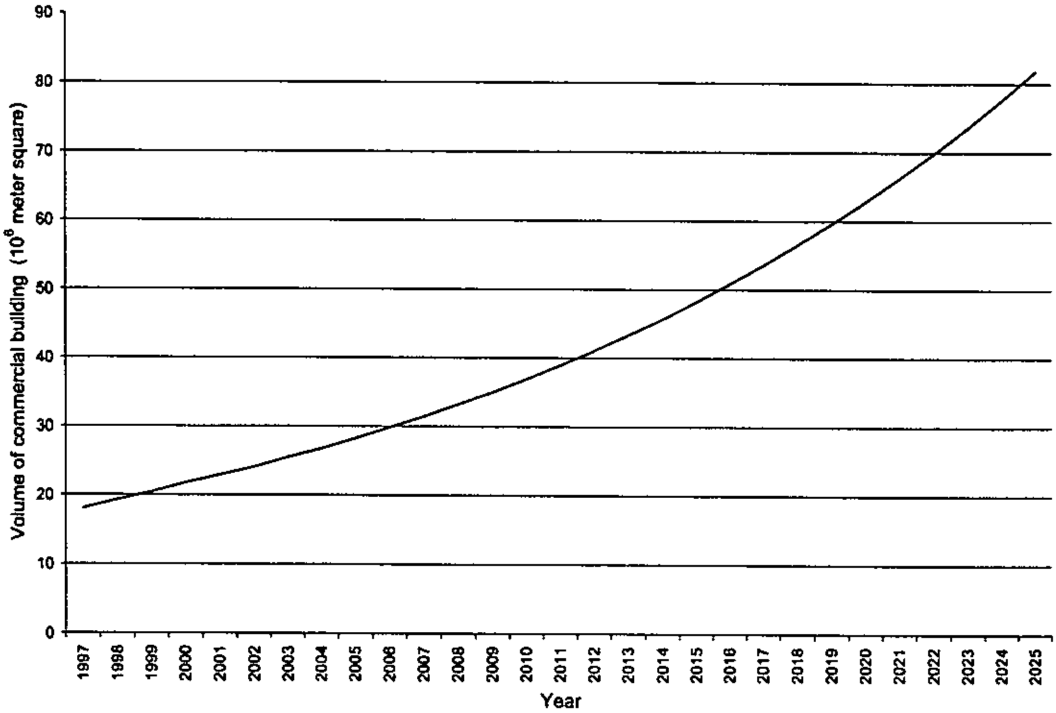



Figure 4.1 Forecast of development of commercial buildings until year 2025

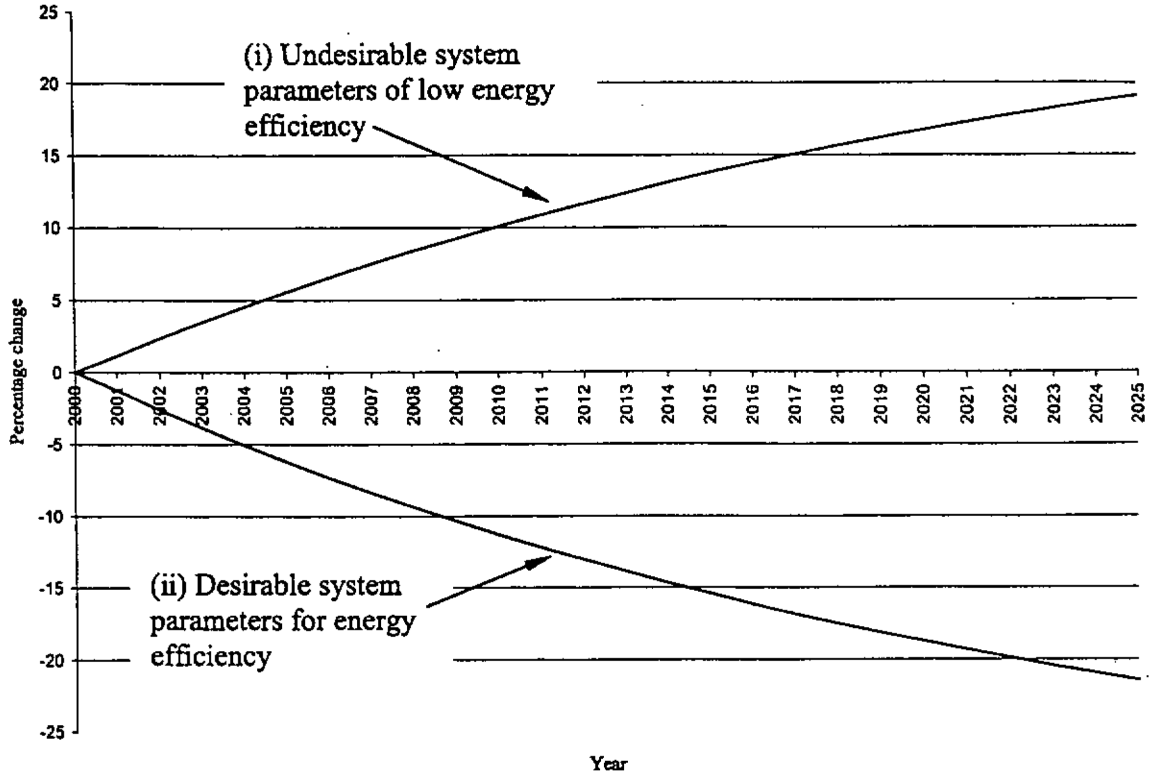



Figure 4.2 Percentage change in the total electricity demand for commercial buildings with (i) undesirable system parameters of low energy efficiency vs. (ii) desirable system parameters for energy efficiency

Table 4.1 Summary of annual electricity consumption for buildings with various parameters affecting energy efficiency

| Building | Change of energy-related parameters | Remark | Lighting (MWh) | Space cool (MWh) | HVAC (MWh) | Fan energy (MWh) | Total (MWh) | Normalised ($kWh/m^2$) |
|---|---|---|---|---|---|---|---|---|
| | Change of "lighting-intensity" : | | | | | | | |
| base case | 20 ($W/m^2$) | Average | 2615.9 | 3012.9 | 4680.8 | | 8605.5 | 200.9 |
| 03 | 10 ($W/m^2$) | | 1308.0 | 2626.6 | 4140.9 | | 6757.7 | 157.7 |
| 04 | 12 ($W/m^2$) | | 1569.7 | 2708.1 | 4263.4 | | 7141.9 | 166.7 |
| 05 | 15 ($W/m^2$) | High efficacy lighting | 1961.9 | 2821.9 | 4417.7 | | 7688.4 | 179.5 |
| 06 | 18 ($W/m^2$) | | 2354.2 | 2935.4 | 4574.4 | | 8237.4 | 192.3 |
| 07 | 22 ($W/m^2$) | | 2877.5 | 3101.2 | 4827.5 | | 9013.8 | 210.4 |
| 08 | 25 ($W/m^2$) | Low efficacy lighting | 3269.8 | 3217.7 | 4991.2 | | 9569.8 | 223.4 |
| | Change of "room temperature" : | | | | | | | |
| 09 | 25°C | Acceptable for comfort | 2615.9 | 2852.1 | 4361.5 | | 8286.2 | 193.4 |
| 10 | 23°C | | 2615.9 | 3233.8 | 5155.4 | | 9080.1 | 212.0 |
| 11 | 22°C | Poor control, setting is too low | 2615.9 | 3423.6 | 5559.2 | | 9483.9 | 221.4 |
| | Change of "COP of chiller" : | | | | | | | |
| 12 | 2.4, air-cooled reciprocating chiller | Min. for small RC | 2615.9 | 4017.5 | 5638.2 | | 9562.9 | 223.2 |
| 13 | 2.7, air-cooled reciprocating chiller | Min. for large RC | 2615.9 | 3573.2 | 5193.9 | | 9118.6 | 212.9 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 14 | 2.7, air-cooled centrifugal chiller | Min. for CC | 2615.9 | 3278.7 | 4946.6 | | 8871.3 | 207.1 |
| 15 | 3.2, water-cooled reciprocating chiller | Min. for water-cooled RC | 2615.9 | 3405.9 | 5062.5 | | 8987.2 | 209.8 |
| 16 | 3.8, water-cooled reciprocating chiller | Min. for water-cooled RC | 2615.9 | 2866.4 | 4521.3 | | 8446.0 | 197.2 |
| 17 | 3.8, water-cooled centrifugal chiller | Min. for water-cooled CC | 2615.9 | 2596.2 | 4257.4 | | 8182.1 | 191 |
| 18 | 4.2, water-cooled centrifugal chiller | | 2615.9 | 2349.5 | 4009.9 | | 7934.6 | 185.2 |
| 19 | 5.2, water-cooled centrifugal chiller | Min. for water-cooled CC > 1000 | 2615.9 | 1898.5 | 3557.5 | | 7482.2 | 174.7 |
| 20 | 6.5, water-cooled centrifugal chiller | High COP possible nowadays | 2615.9 | 1518.5 | 3176.3 | | 7101.0 | 165.8 |
| 21 | 6.5, water-cooled centrifugal chiller | Cooling tower W variable speed fan | 2615.9 | 1518.5 | 3146.2 | | 7070.9 | 165.1 |
| | Change of "fan efficiency" : | | | | | | | |
| 22 | 0.6 | IGV system, higher fan efficiency | 2615.9 | 2957.6 | 4475.2 | 710.4 | 8399.9 | 196.1 |
| 23 | 0.65 | IGV system, higher fan efficiency | 2615.9 | 2934.7 | 4393.6 | 655.6 | 8318.3 | 194.2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 0.7 | IGV system, higher fan efficiency | 2615.9 | 2915 | 4323.9 | 608.7 | 8248.6 | 192.5 |
| 25 | 0.75 | IGV system, higher fan efficiency | 2615.9 | 2898.2 | 4263.8 | 568.1 | 8188.5 | 191.1 |
| 26 | 0.75 | Variable speed control | 2615.9 | 2859.4 | 4100.2 | 445.2 | 8024.9 | 187.3 |
| 27 | 0.52 / 0.45 | CAV system, inlet guide vane control | 2615.9 | 3039.5 | 5154.5 | 1374.0 | 9079.2 | 211.9 |
| 28 | VAV system,<br>Fan efficiency=0.75,<br>Variable speed control<br>Indoor temperature = $24^0$C,<br>Lighting intensity = 15 W/$m^2$,<br>Water-cooled centrifugal chiller,<br>COP = 6.5 | Combination of desirable system parameters for energy efficiency | 1961.9 | 1341.3 | 2499.0 | 405.0 | 5769.7 | 134.7 |
| 29 | VAV system,<br>Fan efficiency=0.75,<br>Variable speed control<br>Indoor temperature = $24^0$C,<br>Lighting intensity = 15W/$m^2$,<br>Water-cooled centrifugal chiller,<br>COP = 6.5, OTTV = 20.6 W/$m^2$ | Energy efficient building with desirable system parameters and building envelope | 1961.9 | 1233.0 | 2240.7 | 368.4 | 5511.4 | 128.7 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 30 | CAV system,<br>Fan efficiency = 0.52 / 0.45,<br>Indoor temperature = $23^0$C,<br>Lighting intensity = 25 W/$m^2$,<br>Air-cooled reciprocating chiller,<br>COP = 2.7,<br>OTTV = 20.6 W/$m^2$ | Combination of undesirable system parameters | 3269.8 | 4104.8 | 6513.6 | 1641.8 | 11092.2 | 258.9 |
| 31 | CAV system,<br>Fan efficiency = 0.52 / 0.45,<br>Indoor temperature = $23^0$C,<br>Lighting intensity = 25 W/$m^2$,<br>Air-cooled reciprocating chiller,<br>COP = 2.7,<br>OTTV = 38.3 W/$m^2$ | Energy inefficient building with undesirable system parameters and poor building envelope | 3269.8 | 4217.8 | 6710.9 | 1699.2 | 11289.5 | 263.5 |

# Chapter 5

# Results of Using Multiple Regression Analysis on Energy Consumption

## 5.1 Statistical trend of economic factors and electricity demand

Through the energy regression analysis described in chapter 3, energy demand models have been developed based on various economic indicators and building data in Hong Kong. All related variables using in the regression analysis in this research are categorized in Table 5.1.

Table 5.1 Symbol of Energy, Economic and building data using in energy models

1. Energy / electricity consumption (TED/E)
2. Composite consumer price 89/90 (CPI)
3. Fuel price in Hong Kong (FP)
4. Gross domestic product at constant price of 89/90 (R)
5. Government expenditure and equity investment (GE)
6. Volume of trade (VOT)
7. Average price of electricity of the two power companies ( P)
8. Population (POP)
9. Units of public owned and saleable estates (TUGO/TUSG)
10. Volume of non-commercial building (VONC)
11. Total area of commercial, industrial & private residential building (C/IN/D)

Linearity is found in the time series of the related variables from 1986 to 1997. The statistic trend of real national income indicated that there was rapid increase in economic growth in the decade up to 1997. In 1997, as the East Asian currency turmoil intensified the Hong Kong economy faced a slowdown of economy. Growth in the Gross Domestic Product (GDP) was setback to only around 8000 thousand million in the end of 1997. The domestic property market went to buoyancy starting at 1997. The commercial properties have slackened since 1997. The market for industrial property remained slack off throughout

1997, in line with the continued relocation of production processes away from Hong Kong to mainland. Government consumption expenditure was counted on a national account basis and recorded a 2.8% increase in 1997. In 1997, total electricity consumption rose by 2% over the amount in 1996 to 32,243 million kilowatt hours. However, commercial consumption increased by 5%, while domestic and industrial consumption fell by 1% and 5% respectively. Their respective shares in total electricity consumption in 1997 were 57%, 25% and 16%. The energy regression analysis models in section 6.2 are based on the time series from 1986 to 1997. A short run of electricity demand and final energy demand in estimation to 2003 is calculated. The predictions of different economic variables are calculated by statistic program "Simple-E" regarding to government released economic information. The predicted trend up to year 2003 is shown in Figure 5.1 to Figure 5.10. The predicted final energy demand and electricity demand are influenced by the recent unstable economy in the world and the degrees of influences are reflected by the elasticity of each independent variable.

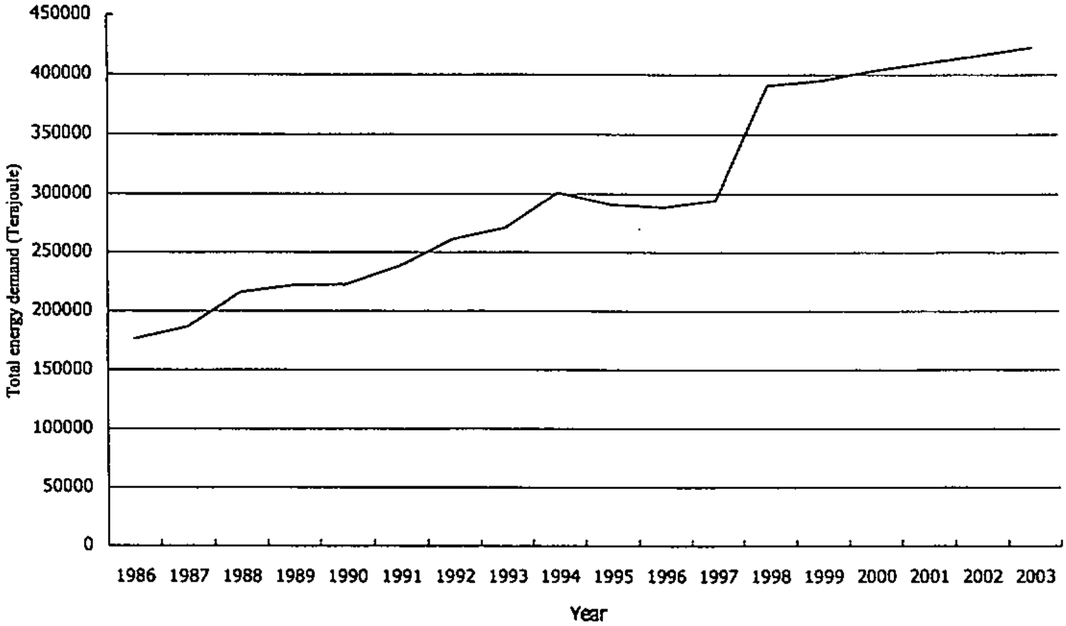



Figure 5.1 Actual and forecast of total energy demand (include coal, oil, electricity & gas) from 1986 - 2003

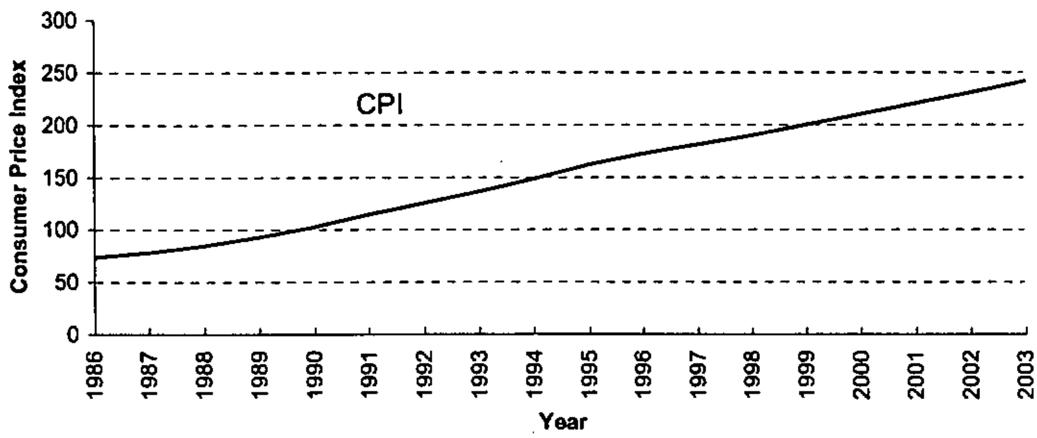



Figure 5.2 Actual and forecast of consumer price index based (1989/90) from 1986 - 2003

