بسم الله الرحمن الرحيم

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COLLEGE OF GRADUATE STUDIES

A Computer Programme for the Economic Evaluation for Cogeneration Applications

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A Thesis submitted in partial fulfillment for the requirement of the degree of M.Sc. in mechanical Engineering (Power Plant)

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آيـة

قال تعالي :

﴿ مَآ أَصَابَ مِن مُّصِيبَةٖ فِي ٱلۡأَرۡضِ وَلَا فِيٓ أَنفُسِكُمۡ إِلَّا فِي كِتَٰبٖ مِّن
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(٢٣) ﴾

صدق الله العظيم

سورة الحديد الآيات (من22-23)

Dedication

I dedicated this thesis to my father, mother, my beloved wife "Mawia", and sweet daughter "Ebtisam".

Acknowledgement

First and foremost, I would like to express my sincere gratitude and acknowledgement to the Allah for His grace, strength, protection and guidance on the successful completion of this work.

It is my utmost pleasure to express my appreciation and thanks to my supervisor, Dr Ali Mohammed Hamdan Adam, for his support, encouragement, instruction, untiring help, invaluable suggestions and constructive criticism throughout this research.

I sincerely owe a debt of gratitude my dear brothers and my sisters. My next appreciation goes to my wonderful wife, Mawia and my sweet daughter, Ebtisam , for their prayers, patience and sacrifices throughout my work.

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Abstract

This thesis intends to show the current state of Combined Heat and Power (CHP) Systems and highlights the different aspects of the technologies. The theoretical principals for planning and analysis of a CHP system are described. Economic and technical evaluation was conducted to a CHP system by using Suzuki models. Matlab program were developed in order to investigate on the main factor effects the profit index of CHP systems. These factors include capacity factor, annual cost rate for construction cost, average unit selling price of electricity, average unit selling price of heat, unit cost of the fuel, average power generating efficiency and average heat generating efficiency.

مستخلص

تهدف هذه الأطروحة لإظهار الحالة الراهنة من أنظمة الحرارة والطاقة المؤتلفة ويسلط الضوء على جوانب مختلفة من التكنولوجيات. تم توضيح المبادئ النظرية لتخطيط وتحليل نظام الحرارة والطاقة المؤتلفة. أجري التقييم الاقتصادي والتقني لنظام الحرارة والطاقة المؤتلفة باستخدام نموذج سوزوكي. وقد طور برنامج ماتلاب من أجل التحقيق في التأثيرات الرئيسية على مؤشر الربح من نظم الحرارة والطاقة المؤتلفة. وتشمل هذه العوامل معامل القدرة ومعدل التكلفة السنوية لتكلفة البناء ومتوسط سعر بيع الوحدة للكهرباء ومتوسط سعر بيع الوحدة للحرارة وتكلفة وحدة الوقود ومتوسط كفاءة توليد الطاقة ومتوسط كفاءة توليد الحرارة.

Contents

List of Figures

List of Symbols and Abbreviations

Symbols	**Descriptions**
CHP	Combined Heat and Power
CGS	Co-Generation System
CGSs	Co-Generation Systems
Q_e	Electric power
α	Capacity factor
Q_h	Heat power
Q_f	Fuel power
C_e	Unit selling price of electricity
C_h	Unit selling price of heat
C_f	Unit cost of the fuel
P_f	Gross profit of the CGS system
η_e	Electric power generating efficiency
η_h	Heat generating efficiency
P_u	Profit per unit electric power output
X	Unit construction cost of the CGS
I_p	Profit index
R	Annual cost rate for the construction cost
r	Annual interest rate
n	Pay-out period
GUI	Graphical User Interface

CHAPTER ONE

INTRODUCTION

1.1 Background

Energy consumption increases continuously due to increases in population, industrial and commercial needs for power. The value for Electric power consumption (kWh per capita) in Sudan was 158.66 as of 2013. As the graph below shows, over the past 42 years this indicator reached a maximum value of 158.66 in 2013 and a minimum value of 26.08 in 1971[1].

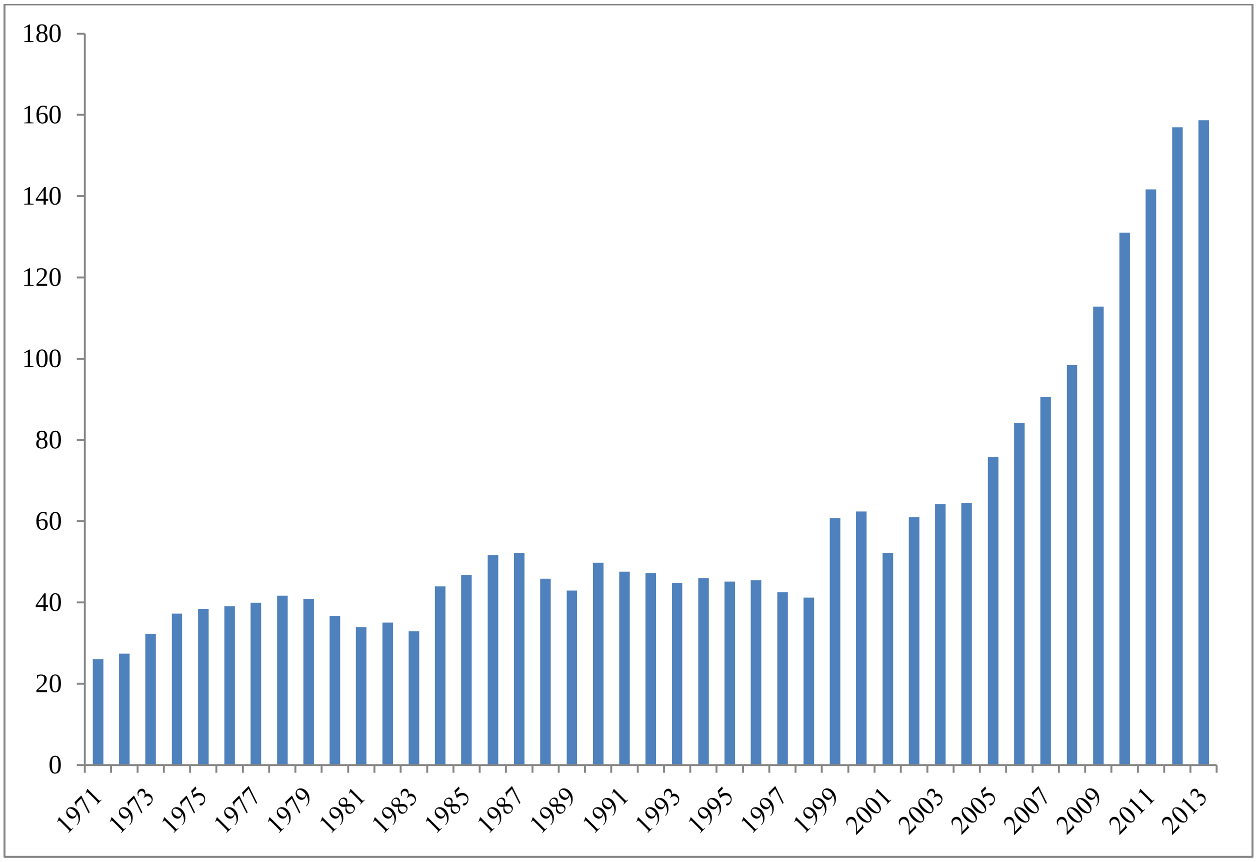


Figure 1.1: electric power consumption in Sudan for several years [1]

