IMPROVEMENT OF ENERGY EFFICIENCY AND MITIGATION OF AIR POLLUTION FROM INDUSTRIAL SECTOR OF THAILAND

Miss Sasithon Monthip

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Environmental Engineering

Suranaree University of Technology

Academic Year 2002

ISBN 974-533-169-4

การปรับปรุงประสิทธิภาพการใช้พลังงานและการลดมลภาวะทางอากาศ
จากโรงงานอุตสาหกรรมในประเทศไทย

นางสาว ศศิธร มณทิพย์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตร์มหาบัณฑิต
สาขาวิชาวิศวกรรมสิ่งแวดล้อม
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2545
ISBN 974-533-169-4

ศศิธร มณทิพย์ : การปรับปรุงประสิทธิภาพการใช้พลังงานและการลดมลภาวะทางอากาศจากโรงงานอุตสาหกรรมในประเทศไทย (Improvement of Energy Efficiency and Mitigation of Air Pollution from Industrial Sector of Thailand)
อาจารย์ที่ปรึกษา : ดร.สุดจิต ครุจิต, 159 หน้า. ISBN 974-533-169-4.

ภาคอุตสาหกรรมมีความสำคัญต่อระบบเศรษฐกิจของประเทศไทย และมีความต้องการใช้พลังงานมากเมื่อเปรียบเทียบกับภาคอื่นๆ การศึกษานี้ได้พิจารณาถึงประสิทธิภาพการใช้พลังงานและมลภาวะทางอากาศซึ่งเกิดจากการใช้พลังงานในกระบวนการอุตสาหกรรม ในปี พศ. 2534 ถึง 2554 นอกจากนั้นได้ทำการศึกษาสถานการณ์ และรูปแบบการใช้พลังงานในปัจจุบันของภาคอุตสาหกรรม และนำเสนอแนวทางการปรับปรุงประสิทธิภาพการใช้พลังงาน และลดปริมาณการปล่อยก๊าซคาร์บอนไดออกไซด์ (CO_2), ซัลเฟอร์ไดออกไซด์ (SO_2) และไนโตรเจนออกไซด์ (NO_x)

การใช้พลังงานในภาคอุตสาหกรรมในปี พศ. 2534 ถึง 2542 เป็นผลมาจากการเติบโตทางเศรษฐกิจของประเทศมากกว่า 50% จากการเปลี่ยนแปลงโครงสร้างอุตสาหกรรมประมาณ 40% และจากดัชนีการใช้พลังงานประมาณ 2% ในขณะที่ประสิทธิภาพการใช้พลังงานโดยส่วนใหญ่ในสาขาย่อยของภาคอุตสาหกรรมลดต่ำลง โดยกลุ่มอุตสาหกรรมโลหะประดิษฐ์มีประสิทธิภาพการใช้พลังงานสูงสุด ขณะที่อุตสาหกรรมแร่อโลหะมีประสิทธิภาพการใช้พลังงานต่ำที่สุด จากการศึกษาพบว่า ในปี พศ. 2554 ความต้องการใช้พลังงานจะเพิ่มเป็น 37,187.93 พันตันน้ำมันดิบเทียบเท่า โดยมีอัตราเพิ่มเฉลี่ย 7.21% ต่อปี ในขณะที่ปริมาณ SO_2 จะเพิ่มขึ้นอย่างรวดเร็วที่ 13.71% ต่อปี ตามด้วย CO_2 และ NO_x ซึ่งจะเพิ่มขึ้นที่อัตราเพิ่มเฉลี่ย 7.74% และ 6.85% ต่อปี ตามลำดับ ทั้งนี้การเพิ่มขึ้นของ SO_2 เป็นผลเนื่องมาจากการเพิ่มขึ้นอย่างมากของความต้องการใช้ผลิตภัณฑ์ปิโตรเลียม อย่างไรก็ตาม CO_2 จะยังคงเป็นปัญหาหลัก ตามด้วย SO_2 และ NO_x จากข้อมูลที่ได้รับจากการตอบแบบสอบถามจากโรงงานผลิตอิฐทนไฟ โรงงานผลิตขวดแก้ว และโรงงานซีเมนต์ ว่าการปรับสัดส่วนอากาศและเชื้อเพลิงให้เหมาะสมและการนำความร้อนทิ้งมาเพิ่มอุณหภูมิให้กับอากาศก่อนเข้าระบบ การเปลี่ยนชนิดของพลังงานที่ใช้ และการแทนที่ด้วยอุปกรณ์ไฟฟ้าที่มีประสิทธิภาพสูง เป็นวิธีการที่สามารถเพิ่มประสิทธิภาพการใช้พลังงานและยังสามารถลดมลภาวะทางอากาศได้ โดยสามารถลด CO_2, NO_x, และ SO_2 ได้สูงสุดถึง 13.12%, 7.94%, และ 100% ตามลำดับ

สาขาวิชาวิศวกรรมสิ่งแวดล้อม	ลายมือชื่อนักศึกษา..
ปีการศึกษา 2545	ลายมือชื่ออาจารย์ที่ปรึกษา................................

SASITHON MONTHIP : IMPROVEMENT OF ENERGY EFFICIENCY AND MITIGATION OF AIR POLLUTION FROM INDUSTRIAL SECTOR OF THAILAND.
THESIS ADVISOR : DR. SUDJIT KARUCHIT, Ph.D. 159 PP. ISBN 974-533-169-4.

ENERGY/ENERGY EFFICIENCY/EMISSION/IMPROVEMENT

Industrial sector is one of the largest energy consumers. This study addresses the energy efficiency and energy-related pollutant emission from the industrial sector of Thailand. In addition, it examines the existing energy consumption situations of the industrial sector in order to formulate and effectively implement the most suitable techno-economic policy option for the improvement of the energy efficiency and reduction in the CO_2, NO_x, and SO_2 emissions.

From 1991 to 1999, the energy consumption in the industrial sector in Thailand was contributed by the economic growth more than 50%, the structural change about 40%, and the energy intensity about 2%. The energy efficiency of the industrial sub-sectors are in the range of 8.83 to 275.30 million baht/ktoe. It has been declining in most sub-sectors. Fabricated metal industry has the highest energy efficiency. Non-metal industry has the lowest energy efficiency. Based on the forecast, the energy demand will reach 37,187.93 ktoe in 2011 with the annual average growth of 7.21%. SO_2 emission will increase very fast with the annual average growth rate of 13.17% followed by CO_2 and NO_x emissions, 7.74% and 6.85%, respectively. Rapid increase in SO_2 emissions will be due to high growth rate of petroleum products. However, CO_2 will still be the major concern for pollutants' emission, followed by SO_2, and NO_x. Based on the questionnaires obtained from a cement factory, a firebrick factory, and a glass bottle factory, standard air-fuel ratio adjustment and preheating of the air supplied, fuel switching, and replacement with high efficiency electric equipment are recommended for improvement options. Potential reduction in CO_2, NO_x, and SO_2 emissions are expected to be up to 13.12%, 7.94%, and 100%, respectively.

สาขาวิชาวิศวกรรมสิ่งแวดล้อม	ลายมือชื่อนักศึกษา...
ปีการศึกษา 2545	ลายมือชื่ออาจารย์ที่ปรึกษา................................

Acknowledgements

The author wishes to express her sincere appreciation and thanks to her thesis advisor, Dr. Sudjit Karuchit, for his guidance and advice towards the completion of this study. The author would also like to extend her thanks to Assist. Prof. Dr. Ranjna Jindal and Dr. Pornsiri Jongkol who served as members of her thesis examination committee. Special thanks are due to Assist. Prof. Dr. Ram Sharma Tiwaree who had provided valuable suggestions and comments as a former advisor.

Special thanks are extended to Rungsun Sarochakawisit and Khun Asawin for their great help in data collection.

Finally, the author wishes to express her deep sense of gratitude to her parents and grandmother for their support and encouragement throughout her course of study at the Suranaree University of Technology (SUT).

Sasithon Monthip

Table of Contents

Page

Table of Contents (Cont.)

Page

Table of Contents (Cont.)

Page

Table of Contents (Cont.)

Page

List of Tables

Table **Page**

List of Tables (Cont.)

Table **Page**

List of Figures

Figure **Page**

List of Figures (Cont.)

Figure Page

List of Figures (Cont.)

Figure Page

List of Abbreviations

BAU	=	Business-as-usual
Btu	=	British thermal unit
Cal	=	Calorie
CO	=	Carbon monoxide
CO_2	=	Carbon dioxide
DEDP	=	Department of Energy Development and Promotion
EIA	=	Energy Information Administration
GDP	=	Gross domestic product
GHG	=	Greenhouse gas
GJ	=	Giga joules
IPCC	=	Intergovernmental Panel on Climate Change
J	=	Joule
ktoe	=	Kilo ton of oil equivalent
kg	=	Kilogram
Mton	=	Million ton
Mtoe	=	Million ton of oil equivalent
NO_x	=	Nitrogen oxides
SO_2	=	Sulfur dioxide
tce	=	Ton of coal equivalent
TDRI	=	Thailand Development Research Institute
TJ	=	Tera joules
toe	=	Ton of oil equivalent
TSIC	=	Thailand Standard Industrial Classification
USEPA	=	The United Stated Environmental Protection Agency

Chapter I
Introduction

1.1 Introduction

Energy is an important parameter for the economic development of a nation. Consumption of energy in a society supports the expansion of economic activities and improves the standard of living of the people. At present, the demand for energy has been largely met by fossil fuels and bio-mass in all parts of the world. Fossil fuels are non-renewable resources. Nevertheless, they are still sufficiently available to meet the presently growing demand for energy in our society. Moreover, fossil fuels and bio-mass are still low-cost energy sources. On the other hand, these fuels are major sources of various air pollutants. Burning of coal, oil, bio-mass or natural gas (to a certain extent) produce undesirable gases like carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other pollutants. In addition to the local air pollution problem, emissions of these gases are the causes of regional and global environmental problems, namely, acid rain and global warming.

Along with the strong economic growth propelled by the significant growth in industrial production in the last decade, energy consumption in Thailand has a sharp rise. Total energy consumption in Thailand in the year 1998 was 45.7 Mtoe (petroleum products 57.46%, renewable energy 18.52%, electricity 15.01%, coal & coke 7.09%, and natural gas 1.93%) (Department of Energy Development and Promotion [DEDP], 1998) and the corresponding CO_2 emission was about 43 MtonC, which is 1.17% of CO_2 emission from APEC countries (Energy Information Administration [EIA], 2000). CO_2 emissions can largely be attributed to the industrial and transportation sectors in Thailand. In the year 1999, the total energy consumption increased 4.4% over the previous year. Likewise, CO_2 emission increased about 2.86% over the previous year.

Industrial sector is the large consumer of energy in Thailand. Industrial sector's energy consumption in the year 1999 accounted for 34.5% of the total consumption or 16,129 ktoe. The energy consumption in this sector is very intensive as compared with other sector. The energy consumption is the cause of the emissions of air pollutants. Moreover, the inefficient use of energy has resulted in increased consumption of energy and emission of air pollutants. Therefore, the objectives of this study were set to examine the existing and future situations of industrial sector in Thailand and, for selected cases, and to recommend suitable techno-economic options for the improvement of energy efficiency and the reduction in the emission of air pollutants. From this study, CO_2, SO_2, and NO_x emissions from the industrial sector could be clearly estimated. The findings of this study could be useful to the individual industrial enterprises in such a way that they can improve their existing production technology or replace it by the advanced production technology that is more environmentally than the existing one.

1.2 Research Objectives

The main objectives of this study were:

1.2.1 To estimate the energy use and energy efficiency of the industrial sector of Thailand.

1.2.2 To estimate the energy related emissions of CO_2, SO_2, and NO_x from the industrial sector of Thailand.

1.2.3 To estimate future energy use and pollutant emissions from the industrial sector of Thailand.

1.2.4 To recommend the most appropriate measures to improve existing energy efficiency of and to mitigate the emissions of CO_2, SO_2, and NO_x from the selected industrial sector of Thailand.

1.3 Scope and Limitations of the Study

1.3.1 Information on energy use, energy efficiency, and emission of exhaust gases, such as CO_2, SO_2, and NO_x from industries was collected and/ or estimated for a period of past 9 years (1991-1999).

1.3.2 The energy data include all types of energy including petroleum products, natural gas, coal and lignite, electricity, and bio-mass that have been in use by the industries.

1.3.3 The industrial classification was based on Thailand Standard Industrial

Classification (TSIC).

1.3.4 Estimation of the future energy use and pollutant emission was performed under business-as-usual scenario (BAU) using appropriate mathematical equations.

1.3.5 Techno-economic analyses for the improvement of energy efficiency, and reduction of the emissions of the pollutants were done for the three industries in non-metal sub-sector, which included firebrick industry, glass industry, and cement industry.

Chapter II
Literature Review

2.1 Energy

2.1.1 Sources of Energy

The sources of energy in Thailand can be divided into two main groups. The first group is non-renewable energy the other group is renewable energy. Both types of fuel have been used in Thailand (Rungsun Sarochakawisit, 1998).

(i) Non-renewable resources. Natural resources which once consumed cannot be replaced. It generally refers to fossil fuels. Fossil fuel developed from plants and animals become embodied in the earth and is changed to their present forms over an extended period. Fossil fuels consist of fuels such as coal, lignite, natural gas, liquid petroleum, and various forms of petroleum such as gasoline, diesel, airplane fuel, kerosene, and furnace oil.

(ii) Renewable energy resources. Those sources of energy, which do not rely on the energy of, limited quantity. Renewable sources depend on the energy from the sun or gravitation forces. The renewable energy resources are generally considered to include: solar, biomass, wind, wave, tidal, and hydro.

Energy can also be classified as:

(a) *Gaseous fuels* such as natural gas and petroleum gas.

(b) *Liquid fuels* such as gasoline, diesel, kerosene, airplane fuel, and furnace oil.

(c) *Solid fuels* such as bituminous, anthracite, and coke & coal.

2.1.2 Energy Flows

It was noticed earlier that energy conversions from the original form to the useful form often takes place in a number of intermediate stages. The energy flow from one stage to another at each conversion, transformation or transport step, and these steps can be considered as a chain (Food and Agriculture Organization of the United Nations [FAO], 1997) as shown in Figure 2.1.

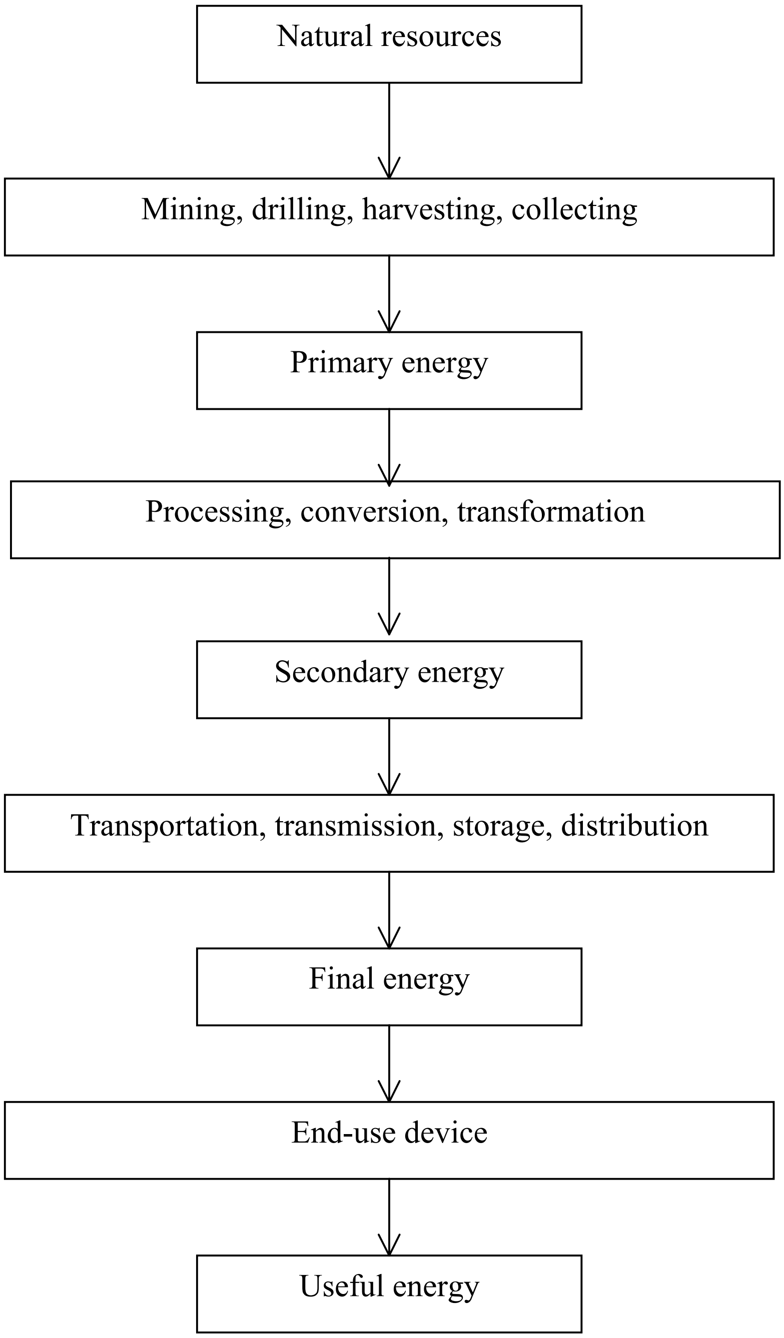

Figure 2.1. Energy flow diagram (FAO, 1997).

When constructing the chain, energy is classified into four types (Hall and Hinman, 1983):

(i) Primary energy. Energy considered to be coming from natural and original source. Although solar and nuclear are considered the most basic energy

source, the generally accepted primary source of energy are solar, coal, oil, natural gas, falling and flowing water, wind, uranium, geothermal, and biomass. Some sources of primary energy are used directly for fuel and some are converted to a secondary form.

ii) Secondary energy. Fuel which is produced by processing primary energy sources. The secondary energy has more desirable properties than the primary source. Secondary energy may be solid, such as coal or coke; liquid, such as gasoline, diesel or fuel oil; or gas.

(iii) Final energy. This is the energy that the consumer buys or receives.

(iv) Useful energy. This is the energy actually required to perform the work.

2.1.3 Unit of Energy

There are many ways of measuring energy, and although most scientists internationally use the same unit, the joule (J), it is quite common to find other units in everyday use. Americans and many engineers, particularly when talking about steam, use British thermal unit (Btu), and in India, the calorie (cal) is still common. National energy statistics use ton of coal equivalent (tce) or ton of oil equivalent (toe).

2.1.4 Energy Use in Thailand

In the year 1999, the Thai economy has generally recovered resulting in an increase of 4.4% in the total energy demand from the year 1998. The total energy consumption for the year 1999 was 47,699 ktoe. Petroleum product still showed the greatest of the total energy consumption. Petroleum products consumption totaled 26,873 ktoe, and a accounted for 56.3% of the total energy consumption, followed by renewable energy consumption accounted for 18.6% (8,892 ktoe) of the total energy consumption and electricity consumption accounted 14.6% (6,941 ktoe) of the total energy consumption. The coal, lignite, and natural gas were the small proportion in the total energy consumption. Coal and lignite consumption amounted to 3,876 ktoe, and accounted for 8.1% of the total energy consumption. While natural gas consumption totaled 1,117 ktoe, it was about 2.4% of the total energy consumption in Thailand.

The energy consumption in mining sector in the year 1999 increased very rapidly about 112.5% over the year 1998, but it still shared the least proportion (0.2% of the total energy consumption). All energy consumed in this sector was petroleum products only.

Moreover, petroleum products consumption was the major contributor in energy consumption in the agricultural sector, its share about 99.4% and the remaining was electricity. In the year 1999, agricultural sector consumed energy 2,160 ktoe, accounted for 4.5% of the total energy consumption. It increased by 14.9% from the year 1998.

Energy consumption in manufacturing sector was 16,129 ktoe, an increase of 12.1% over the year 1998, and accounted for 33.8% of the total energy consumption. The major energy consumption was renewable energy, followed by petroleum product, coal and lignite, electricity, and natural gas.

Energy consumption in Transportation sector was a slight increase about 0.7% from the year 1998. It accounted for 39.8% of the total energy consumption (18,991 ktoe). Most of the energy consumed in this sector was petroleum product. A small volume of natural gas for vehicle (NGV) was also consumed in some air-conditioned buses in Bangkok Metropolitan Region.

Energy consumption in construction, residential and commercial sectors was declined by 10.6% and 1.4% of the total energy consumption from the year 1998 respectively. All energy consumed in construction sector was petroleum products, it was 273 ktoe and accounted for 0.5% of the total energy consumption. The residential and commercial sectors consumed energy 10,114 ktoe, it was about 21.2% of the total energy consumption. Energy consumed in this sector comprised renewable energy, electricity, and petroleum products.

2.2 Energy Efficiency

According to Gunn (1997), energy efficiency is often confused with energy conservation. Conservation simply means using less energy, typically by “switching off”, whereas efficiency relates to achieving the same quality and level of some “end-use” of energy (e.g., heating, cooling, lighting, motive power, and watching TV) with a lower level of energy input. Proponents of such a view identify at least five key reasons for advocating energy efficiency:

(a) saving money by investing in those technologies between the naturally occurring potential and the economic potential.

(b) reducing energy dependence; especially on imports of fossil fuels.

(c) enhancing intergenerational and international equity.

(d) mitigating environmental effects and global warming.

(e) moving toward sustainability.

According to Patterson (1996), energy efficiency is a generic term, and there is no one unequivocal quantitative measure of energy efficiency. Instead, one must rely on series of indicators to quantify changes in energy efficiency. In general, energy efficiency refers to using less energy to produce the same amount of services or useful output. Hence, energy efficiency is often broadly defined by the simple ratio:

$$\text{Energy efficiency} = \frac{\text{useful output of a process}}{\text{energy input into a process}} \tag{2-1}$$

A number of indicators can be used to monitor changes in energy efficiency. These indicator fall into four main groups:

(i) Thermodynamic: These are energy efficiency indicators that rely entirely on measurements derived from the science of thermodynamics. Some of these indicators are simple ratios and some are more sophisticated measures that relate actual energy usage to an "ideal" process.

(ii) Physical-thermodynamic: These are hybrid indicators where the energy input is still measured in thermodynamic unit, but the output is still measured in physical units. These physical units attempt to measure the service delivery of the process e.g., in terms of tones of product or passenger miles.

(iii) Economic-thermodynamic: These are also hybrid indicators where the service delivery (output) of the process is measured in term of market prices. The energy input, as with the thermodynamic and physical-thermodynamic indicators, is measured in terms of conventional thermodynamic units. Economic-thermodynamic indicators are more useful for macro-level policy analysis.

(iv) Economic: These indicators measure changes in energy efficiency purely in terms of market values ($). That is, both the energy input and service delivery (output) are enumerated in monetary terms.

The effectiveness of energy is used to measure the innovation of energy used. The comparison on base year method is done by assessing the quantity of energy used in the present compared with the base year data. Decrease of used energy means improvement in the usage method while increases in energy usage means there are no improvements or the system is degraded (DEDP, 2000a). Thus, energy efficiency in the year t can be estimated as:

$$\text{Energy efficiency in the year t (\%)} = \frac{(B - A)}{A} \times 100 \qquad (2\text{-}2)$$

where

A = Energy used in base year

B = Energy use in the year t

2.3 Chemistry of Carbon Dioxide (CO_2)

CO_2 is a colorless, odorless, and slightly acid-tasting gas molecule, which consists of one atom of carbon and two atoms of oxygen (CO_2). It is produced in a variety of ways; by combustion or oxidation of materials containing carbon, such as coal, wood, oil, or foods by fermentation of sugars and by decomposition of carbonates under the influence of heat or acids (Nevers, 1995).

CO_2 is a large contributor to the greenhouse effect. There are small amounts of it in the atmosphere to keep reflected heat from escaping. Humans have made buildings and machines that release CO_2 into the air. The CO_2 count in the air has nearly doubled since the beginning of the industrial era. Trees help remove CO_2 from the air as a natural process, but as humans keep on cutting down trees, there will be fewer and fewer recycled molecules of CO_2, causing more CO_2 to be in the air. Large amounts of CO_2 in the atmosphere causes more heat to be kept in, causing global warming.

Absorption of CO_2 by water leads to the following equilibria (Nevers, 1995):

$$CO_{2(g)} + H_2O \longrightarrow CO_2H_2O \quad (2\text{-}3)$$

$$CO_{2(g)} + H_2O \longrightarrow H_2CO_3 \longrightarrow H^+ + HCO_3^- \quad (2\text{-}4)$$

$$HCO_3^- \longrightarrow H^+ + CO_3^{2-} \quad (2\text{-}5)$$

Carbonic acid is a weak acid, with the acid concentration in the rain depending on the concentration of the CO_2 in the air. Generally, any rain with a pH less than 5.6 is considered acidic, but damage to plants and an animal does not begin to become apparent until a pH of about 4.5 or less is reached.

2.4 Chemistry of Sulfur Dioxide (SO_2)

The overall reaction for the formation of SO_2 from sulfur in fossil fuels are (Nevers, 1995).

$$S + O_2 \longrightarrow SO_2 \quad (2\text{-}6)$$

In addition to SO_2, a small quantity of sulfur trioxide (SO_3) is formed in the combustion reaction. In the combustion of fossil fuels, the SO_2/SO_3 ratio is typically 40:1 to 80:1 (Cheng and Mori, 2000).

There are several potential reactions that can contribute to the oxidation of SO_2 in the atmosphere, each with varying success. One possibility is photooxidation of SO_2 by ultraviolet light. Light in this region of the electromagnetic spectrum has the potential to excite the molecule and lead to the subsequent oxidation by O_2. This reaction was found to be an unimportant contributor to the formation of sulfuric acid. A second possibility is the reaction of SO_2 with atmospheric oxygen by the following reactions:

$$2SO_2 + O_2 \longrightarrow 2SO_3 \quad (2\text{-}7)$$

$$SO_3 + HO_2 \longrightarrow H_2SO_4 \quad (2\text{-}8)$$

Reaction (2-8) occurs quickly. Therefore, the formation of SO_3 in the moist atmosphere is assumed to lead to the formation of SO_2. However, reaction (2-7) is very slow in the absence of a catalyst. Therefore, this is also not a significant contributor. There are several other potential contributors including oxidation by products of alkene-ozone reactions, oxidation by reactions of N_xO_y species, oxidation by reactive oxygen transients, and oxidation by peroxy radicals. All of these reactions, however, prove to be insignificant for varying reasons (i.e., too slow). Although each of these reactions may make a minor contribution to the oxidation of SO_2, it is thought to be only one significant reaction. The reaction occurs as follows:

$$HO + SO_2 \longrightarrow HOSO_2 \quad (2\text{-}9)$$

This reaction occurs at an appreciable rate and is thought to be the sole contributor to the oxidation of SO_2 in the atmosphere. The hydroxy radical is produced by the photo-decomposition of ozone and is considered to be highly reactive with many species (Seinfeld, 1986).

In the aqueous phase, SO_2 exists as three species:

$$[S(IV)] \longrightarrow [SO_{2(aq)}] + [HSO_3^{2-}] + [SO_3^{2-}] \quad (2\text{-}10)$$

This dissociation occurs by a two-fold process:

$$SO_{2(aq)} \longrightarrow H^+ + HSO_3^- \quad (2\text{-}11)$$

$$HSO_{3(aq)}^- \longrightarrow H^+ + SO_3^{2-} \quad (2\text{-}12)$$

The establishment of the above equilibrium is dependent upon such things as pH, droplet size, the "sticking coefficient" for SO_2 on water, etc.

The oxidation of aqueous SO_2 by molecular oxygen relies on a metal catalyst, such as, Fe^{3+} or Mn^{2+} or a combination of the two. Oxidation by ozone, however, is a more appreciable process because it does not require a catalyst and it is 10^{-8} to 10^{-9} more abundant in the atmosphere than molecular oxygen. The dominant oxidation process occurs by hydrogen peroxide (formed in the gas phase from free radicals). The reaction involves the formation of an intermediate (A^-), possibly a peroxymonosulfurous acid ion (Cheng and Mori, 2000), and proceeds as follows:

$$HSO_3^- + H_2O_2 \longrightarrow A^- + H_2O \quad (2\text{-}13)$$

$$A^- + H^+ \longrightarrow H_2SO_4 \quad (2\text{-}14)$$

2.5 Chemistry of Nitrogen Oxides (NO_x)

Wark et al. (1998) reported that about 90% of all the man-made nitrogen oxides that enter our atmosphere is produced by the combustion of various fuels. Among the possible atmospheric reaction for the formation of nitric acid are:

$$O_3 + NO_2 \longrightarrow NO_3 + O_2 \quad (2\text{-}15)$$

$$NO_3 + NO_2 \longrightarrow N_2O_5 \quad (2\text{-}16)$$

$$N_2O_5 + H_2O \longrightarrow 2HNO_3 \quad (2\text{-}17)$$

$$OH + N_2O \longrightarrow HNO_3 \quad (2\text{-}18)$$

There are several other existing possibilities, such as, oxidation by atmospheric oxygen. However, none of them occurs at a substantial rate in the atmosphere to become significant contributor to the formation of nitric acid (Cheng and Mori, 2000).

There are three equilibria to consider in the aqueous oxidation of NO_x. They are:

$$2NO_{2(g)} + H_2O_{(l)} \longrightarrow 2H^+ + NO_3^- + NO_2^- \quad (2\text{-}19)$$

$$NO_{(g)} + NO_{2(g)} + H_2O_{(l)} \longrightarrow 2H^+ + 2NO_2^- \quad (2\text{-}20)$$

$$3NO_{2(g)} + H_2O_{(l)} \longrightarrow 2H^+ + 2NO_2^- + NO_{(g)} \quad (2\text{-}21)$$

These reactions are limited by their dependence upon the partial pressures of NO_x present in the atmosphere, and the low solubility of NO_x. Potential for increase in reaction rate exists with the use of metal catalysts, similar to those used in the aqueous oxidation of SO_2.

2.6 The Effects of Emissions of Carbon Dioxide, Sulfur Dioxide, and Nitrogen Oxides

Air pollution, acid rain, and greenhouse effects are major environmental problems caused by burning of fossil fuels. For each of these problems, coal is the main worst offender. Air pollution is caused by emission of toxic gases such as SO_2, NO_x and CO together with fly ash and suspended particles. It can cause a serious threat to health, and cause a high incident of respiratory problems. Coal and high sulfur fuel oil are the worst offenders in producing acid rain.

CO_2 constitutes about 50% of the greenhouse gas (GHG) emissions in the world and most of the CO_2 is released by fossil fuel combustion (Yu, 1995). Before the industrial revolution (1750-1800), the amount of CO_2 in the atmosphere was about 270 ppm and had increased to 356 ppm in the 1990. This figure is expected to double that of the pre-industrial level by 2100 (Thailand Environment Institute [TEI], 1990).

TEI (1990) reported that the amount of GHG emissions from Thailand was 225 Mton of CO_2 equivalents in the year 1990. The emission of CO_2 was 164 MtonCO_2 or 73% of the three significant green house gas (CO_2, CH_4, and N_2O), followed by CH_4 emission was 2.8 MtonCH_4 or 58 Mton of CO_2 equivalent and N_2O emission was 0.01 MtonNO_2 or 3 Mton of CO_2 equivalent. The other GHGs, nitrogen oxide, carbon monoxide, and non-methane volatile organic carbon were emitted in small qualities, 0.5, 1.85, and 0.27 Mton, respectively.

In the year 1990, the total GHG emissions from industrial sector of Thailand were 17 Mton (CO_2 emission was 16.39 MtonCO_2, CH_4 315 tonCH_4, and volatile organic compounds 122 ton). The CO_2 emission from cement production was 9 MtonCO_2, lime manufacturing was 238,240 MgCO_2, glass production was 28,745.9 MgCO_2, and Pulping Process was 32,029 MgCO_2. In 1994, the increasing emission rates of the CO_2 were 39.68%, 74.05%, 54.81%, and 35.02% respectively. The NO_x emission from glass production was 874.4 MgNO_x in 1990 and 1934.97 MgNO_x in 1994 (Chuntisa Kessmanee, 1997).

Lenz and Cozzarini (1999) reported that despite of efforts in many industrialized nations to reduce CO_2, the emissions would nevertheless increase in the future. Because of their increasing energy consumption in the course of economic growth, countries in Asia, Oceania, and Central and South America will contribute the greatest amount of CO_2 emissions during the coming years. However, CO_2 emissions in North America and Europe will continue to decrease in the future (Figure 2.2).

2.6.1 Greenhouse Effects

If the greenhouse effect causes the earth's mean temperature to rise even slightly climatic changes will result. The form these changes will take is unknown. Large-scale computer modeling of the atmosphere suggests what will happen, but the calculations are still considered somewhat speculative. If rising temperatures were to melt the ice cap in Antarctica, the world sea level would rise several hundred feet, flooding most of the coastal cities and agricultural areas of the world (Nevers, 1995). Temperature increases much smaller than those needed to melt the ice caps would cause the deserts and the temperate zones to extend farther from the equator. Agricultural areas that are currently highly productive would become dry and hotter, while sub-Arctic regions would become warmer and wetter.

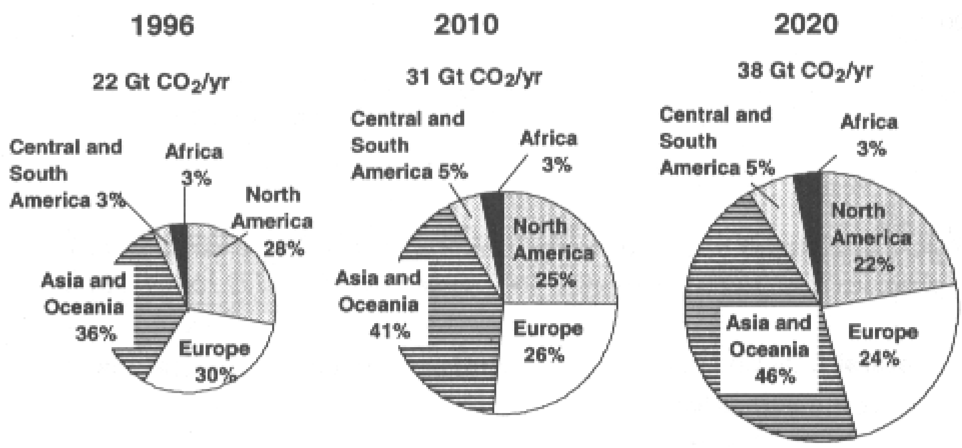

Figure 2.2. Prognosis for the contribution of individual continents to carbon dioxide emissions from fossil fuel burning (Lenz and Cozzarini, 1999).

The best current estimates are that, for a business-as-usual projection of future emissions of all greenhouse gases, the global mean temperature will increase by 0.2° to 0.5° per decade for the next century. This change in global temperature is more rapid than any other that has occurred in the past 10,000 years. The corresponding projection of world sea level is for a rise of 3 to 10 cm/decade over the same period (Nevers, 1995).

The greenhouse problem has a strong overshoot. The oceans have several hundred times the heat storage capacity of the atmosphere. As greenhouse warming raises the temperature of the atmosphere, at first the cooler oceans will remove heat, slowing the rate of atmospheric temperature increase. However, as the surface layers of the ocean become warmer, that cooling effect will decline, thus producing a temperature overshoot in the atmosphere. This overshoot is likely to have a time scale of several hundred years at current emission rates. Thus, if we were to take steps that guaranteed that the composition of the atmosphere remained at its current state, there would still be a significant atmospheric temperature increases in the next few decades due to this overshoot.

2.6.2 Acid Rain

The United States Environmental Protection Agency [EPA] (1999) reported that air pollution creates acid rain. Scientists have discovered that air pollution from the burning of fossil fuels is the major cause of acid rain. Acid deposition, or acid rain as it is commonly know, occurs when emissions of SO_2 and NO_x react in the atmosphere with water, oxygen, and oxidants to form various acidic compounds. This mixture forms a mild solution of sulfuric acid and nitric acid. Sunlight increases the rate of most of these reactions. These compounds then fall to the earth in either wet form (such as rain, snow, and fog) or dry form (such as gas and particles). About half of the acidity in the atmosphere falls back to earth through dry deposition as gases and dry particles. The wind blows these acidic particles and gases onto buildings, cars, homes, and trees. In some instances, these gases and particles can harm the things on which they settle. Dry deposited gases and particles are sometimes washed from trees and other surfaces by rainstorms. When that happens, the runoff water adds those acids to the acid rain, making the combination more acidic than the falling rain alone. Prevailing winds transport the compounds, sometimes hundreds of miles, across state and national borders.

Acid rain causes acidification of lakes and streams and contributes to damage of trees at high elevations (for example, red spruce trees above 2000 feet in elevation). In addition, acid rain accelerates the decay of building materials and paints, including irreplaceable building, statuses, and sculptures that are part of cultural heritage. Prior to falling to the earth, SO_2 and NO_x gases and their particulate matter derivatives, sulfates and nitrates, contribute to visibility degradation and impact public health.

2.7 Estimation of Emissions of Carbon Dioxide, Sulfur Dioxide, and Nitrogen Oxides

Statistical method developed for the energy consumption can be used for the analysis of atmospheric pollutant emissions. Sectoral emissions can be estimated from energy consumption, following the method presented by the Intergovernmental Panel on Climate Change [IPCC]. The emissions of these gases depend on the fuel type used, combustion technology, operating conditions, control technology, and maintenance and age of the equipment (Intergovernmental Panel on Climate Change [IPCC], 1996). The amount of emissions can be estimated from fossil fuel consumption data since emissions from combustion depends on content of the fossil fuel type, which can be obtained through element analysis of each fossil fuel type (Kumar, 1993).

2.8 Emission Reduction associated with Energy Use and Control Technologies

EIA (1992) proposed the type of activities that may be undertaken to reduce energy consumption and the associated emission of pollution gases. These include:

(a) Use of energy efficient equipment and processes

(b) Switching from high-emitting fuel to lower-emitting fuels

(c) Cogeneration steam and electricity

(d) Improving operational and maintenance practices

(e) Recycling input materials

(f) Undertaking efforts to improve productivity.

Methods to improve the system to be more energy-efficient and new alternative technologies involving process and equipment, which consumes less energy, can be classified as energy efficiency and conservation measures. These measures could be categorized into three options (Mohanty, 1997):

(a) Short-term measures: These are the immediate actions which can be taken without substantial investment to achieve a certain level of energy saving. Examples of these measures are simple housekeeping and maintenance of the energy consuming equipment, air-fuel ratio adjustment in boiler, stove or furnace and improvement of insulation in the steam network.

(b) Medium-term measures: These measures include switching to new and more efficient technologies as well as recovery of material and waste heat with moderate capital expenditures, such as replacement of boilers and motors and installing air preheater and economizer to reuse the fuel gas having high temperature.

(c) Long-term measures: These measures include major modifications in the production process to increase the efficiency of the industry such as implementing cogeneration system.

An energy analysis conducted by Wongsuwan (1997) focused on small and medium scale agro-food industries in Northern in Thailand. The energy audit was carried out for 4 different agro-food factories; noodle factory, vegetable drying factory, food preservation factory, and fruit canning factory. It was found that the agro-food industries in Northern Thailand consumed 70% of the industrial energy consumption in this region. Of this, implementing energy conservation programs could save around 36%.

According to DEDP's energy audit report conducted for Thai diary factories (DEDP, 1997), energy saving opportunities could be obtained from implementing the fuel measures as mentioned below:

(a) Substituting fuel oil grade A with fuel oil grade C could reduce about 8% of fuel cost. Moreover, nearly 30% may be saved if substituting to diesel oil.

(b) Improving combustion efficiency of boilers could save about 10% of fuel consumption.

(c) Approximately 80% of energy loss in condensation could be received by condensation recovery method.

Wongratanapornkul (1999) conducted energy audit in the milk powder plant and the pasteurized milk plant in the Royal Chitrada Project to evaluate the energy conservation potential. In the milk powder plant, he found that there were opportunities to reduce fuel and electricity consumption nearly by 65% and 26.5%, respectively, while steam modifying of the exiting cleaning procedure could save consumption. In the pasteurized plant, he noted that improving the cleaning method could save approximate 31% of electrical energy.

Priambodo (1998) reported that the sub-sector emitting largest amount of CO_2 per unit of product among audited SMIs sub-sectors in Thailand is garment subsector with 3901 tonCO_2/kton of unit product. Using simple energy conservation, CO_2 emission can be reduced by 16%.

Preadpreaw Wongwuti (1993) reported that the amounts of CO_2 emission from 1992 to 2001 are estimated to increase from 80.2 MtonCO_2 to 134.9 MtonCO_2 for petroleum products, from 7.1 MtonCO_2 to 34.7 MtonCO_2 for natural gas, and from 26.6 MtonCO_2 to 72.5 MtonCO_2 for lignite. CO_2 emission from biomass consumption is estimated to decrease from 48.3 MtonCO_2 in 1992 to 44.6 MtonCO_2 in 2001 as forests in Thailand have been depleted and yields from other biomass fuels, mainly husk, bagasses, hardly increase. If planed hydro resources are utilized as alternative to lignite for electric generation, the total CO_2 emission should be reduced by 51.0 MtonCO_2 in 1993, and 110.0 MtonCO_2 in 2002.