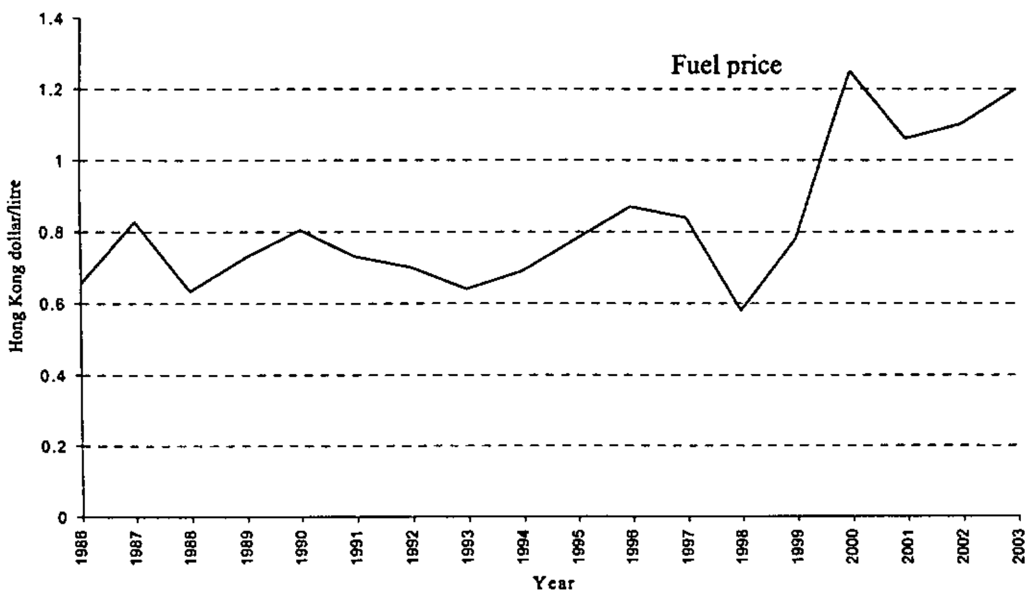



Figure 5.3 Actual and forecast of fuel price in Hong Kong from 1986 - 2003

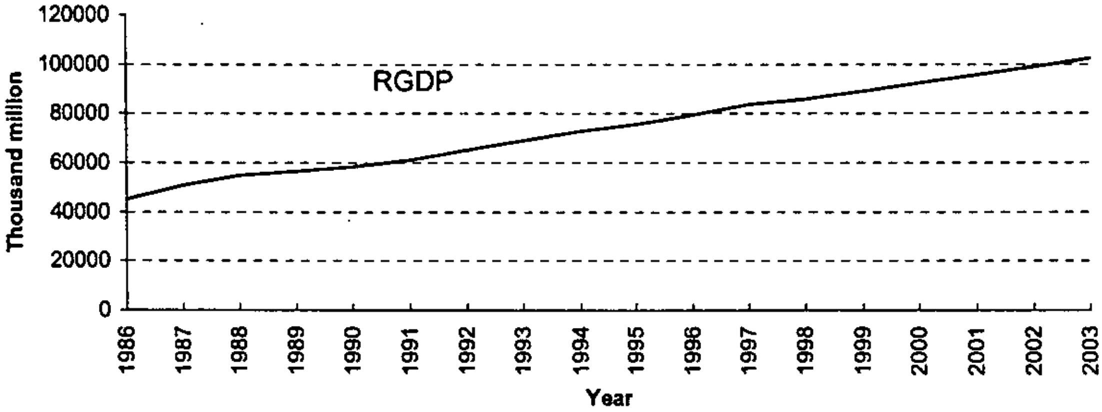



Figure 5.4 Actual and forecast of real gross domestic product in term at constant price from 1986 - 2003

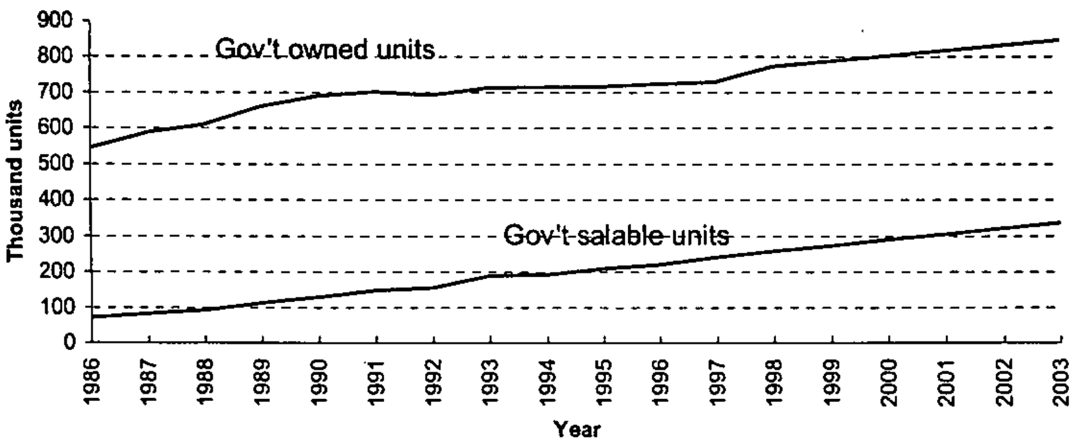



Figure 5.5 Actual and forecast of total units of government owned and salable estates from 1986 - 2003

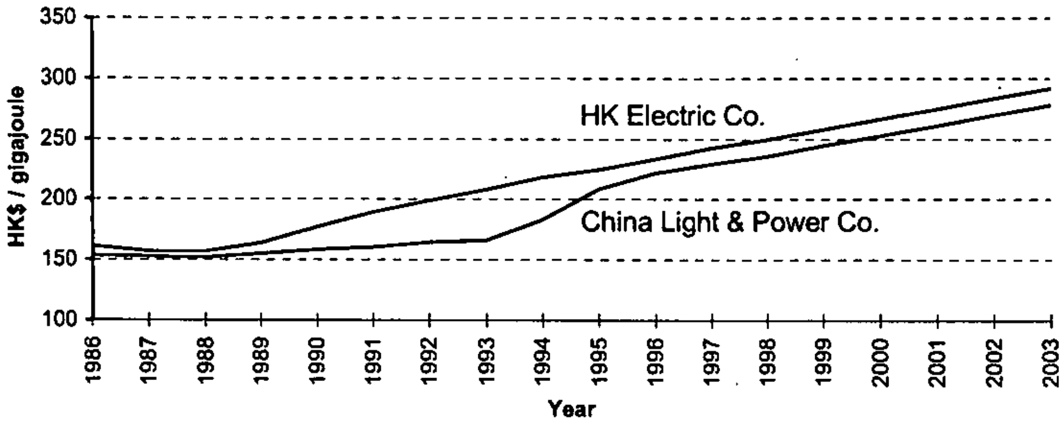



Figure 5.6 Actual and forecast of price of electricity in Hong Kong from 1986 - 2003

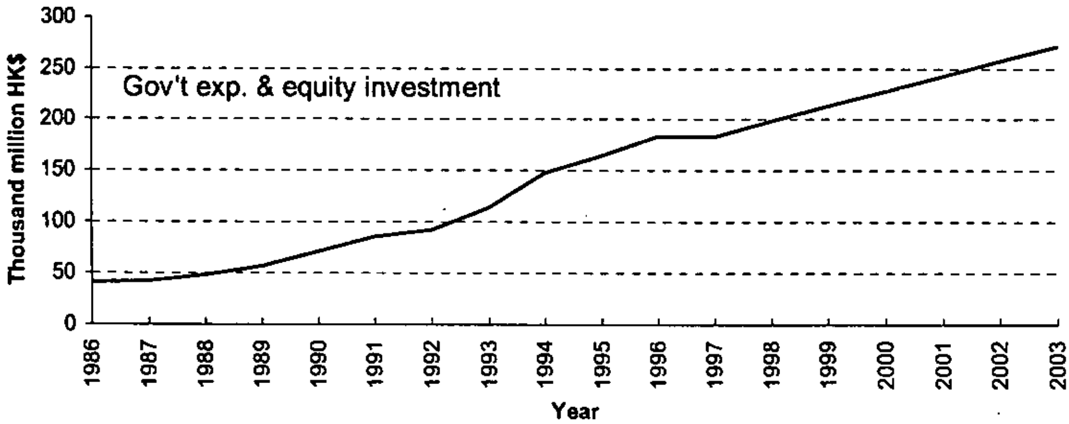



Figure 5.7 Actual and forecast of government expenditure and equity investment from 1986 - 2003

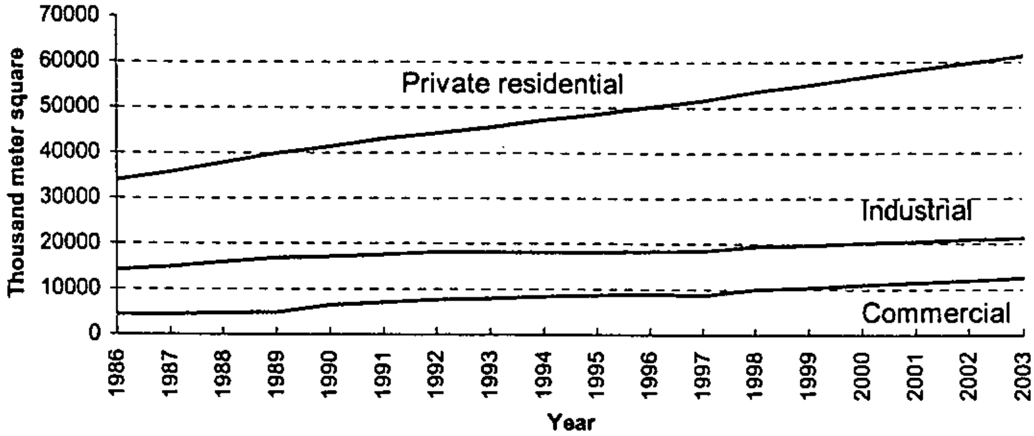



Figure 5.8 Actual and forecast of total floor areas of private resident, industrial and commercial buildings from 1986 - 2003

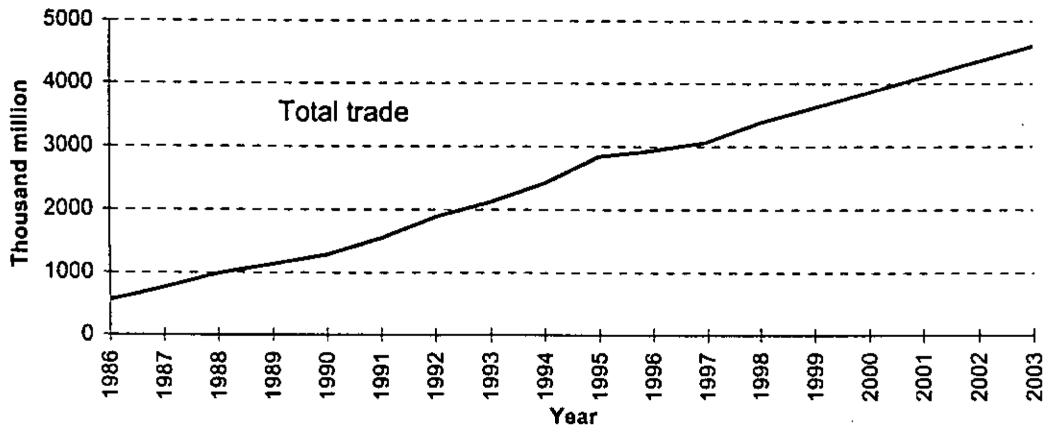



Figure 5.9 Actual and forecast of total amount of trading in Hong Kong dollars from 1986 - 2003

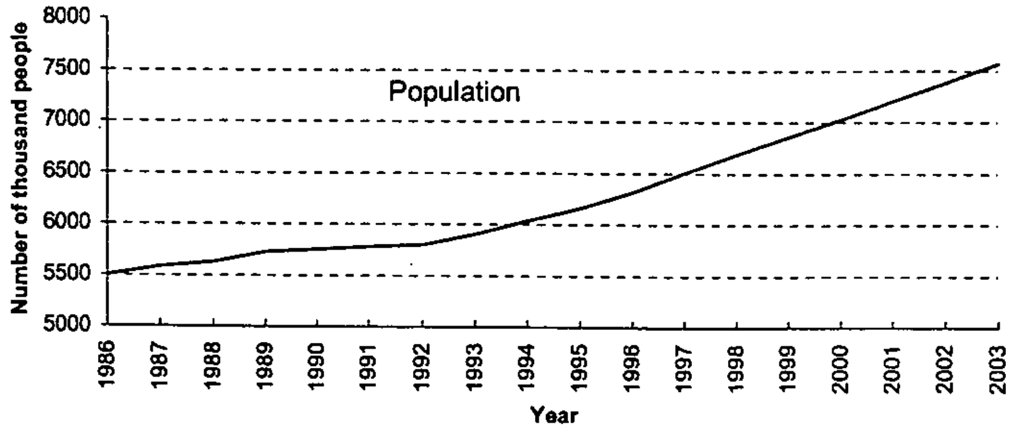



Figure 5.10 Actual and forecast of population growth from 1986 - 2003

## 5.2 Modeling of electricity and total energy demand

To establish the electricity demand trend and predict future energy demand, regression analysis method is applied. The statistic software "SPSS 9.0" is used to assist the regression analysis. Let electricity demand be a regression function as follows:

$$E = f(GE, P, POP, R, TUGO, C, IN, VOT) \quad (5.1)$$

where the descriptions of all variables are explained in chapter 3. Incorporating all graphical information of economic, building and energy consumption provided in this chapter, the regression output yields the following log-linear energy model:

$$\log(E) = -13.32 + \underset{t=(0.96)}{0.006 \log(GE)} + \underset{t=(0.479)}{0.008 \log(P)}$$

$$- \underset{t=(-0.09)}{0.007 \log(POP)} + \underset{t=(4.529)}{0.788 \log(R)} + \underset{t=(1.985)}{0.321 \log(TUGO)}$$

$$+ \underset{t=(0.422)}{0.004 \log(C)} + \underset{t=(1.672)}{0.431 \log(IN)} - \underset{t=(-1.868)}{0.151 \log(VOT)} \quad (5.2)$$

The assumption of hypothesis of the economic variables is expected to have positive impact to electricity demand and the variable itself is in linearity status, so one-sided test is applied and processed. There are 11 degrees of freedom at 5% significance level. $R^2$ is 0.999 of the model (5.2). The appropriate critical t-value with which to test the calculated t-value is a one tailed critical t-value with 11 degrees of freedom. The null hypothesis statement of the range of values for the regression coefficient of R is that to be expected to occur if the assumption of hypothesis is not correct. The alternative hypothesis is used to specify the range of values of the coefficient of R that would be expected to occur. Now, we expect the sign of coefficient of R is positively related to electricity demand. Accordingly, null hypothesis is $H_0$: $\beta$ < or = 0 (the values which do not expect) and alternative hypothesis is $H_a$: $\beta > 0$ (the values which are expected to occur). However, with the exception of the variables R and TUGO, the absolute calculated t-values of all the independent variables in the electricity model are less than the critical t-value of 1.796. We do not reject the null hypothesis $H_0$: $\beta \leq 0$ of those econometric variables whose absolute calculated t-values are less than the critical t-value and imply that the correlation between the dependent and the independent variables is significant. The calculated t-value of R and TUGO are 4.529 and 1.985 respectively, which are larger than critical t-value 1.796 and carries a positive sign, so that R and TUGO should be rejected and removed from the regression model.

To understand the relation between an independent variable and electricity demand in the model (5.2), elasticity provides the responsiveness of energy demand to the change of the variable. For example, the elasticity of commercial building to total electricity demand is 0.004, by 3 decimal places. This means that

1% change on the volume of a commercial building can cause about 0.4% change in electricity consumption in short run. The long run elasticity is calculated as the short run elasticity divided by 1 minus the rest of other short run elasticity except itself. For example, the long run elasticity of volume of commercial building to electricity consumption is 0.004 divided by 1 - [(0.006) + (0.008) + (-0.007) + (0.788) + (0.321) + (0.431) + (-0.151)]. Then, the long run elasticity for commercial building to electricity consumption is -0.00098. This means that 1% change on the volume of commercial building can cause -0.098% change in electricity consumption. The negative sign of elasticity may be caused by the non-stationarity of commercial buildings time series. A more accurate estimation will be discussed in chapter 7. Accordingly, the elasticity of all the independent variables using in model (5.2) related to electricity demand in short run are calculated and summarized in Table 5.2.