Many power plants are available in Sudan to provide the need of electrical power for the users including, hydro-electric, thermal, steam and diesel power plants. However, due to the limited power produced by these plants, there is a need for combined heat and power system (CHP) or sometime called co-generation system. The CHP system has ability to produce both thermal and electrical power simultaneously, by better organizing the overall system. The increases of required power motivated the operators to think about well usage of the available power. This can be by evaluating the available power-station economically and technically. The use of CHP has a degree of advantage of the traditional power plant in which both heat and electricity can be generated. An example of CHP plants in Sudan are Kenana Sugar factory, and Asalaia sugar factory.

CHP was used to either supplement or replace conventional separate heat and power systems. Energy users typically purchase electricity from the local utility and burn fuel for a boiler to produce steam or hot water, but by using CHP systems those energy users can provide both electrical and thermal energy services in one efficient process. CHP systems require less fuel than equivalent separate electrical and thermal energy systems to produce the same amount of energy for the end user by capturing and utilizing waste heat. This study focused on evaluating a CHP system economically and technically.

1.2 Problem Statement

Nowadays, the CHP system had a wide range of applications. Two factors are necessary for selecting the appropriate CHP system, includes the technical information (i.e. CHP efficiency), and the economical factors (i.e. total cost). However, due to the large ranges of economic and technical factors that can affect any CHP system, it has been difficult to evaluate the need for such system economically and technically simultaneously. Moreover, the simultaneous evaluation of CHP is a time consuming, since the large ranges of factors are exist. Therefore, there is a need for a computer program that can be used for CHP evaluations. Comprehensive evaluations can be done for the CHP in a short time with less effort by using a computer program.

1.3 Research Objectives

The main objectives of this study are:

1. To develop computer program for evaluating the economics of CHP system.
2. To investigate the effect of various economic and technical parameters that affects the CHP system.

1.4 Research Methodology

In this research the mathematical models for evaluating the economic and technical of Combined Heat and Power applications is used. Matlab codes were developed in order to investigate on the main factor effects the profit index of CHP systems.

1.5 Thesis Structure

This thesis has been structured as follows:

Chapter 1 – Introduction – this chapter provides the research motivation, the research background, problem statement, research objective, research methodology as well as the thesis structure.

Chapter 2 –Literature Review and Theoretical Background – this chapter provides literature on the fundamental of combined heat and power systems, CHP applications, economic and technical relevant literature of CHP systems.

Chapter 3 – Methodology – this chapter describes the mathematical model for evaluating the economic and technical of the CHP applications, data considered in this study with description for developing a computer program for evaluating the CHP system.

Chapter 4 – Results and Discussion – this chapter reports the results of economic and technical evaluation of CHP system. Moreover, the effect of several parameters on CHP system was presented.

Chapter 5 – Conclusion and Recommendation – these chapter summaries the outcomes of this study including conclusions and recommendation for future work.

CHAPTER TWO

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Chapter Overview

This Chapter reviewed the relevant works of this work including, fundamental of CHP, applications, advantages and disadvantages of using CHP system. Moreover, the Chapter described the methods that were used for economical assessment of any CHP system.

2.2 Combined Heat and Power (CHP)

Combined Heat and Power (CHP) system is an energy technology that provides electrical and thermal power simultaneously. The CHP has advantage of providing a thermal energy at high efficiency by utilizing excess heat from the process of electricity generation. Figure 2.1 shows a comparison between traditional system and CHP system.

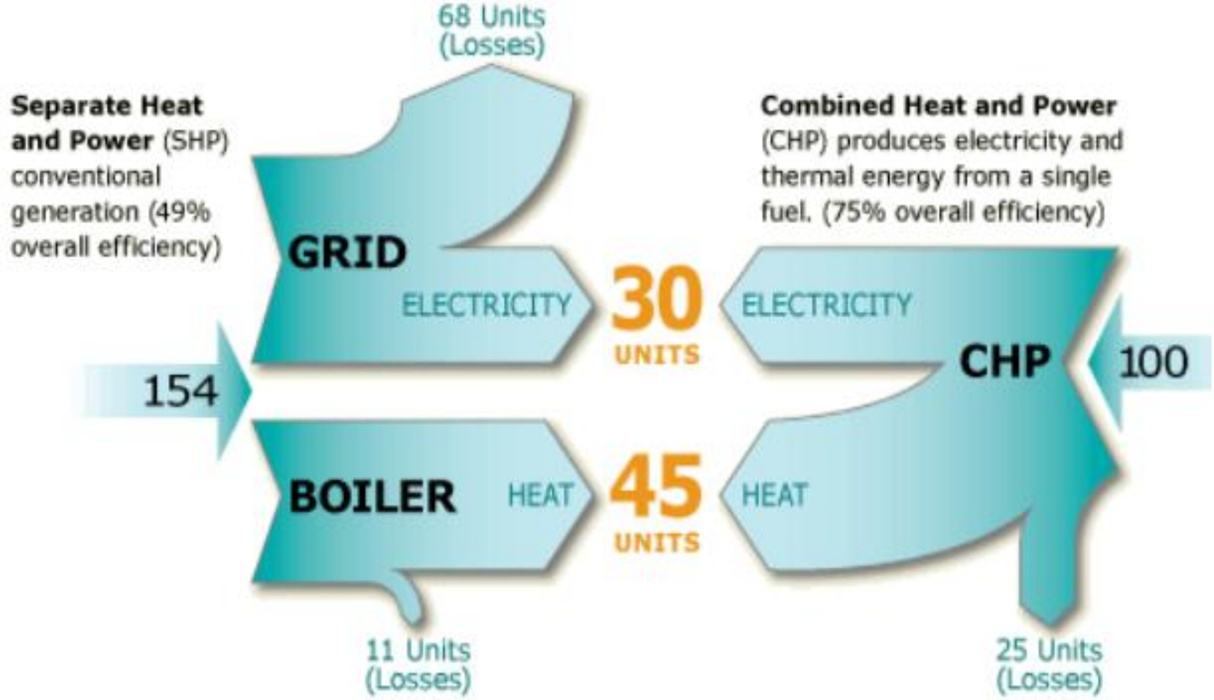


Figure 2.1: Comparison between traditional system with the CHP System [2]

CHP is usually used to either replace or supplement the conventional system which usually is available as separate system. Energy users typically purchase electricity from the local utility and burn fuel for a boiler to produce steam or hot water. However, by using CHP systems the energy users can provide both electrical and thermal energy services in one efficient process.