Li et al. (2000) reported new high efficiency and low combustion technology, which can automatically adjust the pulverized coal concentration of every burner according to the boiler load, and make the boiler, operate in optimum combustion mode. The operation practice of the technology used in some power plants indicated that the boiler efficiency increases about 2% and the NO_x amount decreases about 120 mg/Nm^3.

Piccot et al. (1990) focused on emission control technologies. Emission control technology for industrial boiler includes six control technologies (low excess air (LEA), overfire air (OFA), low NO_x burner (LNB), flue gas recirculation, ammonia injection, and selective catalytic reduction). The removal efficiencies for LEA, OFA, and LNB are dependent on the data source. These technologies generally have impact only on NO_x emission and no significantly impact on the emission of CO_2. Selective catalytic reduction (SCR) is primarily most effective in reducing NO_x by about 80%. On the average, ammonia injection and flue gas recirculation are capable of reducing 60% and 40% of NO_x, respectively. Several control technologies applicable to kilns, ovens, and dryers, such as, LEA, LNB, SCR, nitrogen injection, and flue staging. Both LEA and LNB are applicable to kilns and dryers, whose removal efficiencies are 14% and 35% of NO_x, respectively. Nitrogen injection and flue staging are capable of reducing 30% and 50% of NO_x, respectively. The most effective one is SCR that can reduce NO_x by about 80%.

Approximately 10% of the electricity use in the industrial sector in Thailand is for lighting. Fluorescent tube lamps (FTL) represent about 90% of the total lamp used in the industrial sector. It is estimated from the market survey that efficient FTL scale to industrial sector was nearly 4 million units in 1995, it increased to 5.6 million in 1996 and 6 million in 1997. The growth rate of efficient will be 4% in future. It is estimated that energy saving in cement and cement production efficient fluorescent lamp program were 5.91, 20.36, 24.13, 27.30, and 30.89 GWh in 1995, 2000, 2005, 2010, and 2015 respectively (Srikrishnarajah, 1998).

Ekkasit Suwansri (2000) focused on the improvement of energy management. The energy management in cement process can be improve by mean of the following method:

(a) Set up management policy and target in energy saving process.

(b) Assign the master plant on improvement of the energy management process and plan in the section level.

(c) Improve organization the operation in every process.

(d) Plan to operate the machine in appropriately process by control electrical maximum peak demand.

(e) Improve using energy determine and analysis by provide the standard document in determination and appoint the energy audit team to continuously verify the energy utilization.

(f) Improve the follow-up system for the operation energy management of cement process.

From these improvement processes, the specific electrical cost per ton of cement is lower by 25.44%, the thermal cost per clinker unit is reduced by 3.37%, and the capital energy cost is 218.01 million baht lower.

Chapter III
Methodology

This chapter contains information regarding the data collection and the methods to estimate in this study. The steps of the research methodology are shown in Figure 3.1.

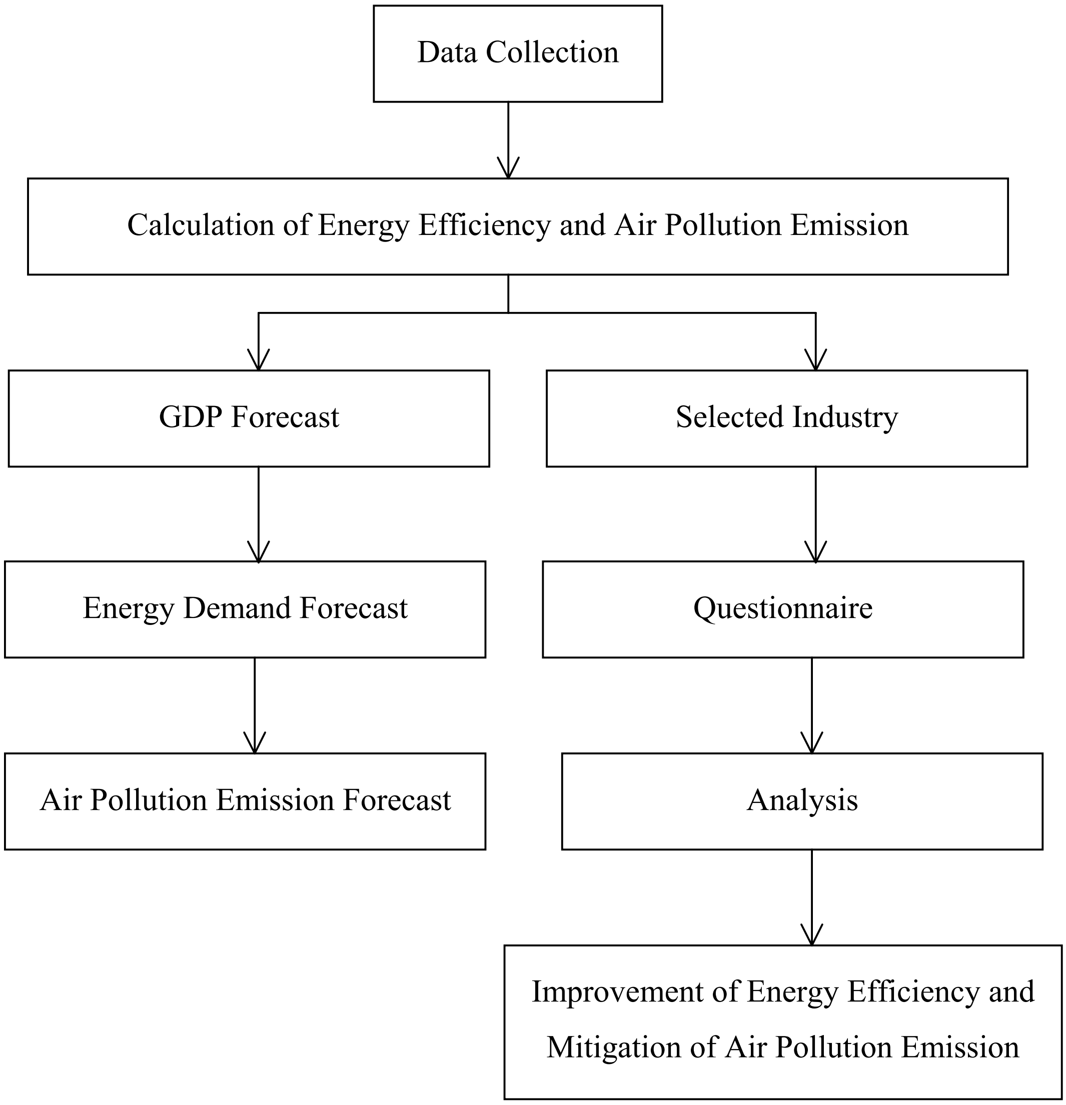

Figure 3.1. Steps of the methodology

3.1 Data Collection

In this study, the analysis were based on the information obtained from various sources as follows:

3.1.1 Energy Consumption Data

Energy consumption data were obtained for 9 years (1991-1999) from Thailand Energy Situation annual reports prepared by the Department of Energy Development and Promotion (DEDP). The energy consumption data can be classified by type of fuels and economic sectors as follows:

a) Type of energy

- Petroleum products (liquefied petroleum gas, unleaded premium gasoline, unleaded regular gasoline, jet fuel & aviation, kerosene, high speed diesel, low speed diesel, fuel oil, and bitumen)
- Natural gas
- Coal and lignite.
- Electricity (primary and secondary)
- Bio-mass (fuel wood, charcoal, paddy husk, and bagasse)

b) Industrial sector

(i) Thailand Standard Industrial Classification (TSIC); Industrial activities are classified into the 9 divisions of industry as shown below: types of industry in each division are presented in Appendix A.

- Food and beverages industries
- Textile industries
- Wood products
- Paper industries
- Chemical products
- Basic metal industries
- Non-metallic industries
- Fabricated metal industries
- Other including unclassified industries

(ii) Scale of industries;

- Small industries (establishments with less than 10 million bahts of registered capital)

- Medium industries (establishments with 10 – 99 million bahts of registered capital)
- Large industries (establishments with 100 million bahts and more of registered capital).

3.1.2 Gross Domestic Product at Factor Cost by Industrial Origin Data

Gross Domestic Product (GDP) data at factor cost for each industrial group were obtained from Office of the National Economic And Social Development Board (NESDB), Office of The Prime Minister.

3.2 Calculation of Energy Efficiency

Energy efficiency of the industries was estimated using economic-thermodynamic indicator, i.e., the energy input were measured in thermodynamic unit (toe) and the output were measured in term of market price unit (GDP at factor cost by industrial group, in Thai baht) as given below.

$$\text{Energy efficiency} = \frac{\text{useful output of a process}}{\text{energy input into a process}} \qquad (3\text{-}1)$$

The efficiency of energy in each year was compared with the base year data as mentioned below.

$$\text{Energy efficiency in the year t (\%)} = \frac{(\text{B} - \text{A})}{\text{A}} \times 100 \qquad (3\text{-}2)$$

where

A = Energy efficiency in base year

B = Energy efficiency in the year t

An example of the energy efficiency calculation for the year 1991 to 1999 is shown in Table B.1, Appendix B.

3.3 Estimation of Carbon Dioxide, Sulfur Dioxide, and Nitrogen Oxides Emissions

Emission of pollutants from energy consumption in each industrial sector was determined by using the Intergovernmental Panel on Climate Change revised methodology 1996 (IPCC, 1996) and emission factors obtained from Department of Energy Development and Promotion which are emission factors for energy consumption in Thailand.

Sectoral emissions were determined by multiplying energy consumption data obtained from the Department of Energy Development and Promotion and concerned industries by the concerned emission factor of a pollutant for each industrial sector.

$$\text{Emission of pollutant} = \text{energy consumption} \times \text{emission factor} \quad (3\text{-}3)$$

3.3.1 Estimation of Carbon Dioxide Emissions

By using the method presented by the Intergovernmental Panel on Climate Change revised methodology 1996 (IPCC, 1996) the sectoral emission of CO_2 from energy consumption were estimated as follow:

$$\text{Emission of } CO_2 = \text{energy consumption} \times EF_{CO_2} \quad (3\text{-}4)$$

$$EF_{CO_2} = \frac{44}{2} \times C \times F \times 10^3 \quad (3\text{-}5)$$

where

EF_{CO2} = Emission factor for CO_2 (kg/TJ)

C = Carbon emission factor (ton/TJ)

F = Fraction of carbon oxidized

10^3 = Unit conversion factor (from ton to kg)

As CO_2 emission factors were calculated and considered from the data published by Department of Energy Development and Promotion. Example of CO_2 emission calculation is given in Table B.2, Appendix B.

3.3.2 Estimation of Sulfur Dioxide Emissions

Sectoral emission of SO_2 from energy consumption were estimated from the following relationship (IPCC, 1996):

$$\text{Emission of } SO_2 = \text{energy consumption} \times EF_{SO_2} \tag{3-6}$$

$$EF_{SO_2} = A \times D \times \frac{1}{Q} \tag{3-7}$$

where

EF_{SO2} = Emission factor for SO_2 (kg/TJ)

A = Molecular weight of SO_2/S (kg/kg)

D = Sulfur content in fuel (kg/L)

Q = Net calorific value (MJ/L)

Data of energy consumption, sulfur content in fuel and net calorific value were extracted from the Department of Energy Development and Promotion, and energy consumption were converted into a common energy unit (TJ). Example of SO_2 emission calculation is given in Table B.3, Appendix B.

3.3.3 The Estimation of Nitrogen Oxide Emissions

Sectoral emissions of NO_x from energy consumption were calculated from the following relationship (IPCC, 1996):

$$\text{Emission of } NO_x = \text{energy consumption} \times EF_{NO_x} \tag{3-8}$$

In this study, NO_x emission factors were considered from the data published by Department of Energy Development and Promotion. Example of NO_x emission calculation is given in Table B.4, Appendix B.

3.4 Macro-Economic Development Trend in Future

The condition and change in the economy are governed by major two factors. The first is uncontrolled economic mechanisms. The second is government policies that can directly or indirectly affect the economy. Macro-economic developments were proposed by Thailand Development Research Institute (TDRI), it is made by incorporating these two major factors into consideration. Thai-economy assumptions were identical to the world economy. The economic development assumptions and the projection of population are provided in Table 3.1.

The manufacturing outputs of the various industries between the years 2000 to 2011 were carried out by stepwise regression with the Statistical Package for the Social Sciences (SPSS) program. It was based on the level of real output from the years 1980 to 1999. Coefficients and evaluation statistics for estimating equations are provide in Appendix C. The actual values of output between the years 1991 to 1999 and forecasted values from the year 2000 through 2011 are also shown in Table D.1.

Table 3.1. Assumption on economic growth and population projection during 2000 –2011.

Year	**2000**	**2001**	**2002-2006**	**2007-2011**
Economic Growth				
GDP	4.2%	3.8%	5.6%	5.7%
Value added				
Agriculture	0.8%	2.2%	2.1%	2.3%
Industry	5.8%	4.3%	6.5%	6.4%
Services	3.6%	3.8%	5.4%	5.6%
Population projection				
Population (million)	61.88	62.4		
Population Growth			0.8%	0.7%

Source Thailand Development Research Institute (TDRI).

3.5 Energy Demand Forecast

The demands for energy under business-as-usual (BAU) scenario were calculated by using the Energy Use Model (Sun, 1997) for the years 2000-2011. The change in energy use is attributed to varying contributions of the sectoral energy intensity effect (EI_{effect}), the structural shift effect (ES_{effect}) and the economic activity effect (V_{effect}). Here, the economic activity effect (V_{effect}) is the basic effect that determines the energy consumption. It may be regarded as the theoretical demand for energy created by economic activity based on the technological level and economic structure in the year under comparison. The energy demand forecast were estimated from the following relationship:

$$E = \sum_i \sum_j \left[\frac{E_{ij}}{V_i} \times \frac{V_i}{V} \times V \right] \tag{3-9}$$

or,

$$E = \sum_i \sum_j \left[I_{ij} \times S_i \times V \right] \tag{3-10}$$

where

i	=	Industry sub-sector
j	=	Fuel type
E	=	Energy damand
E_{ij}	=	Consumption of fuel j in sector i
V_i	=	Value added of sector i
V	=	Total value added
I_{ij}	=	Energy intensity of fuel j in sector i ($I_{ij} = E_{ij}/V_i$)
S_i	=	Structural shift in sector i ($S_i = V_i/V$)

Thus, energy use in time t, or E_t, can be estimated from:

$$\Delta E = E_t - E_{t-1} = EI_{eff} + ES_{eff} + V_{eff} \tag{3-11}$$

$$E_t = \left[1 + \frac{EI_{eff}}{E_{t-1}} + \frac{ES_{eff}}{E_{t-1}} + \frac{V_{eff}}{E_{t-1}} \right] \times E_{t-1} \tag{3-12}$$

where

EI_{eff} = Energy intensity effect

ES_{eff} = Structural shift effect

V_{eff} = Total value added effect

$$EI_{eff} = \sum_i \sum_j \left\{ \left(\Delta I_{ij} \times S_{i,t-1} \times V_{t-1} \right) + \left[\Delta I_{ij} \times \frac{\left(\Delta S_i \times V_{t-1} \right) + \left(S_{i,t-1} \times \Delta V \right)}{2} \right] + \left(\frac{\Delta I_{ij} \times \Delta S_i \times \Delta V}{3} \right) \right\} \quad (3\text{-}13)$$

$$ES_{eff} = \sum_i \sum_j \left\{ \left(I_{ij,t-1} \times \Delta S_i \times V_{t-1} \right) + \left[\Delta S_i \times \frac{\left(\Delta I_{iji} \times V_{t-1} \right) + \left(I_{ij,t-1} \times \Delta V \right)}{2} \right] + \left(\frac{\Delta I_{ij} \times \Delta S_i \times \Delta V}{3} \right) \right\} \quad (3\text{-}14)$$

$$V_{eff} = \sum_i \sum_j \left\{ \left(I_{ij,t-1} \times S_{,t-1i} \times \Delta V \right) + \left[\Delta V \times \frac{\left(\Delta I_{iji} \times S_{i,t-1} \right) + \left(I_{ij,t-1} \times \Delta S_i \right)}{2} \right] + \left(\frac{\Delta I_{ij} \times \Delta S_i \times \Delta V}{3} \right) \right\} \quad (3\text{-}15)$$

The energy demand forecast was determined by using equation (3-12). Example of calculation is given in Table B.5, Appendix B. Data of energy consumption, structural shift and gross domestic product were obtained from various government institutions and private institutes, such financial institutions, economic societies, and Ministry of Science, Technology and Energy.

3.6 Estimation of Future Carbon Dioxide, Sulfur Dioxide, and Nitrogen Oxides Emissions

Air pollution emissions due to energy consumption in industries were estimated for the years 2000 to 2011 by applying the Divisia Method (Viguier, 1999) under BAU scenario.

$$P = \sum_i \sum_j \left[\frac{P_{ij}}{E_{ij}} \times \frac{E_{ij}}{V_i} \times \frac{V_i}{V} \times V \right] \quad (3\text{-}16)$$

or,

$$P = \sum_i \sum_j \left[U_{ij} \times I_{ij} \times S_i \times V \right] \quad (3\text{-}17)$$

where

i	=	Industry sector
j	=	Fuel type
P	=	Air pollution emissions from energy consumption
P_{ij}	=	Air pollution emissions from energy consumption of fuel j in sector i
E_{ij}	=	Consumption of fuel j in sector i
V_i	=	Value added of sector i
V	=	Total value added
I_{ij}	=	Energy intensity of fuel j in sector i ($I_{ij} = E_{ij}/V_i$)
S_i	=	Structural shift in sector i ($S_i = V_i/V$)
U_{ij}	=	Emission factor of fuel j in sector i ($U_{ij} = P_{ij}/E_{ij}$)

From equation (3-17), growth rate of air pollution emission (P) can be calculated as given below:

$$\frac{dP/dt}{P} = \left[\frac{dU_{ij}/dt}{U_{ij}} + \frac{dI_{ij}/dt}{I_{ij}} + \frac{dS_i/dt}{S_i} + \frac{dV/dt}{V} \right] \tag{3-18}$$

$$\frac{d\ln P}{dP} = \left[\frac{d\ln U_{ij}}{dt} + \frac{d\ln I_{ij}}{dt} + \frac{d\ln S_i}{dt} + \frac{d\ln V}{dt} \right] \tag{3-19}$$

$$\frac{p_{t+1}}{P_t} = \exp \ln\left(\frac{U_{ij,t+1}}{U_{ij,t}} \right) \times \exp \ln\left(\frac{I_{ij,t+1}}{I_{ij,t}} \right) \times \exp \ln\left(\frac{S_{i,t+1}}{S_i} \right) \times \exp \ln\left(\frac{V_{t+1}}{V} \right) \tag{3-20}$$

$$P_{t+1} = \left[\exp \ln\left(\frac{U_{ij,t+1}}{U_{ij,t}} \right) \times \exp \ln\left(\frac{I_{ij,t+1}}{I_{ij,t}} \right) \times \exp \ln\left(\frac{S_{i,t+1}}{S_i} \right) \times \exp \ln\left(\frac{V_{t+1}}{V} \right) \right] \times P_t \tag{3-21}$$

In this study, air pollution emissions from energy consumption were determined by using equation (3-21). Example of calculation is given in Table B.6, Appendix B. The energy data and other required data for the last 9 years (1991-1999) obtained from Department of Energy Development and Promotion, Department of Industry, and other government institutions. Future emissions of the air pollutants (such as CO_2, SO_2, and NO_x) were calculated for the years 2000 to 2011.

3.7 Improvement of Energy Efficiency and Reduction of Pollution of Selected Industrial Enterprises

An industrial group was selected for further studies, which include energy efficiency improvement and abatement of pollutant emissions. The industrial group with reasonably low energy efficiency and relatively high emissions of different air pollutants was considered for this purpose.

High intensities in the energy consumption, high emission in environmental pollution, and low energy efficiency characterize the selected industrial enterprises.

Improvement of energy efficiency in an industrial enterprise results in the reduction of emissions of pollutants. Therefore, any improvement of energy efficiency can be considered as one mitigation measure for pollutants' emission, and the pollution mitigation potential can be estimated by the following equation (Priambodo, 1998):

$$P_{reduction} = P_{actual} - P_{possible} \tag{3-22}$$

where

$P_{reduction}$ = pollution reduction potential

P_{actual} = pollution estimated at actual condition

$P_{possible}$ = pollution estimated from possible various actions for reducing pollution emissions

The degree of pollution reduction can be estimated from many types of activities. This estimation would be in percentage of reduction. The methods of technical abatement options of pollution emissions are as follows:

1) Energy efficiency improvement: This is done by considering (i) the end use side, such as variable speed motors and insulation; and (ii) the conversion side, such as co-generation application and advanced boiler.

2) Fuel substitution: This is done by switching from high-emitting fuels to lower-emitting fuels (such as fuel switching from coal to gas or electricity).

3) Improvement of the production technology: considering in the energy-orientated design, careful maintenance and upgrading or replacement of existing production technology.

Selection of a suitable production technology or equipment for improving energy efficiency and reduction in the emission of the pollutants were based on the techno-economic analysis. The analysis was based on estimation of the costs associated with each of the technology and comparison of the differences in cost between the alternatives.

Chapter IV
Results and Discussion

4.1 Energy Situation in Thailand

In 1999, the industrial sector consumed about 34.45% of total energy consumption in Thailand (DEDP, 1999), as shown in Figure 4.1. It consists of 3 sub-sectors: manufacturing, construction, and mining. It can be seen that the industrial sector is the second highest sector with respect to energy consumption (after transportation sector).

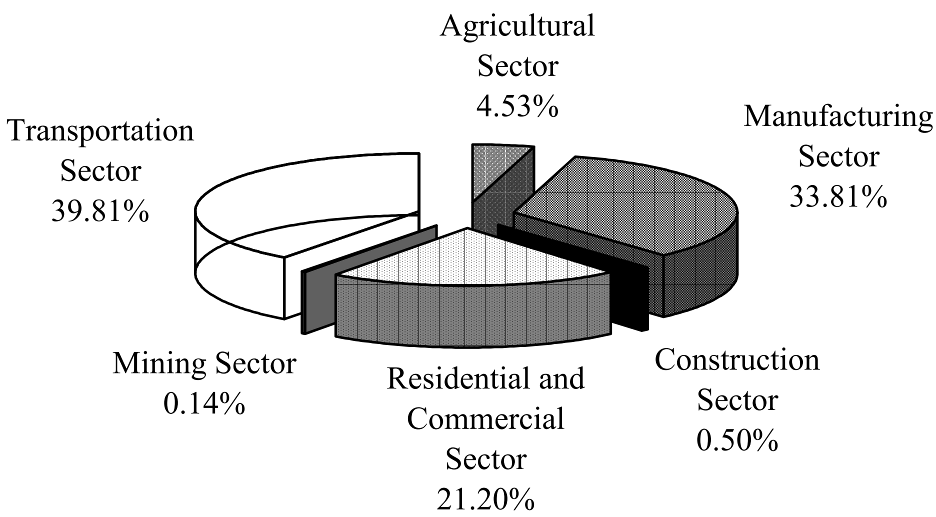

Figure 4.1. Thailand's energy consumption by economic sector in the year 1999 (DEDP, 1999).

The industrial sector is very important in the development of Thai economy. There is a close relationship between economic growth and energy consumption. In the last decade, the economic growth rate and the energy consumption growth rate were almost same, eventhrough the energy consumption growth rate was higher in some years. Figure 4.2 illustrates the annual growth rate of industrial output in the period 1991 to 1999. It can be observed that between the years 1991 to 1996 the annual average growth rate was 10.20% while the annual average between the years

1997 to 1999 periods were –2.78%. The amount of energy consumed by this sector also increased at average growth rate of 7.02% per year during the years 1991 to 1999. The relationship between energy consumption and output of industrial sector can be explained by energy intensity. The energy intensity is the ratio of final energy used to produce the industrial output (toe/million baht of industrial production). As shown in Figure 4.2, upward and downward trends of energy intensity indicated that the increase and decrease in energy consumption in manufacturing of industrial output was a result of industrial output. If the energy intensity were not reduced, the amount of energy to be consumed would increase even more. The energy consumption in industrial sector depends on the amount of industrial output and the price of energy used to produce the industrial sector also increased at average growth rate of 7.02% per year during the years 1991 to 1999. The relationship between energy consumption and output of industrial sector can be explained by energy intensity. The energy intensity is the ratio of final energy used to produce the industrial output (toe/million baht of industrial production). As shown in Figure 4.2, upward and downward trends of energy intensity indicated that the increase and decrease in energy consumption in manufacturing of industrial output was a result of industrial output. If the energy intensity were not reduced, the amount of energy to be consumed would increase even more. The energy consumption in industrial sector depends on the amount of industrial output and the price of energy used to produce the industrial output.

4.1.1 Energy Consumption by Type of Fuel

From Figure 4.1, when compared in industrial sector, the proportion of manufacturing sector is more than 97% of the total energy consumed in this sector. Therefore, industrial sector in this study is aimed at manufacturing, which is classified into 9 sub-sectors according to the TSIC (see in Appendix A). The composition of Thai industrial sector's final energy consumption in 1999 was shown in Figure 4.3. This sector consumed 16,129 ktoe of energy, of which 25.34% or 4,087 ktoe was renewable energy, 24.62% or 3,971 ktoe was petroleum products, 24.03% or 3,876 ktoe was solid fossil fuel, 19.11% or 3,083 ktoe was electricity, and 6.89% or 1,112 ktoe was natural gas.

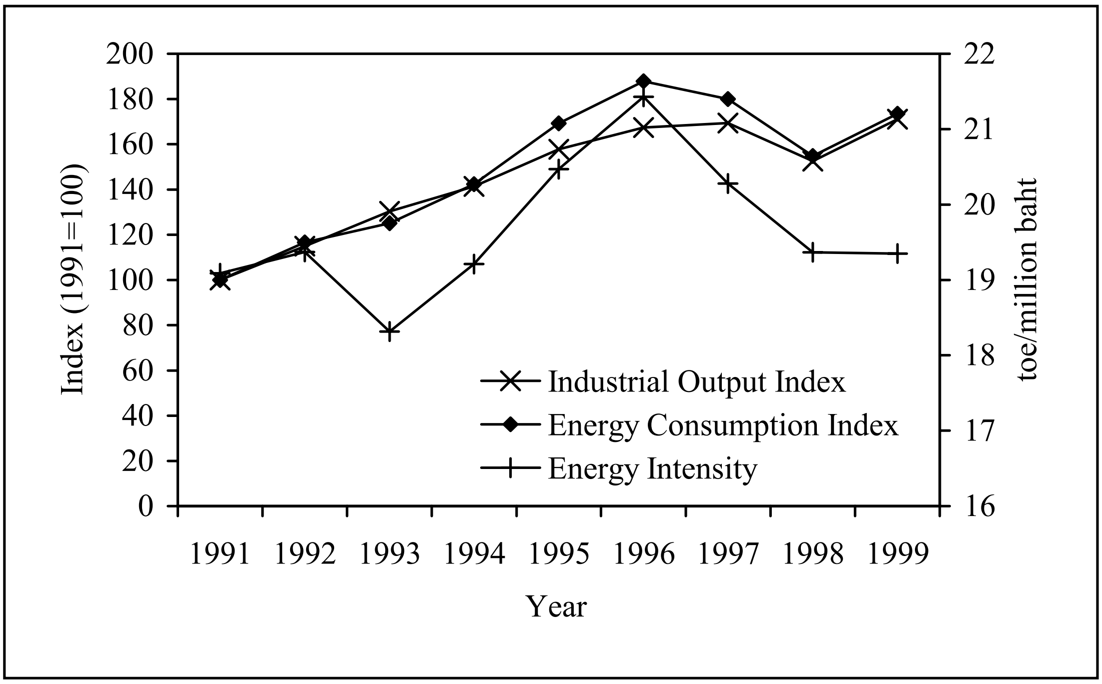

Figure 4.2. Industrial output and energy consumption in industrial sector during the years 1991 to 1999. (DEDP, 1999)

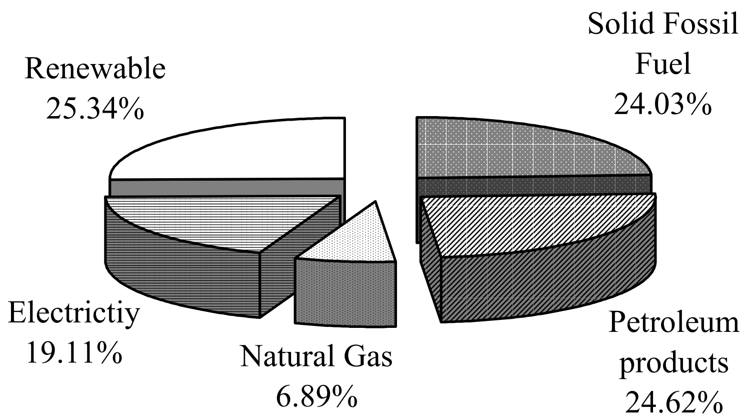

Figure 4.3. The proportion of energy consumption in the industrial sector in the year 1999 (DEDP, 1999).

Figure 4.4 shows that the total energy consumption in industry increased from 9,300 ktoe in the year 1991 to 16,129 ktoe in the year 1999. Out of this, modern energy consumption, which includes solid fossil fuel, petroleum product, natural gas, and electricity, grew at 8.45% from 6,293 ktoe in the year 1991 to 12,042 ktoe in the year 1999 and renewable energy increased with annual average growth rate of 3.91% from 3,007 ktoe to 4,087 ktoe. Consider the modern energy, in the period of the years 1991 to 1996, consumption of modern energy increased very fast by an annual average growth rate of 15.64%. Although its decreased in 1997 and 1998 due to negative economic growth. The energy consumption was driven by economic activities such as market mechanism and fuel distribution to consumer.

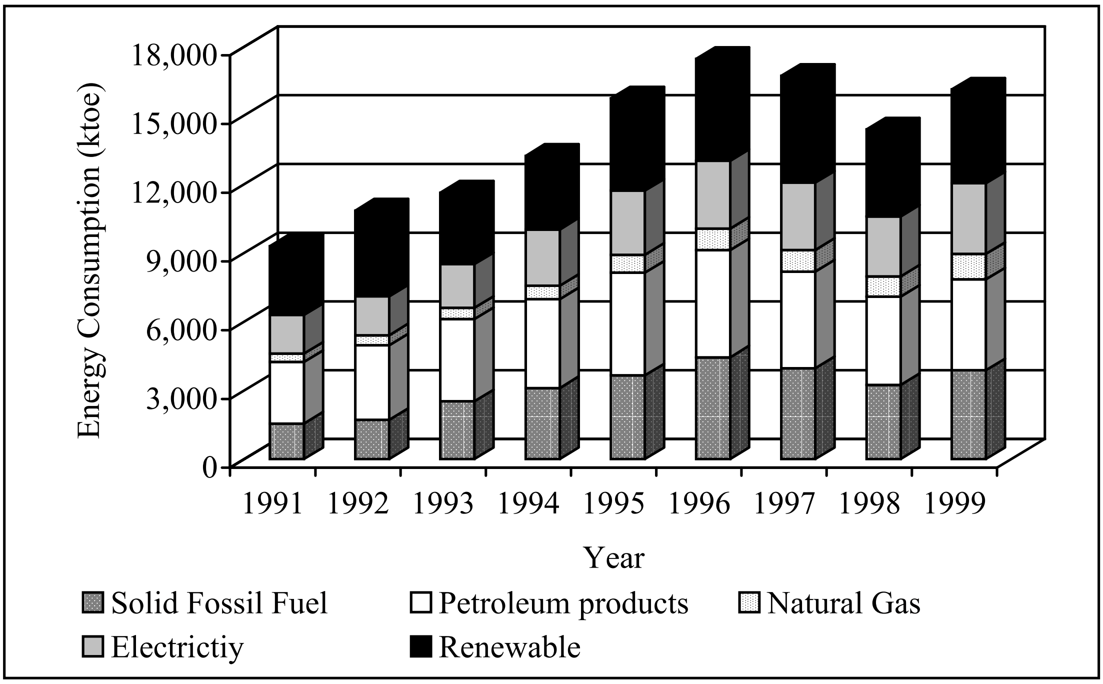

Figure 4.4. The energy consumption in industrial sector by fuel type (DEDP, 1999)

As shown in Figures 4.4 and 4.5, in the year 1991 to 1999 period, ***petroleum products*** played a dominant role in overall of modern energy consumption in industrial sector. Petroleum products grew at 5.01% from 2,686 ktoe in 1991 to 3,971 ktoe in 1999. Its share decreased from 28.88% to 24.62%. While ***solid fossil fuel*** consumption increased very fast from 1,559 ktoe to 3,876 ktoe by 12.06% per year, and its share increased from 16.76% to 24.03% in the same time. Because of changes in the prices of energy, when energy increase, energy used drops accordingly.

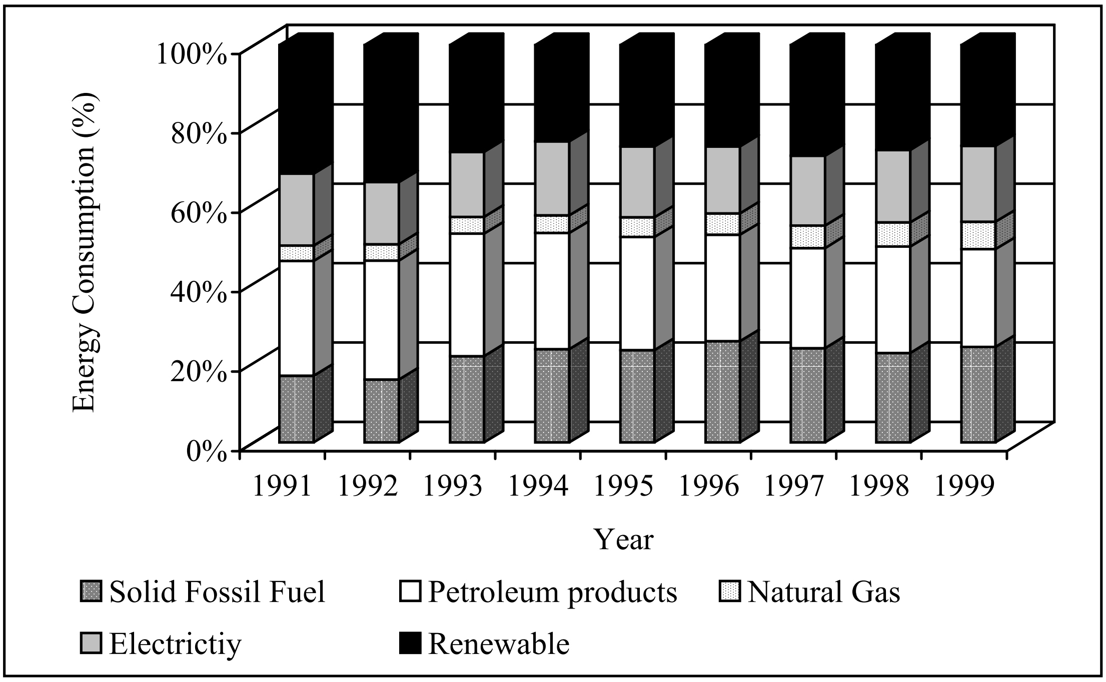

Figure 4.5. The share of energy consumption in industrial sector by fuel type (DEDP, 1999).

Renewable energy consumption increased very slowly by an average growth rate of 3.91% from 3,007 ktoe to 4,087 ktoe. Because the increase occurred apparently at expense of renewable energy consumption, of which the share declined from 32.33% to 25.34%. Although the consumption of ***the natural gas*** accounted for only small proportion of final energy consumption (6.89% in 1999), but the rate increase is very high, accounting of about 15.14% per year in 1991-1999 period. Its share increased from 3.87% to 6.89%. During the same time, the share of ***the electricity*** in final energy consumption was rather stable at 17.16% between 1991 and 1999.

Moreover, it can be noted that there were trends of the substitution of electricity and natural gas by petroleum products and renewable energy. Solid fossil fuel is another source of the energy that is found to have increasing use in industrial application in place of the petroleum products and renewable energy.

4.1.2 Energy Consumption by Sub-Sector

Industrial sector in this study is classified into 9 sub-sectors. Food industry and non-metal industry are the two biggest energy consumers in industrial sector of Thailand, as shows in Figure 4.6.

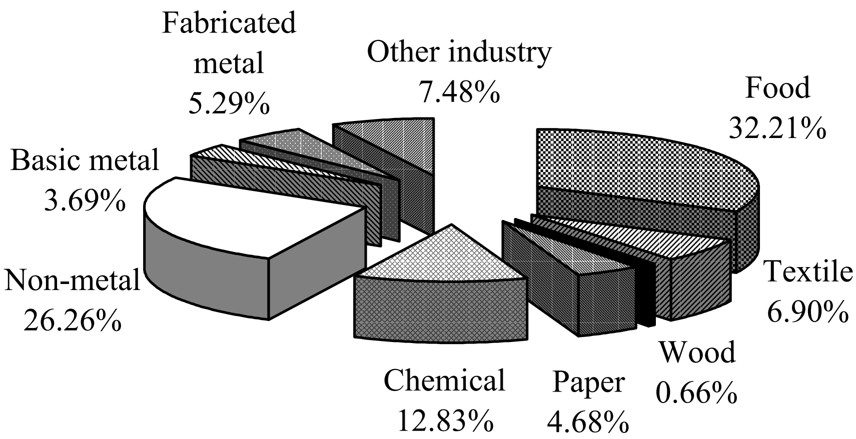

Figure 4.6. The proportion of energy consumption in industrial sector by sub-sector in the year 1999 (DEDP, 1999).

As shown in Figure 4.7 and 4.8, ***Food industry*** is largest energy consumer of total industry. It increased from 3,685 ktoe to 5,195 ktoe at the rate of 4.39% per year. Renewable energy is the most important source of energy. The consumption of renewable energy, which is by-products of the related industries, accounts for 73.30% of total energy consumption in this sub-sector. Solid fossil fuel consumed by this industry decreased from 3.15% in 1991 to 1.29% in 1999, while petroleum products increased from 12.48% to 14.46%.

Non-metal industry is one of small industries in terms of industrial output, but it was the second largest energy consumer after food industry. Energy consumption grew at 8.18% from 2,258 ktoe to 4,235 ktoe in 1991 to 1999. Solid fossil fuels it the major source of energy, which increased from 45.35% to 62.81%. Petroleum products decreased very fast from 30.25% to 10.53% in the same period.

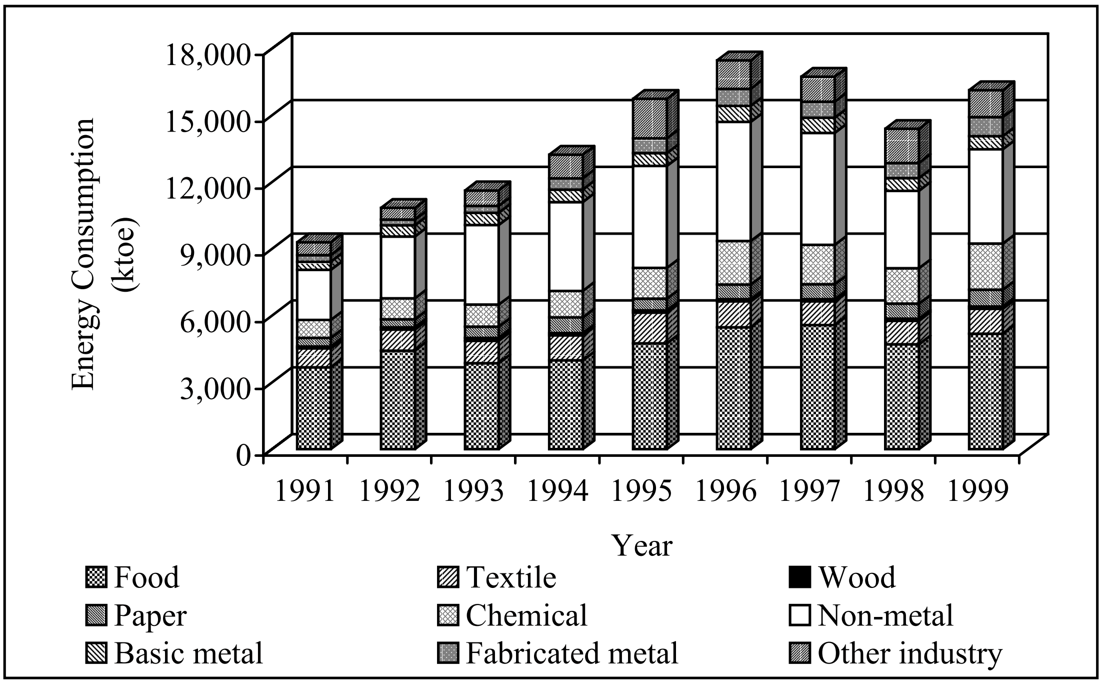

Figure 4.7. Energy consumption in industrial sector by sub-sector during the years 1991 to 1999 (DEDP, 1999).