Table 5.2 Influence on the electricity demand by change on an independent variable and the related t-value

| **Independent variables in model (5.2)** | **Percentage change in the amount of electricity demand (E) due to 1% change in the corresponding independent variable** | **t-value** |
|---|---|---|
| Government expenditure and equity investment (GE) | 0.006% | 0.96 |
| Average price of electricity (P) | 0.008% | 0.479 |
| Population growth (POP) | 0.007% | -0.09 |
| Real gross domestic product (R) | 0.788% | 4.529 |
| Public owned estate units (TUGO) | 0.321% | 1.985 |
| Commercial building (C) | 0.004% | 0.422 |
| Industrial building (IN) | 0.431% | 1.672 |
| Volume of trade (VOT) | 0.151% | -1.868 |

On the other hand, the influences on total energy demand by economic variables and building sectors can be studied. The effect of commercial and non-commercial buildings on total energy consumption is analyzed with the energy model (5.3) as follows. The original final energy model (Chan and Lee, 1998) has been modified and stated as model (5.4). Let the regression model of total final energy consumption in Hong Kong be a regression function as follows:

$$\text{TED} = f(\text{CPI, FP, POP, R, TUGO, TUSG, C, VONC}) \qquad (5.3)$$

where the descriptions of all variables are explained in Table 5.1 and the regression of log-linear final energy consumption model is developed as follows:

$$\begin{aligned} \log(\text{TED}) = 4.043 &+ \underset{t=(0.554)}{1.17\log(\text{CPI})} - \underset{t=(-2.24)}{0.287\log(\text{FP})} - \underset{t=(-0.939)}{2.879\log(\text{POP})} \\ &- \underset{t=(-0.302)}{0.196\log(\text{R})} - \underset{t=(-0.156)}{0.381\log(\text{TUGO})} - \underset{t=(-0.284)}{0.236\log(\text{TUSG})} \\ &- \underset{t=(-0.510)}{0.231\log(\text{C})} + \underset{t=(0.492)}{1.622\log(\text{VONC})} \end{aligned} \qquad (5.4)$$

The hypothesis of the economic variable in the energy demand model (5.3) is expected to be positively related to final energy demand, so one-sided test is processed. There are 11 degrees of freedom at 5% significance level. $R^2$ is 0.995 of the model. The appropriate critical t-value with which to test the calculated t-value is a one tailed critical t-value with 11 degrees of freedom. The absolute calculated t values of the independent variables are less than the critical value of 1.796 except the variable of fuel price (FP). Hence, we do not reject the null hypothesis of the economic variable's coefficient that is less than zero, i.e., the sign of the coefficient is negative. The calculated t-value of FP is the absolute value of –2.24, which is larger than the critical t-value of 1.796 and the calculated t-value is negative. Therefore, we do not reject the null hypothesis of the coefficient of FP. The elasticity of total energy consumption with respect to the various independent variables are given in Table 5.3:

Table 5.3 Influence on the total energy demand by change on an independent variable and the related t-value

| Independent variables in model (5.4) | Percentage change in the Total Energy Demand (TED) due to 1% change in the corresponding independent variable | t-value |
|---|---|---|
| Consumer price index (CPI) | 1.17% | 0.554 |
| Fuel price (FP) | 2.87% | -2.24 |
| Population growth (POP) | 2.879% | -0.939 |
| Real gross domestic product (R) | 0.196% | -0.302 |
| Government owned units (TUGO) | 0.381% | -0.156 |
| Government salable units (TUSG) | 0.236% | -0.284 |
| Commercial buildings (C) | 0.231% | -0.231 |
| Non-commercial buildings (VONC) | 1.622% | 0.492 |

The demand trend obtained from the final energy demand model expressed in model (5.4) is shown in Figure 5.11. The predicted total energy demand in year 2003 will reach 350,000 terajoule. The forecast trend has reflected the overall economy and business since 1986. There has been a decrease in the total final energy demand since 1994, because of the reduction in oil and coal consumption as well as the transference of industries to other regions. However, in view of the recent downturn of economy, an adjusted trend is produced to reflect the recent changes on electricity generation, vehicle fuel consumption and the downgrade economy situation. In the short term, the total energy demand may drop slightly. However, in a longer period later, the demand is expected to follow the average trend based on the period from 1986 to present. It is interesting to note that though total energy consumption dropped in the period from 1994 to 1997, the electricity consumption kept on increasing.

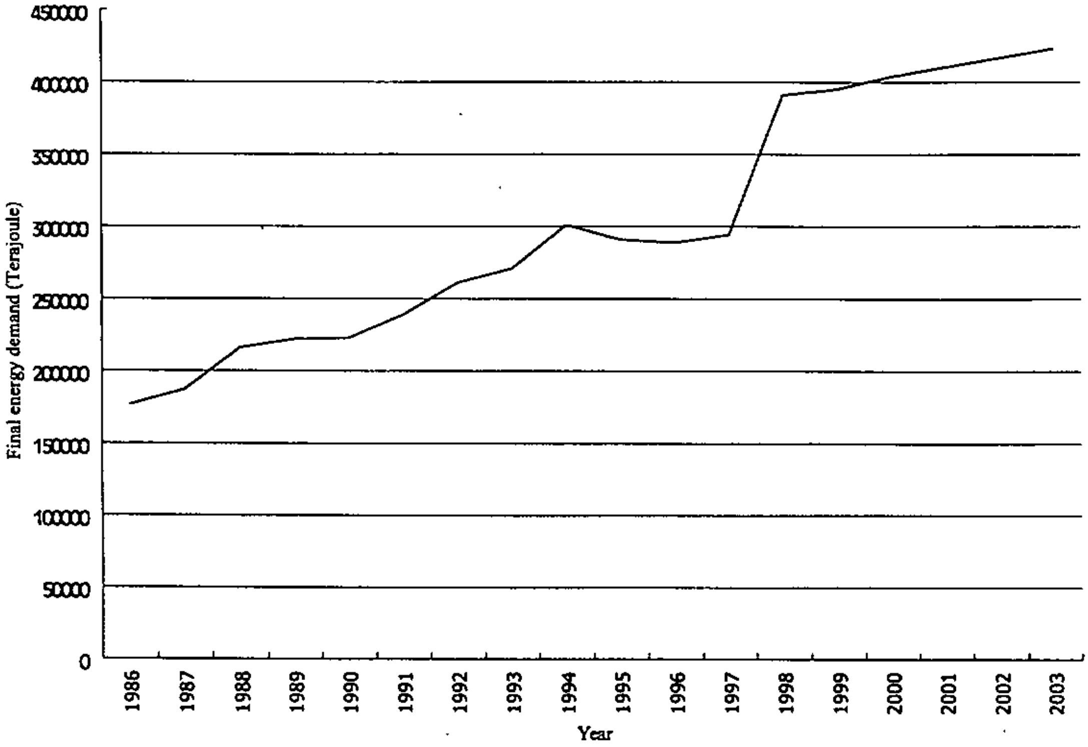



Figure 5.11 Actual and forecast of final energy demand from year 1986 to 2003 (include coal, oil, electricity & gas)

## 5.3 Effect of commercial building envelope designs on future energy demand

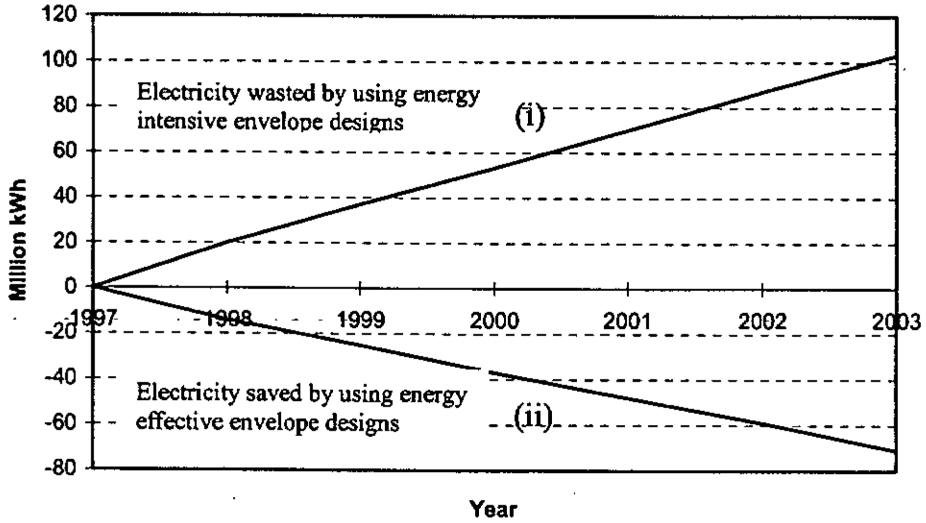
The influence of the design of commercial building envelopes on the future energy demand is investigated in this section. Electricity consumption of local commercial buildings would be changed by varying the building energy parameters of the building. The envelope construction characteristics of commercial buildings in Hong Kong have been investigated and reported in chapter 4. The heat transfer and thermal performance of these envelope constructions were studied using the building energy simulation tool DOE-2.1E. Forty buildings of varying envelope constructions were investigated. Their annual cooling energy consumption were calculated based on identical internal characteristics and cooled with same air conditioning system for 2860 hours in a year to maintain indoor temperature of 24 $^0$C.

Among the 40 buildings, the maximum and minimum electricity consumption was recorded as 231 kWh/m$^2$ floor area (energy intensive envelope design) and 173 kWh/m$^2$ floor area (energy effective envelope design). The average consumption is 196 kWh/m$^2$, which is the overall average electricity consumption per m$^2$ floor area of commercial buildings in Hong Kong, representing the norm of the whole group of existing commercial buildings. Electricity demand by commercial buildings having energy effective envelope or energy intensive envelope is determined by the projected volume of new commercial buildings (expressed in m$^2$ floor area) and the results of building energy simulation (expressed in kWh/m$^2$ floor area). The difference between the maximum electricity consumption and the norm given by the base case is multiplied with the projected floor areas of new commercial building, and then added to the energy demand predicted by the statistical model to give the anticipated energy demand if all new buildings are constructed of energy intensive envelopes. Similarly, the anticipated energy demand if all new buildings are constructed with energy effective envelopes can be calculated. The results are summarized in Table 5.4.

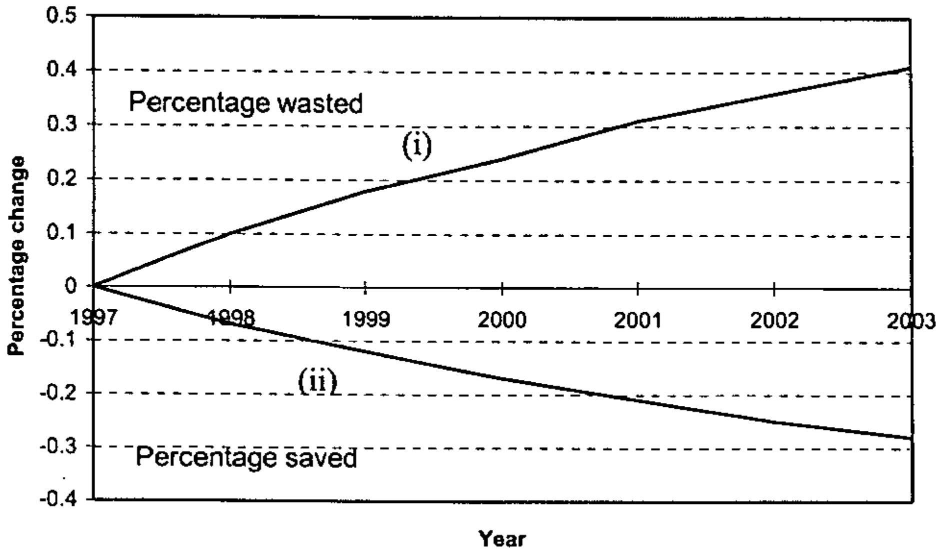
There will be a saving of electricity if the new buildings are constructed with energy effective envelope, and the amount of saving annually will grow with time as the building stock contains an increasing percentage of buildings of energy effective envelope. Conversely, if the new buildings have energy intensive envelope, there will be a growing amount of electricity wastage each year. These are illustrated in Figure 5.12, where part (a) shows the amount of electricity saved or wasted in million kWh and part (b) shows the growth of percentage change with time.

Table 5.4 Predicted electricity demand by the commercial sector

| Year | Average buildings (10⁶ kWh) | New buildings with energy intensive envelope (10⁶ kWh) | New buildings with energy effective envelope (10⁶ kWh) |
|---|---|---|---|
| 1997 | 19,335 | 19,335 | 19,335 |
| 1998 | 19,896 | 19,916 | 19,882 |
| 1999 | 20,906 | 20,943 | 20,881 |
| 2000 | 21,916 | 21,969 | 21,879 |
| 2001 | 22,926 | 22,996 | 22,878 |
| 2002 | 23,936 | 24,023 | 23,877 |
| 2003 | 24,946 | 25,049 | 24,875 |




(a) Amount of difference in million kWh




(b) Percentage change

Figure 5.12 Predicted difference in the total electricity demand for commercial buildings with (i) "Energy Intensive" and (ii) "Energy Effective" envelope designs

Two energy models have been established for the modeling of demand trend and prediction of total energy and electricity consumption in this chapter. The forecasts of total energy and electricity demand have been calculated using prediction models based on various social economic factors. The estimated electricity demand by the commercial sector reaches 90,000 terajoules and the final energy demand reaches 420,000 terajoules in year 2003, taking into account of the recent change in the behavior of final energy production and economy downturn. The predicted energy and electricity demand are affected by the recent unstable economy in Hong Kong and the degree of influence is reflected by the elasticity of each independent variable individually. The amounts of electricity consumption of 40 commercial building envelope designs have been simulated using building energy analysis tool DOE-2.1E. From the results of building simulation, energy effective envelope and energy intensive envelope found in existing commercial buildings and their normalized energy consumption per $m^2$ floor area are identified. For energy effective envelope design, it generates saving of about 70 million kWh of electricity at year 2003, which is equal to 0.3% of total electricity demand by that time. The percentage difference arising from energy intensive and energy effective envelopes can be used to assess the possible energy saving from alternate envelope designs in commercial buildings. This percentage saving is found to be 0.7% in five years from 1997, and it will propagate with time.

## Chapter 6

# Improved Approach of Deriving Energy Regression Equation

### 6.1 Time series approach

Time series model can be characterized as consisting of different explanatory variable with its time trend, a seasonal factor, a cyclical element and an error term. Time series analysis has been developed by researches (e.g. Box and Jenkins, 1970) for several decades. They suggested that the tendency of the variable within regression analysis could be explained or forecasted by the past behavior of the variable itself. The expression of the formula can be classified as an autoregressive model. The Box-Jenkins analysis (Box and Jenkins, 1970) begins by transforming the forecasted variable in stationary time series and an autoregressive model (AR) is one of the presentational forms of time series analysis. In order to explain the energy modeling in time series approach, autoregressive function will be explained in following.

A first order autoregressive function of energy demand ($ed_t$) at year t can be written as follows:

$$ed_t = \beta_0 + \beta_1 ed_{t-1} + \varepsilon \tag{6.1}$$

where $\beta_0$ is a constant term and $\varepsilon$ is an error term

To determine a first order autoregressive model of electricity demand from the period of 1972 to 1998, linear regression analysis is applied and the model is expressed as follows:

$$ed_t = 2044.54 + 1.033 ed_{t-1} + \varepsilon \tag{6.2}$$

The model (6.1) basically means that energy demand of current year is estimated by the energy demand of last year, that is, lag 1 of time series. The AR function is able to break up a time series into the components and generate a logical forecasting behavior of the series. This forecasting technique also attempts to account for changes of energy demand over time by patterns, cycles, or trends, or using information about previous time periods to predict the outcome for a future time period. In the following time series analysis model, yearly data trends have been employed but the seasonal variations are not included in this analysis model. However, there are some basic characteristics to stationary and non-stationary time series, or called integrated series. For tendency of non-stationary economics time series data, unit root test procedure is needed to be applied to make the time series become stationary before developing the forecast model. In order to understand the time series forecasting approach, the general electricity demand function, model (3.2), mentioned in Chapter 3 is modified into a basic time series model as shown in model (6.3).

$$\sum_{i=0}^{t} (\log E_t) = \beta_0 + \beta_1 \sum_{i=0}^{t} (\log C_t) + \beta_2 \sum_{i=0}^{t} (\log D_t) + \beta_3 \sum_{i=0}^{t} (\log IN_t) + \beta_4 \sum_{i=0}^{t} (\log P_t) + \beta_5 \sum_{i=0}^{t} (\log R_t) + \varepsilon_t \quad (6.3)$$

where $\beta_0$ = constant

$\beta_1$ = estimated parameter of coefficient to C

$\beta_2$ = estimated parameter of coefficient to D

$\beta_3$ = estimated parameter of coefficient to IN

$\beta_4$ = estimated parameter of coefficient to P

$\beta_5$ = estimated parameter of coefficient to R

$\varepsilon_t$ = error term of the model

subscript t = year of time

In the applied literature, the basic time series model is usually estimated in linear double log form by least squares and lags of variables are often included as regressors in order to capture the dynamic aspects of energy demand. However, problems such as multicollinearity and non-stationarity arise when estimating long-run relationships in statistical study. To deal with these problems, testing for unit roots is processed before developing the forecast model. Detail of unit root test for the stationary of economic variables in our energy model will be discussed in chapter 7.

## 6.2 Cointegrating relation in long run equilibrium

The problem with economic time series mentioned in the thesis is that those independent variables in the energy model can appear to be spurious error if they have the same underlying trend as the dependent variable such as energy demand. The problem of a superficially strong relationship between two or more economics time series, that may be caused by a statistical fake or spurious correlation, is a nature of the specification of the variable. If the energy regression model is run with the economics time series which are spuriously correlated, the t-scores and overall fit of such spurious regressions are likely to be overstated and untrustworthy. Therefore, a reason of spurious correlation on time series data is caused by non-stationary time series. According to the general error correction model described in model (3.6) of chapter 3, the error term in the right hand side is represented as an error correcting term to indicate the appearance of the long run equilibrium. Hence, the manipulation of general error correcting function is called error correction model in econometric study. The study of this model is important to this research study because of time series effect appearing in the explanatory variables of the energy forecast model and the non-stationary time series data can be tested by the unit roots test procedure.