Furthermore, the use of CHP systems means less fuel than equivalent separate electrical and thermal energy system.

All CHP systems involve use of the excess thermal energy that would be otherwise wasted to produce additional electricity or thermal energy [3]. The recovered energy can provide significant environmental and energy efficiency advantages over the conventional heat and power systems. CHP systems often have higher efficiency ranges from 65 to 75% efficiency, while a conventional system efficiency around 45% . CHP systems can have applications in a range of settings, but this work focuses on CHP systems used in decentralized, on-site energy generation [3].

2.3 Applications of CHP

CHP systems have several applications which are typically identified based upon their prime movers or technology types. These technologies include reciprocating engines, combustion or gas turbines, steam turbines, micro-turbines and fuel cells. The prime mover of CHP system can be operated using a range of fuels, including natural gas, coal, oil and alternative fuels [4]. CHP can be also classified based on the order in which energy flows through the components of the system. In a topping cycle, fuel is used to power a prime mover then the extra thermal energy is used as heat source, cooling as well as dehumidification applications. An alternative of topping cycle is a bottoming cycle, in which fuel is used to drive the thermal process, and the extra thermal energy is usually used to produce power [5]. Figure 2.2 shows the topping-cycle CHP systems, while Figure 2.3 shows the Bottoming-cycle type.

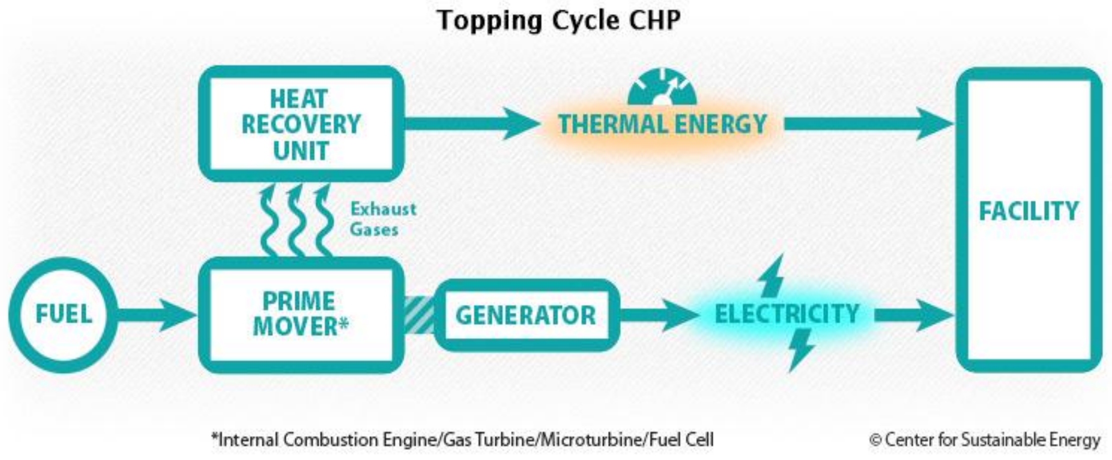


Figure 2.2: Topping-cycle CHP systems [6]

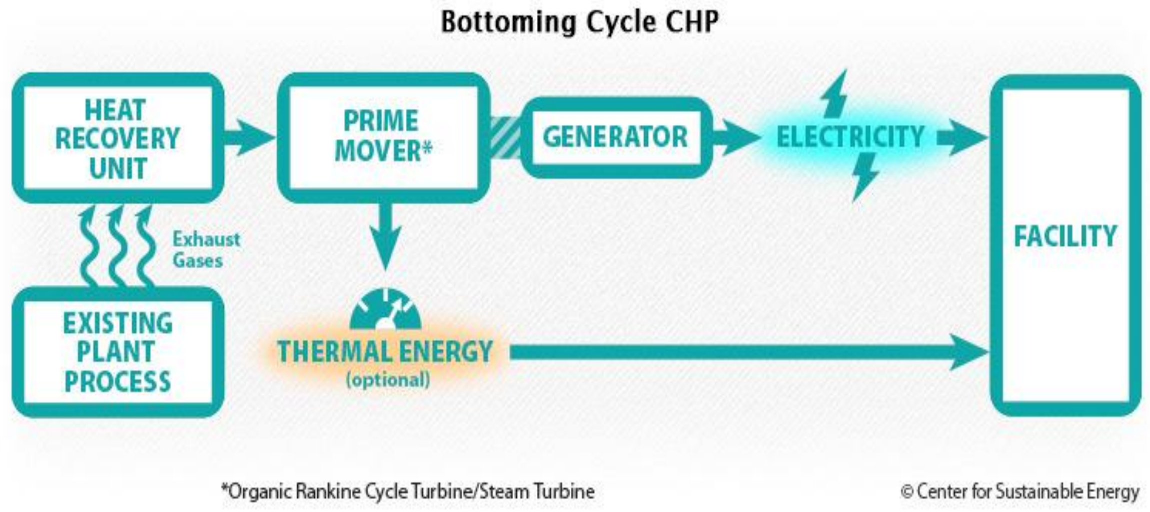


Figure 2.3: Bottoming-cycle CHP systems [6]

Four of the prime movers most common in CHP systems: reciprocating engines, gas turbines, micro-turbines and fuel cells are all used in topping cycles, while steam turbines are typically used in bottoming cycles. However, in this section a detailed description is focused on steam turbine and gas turbine, since these are the most CHP system applied in Sudan.

2.3.1 Steam Turbine

Steam turbines are one of the older and flexible prime movers used previously to generate electricity power. Steam turbines were used in CHP, together with boiler to generate electricity and heat energy. Figure 2.4 shows the main cycle of CHP based steam turbine system. In this system a boiler is used to burn fuel in order to produce steam, and then the generated steam can be used for electricity generation through the steam turbine. The steam exists from turbine with low pressure as exhaust and sends to condenser for another cycle. This is by using a pump which pumps the condensate steam to the boiler again [7].

Steam turbine system is a useful for CHP applications for several reasons, due to the low pressure steam of condenser which is available for use directly in a thermal process to use in generating heating or cooling, used to provide domestic hot water, or used to provide chilled water. However, steam turbine based CHP systems have been costly, despite its many benefits when compared with other prime movers. A wide variety of fuels can be used to power steam turbines, including: natural gas, solid waste, coal, wood, wood waste and agricultural by-products [9]. Therefore, the fuel of steam turbine CHP system is simply burned to create