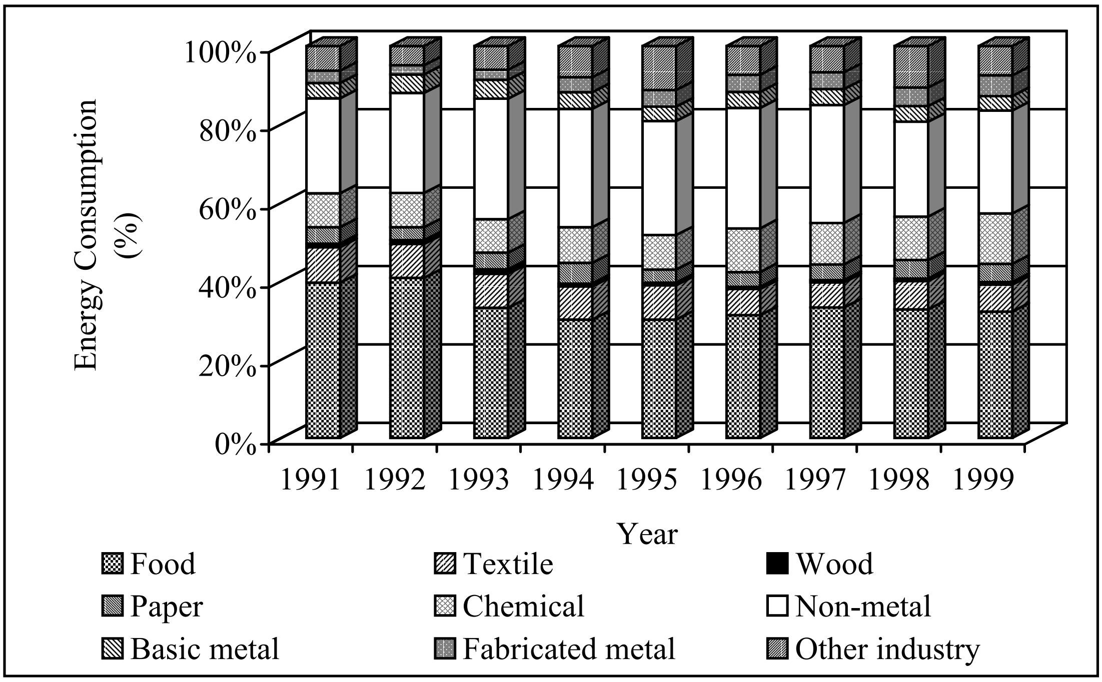

Figure 4.8. The share of energy consumption in industrial sector by sub-sector during the years 1991 to 1999 (DEDP, 1999).

Chemical industry is the third largest energy consumer. The energy consumed by this sub sector increased by 12.58% from 802 ktoe to 2,070 ktoe in the year 1991 to 1999 period.

Petroleum products and electricity were the two major sources of energy for ***textile industry***. This industry consumed 533 ktoe of petroleum products in 1999. It decreased from 52.49% to 47.89%, while solid fossil fuel increased from 3.44% to 7.28% during the years 1991 to 1999. Electricity's proportion in this sub sector was rather stable at 44.5% between the years 1996 to 1999.

Fabricated metal industry consumed energy with a growth rate very fast grew at 14.31% per year from 293 ktoe to 854 ktoe. Electricity was the major source of energy, but it decreased from 83.62% in 1991 to 64.99% in 1999. In this study, natural gas was introduced for use in this industry use in 1994. It grew very fast by 24.28% per year from 26 ktoe in 1994 to 148 ktoe in 1999.

The energy consumption in ***wood industry*** grew very slowly by 2.80% per year. The major source of energy consumed by this sub sector was electricity, which it's increased from 43.43% to 69.81%. Petroleum products and renewable energy decreased from 35.29% to 21.70% and 21.18% to 8.49% respectively.

Paper industry consumed 755 ktoe of energy in 1999, of which 52.72% was solid fossil fuel, 31.39% was petroleum products, and 15.89% was electricity.

Energy that required by ***basic metal industry*** was 4.94% of total industry consumption in 1999. Electricity consumed by this sub sector increased from 37.19% to 48.74%, while petroleum products decreased from 47.66% to 36.97%.

Petroleum products were the largest energy sources consumed by ***other industries***. Its increased from 96.39% to 85.24%, solid fossil fuel and electricity increased from 0.17% to 6.47% and 3.44% to 8.29% respectively.

In the years 1991 to 1999 period, modern energy in food industry was decreased due to substitution of renewable energy consumption. In textile industries, increased of petroleum products and renewable energy consumption might probably be due to a substitution by electricity consumption even through it was not sufficiently supplied.

During the year 1991 to 1999, industrial energy consumption was very elastic to gross industrial product (GIP). Each percentage of GIP change resulted in 1.13% of energy consumption change. While GIP grew at the annual average growth rate of 6.28%, the energy consumption increased at the average growth rate of 7.12% per year from 9,300 ktoe to 16,129 ktoe. The industrial sector was biggest contributor to the gross domestic product. In this study, the economic growth in Thai was the most important reason for the change of energy consumption. It was responsible more than 50% in the total energy increase. The second reason was the structural change contributed for 40% in the total energy change and the energy intensity contributed about 2%. However, the first and second reasons were uncontrolled economic mechanisms. Thus, the opportunity for the energy saving and conservation by the reduction in the energy intensity is large.

4.2 Energy Efficiency in Industrial Sector

The energy intensity gives an indication of the amount of energy required to produce one unit of economic output. Therefore, reductions in energy intensities can be interpreted as improving efficiency. In general, energy efficiency is ratio between the useful output of a process in physical unit and the energy consumption in energy unit. Industries are in the business of producing physical units of output for consumption by end users. However, there are different approaches for measuring output in industry and there are many sub-sectors that the aggregate physical output cannot be easily defined. One alternative is to calculate the value added or contribution to GDP. Therefore, in this study, the energy efficiency were calculated by this alternative, the ratio between useful output in term of monetary unit (value added) and the energy consumption in energy units.

Figure 4.9 presents the energy intensity and energy efficiency index of industrial sector. It also illustrates the interaction between energy efficiency and energy consumption. The growth rate of energy consumption is less than that of industrial output in 1993 because of energy efficiency improvement. During the years 1993 to 1996, the energy efficiency decreased from 50.95 to 42.58 thousand baht of industrial output per toe of energy used, while energy consumption increased from 11,630 ktoe to 17,469 ktoe, which was faster than that of industrial output. It implied that, if energy efficiency were improved, energy consumption would be increased only when industrial output was increased. In 1999, the energy efficiency was 46.30 million baht per ktoe. The trend of energy efficiency is affected by the manufacturing structure change, the result of outdated technology and type of energy consumption.

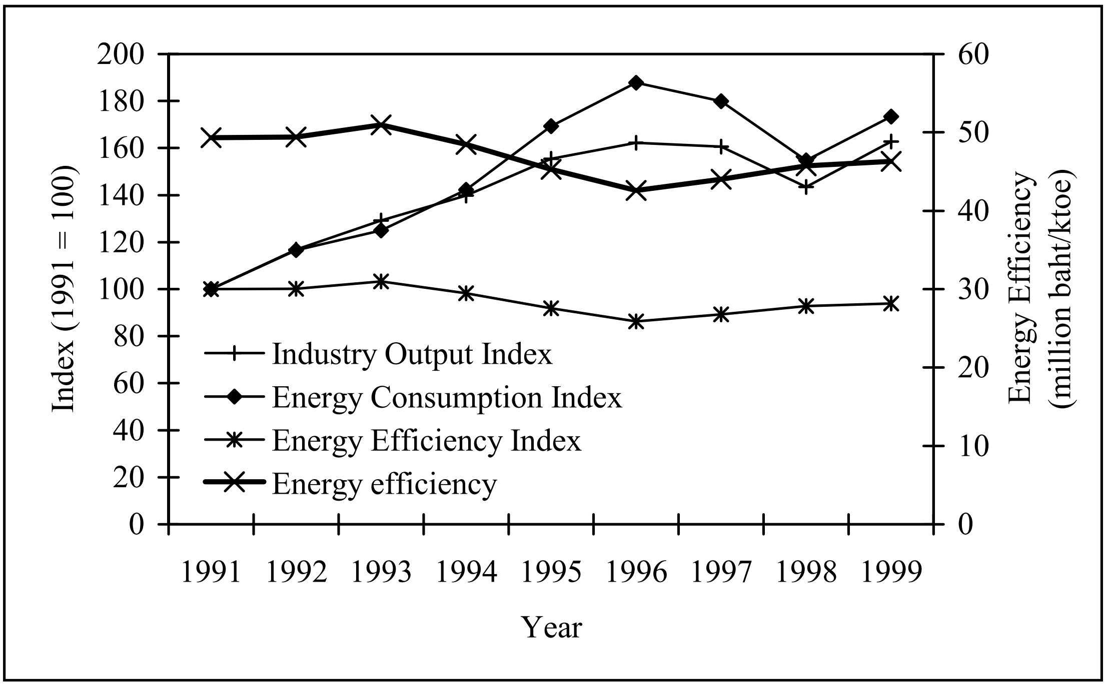

Figure 4.9. Energy intensity index and energy efficiency index of industrial sector.

Figure 4.10 shows the energy efficiency of industrial sub-sectors. It shows that the ***fabricated metal industry*** was the highest energy efficiency in industrial sector. Its energy efficiency was 275.30 million baht of industrial output per ktoe of energy used, 3.33 times higher than wood industry (82.61 million baht/ktoe) and 2.03 times higher than textile industry (135.91 million baht/ktoe) in 1999. The energy used in fabricated metal industry was mainly electricity and petroleum products. The energy efficiency increased at 21.80% per year during the years 1991 to 1993, but it decreased sharply with the growth rate at 34.53% in the year 1993 to 1994. The energy efficiency was 275.30 million baht/ktoe in the year 1999. After one year of decreasing, in the next period of 1994 to 1999, it was still decreasing by 6.25% per year.

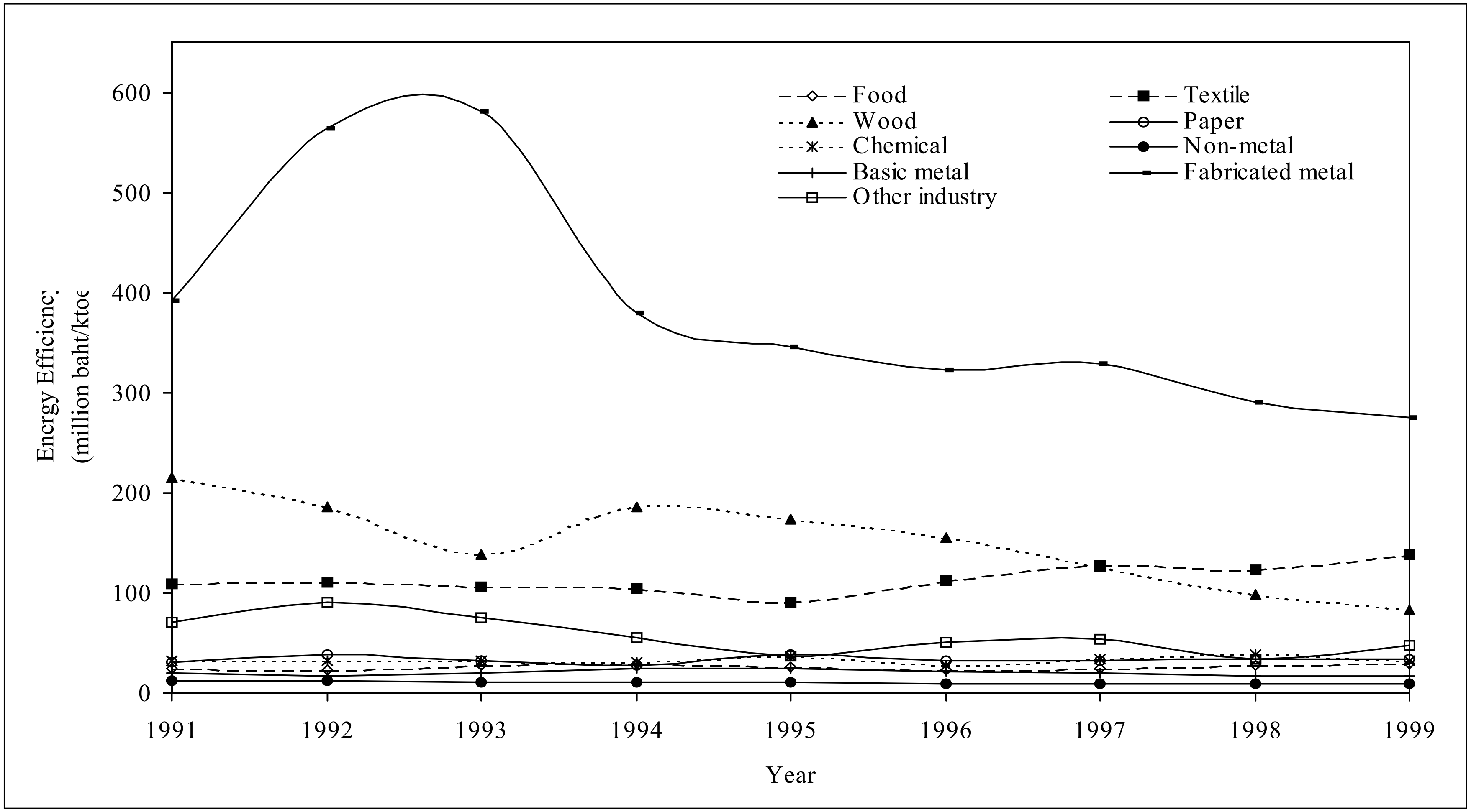

Figure 4.10. The energy efficiency of industrial sub-sector during the years 1991 to 1999.

This decrease occurred apparently at the substitution of petroleum product and natural gas for the electricity and another reason might be explained by the defects of energy management. Because the electricity used is very important for the introduction of the advanced technology and facilities.

Wood industry had second highest energy efficiency after fabricated industry, but its energy efficiency decreased very fast with the annual average growth rate at 11.31% during 1991 to 1999. The rapidly decrease of energy efficiency might be explained by the substitution of petroleum products for the electricity consumption that was not sufficiently supplied in 1992 to 1993 period, and the substitution of petroleum products for the electricity was applied in the last part of the time period. Finally, in the study period, the decrease of output value was referring to change in energy efficiency.

Textile industry has the third highest energy efficiency. Energy efficiency was 135.91 million baht per ktoe in 1999. Although its energy efficiency increased afterward, it was still less than that in 1991. Therefore, the substitution of petroleum products and solid fossil fuel for electricity and natural gas was introduced for this industrial use during the years 1994 to 1996.

Non-metal industry was lowest energy efficient sub sector. In 1999, energy efficient was 8.83 million baht of industrial output per ktoe. Moreover, its energy efficiency index declined at the rate of 3.93% per year from 1991 to 1999. Non metal industry is the second biggest energy consumer but it is one of the small outputs of sub-sector in the industrial sector due to outdated techniques and the difference in the in the quality of energy management.

Petroleum products and electricity were the major source of energy for ***basic metal industry***, which is the second lowest energy efficiency. Its energy efficiency decreased from 20.10 million baht per ktoe in 1991 to 17.32 million baht per ktoe in 1992. The following period, 1993 to 1995, it increased from 19.78 million baht per ktoe to 24.93 million baht per ktoe. After that, it decreased to 16.65 million baht per ktoe in 1999. It might be explained by the share of electricity in their fuel mix that kept increasing and the changes of this sub-sector in manufacturing structure.

Food industry was the third lowest energy efficiency in industry. Nevertheless, the energy efficiency was still increasing from 25.09 million baht per ktoe to 29.76 million baht per ktoe during 1991 to 1999. The major fuel used was the renewable energy, which was low cost by product of the related industries. The quality and structure of raw materials and outdated processes might explain the variation of energy efficiency in ***paper industry*** in the first period, 1991 to 1995. However, during the years 1996 to 1999, it increased very slowly from 31.60 million baht per ktoe to 34.08 million baht per ktoe. As mentioned above, the rising trend of energy consumption occurred almost, as the result of the industrial output growth, this had a relationship with the increases significant by increases in energy efficiency in the same period.

The energy efficiency in ***chemical industry*** was 31.94 million baht/ktoe in 1991, it increased to 37.25 million baht per ktoe in 1995. It decreased sharply to 27.79 million baht per ktoe in 1996 because of the substitution of electricity into petroleum products that gave higher energy efficiency. However, after increasing in 1997 and 1998, it decreased to 32.34 million baht per ktoe in 1999.

The substitution of electricity for other energy sources and the changes of structure in the industrial sector might explained the variation of energy efficiency in ***other industry***.

Moreover, the variation of energy efficiency in each sub-sector and each year depends on many factors:

1. The scale of enterprises
2. The technological level of processes and facilities adopted
3. The status of ownership
4. The structure and quality of raw materials and energy sources
5. Government policies and regulation
6. The level of management
7. The recovery rate of waste energy source and materials.

Overall, the energy efficiency in the industrial sector is in the range of 8.83 to 275.30 million baht per ktoe. It is very low compared the other sector. In this study, the energy efficiency has been declining in the most of sub-sectors, which has resulted in the increasing of the energy demand and air pollution emissions. During the year 1991 to 1999, non-metal industry is the lowest energy efficiency followed by basic metal industry and food industry. In the same time, fabricated metal industry is the highest energy efficiency followed by wood industry and textile industry. Moreover, in the comparison with other sectors, industrial sector has high intensities in the energy consumption and high air pollution emissions. Thus, it is very important to analyze the option to achieve higher energy efficiency and better environmental compatibility in the industry.

Figure 4.11 show the energy efficiency in the industrial sector in this study (million baht/ktoe) is compared to the energy efficiency (million US$/ktoe) in 31 SMIs under 7 sub-sectors in Thailand, which is the result of energy, audited by Wongsuwan (1997). The comparison indicates general agreement. However, a closer comparison is not possible due to the difference method of the study.

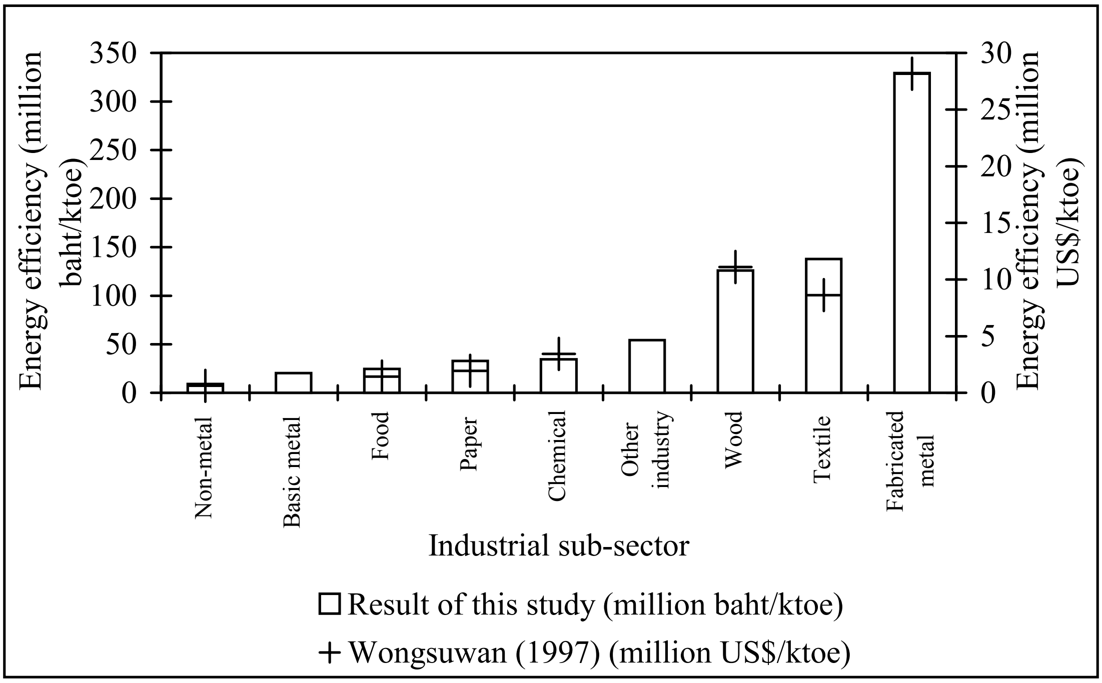

Figure 4.11. The energy efficiency of industrial sub-sector in 1999.

4.3 Pollution Emission

Most of air pollution emissions in Thailand come from energy related activities. The amount of air pollution emission can be estimated from the individual fuel consumption and its emission factor. Emission factors are depending on the quality of fuel and different processes of fuels utilization. In this study, emission factors were obtained from DEDP, which they are assumed to remain the same over time and according to the industrial sector. Figure 4.12 and 4.13 shows the estimated CO_2, SO_2, and NO_x emissions from industrial sector in the year 1999. CO_2 is the largest emission from industrial sector, which was 29,908 ktonCO_2. The emissions of SO_2, and NO_x were 207 ktonSO_2 and 165 ktonNO_x, respectively.

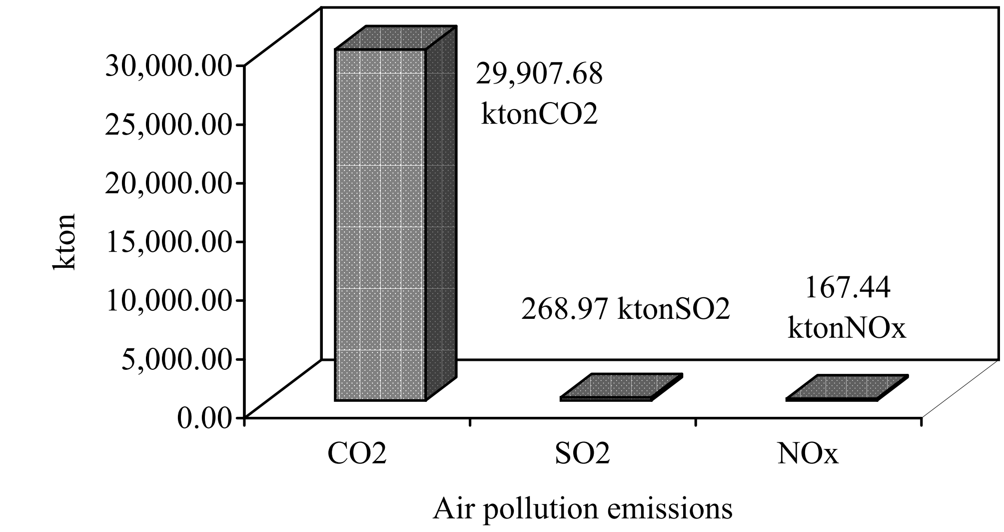

Figure 4.12. CO_2, SO_2, and NO_x emissions from industrial sector in 1999.

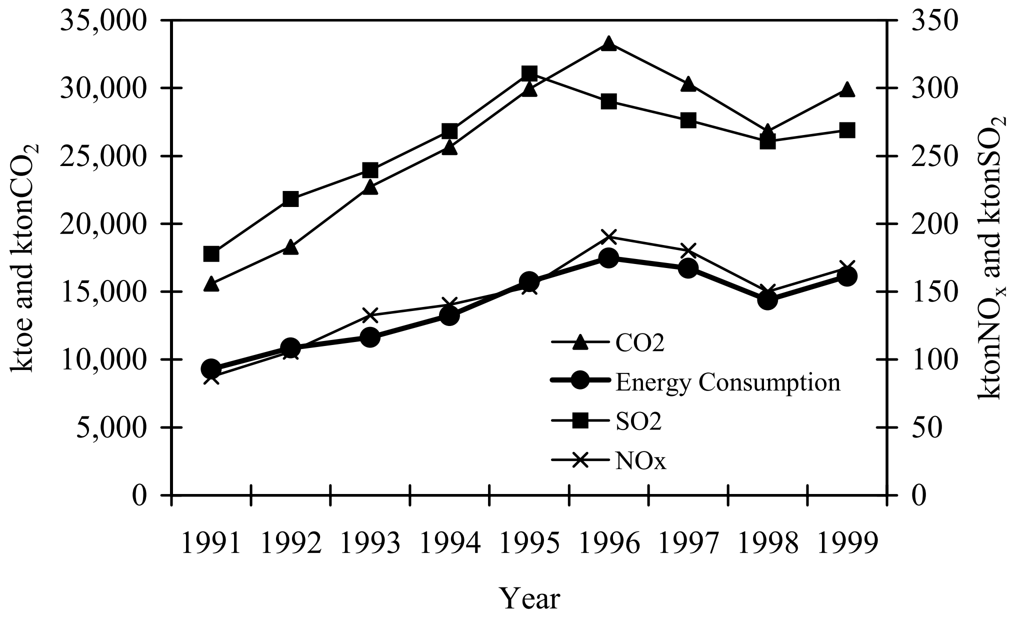

Figure 4.13. Air pollution emissions and energy consumption in industrial sector during the years 1991 to 1999.

4.3.1 CO_2 Emission

The major sources of CO_2 emission are solid fossil fuel and petroleum products. Figure 4.14 shown CO_2 emission from fossil fuel consumption in the years 1991 to 1999. The total CO_2 emission increased from 15,583.16 ktonCO_2 in the year 1991 to 29,907.68 ktonCO_2 in the year 1999.

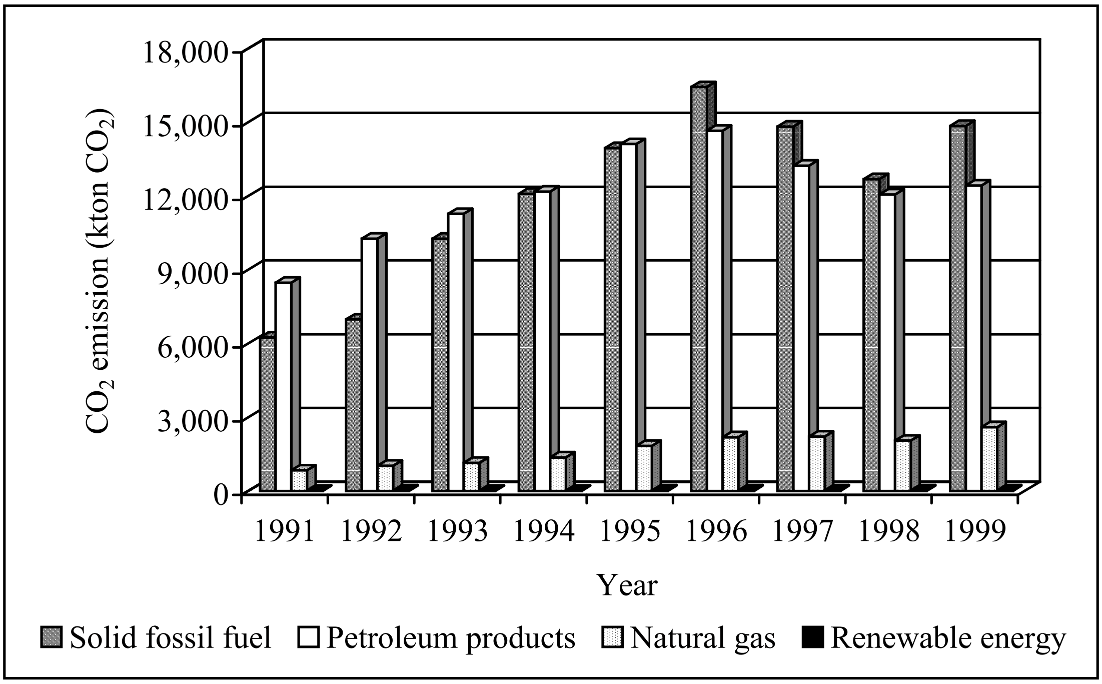

Figure 4.14. CO_2 emission from fuel combustion by type of fuel during the years 1991 to 1999.

Petroleum products are the largest source of CO_2 emission from the years 1991 to 1995 with the average growth rate at 7.90% per year. It was lower than that of solid fossil fuel.

In the year 1996, CO_2 emission from ***solid fossil fuel*** combustion was the largest source, its emission was about 16,430.47 ktonCO_2 and increase to 14854.95 ktonCO_2 in the year 1999. ***Natural gas*** is the second smallest source of CO_2 emission. It increased from 841.34 ktonCO_2 in the year 1991 to 2,598.80 ktonCO_2 in the year 1999 with the annual average growth rate of 15.14%. The ***renewable energy*** is the smallest source. Its share was only 0.09% in the year 1999.

It increased from 20.14 ktonCO_2 to 27.40 ktonCO_2 at the annual average growth rate of 3.92% between the years 1991 to 1999.

Figure 4.15 shown the CO_2 emission in industrial sector by sub-sector in the years 1991 to 1999. ***Non-metal industry*** takes the largest share in industrial sector. CO_2 emission from this sub sector was 6,791.81 ktonCO_2 in the year 1991 and increase to 13,175.75 ktonCO_2 in the year 1999 at the average growth rate of 5.63% per year. Its share increased from 43.58% to 44.05%.

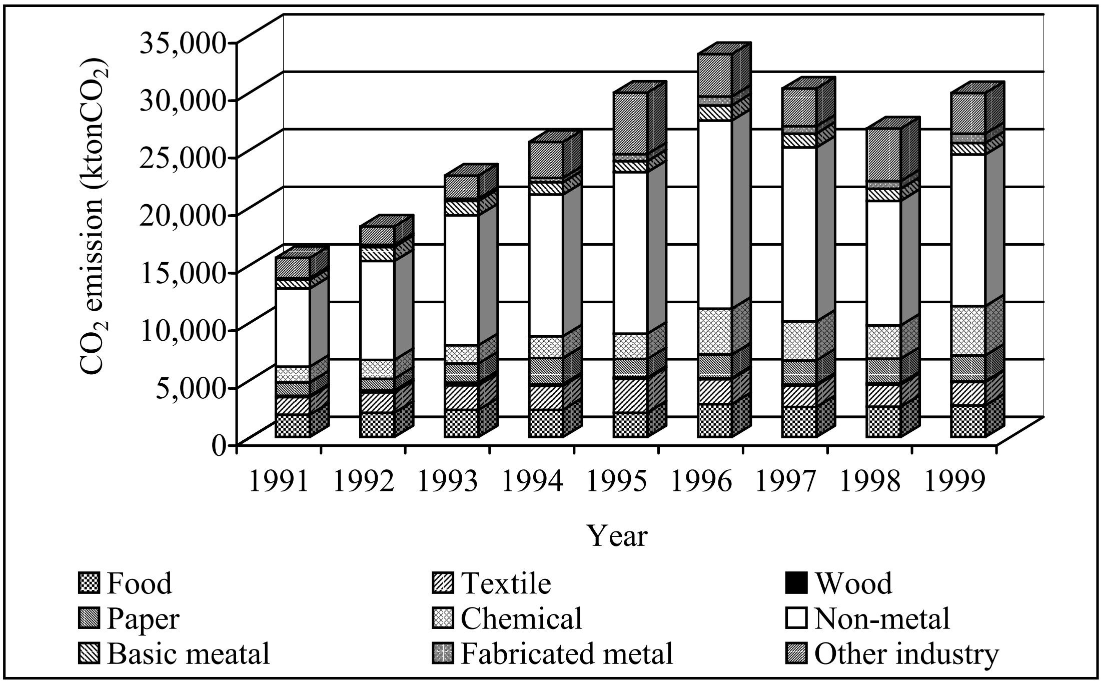

Figure 4.15. CO_2 emission from fuel combustion by sub sector during the years 1991 to 1999.

Chemical industry is the second largest source of CO_2 emission in the year 1999, its increase from 1,376.50 ktonCO_2 in the year 1991 to 4,274.24 ktonCO_2 in the year 1999 with the annual average growth rate at 15.21%.

The contribution of the ***food industry*** to total CO_2 emission was increase from 1,966.03 ktonCO_2 in the year 1991 to 2,754.29 ktonCO_2 in the year 1999. Nevertheless, it decreased to 2,137.52 ktonCO_2 in the year 1995. Its share decreased from 12.62% in the year 1991 and increased very rapidly to 5,333.66 ktonCO_2 in the year 1995, with the strong economic. After that, CO_2 emission in this sub sector was about 9.21% in the year 1999 due to the economic activity and the energy efficiency.

In ***other industry*** sub sector, CO_2 emission increased from 1,768.45 ktonCO_2 in the year 1991 to 3,539 ktonCO_2 in the year 1999. The CO_2 emission in ***textile industry*** was 2,035 ktonCO_2 in the year 1999, its share decreased from 9.81% in the year 1991 to 6.80% in the year 1999.

CO_2 emission in ***paper industry*** increased with the average growth rate at 8.59% per year between the years 1991 to 1999. It was about 1,164 ktonCO_2 in the year 1991 and increased to 2,251.77 ktonCO_2 in the year 1999.

In the year 1999, the CO_2 emission in ***fabricated metal industry*** and ***basic metal industry*** were 797.90 ktonCO_2 and 1,007.23 ktonCO_2 respectively. Their shares were lower than 5% while the proportion of CO_2 emission in ***wood industry*** was lower than 0.5% in the study period.

4.3.2 NO_x Emission

Total NO_x emission in the industrial sector was 87.37 ktonNO_x in the year 1991 and increased to 167.44 ktonNO_x in the year 1999 with the average growth rate at 8.47%, as shown in Figure 4.16.

Solid fossil fuel and petroleum products are the largest source. In the period of the years 1991 to 1994, ***petroleum products*** were the largest source, its share was 31.53%, and increased to 41.10% with the average growth rate at 12.12% per year. The growth rate of NO_x emission from petroleum product was lower than that of solid fossil fuel (about 4.4% per year). NO_x emission from ***solid fossil fuel*** combustion is the largest source during the years 1994 to 1999, it increased from 56.72 ktonNO_x in the year 1994 to 68.81 ktonNO_x in the year 1999.

The emission of NO_x from ***natural gas*** combustion increased from 9.86 ktonNO_x in the year 1991 to 28.89 ktonNO_x in the year 1999 at the average growth rate of 14.38% per year. While NO_x emission from ***renewable energy*** increased vary slowly from 11.90 ktonNO_x in the year 1991 to 13.89 ktonNO_x in the year 1999 with the annual average growth rate of 3.80% due to the renewable energy consumption in industrial sector grew at 3.91% per year.

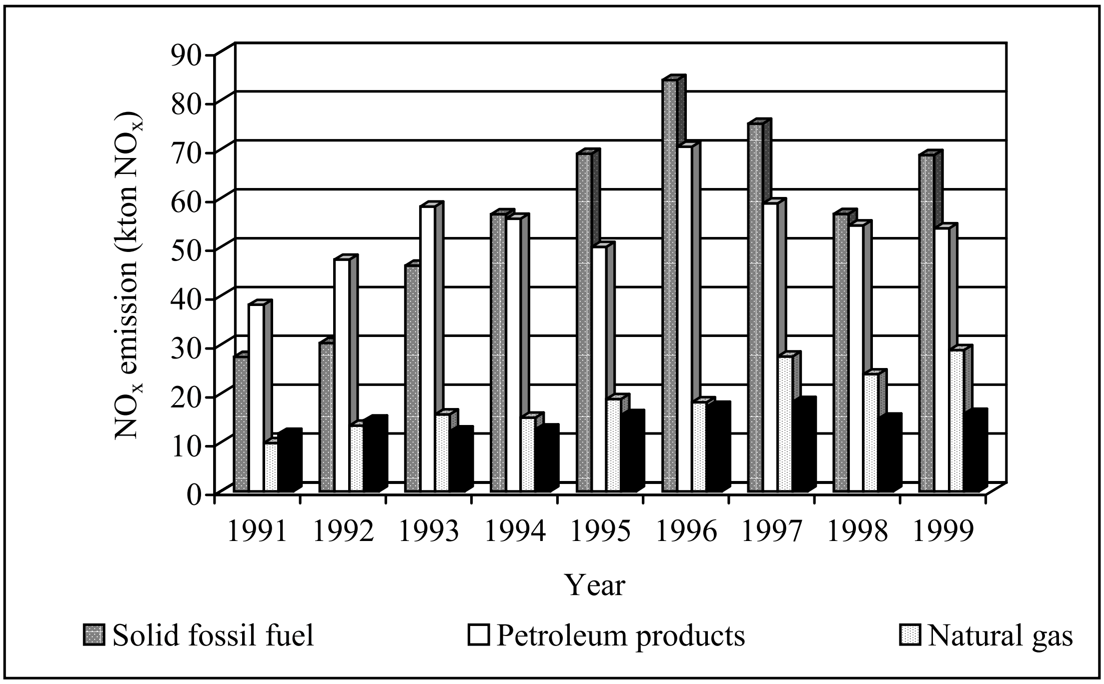

Figure 4.16. NO_x emission from fuel combustion by type of fuel during the years 1991 to 1999.

In the share of NO_x emission by sub-sector, ***food industry*** was the second largest after non-metal industry as shown in Figure 4.17. NO_x emission in food industry increased from 19.01 ktonNO_x to 26.43 ktonNO_x, but its share decreased from 21.77% to 15.77% in the year 1991 to 1999 period due to the increase of solid fossil fuel consumption.

Non-metal industry contributes a major proportion in the overall sub sector (about 58.32% of total NO_x emission in industrial sector). NO_x emission from fuel combustion in this sub-sector increased from 47.55 ktonNO_x to 97.66 ktonNO_x in the year 1991 to 1999, it increased with the annual average growth rate of 9.41%.

The share of NO_x emission in ***other industry*** sub-sector increased from 7.26% in the year 1991 to 8.17% in the year 1999 with the average growth rate at 10.03% per year. NO_x emission in ***chemical industry*** increased from 3.75 ktonNO_x to 13.32 ktonNO_x with very high growth rate.

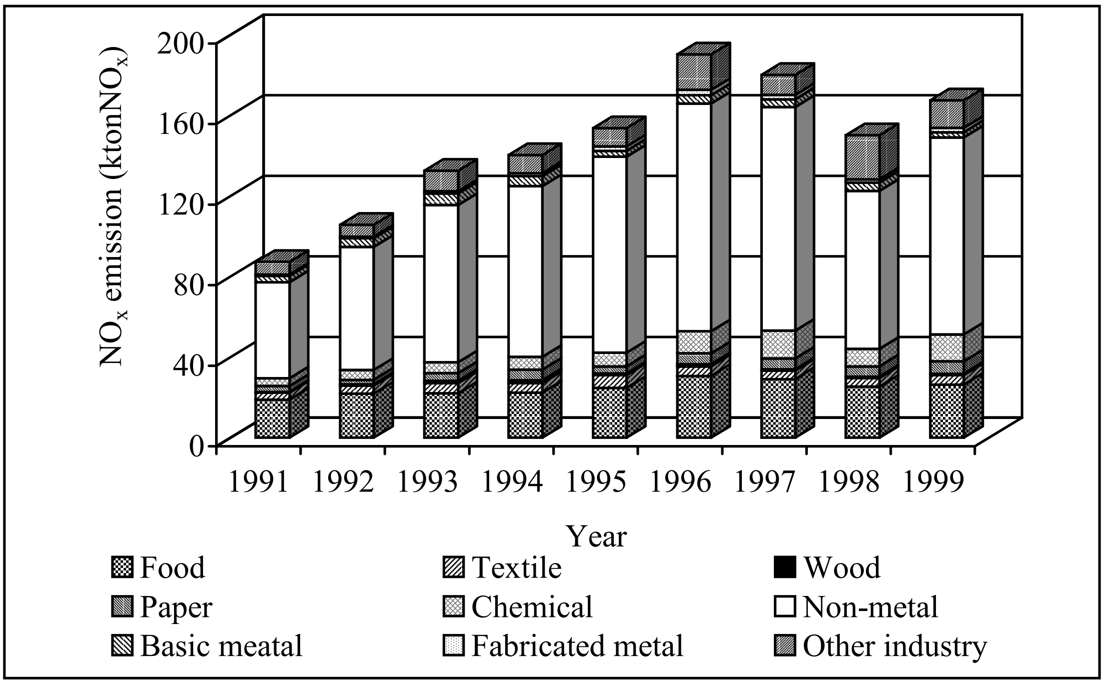

Figure 4.17. NO_x emission from fuel combustion by sub-sector during the years 1991 to 1999.

4.3.3 SO_2 Emission

SO_2 emission in industrial sector increased with the annual average growth rate of 5.30% from 177.88 ktonSO_2 in the year 1991 to 268.97 ktonSO_2 in the year 1999. SO_2 emission from petroleum product shares more than 70% of total source, as shown in Figure 4.18. This emission increased from 136.02 ktonSO_2 in the year 1991 to 196.56 ktonSO_2 in the year 1999 with the annual average growth rate at 4.71%.