Use of the unit root test would not be completed without mention of power of the testing. Unlike many hypothesis tests situations, the power of the testing of the unit root hypothesis against stationary alternatives depends very much on the number of observations by span of data. For a given number of observations, the power is largest when the span is longest. Conversely, for a given span, additional observations obtained using data sampled more frequently lead only to a marginal increase in power, the increase becoming negligible as the sampling interval is decreased. Hence a data set containing fewer annual observations over a long time period will lead to unit root tests having higher power than those computed from a data set containing more observations over a short period of time. The span of economic data used in the energy model is recorded and observed once a year since 1972. This is of some importance when analyzing economics time series, which very often have a large number of observations obtained by sampling at very fine intervals over a fairly short time span. However, according to DeJong et al (1992a, 1992b) the unit root null may be very difficult to reject even if the null hypothesis is false, especially when the alternative hypothesis is a root that is close to but less than unity. However, that is not the case in our energy model.

**Form of cointegration model**

To develop an energy model with cointegrating economics variables, anger (1983) and Engle and Granger (1987) defined the concept of integrating approach. Time series is said to be integrated of order *d*, or *I(d)* if it quires to be differenced d times to yield a stationary, invertible, non-:terministic ARMA representation. Suppose we have a vector $\chi_t$, which contains variables, all of which are *I(d)*. The components of the vector $\chi_t$ , denoted as $Z_t$ , re given by

$$Z_t = \alpha' \chi_t \qquad (6.4)$$

$Z_t$ is a cointegrated vector of order d – b, i.e. *I(d-b)*, where b is a number satisfying ) < b ≤ d, if α ≠0.

Engle and Granger (1987) suggested that if the vector $\chi_t$ contained two variables, $y_t$ and $w_t$, which would be cointegrated when $d = b = 1$. That is, the models for two variables may be given an error correction mechanism representation, as follows:

$$\Delta y_t = A(L)\Delta y_{t-1} + B(L)\Delta w_{t-1} - \gamma_1 Z_{t-1} + \varepsilon_{1t} \qquad (6.5)$$

$$\Delta w_t = C(L)\Delta y_{t-1} + D(L)\Delta w_{t-1} - \gamma_2 Z_{t-1} + \varepsilon_{2t} \qquad (6.6)$$

where $Z_t = y_t - \beta w_t$ and *A(L), B(L), C(L) and D(L)* are finite order lag polynomials. In modern econometric analysis, the functional purpose of cointegration between a set of economics variables in the energy model provides a statistical foundation for the use of error correction model. Error correction model provides the explanation of long-run relationship between the economics variables $(y_t = \beta w_t)$ from the short-run responses of the $\Delta y_t$ and $\Delta w_t$ terms. In that case, all variables in model (6.5) and model (6.6) are stationary. Ordinary least square regression is not functional to test the hypothesis by conventional 't-test' and 'F-test' because the OLS parameters cannot be distributed equally when the economics variables are $I(1)$. That is, the time series set of variables should difference once for cointegrating approach to be processed. In conclusion, in order for the economics variables to be related in the long-run, the test of cointegration must be take place. If we test for cointegration between a vector of economics time series data, we can test for the presence of a long-run equilibrium relationship between the variables data series.

### 6.4 Unit root test

As a prerequisite for testing cointegration, the economics time series of the energy model should share common integration properties and should be integrated of the same order. To test the degree of integration of univariate time series, Dickey-Fuller (DF) tests (Dickey and Fuller, 1979 and 1981) are employed in this energy model. Dickey-Fuller tests attempt to account for temporally dependent and heterogeneously distributed errors by including lagged sequences of innovations in its set of regressors. The test is based on the null hypothesis that a unit root exists in the autoregressive time series model. The basic Dickey-Fuller (DF) statistic to test for the order of integration of the time series is based on the standard regression model:

$$\chi_t = \mu + \alpha\chi_{t-1} + U_t \tag{6.7}$$

To test the regression, it is easier to reparameterise equation (6.7) to become (6.8) as follows:

$$\Delta\chi_t = \mu + (\alpha - 1)\chi_{t-1} + U_t \tag{6.8}$$

The t-statistics on $(\alpha - 1)$is used to test the null hypothesis that this coefficient is equal to zero. If $\alpha = 1$, there is a unit root in the process for $\chi_t$. However, the critical values of t-test and F-test from the standard statistical tables are not suitable to DF test. Those critical values by Dickey and Fuller have been tabulated by Fuller (1976) and Dickey and Fuller (1981). The test applies to differences of the time series in order to find the value of the order of integration. For the reason of 'serial correlation' to modern economics time series data, the modification of simple DF test has been developed as follows:

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \sum_{j-1}^{p} \gamma_j \Delta Y_{t-j} + \varepsilon_t \tag{6.9}$$

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \alpha_2 t + \sum_{j-1}^{p} \gamma_j \Delta Y_{t-j} + \varepsilon_t \tag{6.10}$$

where $\varepsilon_t$ for t = 1, …, N is assumed to be Gaussian white noise. Equation (6.9) is with- constant, no-trend and (6.10) is with-constant, with-trend. The number of lagged term p is chosen to ensure the errors are uncorrelated. The application of the Dickey Fuller test to identify the unit root of economic variables in the energy model will be calculated in chapter 7.

## 6.5 Multivariate maximum likelihood approach to cointegration and error correction modeling

After establishing the unit root of the economic variables being studied, a stationary time series data set is identified in order to carry on cointegration analysis. The multivariate maximum likelihood approach to cointegration is developed by Soren Johansen and Katarina Juselius (1988, 1990) and has been widely studied in recent years. This approach indicates that all variables are treated as endogenous and can be expressed as a linear function of lagged values of the variable itself and the rest of other variables within the model. The set of energy functions can be expressed in the form of single vector autoregressive equation (VAR) mathematically. The approach is based on a k-lag vector autoregressive (VAR) model and written as follows:

$$\chi_t = \delta + \Pi_1 \chi_{t-1} + \ldots + \Pi_k \chi_{t-k} + e_t \tag{6.11}$$

where $\chi_t$ is a (p × 1) vector of non-stationary I(1) variables, $\delta$ is a (p × 1) vector of constant terms, $\Pi_{1,\ldots,}\Pi_k$ are ( p × p)coefficient matrices and $e_t$ is ( p × 1) vector of Gaussian error terms, i.e., minimum variance for the least square estimator. Model (6.11) can be reparameterized into an error correction form as follows:

$$\Delta\chi_t = \delta + \Gamma_1 \Delta\chi_{t-1} + \ldots + \Gamma_{k-1}\Delta\chi_{t-k+1} + \Pi\chi_{t-k} + e_t \tag{6.12}$$

where $\Gamma_i = -I + \Pi_1 + \ldots + \Pi_i (\forall i = 1,\ldots,k-1)$,

and $\Pi = -I + \Pi_1 + \ldots + \Pi_k$.

Conintegration among the variables in $\chi_t$ then implies reduced rank, $r$, of the matrix $\Pi$, which can be partitioned as $\Pi = \alpha\beta'$ where $\beta'$ is the transpose of $\beta$ which is the (p × r) matrix of long-run relational cointegration vectors and $\alpha$ is the ( p × r ) matrix of error correction parameters. The number of cointegrating vectors is equal to the rank of the matrix of coefficients associated with the levels vectors in the vector error correction model. The maximum likelihood estimator of space spanned by $\beta$ is the space spanned by the r canonical variates corresponding to the r largest squared canonical correlations between the residuals of $X_{t-k}$ and $\Delta X_t$ corrected for the effect of the lagged differences of the $X$ process. The likelihood ratio test statistic for the hypothesis that there are at most r cointegration vectors is as follows:

$$-2\log(Q) = -T\sum_{i=r+1}^{p}\log\left(1-\hat{\lambda}_i\right) \quad (6.13)$$

where $\hat{\lambda}_{r+1},\ldots,\hat{\lambda}_p$ are the p − r smallest squared canonical correlations and the residual sum of squares is $Q = \sum(y_i - \alpha - \beta x_i)^2$. Assume the basic regression model is written as $y_i = \alpha + \beta x_i + \varepsilon_i$ and $\varepsilon_i$ is IN $(0, \delta^2)$. The rank of the vector matrix is being tested before starting Johansen method. The procedure is based on the VAR system which can incorporate short and long run dynamic behavior of multiple time series. Canonical correlations concept is applied and a linear combination of multiple time series is found in the energy forecast system, therefore, the correlation between explanatory variables and energy demand is maximized. Then, cointegration can be established by the hypothesis of reduced rank of a regression coefficient matrix from designed energy demand vector autoregressive systems. Johansen likelihood ratio test is received from the computation of eigenvalues of model 6.15. The essence of cointegration is that the cointegrated variables identified in maximum likelihood ratio test of Johansen share a common trend which is removed when producing the cointegration regression residuals. The Johansen likelihood ratio test procedure can be expressed by a simple version of the single vector equation case.

$$Z_t = AZ_{t-1} + \varepsilon_t \quad (6.14)$$

Variable $Z$ in model (6.14) is in terms of a N × 1 vector and parameter $A$ is a N × N matrix of coefficients. In order to apply unit roots test for stationary, $Z_{t-1}$ is subtracted from each side of model (6.14) to become

$$\Delta Z_t = (A - I)Z_{t-1} + \varepsilon_t \quad (6.15)$$

where $I$ is lag term of $Z_{t-1}$. Dickey Fuller test (DF) mentioned in Section 6.4 can be used to find the existence of unit root. Alternatively, Augment Dickey Fuller test (ADF) can be used when there are more than one lagged variables in the regression model. The Dickey Fuller test procedure is designed to regress a differenced element of $Z$ on all its levels elements by row of $A-I$. Hence, testing for the rank of $A-I$ can be interpreted as testing for the number of cointegrating vectors. That is, the number of rows of $A-I$ that do not create zero when multiplied down a vector is equal to the rank of $A-I$, and it is equal to the number of nonzero characteristic roots, eigenvalues, of model (6.15). Johansen's $\lambda_{trace}$ and $\lambda_{\max}$ test statistics (Johansen and Juselius 1988, 1990) for the number of cointegrating vectors are based on estimates of the eigenvalues. By normalizing $A-I$ to put a coefficient of unity on $Z_{t-1}$, then $A-I$ can be rewritten as

$$\Delta Z_t = \sigma\beta Z_{t-1} + \varepsilon_t \qquad (6.16)$$

where $\beta$ is a matrix of normalized cointegrating row vectors and $\sigma$ is a matrix containing the speed-of-adjustment parameters associated with the error correction terms corresponding to each of the cointegrating vectors. Further, an error correction modeling can be interpreted with the speed-of-adjustment parameters to develop the error correction model (ECM).

The error correction model (ECM) developed by Engle and Granger is a means of reconciling the short-run behavior of an economic variable with its long-run behavior. If the cointegrating relationship is identified in Johansen maximum likelihood test, we can use the lagged residuals from the cointegrating regression as an error correction term in an error correction model. The contegrating combination of the explanatory variables is interpreted as an equilibrium relationship and it can be shown that variables in the error correction term in an error correction model must be cointegrated. The adjustment of error correction model provides a more accurate forecast of energy demand in the model. Detailed calculations of Johansen tests and result of the error correction model design are given in chapter 7. The methodology is summarized as follows:

1. To determine the order of integration of the explanatory economic variables by unit root tests.
2. To run the cointegrating regression analysis.
3. It there are more than two explanatory variables in the model, more than one cointegrating relationship could exist, and an alternative estimation procedure such as maximum likelihood ratio test is applied.
4. To implement Johansen maximum likelihood ratio test to test for the existence of cointegration.
5. It cointegration exists in the energy vector autoregressive system, use the lagged residuals from the cointegrating regression as an error correction term in an error correction model.

Accordingly, the long run equilibrium adjustment of energy forecast of our energy regression model from chapter 5 can be developed. The details of the studies are established in chapter 7.

## Chapter 7

# Result of Using Cointegration and Error Correction Model

### 7.1 Order of integration

To understand order of integration of the explanatory variables in the energy model, autocorrelation function is required to study before starting on calculating order of integration. Generally, a function of a normal model is written as

$$X_t = \beta_1 Y_t + \varepsilon \quad (7.1)$$

If both $X_t$ and $Y_t$ are integrated of order 1, there is, *I(1)* or non-stationary. Then, a linear combination of $X_t$ and $Y_t$ would also be *I(1)*, or non-stationary would be expected. The reason is that the two series ($X_t$ and $Y_t$) may have the property that a particular combination such as $Z_t = X_t - bY_t$ is integrated of order zero and the short expression can be written as *I(0)* and the meaning is stationary (Engle and Granger 1987). If the above property holds true, then $X_t$ and $Y_t$ are cointegrated. The concept is that if the time series $X_t$ and $Y_t$ are non-stationary and the linear combination of the two series is stationary, then the standard Granger causal inferences will be invalid and the development of error-correction model would be necessary for the purpose of long-run forecast. In econometric point of view, the Engle-Granger two-stage procedure is commonly used in time series estimation model but it does not account for the possibility of multiple cointegrating relationships (M.M. Masih and Rumi Masih 1996). However, the energy model in the paper is considered as having cointegrated relationship and the application of multivariate analysis is needed. Although asymptotic properties of the Engle Granger causality test have been tested in recent applied literature, Johansen approach has been used extensively in many multivariate systems to avoid the inference bias (Masih and Masih 1994a, 1994b and 1995b). Johansen approach indicates more robust findings comparing to the residual based single equation of Engle Granger ordinal least square approach. As it is possible that more dynamic interactions could exist between two or more time series data, the assumption of the Johansen approach is useful to apply in the analysis of the electricity demand model.

Being a densely populated city with prosperous commercial business, Hong Kong consumes a large amount of electricity that constitutes a large portion of the total final energy requirements. The rate of growth of commercial and residential buildings, the increasing living standard and the use of electrical appliances, particularly for air conditioning, induce further increase in the long-run electricity demand. To fulfill the estimation of electricity demand of commercial buildings in long run, the general multiple regression model of electricity demand has been revised. A reduce multiple regression model with less independent variables but longer building and economic historical data has been developed. The data are yearly, and after the creation of lags, the estimation period runs from 1972 to 2025, with the observations from 1972 to 1998. The period from 1999 to 2025 is taken to be the forecast period in this research study. In the electricity demand model, stationarity of the economic variables have to be identified in order to continue carrying on cointegration analysis. To test a non-stationary time series, which has implications for economics theory and modeling, unit root test is applied to the study. Test statistics of unit root test are based on the ordinary least square estimated results from a suitably specified regression equation (Fuller, Wayne A. 1976). A general form of autoregressive function is written as follow:

$$Y_t = \rho Y_{t-1} + \mu_t \tag{7.2}$$

where it is assumed that the function has a zero mean, constant variance and not autocorrelation. It $\rho = 1$, then $Y_t$ is said to have a unit root and considered to a non-stationary time series. If an autoregressive function contains more than one time lag, the function of testing stationary is called "augmented Dickey Fuller model". A general form of the time series "augmented Dickey-Fuller" regression equation, $Y_t$, without time drift (trend) is as follows:

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \sum_{j-1}^{p} \gamma_j \Delta Y_{t-j} + \varepsilon_t \tag{7.3}$$

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \alpha_2 t + \sum_{j-1}^{p} \gamma_j \Delta Y_{t-j} + \varepsilon_t \tag{7.4}$$

where $\varepsilon_t$ for t = 1, ..., N is assumed to be Gaussian white noise. Equation (7.3) is with-constant, no-trend and equation (7.4) is with-constant, with-trend. The number of lagged terms p is chosen to ensure the errors is uncorrelated. The augmented Dickey Fuller test is identified and used to calculate the stationarity of different independent variables in our electricity model. If the residuals of the explanatory variables are found to be stationary, it means that the variables are cointegrated, and implies the long-run stationarity in their relationships. To work with economic time series, difference method is able to test for nonstationarity before proceeding with estimation. The term integrated can be explained to this concept. A variable is said to be integrated of order *d,* written *I(d)*, if it must be differneced *d* times to be made stationary. For example, a stationary variable is integrated of zero, written *I(0)*, and a variable which must be differenced once to become stationary is said to be *I(1)*, integrated of order one. In general, an integrated time series of order 1 or greater is a non-stationary time series. In recent applied literature of Ashok V Desai 1990, electricity demand model has been emphasized on the explanation of the relation between incomes to electricity consumption. However, my regression analysis of electricity and energy demand models developed in previous chapters has been reconstructed and reported in this chapter for detail study. The time series model in this chapter has more explanation on electricity demand in relation to increase in the commercial building stock and national income of Hong Kong.

The time series are categorised in term of commercial buildings, domestic buildings stock, industrial buildings stock, real gross domestic product and electricity price. The general electricity demand function can be expressed as:

$$E_t = F[C_t, D_t, IN_t, R_t, P_t] \qquad (7.5)$$

where E = electricity demand in terajoule

C = commercial buildings stock in $m^2$ floor area

D = domestic buildings stock in $m^2$ floor area

IN = industrial buildings stock in $m^2$ floor area

R = real gross domestic product in dollars

P = electricity price in dollar per megajoule

In general, the function is estimated by the least squares method with linear double log form and lags of the variables are included as regressors to capture the dynamic aspects of electricity demand. The assumption underpinning this approach is that the variables are stationary with processes of constant unconditional means and variances. To develop a time series regression analysis, the consideration of stationarity of regressors is important. Dickey Fuller (1979) suggested the use of unit root tests for stationarity analysis by examining the hypothesis that the modelled equation has a unit root. Forms of the Augmented Dickey Fuller (ADF) test are used when lagged difference terms are included so that the error term is serially independent. The results of unit root tests of stationarity without drift are shown in Table 7.1. The non-stationary time series parameters are transformed by differences to achieve stationary status to fulfill cointegrating condition, and the required levels of differences to become stationary at 5 % significance are shown in Table 7.2. The time series of the reorganized economic factors are presented in Figure 7.1 to 7.5.