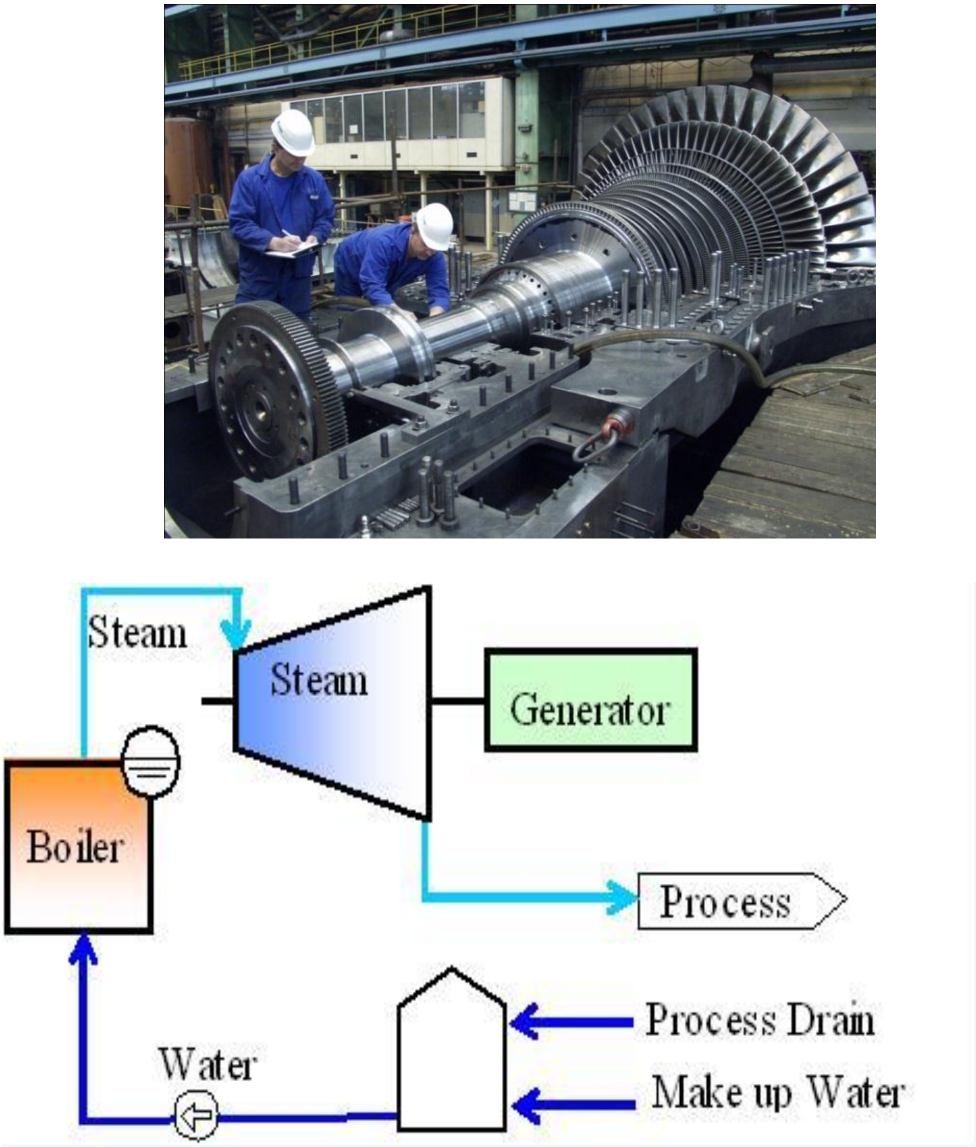


Figure 2.4: photo of steam turbine (Top), and steam turbine cycle (Bottom) [8]

steam in the boiler. A steam turbine-based CHP system has many interrelated subsystems which must often be custom designed. Installed cost for a steam turbine CHP plant includes costs for: the boiler, fuel handling, the storage and preparation system, stack gas cleanup and pollution controls, the steam turbine generator and field construction and plant engineering. The cost of the actual steam turbine is a fraction of the total cost for the system. Due to the complexity of the steam turbine-based CHP system, the costs are usually $2,000 to $3,000/kW or above [4, 9]. Since the costs of the systems necessary for steam turbines to operate within CHP systems are relatively high when compared with other prime mover options, they are typically installed in medium and large-scale industrial and institutional applications where the systems are most cost-effective. The expense of the systems is reduced even further when inexpensive or free waste fuels are available. Steam turbines are common in paper mills, an industrial setting with excess waste fuels, as well as in chemical plants and in the food industry [10].

However, steam turbines have many benefits and several shortcomings when used for CHP applications. Steam turbines are commercially available in sizes from 50 kW to over 250 MW [9], and are very reliable. Steam turbines also have long lives; there are steam turbines which have been in service for over 50 years. The electrical efficiency of steam turbine power plants varies from 10 to 36%, depending upon the size and specifics of the system, and total CHP system efficiency is usually about 80% [10]. Large steam turbines have long start up and shut down times, often several hours. The systems must be warmed up and cooled down slowly in order to minimize the differential expansion between parts within the technology. Steam turbines work well as CHP prime movers in medium and large-scale industrial and institutional applications, but are not the most cost-effective or efficient option outside these scenarios.

2.3.2 Gas Turbine

Gas turbine is a well-established power generation machine which operates based on Brayton thermodynamic cycle. Figure 2.5 shows an example of gas turbine together with the gas turbine based CHP.

Gas turbine system composed of compressor, combustor and turbine. The compressor takes air from atmospheric and increases its pressure for the inlet of combustor, and then the combustor mix the entered air together with fuel to complete the combustion process. Then, the exhaust gases used to drive the turbine, in which where the thermal energy converted into mechanical work [12]. The gas turbine system is used for CHP applications in order to produce electricity as well as mechanical work. The exhaust temperature of gas turbine is approximately at 427ºC to 593ºC, depending on the type of turbine. These high exhaust temperatures allow the thermal energy to be used directly for industrial applications (e.g. heating, cooling, for domestic uses, to provide chilled water, etc). Additionally, the high quality heat from the gas turbine exhaust allows the thermal energy to be used to provide electricity using a steam turbine along with the gas turbine in a combined cycle process. In