Fuel oil played an important role in the overall SO_2 emission from ***petroleum products***, it was about 134 ktonSO_2 and increased 193.13 ktonSO_2 between the year 1991 to 1999 at the rate of 4.67% per year.

Lignite is the only source of SO_2 emission in ***solid fossil fuel***. Thus, the growth rate of emission had the same trend that of the lignite consumption (7.18% per year). The emission of SO_2 from lignite combustion is 0.0341 ktonSO_2 per ktoe; it increased from 41.84 ktonSO_2 in the year 1991 to 72.41 ktonSO_2 in the year 1999.

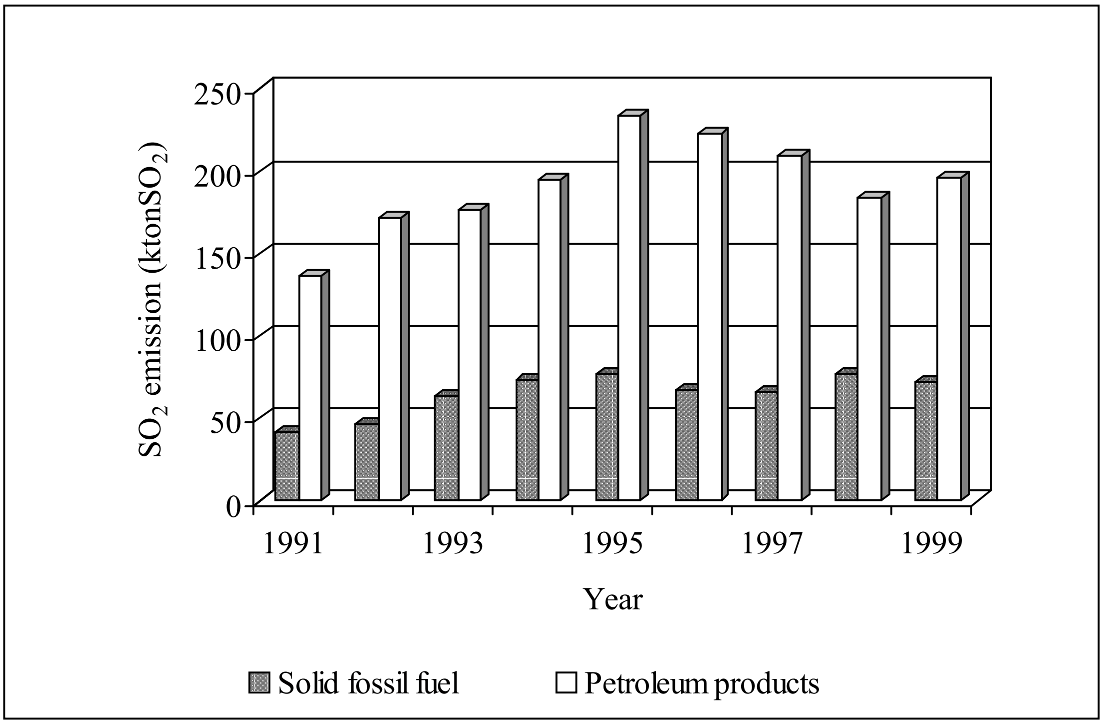

Figure 4.18. SO_2 emission from fuel combustion by type of fuel during the years 1991 to 1999.

As shown in Figure 4.19, the major energy consumption in ***non-metal*** industry was solid fossil fuel, which share about 68.63% of solid fossil fuel in industrial sector. Moreover, lignite was the major source of solid fossil fuel. Thus, non-metal is the largest source of SO_2 emission. SO_2 emission in this sub-sector was 68.49 ktonSO$_2$ in the year 1991 and increased to 79.98 ktonSO$_2$ in the year 1999. Nevertheless, its share decreased from 38.50% to 29.73%.

SO_2 emission in ***food industry*** increased from 25.52 ktonSO$_2$ in the year 1991 to 31.34 ktonSO$_2$ in the 1994 and decreased sharply in the year 1995 to 24.20 ktonSO$_2$. After that, it increased very slowly from 36.84 ktonSO$_2$ in the year 1996 to 38.07 ktonSO$_2$ in the year 1999 due to the energy intensity and fuel mix.

The second largest emission source of SO_2 emission was the ***other industry*** sub sector. Its share increased from 15.84% in the year 1991 to 19.31% in the year 1999. In the year 1995, its share increased sharply to 31.79% because of the increased in petroleum product consumption in this sub sector.

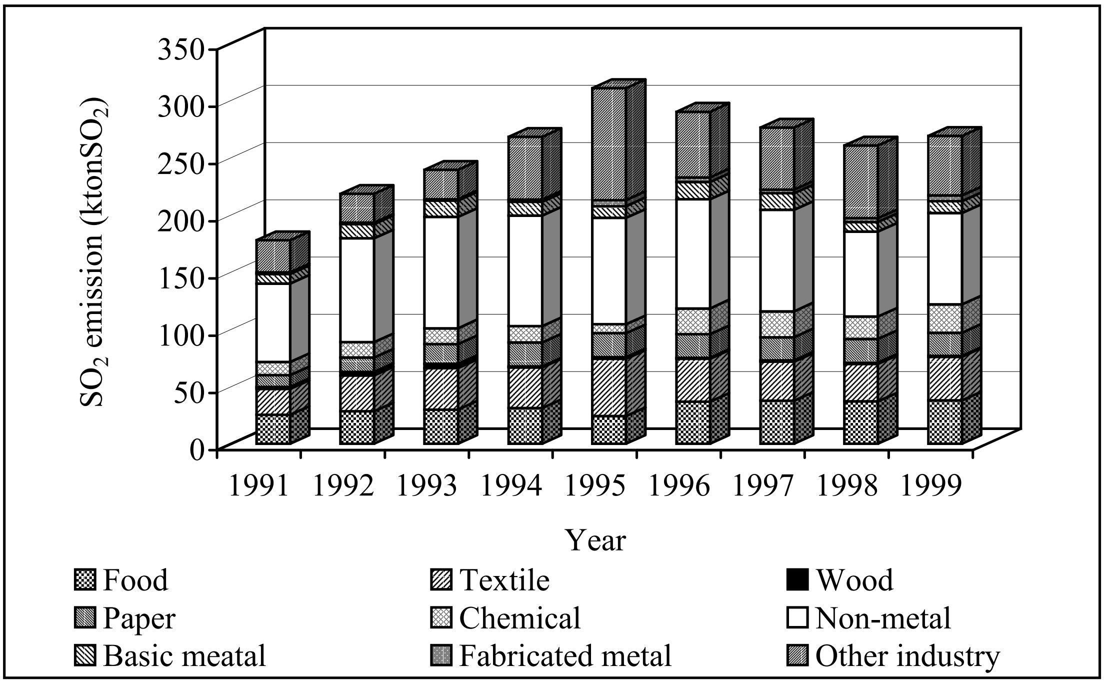

Figure 4.19. SO_2 emission from fuel combustion by sub-sector during the years 1991 to 1999.

The share of SO_2 emission in ***chemical industry*** increased from 6.42% to 9.16% in the years 1991 to 1999 while the share of SO_2 emission in ***textile industry*** increased very fast from 1.27% to 14.15%.

The ***fabricated metal industry*** and ***basic metal industry*** took very small part of SO_2 emission, its share lower than 5%. Moreover, wood industry was the smallest, its share was lower than 0.50% in the year 1999.

The amounts of air pollution emission in this study come form fuel combustion in the industrial production. The type of pollutants depends on the type of energy are used in each industry. The major sources of air pollution emission are solid fossil fuel and petroleum products, especially lignite and fuel oil. This energy is the large share in the three sub-sectors: non-metal sub-sector, other industry sub-sector, and chemical sub-sector. These three sub-sectors are the largest emitter of air pollution emissions. The opportunity for mitigation of air pollution in the industrial sector may be done by improvement of energy efficiency and fuel switching in the industry.

4.4 Energy Demand Forecasting

The forecast of energy demand of manufacturing was calculated by "Energy Used Model" base on business-as-usual scenario (BAU). The results are listed shown in Appendix D.

In BAU scenario, the total energy consumption is 16,129 ktoe for base year 1999. In the year 2000, total energy consumption was 17,436.89 ktoe or the annual average growth rate was 8.12% and it will increase to 5.10% from the year 2000 to 2001. The annual average growth rate in the next two five-year periods were 7.17% in the ninth national economic and social development plan (2002 to 2006) and will increase with 7.56% in tenth national economic and social development plan (2007 to 2011). During the planing, the differences of GDP growth rate in the three periods are 5.55% between 2000 to 2001, 7.62% and 7.84% in 9^{th} and 10^{th} plan respectively. In contrast, the difference of energy demand growth rates are only 0.45%, 0.45% and 0.28% in the same periods. The results will be analyzed later by type of fuel and sub-sector.

4.4.1 Energy Demand by Type of Fuel

Under the BAU scenario, the total energy demand is expected to grow at the average growth rate of about 7.21% per year in the forecasted period, it will reach 37,187.93 ktoe in the year 2011 from 16,129 ktoe in the year 1999. In this period, the modern energy demand growth rate has annual average of 7.86%. The growth rate of modern energy demand is higher than that of renewable energy.

The energy demand of ***solid fossil fuel, petroleum product, natural gas*** and ***electricity*** grow at a most the same growth rate 7.53%, 8.25%, 8.07%, and 7.68% respectively. The shares of solid fossil fuels will increase from 24.03% to 24.92% of total energy demands, in the years 1999 to 2011. Petroleum products demand will reach 10,278.79 ktoe by the year 2011 from 3,971 ktoe in the year 1999 as shown in Figure 4.20. Its share was 24.62% during 1999 and will grow up to 27.64% of total energy demand in the year 2011.

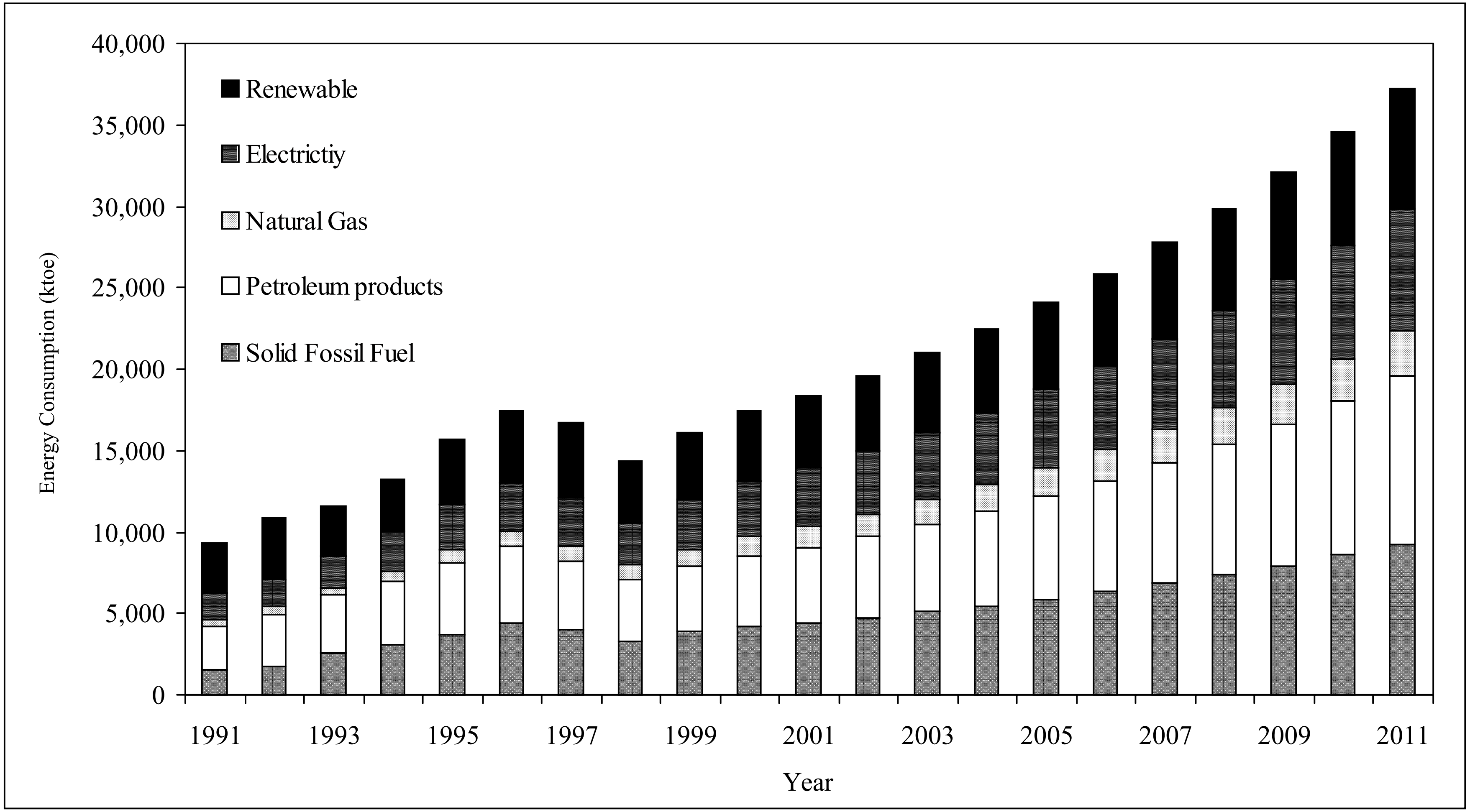

Figure 4.20. Energy demand by type of fuel during the years 1991 to 2011.

Solid fossil fuels and petroleum products are the major parts of the energy demand. The electricity demand is the second lowest portion of total energy demands. It share will increase to 20.15% in the year 2011 from 19.11% in the year 1999. The smallest portion of the total energy demand is natural gas, but it grows up with highest average growth rate at 8.07% per year. The share of natural gas demand per total energy demand will increase from 6.89% (1,112 ktoe) in the year to 7.59% (2,822.10 ktoe) in the year 2011. However, in the period of this study, natural gas will remain the smallest portion of the total energy demand.

Renewable energy demand for BAU scenario was forecasted to be 7,327.20 ktoe by the year 2011 from 4,087 ktoe in the year 1999. It grows up slowly with average growth rate of 4.98% per year and its share will decrease from 25.34% in the year 1999 to 19.73% in the year 2011.

According to the above forecast, the share of renewable energy demand will decrease as the renewable energy is the major portion of total energy demand in food industry, while the share of food industry will decrease in the study period.

4.4.2 Energy Demand by Sub-Sector

From the years 1991 to 1999, food industry and non-metal industry were the large energy consumers. As shown in Figure 4.21, Energy consumption in ***food industry*** was 5,195 ktoe in the year 1999 and was bigger than that in non-metal industry, and it will grows up slowly with the average growth rate of 4.76% per year. However, by the year 2011 energy demand in food industry will be 9,077.52 ktoe and will still be bigger than that of non-metal industry.

Non-metal industry is the second consumer. Energy demand in this sub sector in the year 1999 was 4,235 ktoe and will increased rapidly to be 8,172.36 ktoe in the year 2011 with the annual average growth rate of 5.63%.

Basic metal industry took the second lowest share of the energy consumption (after wood industry) in the year 1999, which was 595 ktoe. It will increase sharply by the rate of 5.16% per year from the years 1999 to 2011 period. Energy demand in this sub sector will be 1,088.25 ktoe in the year 2011. It will be still bigger than the energy demand in wood industry.

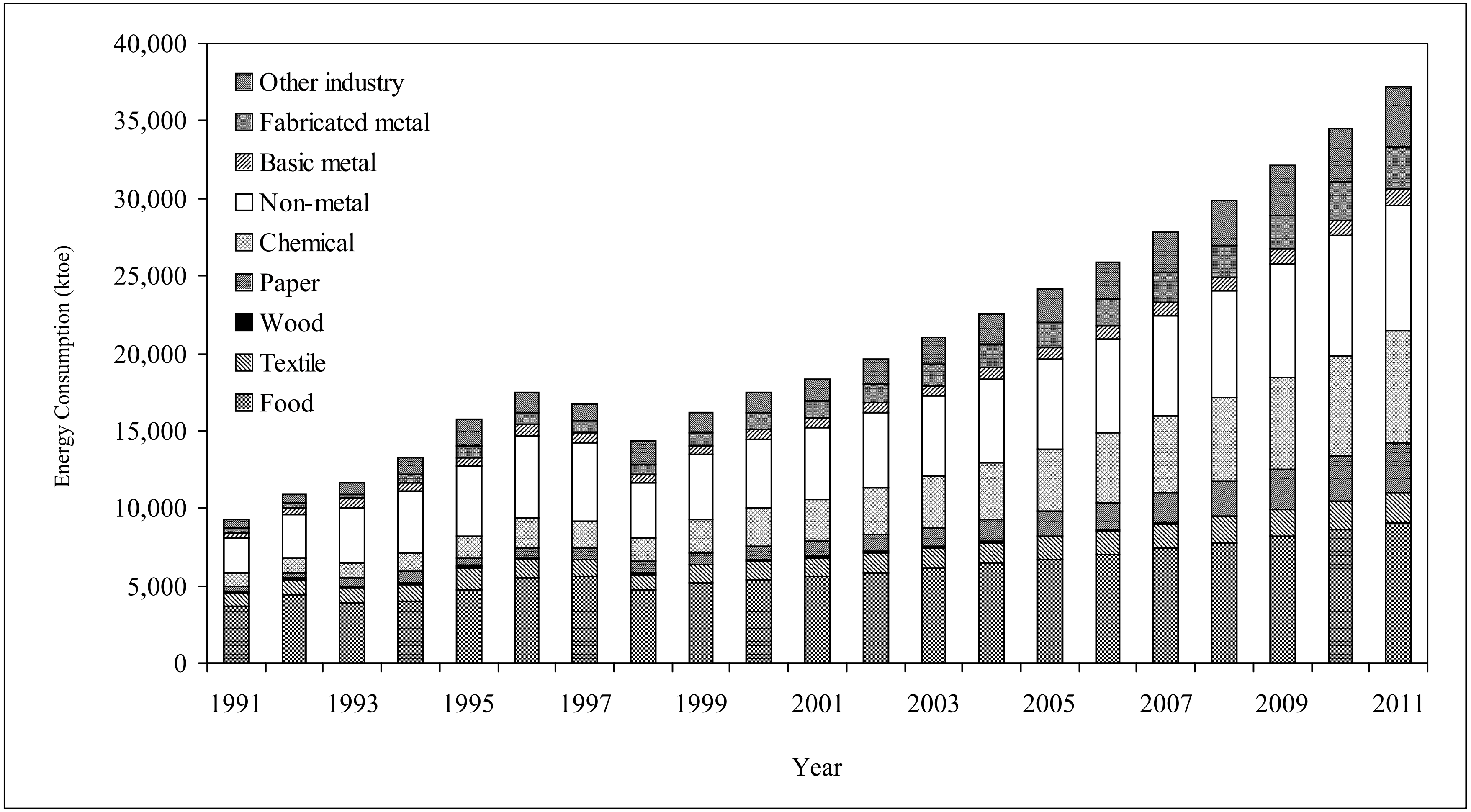

Figure 4.21. Energy demand by sub-sector during the years 1991 to 2011.

Other industry and ***Fabricated metal industry*** are the high rank in terms of energy demands increase. From the year 1999 to 2011, energy demands increase from the average growth rate of 10.18% and 9.92% in other industry and fabricated metal industry respectively.

Solid fossil fuel is the major energy source in the ***paper industry***. In the year 1999, This sub sector consumed 755 ktoe out of the energy consumption in this sub sector. The energy demand under the BAU scenario is forecast to be 1,514.65 ktoe in the year 2011 (with growth rate about 13% per year).

Chemical industry is the third largest consumer and the energy consumption will increase to be 7,134 ktoe in the year 2011 from 2,070 ktoe in the year 1999 with annual average growth rate a of 10.86%. However, chemical industry will remain be the third largest energy consumer compared to all sub sectors in industrial sector.

The share of energy demand in ***Wood industry*** is very small compare to overall energy demand in industrial sector. It was about 0.66% (106 ktoe) in the year 1999 and will go down to 0.12% or 42.51 ktoe in the year 2011 with the average growth rate of about 7% per year and this sub sector will still be the smallest energy consumer.

Textile industry is the smallest in terms of energy demand increase. Energy demand will be 1,874.41 ktoe in the year 2011 from 1,113 ktoe in the year 1999 (with growth rate of 4.44% per year). Its share in energy demand will increase from the fifth largest energy consumer to the third largest energy consumer in the year 2011.

In this study, the variation of industry energy demand is caused by the economic activity. The proportion of the energy demand in textile industry decrease to the third smallest energy consumer in 2011 from the fifth smallest energy consumer in 1999 due to the industrial output share in this sub sector. This share was 20.26% in the year 1999 and will go down to 5.36% in 2011. In other sub-sectors, the proportion of the energy demands in non-metals industry will be the smaller than that of the food industry. In the forecast study, the energy consumption growth rate of food industry will be least than that of non-metal industry. However, the proportion of the energy demands in non-metals industry will still be the smaller than that of the food industry.

The assumed scenario and economic activity led to these results in the period of the study. Base on BAU scenario, the total energy demand in the industrial sector will increase with 7.17% in the year 2002 to 2006 and 7.56% in the year 2007 to 2011, due to the increasing of GDP growth rate are 7.62% and 7.84% at the same period. In the study period, petroleum product will be the largest share of the total energy demand with the highest growth rate. While food sub-sector will still be the biggest consumer, followed by non-metal sub-sector.

4.5 Pollution Emission Forecast from Energy Combustion

In case of pollution emission forecasting, most of the factors for technologies were collected from DEDP and IPCC emission coefficients. The Divisia Method is the toll to calculate pollutant emission.

4.5.1 CO_2 Emission Forecast

Figures 4.22 and 4.23 present CO_2 emission from combustion in industrial sector. Total CO_2 emission was 29,907.68 ktonCO_2 in the year 1999 and will reach 73,864.19 ktonCO_2 in the year 2011. It will grow up with the annual average growth rate of 7.82%.

Figure 4.22 presents CO_2 emission from fuel combustion by type of fuel. ***Solid fossil fuel*** is the largest source of CO_2 emission. It will increase to 35,117.00 tonCO_2 in the year 2011 from 14,854.95 ktonCO_2 in the year 1999. It will growth up with the average growth rate of 7.43% per year. The share of CO_2 emission is forecasted to decrease from 49.67% in the year 1999 to 47.53% in the year 2011.

CO_2 emission is the first rank in terms of total emission from ***petroleum product***. Its share is forecasted to in crease from 41.55% in the year 1999 to 43.46% in the year 2011 with the annual average growth rate of 8.23%.

At the same time, CO_2 emission from ***natural gas*** combustion will increase from 2,598.80 ktonCO_2 to 6,595.40 ktonCO_2 with the growth rate of 8.07% per year. The share of CO_2 emission from natural gas will be a little change, it will increase from 8.69% in the year 1999 to 8.96% in the year 2011.

From the ***renewable energy*** demand, CO_2 emission will increase slightly during the years 1999 to 2011. CO_2 emission from renewable energy was 27.40 ktonCO_2 in the year 1999 and will reach 48.25 ktonCO_2 in the year 2011.

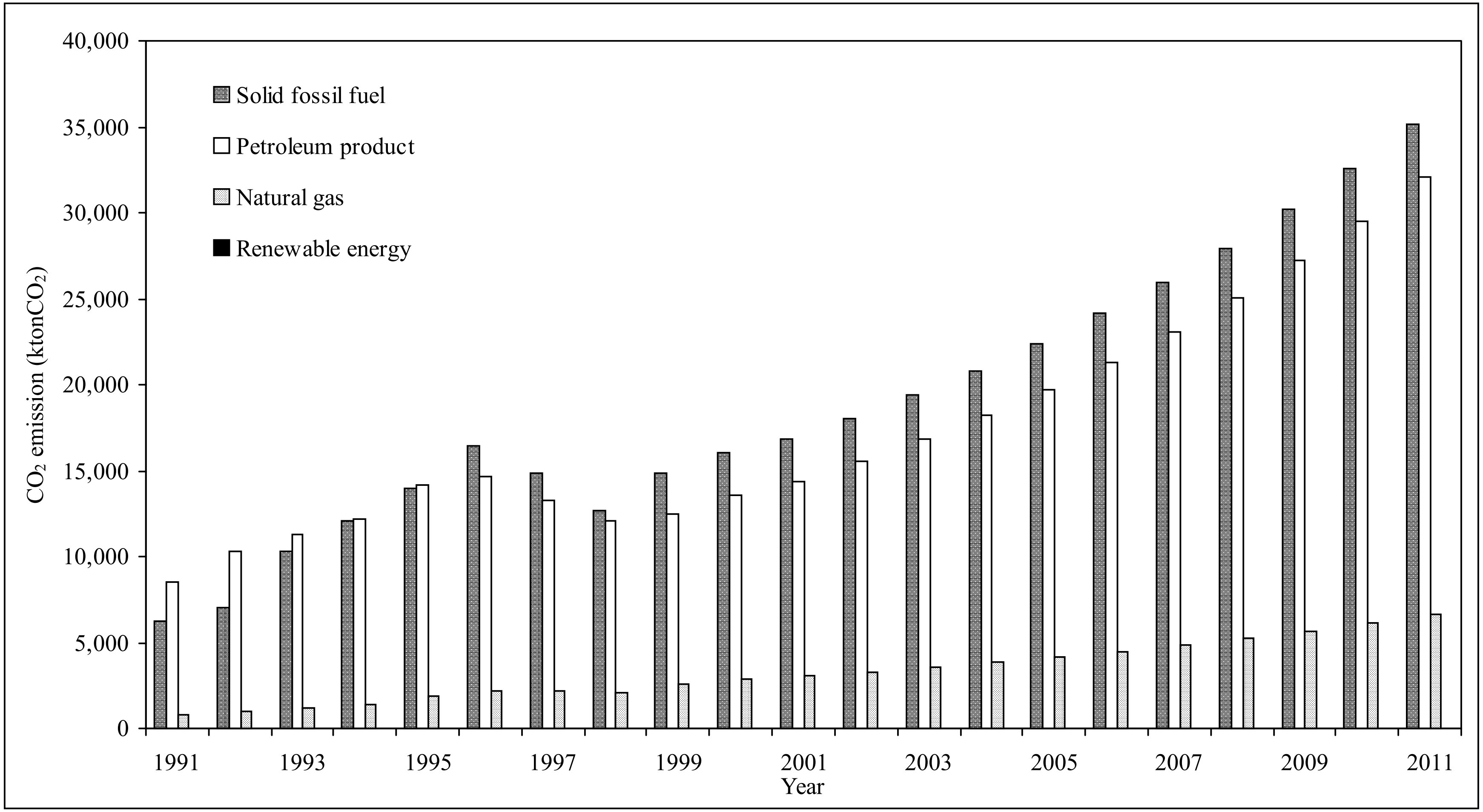

Figure 4.22. CO_2 emission from fuel combustion in industrial sector during the years 1991 to 1999 (by type of fuel).

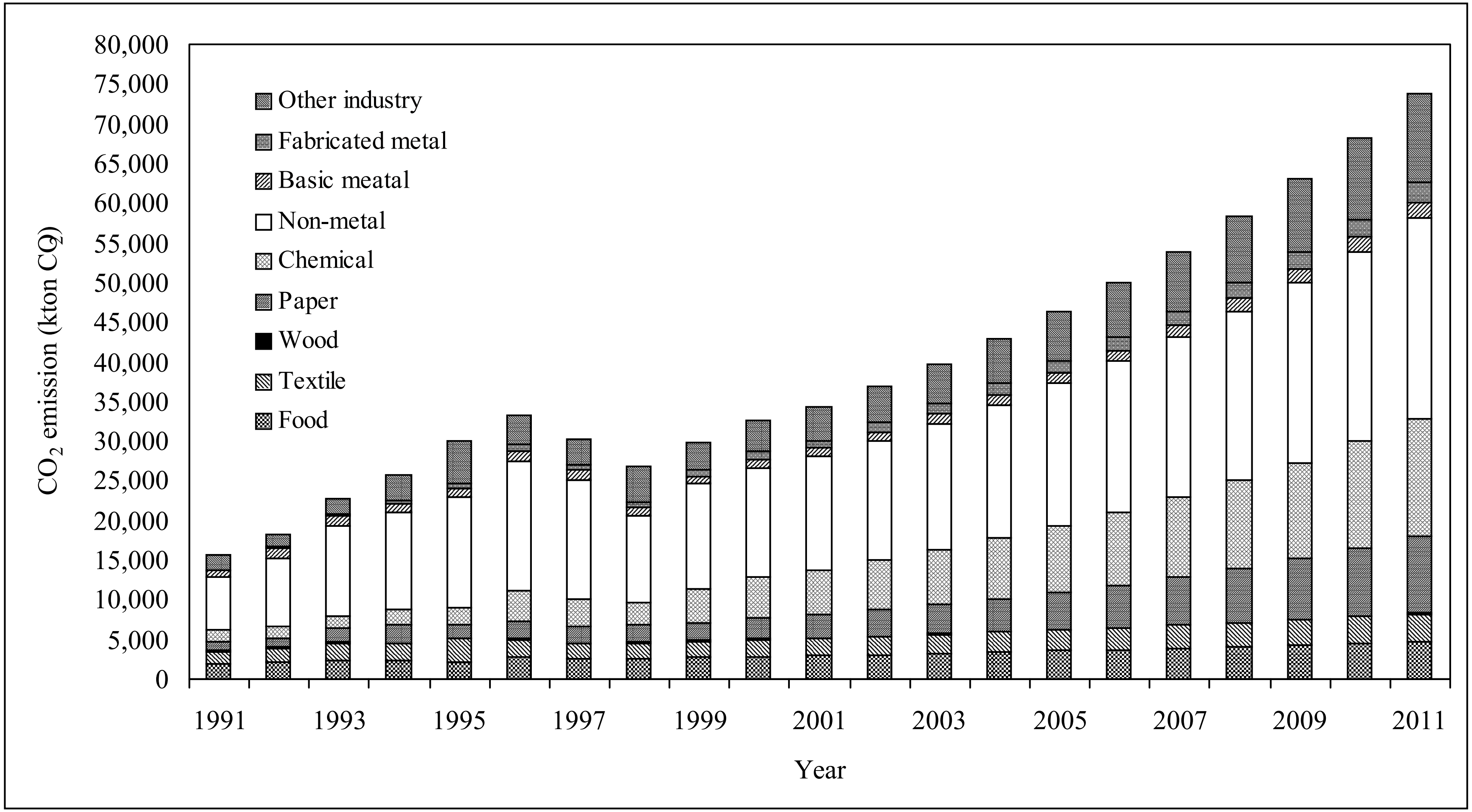

Figure 4.23. CO_2 emission from fuel combustion in industrial sector during the years 1991 to 1999 (by sub-sector).

Non-metal industry accounted for the largest CO_2 emission, as shown in Figure 4.22. The share of CO_2 emission in this sub sector was 44.05% in the year 1999 and will decrease to 34.42% in the year 2011. CO_2 emission takes the major proportion of air pollution emission from ***food industry***. CO_2 emission from food industry is forested to decrease from 9.21% in the year 1999 to 6.51% in the year 2011.

Chemical industry was the second largest sub sector in terms of CO_2 emission in industrial sector. The CO_2 emission is forecasted to be 4,274.24 ktonCO$_2$ in the year 1999 and will reach 14,730.64 ktonCO$_2$ in the year 2011. The share of CO_2 emission was 14.29% of total CO_2 emission in industrial sector in the year 1999 and will increase to 19.94% in the year 2011. The share of CO_2 emission from fuel combustion in ***textile industry*** will decrease about 1.92% between the years 1999 to 2011. Its share was about 6.56% in the year 1999 and go down to 4.64% in the year 2011.

Fabricated metal industry and ***other industry*** sub sector will be the highest CO_2 emission growth rate during the years 1999 to 2011. The share of CO_2 emission in fabricated metal industry was 2.67% (797.90 ktonCO$_2$) and up to 3.36% (2,483.77 ktonCO$_2$) with the annual average growth rate of 9.92%. While its share in other industry sub sector will increase with the average growth rate of 10.18% per year, it was 3,539.51 ktonCO$_2$ in the year 1999 and will increase to 11,332.91 ktonCO$_2$ in the year 2011. The CO_2 emission in food industry will increase from 2,251.77 ktonCO$_2$ in the year 1991 to 9,779.76 ktonCO$_2$ in the year 2011 with the highest average growth rate at 13.02% per year.

CO_2 emission in ***basic metal industry*** is forecasted to be 1,007.23 kotnCO$_2$ in the year 1999 and will reach to 1,842.22 ktonCO$_2$ in the year 2011. During the years 1999 to 2011 the share of CO_2 was 0.24% and will decrease very sharply with the average growth rate of -7.33% per year. Thus, by the year 2011 CO_2 emission in this industry will be 0.04% (from 0.24% in the year 1999).

4.5.2 NO_x Emission Forecast

Figures 4.24 and 4.25 illustrate the share of NO_x from fuel combustion. NO_x emission will increase from 167.44 ktonNO$_x$ in the year 1999 to 370.90 ktonNO$_x$ in the year 2011 with the annual average growth rate of 6.85%.

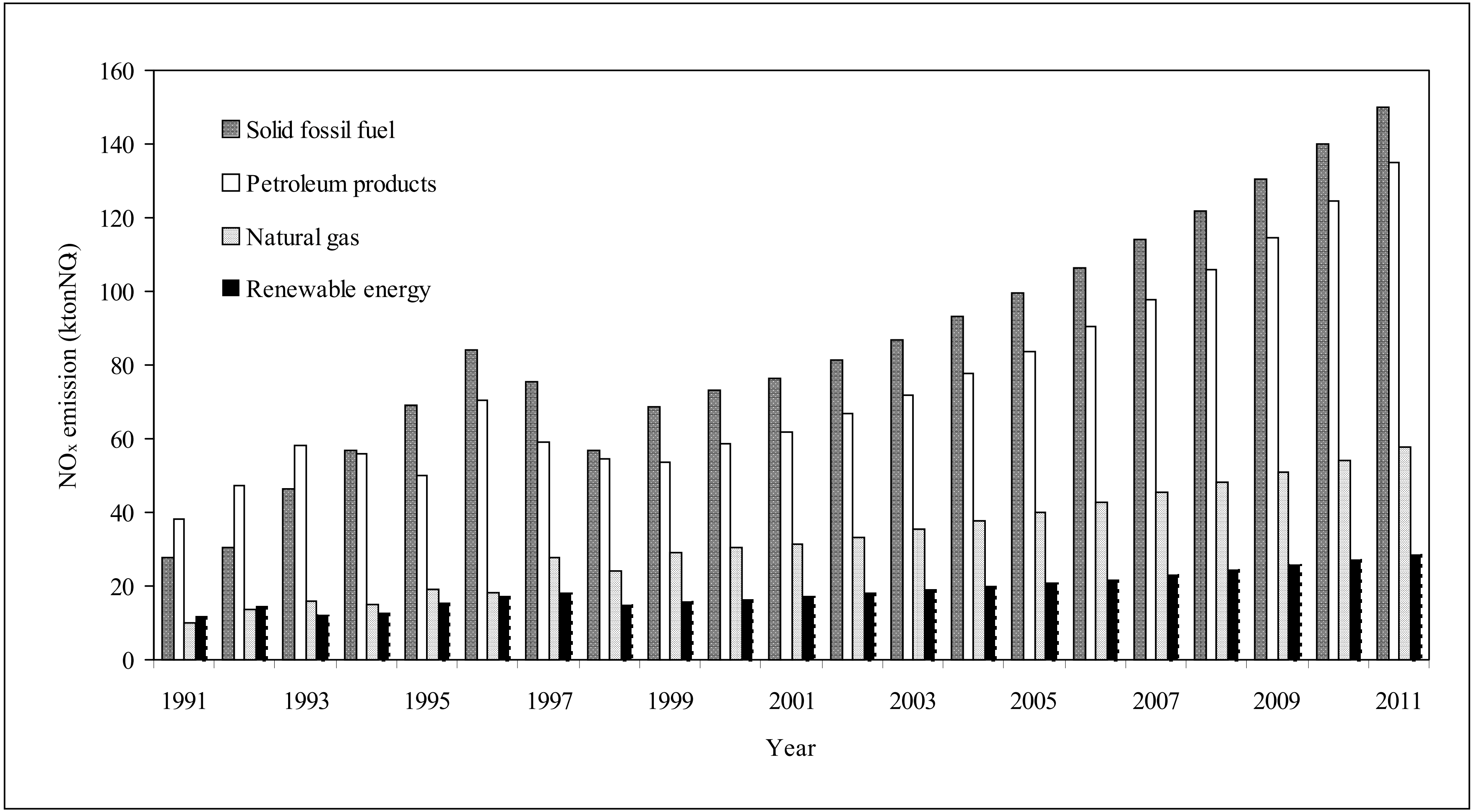

Figure 4.24. NO_x emission from fuel combustion in industrial sector during the years 1991 to 2011 (by type of fuel).

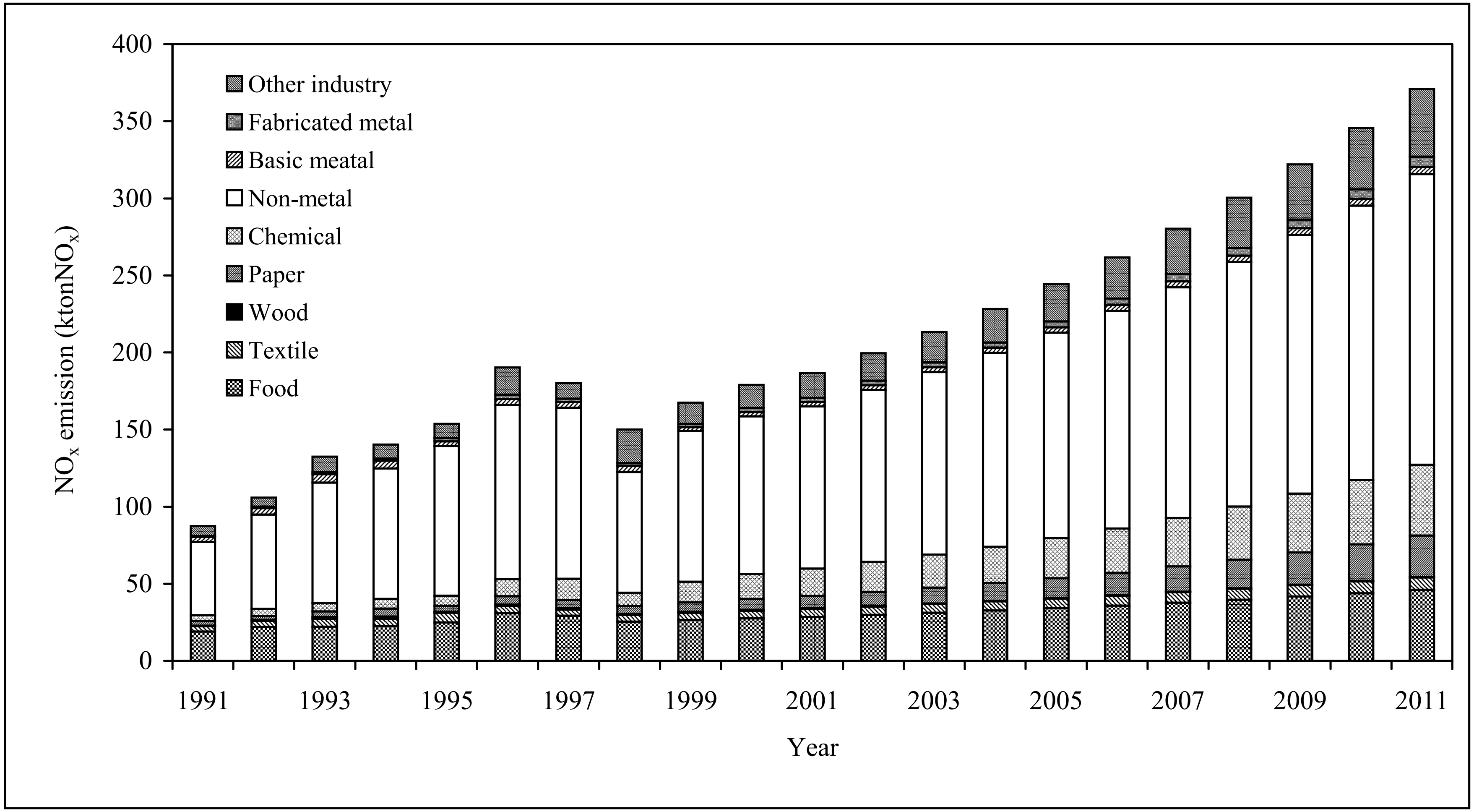

Figure 4.25. NO_x emission from fuel combustion in industrial sector during the years 1991 to 2011 (by sub-sector).