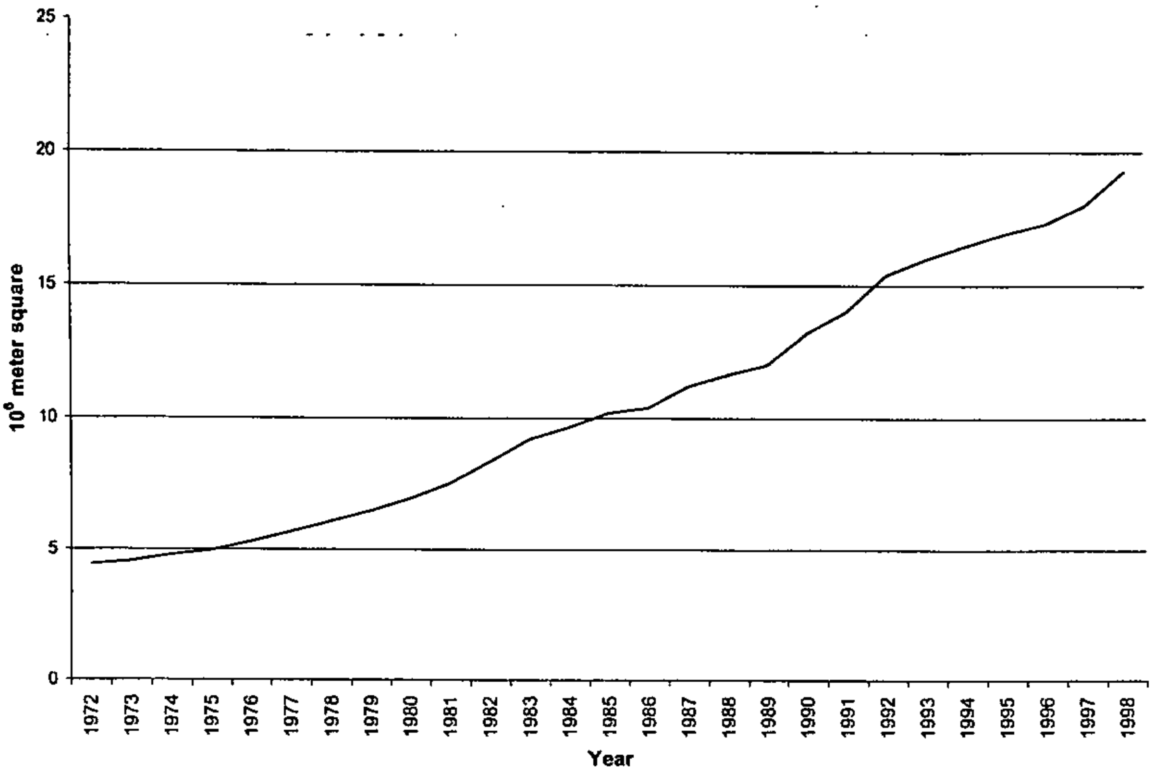



Figure 7.1 Time series of commercial buildings stock from 1972-1998

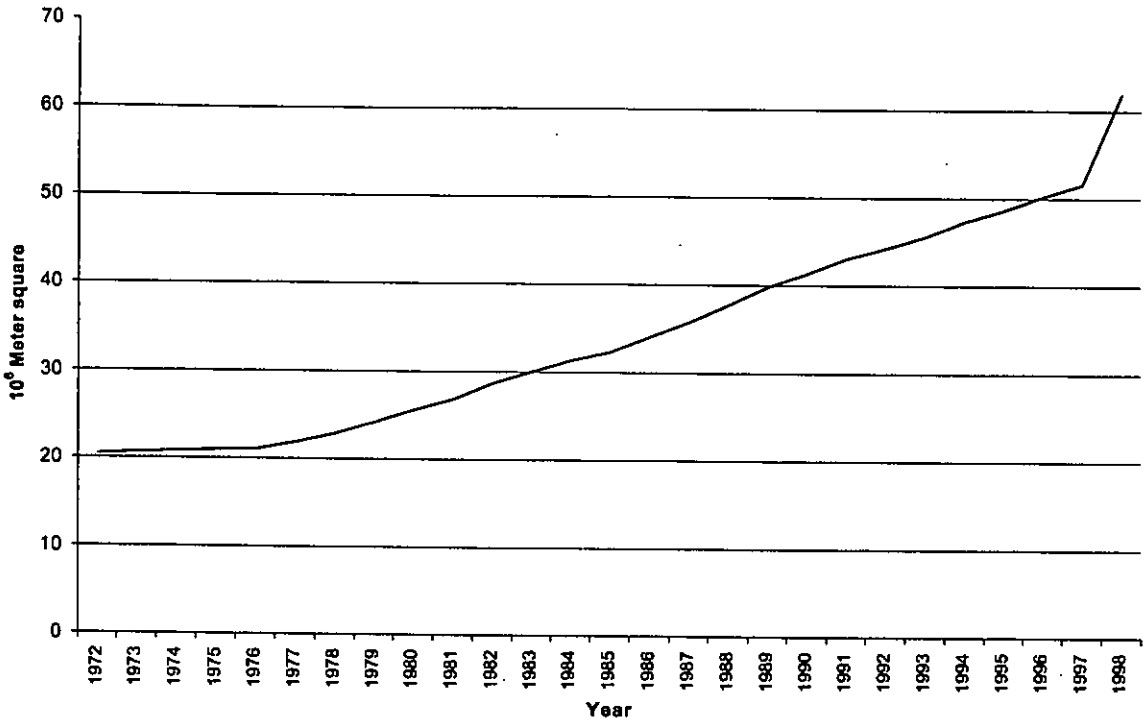



Figure 7.2 Time series of domestic buildings stock from 1972-1998

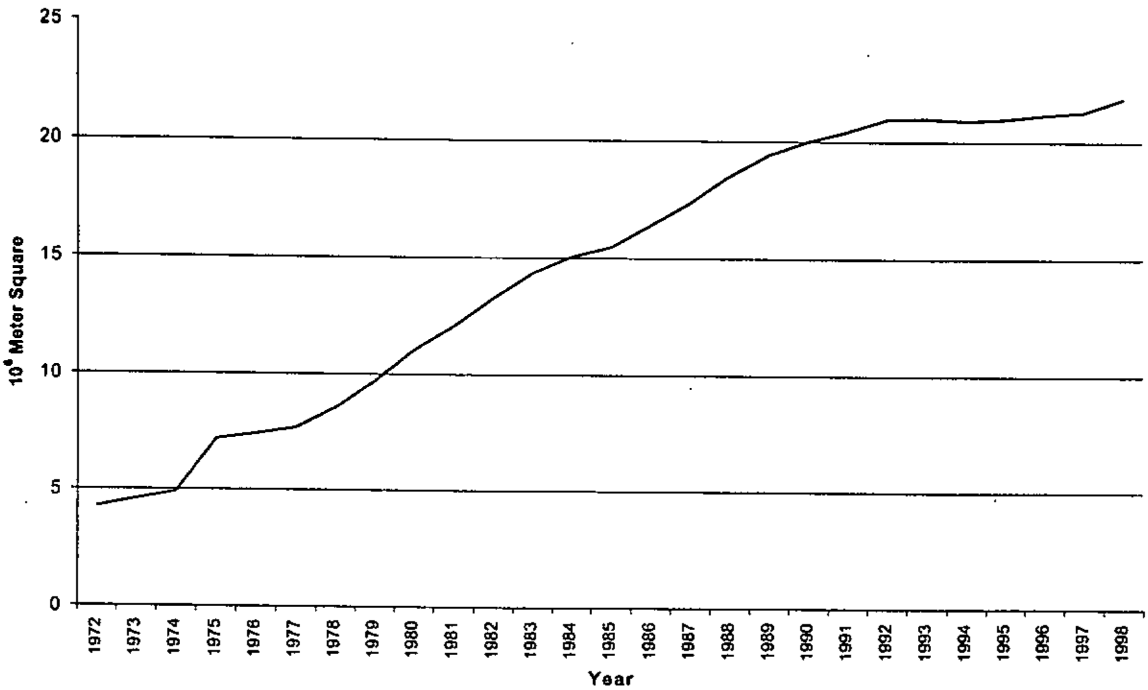



Figure 7.3 Time series of industrial buildings stock from 1972-1998

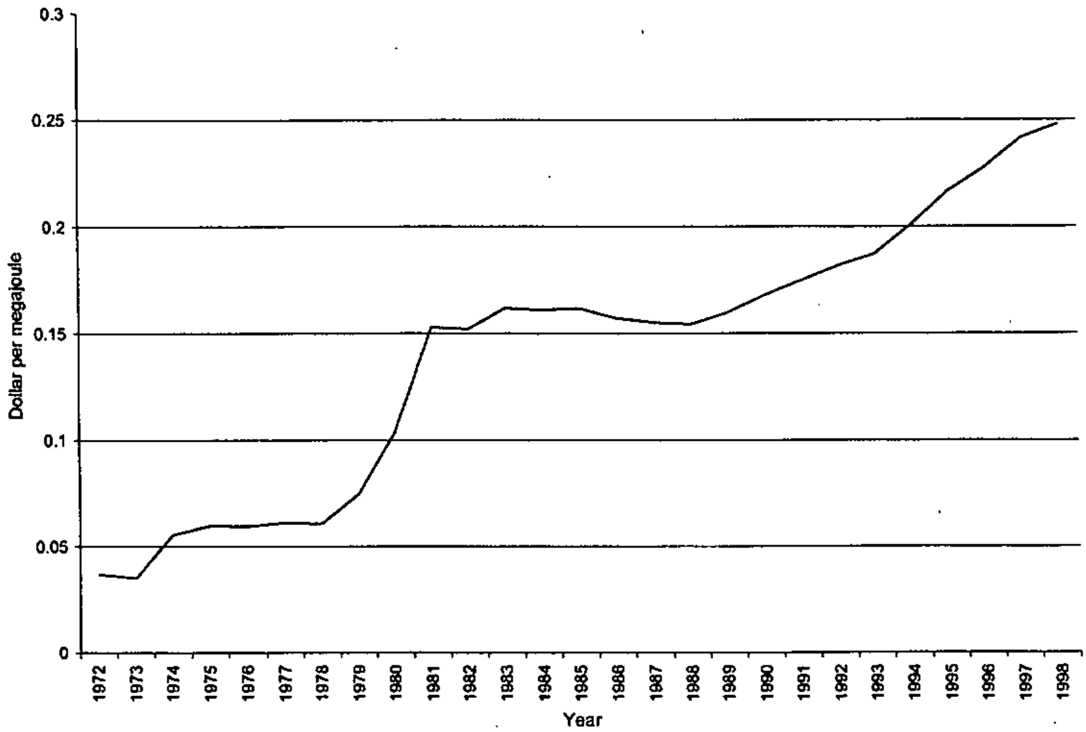



Figure 7.4 Time series of average price of electricity companies from 1972 - 1998

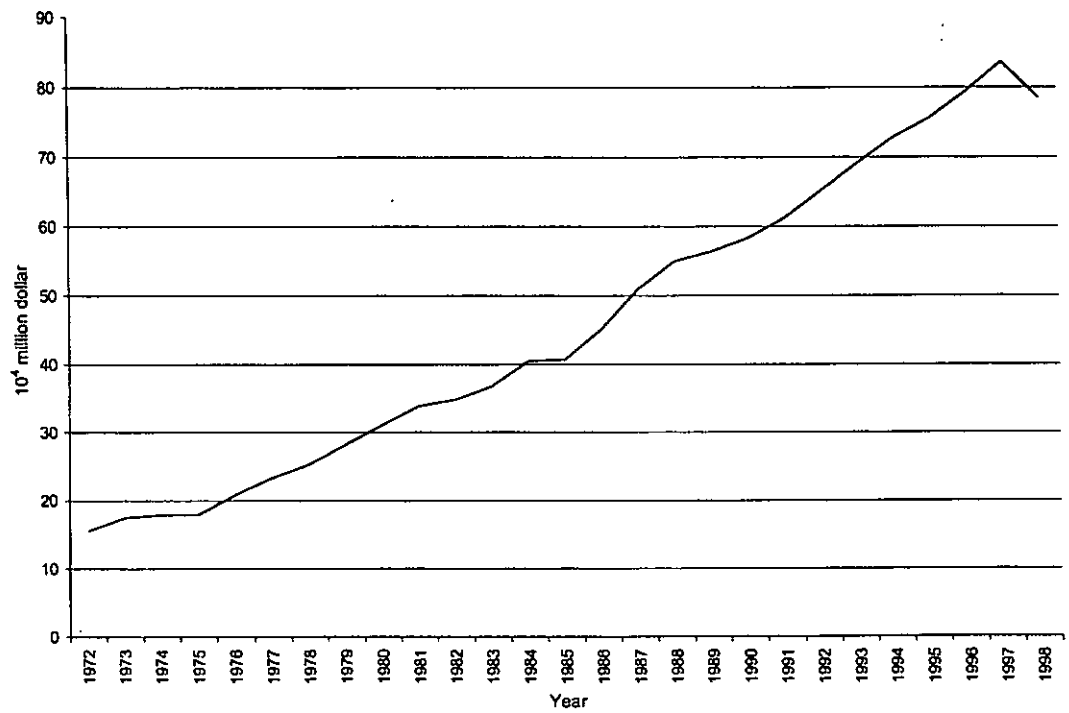



Figure 7.5 Time series of real gross domestic product from 1972-1998

Table7.1 Unit root tests of stationarity without drift ( Null hypothesis: $\alpha_1 = 0$)

| | | Commercial buildings | Domestic buildings | Industrial buildings | Electricity price | Real GDP | t critical value |
|---|---|---|---|---|---|---|---|
| Zero difference | Lags no. | 0 | 0 | 0 | 0 | 0 | |
| | 1 % significance | - 0.91 | 1.74 | - 3.68 | - 2.01 | - 2.41 | -3.43 |
| | 5 % significance | - 0.91 | 1.74 | - 3.68 | - 2.01 | - 2.41 | - 2.86 |
| | 10 % significance | - 0.91 | 1.74 | - 3.68 | - 2.01 | - 2.41 | - 2.57 |
| 1st difference | Lags no. | 4 | 0 | nil | 0 | 2 | |
| | 1 % significance | -1.80 | -1.29 | nil | -3.92 | -1.295 | -3.43 |
| | 5 % significance | -1.80 | -1.29 | nil | -3.92 | -1.295 | -2.86 |
| | 10 % significance | -1.80 | -1.29 | nil | -3.92 | -1.295 | - 2.57 |
| 2nd difference | Lags no. | 1 | 0 | nil | nil | 2 | |
| | 1 % significance | -3.61 | -2.51 | nil | nil | -3.59 | -3.43 |
| | 5 % significance | -3.61 | -2.51 | nil | nil | -3.59 | -2.86 |
| | 10 % significance | -3.61 | -2.51 | nil | nil | -3.59 | -2.57 |
| 4rth difference | Lags no. | nil | 1 | nil | nil | nil | |
| | 1 % significance | nil | -3.29 | nil | nil | nil | -3.43 |
| | 5 % significance | nil | -3.29 | nil | nil | nil | -2.86 |
| | 10 % significance | nil | -3.29 | nil | nil | nil | -2.57 |
| 5th difference | Lags no. | nil | 1 | nil | nil | nil | |
| | 1 % significance | nil | -6.18 | nil | nil | nil | -3.43 |
| | 5 % significance | nil | nil | nil | nil | nil | -2.86 |
| | 10 % significance | nil | nil | nil | nil | nil | -2.57 |

The Dickey Fuller test of existence of a unit root is calculated by Shazam 8.0. The time series independent variables, measured in natural logarithms, are tested via ADF with various differences filter and lag numbers to satisfy stationarity. In the ADF test of significance, the null hypothesis is $\alpha_1 = 0$ and the alternative hypothesis is $\alpha_1 < 0$. If the estimated value of $\alpha_1$ is significantly less than 0, the null hypothesis of non-stationarity will be rejected. In this study the tests are performed up to the fourth differences when all the parameters become stationary at 5% significance, and are summarised in Table 7.1. In each test the unit root hypothesis can be rejected if the t-test statistic is smaller than the critical value. For example, the ADF test statistic of commercial buildings stock at first difference shown in Table 7.1 is –1.80, which exceeds the critical value of –2.86 at 5% significance. This indicates that the time series of commercial buildings stock is not long-run stationary. The calculated second difference ADF test statistic is -3.81 at 5% significance with lag 1 for the variable of commercial buildings stock, which is smaller than the critical value of –2.86, and the null hypothesis of non-stationarity can be rejected. We conclude that the time series of commercial buildings stock is stationary after taking the second differences. The order of integration (level of differences) of the independent variable to approach stationarity status is indicated in Table 7.2.

Table 7.2 Level of differences for stationarity

| Level of Difference | Independent Variables |
|---|---|
| Difference (0) | Industrial buildings stock (IN) |
| Difference (1) | Electricity price (P) |
| Difference (2) | Commercial buildings stock (C)<br>Real gross domestic product (R) |
| Difference (4) | Domestic buildings stock (D) |

From the ADF tests, the industrial buildings stock (IN) time series is found to be stationary, whereas the regressor electricity price (P) is non-stationary but becomes stationary at first difference without lag. At the second difference ADF tests, the test statistics of the commercial buildings stock time series (C) with lag one and the real gross domestic product time series (R) with lag two are significant for the null hypothesis, and it means that they are stationary after second difference. The time series of the domestic buildings stock is stationary at 5% level of significance after taking the fourth difference with lag one, but at 1% level of significance the original series has to be differenced five times to become stationary. When the order of integration is calculated by Dickey Fuller test, cointegration analysis can be taken place. Error correction model of long term electricity demand can be developed with implementation of likelihood ratio test (Johansen and Juselius 1990). Detail of the study is given in next section.