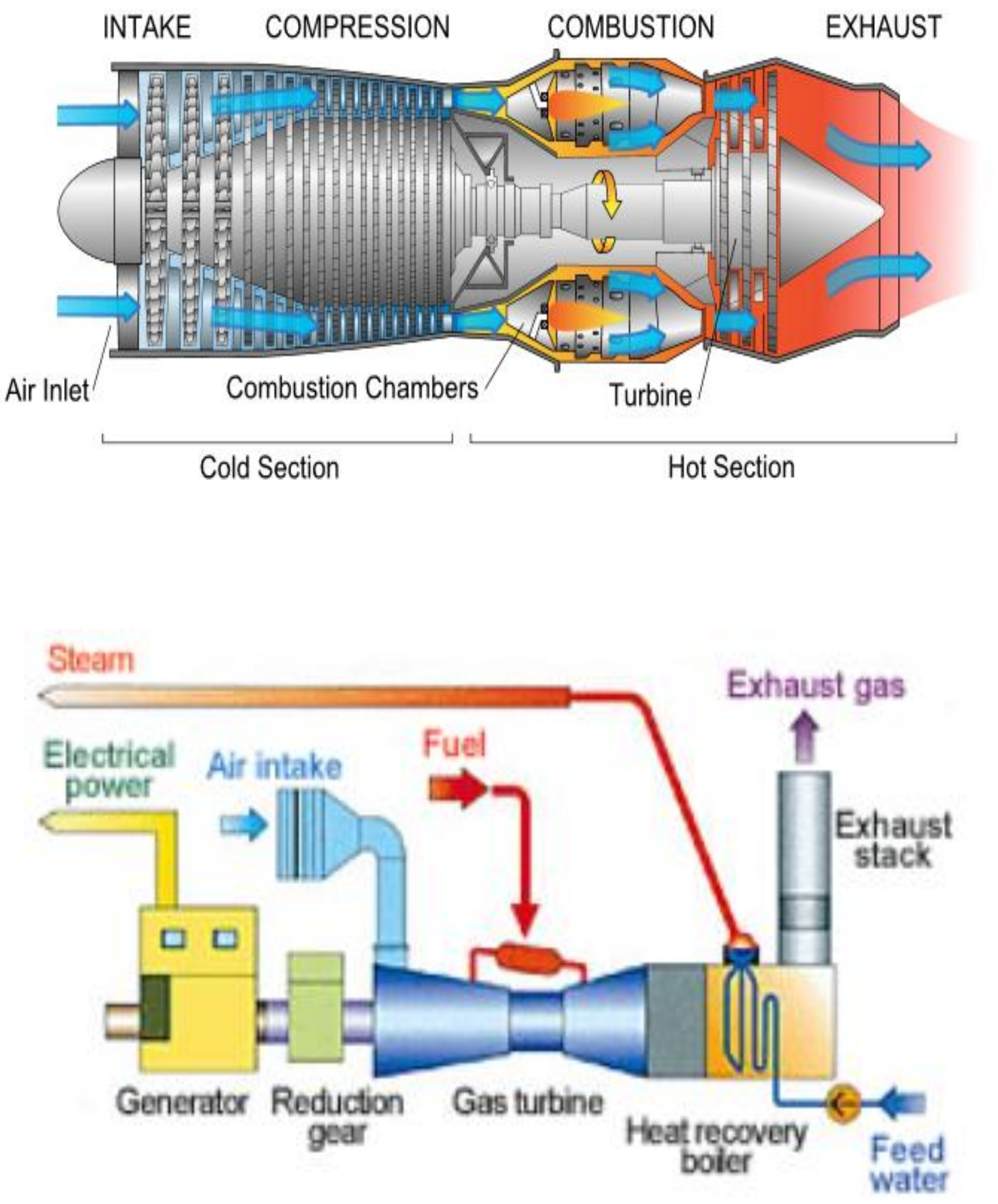


Figure 2.5: An example of gas turbine (Top), and gas turbine based CHP system (Bottom) [11]

CHP cycle, the gas turbine exhaust is usually used to generate power using steam turbine which used for electricity production. In this configuration only electricity is produced for end use. Since 2008, most of the U.S. CHP installations which included gas turbines were large combined cycle systems [9].

Gas turbine is an efficient heat engine, cost-effective, and can run using various fuels such as natural gas, petroleum fuels, synthetic gas, biogas or landfill gas, or can use a combination of these fuels [9]. Moreover, the gas turbines are available commercially in different sizes ranging from several 100 kW up to 200 MW. It had an electrical efficiency ranges from 20% to 40%, with overall efficiency between 65% to 80%. The total cost of CHP plant which work based on gas turbine is mainly based on it components and can be approximately in the range between $900/kW to about $1,500/kW [9]. These components are gas turbine, gearbox, electric generator, inlet and exhaust ducting, inlet air filtration, lubrication and cooling system, starter system and exhaust system. Gas turbines were used as prime mover for several CHP applications, which were mainly located at industrial and institutional facilities. Some gas turbine-based CHP system was operated in applications such as: oil recovery, chemicals, paper production, food processing and universities in which a power up to 40 MW can be generated.

Use of gas turbine in a CHP system has several drawbacks, first the relation between load percent of gas turbine and the overall efficiency of CHP system. Gas turbine was reduced the output power due to reduction in combustion temperature, so its efficiency can be much lower as compared to the case of full capacity operation. Gas turbines do not follow load well, and become inefficient at low percent load. Figure 2.6 shows relation between load percentage and efficiency for a gas turbine. The plot showed a significant decrease in electrical efficiency of gas turbine as the percent load decreases, with low efficiency at load below 50%. Emission is also generally increased at part load conditions, especially at half load and below.

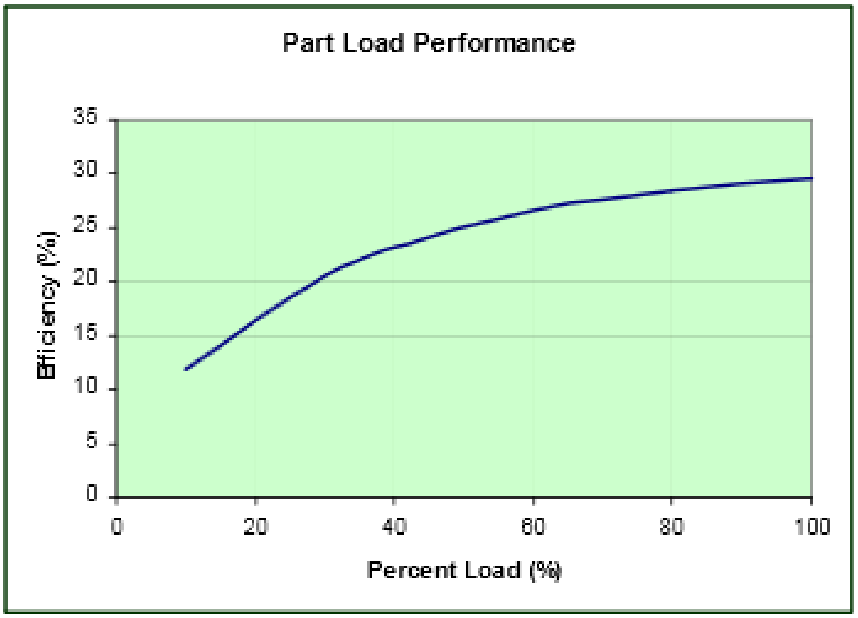


Figure 2.6: Part Load Performance for Typical Gas Turbine

Gas turbines were designed for ISO condition which works at 15ºC and an altitude of sea level. Any changes in these conditions influence the gas turbine output power as well as its efficiency. As increasing the inlet air temperature for gas turbine cycle, both output power output and efficiency will decrease. This is due to decreases in inlet air density with increasing the temperature. However, gas turbine can operate efficiently with power greater than ISO-rated power, in case of low temperature. This is because of increasing of the inlet air density with low temperature [9, 13]. Figure 2.7 shows the impact of ambient temperature on the output power and efficiency of a gas turbine. Changes in altitude also impact the output power and efficiency of any gas turbine.