The share of NO_x emission from ***solid fossil fuel*** combustion will increase from 68.82 ktonNO_x in the year 1999 to 149.85 ktonNO_x in the year 2011 with the average growth rate of 6.70% per year.

At the same time, the NO_x emission from ***petroleum product*** combustion will grow up from 53.85 ktonNO_x to 134.82 ktonNO_x with the average growth rate of 7.95%.

NO_x emission from ***natural gas*** is the second smallest proportion, which was 28.89 ktonNO_x in the year 1999 and up to 57.76 ktonNO_x in the year 2011. The share of NO_x emission is forecasted go down to 15.52% in the year 2011 from 17.25% in the year 1999.

Renewable energy is the smallest NO_x emitter in industrial sector. NO_x from renewable energy combustion will increase from 15.89 ktonNO_x to 28.19 ktonNO_x. As present in Figure 4.24, its share will has a little change.

As presented in figure 4.25, NO_x emission in ***non-metal industry*** contributes a major part in all sub sectors, it was about 58.32% of total NO_x emission in the year 1999. Its increase from 97.66 ktonNO_x in the year 1999 to 188.46 ktonNO_x in the year 2011 with the annual average growth rate of 5.63%.

Food industry was the second largest emitter, it was 26.43 ktonNO_x in the year 1999. It is forecasted to increase with the average growth rate of about 4.76% per year.

NO_x emission in ***basic metal industry*** will increase from 2.63 ktonNO_x in the year 1999 to 4.802 ktonNO_x in the 2011 with the average growth rate of 5.16% per year.

NO_x emission in ***paper industry*** will grow with highest growth rate during the years 1999 to 2011, it was about 13% per year. NO_x emission from this sub sector is forecasted to increase from 6.18 ktonNO_x in the year 1999 to 26.85 ktonNO_x in the year 2011.

The growth rate of NO_x emission in ***chemical industry*** and ***other industry*** sub sector was about 10% per year. NO_x emission in chemical industry is forecasted to be 45.90 ktonNO_x in the year 2011 while NO_x emission in other industry sub sector will increase to 43.80 ktonNO_x.

Fabricated metal industry is the second smallest emitter, its share was 1.27% in the 1999 and reach 1.78% in the year 2011. NO_x emission from fuel combustion in this sub sector will increase to the third smallest emitter with the average growth rate of 9.93% per year.

NO_x emission in ***food industry*** and ***textile industry*** will increase slowly from 26.43 ktonNO$_x$ in the year 1999 to 46.19 ktonNO$_x$ in the year 2011 for food industry and will increase from 4.77 ktonNO$_x$ to 8.03 ktonNO$_x$ for textile industry.

The NO_x emission in ***wood industry*** is forecasted to decrease from 0.65 ktonNO$_x$ in the year 1999 and go down to 0.26ktonNO$_x$ in the 2011.

4.5.3 SO_2 Emission Forecast

Figures 4.26 and 4.27 shows SO_2 emission in industrial sector is forecasted to increase to 1,278.63 ktonSO$_2$ in the year 2011 from 268.97 htonSO$_2$ in the year 1999 with the average growth rate of 13.87% per year.

Petroleum product is the largest source of SO_2 emission followed by solid fossil fuel. The share of SO_2 emission was about 70% for petroleum product and 30% for solid fossil fuel as shown in Figure 4.26.

SO_2 emission from ***petroleum product*** combustion will increase with very high growth rate (13.96% per year), it will increase from 196.56 ktonSO$_2$ in the year 1999 to 943.24 ktonSO$_2$ in the year 2011. SO_2 emission from fuel oil is the largest source from petroleum product.

Lignite is only one source of SO_2 emission from ***solid fossil fuel***. SO_2 emission from lignite combustion is forecasted to be 72.41 ktonSO$_2$ in the year 1999 and will reach 335.39 ktonSO$_2$ with the annual average growth rate of 13.63%.

In the total SO_2 emission in industrial sector, the share of ***non-metal industry*** major part was about 29% (see in Figure 4.27). SO_2 emission in this sub sector will increase from 79.98 ktonSO$_2$ in the year 1999 to reach 381.64 ktonSO$_2$ in the year 2011 with the growth rate of 13.91% per year.

The second was ***other industry*** sub sector, as shown in Figure 4.27. Its share will increase from 19.31% in the year 1999 to 30.32% in the year 2011. It will increase to 411.17 ktonSO$_2$ in the year 2011 with the annual average growth rate of 19.82%.

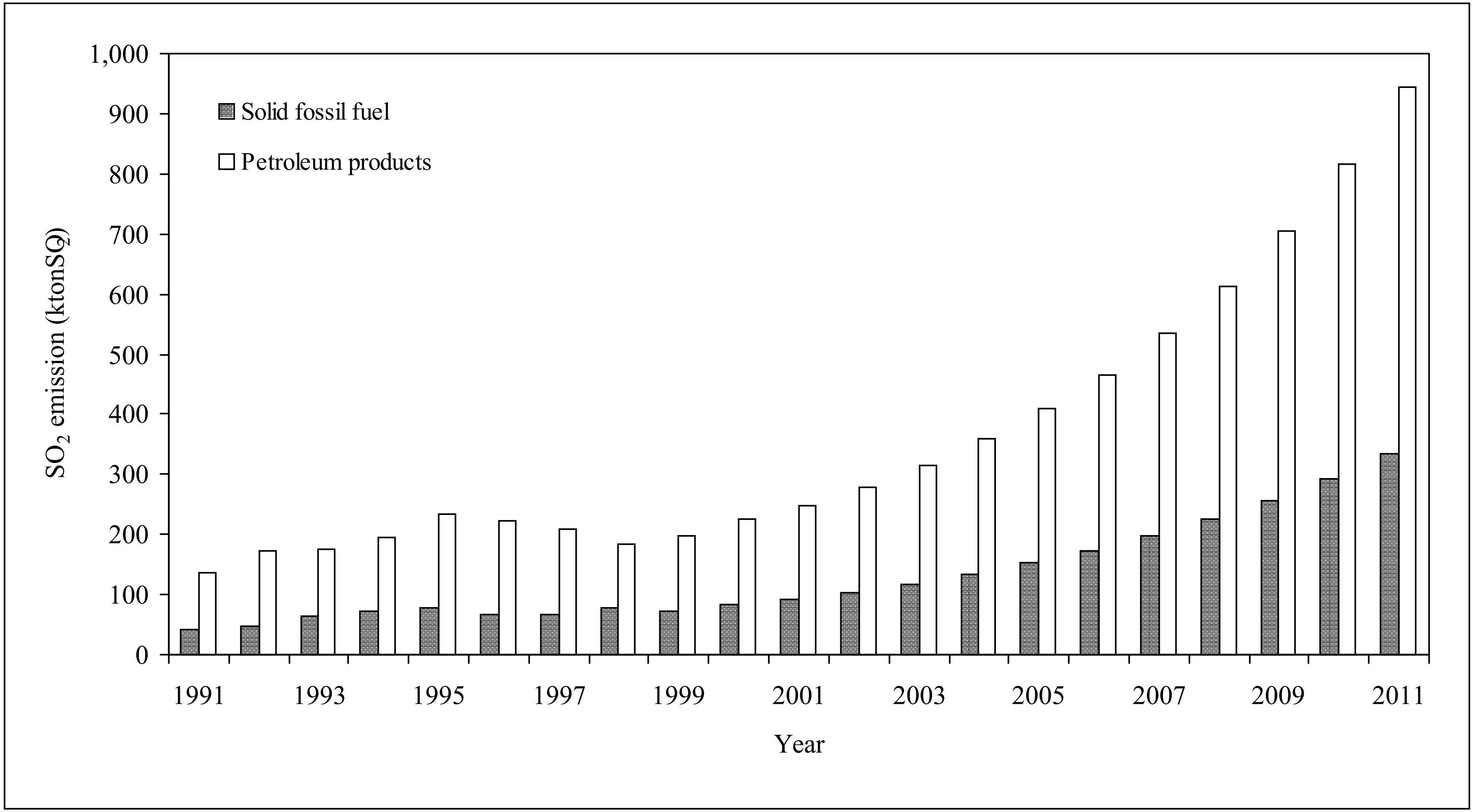

Figure 4.26. SO_2 emission from fuel combustion in industrial sector during the years 1991 to 2011 (by type of fuel).

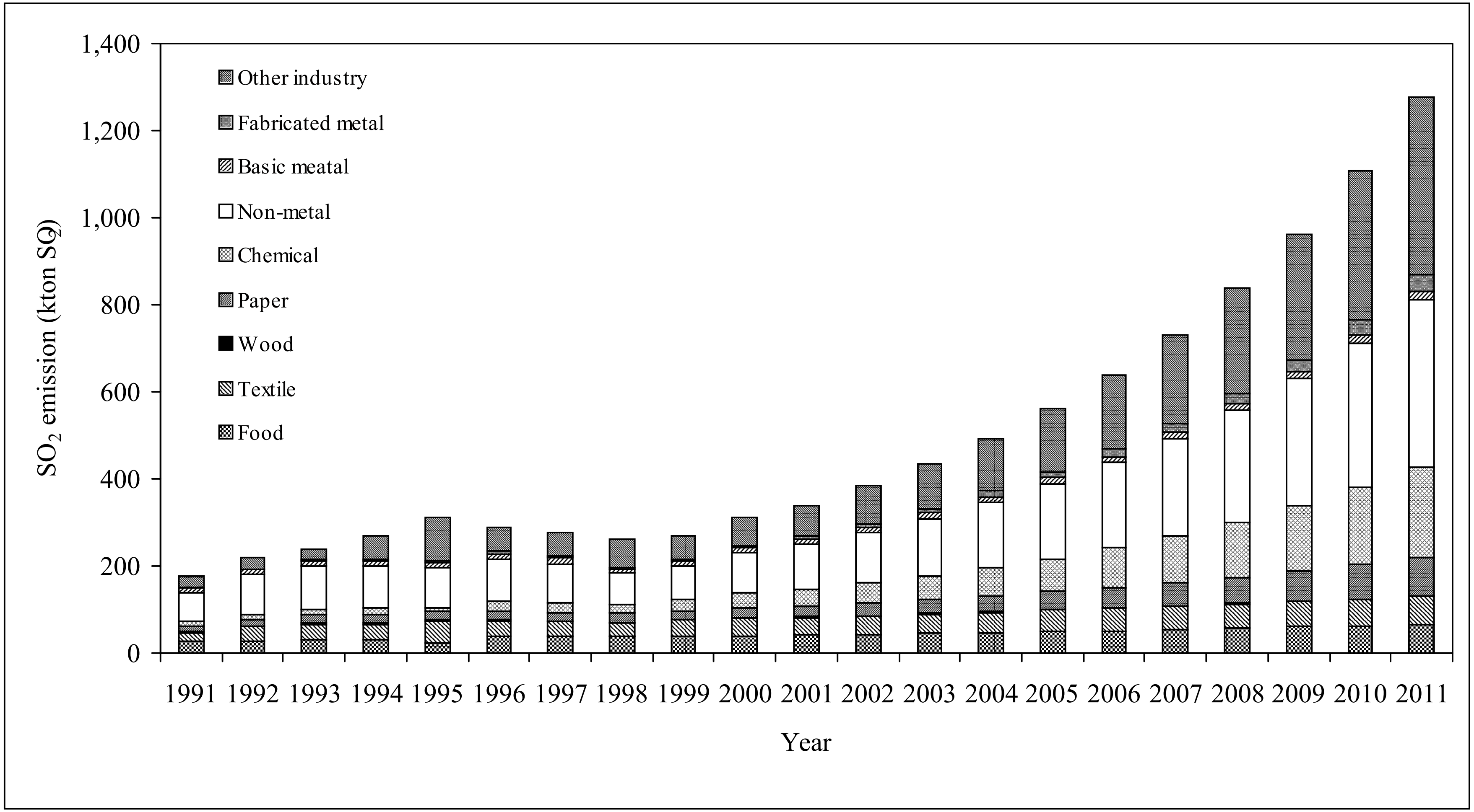

Figure 4.27. SO_2 emission from fuel combustion in industrial sector during the years 1991 to 2011 (by sub-sector).

At the same time, SO_2 emission from ***fabricated metal industry*** is forecasted to increase with the growth rate of 18.55% per year. Its share will increase to 2.99% in the year 2011 from 1.84% in the year 1999.

Chemical industry had highest SO_2 emission growth rate, about 19.55% per year in the period of the years 1999 to 2011. SO_2 emission was 24.64 ktonSO$_2$ in the year 1999 and will increase to 209.97 ktonSO$_2$ in the year 2011.
SO_2 emission in ***paper industry*** was about 20.20 ktonSO$_2$ in the year 1999 and will increase to 87.72 ktonSO$_2$ in the year 2011 with the average growth rate of 13.91% per year. The SO_2 emission from ***textile industry***, ***food industry***, ***and basic metal industry*** are forecasted to increase with the annual average growth rate of 4.44%, 4.76%, and 5.16% respectively.

In the forecast period, the smallest part of SO_2 emission is ***wood industry***. SO_2 emission in this industry will decrease from 0.74 ktonSO$_2$ to 0.30 ktonSO$_2$ with the rate of –7.25% per year. Its share was 0.28% in the year 1999 and will down to 0.02% in the year 2011.

In this study, the amounts of pollutant emission depend on the amount and type of energy consumption in each industry, based on BAU scenario. Energy consumption is affected by economic activity. In the year 1999 to 2011, The emission of SO_2 will increase very rapidly compared to CO_2 emission and NO_x emission, due to the high growth rate of petroleum product. However, CO_2 emission from fuel combustion will still be the major problem in air pollution emission, followed by SO_2 and NO_x emissions.

4.6 Improvement of Energy Efficiency and Pollution Mitigation of Selected Industrial Enterprises

Between the years 1991 to 1999, the energy use in the industrial sector, which includes the food, textile, wood, paper, chemical, basic metal, non-metal, fabricated metal, and other industry accounted for most of the increase in the energy consumption in the economic sector of Thailand. Figure 4.28 shown the energy consumption in industrial sector in the year 1999. Food industry was the biggest consumer while the renewable energy was the major part of the total energy consumption. Nevertheless, this sub sector was the third biggest consumer in term of modern energy consumption, after non-metal industry and chemical industry respectively.

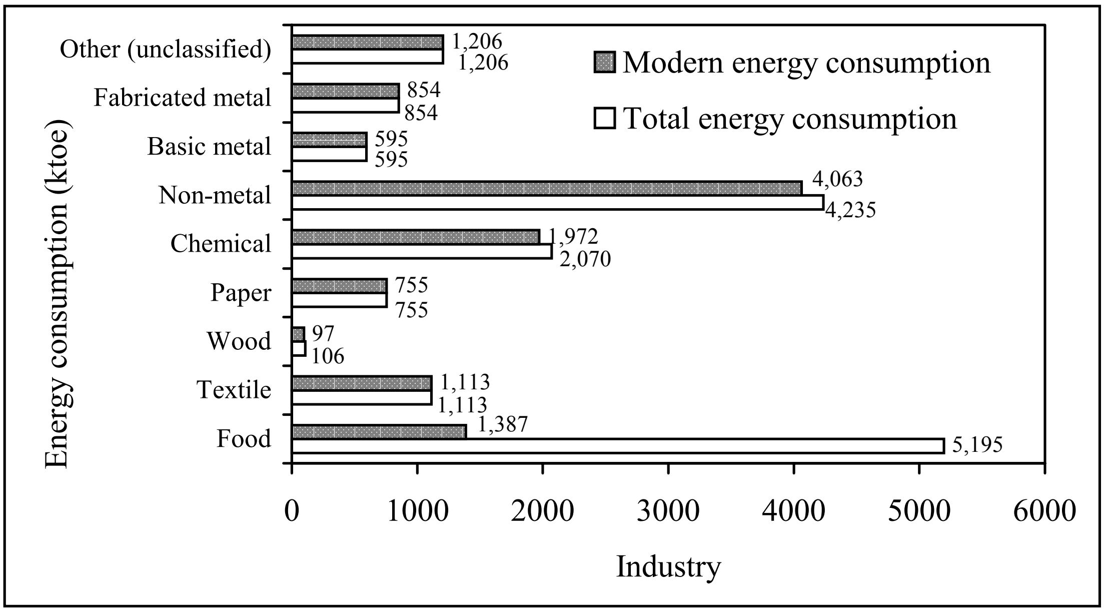

Figure 4.28. The energy consumption in the industrial sector in 1999 (Watchara Mingwithitikul, 2001).

The type and amount of energy consumption have resulted in air pollution emission. Through out of the studies years, CO_2 emission is the major portion, followed by SO_2 and NO_x emissions. The largest emitters of air pollution emissions in industrial sector are the non-metal, other industry, chemical, and food industry (as shown in Figure 4.29 - 4.31). Moreover, there was the low energy efficiency (see in Figure 4.32). From this study, non-metal industry has the lowest energy efficiency and high emission of air pollution.

Non-metal industry includes 5 groups: firebrick and ceramic, glass, concrete, cement, and other groups industry. Non metal industry plays an important role in the industrial sector of Thailand. It is the biggest consumer (exclude the energy renewable energy) due to contributes a small share in industrial output. Energy intensity in non-metal industry is higher than that of other industries sub sector. The thermal energy is the major part in this sub sector. It was about 91% of total energy used in the year 1999. The major energy is the solid fossil fuel (as shown in Figure 4.33). The type of energy used in this industry has resulted in the CO_2, SO_2, and NO_x emissions. This sub- sector is the largest emitter in industrial sector. CO_2 emission is the major part of air pollution emission followed by SO_2 and NO_x emissions.

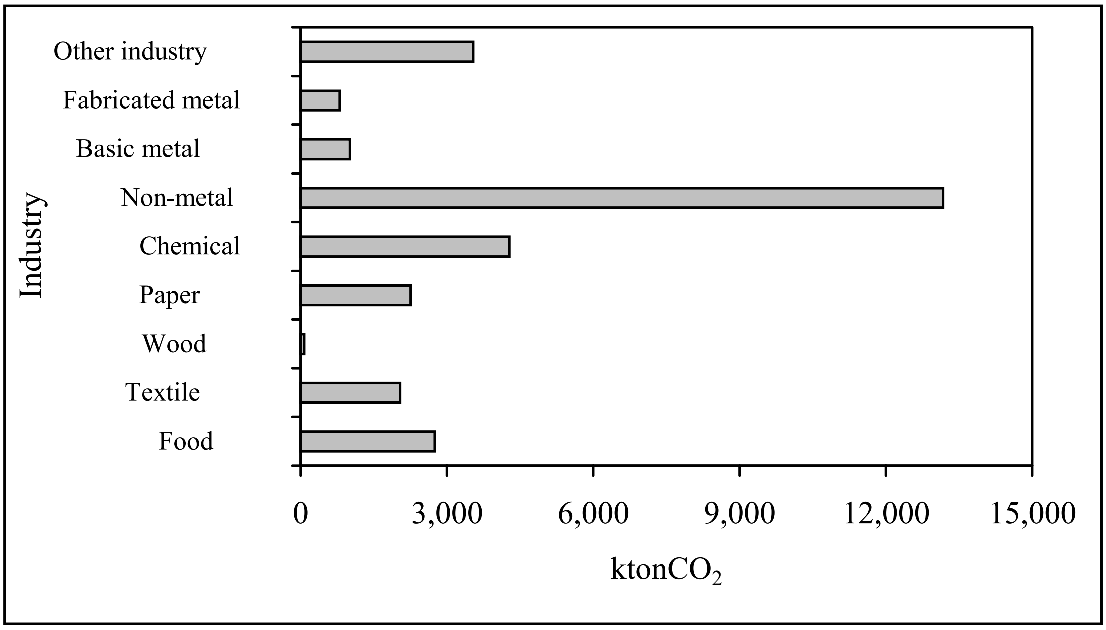

Figure 4.29. CO_2 emission from fuel consumption in industrial sector in 1999.

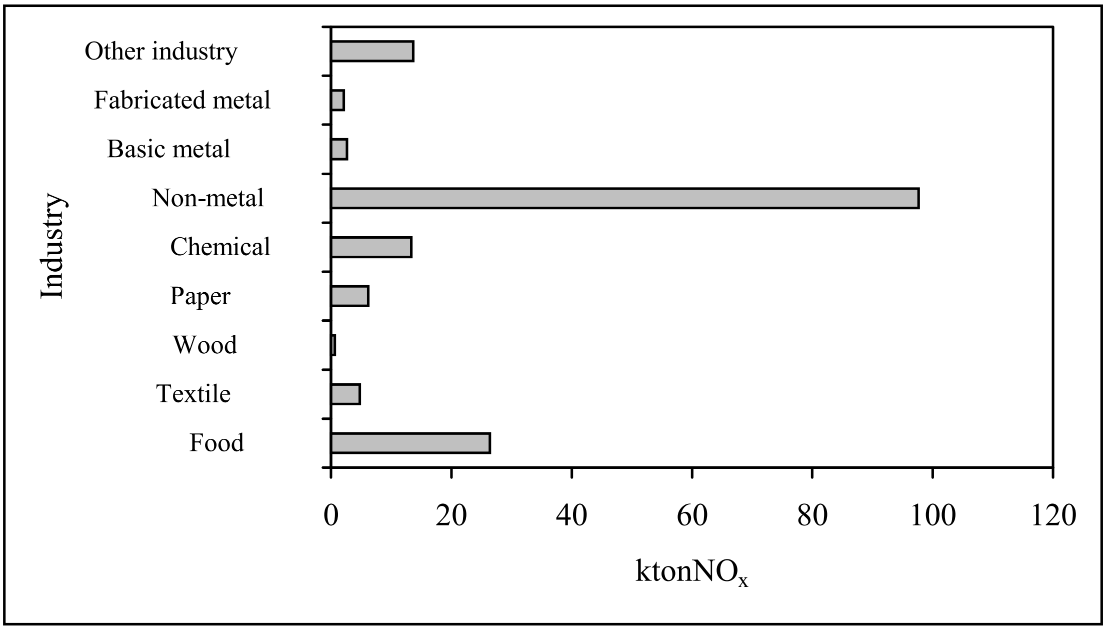

Figure 4.30. NO_x emission from fuel consumption in industrial sector in 1999.

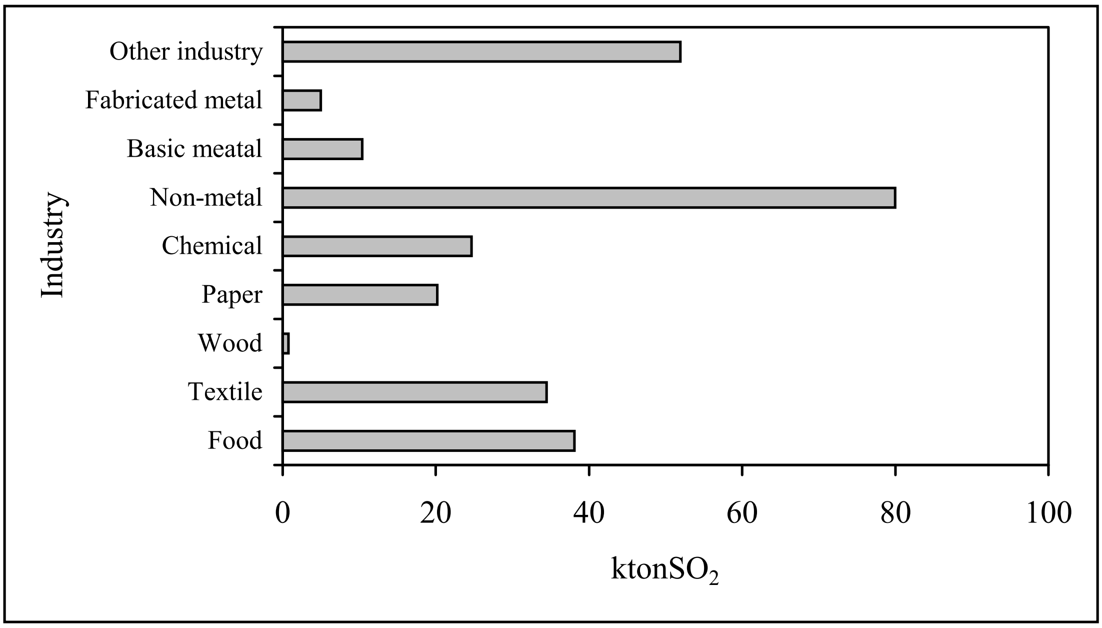

Figure 4.31. SO_2 emission from fuel consumption in industrial sector in 1999.

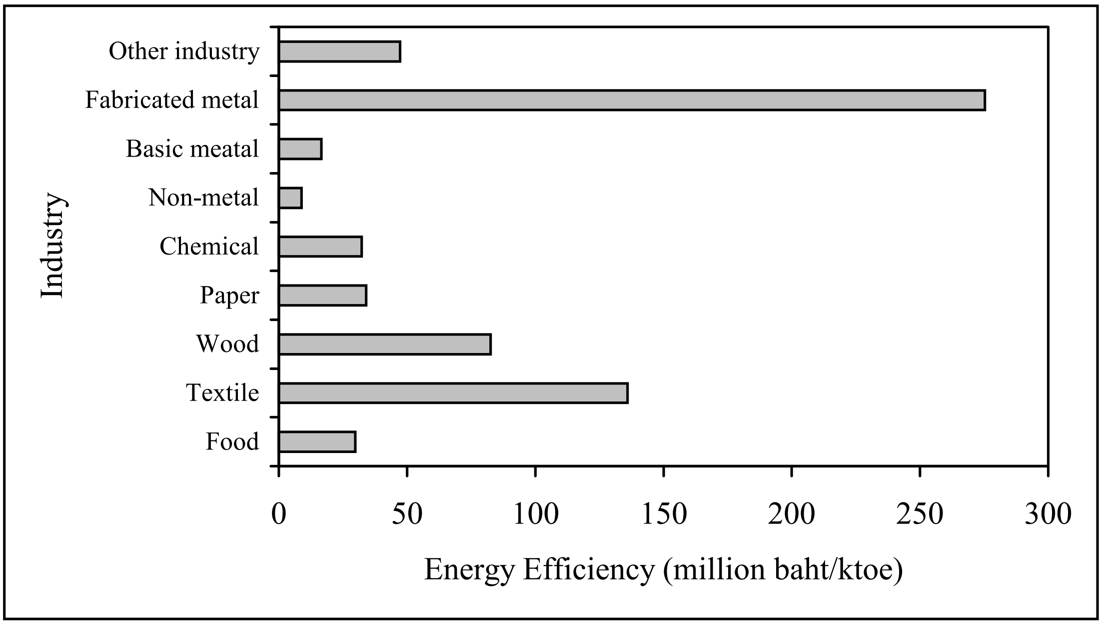

Figure 4.32. Energy efficiency of the industrial sector in 1999.

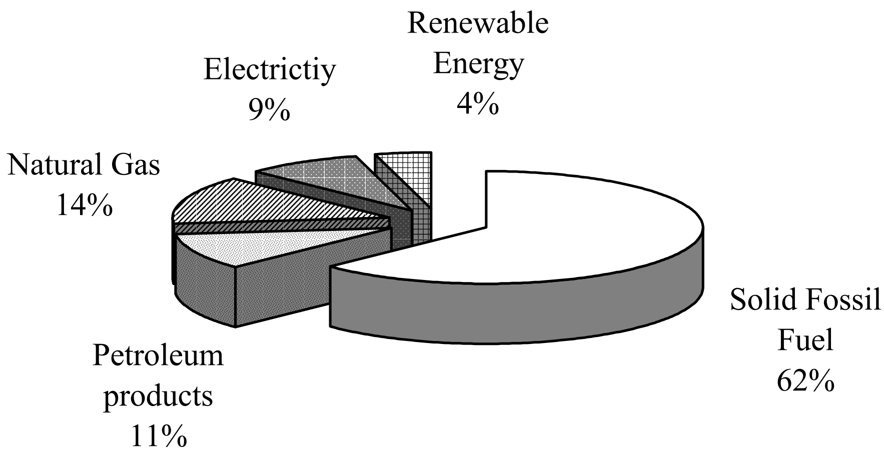

Figure 4.33. The share of fuel consumption in non-metal industry in 1999.

Non-metal industry is characterized by high intensities in energy consumption and high emission pollution and by low energy efficiency. In this study, the questionnaire sent to 90 factories in 5 groups of non-metal industrial sub-sector. Based on the questionnaire obtained from 3 factories, the analysis is focused in to 3 groups of the non-metal industry, it includes firebrick industry, glass bottle industry, and cement industry.

The improvement of efficiency in the selected industry would play a major role in reducing energy demand and pollution emissions. Information data from the questionnaire data, the major energy consumption is thermal energy used in the kiln/furnace at very temperature. Due to limitations, assumptions have been made based on observation and information data from the literature, as presented in Appendix E1. The measure of energy conservation in industrial sector in Thailand, the related equipment and type of measure considered by DEDP (see in Table E1.7, Appendix E1). Therefore, the opportunity for energy saving and reducing pollutant emissions by flue gas recovery is large. Moreover, fuel switching is the important option because of the high pollution emission level of the old energy used. Other significant saving can be done by replacement of old low efficiency equipment by high efficient ones.

4.6.1 Firebrick Industry

The information from questionnaire has been presented in Table E2.1. The production process in the selected firebrick factory is illustrated in Figure 4.34.

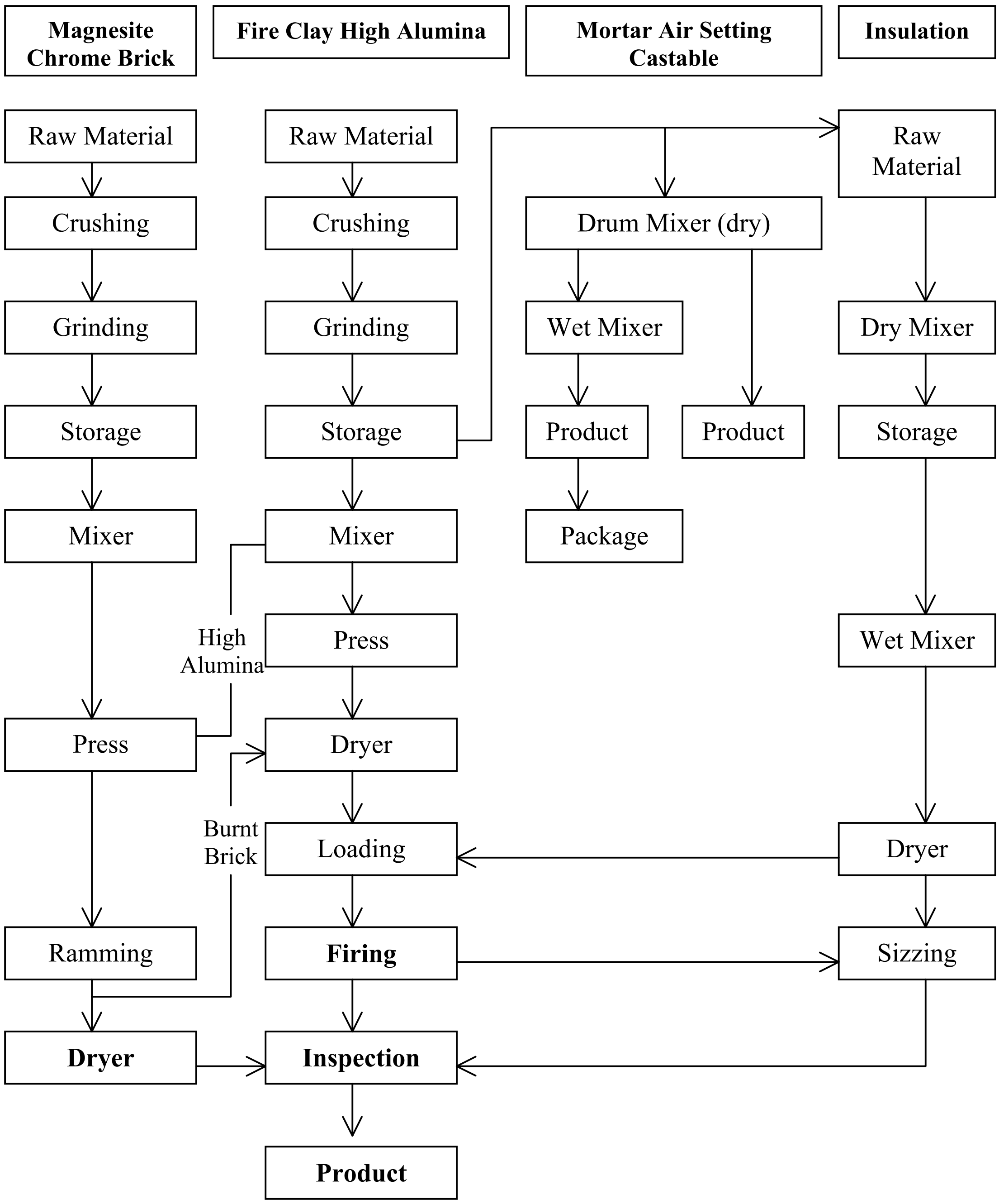

Figure 4.34. Firebrick manufacturing processes in the selected firebrick factory.

The production of this factory is firebrick. The production of this factory was about 7,980 ton of firebrick in the year 2000. The major energy is thermal energy from fuel oil used in the furnace. The electricity is used for other equipment in the processes, such as crusher, grinder, press, dryer, and others. The share of energy consumption in the production process has little change in the period of the years 1997 to 2000.

The noted of this factory, the energy consumption data are reported only the fuel oil and electricity. In the years 1997 to 2000, the fuel oil consumption is in rage of 960 to 1,260 ktoe, and the electricity was constant at 780,000 kWh per year.

The estimation of CO_2 emission is the major air pollution from fuel combustion in this factory. Its emission was 3,579.54 tonCO_2, in the year 2000, followed by SO_2 and Ox emissions (68.23 tonSO_2 and 24.02 tonNO_x respectively).

Base on observation data, the energy efficiency in firebrick factory is in rang 4.95 to 8.62 ton/toe, it depend on the amount of production. The energy efficiency was 6.3703 ton/toe in the year 2000. The fuel oil combustion in fire-brick furnace may improve by standard air fuel ratio adjustment to 1.4 for alumina and lime (Takamura, 2000) and preheating of the air supplied to the furnace, the fuel oil efficiency may increase about 3.88%. Nevertheless, air pollution emission may decrease a little change (see in Table 4.1). In the other hand, the substitution of fuel oil by natural gas is one way to reduce the air pollution emission and fuel cost. From the calculation in Appendix E2, fuel switching may reduce CO_2 and SO_2 emissions about 27.12% for CO_2 emission and 100% for SO_2 emission, but NO_x emission may increase from 2.997.kg/ton to 6.319 kg/ton, as reported in Table 4.2.

Table 4.1. Preheat air in the selected firebrick factory.

Option	**Existing**	**Preheated air**
Fuel oil consumption (GJ/ton)	5.688	5.476
CO_2 emission kgCO_2/ton	435.708	419.442
SO_2 emission kgSO_2/ton	8.536	8.218
NO_x emission kgNO_x/ton	2.998	2.886

<u>Source</u> Calculated from this study

Table 4.2. Fuel switching in the selected firebrick industry.

Option	Existing (fuel oil)	Fuel switching (Natural gas)
Energy consumption (GJ/ton)	5.688	5.688
CO_2 emission kgCO_2/ton	435.708	317.535
SO_2 emission kgSO_2/ton	8.536	0
NO_x emission kgNO_x/ton	2.998	6.319

Source Calculated from this study

The electricity management should improve in this factory. The replacement of existing electric motor by highly efficient electric motors, the electricity efficiency may improve from 0.0128 to 0.0130 ton/kWh (see in Appendix E2). Moreover, if change to voltage regulator may save electricity about 78,000 kWh.

4.6.2 Glass Industry

The general data of glass bottle glass factory, which is obtained from the questionnaire, are report in Table E3.1, Appendix E3. The production process of this factory is shown in Figure 4.35.

This factory produces glass bottles for beverage, beer, food, pharmaceutical, and cosmetic. The production of glass bottles per year is around 16,500 ton. Base on the observation of energy consumption, fuel oil is the major energy used. Fuel oil used for furnace annually accounts for 70% of total energy used and the rest, natural gas, and electricity are used for forming process, emailing, and others.

From the estimation in this study, CO_2 emission from fuel combustion is the largest pollutant. It was about 63,565.45 tonCO_2 followed by SO_2 was about 1,077.05 tonSO_2 and NO_x was about 549.22 tonNO_x.

The energy consumption in the selected glass bottle factory has resulted in the energy efficiency. In the year 2000, the energy efficiency is 7.9759 ton/toe. Its is lower than that in the year 1997. The fuel oil efficiency may increase from 0.0091 ton/L to 0.0130 ton/L. By the standard air fuel ratio adjustment is 1.4 for melting furnace in glass industry (Takamura, 2000) and heat recovery on exhaust gas which can save by 12.62 L/ton of fuel oil or 0.502 GJ/ton of fuel energy, as shown in

Table 4.3. These calculations are given in Appendix E3. The calculation of CO_2 emission may reduce to 242.821 kgCO_2/ton from 333.188 kgCO_2/ton by switching from fuel oil to natural gas. Moreover, natural is not a source of SO_2 emission but NO_x may increase from 2.292 kg NO_x/ton to 4.833 kgNO_x/ton (see in Table 4.4).

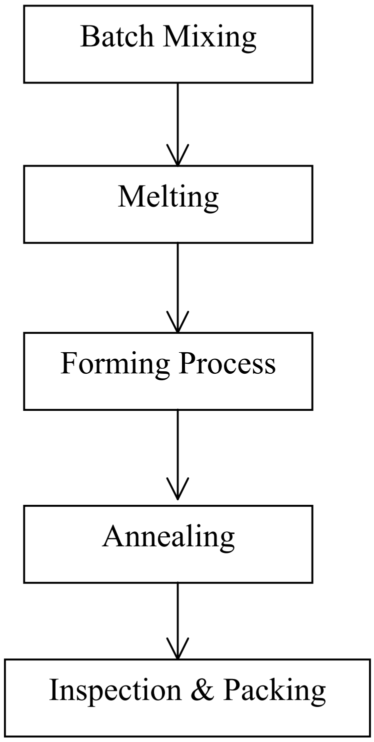

Figure 4.35. Glass bottle manufacturing process in the selected glass bottle factory.

Table 4.3. Preheat air in the selected glass bottle factory.

Option	Existing	Preheated air
Fuel oil consumption (GJ/ton)	4.350	3.848
CO_2 emission kgCO_2/ton	333.188	294.746
SO_2 emission kgSO_2/ton	6.527	5.774
NO_x emission kgNO_x/ton	2.292	2.028

Source Calculated from this study

Table 4.4. Fuel switching in the selected glass bottle factory.

Option	Existing (fuel oil)	Fuel switching (Natural gas)
Energy consumption (GJ/ton)	4.350	4.350
CO_2 emission $kgCO_2$/ton	333.188	242.821
SO_2 emission $kgSO_2$/ton	6.527	0
NO_x emission $kgNO_x$/ton	2.292	4.833

Source Calculated from this study

The electricity consumption may reduce about 4,333,300 kWh by change to high efficiency voltage regulator and if change to high efficiency electric motor may improve electricity efficiency from 0.00476 to 0.00485 ton/kWh (see in Appendix E3).

4.6.3 Cement Industry

Many cement industries is located in Saraburi, middle of Thailand. The information data, which obtained from the questionnaire, is shown in Table E4.1, Appendix E4. The production process of this factory is shown in Figure 4.36.

The dry process including the pre-heater are used in this plant, which it is really a good technology (Nguyen Tha Tam, 2000).

Coal is the major fuel to produce heat for clinker production in rotary kiln cement plant. Electricity is the second major energy source to produce heat in this process, but it is major energy source for cement production in cement kiln. The energy used in this factory given in Table E4.1, Appendix E4.

The amount of air pollution emission came from fuel combustion in production processes was 761.429 $ktonCO_2$ and followed by 4.475 $ktonNO_x$ and 4.277 $ktonSO_2$ respectively. Based on this estimated, the major pollution emission was CO_2 emission, which generated from fuel combustion

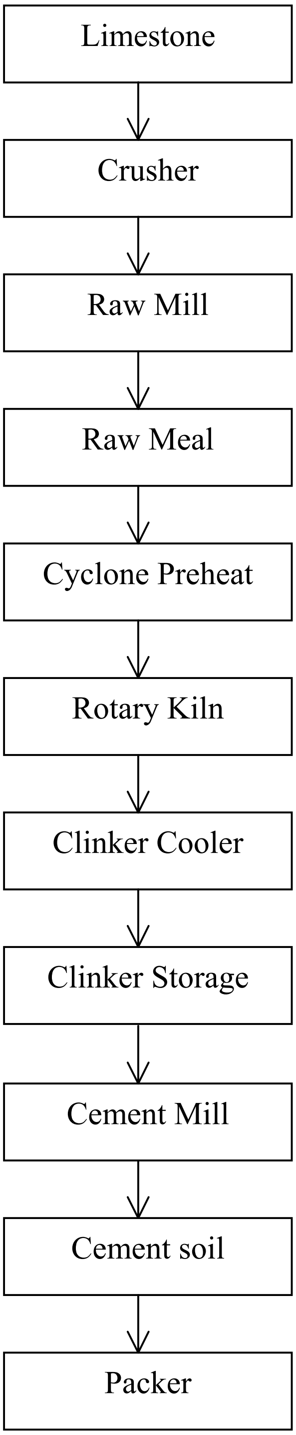

Figure 4.36. Cement manufacturing process in the selected cement factory.