## 7.2 The Cointegration Analysis

Cointegration is a relationship that may hold between the integrated time series variables in the forecasting model, and implies that some of the time series have common unit root components that cancel when the appropriate linear combinations. Thus, cointegration implies restrictions on systems of equations. Granger representation theorem in Engle and Granger (1987), Engle and Yoo (1991) provide extensions and simplified proofs using Smith-McMillan–Yoo forms. Johansen (1988b) used mathematical formulas to identify the relationship. To understand the theory of forecasting in cointegrated systems, vector autoregressive representation (VAR) is applied in our energy model. Maximum likelihood ratio test (Johansen and Juselius 1990) is applied in the study to determine the long-run relationships that exist between the dependent variable of electricity demand and the regressors. Restriction of time drift to the long-run solution of the electricity multivariate systems is involved. Johansen and Juselius (1990) pointed out that the constant should be included in the cointegrating system if there is no linear trend in the process. Engle and Granger (1987) demonstrated that once the numbers of variables (e.g. $X_t$ and $Y_t$) were found to be cointegrated, there was always a related error correction representation. It implies that changes in the dependent variables are functions of the level of disequilibrium in the cointegrating relationship as well as changes in other explanatory variables. In the electricity demand model, we investigate the possibilities of having cointegrating relationships among the independent variables through the Johansen maximum likelihood procedure.

The work of Johansen (1988), and also the similar work of Stock and Watson (1988) have identified the cointegrating rank r to provide estimates of the cointegrating and adjustment mechanism using the maximum likelihood method. In the Johansen maximum likelihood method, the dependent and independent variables in the time series regression model are viewed as endogenous and each variable can be expressed as a linear function of lagged values of itself and the other variables within the model. This set of equations is expressed mathematically in the form of a single vector autoregressive equation, said VAR. Manipulation of this vector equation produces a vector error correction in which differenced vector terms are explained as lagged differenced vector terms plus a lagged levels term which represents the error correction phenomenon. It turns out that the number of cointegrating vectors is equal to the rank of the matrix of coefficients associated with the levels of variables in the vector error correction model. Suppose that I want to test cointegration of the historical data among the electricity demand variable and the independent economic variables from the period of 1972 to 1998, for which the log values are tested as linear trend. Using the ADF test we have found the level of integration order of all independent variables as shown in Table 7.2. Shazam, an econometric package, includes the Johansen likelihood test as a standard procedure and the results of likelihood ratio test are stated in Table 7.3.

Table 7.3 Integration likelihood ratio test

| Null | Alternative | Statistic | 90% Critical value | 95% Critical value | 99% Critical value |
|---|---|---|---|---|---|
| | | Maximal Eigenvalue | | | |
| $r = 0$ | $r = 1$ | 43.27 | 30.82 | 33.26 | 38.86 |
| $r \leq 1$ | $r = 2$ | 18.53 | 24.92 | 27.34 | 32.62 |
| $r \leq 2$ | $r = 3$ | 15.86 | 18.96 | 21.28 | 26.15 |
| $r \leq 3$ | $r = 4$ | 5.90 | 12.78 | 14.60 | 18.78 |
| $r \leq 4$ | $r = 5$ | 4.18 | 6.69 | 8.08 | 11.58 |
| | | Trace | | | |
| $r = 0$ | $r \geq 1$ | 87.74 | 65.96 | 69.98 | 77.91 |
| $r \leq 1$ | $r \geq 2$ | 44.47 | 45.25 | 48.42 | 55.55 |
| $r \leq 2$ | $r \geq 3$ | 25.94 | 28.44 | 31.26 | 37.29 |
| $r \leq 3$ | $r \geq 4$ | 10.07 | 15.58 | 17.84 | 21.96 |
| $r \leq 4$ | $r = 5$ | 4.18 | 6.69 | 8.08 | 11.58 |

The Johansen maximum likelihood estimation is applied to analyse the cointegrating relation of model (7.7). The maximal and trace tests statistics are reported in Table 7.3, which test for the existence of cointegration relation. The calculated statistic values of different hypothesis tests are the results of using maximum likelihood model stated in model (6.13), using the statistic package Shazam. For example, to test the null that $r \leq 1$ against the alternative that $r = 2$, the maximal eigenvalue test statistic is determined to be 18.53 which is less than the 95% critical value of 27.34 (Johansen and Juselius, 1990) and the null is not rejected. Then take the hypothesis that there is no cointegrating vector ($r = 0$) and the alternative that $r = 1$. If the null hypothesis is not rejected, it will mean that there has not found another cointegrating vector. As this null hypothesis of no cointegrating vector is rejected, the dimension of the cointegrating space is set to one with a basis given by the one eigenvector corresponding to the one largest eigenvalue. Next, the null hypothesis of one or less cointegrating relation ($r \leq 1$) is tested with the trace test statistic against the 95% critical value, and is not rejected. For the hypothesis $r = 0$, the alternative that $r \geq 1$ is accepted as the calculated value of 87.74 is larger than the 95% critical value of 69.98. It is concluded that there is significance for one cointegrating relation of the explanatory variables in the model. The estimate of the single cointegrating vector in normal form has been estimated with Shazam to be [1.0000 -0.8516 0.2907 0.1511 -0.7032 -0.3467], the corresponding long run relationship is given in model (7.6) as follows:

$$\log(E) = 0.8516 \log(C) - 0.2907 \log(D) + 0.1511 \log(IN) + 0.7032 \log(P) + 0.3467 \log(R) \quad (7.6)$$

The estimate of the equilibrium relation in the long-run is given in model (7.7) as follows:

$$\log(E) = 0.0484 \log(C) - 0.9318 \log(D) - 0.2122 \log(IN) + 0.0049 \log(P) - 0.0897 \log(R) + 0.2764 \quad (7.7)$$

Using the Dickey Fuller test of existence of unit root, i.e., finding the cointegration relationship of the time series regression model, the elasticity of commercial buildings to electricity demand in long run becomes 4.84 % by the estimation of cointegration analysis.

## 7.3 Error Correction Modelling and Long Run Electricity Demand Adjustment

Use of regression analysis in previous chapters explains the relationships among electricity demand to various economic factors and are represented in mathematical expressions. However, econometric models of different levels of complexity can be formulated to estimate the elasticity coefficients with respect to those economic factors in short-run and long-run. The electricity demand is indicated by the model using simple multiple regression in Chapter 5. For long-run forecast by the work of Johansen (1988) and similar work of Stock and Watson (1988), the estimation of cointegration relationship and adjustment matrices using the maximum likelihood method have been studied. Using the methodology of maximum-likelihood approaeh by Johansen, results of trace test and maximum eigenvalue tests can be undertaken to identify the number of cointegrating vectors in the energy model.

An error-correction model (ECM) gives the corrected long-run behaviour from the cointegration analysis. From the regression analysis in section 7.2, the electricity consumption was recorded as 19,484 terajoules in the year of 1972 and 125,276 terajoule in the year of 1998. In the short-run, the estimated electricity demand will be increased to more than 165,000 terajoules in the year of 2010. The ECM for long-run estimation, incorporating a cointegrating vector as an error-correction mechanism measuring the over-estimated or under-estimated electricity demand, is developed as shown in model (7.8) and model (7.9). The estimation is run with the time series of the economic variables as the parameters for the period 1972 to 1998, giving the following diagnostic statistics: Coefficienct of determination ($R^2$) = 0.9996, Durbin-Watson (DW) = 1.204, Residual sum of squares (RSS) = 0.0098, and the t-values at 5% significant level are shown in parentheses. For the long-run case, one cointegrating relationship to the estimated equation of the vector error correction model is shown in model (7.8)

$$\Delta^1\log(E_t)=(-0.1152) - 0.0022\,\Delta^2\log(C_{t-1}) - 0.0017\,\Delta^4\log(D_{t-1}) - 0.0002\,\log(IN_t)$$

$$(t= 7.627) \qquad (t= -1.760) \qquad (t= -0.9958)$$

$$+\,0.0207\,\Delta^1\log(P_t) + 0.2093\,\Delta^2\log(R_{t-2}) + 0.0423\,[Z] + \varepsilon_t$$

$$(t= 0.5403) \qquad (t=1.74) \qquad (t=1.069) \qquad (7.8)$$

where Z is the estimated cointegrating vector, given by:

$$Z = \log(E_{t-1}) - 0.6787\log(C_{t-1}) + 0.2907\log(D_{t-1}) + 0.1511\log(IN_{t-1})$$

$$-\,0.7032\log(P_{t-1}) - 0.3467\log(R_{t-1}) \qquad (7.9)$$

From the result of model (7.8), the coefficient of the estimated equilibrium error is 0.0423 at 5% significant level, which is the speed of adjustment to equilibrium values of electricity demand through the error correction mechanism. The result of model (7.9), estimated cointegrating vector, gives comparison to the first difference of real electricity demand, i.e., integration of order (1). To identify the function of error correction modeling, we make the comparison of real electricity consumption time series and estimated time series by error correction model. The compared period is from year 1976 to year 1997, which has to be compromised with the time lag of the correction model and the result is shown in Figure 7.6.

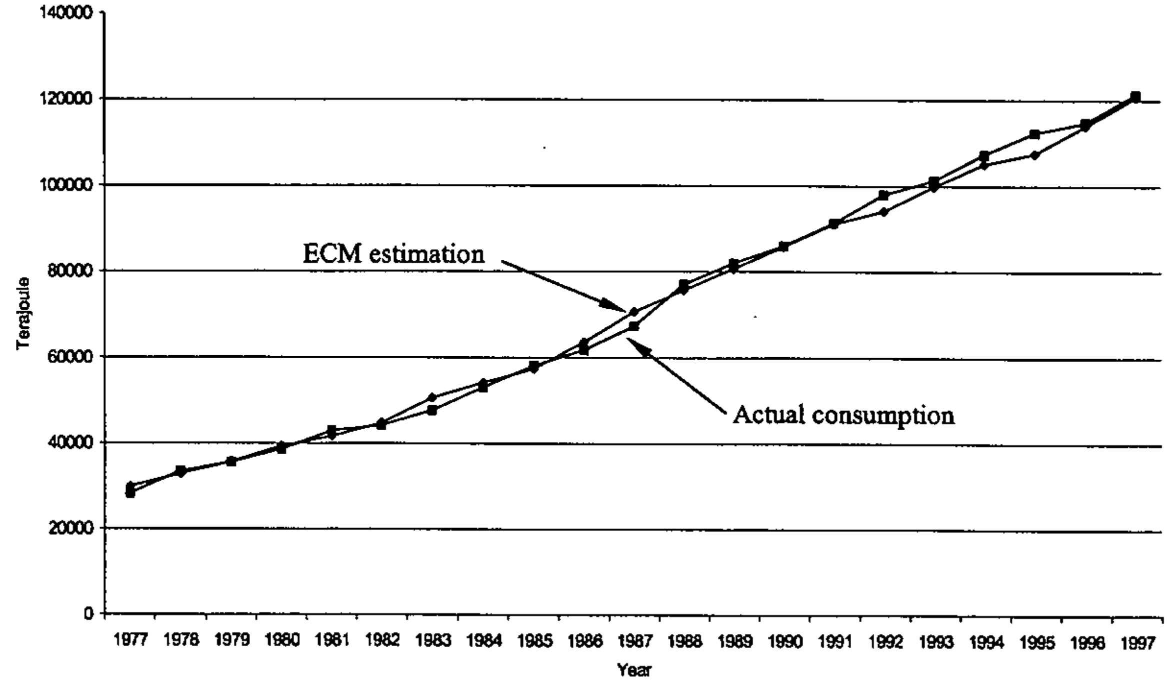



Figure 7.6 Comparison of actual electricity consumption and estimation of error correction model (ECM)

Finally, the study of model (7.8) indicated the model of forecasting long-run electricity demand with long-run equilibrium adjustment. Using the estimation by model (7.9), the estimated electricity consumption is closed to actual consumption as indicated in Figure 7.6. In long-run estimation, the model (7.7) provides the information of long-run effect of economic factors to electricity demand. The dynamic response of electricity demand to changes of real gross domestic product is about positive 21 % with a time lag of two years. That is, if there were 21 % increase in the amount of real gross domestic product in year (t – 2), there would be 1 % increase in electricity demand in year t. We can say this is a short-term effect of the variable 'RGDP' to the long-term adjustment of electricity demand. The RGDP, with elasticity 8.9 % to electricity demand in the long-run estimation by model (7.7), indicates a major effect to energy consumption of Hong Kong. On the other hand, the error correction term in the model (7.8) is significant with an adjustment coefficient of positive 0.0423. This coefficient means that there is 4.23 % of the adjustment taking place for its overall electricity demand to its long-run equilibrium level. The adjustment is taken by the error correction mechanism of model (7.9) due to the cointegrating relationship of the variables in long-run. Therefore, the short-term effects to electricity demand by various economic variables are shown in model (7.7) and the long-term effect to the change of electricity demand by those economic variables is shown in the error correction model (7.8) accordingly.

To estimate and apply the ECM in long run, every econometric variable within the model is necessary to project for a long period. Result of the projection can be input to the ECM for adjusting the long term forecast demand. To predict the econometric variable of itself in long term, the approach of autoregressive (AR) process is adopted, which is a regression of a variable on itself with a lag as one of the explanatory variable. Under the process of AR analysis, a linear trend of the econometric data can be received. For the assumption of stationary time series modeling, the data to be generated for modeling should be stationary. Hence, the resulting stationary time series by application of Dickey-Fuller unit root from last section are used in the AR process. Correlogram and partical correlogram computed by SPSS are applied in identification of appropriate significant lag number in the autoregressive function. The estimation of long-run electricity demand with long-run equilibrium adjustment is shown in Figure 7.7.

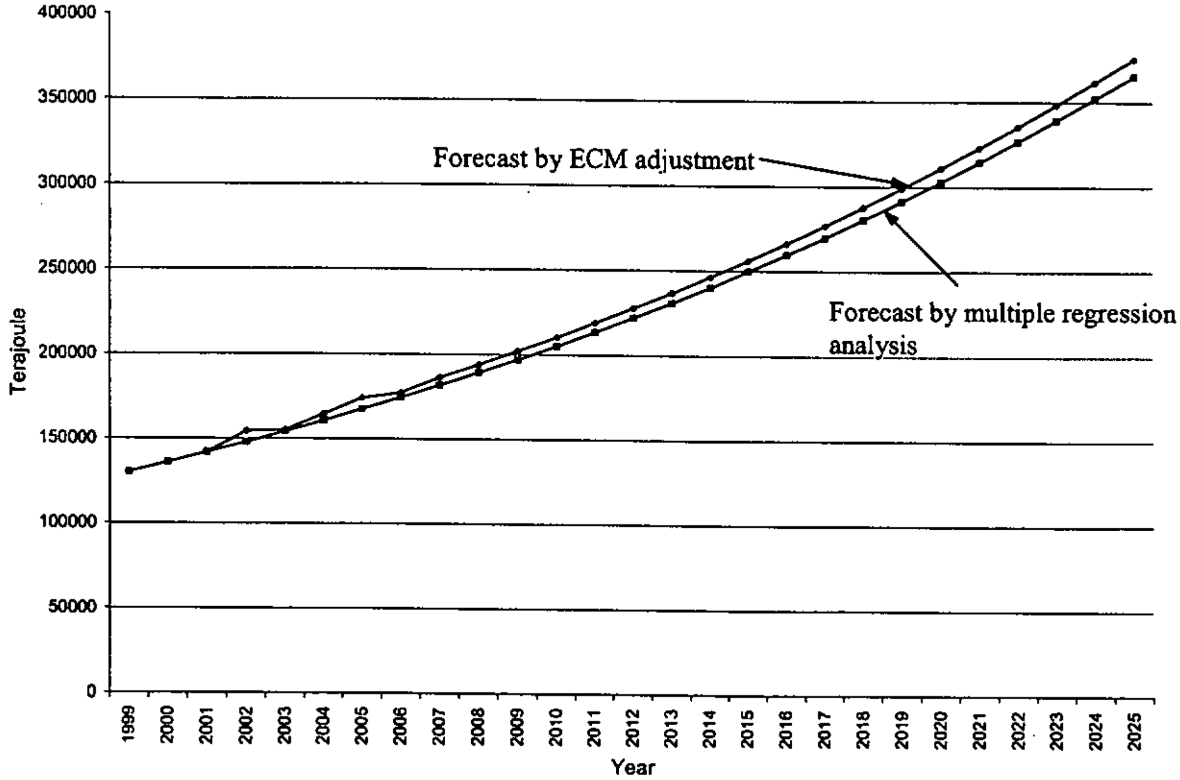



Figure 7.7 Comparison of electricity demand forecast by linear multiple regression and forecast under adjustment of error correction modeling (ECM)

Under the adjustment of error correction modeling, the long-run electricity demand trend has been shifted up from the period of year 2003 to 2004. The reason of the long-run adjustment is caused by the error correcting approach, which is expressed in model 7.8. There is about 3% adjustment in annual electricity demand between multiple regression analysis and error correction modeling. In 2025, the electricity demand will reach 365,200 terajoule by multiple regression analysis but the demand will shift up to 375,500 terajoule after error correcting approach being applied. The calculation of the change of electricity demand trend of model 7.8 is presented in Table 7.4.

## 7.4 Influence of the building energy parameters on the long run energy demand

Predicting a change over time or extrapolating from present conditions to future conditions is not the function of regression analysis. To make estimates of the future, forecasting is an important part of econometric analysis. To forecast future electricity demand, the estimation of the growth of each independent variable in the energy model needs to be studied. The autocorreclation function (ACF) and partial autocorrelation function (PACF) are used to produce long term estimation. The reason of not using Integrated Autoregressive Moving-Average Models is that the time series data in this research study are collected as yearly base and the moving average technique is better to employ in quarterly data. Therefore, autoregressive function is applied in the forecast model. The autocorrelation and partial autocorrelation of the independent variables are computed by SPSS.