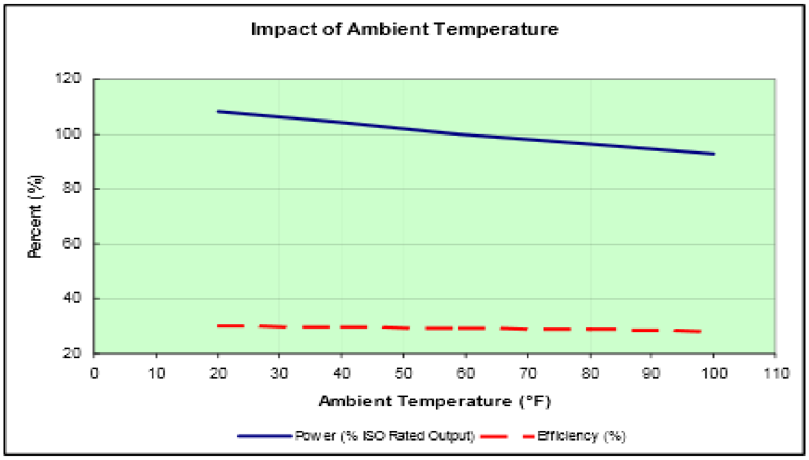


Figure 2.7: Impact of Ambient Temperature on Gas Turbine Power Output and Efficiency

The density of air decreases as altitude increases, and so the percent of full load of the technology decreases. Figure 2.8 shows the impact of altitude on the gas turbine percent load.

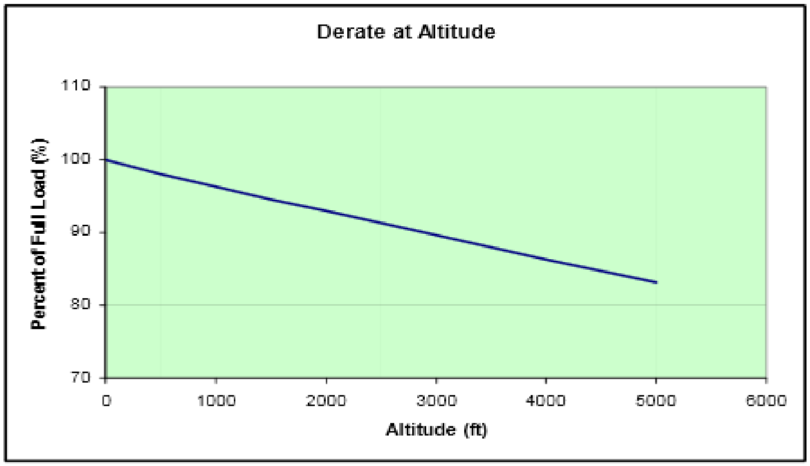


Figure 2.8: Impact of Altitude on Gas Turbine Percent Load (Energy and Environmental Analysis Inc 2008b)

Finally gas turbines had been an efficient and cost-effective, and flexibility within installation configurations. This motivated the operators to use the gas turbine as prime mover for CHP systems.

2.4 Advantages and Disadvantages of Using CHP

CHP has several advantages over the conventional separate electrical and heat system. A significant reduces in the level of carbon emissions can be by using CHP systems, as well as the energy cost can be reduced due to the proper uses of energy. Figure 2.9 shows a comparison between the conventional separate system and CHP system [14].

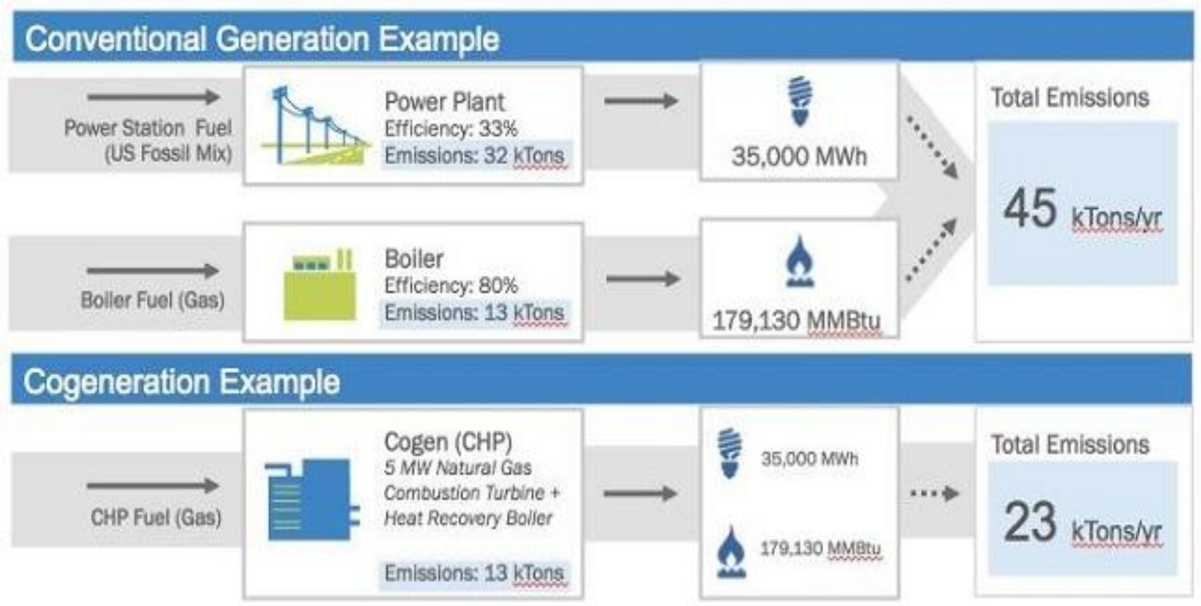


Figure 2.9: A comparison between conventional and CHP systems [14]

The combustion efficiency for conventional system ranged between 40% to 50%, while by using CHP system a 80% efficiency can be gained. The higher efficiency in CHP justifies the low carbon emissions as compared to the emission of conventional system. Generally the CHP has many advantages which can be summarized as follow:

- Enhancing operational efficiency to lower overhead costs.
- Reducing energy waste, thereby increasing energy efficiency.
- Offering greater energy independence by moving a portion of the load off the grid.
- Allowing companies to replace aging infrastructure.
- Reduces dependence on the grid.
- Allows for “islanding”.
- Provides for power when the grid is down.

When combined with a renewable fuel supply, such as biomass or biogas, CHP is an environmentally responsible source of reliable, base load generation. These benefits have attracted the attention of many large-scale facilities.

However the disadvantages of using CHP can be summarized as:

- CHP is more complex.
- Requires a balance between thermal load and electrical load.
- Implies the need for more redundancy to “island”.
- Can be costly.

2.5 Economic Assessment of CHP Systems

An economical assessment is required for any CHP plant prior implementation. This is includes both low and high power range CHP plants. This is because of high cost of such projects which need to be studied well prior investment decision.

CHP projects investment can be characterized into two including mid payment and long term payment system. In all cases the economics of CHP project should be assessed. Several methods were proposed previously for assessing the financial impact of any investment. Figure 2.10 illustrates classification of economic calculations methods for any project, which was grouped into static and dynamic methods [13].