For this reason, the focus of mitigation potential action can be given to quantify energy saving and mitigated in pollutant. In this factory, important thermal saving potential can be realized from kiln efficiency improvement techniques. Bitumen and lignite are used for kiln, while the heat value of light is lower than that of bitumen. Moreover, from fuel cost record of 2000 data, the cost of bitumen is 956 baht/ton, as same the lignite price. SO, lignite may substitute by bitumen, it can save energy cost about 77,785,896 baht per year. As shown in table 4.5, CO_2 emission may reduce by 59.124 tonCO_2 per ton cement and SO_2 emission may reduce by 2.392 tonSO_2 per ton cement while amount of NO_x emission may still be 1.548 tonNO_x/ton cement. The calculation is given in Appendix E4.

Table 4.5. Fuel switching in the selected cement industry (switching of lignite to bitumen).

Option	Existing (lignite)	Fuel switching (bitumen)
Energy consumption (GJ/ton)	2.938	2.938
CO_2 emission kgCO_2/ton	291.399	232.275
SO_2 emission kgSO_2/ton	2.392	0
NO_x emission kgNO_x/ton	1.548	1.548

Source Calculated from this study

As shown in Table 4.6, the CO_2 emission and SO_2 emission may reduce about 1.8 kgCO_2/ton and 0.133 kgSO_2/ton from the substitution of fuel oil by natural gas. But NO_x emission from natural gas combustion was 0.099 kgNO_x/ton, which it increased by 0.05 kgNO_x/ton from fuel oil combustion. However, this replacement can save cost about 8,688,400.83 baht per year.

In this factory, the electricity cost was about 48% of total energy cost. Thus, the electricity management is very necessary in this industry. The electricity demand may decrease about 49,381,800 kWh by replacement of existing damper and controller motor, while its efficiency increase about 0.00017 ton/kWh by replacement of existing electric motors with highly electric motors, as shown in Appendix E4.

Table 4.6. Fuel switching in the selected cement industry (switching of fuel oil to natural gas).

Option	Existing (fuel oil)	Fuel switching (natural gas)
Energy consumption (GJ/ton)	0.0889	0.0889
CO_2 emission $kgCO_2$/ton	6.808	4.961
SO_2 emission $kgSO_2$/ton	0.133	0
NO_x emission $kgNO_x$/ton	0.047	0.099

Source Calculated from this study

4.6.4. Summary Options

Firebrick Industry

The energy saving and emission reducing opportunities of the selected factory are present in Figure 4.37 and Table 4.7. It is found that highest value of potential energy saving in this study can be gained from the heat recovery. The other significant energy saving come from replacement by high efficiency electric motor or high efficiency voltage regulators. The substitution of fuel oil by natural gas can reduce the fuel cost and pollution emissions. This measure can reduce very high compared to other measure. However, it is long term measure with high investment for new burner and other equipment.

Glass Industry

Fuel oil is the main thermal energy source and it used at high temperature. Thus, heat recovery is highest thermal energy saving potential with the medium level in term of pay back period (see in Figure 4.38 and Table 4.8). Moreover, heat recovery of air in the furnace can reduce pollution emission about 6% to 10% with the medium term measures. The substitution of fuel oil by natural gas, long term measure, can not saved in term of thermal energy. However, it is important to reduce CO_2 and SO_2 emissions from fuel combustion in the processes, but NO_x emission from natural gas combustion is higher than NO_x emission from the existing fuel combustion (fuel oil). Therefore, the opportunity for thermal energy saving and reducing pollutant emission from fuel combustion in the processes by preheats air is large. The opportunity for electricity saving may be done by change to high efficiency voltage regulator or replacement by high efficiency motor with the medium level in term of pay back period.

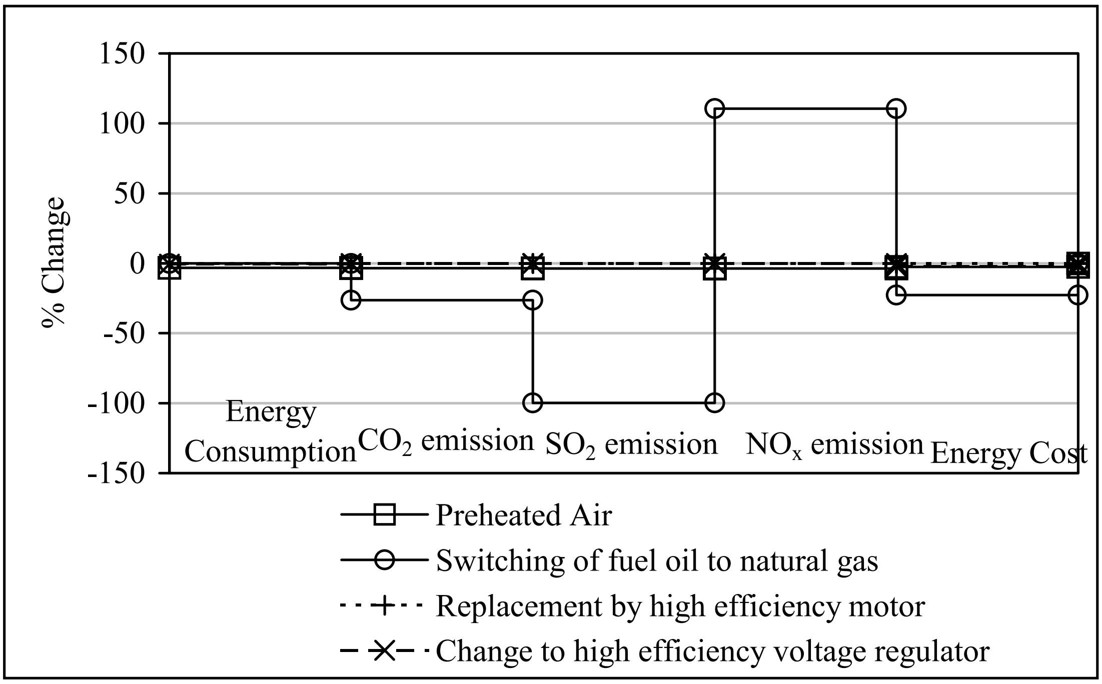

Figure 4.37. Reduction of energy consumption and air pollution in firebrick industry

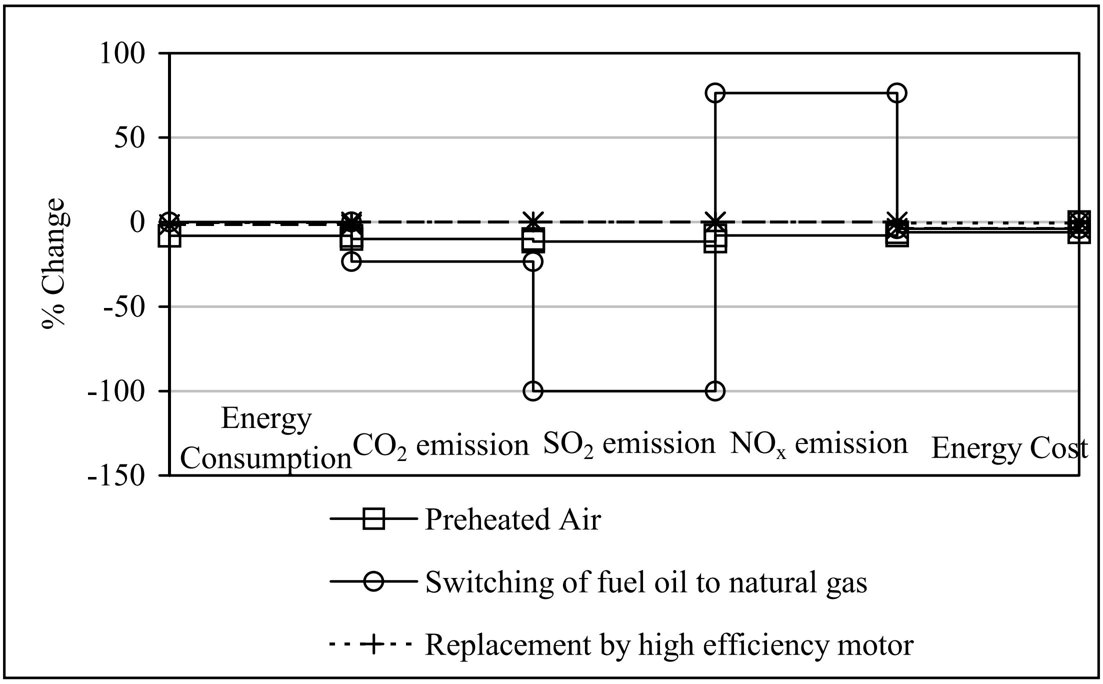

Figure 4.38. Reduction of energy consumption and air pollution in glass bottle industry

Table 4.7. Reduction of energy consumption and air pollution in firebrick industry.

Option	Existing	Preheated air	Fuel switching	Replacement by high efficiency motor	Change to high efficiency voltage regulator	Replacement by inverter
Energy consumption						
Fuel energy consumption (toe/ton)	0.13894	0.13392	0.13894	0.13894	0.13894	
Electricity consumption (toe/ton)	0.00833	0.00833	0.00833	0.00820	0.00750	
Total energy consumption (toe/ton)	0.14727	0.14225	0.14727	0.14715	0.14644	
Pollution emission						
CO_2 emission (tonCO_2/ton)	0.44856	0.43230	0.33039	0.44856	0.44856	
SO_2 emission (tonSO_2/ton)	0.00855	0.00823	0.00002	0.00855	0.00855	
NO_x emission (tonNO_x/ton)	0.00301	0.00290	0.00633	0.00301	0.00301	
Economic evaluation						
Energy cost (Baht/ton)	1,187.87	1,155.53	916.76	1,184.00	1,162.84	
Type of measure		P	M	P	P	
Pay back period		Medium term	Long term	Medium term	Medium term	

H = House keeping

P = Process improvement

M = Major change of equipment

Table 4.8. Reduction of energy consumption and air pollution in glass bottle industry.

Option	Existing	Preheated air	Fuel switching	Replacement by high efficiency motor	Change to high efficiency voltage regulator	Replacement by inverter
Energy consumption						
Fuel energy consumption (toe/ton)	0.12505	0.11317	0.12505	0.12505	0.12505	
Electricity consumption (toe/ton)	0.02238	0.02238	0.02238	0.02205	0.02014	
Total energy consumption (toe/ton)	0.14743	0.13555	0.14743	0.14710	0.14519	
Pollution emission						
CO_2 emission ($tonCO_2/ton$)	0.38525	0.34680	0.29488	0.38525	0.38525	
SO_2 emission ($tonSO_2/ton$)	0.00653	0.00577	0.00000			
NO_x emission ($tonNO_x/ton$)	0.00333	0.00306	0.00587	0.00333	0.00333	
Economic evaluation						
Energy cost (Baht/ton)	1,454.76	1,367.68	1,397.86	1,446.54	1,399.61	
Type of measure		P	M	P	P	
Pay back period		Medium term	Long term	Medium term	Medium term	

H = House keeping

P = Process improvement

M = Major change of equipment

Cement Industry

The energy saving and mitigation of air pollution emission in cement industry are presented in figure 4.39 and Table 4.9 in with medium term measures are shown as highest potential. Fuel switching is very important role of pollution reducing in this study. Lignite accounts about 53% of thermal energy used and takes main portion in this industry. The replacement of lignite by bitumen for existing kiln can be done. It can be reduced the cost of energy consumption. Because of the net calorific value of bitumen is higher than that of lignite at the same prices. Moreover, the replacement of the existing efficiency electric motor with high efficiency electric motor is an important in this industry because of the cost of electricity accounts about 48% of total energy cost with medium term measures.

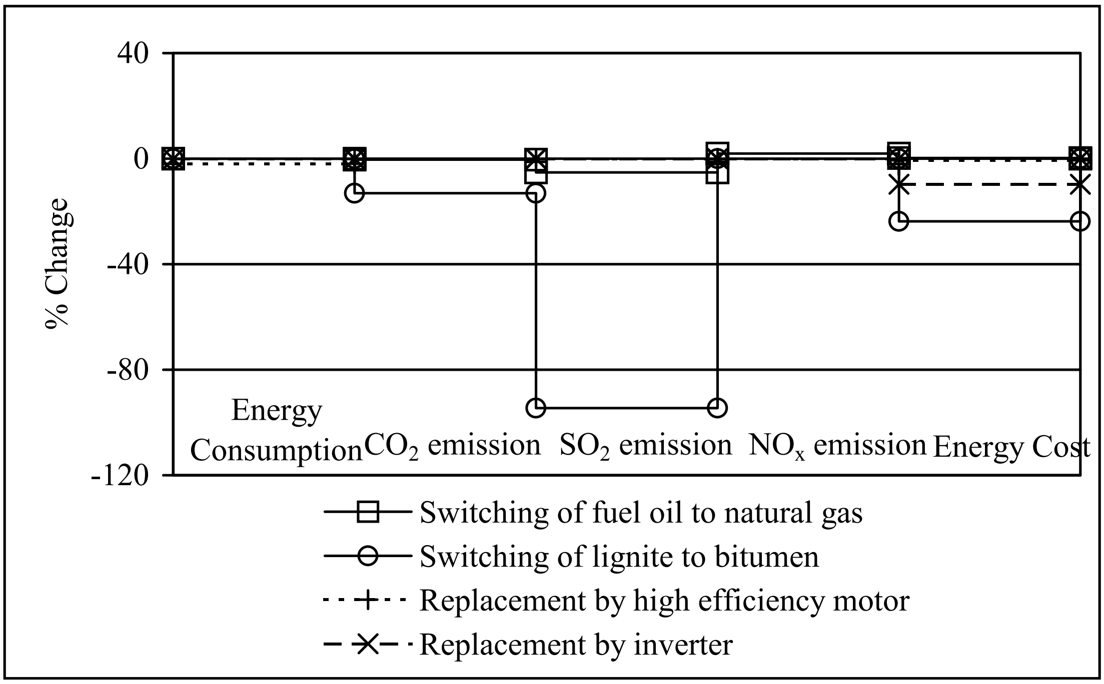

Figure 4.39. Reduction of energy consumption and air pollution in cement industry

Table 4.9. Reduction of energy consumption and air pollution in cement industry.

Option	Existing	Fuel switching to Natural Gas	Fuel switching to Bitumen	Replacement by high efficiency motor	Change to high efficiency voltage regulator	Replacement by inverter
Energy consumption						
Fuel energy consumption (toe/ton)	0.11742	0.11742	0.11742	0.11742		0.11742
Electricity consumption (toe/ton)	0.01246	0.01246	0.01246	0.01231		0.00996
Total energy consumption (toe/ton)	0.12988	0.12988	0.12988	0.12738		0.12973
Pollution emission						
CO_2 emission (tonCO_2/ton)	0.45074	0.44889	0.39161	0.45074		0.45074
SO_2 emission (tonSO_2/ton)	0.00253	0.00240	0.00014	0.00253		0.00253
NO_x emission (tonNO_x/ton)	0.00265	0.00270	0.00265	0.00265		0.00265
Economic evaluation						
Energy cost (Baht/ton)	480.94	481.85	366.73	478.19		434.17
Type of measure		P	M	P		P
Pay back period		Medium term	Long term	Medium term		Long term

H = House keeping

P = Process improvement

M = Major change of equipment

Table 4.10 shows the improvement of energy consumption and emission reduction opportunities for the non-metal industry. The highest value of the improvement of energy efficiency in this study can be gained from preheated air measure. It can improve energy efficiency about 3.41% - 8.06%. Moreover, it can reduce air pollution emission (CO_2, SO_2, and NO_x emissions) about 3.63% - 11.54% with the medium level in the term of pay back period.

Fuel switching to high quality energy is significant in the reduction of SO_2 emission (about 5.27% - 100%). Moreover, It can reduce CO_2 emission about 0.41% - 26.34%. NO_x emission may be increase about 76.32% - 100% from the substitution of fuel oil by natural gas. However, NO_x emission may be control by the adjustment in the combustion process. Out of this, the several emission control technology have impact on emission of NO_x, such as selective catalytic reduction (SCR) can reduce NO_x emission by about 80% (Piccot et al, 1990) but the emission control technology requires very high investment.

The replacement of the existing efficiency electric equipment with high efficient can improve energy efficiency about 0.09% - 1.92% with the medium level in the term of pay back period.

In this study, the improvement of energy efficiency and mitigation of air pollution potential depends on the type and among of energy consumption in the industrial process.

Table 4.10. Percent reduction of energy consumption and air pollution in the 3 studied factories

Reduction	Preheated air	Fuel switching to Natural Gas	Fuel switching to Bitumen	Replacement by high efficiency motor	Change to high efficiency voltage regulator	Replacement by inverter
Total energy consumption	3.41-8.06	-	-	0.09-0.23	0.57-1.52	0.11000
CO_2 emission	3.63-9.98	0.41-26.34	13.12000	-	-	-
SO_2 emission	3.74-11.54	5.27-100	94.49000	-	-	-
NO_x emission	3.75-7.94	(+76)-(+100)	-	-	-	-
Energy cost	2.72-9.98	22.82-(+0.19)	23.75	0.33-0.57	2.15-3.79	9.72000
Type of measure	P	M	M	P	P	P
Pay back period	Medium term	Long term	Long term	Medium term	Medium term	Medium term

H = House keeping

P = Process improvement

M = Major change of equipment

Chapter V
Conclusion and Recommendations

5.1 Conclusions

1. The energy consumption in industrial sector of Thailand, between the years 1991 to 1999, was contributed by the economic growth in Thailand more than 50%, the structure change about 40% and the energy intensity about 2%.

2. In this study, manufacturing structure change, the result of outdated technology and the amount and type of energy consumption effect the trend of energy efficiency.

3. Based on the forecast, the energy demand in industrial sector will reach 37,187.93 ktoe in the year 2011. It will increase with 7.17% in the ninth national economic and social development plan (2002 to 2006) and 7.56% in the tenth national economic and social development plan (2007 to 2011) due to the increasing of GDP. The increasing of the growth rate will be 7.62% and 7.84% at the same period.

4. The modern energy is the major part of the energy demand in industrial sector. It increases very rapidly. Petroleum product and solid fossil fuel will continue to be the largest portion of the total energy consumption, during the year 1991 to 2011. Renewable energy will increase very slowly and its share will decrease in the forecasted period.

5. Of the total energy consumption in 1991 to 1999, the petroleum product played a dominant role in all of the modern energy consumption, but its share decreased from 28.88% to 24.62%. The solid fossil fuel consumption increased from 16.76% to 24.16% after the oil and economic crisis. The energy consumption of this sector has resulted in the air pollution emission. Throughout the studied years, CO_2 emission is the major portion, followed by SO_2 and NO_x emissions.

6. In the year 2011, CO_2, SO_2, and NO_x emissions from fuel consumption in the industrial sector will reach 73,864.19 ktonCO$_2$, 1,278.63 ktonSO$_2$, and 370.9 ktonNO$_x$, respectively.

7. During the year 1999 to 2011, the emission of SO_2 is forecasted to increase very rapidly compared to CO_2 emission and NO_x emission, due to the high growth rate of petroleum product. However, CO_2 will still be the major pollution emission, followed by SO_2, and NO_x emissions.

8. The energy efficiency in the total industrial sub-sector is in the range 8.83 to 275.30 million baht/ktoe. In the year 1991 to 1999, the energy efficiency has been declining in the most of sub-sector. Fabricated metal industry is the highest energy efficiency. Non-metal industry is the lowest energy efficiency in the industrial sector followed by basic metal industry and food industry.

9. Non-metal industry is the lowest energy efficiency sub-sector compared the other industry sub-sectors. It also has high intensities in the energy consumption and air pollution emission.

10. For the 3 selected factories, standard air-fuel ratio adjustment and preheating of the air supplied in the kiln/furnace can improve energy efficiency about 3.41% to 8.06% and can reduce CO_2, SO_2, and NO_x emissions about 3.63% to 11.54%.

11. In this study, fuel switching to high quality energy, e.g. natural gas, is the significant in the mitigation of CO_2 emission and SO_2 emission (about 0.41% for CO_2 emission and 5.27% to 100% for SO_2 emission). However, NO_x may be increased from the substitution of fuel oil by natural gas.

12. The replacement of exiting electric equipment with high efficiency one can improve energy efficiency about 0.09% to 1.92%.

5.2 Recommendations

1. Using coal as fuel has the benefit of availability, low cost and high calorific value compared with other energy. However, it is the major source of SO_2 emission and appropriate control technologies must be applied to reduce the pollution.

2. The improvement of the energy efficiency and mitigation of air pollution should be made with very small investment and high rate of return. Suggested energy saving items of short-term measures include air fuel adjustment and energy management.

3. Energy and environmental audit is very important to identify the possible

energy and air pollution reduction. Therefore, primary audit in the selected factory could be done for in-depth study for energy efficiency improvement and abatement of pollutant emissions.

References

Cheng, M and Mori, L. (2000). **The ABC's of acid rain**. [On-line]. Available: http://qlink.queencu.ca/~4lrm4/.

Chuntisa Kessmanee. (1997). **A study of greenhouse gas emission from the industrial process.** M.S. thesis (ISBN 974-624-074-9), King Mongkut's University of Technology Thonburi, Thailand.

Department of Energy Development and Promotion (DEDP). (1997). **Report of a analysis and proposal for energy saving of DEDP**. Bangkok: Department of Energy Development and Promotion (DEDP).

Department of Energy Development and Promotion (DEDP). (1998). **Thailand energy situation 1998**. Bangkok: Department of Energy Development and Promotion (DEDP).

Department of Energy Development and Promotion (DEDP). (1999). **Thailand energy situation 1999**. Bangkok: Department of Energy Development and Promotion (DEDP).

Department of Energy Development and Promotion (DEDP). (2000a). **Energy conservation in the industry**. Bangkok: Department of Energy Development and Promotion (DEDP).

Department of Energy Development and Promotion (DEDP). (2000b). **Fuel combustion and burning**. Bangkok: Department of Energy Development and Promotion (DEDP).

Ekkasit Suwansri. (2000). **Energy management improvement in the cement production process.** M.E. thesis (ISBN 974-346-430-1), Chulalongkorn University, Thailand.

Energy Information Administration. (EIA). (2000). **Regional overview: Asia-Pacific economic cooperation (APEC)**. [On-line]. Available: http://www.eia.doe.gov/emeu/cabs/apec.html.

Food and Agriculture Organization of the United Nations [FAO]. (1997). **Energy and environment basics.** Bangkok: Food and Agriculture Organization of the United Nations.

Gunn, C. (1997). Energy efficiency vs economic efficiency? New Zealand electricity sector reform in the context of the national energy policy objective. **Energy Policy**. 4 (25): 445-458.

Hall, C. W. and Hinman, G. W. (1983). **Dictionary of Energy.** New York: Marcel Dekker.

Intergovernmental Panel on Climate Change (IPCC). (1996). **The reference manual volume 3**. [On-line]. Available: http://www.ipcc.ch.

Jennrich, R. I. (1995). **An introduction to computational statistics regression analysis.** USA: Prentice-Hall.

Kleinbaum, D. G., Hupper, L. L., Muller, K. E., and Nizam, A. (1998). **Applied regression analysis and other multivariable methods.** USA: Duxbury Press.

Kumar, A. (1993). **Factor affecting SO_2 and CO_2 emission intensities in India: A divisia decomposition approach**. M.E. thesis (ET-93-26), Asian Institute of Technology, Thailand.

Lenz, H. P. and Cozzarini, C. (1999). **Emission and air quality**. USA: SAE.

Li, Y. H., Liu, Y. F., Chen, H. W., and Liu, J. Z. (2000). Study on the application of a new high efficiency and low pollution combustion technology. In X. Hu and P. L. Yue (ed.). **Sustainable energy and environmental technologies** (pp 304-308). Singapore: World Scientific.

Mohanty, B. (1997). **Rational use of energy in industry**. Asian Institute of Technology, Thailand. (Unpublished manuscript).

Nevers, N. D. (1995). **Air pollution control engineering.** Singapore: McGraw-Hill.

Patterson, M. G. (1996). What is energy efficiency? Concept, indicator and methodological issues. **Energy Policy**. 5 (24): 377-390.

Piccot, S.D., Buzun, J. A., and Frey, H. C. (1990). **Emissions and cost estimates for globally significant anthropogenic combustion sources of NO_x, N_2O, CH_4, CO, and CO_2**. Washington: Environmental Protection Agency (EPA).

Preadpreaw Wongwiti. (1993). **Carbon dioxide emission from combustion of fuels in Thailand.** M.S. thesis, King Mongkut's University of Technology Thonburi, Thailand.

Priambodo, A. (1998). **GHG mitigation potential in small and medium scales industries in Indonesia and Thailand**. M.E. thesis (ET-98-06), Asian Institute of Technology, Thailand.

Rungsun Sarochakawisit. (1998). **The study on emission of air pollution and energy used in Thailand**. Department of Energy of Development and Promotion (DEDP), Ministry of Science, Technology and Environmental. (Unpublished manuscript).

Seinfeid, J. H. (1986). **Atmospheric Chemistry and Physics of Air Pollution**. USA: John Wiley & sons.

Srikrishnarajah, S. (1998). **Economic impacts of demand side management: the case of Thailand.** M.E. thesis (ET-98-24), Asian Institute of Technology, Thailand.

Stepanow, V. S.(1993). **Analysis of energy efficiency of industrial processes.** USA: Springer-Verlag.

Sun, J. W. (1998). Accounting for energy use in China, 1980-94. **Energy Policy**. 10 (23): 835-849.

Takamura, Y. (2000). **Thermal energy conservation in the manufacturing.** Bangkok: Technology Promotion Association (Thailand-Japan).

Tam, N. T. (2000). **Assessment of techno-economical potential of energy saving from technological improvements in the industry sector of Vietnam.** M.E. thesis (ET-00-09), Asian Institute of Technology, Thailand.

Thailand Environmental Institute (TEI). (1990). **Greenhouse Gas Emission from Thailand in 1990.** Bangkok: Thailand Environmental Institute (TEI).

Thawachai Nwangsuntiwong. (1999). **SPSS/PC+ SPSS for windows.** (3nd ed). Bangkok: 21 Century.

United States Environmental Protection Agency (EPA). (1999). **Environmental effects of acid rain**. [On-line]. Available: http://www.epa.gov/acidrain/effects/envben.html

Viguier Laurent. (1999). Emission of SO_2, NO_x, and CO_2 in transition economies: emission inventories and Divisia index analysis. **The energy journal**. 2(20): 59-87.

Wachara Mingwithitkul. (2001). **Process and Technical: Energy save cost in the building and manufacturing.** Bangkok: The Energy Conservation Center of Thailand (ECCT).

Wark, K., Warner, C.F., and Davia, W. T. (1998). **Air pollution; Its origin and control.** (3nd ed.). USA: Addision-Westey.

Wongratanapornkul, C. (1999). **A study of energy conservation potential in the dairy industry of Thailand.** M.E. thesis (ET-99-23), Asian Institute of Technology, Thailand.

Wongsuwan, W. (1997). **Energy conservation in small and medium scale agro-food industries in Northern in Thailand**. M.E. thesis (ET-97-16), Asian Institute of Technology, Thailand.

Yu, W (1995). **Energy and the environmental in China: potions for energy efficiency improvement and environmental pollution abatement in energy intensive and polluting industries**. M.E. thesis (ET-95-10), Asian Institute of Technology, Thailand.

Appendix A

Thailand Standard Industrial Classification (TSIC)

Table A.1. Industrial establishments by division of industry and industry.

Division of Industry	Industry
Manufacture of food, beverages, and tobacco	- Slaughtering - Manufacture of other meat products - Dairies - Milk factories - Manufacture of ice-cream - Canning of fruit and vegetables - Manufacture of soy sauce and soy curds - Other canning and preserving of fruit and vegetables - Canning of fish - Manufacture of fish sauce - Other canning, preserving and processing of fish, shellfish and other sea foods - Manufacture of oils and fats - Rice mills - Drying of maize - Grain flour mills - Tapioca mills - Manufacture of grain mill products, other - Bakeries - Manufacture of biscuits - Manufacture of noodles and similar products - Sugar factories - Sugar refineries

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Manufacture of food, beverages, and tobacco	- Manufacture of cocoa, chocolate and sugar confectionery - Manufacture of starches - Manufacture of ice - Manufacture of monosodium glutamate monohydrate - Manufacture of other food products - Manufacture of prepared animal feeds - Distilling, rectifying and blending spirits - Wine industries - Breweries - Soft drinks and carbonated waters industries - Tobacco curing - Tobacco redrying - Manufacture of tobacco products
Manufacture of textiles, wearing apparel, leather and leather products	- Silk reeling - Cotton ginning - Spinning of cotton and man-made fibres - Silk weaving - Weaving of cotton and man-made fidres - Jute mills - Textile printing - Textile finishing - Other spinning and weaving

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Manufacture of textiles, wearing apparel, leather and leather products	- Manufacture of made-up textile goods, except wearing apparel - Knitting mills - Manufacture of carpets and rugs - Cordage, rope and twine industries - Manufacture of textiles not elsewhere classified - Manufacture of men's, and boy's clothes - Manufacture of women's, girl's and infant's clothes - Manufacture of other wearing apparel and accessories - Tanneries, leather finishing, fur dressing - Manufacture of products of leather and leather substitutes, except footwear and wearing apparel - Manufacture of footwear, except vulcanized or molded rubber or plastic footwear
Manufacture of wood and wood products, including furniture	- Sawmills and planing mills - Manufacture of veneer, plywood and veneered panel - Manufacture of builder's woodwork - Manufacture of wooden and cane containers and small cane ware - Manufacture of wood and cork products not elsewhere classified

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Manufacture of wood and wood products, including furniture	- Manufacture of furniture, fixture and flooring, except primary of metal or rattan - Manufacture of rattan furniture
Manufacture of paper and paper products, printing and publishing	- Manufacture of pulp, paper and paperboard by machine - Manufacture of fiberboard - Manufacture of containers and boxes of paper and paperboard - Manufacture of pulp, paper and paperboard articles not elsewhere classified - Printing and publishing of newspapers - Printing and publishing other printed matters than newspapers - Printing
Manufacture of chemicals and chemical, petroleum, coal rubber and plastic products	- Manufacture of basic industrial chemicals, except charcoal and fertilizers - Manufacture of charcoal - Manufacture of fertilizers and pesticides - Manufacture of synthetic resins, plastic materials and artificial fibers except glass - Manufacture of paints, varnishes and lacquers - Manufacture of drugs and medicine

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Manufacture of chemicals and chemical, petroleum, coal rubber and plastic products	- Manufacture of soap and cleaning preparations - Manufacture of perfumes, cosmetics and other toilet preparations - Manufacture of explosives and ammunitions - Manufacture of glues - Manufacture of incense products - Manufacture of matches - Manufacture of other chemical products - Petroleum refineries - Manufacture of miscellaneous products of petroleum and coal - Tyre and tube industries - Manufacture of rubber sheets and block rubber - Manufacture of rubber footwear - Manufacture of other rubber products - Manufacture of plastic containers - Manufacture of other plastic products
Non-metal industries	- Manufacture of pottery - Manufacture of glass and glass products - Manufacture of structure clay products - Manufacture of cement

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	**Industry**
Non-metal industries	- Manufacture of lime and plaster - Manufacture of concrete products - Manufacture of asbestos-cement products - Manufacture of non-metallic mineral product not elsewhere classified
Basic metal industries	- Iron and steel works and rolling mills - Iron and steel foundries - Non-ferrous metal basic industries
Manufacture of fabricated metal products machinery and equipment	- Manufacture of cutlery, hand tools and general hardware - Manufacture of furniture and fixture primarily of metal - Manufacture of structure metal products - Manufacture of metal cans and shipping containers - Manufacture of metal cans and shipping containers - Manufacture of wire and wire products - Coating, engraving and allied services - Manufacture of other fabricated metal products not elsewhere classified

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Manufacture of fabricated metal products machinery and equipment	- Manufacture of agricultural machinery and equipment - Manufacture of wood and metal working machinery - Manufacture of engines and turbines - Manufacture of special machinery and equipment except wood and metal working machinery - Manufacture of office, computing and accounting machinery - Manufacture of household machinery and appliances - Manufacture of air-conditioning machines - Machinery repair shops - Manufacture of other machinery except electrical - Manufacture of electrical industrial machinery and apparatus - Manufacture of radio, television and communication equipment and apparatus - Manufacture of electrical appliances and housewares - Manufacture of insulated wire and cable

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Manufacture of fabricated metal products machinery and equipment	- Manufacture of electric accumulators and batteries - Manufacture of other electrical apparatus and supplies - Building and repairing of steel ships - Building and repairing of wooden boats - Building and repairing of other boats - Other shipbuilding and repairing not elsewhere classified - Manufacture of railroad equipment - Assembly of automobiles - Manufacture of motor vehicle industry - Manufacture of motorcycles, tricycle and bicycles - Manufacture of transport equipment not elsewhere classified - Manufacture of professional and scientific and measuring and controlling equipment not elsewhere classified, and of photographic and optical goods - Cutting and polishing of gem stones
Other manufacturing industries	- Manufacture of jewelry - Manufacture of silverware and ninelloware

Table A.1. Industrial establishments by division of industry and industry (Cont.).

Division of Industry	Industry
Other manufacturing industries	- Manufacture of sporting and athletic goods - Manufacture industries not elsewhere classified

Appendix B

Example of Calculations

Table B.1. Example of the energy efficiency calculation.

Sub-sector: Food industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	D = $[C_t - C_{1991})/C_{1991}]$ x 100
1991	3,685	92,443	25.09	0.00
1992	4,433	103,730	23.40	-6.72
1993	3,862	107,078	27.73	10.52
1994	3,996	116,843	29.24	16.56
1995	4,754	124,331	26.15	4.25
1996	5,474	130,329	23.81	-5.09
1997	5,572	136,657	24.53	-2.23
1998	4,716	129,390	27.44	9.37
1999	5,195	154,597	29.76	18.63
Sub-sector: Textile industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	D = $[C_t - C_{1991})/C_{1991}]$ x 100
1991	842	120,199	142.75	0.00
1992	936	134,131	143.30	0.38
1993	1,013	138,102	136.33	-4.50
1994	1,119	142,600	127.44	-10.73
1995	1,380	145,910	105.73	-25.93
1996	1,165	144,480	124.02	-13.13
1997	1,070	147,637	137.98	-3.35
1998	1,051	145,102	138.06	-3.29
1999	1,113	151,270	135.91	-4.79
Sub-sector: Wood industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	D = $[C_t - C_{1991})/C_{1991}]$ x 100
1991	85	18,343	215.80	0.00
1992	103	19,154	185.97	-13.82
1993	131	18,193	138.88	-35.64
1994	103	19,180	186.21	-13.71
1995	101	17,527	173.54	-19.58
1996	100	15,457	154.57	-28.37
1997	95	11,958	125.88	-41.67
1998	92	9,023	98.08	-54.55
1999	106	8,757	82.61	-61.72

Table B.1. Example of the energy efficiency calculation (Cont.)

Sub-sector: Paper industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	$D = [C_t - C_{1991})/C_{1991}] \times 100$
1991	390	11,695	29.99	0.00
1992	360	13,748	38.19	27.35
1993	494	15,948	32.28	7.65
1994	696	18,881	27.13	-9.54
1995	531	20,575	38.75	29.21
1996	660	20,856	31.60	5.38
1997	676	22,312	33.01	10.06
1998	672	22,691	33.77	12.60
1999	755	25,728	34.08	13.64
Sub-sector: Chemical industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	$D = [C_t - C_{1991})/C_{1991}] \times 100$
1991	802	25,614	31.94	0.00
1992	946	30,386	32.12	0.57
1993	995	32,490	32.65	2.24
1994	1,203	37,289	31.00	-2.95
1995	1,383	51,511	37.25	16.62
1996	1,948	54,144	27.79	-12.97
1997	1,769	61,087	34.53	8.12
1998	1,600	60,287	37.68	17.98
1999	2,070	66,952	32.34	1.27
Sub-sector: Non-metal industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	$D = [C_t - C_{1991})/C_{1991}] \times 100$
1991	2,258	27,527	12.19	0.00
1992	2,773	32,444	11.70	-4.03
1993	3,574	38,443	10.76	-11.77
1994	3,994	42,535	10.65	-12.64
1995	4,581	46,047	10.05	-17.55
1996	5,367	49,278	9.18	-24.69
1997	5,032	45,984	9.14	-25.04
1998	3,484	32,800	9.41	-22.78
1999	4,235	37,407	8.83	-27.55

Table B.1. Example of the energy efficiency calculation (Cont.)

Sub-sector: Basic metal industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	D = $[C_t - C_{1991})/C_{1991}]$ x 100
1991	363	7,297	20.10	0.00
1992	510	8,836	17.32	-13.81
1993	555	10,981	19.78	-1.58
1994	562	13,490	24.00	19.42
1995	578	14,411	24.93	24.03
1996	709	14,718	20.76	3.27
1997	681	13,945	20.48	1.88
1998	568	9,246	16.28	-19.02
1999	595	9,908	16.65	-17.16
Sub-sector: Fabricated metal industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	D = $[C_t - C_{1991})/C_{1991}]$ x 100
1991	293	114,708	391.49	0.00
1992	259	146,137	564.24	44.12
1993	307	178,294	580.76	48.34
1994	503	191,247	380.21	-2.88
1995	660	228,103	345.61	-11.72
1996	774	249,670	322.57	-17.61
1997	717	236,039	329.20	-15.91
1998	683	197,844	289.67	-26.01
1999	854	235,104	275.30	-29.68
Sub-sector: Other industry				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	D = $[C_t - C_{1991})/C_{1991}]$ x 100
1991	582	40,811	70.12	0.00
1992	527	47,438	90.01	28.37
1993	699	52,967	75.77	8.06
1994	1,059	59,207	55.91	-20.27
1995	1,772	64,601	36.46	-48.01
1996	1,272	64,884	51.01	-27.26
1997	1,120	60,903	54.38	-22.45
1998	1,523	51,711	33.95	-51.58
1999	1,206	56,998	47.26	-32.60

Table B.1. Example of the energy efficiency calculation (Cont.)

Sub-sector: Total industrial				
Year	Energy consumption (ktoe)	GDP (Million baht/ktoe)	Energy efficiency (million baht/ktoe)	Energy efficiency in the year t (%)
	A	B	C = B/A	$D = [C_t - C_{1991})/C_{1991}] \times 100$
1991	9,300	458,637	49.32	0.00
1992	10,847	536,003	49.41	0.20
1993	11,630	592,495	50.95	3.30
1994	13,234	641,273	48.46	-1.74
1995	15,740	713,015	45.30	-8.14
1996	17,469	743,815	42.58	-13.66
1997	16,732	736,524	44.02	-10.74
1998	14,389	658,094	45.74	-7.26
1999	16,129	746,720	46.30	-6.12

Table B.2. Example of CO_2 emission calculation for the year 1999.

Module	CO_2 from Fuel Combustion								
Sub-sector	**Food**								
Year	**1999**								
	A	B	C	D	E	F	J	K	I
Fuel	Consumption	Conversion Factor (TJ/unit)	Consumption (TJ)	Carbon Emission Factor (t C/TJ)	Carbon Content (t C)	Carbon Content (Gg C)	Fraction of Carbon Oxidised	Actual Carbon Emissions (Gg C)	Actual CO_2 Emissions (KTon CO_2)
			C = (AxB)		E = (CxD)	F = (Ex10-3)		K = (FxJ)	I= (Kx44/12)
A) Modern Energy									
Solid Fossil Fuel (KTOE)									
1) Bituminous		41.868	0.00	25.8	0.00	0.00	0.98	0.00	0.00
2) Antracite		41.868	0.00	26.8	0.00	0.00	0.98	0.00	0.00
3) Coke		41.868	0.00	25.8	0.00	0.00	0.98	0.00	0.00
4) Lignite	67	41.868	2,805.16	27.6	77,422.31	77.42	0.98	75.87	278.20
5) Other Coal		41.868	0.00	25.8	0.00	0.00	0.98	0.00	0.00
Petroleum Product (KTOE)									
1) LPG	45	41.868	1,884.06	17.2	32,405.83	32.41	0.99	32.08	117.63
2)Gasoline	2	41.868	83.74	18.9	1,582.61	1.58	0.99	1.57	5.74
3)Kerosene		41.868	0.00	19.5	0.00	0.00	0.99	0.00	0.00
4) Diesel	146	41.868	6,112.73	20.2	123,477.11	123.48	0.99	122.24	448.22
5) Fuel Oil	558	41.868	23,362.34	21.1	492,945.46	492.95	0.99	488.02	1,789.39
Natural Gas (KTOE)	38	41.868	1,590.98	15.3	24,342.06	24.34	0.995	24.22	88.81
Sub - Total									**2,728.00**

Source A, B = Department of Energy Development and Promotion
D, J = Intergovernment Panel on Climate Change

Table B.2. Example of CO_2 emission calculation for the year 1999 (Cont.)