The estimated future electricity demand so obtained with the econometrical model at macro level represents the norm of electricity demand when the new buildings constructed each year are average in energy performance in respect of their envelope design and energy-related system design parameters as for the base case building described in Chapter 4. Changes in the energy requirement at micro level in individual commercial building due to different envelope design and energy-related system design parameters are determined by thermal models of building and system, using DOE-2.1E for simulation, as reported in Chapter 4. System design parameters that have studied in the simulation include space temperature, constant vs. variable air volume flow, fan efficiency, heat rejection method and chiller COP, and lighting intensity.

Alternative building envelope designs, including energy effective one that restricts thermal heat gain and energy intensive one that permits more heat flow from outdoor to indoor, have been evaluated.

If all the new commercial buildings were constructed with desirable energy-related system design parameters and energy effective envelope design, the future electricity demand would be greatly reduced. On the other hand, if all the new buildings were constructed with undesirable system parameters and energy intensive envelope design, there would be extra electricity demand increasing from year to year. At this point the amount of electricity saved due to having desirable system design parameters in new buildings, expressed in a time series, can be identified as shown in Figure 7.8 and Table 7.4 Similarly, the amount of electricity wasted (or extra demand) due to having system design parameters undesirable for energy performance is calculated, also shown in Figure 7.8 and Table 7.4.

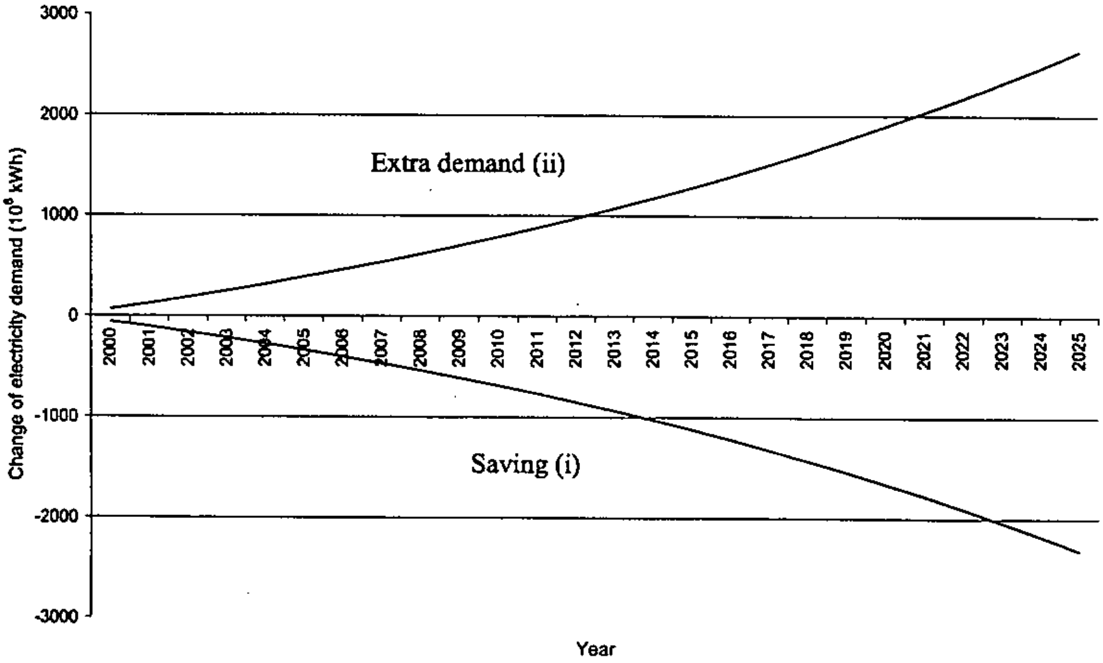



Figure 7.8 Predicted difference in the electricity demand for commercial buildings with (i) desirable building system parameters vs. (ii) undesirable building system parameters, in long term forecast from 2000–2025

Table 7.4 Predicted long-run electricity demand by linear multiple regression and error correction modeling from 2002-2025

| Year | Multiple regression forecast (Terajoule) | Adjustment of error correction modeling (Terajoule) | Long-run electricity demand after ECM (Terajoule) |
|---|---|---|---|
| 2000 | 135,800 | nil | nil |
| 2001 | 141,900 | nil | nil |
| 2002 | 147,800 | 6,400 | 154,200 |
| 2003 | 154,000 | 900 | 154,900 |
| 2004 | 160,500 | 3,900 | 164,400 |
| 2005 | 167,300 | 6,600 | 173,900 |
| 2006 | 174,300 | 2,800 | 177,100 |
| 2007 | 181,500 | 4,500 | 186,000 |
| 2008 | 189,000 | 4,700 | 193,700 |
| 2009 | 196,800 | 5,100 | 201,900 |
| 2010 | 204,800 | 5,300 | 210,100 |
| 2011 | 213,200 | 5,500 | 218,700 |
| 2012 | 221,800 | 5,700 | 227,500 |
| 2013 | 230,800 | 5,900 | 236,700 |
| 2014 | 240,000 | 6,200 | 246,200 |
| 2015 | 249,600 | 6,400 | 256,000 |
| 2016 | 259,500 | 6,700 | 266,200 |
| 2017 | 269,800 | 7,000 | 276,800 |
| 2018 | 280,400 | 7,200 | 287,600 |
| 2019 | 291,400 | 7,700 | 299,100 |
| 2020 | 302,700 | 8,100 | 310,800 |
| 2021 | 314,400 | 8,500 | 322,900 |
| 2022 | 326,500 | 8,800 | 335,300 |
| 2023 | 339,000 | 9,300 | 348,300 |
| 2024 | 351,900 | 9,800 | 361,700 |
| 2025 | 365,200 | 10,300 | 375,500 |

If the new buildings with desirable system parameters are also equipped with energy effective envelope, the energy requirement of these buildings will be further reduced, giving more energy saving than the previous case. This is the optimum situation. Taking year 2000 to be the division line, following the trend of growth of commercial building stock and that all commercial buildings built afterwards are energy efficient buildings, the amount of saving of electricity in year 2005 would be 422 million kWh and it would grow to become a saving of 2,887 million kWh in year 2025. The worst situation, i.e., largest electricity demand or most wastage of electricity, occurs if all the new commercial buildings are constructed with both undesirable energy-related system parameters and energy intensive envelope. In that case the extra electricity demand (or wastage) would be 366 million kWh in year 2005, expanding to become 2,503 kWh in year 2025. These are shown in Figure 7.9, Table 7.5 and Table 7.6.

Table 7.5 Predicted difference in the electricity demand in long term forecast with (i) desirable building system parameters, and (ii) undesirable building system paramters from 2000–2025

| Year | (i) New commercial buildings having desirable building system parameters | (ii) New commercial buildings having undesirable building system parameters |
|---|---|---|
| | Electricity save ($10^6$ kWh) | Electricity waste ($10^6$ kWh) |
| 2000 | 65 | 57 |
| 2001 | 120 | 106 |
| 2002 | 184 | 161 |
| 2003 | 248 | 217 |
| 2004 | 316 | 277 |
| 2005 | 386 | 338 |
| 2006 | 460 | 403 |
| 2007 | 536 | 470 |
| 2008 | 616 | 540 |
| 2009 | 699 | 613 |
| 2010 | 786 | 689 |
| 2011 | 877 | 768 |
| 2012 | 972 | 851 |
| 2013 | 1,071 | 938 |
| 2014 | 1,173 | 1,028 |
| 2015 | 1,281 | 1,122 |
| 2016 | 1,393 | 1,220 |
| 2017 | 1,510 | 1,323 |
| 2018 | 1,632 | 1,430 |
| 2019 | 1,759 | 1,541 |
| 2020 | 1,892 | 1,658 |
| 2021 | 2,030 | 1,779 |
| 2022 | 2,175 | 1,905 |
| 2023 | 2,326 | 2,038 |
| 2024 | 2,483 | 2,175 |
| 2025 | 2,647 | 2,319 |

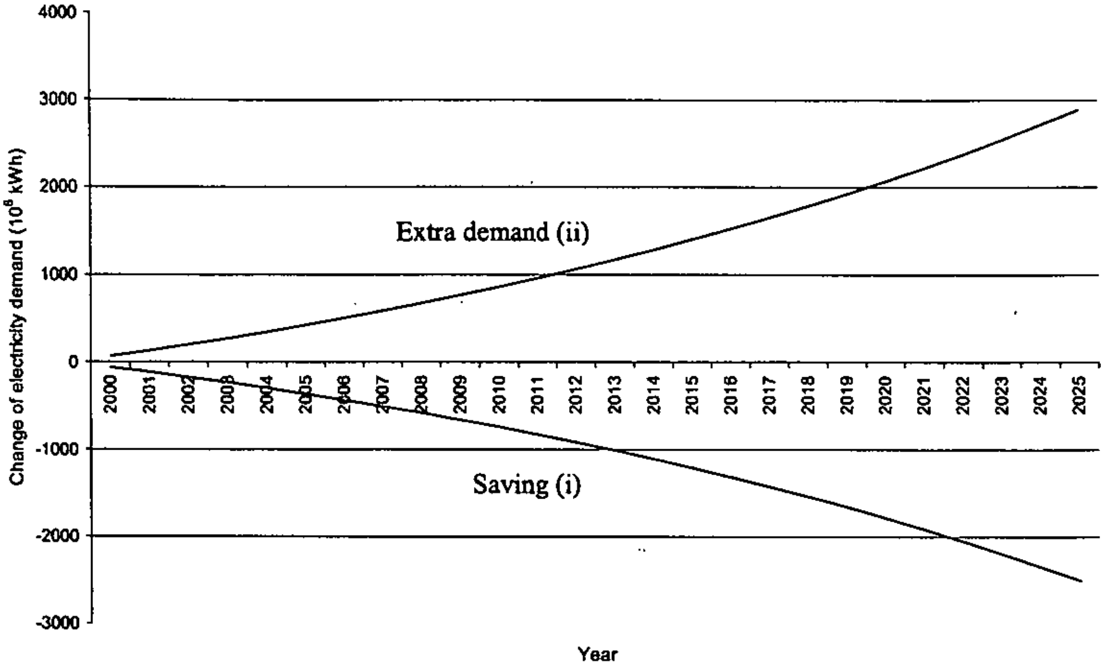



Figure 7.9 Predicted difference in the electricity demand due to new commercial buildings (i) with desirable building system parameters and effective envelope design, vs. (ii) with undesirable building system parameters and energy intensive envelope design, in long term forecast from 2000–2025

Table 7.6 Predicted difference in the electricity demand in long term forecast with (i) desirable building system parameters and energy effective envelope design, and (ii) undesirable building system parameters and energy intensive envelope design from 2000–2025

| Year | **(i) New commercial buildings having desirable building system parameters and energy effective envelope design** | **(ii) New commercial buildings having undesirable building system parameters and energy intensive envelope design** |
|---|---|---|
| | **Electricity save ($10^6$ kWh)** | **Electricity waste ($10^6$ kWh)** |
| 2000 | 71 | 62 |
| 2001 | 132 | 114 |
| 2002 | 201 | 175 |
| 2003 | 271 | 235 |
| 2004 | 345 | 299 |
| 2005 | 422 | 366 |
| 2006 | 502 | 435 |
| 2007 | 585 | 508 |
| 2008 | 673 | 583 |
| 2009 | 763 | 662 |
| 2010 | 858 | 744 |
| 2011 | 957 | 830 |
| 2012 | 1,060 | 919 |
| 2013 | 1,168 | 1,013 |
| 2014 | 1,280 | 1,110 |
| 2015 | 1,398 | 1,212 |
| 2016 | 1,520 | 1,318 |
| 2017 | 1,647 | 1,428 |
| 2018 | 1,780 | 1,544 |
| 2019 | 1,919 | 1,664 |
| 2020 | 2,064 | 1,790 |
| 2021 | 2,215 | 1,921 |
| 2022 | 2,373 | 2,057 |
| 2023 | 2,537 | 2,200 |
| 2024 | 2,708 | 2,348 |
| 2025 | 2,887 | 2,503 |

Finally, let us come back to the forecast of electricity demand given in Figure 7.7. The forecast by multiple regression has been rectified through the error correction modeling (ECM) process. Now the annual amount of electricity saving resulting from new commercial building having desirable building system parameters and energy effective envelope can be deducted from ECM corrected forecast to give the lower boundary of the anticipated electricity demand in the long-run. The upper boundary is given by adding the extra electricity demand resulting from new commercial buildings having undesirable system parameters and energy intensive envelope to the ECM corrected forecast. The calculation is summarized in Table 7.7 and the final forecast is shown in Figure 7.10.

Table 7.7 Estimate of long-run electricity demand by the error correction model with the combination of commercial buildings with (i) desirable building system parameters and effective envelope design, and (ii) undesirable building system parameters and energy intensive envelope design from 2000–2025

| Year | **Long-run electricity demand after ECM (Terajoule)** | | |
|---|---|---|---|
| | **Norm** | **(i) with desirable system parameters and energy effective envelope** | **(ii) with undesirable system parameters and energy intensive envelope** |
| 2001 | nil | nil | nil |
| 2002 | 154,200 | 153,400 | 154,800 |
| 2003 | 154,900 | 153,900 | 155,700 |
| 2004 | 164,400 | 163,100 | 165,400 |
| 2005 | 173,900 | 172,300 | 175,200 |
| 2006 | 177,100 | 175,200 | 178,600 |
| 2007 | 186,000 | 183,800 | 187,800 |
| 2008 | 193,700 | 191,200 | 195,700 |
| 2009 | 201,900 | 199,100 | 204,200 |
| 2010 | 210,100 | 207,000 | 212,700 |
| 2011 | 218,700 | 215,200 | 221,600 |
| 2012 | 227,500 | 223,600 | 230,800 |
| 2013 | 236,700 | 232,400 | 240,300 |
| 2014 | 246,200 | 241,500 | 250,100 |
| 2015 | 256,000 | 250,900 | 260,300 |
| 2016 | 266,200 | 260,700 | 270,900 |
| 2017 | 276,800 | 270,800 | 281,900 |
| 2018 | 287,600 | 281,100 | 293,100 |
| 2019 | 299,100 | 292,100 | 305,000 |
| 2020 | 310,800 | 303,300 | 317,200 |
| 2021 | 322,900 | 314,900 | 329,800 |
| 2022 | 335,300 | 326,700 | 342,700 |
| 2023 | 348,300 | 339,100 | 356,200 |
| 2024 | 361,700 | 351,900 | 370,100 |
| 2025 | 375,500 | 365,100 | 384,500 |

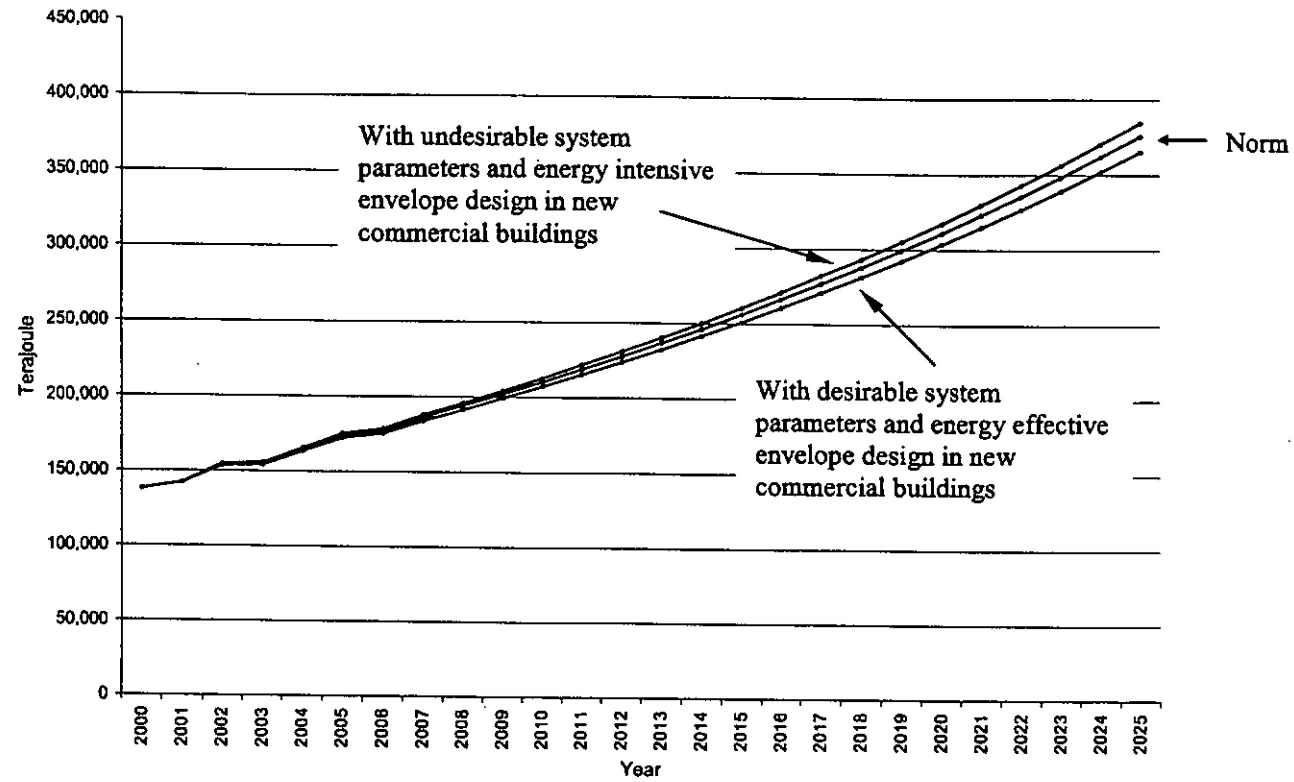



Figure 7.10 Forecast of long-run electricity demand by the error correction Model (ECM)

Figure 7.11 shows the estimated 9000TJ wastage of electricity in year 2025, and the percentage wastage attributed to five energy-related parameters, if the commercial buildings constructed after 2001 are energy intensive represented by an undesirable building model comparing to the norm. When lighting fittings of low efficacy are used, causing the lighting intensity to be $5kW/m^2$ higher than the norm, the resulting electricity wasted is 3309TJ or 36% of the total estimated wastage. Using air-cooled chillers with COP of 2.7, that is also the minimum chiller efficiency stipulated in the Code of Practice for Energy Efficiency (EMSD, 1998), the electricity wastage is 1761TJ (20% of total wastage). Note that the wastage due to this drop of chiller efficiency is less than the effect of lighting intensity, simply because the chiller efficiency in the norm is already low as air-cooled chillers are widely used in Hong Kong. VAV system is assumed in the norm, which requires less fan energy relatively. If CAV system is installed, an extra amount of 1625TJ (18% of the total wastage) will be consumed for air delivery. If the design room temperature is lowered from 24°C to 23°C, there will be wastage of 1628TJ (18% of total wastage). We can see from this point that substantial energy will be wasted if the room temperature is kept unnecessarily low, and it is often found to be freezing in many occupied spaces. Lastly, another amount of 677TJ (8% of total wastage) will be consumed if new commercial buildings are constructed with energy intensive envelope. As implied by this last point, the building services system design has much larger impact on energy conservation comparing to the building envelope design.