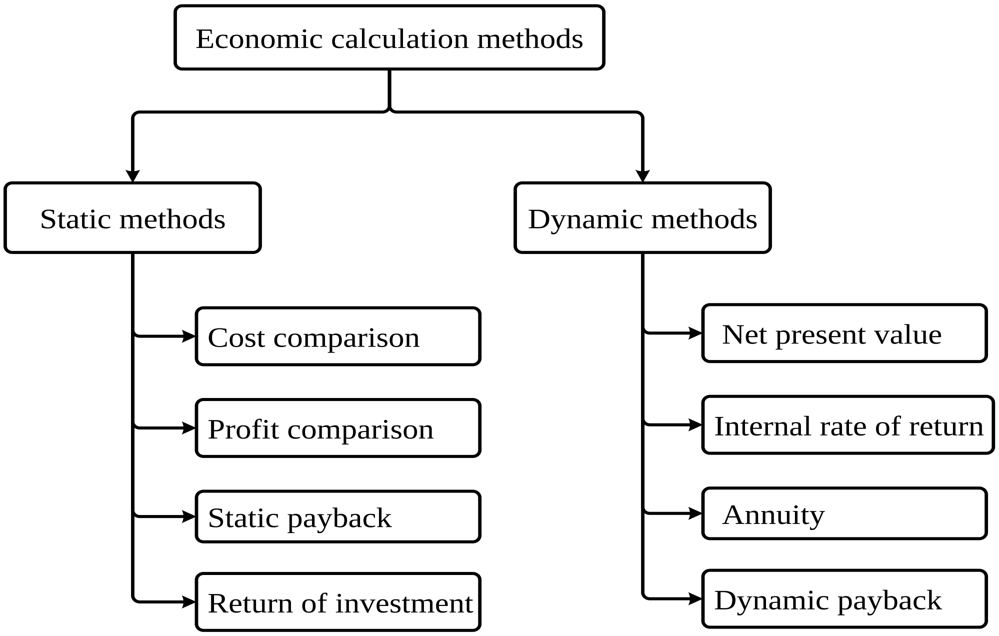


Figure 2.10: Classification of economic calculation methods for CHP project (summarized from [13])

General, static methods do not consider the time structure of payments. For example there is no distinction can be made whether payment incur today or in five years. To obtain a better decision basis, more than one calculation method is often used to evaluate an investment. Annuity and dynamic payback methods outperformed the others in term of understanding the economic situation of CHP project.

2.5.1 Annuity Method

The main idea of annuity is to evenly distribute payment which is associated with an investment during operation lifetime. The annuity method allows the combination of one-time payment / investment and current payment with the help of an annuity factor, during the observation period. The payment in annuity method includes several costs, namely, fixed capital cost, usage cost, operating cost, and others. Depending on the project and the operation, the deposit payments may have the same results as the disbursements described above. This is especially true for capital-linked deposits. If such grants are awarded for investments or for tax benefits. The difference between the deposit annuity and disbursement annuity gives the cumulative annuity. Small-scale CHP plants are usually not designed for goal of generating profit. Therefore, it is the rule that the best system is the one which costs the least [15].

For CHP system, the assignment of separate costs of electricity and heat is not appropriate. For an economic analysis, the capital, fuel and operating costs and revenues from CHP operation are compared with the cost of separate power and heat plant. The annual heat production cost is measured from the overall annual cost of CHP system after deducting the value of its electricity. The annual costs here represent the sum of fixed capital costs, usage costs, operating costs, and other costs. The usage and operating costs also depend on how much of the CHP production is used to cover the demand for heat and electricity [13].

2.5.2 Capital Related Costs

The key is to distribute the investment payments with considering interest and compound interest over the system's lifetime. In this case the investment costs were divided into several equal annual parts. The annual capital-related costs - the annuity - consist of two parts: One is the percentage of recovery of invested capital and the other part is the interest rate, which represents the interest on the outstanding payments at the beginning of each period.

The following are the main components for any CHP investment:

- CHP system
- Peak boiler
- Thermal storage tank
- Technical integration of CHP
- Power supply
- Construction measures
- Fuel storage
- Additional costs for planning and approval

Useful lifetime:

For the calculation of annuity of individual CHP investment, the useful lifetime is a critical factor. The calculated lifetime ends before required repair, overhaul and maintenance costs for the renovation of individual system components are more expensive than the acquisition cost. From a technical point of view it makes sense to put the useful life equal to the lifetime. Under the security aspect of an investment, however, the choice of a shorter useful life, and therefore the distribution of costs over a shorter period are reasonable to minimize the risks.

Interest rate:

In addition to the life span, the discount rate is of particular importance for the economic analysis. The amount of the discount rate depends on the type of financing for the planned investment. In a fully self-financed project, the discount rate is set at least at the level of the interest rates of a particular capital market investment. The interest rate for debt financing determines the lower limit, if money needs to be borrowed. Since the resulting investments and the useful time can be risky, an additional risk factor can be added in both cases. Mixed financing from equity and debt can be used with an interest rate that is set by the discount rate for equity as well as the invested capital. The discount rate and the useful lifetime are determined based on the economic analysis and the specific point of view of the planner or operator [15].

2.5.3 Consumption related costs

The consumption related costs, also referred to as fuel costs, are composed of the annual fuel costs for the CHP system and the boiler, as well as the annual power supply costs. When natural gas is chosen as fuel some tax systems may include a demand charge in addition to a pure energy price.

2.5.3.1 Operating costs

The annual operating costs include maintenance and personnel costs. The maintenance refers to maintenance, inspection and repair. Very often full service contracts with the manufacturer are completed for CHP modules. These agreements provide a comprehensive service at a fixed rate per kilowatt hour of electricity produced. This includes all work which is generally understood to be necessary for the smooth operation of a system and includes inspection, all maintenance and repair, spare parts and supplies (except fuel). A major overhaul is usually also included in long-term contracts. Besides the good predictability of such contracts, another advantage is that the execution of all work on the CHP is transferred to the seller, and the technical risks are covered, e.g. an engine failure, by the full maintenance contract [15].

Review of self-power generation

The value of the electrical energy generated in CHP systems (for both: power and energy) is calculated as follows:

-Costs of additional electricity acquisition

- Additional costs for electricity purchases
- Cost of backup power purchase

+ If needed: credit for excess / residential electricity supply = Value of own power generation.

The additional electricity acquisition costs arise if the power company has no self-generated power supply. The electricity, which is still needed after installation of a CHP plant as additional power is called excess - or residual electricity. Costs for backup power may arise when a higher power rating is used than ordered. These costs are dependent on the rate for backup power ordered from the utility companies. When supplying excess power into the grid, revenues can be credited.

The energy generation characteristics need to be known for the CHP system to evaluate the self-generated electricity. The superposition of the power load profile and the electricity generation by the CHP system defines the fractions of electricity fed into the grid and the additional electrical power needed. For this calculation, a simulation based on hourly values is inevitable. Specialized software for the design of CHP plants simulates typical load curves for calculated usage.