Module	CO_2 from Fuel Combustion (Cont.)				
Sub-sector	Food				
Year	1999				
	A	B	C	D	E
Fuel	Consumption	Conversion Factor	consumption	CO_2 Emission Factor	Actual CO_2 Emissions
		(TJ/unit)	(TJ)	(kg/TJ)	KTON CO_2
			C = (AxB)		$E = (CxD)/10^6$
B) Renewable Energy (KTOE)					
1) Fuel Wood	474	41.868	19,845.43	95.764	1.90
2) Paddy Husk	658	41.868	27,549.14	100.833	2.78
3) Bagass	2,676	41.868	112,038.77	192.826	21.60
Sub - Total					**26.28**
Total					**2,754.29**

Source A, B = Department of Energy Development and Promotion
D, J = Intergovernment Panel on Climate Change

Table B.3. Example of SO_2 emission calculation for the year 1999

Module	SO_2 from Fuel Combustion								
Sub-sector	Food								
Year	1999								
	A	B	C	D	E	F	G	H	I
Fuel	Consumption	Conversion Factor (TJ/unit)	Consumption (TJ)	Sulfur Content of Fuel (% by weight)	Sulfur Content of Fuel (kg/L)	Net Clorific Value (MJ/L)	SO_2 Emission factor (kg/TJ)	Emissions (TON SO_2)	Emissions (KTON SO_2)
			C = (AxB)					H = (CxG)/1000	I = H/1000
A) Modern Energy									
Solid Fossil Fuel (KTOE)									
1) Bituminous		41.868	0.00					0.00	0.00
2) Antracite		41.868	0.00					0.00	0.00
3) Coke		41.868	0.00					0.00	0.00
4) Lignite	67	41.868	2,805.16				814.300	2,284.24	2.28
5) Other Coal		41.868	0.00					0.00	0.00
Petroleum Product (KTOE)									
1) LPG	45	41.868	1,884.06		0.000000343	26.62	0.026	0.05	0.00
2)Gasoline	2	41.868	83.74	0.1	0.71693	31.48	45.548	3.81	0.00
3)Kerosene		41.868	0.00	0.2	0.83968	34.53	97.270	0.00	0.00
4) Diesel	146	41.868	6,112.73	0.25	0.86967	36.42	119.395	729.83	0.73
5) Fuel Oil	558	41.868	23,362.34	3	0.99462	39.77	1,500.558	35,056.56	35.06
Natural Gas (KTOE)	38	41.868	1,590.98					0.00	0.00
B) Renewable Energy (KTOE)									
1) Fuel Wood	474	41.868	19,845.43					0.00	0.00
2) Paddy Husk	658	41.868	27,549.14					0.00	0.00
3) Bagass	2,676	41.868	112,038.77					0.00	0.00
Total								38,074.48	38.07

Source A, B, D, E, F, and G = Department of Energy Development and Promotion

Table B.4. Example of NO_x emission calculation for the year 1999.

Module	NO_x from Fuel Combustion					
Sub-sector	Food					
Year	1999					
	A	B	C	F	G	H
Fuel	Consumption	Conversion Factor (TJ/unit)	Consumption (TJ)	NO_x Ession factor (kg/TJ)	Emissions (TON NO_x)	Emissions (KTON NO_x)
			C = (AxB)		G = (CxF)/1000	H = G/1000
A) Modern Energy						
Solid Fossil Fuel (KTOE)						
1) Bituminous		41.868	0.000	329	0.00	0.00
2) Antracite		41.868	0.000	329	0.00	0.00
3) Coke		41.868	0.000	329	0.00	0.00
4) Lignite	67	41.868	2805.156	162.9	456.96	0.46
5) Other Coal		41.868	0.000	329	0.00	0.00
Petroleum Product (KTOE)						
1) LPG	45	41.868	1884.060	59	111.16	0.11
2)Gasoline	2	41.868	83.736	365	30.56	0.03
3)Kerosene		41.868	0.000	64	0.00	0.00
4) Diesel	146	41.868	6112.728	1211	7,402.51	7.40
5) Fuel Oil	558	41.868	23362.344	161	3,761.34	3.76
Natural Gas (KTOE)	38	41.868	1590.984	67	106.60	0.11
B) Renewable Energy (KTOE)						
1) Fuel Wood	474	41.868	19845.432	115	2,282.22	2.28
2) Paddy Husk	658	41.868	27549.144	88	2,424.32	2.42
3) Bagass	2,676	41.868	112038.768	88	9,859.41	9.86
Total					26,435.09	26.44

Source A, B, and F = Department of Energy Development and Promotion

Table B.5. Estimation of energy demand.

Sub sector : Food industry

Year	GDP of Total industry (Millions of Baht)	Value Added (Millions of Baht)	Energy consumption (ktoe)	I	ΔI	S	ΔS	ΔGDP
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
				$D = C/B$	$E=D_t-D_{t-1}$	$F = B/A$	$G=F_t-F_{t-1}$	$H=A_t-A_{t-1}$
1991	458,637	92,443	3,685	0.040		0.20		
1992	536,003	103,730	4,433	0.043	0.00	0.19	-0.01	77,366.27
1993	592,495	107,078	3,862	0.036	-0.01	0.18	-0.01	56,492.36
1994	641,273	116,843	3,996	0.034	0.00	0.18	0.00	48,777.66
1995	713,015	124,331	4,754	0.038	0.00	0.17	-0.01	71,742.45
1996	743,815	130,329	5,474	0.042	0.00	0.18	0.00	30,800.03
1997	736,524	136,657	5,572	0.041	0.00	0.19	0.01	-7,291.74
1998	658,094	129,390	4,716	0.036	0.00	0.20	0.01	-78,429.28
1999	746,720	154,597	5,195	0.034	0.00	0.21	0.01	88,625.99
2000	832,846	162,843		0.033	0.00	0.20	-0.01	86,125.32
2001	879,075	169,385		0.033	0.00	0.19	0.00	46,229.07
2002	944,818	178,333		0.033	0.00	0.19	0.00	65,743.27
2003	1,016,047	187,754		0.033	0.00	0.18	0.00	71,228.90
2004	1,093,241	197,672		0.033	0.00	0.18	0.00	77,194.13
2005	1,176,925	208,114		0.032	0.00	0.18	0.00	83,683.72
2006	1,267,672	219,108		0.032	0.00	0.17	0.00	90,746.75
2007	1,365,393	231,359		0.032	0.00	0.17	0.00	97,721.04
2008	1,471,363	244,294		0.032	0.00	0.17	0.00	105,970.77
2009	1,586,318	257,953		0.032	0.00	0.16	0.00	114,954.47
2010	1,711,060	272,375		0.032	0.00	0.16	0.00	124,741.81
2011	1,846,469	287,603		0.032	0.00	0.16	0.00	135,409.35

Source $A_{(1991-1999)}$ and $B_{(1991-1999)}$ = Office of the National Economic And Social Development Board

$C_{(1991-1999)}$ = Department of Energy Development and Promotion

$A_{(2000-2011)}$ and $B_{(2000-2011)}$ = Stepwise regression analysis

Table B.5. Estimation of energy demand (Cont.)

Year	$(\Delta I)*(S_{t-1})*GDP_{t-1})$	$(\Delta I)[(\Delta S)*GDP_{t-1}+S_{t-1}*\Delta GDP]/2$	$(\Delta I)*(\Delta S)*(\Delta GDP)/3$	EIeff
	I	*J*	*K*	*L*
	$I=E*F_{t-1}*A_{t-1}$	$J=E[(G*A_{t-1})+(F_{t-1}*H)]/2$	$K=E*G*H/3$	$L=I+J+K$
1991				
1992	265.61	17.11	-0.60	282.12
1993	-691.73	-13.57	1.61	-703.69
1994	-199.98	-9.05	-0.05	-209.08
1995	471.70	16.25	-0.76	487.19
1996	468.07	11.24	0.03	479.35
1997	-160.03	-3.93	0.03	-163.93
1998	-591.11	13.84	1.25	-576.02
1999	-368.04	-34.54	-0.88	-403.45
2000	-74.32	-2.22	0.16	-76.38
2001	-18.98	-0.39	0.01	-19.36
2002	-27.13	-0.74	0.01	-27.86
2003	-28.45	-0.77	0.02	-29.21
2004	-29.78	-0.81	0.02	-30.58
2005	-31.12	-0.85	0.02	-31.95
2006	-32.46	-0.89	0.02	-33.33
2007	-28.88	-0.83	0.01	-29.69
2008	-30.37	-0.87	0.02	-31.23
2009	-31.89	-0.92	0.02	-32.79
2010	-33.45	-0.96	0.02	-34.39
2011	-35.03	-1.01	0.02	-36.02

Table B.5. Estimation of energy demand (Cont.)

Year	$(I_{t-1})*(\Delta S)*GDP_{t-1})$	$(\Delta S)[(\Delta I)*GDP_{t-1}+I_{t-1}*\Delta GDP]/2$	$(\Delta I)*(\Delta S)*(\Delta GDP)/3$	ESeff
	M	*N*	*O*	*P*
	$M=D_{t-1}*G*A_{t-1}$	$N=G[(E*A_{t-1})+(D_{t-1}*H)]/2$	$O=E*G*H/3$	$P=M+N+O$
1991				
1992	-146.88	-17.68	-0.60	-165.15
1993	-293.26	7.43	1.61	-284.23
1994	31.67	0.48	-0.05	32.11
1995	-171.76	-19.75	-0.76	-192.26
1996	22.99	1.63	0.03	24.65
1997	322.62	-6.30	0.03	316.36
1998	332.41	-35.33	1.25	298.33
1999	249.96	7.08	-0.88	256.17
2000	-288.77	-14.59	0.16	-303.19
2001	-78.37	-2.04	0.01	-80.40
2002	-114.23	-3.99	0.01	-118.21
2003	-122.90	-4.33	0.02	-127.21
2004	-132.03	-4.70	0.02	-136.71
2005	-141.67	-5.08	0.02	-146.73
2006	-151.85	-5.49	0.02	-157.32
2007	-138.78	-5.07	0.01	-143.83
2008	-149.48	-5.49	0.02	-154.96
2009	-160.85	-5.95	0.02	-166.79
2010	-172.94	-6.45	0.02	-179.37
2011	-185.79	-6.97	0.02	-192.75

Table B.5. Estimation of energy demand (Cont.)

Year	$(I_{t-1})*(S_{t-1})*\Delta GDP)$	$(\Delta GDP)[(\Delta I)*S_{t-1}+I_{t-1}*\Delta S]/2$	$(\Delta I)*(\Delta S)*(\Delta GDP)/3$	GDPeff
	Q	*R*	*S*	*T*
	$Q=D_{t-1}*F_{t-1}*H$	$R=H[(E*F_{t-1})+(D_{t-1}*G)]/2$	$S=E*I*J/3$	$T=Q+R+S$
1991				
1992	621.61	10.01	-0.60	631.03
1993	467.22	-51.91	1.61	416.92
1994	317.94	-6.93	-0.05	310.97
1995	447.05	16.78	-0.76	463.07
1996	205.36	10.61	0.03	216.00
1997	-53.66	-0.80	0.03	-54.43
1998	-593.34	13.77	1.25	-578.31
1999	635.11	-7.95	-0.88	626.28
2000	599.18	-20.94	0.16	578.40
2001	299.40	-2.70	0.01	296.70
2002	418.12	-5.29	0.01	412.84
2003	441.59	-5.71	0.02	435.90
2004	466.26	-6.15	0.02	460.13
2005	492.18	-6.61	0.02	485.59
2006	519.44	-7.11	0.02	512.35
2007	544.12	-6.46	0.01	537.67
2008	576.08	-6.98	0.02	569.12
2009	609.83	-7.53	0.02	602.32
2010	645.47	-8.11	0.02	637.37
2011	683.11	-8.74	0.02	674.39

Table B.5. Estimation of energy demand (Cont.)

Year	GDP of Total industry (Millions of Baht)	Value Added (Millions of Baht)	Energy consumption (ktoe)	EIeff	ESeff	GDPeff	Et
	A	*B*	*C*	*L*	*P*	*T*	E_t
							$E_t=E_{t-1}+L+P+T$
1991	458,636.68	92,442.60	3,685.00	0.00	0.00	0.00	3,685.00
1992	536,002.95	103,730.42	4,433.00	282.12	-165.15	631.03	4,433.00
1993	592,495.31	107,077.69	3,862.00	-703.69	-284.23	416.92	3,862.00
1994	641,272.97	116,843.40	3,996.00	-209.08	32.11	310.97	3,996.00
1995	713,015.43	124,331.11	4,754.00	487.19	-192.26	463.07	4,754.00
1996	743,815.46	130,329.15	5,474.00	479.35	24.65	216.00	5,474.00
1997	736,523.72	136,657.49	5,572.00	-163.93	316.36	-54.43	5,572.00
1998	658,094.44	129,389.97	4,716.00	-576.02	298.33	-578.31	4,716.00
1999	746,720.43	154,596.70	5,195.00	-403.45	256.17	626.28	5,195.00
2000	832,845.75	162,843.13		-76.38	-303.19	578.40	5,393.83
2001	879,074.83	169,384.78		-19.36	-80.40	296.70	5,590.77
2002	944,818.10	178,332.80		-27.86	-118.21	412.84	5,857.54
2003	1,016,047.00	187,753.52		-29.21	-127.21	435.90	6,137.02
2004	1,093,241.13	197,671.90		-30.58	-136.71	460.13	6,429.86
2005	1,176,924.85	208,114.24		-31.95	-146.73	485.59	6,736.77
2006	1,267,671.61	219,108.21		-33.33	-157.32	512.35	7,058.47
2007	1,365,392.65	231,358.63		-29.69	-143.83	537.67	7,422.62
2008	1,471,363.42	244,293.98		-31.23	-154.96	569.12	7,805.55
2009	1,586,317.89	257,952.55		-32.79	-166.79	602.32	8,208.28
2010	1,711,059.69	272,374.77		-34.39	-179.37	637.37	8,631.89
2011	1,846,469.05	287,603.34		-36.02	-192.75	674.39	9,077.52

Table B.6. Estimation of air pollution emission.

Sub-sector: Food industry

Type of Fuel: Fuel oil

Year	Emission$_{ij}$ (P_{ij})	Energy$_{ij}$ (E_{ij})	Value Added (Millions Baht)	GDP of Total industry (Millions Baht)	P_{ij}/E_{ij} (U_{ij})	$\exp(\ln(U_{ij,t+1}/U_{ij,t}))$
	A	*B*	*C*	*D*	*E*	*F*
					$E=A/B$	$F=exp(ln(E_{t+1}/E_t)$
1991	1,074.28	335.00	92,442.60	458,636.68	3.21	1.00
1992	1,237.82	386.00	103,730.42	536,002.95	3.21	1.00
1993	1,295.55	404.00	107,077.69	592,495.31	3.21	1.00
1994	1,382.13	431.00	116,843.40	641,272.97	3.21	1.00
1995	1,048.62	327.00	124,331.11	713,015.43	3.21	1.00
1996	1,638.67	511.00	130,329.15	743,815.46	3.21	1.00
1997	1,776.56	554.00	136,657.49	736,523.72	3.21	1.00
1998	1,709.22	533.00	129,389.97	658,094.44	3.21	1.00
1999	1,789.39	558.00	154,596.70	746,720.43	3.21	1.00
2000		579.36	162,843.13	832,845.75	3.21	1.00
2001		600.51	169,384.78	879,074.83	3.21	1.00
2002		629.16	178,332.80	944,818.10	3.21	1.00
2003		659.18	187,753.52	1,016,047.00	3.21	1.00
2004		690.64	197,671.90	1,093,241.13	3.21	1.00
2005		723.60	208,114.24	1,176,924.85	3.21	1.00
2006		758.16	219,108.21	1,267,671.61	3.21	1.00
2007		797.27	231,358.63	1,365,392.65	3.21	1.00
2008		838.40	244,293.98	1,471,363.42	3.21	1.00
2009		881.66	257,952.55	1,586,317.89	3.21	1.00
2010		927.16	272,374.77	1,711,059.69	3.21	1.00
2011		975.02	287,603.34	1,846,469.05	3.21	

Source A = CO_2 emission from fuel oil consumption

$B_{(1991\text{-}1999)}$ = Department of Energy Development and Promotion

$C_{(1991\text{-}1999)}$ and $D_{(1991\text{-}1999)}$ = Office of the National Economic And Social Development Board

$B_{(2000\text{-}2011)}$ = Estimation of fuel oil demand

$C_{(2000\text{-}2011)}$ and $D_{(2000\text{-}2011)}$ = Stepwise regression analysis

Table B.6. Estimation of air pollution emission (Cont.)

Sub-sector: Food industry
Type of Fuel: Fuel oil

Year	E_{ij}/Value (I_i)	$exp(ln(I_{i,t+1}/I_{i,t}))$	S_i	$exp(ln(S_{i,t+1}/S_{i,t}))$	$exp(ln(GDP_{t+1}/GDP_t))$	$P_{i,t+1}/P_{i,t}$	$Emission_{ij}$
	G	*H*	*I*	*J*	*K*	*L*	*M*
	G=B/C	$H=exp(ln(G_{t+1}/G_t))$	*I=C/D*	$J=exp(ln(I_{t+1}/I_t))$	$K=exp(ln(D_{t+1}/D_t))$	*L=F*H*J*K*	*M=A*L*
1991	3.624E-03	1.03	0.20	0.96	1.17	1.15	
1992	3.721E-03	1.01	0.19	0.93	1.11	1.05	1,237.82
1993	3.773E-03	0.98	0.18	1.01	1.08	1.07	1,295.55
1994	3.689E-03	0.71	0.18	0.96	1.11	0.76	1,382.13
1995	2.630E-03	1.49	0.17	1.00	1.04	1.56	1,048.62
1996	3.921E-03	1.03	0.18	1.06	0.99	1.08	1,638.67
1997	4.054E-03	1.02	0.19	1.06	0.89	0.96	1,776.56
1998	4.119E-03	0.88	0.20	1.05	1.13	1.05	1,709.22
1999	3.609E-03	0.99	0.21	0.94	1.12	1.04	1,789.39
2000	3.558E-03	1.00	0.20	0.99	1.06	1.04	1,857.88
2001	3.545E-03	1.00	0.19	0.98	1.07	1.05	1,925.71
2002	3.528E-03	1.00	0.19	0.98	1.08	1.05	2,017.60
2003	3.511E-03	1.00	0.18	0.98	1.08	1.05	2,113.87
2004	3.494E-03	1.00	0.18	0.98	1.08	1.05	2,214.73
2005	3.477E-03	1.00	0.18	0.98	1.08	1.05	2,320.45
2006	3.460E-03	1.00	0.17	0.98	1.08	1.05	2,431.25
2007	3.446E-03	1.00	0.17	0.98	1.08	1.05	2,556.68
2008	3.432E-03	1.00	0.17	0.98	1.08	1.05	2,688.58
2009	3.418E-03	1.00	0.16	0.98	1.08	1.05	2,827.30
2010	3.404E-03	1.00	0.16	0.98	1.08	1.05	2,973.21
2011	3.390E-03		0.16				3,126.71

Appendix C
Stepwise Regression Analysis

Stepwise procedures have criteria for accepting or deleting independent variable from the model. The criteria may be based on the level of significance of F in the analysis of variance that accompanies each variable entry or in the amount, a new variable would increase R^2. SPSS requires the probability of F to be 0.05 or less to enter a variable and 0.1 or more to remove a variable. The stepwise regression step can be considered as chain as shows in Figure C.1.

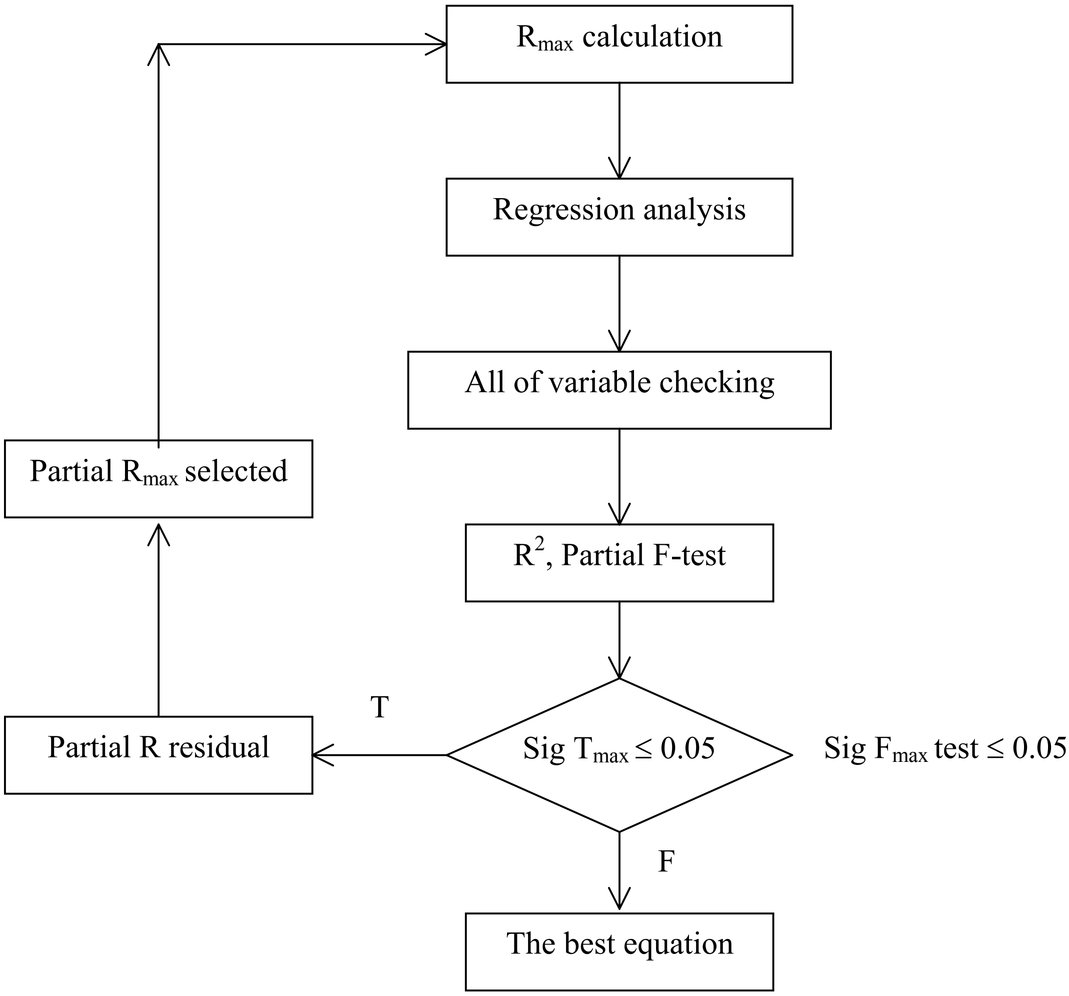

Figure C.1. Stepwise regression diagram.

Tolerance (index of linear dependence) checking is very important in the stepwise regression analysis. It is this control over tolerance that makes stepwise regression a choice for dealing with the collinearity problem (Jennrich, 1995).

Tolerance is to be concerned with any value smaller than 0.1 (Kleinbaum et al., 1998 and Jennrich, 1995).

For the multiple regression analysis of each industry, the dependent variable is growth rate of manufacturing output of the industry, and the independent variables are the growth rate of 7 variables concerning significant factor that affect the output. The list of the independent variable s in percentage is shown in Table C.1. The significant level for an independent variable to enter the model, or the "*p*-to-enter", used is 0.05, and the significant level for an independent variable is remove the model, or the "*p*-to-remove", used is 0.10. The final models are present is Table C.2.

Table C.1. List of independent variable and description.

Independent variable	Description
Total industrial output	Growth rate of goods produced by manufacturing
Agriculture	Growth rate of value added of agriculture sector
Import	Merchandise import value growth
Export	Merchandise export value growth
Net capital movement	Investment growth
Inflation rate	An abnormal increase in available currency and credit, resulting in a rise in price levels
Population	Growth rate of people

Table C.2. Estimating equation for hypothestic industrial output.

Sub-sector	n	Dependent Variable	Independent Variable	Coefficients	*p*	Adj R^2	method
Food industry	19	Food industrial output	Total industrial output	0.984	0.000	0.764	Stepwise
			Net capital movement	-0.309			
			Agriculture	0.643			
			(Constant)	-0.206			
Textile industry	19	Textile industrial output	Total industrial output	0.602	0.001	0.539	
			Export	0.206			
			(Constant)	-0.551			
Wood industry	19	Wood industrial output	Total industrial output	0.847	0.000	0.658	
			Population	9.979			
			Inflation	-1.261			
			(Constant)	-16.327			
Paper industry	19	Paper industrial output	Total industrial output	0.496	0.007	0.399	
			Population	-6.948			
			(Constant)	14.602			
Chemical industry	19	Chemical industrial output	Import	0.309	0.011	0.281	
			(Constant)	7.139			
Non-metal industry	19	Non-metal industrial output	Total industrial output	1.511	0.000	0.921	
			(Constant)	3.659			

Table C.2. Estimating equation for hypothestic industrial output.

Sub-sector	n	Dependent Variable	Independent Variable	Coefficients	p	Adj R^2	method
Basic metal industry	19	Basic metal industrial output	Total industrial output	1.274	0.000	0.664	Stepwise
			Inflation	-1.508			
			(Constant)	1.119			
Fabricated metal industry	19	Fabricated metal industrial output	Total industrial output	1.256	0.000	0.784	
			Import	0.3			
			(Constant)	-1.911			
Other industry (Unclassified)	19	Other industrial output	Total industrial output	1.386	0.000	0.646	
			(Constant)	1.367			

Note 1. The smallest tolerance observed was 0.275. (Tolerance (t_r) is an index of liner dependence. If R_r is the multiple correlation between x_r and the other independent variables, then the tolerance of x_r is $t_r = 1 - R_r^2$. If x_r is an exact liner function of the other independent variables the $R_r = 1$ and $t_r = 0$. A small value of tr mean is almost a linear funtion of the other independent variables. From the statistical point of view acceptable value is 0.1 for tolerance (Jennrich, 1995)).

2. Statistically significant correlations among the predictor variables in the model are:
   2.1. 0.852 for Total industrial output and Net capital movement in food industry model.
   2.2. 0.569 for Total industrial output and Import in fabricated metal industry model.
3. Due to considerably high correlations among the independent variables in the food industry and fabricated metal industry models, alternative models for the industries were investigated and present in Table C.3. However, they were not used in the predictor for the study.

Table C.3. Alternative models for the food industry and fabricated metal industry.

Sub-sector	n	Dependent Variable	Independent Variable	Coefficients	*p*	Adj R^2	method
Food industry	19	Food industrial output	Total industrial output	0.418	0.001	0.571	Enter
			Agriculture	0.490			
			(Constant)	1.891			
	19	Food industrial output	Net capital movement	0.0547	0.041	0.245	Enter
			Agriculture	0.703			
			(Constant)	4.218			
	19	Food industrial output	Total industrial output	0.516	0.001	0.444	Stepwise[1]
			(Constant)	2.594			
Fabricated metal industry	19	Fabricated metal industrial output	Total industrial output	1.664	0.000	0.735	Enter
			(Constant)	-1.308			
	19	Fabricated metal industrial output	Import	0.702	0.000	0.541	Enter
			(Constant)	3.337			
	19	Fabricated metal industrial output	Total industrial output	1.664	0.000	0.735	Stepwise[2]
			(Constant)	-1.308			

Note [1] = Total industrial output is to be considered in this analysis. Due to the correlation between the total industrial output and food industrial output (0.689) is larger than the correlation between the net capital movement and food industrial output (0.372).

[2] = Total industrial output is to be considered in this analysis. Due to the correlation between the total industrial output and fabricated metal industry (0.866) is larger than the correlation between the net capital movement and fabricated metal industry (0.744).

Appendix D
Results

Table D.1. Industrial output in the industrial sector during the years 1988 to 2011.

unit : Million Baht

Year	Food	Textile	Wood	Paper	Chemical	Non-metal	Basic metal	Fabricated metal	Other industry	Total industry
1988	67,478.38	78,134.59	14,102.42	7,887.31	38,505.94	16,024.88	5,369.43	61,120.16	19,823.89	308,447.00
1989	78,782.75	92,039.46	15,062.40	8,890.20	44,268.55	20,320.69	5,988.15	78,574.22	25,451.02	369,377.44
1990	81,632.99	105,550.26	17,328.76	10,095.76	48,292.86	24,158.66	6,710.78	100,264.94	34,051.68	428,086.69
1991	92,442.60	120,199.09	18,342.99	11,695.33	25,613.77	27,527.35	7,296.51	114,707.61	40,811.43	458,636.68
1992	103,730.42	134,130.72	19,154.49	13,747.80	30,385.86	32,443.53	8,835.57	146,136.90	47,437.66	536,002.95
1993	107,077.69	138,102.33	18,193.21	15,947.81	32,489.87	38,443.35	10,980.78	178,293.60	52,966.67	592,495.31
1994	116,843.40	142,600.41	19,179.71	18,880.90	37,288.74	42,535.26	13,490.44	191,247.49	59,206.61	641,272.97
1995	124,331.11	145,910.08	17,527.37	20,574.84	51,511.10	46,046.55	14,410.50	228,103.27	64,600.61	713,015.43
1996	130,329.15	144,479.78	15,457.14	20,855.92	54,143.99	49,277.61	14,717.92	249,669.70	64,884.25	743,815.46
1997	136,657.49	147,636.93	11,958.46	22,312.25	61,087.46	45,984.22	13,945.47	236,038.52	60,902.91	736,523.72
1998	129,389.97	145,101.78	9,023.37	22,691.37	60,286.79	32,800.18	9,245.51	197,844.41	51,711.06	658,094.44
1999	154,596.70	151,270.17	8,756.60	25,728.30	66,952.29	37,406.58	9,907.89	235,103.91	56,998.01	746,720.43
2000	162,843.13	164,311.23	7,684.98	30,010.46	79,961.82	39,315.41	10,511.78	275,848.21	62,358.74	832,845.75
2001	169,384.78	170,195.14	7,111.99	33,280.42	87,917.45	40,430.75	10,808.91	293,018.10	66,927.30	879,074.83
2002	178,332.80	178,718.69	6,667.91	37,361.95	96,555.99	42,921.46	11,384.79	319,003.32	73,871.18	944,818.10
2003	187,753.52	187,669.12	6,251.56	41,944.06	106,043.33	45,565.61	11,991.36	347,292.94	81,535.51	1,016,047.00
2004	197,671.90	197,067.79	5,861.20	47,088.11	116,462.87	48,372.65	12,630.24	378,091.33	89,995.04	1,093,241.13
2005	208,114.24	206,937.16	5,495.22	52,863.04	127,906.21	51,352.61	13,303.15	411,620.95	99,332.26	1,176,924.85
2006	219,108.21	217,300.80	5,152.09	59,346.21	140,473.95	54,516.16	14,011.92	448,124.03	109,638.24	1,267,671.61
2007	231,358.63	228,142.11	4,781.11	67,007.42	154,059.62	57,792.23	14,761.73	486,628.24	120,861.55	1,365,392.65
2008	244,293.98	239,524.31	4,436.84	75,657.63	168,959.21	61,265.18	15,551.67	528,440.85	133,233.75	1,471,363.42
2009	257,952.55	251,474.37	4,117.36	85,424.53	185,299.79	64,946.82	16,383.88	573,846.13	146,872.45	1,586,317.89
2010	272,374.77	264,020.64	3,820.89	96,452.28	203,220.71	68,849.72	17,260.62	623,152.78	161,907.30	1,711,059.69
2011	287,603.34	277,192.84	3,545.76	108,903.63	222,874.83	72,987.15	18,184.27	676,696.00	178,481.23	1,846,469.05

Table D.2. The energy consumption in the industrial sector during the years 1991 to 2011.

unit : ktoe

Year	Food	Textile	Wood	Paper	Chemical	Non metal	Basic metal	Fabricated metal	Other industry	Total industry
1991	3,685.00	842.00	85.00	390.00	802.00	2,258.00	363.00	293.00	582.00	9,300.00
1992	4,433.00	936.00	103.00	360.00	946.00	2,773.00	510.00	259.00	527.00	10,847.00
1993	3,862.00	1,013.00	131.00	494.00	995.00	3,574.00	555.07	307.00	699.00	11,630.07
1994	3,996.00	1,119.00	103.00	696.00	1,203.00	3,994.00	562.00	503.00	1,059.00	13,235.00
1995	4,754.00	1,380.00	101.00	531.00	1,383.00	4,581.00	578.00	660.00	1,772.00	15,740.00
1996	5,474.00	1,165.00	100.00	660.00	1,948.00	5,367.00	709.00	774.00	1,272.00	17,469.00
1997	5,572.00	1,070.00	95.00	676.00	1,769.00	5,032.00	681.00	717.00	1,120.00	16,732.00
1998	4,716.00	1,051.00	92.00	672.00	1,600.00	3,484.00	568.00	683.00	1,523.00	14,389.00
1999	5,195.00	1,113.00	106.00	755.00	2,070.00	4,235.00	595.00	854.00	1,206.00	16,129.00
2000	5,393.83	1,166.02	93.03	882.10	2,489.58	4,437.62	630.85	1,026.52	1,317.35	17,436.89
2001	5,590.77	1,203.52	85.87	980.07	2,749.45	4,557.70	648.47	1,093.87	1,415.79	18,325.51
2002	5,857.54	1,257.66	80.42	1,102.20	3,026.95	4,835.62	682.85	1,198.62	1,566.16	19,608.02
2003	6,137.02	1,314.23	75.32	1,239.62	3,332.44	5,130.38	719.05	1,313.19	1,732.53	20,993.77
2004	6,429.86	1,373.35	70.55	1,394.25	3,668.73	5,443.02	757.17	1,438.47	1,916.60	22,492.00
2005	6,736.77	1,435.15	66.09	1,568.26	4,038.92	5,774.62	797.31	1,575.42	2,120.26	24,112.80
2006	7,058.47	1,499.76	61.92	1,764.10	4,446.42	6,126.34	839.57	1,725.10	2,345.59	25,867.29
2007	7,422.62	1,568.15	57.43	1,996.57	4,887.54	6,489.90	884.29	1,881.77	2,591.46	27,779.72
2008	7,805.55	1,639.64	53.27	2,259.89	5,372.34	6,874.96	931.38	2,052.22	2,863.12	29,852.38
2009	8,208.28	1,714.41	49.41	2,558.18	5,905.13	7,282.81	980.98	2,237.62	3,163.29	32,100.11
2010	8,631.89	1,792.61	45.83	2,896.14	6,490.62	7,714.80	1,033.22	2,439.23	3,494.95	34,539.29
2011	9,077.52	1,874.41	42.51	3,279.08	7,134.00	8,172.36	1,088.25	2,658.39	3,861.41	37,187.93

Table D.3. The energy consumption in the industrial sector during the years 1991 to 2011 (by type of fuel).

unit : ktoe

Year	Solid Fossil Fuel					Petroleum Product					Natural Gas	Electricity	Renewable Energy			Total
	Bituminous	Antracite	Coke	Lignite	Other	LPG	Gasoline	Kerosene	Diesel	Fuel oil			Fuel wood	Paddy husk	Bagass	
1991	192.00	14.00	56.00	1,228.00	69.00	140.00	20.00	45.00	263.00	2,218.00	360.00	1,688.00	629.00	410.00	1,968.00	9,300.00
1992	16.00	14.00	48.00	1,358.00	277.00	186.00	16.00	47.00	293.00	2,713.00	441.00	1,697.00	668.00	570.00	2,503.00	10,847.00
1993	0.07	16.00	54.00	1,852.00	602.00	210.00	63.00	49.00	504.00	2,761.00	492.00	1,906.00	714.00	547.00	1,860.00	11,630.07
1994	884.00	6.00	72.00	2,144.00	0.00	257.00	38.00	52.00	462.00	3,064.00	583.00	2,465.00	775.00	472.00	1,961.00	13,235.00
1995	1,431.00	10.00	65.00	2,143.00	9.00	280.00	61.00	45.00	400.00	3,694.00	784.00	2,800.00	739.00	594.00	2,685.00	15,740.00
1996	2,292.00	38.00	82.00	1,981.00	50.00	383.00	104.00	47.00	668.00	3,483.00	935.00	2,952.00	812.00	634.00	3,008.00	17,469.00
1997	1,888.00	10.00	54.00	1,948.00	70.00	326.00	30.00	41.00	522.00	3,296.00	946.00	2,943.00	1,006.00	675.00	2,977.00	16,732.00
1998	813.00	23.00	52.00	2,247.00	103.00	317.00	52.00	26.00	577.00	2,880.00	877.00	2,627.00	824.00	733.00	2,238.00	14,389.00
1999	1,313.00	85.00	54.00	2,138.00	286.00	369.00	35.00	25.00	523.00	3,019.00	1,112.00	3,083.00	735.00	676.00	2,676.00	16,129.00
2000	1,466.94	94.54	60.29	2,269.79	300.22	416.34	38.36	27.80	569.60	3,288.10	1,239.53	3,405.65	779.27	702.05	2,778.42	17,436.89
2001	1,566.14	100.03	63.99	2,357.86	308.63	446.04	41.00	29.67	603.46	3,483.70	1,311.46	3,592.86	813.30	727.50	2,879.86	18,325.51
2002	1,700.49	107.30	68.85	2,521.37	327.56	485.25	44.84	32.52	651.14	3,758.47	1,415.26	3,854.79	860.42	762.47	3,017.28	19,608.02
2003	1,847.29	115.16	74.11	2,697.41	347.65	528.16	49.08	35.66	703.18	4,058.04	1,527.73	4,139.25	910.67	799.12	3,161.24	20,993.77
2004	2,007.79	123.66	79.81	2,887.08	368.97	575.17	53.76	39.11	760.02	4,384.84	1,649.63	4,448.24	964.28	837.54	3,312.09	22,492.00
2005	2,183.33	132.85	85.99	3,091.59	391.60	626.65	58.93	42.90	822.12	4,741.58	1,781.80	4,783.97	1,021.49	877.82	3,470.18	24,112.80
2006	2,375.43	142.79	92.69	3,312.25	415.62	683.08	64.63	47.07	889.98	5,131.23	1,925.12	5,148.88	1,082.57	920.07	3,635.89	25,867.29
2007	2,585.35	153.45	99.87	3,550.51	440.49	744.46	70.85	51.57	964.15	5,558.48	2,077.06	5,542.76	1,149.51	967.73	3,823.47	27,779.72
2008	2,815.55	164.98	107.65	3,808.48	466.85	811.71	77.71	56.51	1,045.21	6,025.70	2,241.60	5,970.78	1,221.05	1,017.87	4,020.72	29,852.38
2009	3,068.15	177.46	116.09	4,088.07	494.80	885.42	85.27	61.93	1,133.84	6,536.93	2,419.81	6,436.03	1,297.53	1,070.62	4,228.17	32,100.11
2010	3,345.48	190.97	125.23	4,391.40	524.43	966.23	93.61	67.88	1,230.78	7,096.67	2,612.89	6,941.92	1,379.30	1,126.11	4,446.38	34,539.29
2011	3,650.18	205.60	135.15	4,720.85	555.85	1,054.86	102.81	74.41	1,336.85	7,709.86	2,822.10	7,492.20	1,466.78	1,184.50	4,675.93	37,187.93

Table D.4. CO2 emission in the industrial sector in the years 1991 to 2011.