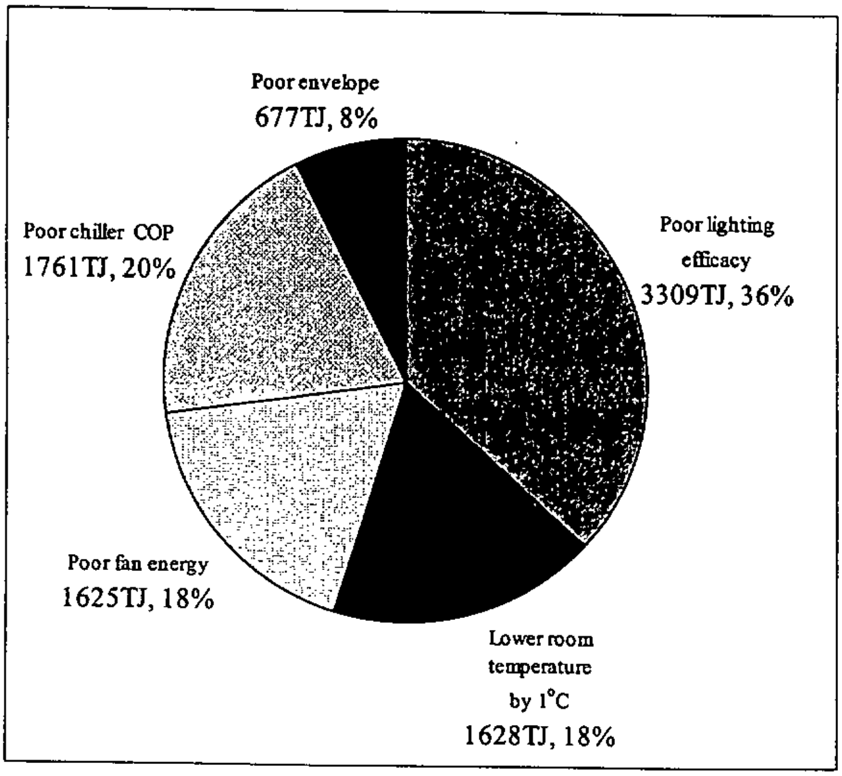



Figure 7.11 Electricity wasted in Year 2025 if commercial buildings constructed after 2001 are energy intensive

The above energy-related parameters are tuned to desirable but practical values represented by an energy efficient building model. If all the new commercial buildings built after 2001 are similar to this energy efficient building model at design room temperature of 24°C, the potential saving of electricity in year 2025 will be 10400TJ. The portion of the saving resulted by using water-cooled chillers of high COP is dominant, reducing consumption of 4799TJ which is 46% of the total saving of the desirable building model. This is achievable if water is available for heat rejection and that the current technology has enabled manufacturing of water-cooled chillers with COP as good as 6.5. When the lighting intensity is reduced by 5kW/m$^2$ by using higher efficacy lighting fittings, there will be 2925TJ (28%) saved. If the supply and return fans are sized properly to obtain an improved operating efficiency of 0.75 at design load, a saving of 1852TJ (18% of total saving) can be obtained in year 2025. The building envelope may also be designed to be energy effective with reasonable OTTV of 20.6W/m$^2$, which will produce energy saving of 824TJ (8% of total saving of the desirable building model), bearing in mind at the same time that it is undesirable to make the OTTV to be too low by using highly reflective window glazing of very low shading coefficient.

From these, we can see that there is much room of energy reduction in the current level of chiller and fan operating efficiency represented by the norm, and effort should be made in the new building design to achieve higher efficiency of chillers and fans.

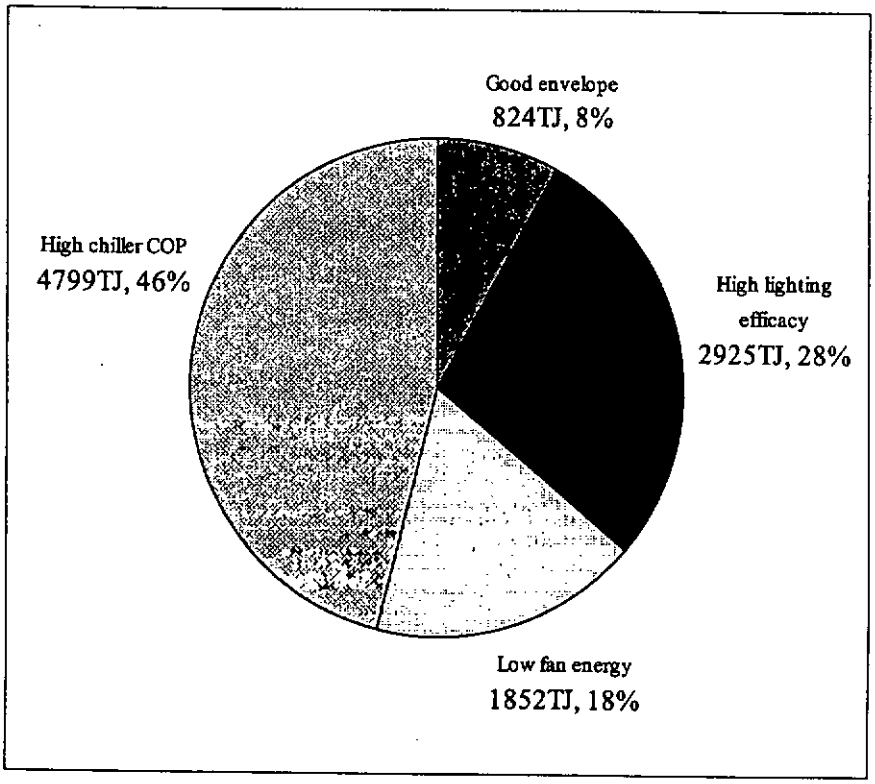



Figure 7.12 Electricity saved in Year 2025 if commercial buildings constructed after 2001 are energy effective

# Chapter 8

# Conclusions and Recommendations

In this study, focuses are placed on the major social and economic factors and the energy-related parameters of commercial buildings, which affect the pattern of energy consumption. Regression analysis is used to estimate the long-term electricity demand in Hong Kong SAR. Different types of envelope construction including energy intensive and energy effective building envelope for commercial buildings are investigated. Changes to building energy requirement due to system parameters such as lighting efficacy, chiller coefficient of performance, space temperature and fan system used in commercial building are calculated using the DOE-2E simulation software. The forecasts of the impact of energy effective and intensive envelope designs with desirable and undesirable building system parameters are indicated. Time series analysis is used as a statistical modeling to estimate the long-run electricity demand trend and cointegration modeling is developed to calculate the adjustment of electricity demand in long-run equilibrium. Also, the relations of various economic variables to electricity demand are studied via multiple regression analysis. Accordingly, the impacts of building energy parameters on future electricity used of commercial building are evaluated.

## 8.1 Application of statistical energy model

Energy demand analysis is an important component of integrated energy planning and policy. Electricity supply groups and energy policy makers of the Hong Kong government need to have realization of the internal and external factors affecting the growth and pattern of energy demand for making policy. To keep a balance of electricity supply capacity and peak demand in Hong Kong, there is a need to undertake detailed demand studies of electricity demand trend at the aggregate level. This research study is mainly focused on electricity demand of commercial building and the demand affecting by economic factors. The thesis started with a multiple linear regression analysis to have a basic image of how the energy consumption related to various economic sectors in Hong Kong. There are the composite consumer price 89/90, fuel price in Hong Kong, gross domestic product at constant price of 89/90, government expenditure and equity investment, volume of trade, average price charged of the power companies, population, units of public owned and saleable estates and total area of commercial, industrial and private residential buildings. There were totally nine independent economic and building factors studied for the influence to electricity and final energy consumption. The relationship is indicated by the elasticity of related variable.

An in-depth analysis of economic factors affecting energy consumption is helpful to understand the pattern of energy demand in future and for formulating energy policy. Such analyses can be done at macro level relating electricity consumption with population, real gross domestic product, average price of electricity supply and various building sectors in the statistical model. Time series analysis is another statistical modeling taken in this study in order to process Dickey Fuller test for identification of the stationarity of different independent variables in our electricity model. The method is to transform the time series data status from non-stationary to stationary by differencing and cointegrating process. The basic Dickey Fuller test is used to test for the order of integration of the economic time series. In the energy statistical model, Augmented Dickey Fuller (ADF) test is applied to take account of the serial correlation time series. The benefit of ADF is that ADF test is sensitive to non-linear transformations of the economic data when the economic variable is found to be non-stationary in levels but being stationary in logarithms expression. We found that the time series of industrial building stock (IN) is stationary. Time series of electricity price (P) is found to be differenced once to become stationary. Time series of commercial buildings stock (C) and real gross domestic product (R) need to be differenced twice to become stationary. Lastly, differencing four times are necessary to achieve stationary for the time series of domestic buildings stock (D). Also, cointegration analysis is untaken to verify the adjustment of long-term equilibrium of time series electricity model. Short-term and long-term forecasts by regression analysis are made to show the influence of building energy parameters on the effectiveness of energy used in commercial building.

Because of the social and economic activities, demand for commercial buildings in Hong Kong is high in next two decades. The demand will reach 60 million $m^2$ floor area in year 2025. Estimating by regression analysis, the electricity demand of commercial buildings with regular building system parameters and envelope design will reach 375,500 terajoules in year 2025. Comparing to the 110,000 terajoules in year 1997, the electricity demand in year 2025 is 3.3 times more than the 1997. Hence, use of electricity in commercial buildings is one of the major issues of energy conservation in Hong Kong.

## 8.2 Sensitivities of building energy efficiency parameters

Among the energy effective and intensive envelope designs and the system parameters, their influences on the building energy used in commercial buildings vary. DOE-2.1E is employed to simulate the building energy and study the sensitivities of those energy-related parameters. Such sensitivities will indicate the relative importance of commercial building envelope designs and provide insight to the engineers on effective means to optimize the design of envelope constructions. They also provide guidelines on possible trade off among the envelope parameters in gearing the designs to meet with Code of Practice for Energy Efficiency on envelope constructions and energy saving purposes. The study includes testing the impacts of chiller efficiency, space cooling temperature, variable versus constant air flow, fan efficiency and lighting intensity on the building energy requirement.

A combination of desirable system parameters for energy efficiency of commercial buildings is designed as a VAV system, fan system efficiency of 0.75 at design flow, variable speed control, space temperature of $24^0$C, lighting intensity of 15 W/m$^2$ and using water cooled centrifugal chillers with nominal coefficient of performance equal to 6.5. The building has an effective envelope of OTTV of 20.56 W/m$^2$. The combination of these system parameters with the effective envelope design generates energy efficient building with annual electricity consumption of 128.7 kWh/m$^2$. An energy inefficient building has been established with undesirable system parameters including a CAV system, fan system efficiency of 0.52, space temperature of $23^0$C, lighting intensity of 25 W/m$^2$, using air-cooled reciprocating chillers with nominal coefficient of performance of 2.7, and having an energy intensive envelope of OTTV of 38.3 W/m$^2$. With these building system parameters and intensive envelope design, the annual electricity consumption of the reference building is recorded to be as high as 263.5 kWh/m$^2$ from the simulation.

### 8.3 Significance of the error correction model

To understand the relationship of different economic factors to energy demand, this thesis indicates the short and long-run elasticity of various economics variables to the change of energy demand by regression analysis using annual data from 1972 to 1998. Given the time series data set, the long-run elasticities of economic variables as of Commercial buildings stock (C), Domestic buildings stock (D), Industrial buildings stock (IN), Electricity price (P) and Real gross domestic product (R) in Hong Kong are calculated by multiple regression analysis. In further study of estimating short run elasticities of all independent variables influencing the short term change of electricity demand, an error correction model was employed to study the short term dynamics of electricity demand pattern. We have investigated the cointegrating relationship of electricity demand among all the economics variables. The time series properties of the parameters were analysed by the method of unit root test. After verifying the required level of differences for stationarity, the cointegrating relationship was analysed using the maximum likelihood ratio test developed by Johansen and Juselius. The error-correction model of electricity demand was developed after the identification of cointegrating relation. It provided the examination of the causality relationship with the short-run dynamics without loss of any long-run information. In our electricity demand model, the explanatory variable are integrated of different orders and lags but still cointegrated. There is one cointegrating relation among the variables via analysis of maximum likelihood ratio test.

Having derived models of the electricity consumption, we are able to estimate the future electricity demand for this unique city of rapidly increasing stock of high rise buildings. Using error correction modelling can investigate the short term elasticity of the independent economic variables to electricity demand but not losing the long term information inherent in the electricity demand system. The specification of error correction model indicated that when the economic variables are cointegrated, equilibrium of its trend in long term movement will feed back on the changes in the economic variable in order to force the movement towards the long term equilibrium. That is, under error correction modelling, the short run commercial sector elasticity to change in electricity demand is -0.0022 and the negative sign indicates that the second difference of commercial building stock at lag one has a short term decreasing effect on the first difference of electricity demand. Then, by economic point of view, the commercial users will restore to normal consumption behaviour in long run and the elasticity return to positive which is 0.0484 in long period of time. On the other hand, the elasticity of real gross domestic product to change in electricity demand in short term is calculated as positive 0.2093 and negative 0.0897 in long term. We assume that the higher income of consumers is expected to increase consumption through greater economic activity and the increased purchases of electrical equipment. However, a rise in electricity price and upgraded efficiency of equipment will lead to a fall in consumption of electricity after a period of time.

## 8.4 Recommend future work

The trend of the total energy consumption in the Hong Kong SAR indicates a rapid increase, particulars in the sector of energy consumption in commercial buildings. Energy requirement for lighting and air-conditioning in commercial buildings is an inter-related issue. Its growth in future years is crucial both economical and environmentally. However, envelope designs with high window-to-wall ratio and solar transmittance will admit more natural lighting and reduce the need of artificial lighting but the thermal gain and cooling load will be also increased. Further investigation on the interaction of envelope designs with illumination and cooling requirement is necessary.

There is lack of energy demand forecast in Hong Kong. In other counties, though much works have been done on the macro energy supply and demand trend, investigators rarely include commercial buildings development and energy saving measures as variables in the demand trend analysis. The technical study of energy efficiency of buildings and installations with the statistical forecast of energy demand will contribute to enhance knowledge of the influence of building envelope designs and energy saving schemes in commercial buildings on the total energy demand.

The short-run and long-run properties of the electricity demand are underpinned by the economic changes in the past three decades. Since the early 80s many industrial manufacturing processes have shifted to China mainland, stopping the growth of industrial buildings. In the 1980s the electricity price was stable because of the control scheme put on the power companies by the government, and in effect dropped in real dollar value relative to the general rate of inflation. Then, in the 1990s, there was substantial increase in the electricity price. Notwithstanding the electricity price, the energy demand in the same period increased substantially because of the economy growth. The decisions of commercial and domestic building development are dependent on the market need and government policies, and have been influenced by financial turmoil in 1997. Over the course of 1997 the residential property market went from buoyancy to consolidation after eight years of rapid expansion. The property developers slowed down the construction of new buildings in response to the dropping market demand and stabilised the valuation of assets, whereas larger supply of new residential flats in the longer term was induced by the government policy on land and housing. The models developed in this thesis will be useful as a basis for energy planning and policy making in relation to energy supply regulation, power plant capacity, energy efficiency in buildings and environmental protection.

A limitation of the present work is the omission of a climatic parameter in the modelling, making the model insensitive to the seasonal changes of electricity demand. It is also necessary to include residential buildings in the study, as domestic users constitute a growing and the second largest sector of electricity consumers after the commercial users.

The extent of the influence of the codes of practice for air-conditioning, lighting and electrical installations on building energy use has to be identified. Change of energy demand by implementation of voluntary design guides and energy effective design methodologies is yet to be investigated. Also, construction of new commercial and residential buildings in Hong Kong is ongoing and voluminous. Its implication on the growth of energy demand has to be further investigated.

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