unit : ktonCO_2

Year	Food	Textile	Wood	Paper	Chemical	Non metal	Basic metal	Fabricated metal	Other industry	Total industry
1991	1,966.03	1,528.98	95.87	1,164.65	1,376.50	6,791.81	747.52	143.35	1,768.45	15,583.16
1992	2,119.25	1,776.03	169.33	1,020.07	1,620.87	8,594.94	1,239.44	172.01	1,597.99	18,309.94
1993	2,388.47	2,119.39	227.58	1,671.26	1,571.70	11,294.06	1,255.31	196.65	1,992.94	22,717.34
1994	2,387.63	2,083.54	119.76	2,295.40	1,888.05	12,315.94	1,064.69	385.36	3,113.78	25,654.17
1995	2,137.52	2,940.21	106.30	1,601.12	2,200.45	14,060.15	931.25	616.40	5,333.66	29,927.05
1996	2,875.42	2,159.78	105.74	2,049.73	3,971.05	16,350.44	1,317.86	757.84	3,717.50	33,305.36
1997	2,635.50	1,857.34	91.34	2,085.82	3,387.24	15,110.62	1,215.01	615.07	3,304.80	30,302.75
1998	2,651.94	1,927.36	91.22	2,144.41	2,907.58	10,821.69	1,052.69	650.60	4,574.74	26,822.24
1999	2,754.29	2,035.50	71.50	2,251.77	4,274.24	13,175.75	1,007.23	797.90	3,539.51	29,907.68
2000	2,859.70	2,132.46	62.75	2,630.85	5,140.62	13,806.12	1,067.92	959.09	3,866.31	32,525.81
2001	2,964.11	2,201.05	57.92	2,923.04	5,677.20	14,179.72	1,097.75	1,022.02	4,155.22	34,278.03
2002	3,105.55	2,300.06	54.24	3,287.28	6,250.19	15,044.36	1,155.95	1,119.89	4,596.54	36,914.07
2003	3,253.73	2,403.52	50.80	3,697.13	6,880.98	15,961.42	1,217.23	1,226.93	5,084.82	39,776.55
2004	3,408.98	2,511.64	47.59	4,158.31	7,575.36	16,934.09	1,281.76	1,343.98	5,625.06	42,886.77
2005	3,571.70	2,624.66	44.58	4,677.30	8,339.75	17,965.76	1,349.70	1,471.94	6,222.78	46,268.18
2006	3,742.26	2,742.83	41.77	5,261.39	9,181.18	19,060.02	1,421.26	1,611.79	6,884.11	49,946.60
2007	3,935.32	2,867.88	38.74	5,954.73	10,092.04	20,191.09	1,496.94	1,758.17	7,605.71	53,940.62
2008	4,138.35	2,998.65	35.93	6,740.06	11,093.08	21,389.08	1,576.66	1,917.42	8,403.03	58,292.25
2009	4,351.87	3,135.39	33.32	7,629.71	12,193.19	22,657.96	1,660.63	2,090.65	9,284.00	63,036.72
2010	4,576.46	3,278.40	30.91	8,637.65	13,402.14	24,001.94	1,749.07	2,279.01	10,257.40	68,212.98
2011	4,812.72	3,427.99	28.68	9,779.76	14,730.64	25,425.49	1,842.22	2,483.77	11,332.91	73,864.19

Table D.5. CO_2 emission in the industrial sector during the years 1991 to 2011 (by type of fuel).

unit : ktonCO_2

Year	Solid Fossil Fuel					Petroleum Product					Natural Gas	Electricity	Renewable Energy			Total
	Bituminous	Antracite	Coke	Lignite	Other	LPG	Gasoline	Kerosene	Diesel	Fuel oil			Fuel wood	Paddy husk	Bagass	
1991	635.48	56.45	185.35	5,099.03	267.82	365.97	57.45	134.05	807.41	7,112.67	841.34		2.52	1.73	15.89	15,583.16
1992	52.96	56.45	158.87	5,638.82	1,075.18	486.22	45.96	140.00	899.51	8,700.04	1,030.64		2.68	2.41	20.21	18,309.94
1993	0.23	64.51	178.73	7,690.06	2,336.66	548.95	180.96	145.96	1,547.29	8,853.96	1,149.83		2.86	2.31	15.02	22,717.34
1994	2,925.87	24.19	238.31	8,902.53	0.00	671.82	109.15	154.90	1,418.35	9,825.62	1,362.50		3.11	1.99	15.83	25,654.17
1995	4,763.77	40.32	215.14	8,898.38	34.93	731.94	175.22	134.05	1,228.01	11,845.90	1,832.25		2.96	2.51	21.68	29,927.05
1996	7,586.07	153.21	271.40	8,225.71	194.07	1,001.19	298.73	140.00	2,050.77	11,169.27	2,185.14		2.81	2.68	24.28	33,305.36
1997	6,248.91	40.32	178.73	8,088.68	271.70	852.19	86.17	122.13	1,602.55	10,569.60	2,210.85		4.03	2.85	24.03	30,302.75
1998	2,690.87	92.73	172.11	9,330.22	399.79	828.66	149.37	77.45	1,771.40	9,235.57	2,049.59		3.30	3.09	18.07	26,822.24
1999	4,345.77	342.72	178.73	8,877.62	1,110.11	964.59	100.54	74.47	1,605.62	9,681.32	2,598.80		2.95	2.85	21.60	29,907.68
2000	4,855.29	381.17	199.54	9,424.85	1,165.31	1,088.33	110.18	82.82	1,748.67	10,544.28	2,896.85		3.12	2.96	22.43	32,525.81
2001	5,183.62	403.31	211.79	9,790.56	1,197.95	1,165.99	117.76	88.37	1,852.64	11,171.52	3,064.94		3.26	3.07	23.25	34,278.03
2002	5,628.29	432.64	227.88	10,469.50	1,271.41	1,268.47	128.80	96.87	1,999.00	12,052.66	3,307.52		3.45	3.22	24.36	36,914.07
2003	6,114.18	464.34	245.30	11,200.48	1,349.38	1,380.66	140.98	106.22	2,158.78	13,013.30	3,570.38		3.65	3.37	25.52	39,776.55
2004	6,645.38	498.59	264.17	11,988.04	1,432.14	1,503.52	154.43	116.50	2,333.28	14,061.30	3,855.28		3.87	3.54	26.74	42,886.77
2005	7,226.39	535.63	284.62	12,837.20	1,519.98	1,638.12	169.27	127.80	2,523.92	15,205.28	4,164.16		4.10	3.71	28.02	46,268.18
2006	7,862.22	575.70	306.80	13,753.44	1,613.22	1,785.61	185.64	140.22	2,732.25	16,454.80	4,499.11		4.34	3.88	29.35	49,946.60
2007	8,557.02	618.70	330.56	14,742.80	1,709.75	1,946.06	203.51	153.62	2,959.94	17,824.90	4,854.20		4.61	4.09	30.87	53,940.62
2008	9,318.93	665.21	356.31	15,813.97	1,812.08	2,121.87	223.21	168.32	3,208.80	19,323.17	5,238.73		4.90	4.30	32.46	58,292.25
2009	10,154.97	715.53	384.22	16,974.90	1,920.56	2,314.55	244.93	184.47	3,480.90	20,962.60	5,655.22		5.20	4.52	34.14	63,036.72
2010	11,072.90	770.00	414.49	18,234.43	2,035.57	2,525.80	268.89	202.19	3,778.52	22,757.56	6,106.45		5.53	4.75	35.90	68,212.98
2011	12,081.38	828.98	447.33	19,602.40	2,157.51	2,757.48	295.30	221.66	4,104.16	24,723.96	6,595.40		5.88	5.00	37.75	73,864.19

Table D.6. NO_x emission in the industrial sector during the years 1991 to 2011.

unit : ktonNO_x

Year	Food	Textile	Wood	Paper	Chemical	Non metal	Basic metal	Fabricated metal	Other industry	Total industry
1991	19.01	3.37	0.43	2.98	3.75	47.55	3.25	0.68	6.34	87.37
1992	21.94	4.00	0.66	2.24	4.86	61.08	4.22	0.83	5.92	105.75
1993	22.15	4.97	1.17	3.75	5.42	78.08	5.66	1.11	10.19	132.51
1994	22.44	4.75	1.45	5.24	6.29	84.71	4.91	1.55	9.01	140.34
1995	24.86	6.25	0.78	3.63	6.76	97.23	2.93	2.19	9.01	153.65
1996	30.75	4.76	1.05	5.33	11.00	112.96	4.11	2.75	17.57	190.28
1997	29.16	4.17	0.71	5.42	13.78	110.84	3.91	2.12	10.02	180.12
1998	25.50	4.25	0.65	5.10	8.72	78.34	4.04	1.69	21.80	150.10
1999	26.44	4.77	0.65	6.18	13.32	97.66	2.63	2.12	13.68	167.44
2000	27.45	4.99	0.57	7.22	16.02	102.33	2.78	2.55	14.94	178.86
2001	28.45	5.15	0.53	8.02	17.69	105.10	2.86	2.72	16.06	186.59
2002	29.81	5.39	0.49	9.02	19.48	111.51	3.01	2.98	17.77	199.46
2003	31.23	5.63	0.46	10.15	21.44	118.31	3.17	3.26	19.65	213.31
2004	32.72	5.88	0.43	11.41	23.61	125.52	3.34	3.57	21.74	228.23
2005	34.28	6.15	0.41	12.84	25.99	133.17	3.52	3.91	24.05	244.31
2006	35.92	6.42	0.38	14.44	28.61	141.28	3.71	4.29	26.61	261.65
2007	37.77	6.72	0.35	16.35	31.45	149.66	3.90	4.67	29.40	280.27
2008	39.72	7.02	0.33	18.50	34.57	158.54	4.11	5.10	32.48	300.37
2009	41.77	7.34	0.30	20.94	38.00	167.95	4.33	5.56	35.88	322.07
2010	43.92	7.68	0.28	23.71	41.76	177.91	4.56	6.06	39.65	345.53
2011	46.19	8.03	0.26	26.85	45.90	188.46	4.80	6.60	43.80	370.90

Table D.7. NO_x emission in the industrial sector during the years 1991 to 2011 (by type of fuel).

unit : ktonNO_x

Year	Solid Fossil Fuel					Petroleum Product					Natural Gas	Electricity	Renewable Energy			Total
	Bituminous	Anthracite	Coke	Lignite	Other	LPG	Gasoline	Kerosene	Diesel	Fuel oil			Fuel wood	Paddy husk	Bagass	
1991	3.51	0.14	0.38	22.40	1.12	0.34	0.31	0.11	13.33	24.08	9.86		3.03	1.51	7.25	87.37
1992	0.00	0.01	0.14	25.35	4.83	0.45	0.24	0.12	14.86	31.75	13.46		3.22	2.10	9.22	105.75
1993	0.00	0.03	0.37	33.38	12.42	0.51	0.96	0.12	25.55	31.11	15.74		3.44	2.02	6.85	132.51
1994	17.54	0.01	0.31	38.86	0.00	0.62	0.58	0.13	23.42	31.07	15.11		3.73	1.74	7.23	140.34
1995	28.63	0.05	0.15	40.16	0.09	0.67	0.89	0.13	19.32	29.03	18.89		3.56	2.19	9.89	153.65
1996	45.98	0.24	0.22	36.94	0.81	0.91	1.59	0.12	33.87	34.03	18.25		3.91	2.34	11.08	190.28
1997	36.85	0.03	0.17	36.73	1.48	0.77	0.46	0.11	26.47	31.16	27.61		4.84	2.49	10.97	180.12
1998	13.17	0.08	0.16	41.10	2.27	0.76	0.79	0.07	29.26	23.56	23.96		3.97	2.70	8.25	150.10
1999	21.56	0.29	0.21	40.48	6.27	0.89	0.53	0.06	26.52	25.84	28.89		3.54	2.49	9.86	167.44
2000	23.53	0.35	0.25	42.62	6.58	1.00	0.59	0.07	28.88	27.94	30.47		3.75	2.59	10.24	178.86
2001	24.80	0.39	0.28	43.96	6.76	1.08	0.63	0.07	30.60	29.42	31.40		3.92	2.68	10.61	186.59
2002	26.74	0.43	0.30	46.77	7.17	1.17	0.69	0.08	33.01	31.64	33.38		4.14	2.81	11.12	199.46
2003	28.84	0.47	0.34	49.78	7.61	1.27	0.75	0.09	35.65	34.05	35.48		4.38	2.94	11.65	213.31
2004	31.12	0.52	0.37	52.98	8.07	1.38	0.82	0.10	38.53	36.67	37.72		4.64	3.09	12.20	228.23
2005	33.60	0.57	0.41	56.41	8.57	1.51	0.90	0.11	41.68	39.52	40.11		4.92	3.23	12.79	244.31
2006	36.29	0.63	0.45	60.06	9.09	1.64	0.99	0.12	45.12	42.62	42.64		5.21	3.39	13.40	261.65
2007	39.21	0.69	0.49	63.91	9.63	1.79	1.08	0.13	48.88	45.98	45.27		5.53	3.57	14.09	280.27
2008	42.40	0.76	0.54	68.03	10.20	1.95	1.19	0.14	52.99	49.65	48.07		5.88	3.75	14.81	300.37
2009	45.87	0.84	0.59	72.43	10.81	2.13	1.30	0.16	57.49	53.64	51.04		6.25	3.94	15.58	322.07
2010	49.66	0.92	0.65	77.14	11.45	2.32	1.43	0.17	62.40	58.00	54.20		6.64	4.15	16.38	345.53
2011	53.81	1.01	0.72	82.19	12.13	2.53	1.57	0.19	67.78	62.75	57.56		7.06	4.36	17.23	370.90

Table D.8. SO_2 emission in the industrial sector during the years 1991 to 2011.

unit : ktonSO_2

Year	Food	Textile	Wood	Paper	Chemical	Non metal	Basic metal	Fabricated metal	Other industry	Total industry
1991	25.52	22.55	1.71	10.35	11.42	68.49	8.33	1.32	28.18	177.88
1992	28.39	31.43	3.04	12.53	13.36	90.82	12.49	1.15	25.22	218.43
1993	30.03	36.19	3.53	17.43	13.79	97.44	14.14	1.30	25.59	239.44
1994	31.34	35.46	0.70	21.02	14.25	96.79	11.90	2.03	54.67	268.16
1995	24.20	50.08	1.32	21.02	7.94	92.85	10.25	5.32	97.75	310.73
1996	36.84	37.37	0.97	20.54	22.60	95.28	15.23	3.99	57.28	290.09
1997	37.74	34.04	1.18	20.20	22.60	88.63	14.58	3.05	54.23	276.25
1998	37.07	32.72	1.24	20.65	19.46	74.23	8.44	3.43	63.40	260.63
1999	38.07	38.07	0.74	20.20	24.64	79.98	10.37	4.96	51.93	268.97
2000	39.53	39.89	0.65	23.60	33.05	93.47	10.99	6.66	63.27	311.11
2001	40.98	41.17	0.60	26.22	38.53	101.33	11.30	7.49	71.77	339.38
2002	42.93	43.02	0.56	29.49	45.59	115.55	11.90	8.82	85.33	383.19
2003	44.98	44.96	0.53	33.16	53.97	131.83	12.53	10.39	101.51	433.86
2004	47.12	46.98	0.49	37.30	63.93	150.49	13.20	12.24	120.83	492.59
2005	49.37	49.09	0.46	41.95	75.77	171.88	13.90	14.44	143.90	560.77
2006	51.73	51.31	0.43	47.19	89.85	196.41	14.63	17.03	171.47	640.05
2007	54.40	53.64	0.40	53.41	106.37	224.11	15.41	20.00	204.05	731.80
2008	57.21	56.09	0.37	60.46	126.00	255.83	16.23	23.51	242.94	838.63
2009	60.16	58.65	0.35	68.43	149.32	292.18	17.10	27.64	289.37	963.19
2010	63.26	61.32	0.32	77.48	177.03	333.85	18.01	32.49	344.86	1,108.62
2011	66.53	64.12	0.30	87.72	209.97	381.64	18.97	38.22	411.17	1,278.63

Table D.9. SO_2 emission in the industrial sector during the years 1991 to 2011 (by type of fuel).

unit : ktonSO_2

Year	Solid Fossil Fuel					Petroleum Product					Natural Gas	Electricity	Renewable Energy			Total
	Bituminous	Anthracite	Coke	Lignite	Other	LPG	Gasoline	Kerosene	Diesel	Fuel oil			Fuel wood	Paddy husk	Bagass	
1991				41.87		0.0002	0.05	0.17	1.79	134.01						177.88
1992				46.30		0.0002	0.03	0.19	1.46	170.45						218.43
1993				63.14		0.0002	0.12	0.20	2.52	173.46						239.44
1994				73.10		0.0003	0.07	0.18	2.31	192.50						268.16
1995				77.19		0.0003	0.11	0.18	1.98	231.26						310.73
1996				67.54		0.0004	0.20	0.19	3.34	218.82						290.09
1997				66.41		0.0004	0.08	0.13	2.23	207.39						276.25
1998				76.61		0.0003	0.10	0.11	2.88	180.94						260.63
1999				72.41		0.0004	0.07	0.10	3.27	193.13						268.97
2000				84.17		0.0005	0.08	0.12	3.73	223.01						311.11
2001				91.39		0.0006	0.09	0.14	4.05	243.71						339.38
2002				103.74		0.0007	0.10	0.16	4.54	274.64						383.19
2003				117.88		0.0008	0.12	0.19	5.10	310.58						433.86
2004				134.05		0.0009	0.14	0.22	5.75	352.43						492.59
2005				152.57		0.0010	0.17	0.26	6.50	401.26						560.77
2006				173.80		0.0012	0.20	0.31	7.39	458.35						640.05
2007				197.93		0.0014	0.23	0.37	8.42	524.85						731.80
2008				225.58		0.0016	0.27	0.44	9.63	602.71						838.63
2009				257.28		0.0018	0.32	0.51	11.04	694.03						963.19
2010				293.65		0.0021	0.38	0.61	12.70	801.27						1,108.62
2011				335.39		0.0025	0.45	0.72	14.65	927.41						1,278.63

Table D.10. The energy efficiency in the industrial sector during the years 1991 to 2011.

unit : Million Baht/ktoe

Year	Food	Textile	Wood	Paper	Chemical	Non metal	Basic metal	Fabricated metal	Other industry	Total industry
1991	25.09	142.75	215.80	29.99	31.94	12.19	20.10	391.49	70.12	49.32
1992	23.40	143.30	185.97	38.19	32.12	11.70	17.32	564.24	90.01	49.41
1993	27.73	136.33	138.88	32.28	32.65	10.76	19.78	580.76	75.77	50.95
1994	29.24	127.44	186.21	27.13	31.00	10.65	24.00	380.21	55.91	48.46
1995	26.15	105.73	173.54	38.75	37.25	10.05	24.93	345.61	36.46	45.30
1996	23.81	124.02	154.57	31.60	27.79	9.18	20.76	322.57	51.01	42.58
1997	24.53	137.98	125.88	33.01	34.53	9.14	20.48	329.20	54.38	44.02
1998	27.44	138.06	98.08	33.77	37.68	9.41	16.28	289.67	33.95	45.74
1999	29.76	135.91	82.61	34.08	32.34	8.83	16.65	275.30	47.26	46.30

Appendix E
Calculation for Energy Efficiency and Air Pollution Reduction

Appendix E1. Fuels and Combustion

Fossil fuels combustion

Fossil fuels consist generally of the combustible elements: hydrogen (H_2), carbon (C), and sulfur (S). They often also contain the incombustible element nitrogen (N_2), moisture (H_2O), and minerals.

When combusted, the carbon oxidizes to carbon monoxide (CO) (if insufficient air is present), and carbon dioxide (CO_2), the hydrogen oxidizes to water (steam) (H_2O), and the sulfur (in coals and liquid fuels) becomes sulfur dioxide (SO_2). The carbon and sulfur dioxides dissolve in water to form carbonic (H_2CO_3), and sulfuric (H_2SO_4), acids, which contribute to acid rain.

When combustion temperatures are high, nitrogen in air can combine with oxygen to form the NO_x gases, e.g. nitrous oxide (N_2O), which dissolved in water forms nitric acid (HNO_3). The action of sunlight on exhaust fumes can also form nitrous oxides, the main contributors to photochemical smog.

Excess air

It is often necessary to supply a greater amount of air than the theoretical air so that complete combustion can be assured in particle furnaces. Table 1E.1 given the standard air-fuel ratio for burning.

Table E1.1. Standard air-fuel ratio (M) for industrial furnaces.

Type of furnace	Standard air-fuel ratio (M)
Melting furnace	1.3
Heating furnace (iron)	1.25
Heating furnace	1.3
Heat treatment furnace	1.3
Gas furnace	1.4
Fuel oil furnace	1.4
Treatment cracking furnace	1.3
Cement kiln	1.3
Alumina and lime furnace	1.4
Glass melting furnace	1.3

Source Takamura (2000)

Efficiency

The thermal efficiency of a kiln/furnace is the percent of the input fuel energy that is used to heat the material change with in kiln/furnace, as well as energy efficiency (Yoshihiko, 2000) (given in equation E1-1). The overall efficiency of an industrial facility containing a furnace can be improved by recovering the waste heat from kiln/furnace for use in other equipment (Perry and Chilton, 1973).

$$\text{Thermal energy efficiency} \;\alpha\; \frac{\text{Material input}}{\text{Fuel consumption}} = \frac{1}{\text{Fuel per unit of material}} \qquad \text{(E1-1)}$$

Under the limitation, Figure E1.1 shown heat balance diagram is used in this study in the selected industry.

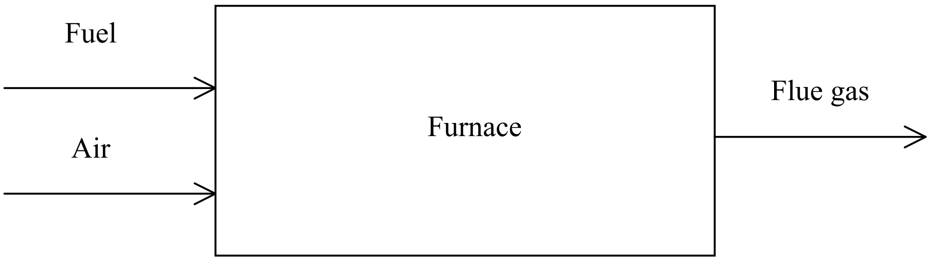

Figure E1.1. Heat balance diagram in furnace.

Heat from fuel combustion:

$$H_{combustion} = \text{net calorific value} \qquad \text{(E1-2)}$$

Heat carried away by the flue gases:

$$H_{carried} = G \times C_p \times (T_g - T_a) \qquad \text{(E1-3)}$$

where

$H_{combustion}$ = Heat from fuel combustion

$H_{carried}$ = Heat carried away by the flue gases

G = Actual amount of flue gas (NM^3/kg fuel)

C_p = Mean specific heat of flue gas (see in Table E1.2)

T_g = Temperature of flue gas (see in Table E1.3)

T_a = Temperature of ambient air (25 $^{\circ}$C)

Heat recovered:

$$H_{recovered} = A \times C_a \times (T_{pre} - T_a) \quad \text{(E1-4)}$$

where

$H_{recovered}$ = Heat recovered

A = Actual amount of air (NM^3/kg fuel)

C_a = Mean specific heat of air (0.241 kcal/NM^3 $^{\circ}$C)

T_{pre} = Temperature of preheated air (see in Table E1.4)

T_a = Temperature of ambient air (25 $^{\circ}$C)

Determining actual amount of air (A) and flue gas (G)

$$A = M(A_0) \quad \text{(E1-5)}$$

$$G = G_0 + (M - 1)A_0 \quad \text{(E1-6)}$$

where

A = Actual amount of air

G = Flue gas

M = Air-fuel ratio (see in Table E1.1)

A_0 = Theoretical amount of air (NM^3/kg fuel)

G_0 = Theoretical amount of flue gas (NM^3/kg fuel)

Theoretical amounts of air (A_0) and flue gas (G_0) are determined using Rosin's formulae;

1 Solid fuels

$$A_0 = \frac{1.01H_L}{1,000} + 0.5 \quad \text{(E1-7)}$$

$$G_0 = \frac{0.89H_L}{1,000} + 1.65 \quad \text{(E1-8)}$$

2 Liquid fuels

$$A_0 = \frac{0.85H_L}{1,000} + 2.0 \quad \text{(E1-9)}$$

$$G_0 = \frac{1.11H_L}{1,000} \quad \text{(E1-10)}$$

where

H_L = Lower calorific value (see in Table E1.6)

Table E1.2. Mean specific heat of flue gas (C_p)

Temperature of flue gas (°C)	**200**	**400**	**600**	**800**
Mean specific heat of flue gas (C_p) (kcal/NM^3 °C)	0.332	0.34	0.348	0.358

Source DEDP (2000b)

Table E1.3. Temperature of flue gas (T_g) of the process

Flue gas	T_g (°C)
Boiler	226 – 375
Turbine	376 – 526
Kiln/furnace	426 – 625
Glass melting	977 – 1,526
Cement kiln	626 – 726
Petrochemical heating furnace	651 – 1,076
Iron melting	928 – 1,026
Incinerator	652 - 977

Source Wachara Mingwithitkul (2001)

Table E1.4. Typical operating temperature of furnaces

Industry	Approximate temperature (°C)	Average efficiency (%)
Aluminium	740	59
Brass	1150	42
Cement	1535	20
Copper	1205	38
Glass	1315	33
Iron	1425/1535	20
Lead	380	73
Lime	1150	41
Carbon steel	900/1200	35
Zinc	395/500	70

Source DEDP (2000a)

Table E1.5. Heat recovery ratio for various temperatures of fuel gases

Fuel gas temperature	**Temperature of fuel gas at the exit of air heater (°C)**	**Temperature of preheated air to the furnace (°C)**	**Approximate amount of heat recovered (%)**
1000	520	375	30
900	470	285	25
800	430	250	25
700	330	220	25
600	290	155	20
500	200	130	20

Source DEDP (2000a)

Table E1.6. Lower calorific values for various fuels (H_L)

Type of fuel	**H_L (kcal/kg fuel)**
Bituminous coal	5,800 – 8,000
Lignite	2,500 – 5,500
Coke	6,500 – 7,000
Kerosene	10,400
Light oil	10,300
Heavy oil	
A heavy oil	10,200
B heavy oil	9,900
C heavy oil	9,600

Source DEDP (2000b)

Table E1.7. Energy conservation measures considered in the survey, the related equipment and type of measure.

No.	Measure	Equipment	Type
1	Combustion improvement	Burner	H
2	Preheat air	Burner	P
3	Preheat raw material	Burner	P
4	Insulate the burner	Burner	P
5	Reduce the weight and heat capacity of the burner	Burner	P
6	Recover the flue gas	Burner	P
7	Install recupurater	Burner	M
8	Repair the leak of the hot air	Burner	H
9	Other improvements of burner	Burner	H
10	Change steam ejector to the vacuum pump	Heat equipment	P
11	Other improvements of heat equipment	Heat equipment	P
12	Change to high efficiency ceramic burner	Burner	M
13	Change to high efficiency class burner	Burner	P
14	Change the thermal machine	Thermal machine	M
15	Other changes the thermal machine	Thermal machine	M
16	Other heat recovery	Thermal machine	M
17	Change motor	Motor	P
18	Correct the motor operating	Motor	H
19	Correct the power generator operating	Motor	H
20	Change M-G set with DC inverter	Motor	M
21	Change damper with VVVF	Motor	P
22	Other improvements of motor	Motor	H

Source DEDP (1996)

Note H = House keeping

P = Process improvement

M = Major change of equipment

Appendix E2. Calculation of firebrick industry.

Table E2.1. Information data of firebrick factory.

Information	Year			
	1997	1998	1999	2000
Products	Firebrick			
Production (ton)	10,060	10,880	4,565	7,980
Energy consumption				
Kerosene (liter)	1,000-2,000	1,000-3,000	1,000-3,000	1,000-3,000
Gasoline (liter)	3,000-4,000	3,000-4,000	3,000-5,000	3,000-5,000
Fuel oil (liter)	900,000-1,100,000	900,000-1,200,000	900,000-1,200,000	1,141,442
Electricity (kWh)	600,000-840,000	600,000-840,000	600,000-960,000	600,000-960,000

Thermal efficiency improvement

Assumption data:

Net calorific value	:	9,500 kcal/L
Gross calorific value (H_L)	:	9,900 kcal/L
Specific gravity of fuel oil	:	0.96
Ambient air temperature	:	25 °C
Temperature of flue gases	:	500 °C
Temperature of preheated air	:	130 °C
Air-fuel ratio (M)	:	1.4
Mean specific heat of flue gases	:	0.34 kcal/NM^3 °C
Mean specific heat of air	:	0.241 kcal/NM^3 °C

Calculation in the year 2000:

Theoretical air (A_0) = $[(0.85 \times 9{,}900)/1{,}000] + 2$

= 10.42 NM^3/kg

Air (A) = 1.4×10.42 NM^3/kg

= 14.59 NM^3/kg

Theoretical flue gases (G_0) = $(1.11 \times 9{,}900)/1{,}000$

	=	10.989 NM^3/kg
Flue gases (G)	=	10.989 + (1.4-1)(10.42)
	=	15.16 NM^3/kg

1. **Heat from fuel oil combustion**

= (9,900 kcal/kg × 1,141,442 L × 0.96)/7,980 ton

= 1,359,431.675 kcal/ton

2. **Heat recovered**

= (14.59 NM^3/kg × 0.241 kcal/NM^3 °C × (130 - 25 °C)

× (1,141,442 L × 0.96)/7,980 ton

= 50,697.18 kcal/ton

3. **Fuel oil saving**

= 50,597.18 kcal/ton /9,500 kcal/L

= 5.34 L/ton

<u>Fuel substitution of fuel oil by natural gas</u>

Information data:

Fuel oil costs per liter	:	6 baht/L
Natural gas casts per MBTU	:	108.87baht/MBTU
Net calorific value of fuel oil	:	0.03977 GJ/L

1. **Energy required for heating:**

= 1,141,442 L × 0.03977 GJ/L

= 45,395.148 GJ

2. **Fuel oil costs per year:**

= (6 baht/L × 45,395 GJ)/0.03977 GJ/L

= 6,848,652 baht/year

3. **Natural gas costs per year:**

= (108.87 baht/MBTU × 45,395 GJ)/1,054.86 GJ/MBTU

= 4,685,214.47 baht/year

4. **Energy saving:**

= 6,848,652 – 4,685,214.47

= 2,163,435.14 baht/year

<u>Replacement of existing electric motors by high efficiency electric motors</u>

Assumption data:

Electric motors account about 80% of the electricity demand in industry (Wachara Mingwithikul, 2001).

Replacement of existing electric motors by high efficiency electric motors can reduce about 2% of electricity efficiency.

1. **Electricity demand in electric motor:**

    = 780,000 × 80% kWh

    = 624,000 kWh

2. **Old electricity efficiency:**

    = 7,980 ton / 624,000 kWh

    = 0.012788 ton/kWh

3. **New electricity efficiency:**

    = 0.012788 + (0.012788 × 2%) ton/kWh

    = 0.012788 + 0.000256 ton/kWh

    = 0.01304 ton/kWh

<u>Change to high efficiency voltage regulator</u>

Assumption data:

The electricity demand can be reduce about 10%-50% of total electricity demand.

1. **Electricity saving:**

    = 780,000 × 10% kWh

    = 78,000 kWh

2. **Electricity demand (after change to high efficiency voltage regulator:**

    = 780,000 – 78,000 kWh

    = 702,000 kWh

Appendix E3. Calculation of Glass bottle factory.

Table E3.1. Information data of glass bottle factory.

Information	Year			
	1997	1998	1999	2000
Products	Glass Bottle			
Production (ton)	165,000	165,000	160,000	165,000
Energy consumption				
Fuel oil (2%S) (liter)	1,800,000	19,400,000	20,642,000	18,048,000
Natural gas (BTU)	156,000	110,400	111,000	145,000
Electricity (kWh)	39,160,000	40,000,000	43,254,000	43,333,000

<u>Thermal efficiency improvement</u>

Assumption data:

Net calorific value	:	9,500 kcal/L
Gross calorific value (H_L)	:	9,900 kcal/L
Specific gravity of fuel oil	:	0.96
Ambient air temperature	:	25 $^{\circ}$C
Temperature of flue gases	:	977 $^{\circ}$C
Temperature of preheated air	:	375 $^{\circ}$C
Air-fuel ratio (M)	:	1.3
Mean specific heat of flue gases	:	0.358 kcal/NM^3 $^{\circ}$C
Mean specific heat of air	:	0.241 kcal/NM^3 $^{\circ}$C

Calculation in the year 2000:

Theoretical air (A_0) $= [(0.85 \times 9{,}900)/1{,}000] + 2$

$= 10.42$ NM^3/kg

Air (A) $= 1.3 \times 10.42$ NM^3/kg

$= 13.55$ NM^3/kg

Theoretical flue gases (G_0) $= (1.11 \times 9{,}900)/1{,}000$

$= 10.989$ NM^3/kg

Flue gases (G) $= 10.989 + (1.3-1)(10.42)$

$= 14.11$ NM^3/kg

1. **Heat from fuel oil combustion**

= (9,900 kcal/kg × 18,048,000 L × 0.96)/165,000 ton

= 1,039,564.8 kcal/ton

2. **Heat recovered**

= (13.55 NM^3/kg × 0.241 kcal/NM^3 °C × (375-25 °C)

× (18,048,000 L × 0.96)/165,000 ton

= 119,927.87 kcal/ton

3. **Fuel oil saving**

= 119,927.87 kcal/ton / 9,500 kcal/L

= 12.62 L/ton

Information data:

Fuel oil costs per liter	:	6.9 baht/L
Natural gas casts per MBTU	:	169 baht/MBTU
Net calorific value of fuel oil	:	0.03977 GJ/L

1. **Energy required for heating:**

= 18,048,000 L × 0.03977 GJ/L

= 717,768.96 GJ

2. **Fuel oil costs per year:**

= (6.9 baht/L × 717,768.96 GJ)/0.03977 GJ/L

= 124,531,200 baht/year

3. **Natural gas costs per year:**

= (169 baht/MBTU × 717,768.96 GJ)/1,054.86 GJ/MBTU

= 114,994,363.5 baht/year

4. **Energy saving:**

= 124,531,200 – 114,994,363.5

= 9,536,836.5 baht/year

<u>Replacement of existing electric motors by high efficiency electric motors</u>

Assumption data:

Electric motors account about 80% of the electricity demand in industry (Wachara Mingwithikul, 2001).

Replacement of existing electric motors by high efficiency electric motors can reduce about 2% of electricity efficiency.

1. **Electricity demand in electric motor:**

    = 43,333,000 × 80% kWh

    = 34,666,400 kWh

2. **Old electricity efficiency:**

    = 165,000 ton / 34,666,400 kWh

    = 0.00476 ton/kWh

3. **New electricity efficiency:**

    = 0.00476 + (0.00476 × 2%) ton/kWh

    = 0.00476 + 0.000095 ton/kWh

    = 0.00485 ton/kWh

<u>Change to high efficiency voltage regulator</u>

Assumption data:

The electricity demand can be reduce about 10%-50% of total electricity demand.

1. **Electricity saving:**

    = 43,333,000 × 10% kWh

    = 4,333,300 kWh

2. **Electricity demand (after change to high efficiency voltage regulator:**

    = 43,333,000 – 4,333,300 kWh

    = 38,999,700 kWh

Appendix E4. Calculation of cement factory

Table E4.1. Information data of cement factory.

Information	Year		
	1998	1999	2000
Products	Cement		
Production (ton)	1,804,500	1,590,000	1,689,300
Energy consumption			
Bitumen (ton)	29,972	78,118	120,459
Lignite (ton)	518,200	596,036	269,463
Gasoline (liter)	10,263	10,167	5,801
Diesel (liter)	2,875,517	3,222,000	2,378,270
Fuel oil (liter)	583,043	6,427,660	3,775,532
Electricity (kWh)	305,911,715	2,427,660	246,909,000

Substitution of lignite by bitumen.

Information data:

Net calorific value of bitumen : 26.39 GJ/ton

Net calorific value of lignite : 18.42 GJ/ton

1. Energy required for heating:

Bitumen = 120,459.00 ton × 26.39 GJ/ton

= 3,178,913.01 GJ

Lignite = 269,463.00 ton × 18.42 GJ/ton

= 4,963,508.46 GJ

2. Replacing by bitumen:

= 4,963,508.46 GJ / 26.39 GJ/ton

= 188,097.18 ton bitumen

3. Energy cost saving:

= (269,463.00 ton - 188,097.18 ton) × 956 Baht/ton

= 77,785,896 Baht

Fuel substitution of fuel oil by natural gas

Information data:

Fuel oil costs per liter	:	6.41 baht/L
Natural gas casts per MBTU	:	108.87 baht/MBTU
Net calorific value of fuel oil	:	0.03977 GJ/L

1. **Energy required for heating:**

    = 3,775,532 L × 0.03977 GJ/L

    = 150,152.9076 GJ

2. **Fuel oil costs per year:**

    = (6.41 baht/L × 150,152.9076 GJ)/0.03977 GJ/L

    = 24,185,680.44 baht/year

3. **Natural gas costs per year:**

    = (108.87 baht/MBTU × 150,152.9076 GJ)/1,054.86 GJ/MBTU

    = 15,497,279.61 baht/year

4. **Energy saving:**

    = 24,185,680.44 – 15,497,279.61 baht/year

    = 8,688,400.83 baht/year

Replacement of existing damper and controller by inverter

Assumption:

Replacement of existing damper and controller by inverter can be save energy about 20%-30% of total electricity demand.

1. **Electricity saving**

    = 246,909,000 × 20% kWh

    = 49,381,800 kWh

2. **Electricity demand (after replacement by inverter)**

    = 246,909,000 – 49,381,800 kWh

    = 197,527,200 kWh

Replacement of existing electric motors by high efficiency electric motors

Assumption data:

Electric motors account about 80% of the electricity demand in industry (Wachara Mingwithikul, 2001).

Replacement of existing electric motors by high efficiency electric motors can increase about 2% of electricity efficiency.

1. **Electricity demand in electric motor:**

    = 246,909,000 × 80% kWh

    = 197,527,200 kWh

2. **Old electricity efficiency:**

    = 1,689,300 ton / 197,527,200 kWh

    = 0.00855 ton/kWh

3. **New electricity efficiency:**

    = 0.00855 + (0.00855 × 2%) ton/kWh

    = 0.00855 + 0.00017 ton/kWh

    = 0.00838 ton/kWh

APPENDIX F

Conversion factors

Table F.1. Energy content of fuels (net calorific value).

Type	unit	kcal/unit	toe/10^6unit	MJ/unit	10^3Btu/unit
Modern energy					
1. Crude Oil	liter	8680	860.00	36.33	34.44
2. Condensate	liter	7900	782.72	33.07	31.35
3. Natural Gas					
3.1 Wet	scf	248	24.57	1.04	0.98
3.2 Dry	scf	244	24.18	1.02	0.97
4. Petroleum Products					
4.1 LPG	liter	6360	630.14	26.62	25.24
4.2 Gasoline	liter	7520	745.07	31.48	29.84
4.3 Aviation Fuel	liter	8250	817.40	34.53	32.74
4.4 Kerosene	liter	8250	817.40	34.53	32.74
4.5 Diesel	liter	8700	861.98	36.42	34.52
4.6 Fuel Oil	liter	9500	941.24	39.77	37.70
4.7 Bitumen	liter	9840	974.93	41.19	39.05
4.8 Petroleum Coke	liter	8400	832.26	35.16	33.33
5. Electricity	kWh	860	85.21	3.60	3.41
6. Hydro-electric	kWh	2236	221.54	9.36	8.87
7. Geothermal-electric	kWh	9500	941.24	39.77	37.70
8. Coal (import)	kg.	6300	624.19	26.37	25.00
9. Coke	kg.	6600	653.92	27.63	26.19
10. Anthracite	kg.	7500	743.09	31.40	29.76
11. Ethane	kg.	11203	1110.05	46.89	44.45
12. Propane	kg.	11256	115.34	47.11	44.67
13. Lignite					
13.1 Li	kg.	4400	435.94	18.42	17.46
13.2 Krabi	kg.	2600	257.60	10.88	10.32
13.3 Mea Moh	kg.	2500	247.70	10.47	9.92
13.4 Chae Khon	kg.	3610	357.67	15.11	14.32

Table F.1. Energy content of fuels (net calorific value) (Cont.).

Type	Unit	kcal/unit	toe/10^6unit	MJ/unit	10^3Btu/unit
Renewable energy	kg.	3820	378.48	15.99	15.16
1. Fuel Wood	kg.	6900	683.64	28.88	27.38
2. Charcoal	kg.	3440	340.83	14.40	13.65
3. Paddy Husk	kg.	1800	178.34	7.53	7.14
4. Bagasse	kg.	1160	114.93	4.86	4.60
5. Garbage	kg.	2600	257.60	10.88	10.32
6. Saw Dust	kg.	3030	300.21	12.98	12.02
7. Agricultural Waste					

Source DEDP (1998)

Table F.2. General conversion factors

1 kcal	= 4186	joules
	= 3.968	Btu
1 toe	= 10.093	Gcal
	= 42.244	GJ
	= 40.047×10^6	Btu
1 barrel	= 158.99	liters
1 cu.m. of solid wood	= 600	kg.
1 cu.m. of charcoal	= 250	kg.
5 kg. of wood	= 1 kg. Of charcoal product	product
1 liter of LPG	= 0.53	kg.

Source DEDP (1998)

Biography

Miss Sasithon Monthip was born on April 27, 1976 in Chumporn. Firstly, she studied in Suntirat Wittayalai School, Bangkok. She graduated from Mahanakorn University of Technology (MUT), Bangkok in the Faculty of Civil Engineering in 1997 and the research was "Research of Ultimate Behavior of Pile Load Test". She started Master Degree Program since 1998.