For the evaluation of electrical energy generation, the knowledge of individual power delivery terms and the conditions of the energy companies is crucial. There is usually a price difference for the agreed day and night rate, also called high- or low-rate, and established winter and summer time rates. With the recognition of the hourly flow data and the linkage with the different price conditions of the utility companies, the cost of the residual current reference for possible back-up power, and the revenues for the supply of surplus power can be calculated. These cost calculations can then be compared with the cost faced by procuring electricity more traditionally.

Heat generation cost and comparison with central heating

The annual cost of the CHP systems are calculated as described in the Section "Capital related Costs". After deducting the self-generated electricity, the annual heat production costs are, calculated as follows:

-Annual costs of heat-und power generation

-Current value of generated electricity

-Annual heat production costs

For alternative heat generation with a boiler, the annual heat production costs can also be calculated from fixed capital, demand/ consumption-bound, operating, and other costs. Dividing the annual heat production costs by the annual amount of heat generation results in the specific heat generation costs [$/kWh] for both systems. According to the criteria of economic efficiency, those power plants are selected, which have the lower annual heat production costs [15, 16].

2.5.3.2 Dynamic Payback Calculation

This payback method is one of the most frequently used methods for the capital budgeting process. The payback period length is a measure of the investment risk and is another criterion for assessment of a system. The owner must decide between the static and dynamic payback calculation. For the static payback period, which was determined by the initial investment. The later was resulted in net cash flows which will be recovered, regardless of the timing and the resulting interest rate effects. The neglect of pay back timing is a major criticism for this type of calculation because payments at different times are not easily compared with each other.

The dynamic calculation of amortization is derived from the capital value method and eliminates this criticism. The annual cash flows are discounted to time zero and the dynamic payback period is reached when the cumulative present value of cash flows is equal to the initial investment. Thus, the fact is taken into account that future payments are worth less than previous payments.

For CHP units, whose aim is self-supply and who earn no profit from the sale of electricity and heat, the amortization of CHP plants cannot be employed. Therefore, the amortization time for the extra investment, which a CHP plant needs, compared to a conventional heating system, is calculated.

All operating and fuel costs for the CHP plant are assessed as disbursements. All operating and fuel costs for the comparable heating system, the values of power generation (avoided electricity purchases, plus revenue from the power supply) are considered as deposits, and tax credit or debits may need to be taken into account. The difference between the payments and deposits will be accounted for annually and discounted to time zero. The values are cumulative and the dynamic payback period is reached when the cumulative net present values are equal to the added investment of the CHP plant. The smaller the payback period, the smaller is the risk of the investment. If the payback period exceeds the life of the CHP, the plant is not economical. For CHP units in residential buildings payback periods that lie within their lifetime and less, or up to 10 years are quite acceptable. For industrial or commercial combined heat and power applications, which follow the business principle of making a profit, shorter payback periods are required [16].

CHAPTER THREE

METHODOLOGY

3.1 Chapter Overview

This Chapter presents the overall methodology for this work, includes a mathematical model that relevant to the economic and technical of the CHP systems, the data uses to evaluate the computer program. Moreover, Matlab language background and the computer program description. Figure 3.1 shows the research methodology flow chart

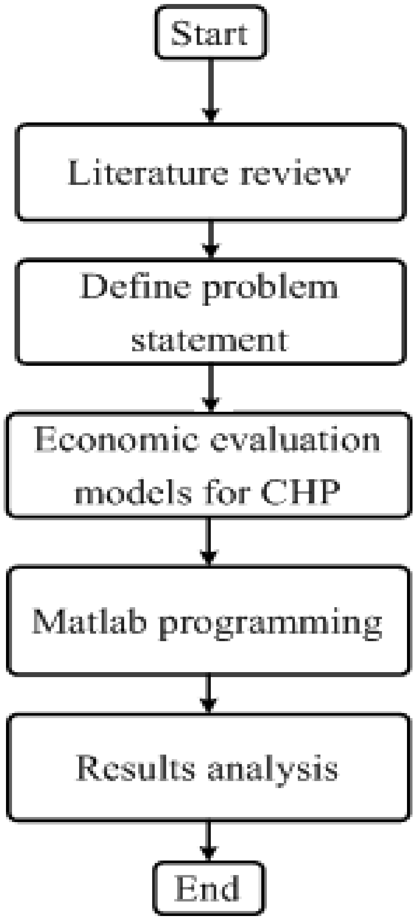


Figure 3.1: Research methodology flow chart

3.2 Evaluation of CHP System

This work focused on economic and technical evaluation of CHP system as detailed description in the following section.

3.3 Economic Evaluation of CHP

For the purpose of wider use of CHP systems, however, it is required to be economically feasible in the first place. Because there exist various factors affecting the economics of the CHP system, it is not so easy to carry out its economic evaluations. Therefore, in most of economic evaluations of CHP systems investigated so far, it is required to set a concrete case in order to determine the detailed specifications by Suzuki et al [16]. Hence, based on these evaluation methods refer to (chapter 2), it has been difficult to comprehensively investigate the effects caused by changes in various economic and technological factors of CHP system on its economics.

The profit index makes it possible to easily evaluate the economics of CHP system, by taking dominant factors determining its economics into consideration. And by using the index, it is possible to discuss generally various strategies to improve the economics of the CHP system [16].

3.4 Mathematical models

It is not easy to evaluate the economics of a cogeneration system (CGS), since a number of factors have to be considered. However, in this section we describe an index that makes it possible to easily evaluate the economics of CGSs.

Let us consider a CGS of rated electric output Q_e watts and an annual capacity factor α, which is determined by taking Q_e as the base. Then, the annual generated electric energy of this CGS can be represented as $8760\ \alpha\ Q_e$ watt hours, the annual generated heat energy as $8760\ \alpha\ Q_h$ watt hours and the annual fuel consumption as $8760\ \alpha\ Q_f$ watt hours, respectively, where Q_h denotes the heat output and Q_f , in watt hours per hour, the fuel consumption rate. Let us denote the average unit selling price of electricity as C_e currency per watt hour, the average unit selling price of heat as C_h currency per watt hour and the unit cost of the fuel as C_f currency per watt hour. The gross profit of the CGS system by selling energy, denoted by P_f currency per year, can be obtained as follows:

P_f = income of selling generated electric and heat energy − fuel cost

$$P_f = 8760\alpha(Q_eC_e + Q_hC_h - Q_fC_f) \qquad (3.1)$$

Since the average electric power generating efficiency η_e and the average heat generating efficiency η_h are calculated as $\eta_e = \frac{Q_e}{Q_f}$ and $\eta_h = \frac{Q_h}{Q_f}$, respectively, the profit per unit electric power output, P_u currency per watt, can be represented as:

$$P_u = 8760\alpha\left(C_e + \frac{C_h\eta_h}{\eta_e} - \frac{C_f}{\eta_e}\right) \qquad (3.2)$$

To make it possible to compare P_u with the unit construction cost of the CGS, denoted by X, in currency per watt , X should be multiplied by the annual cost rate R , or alternatively, P_u should be divided by R, i.e.

$$I_{p=\frac{P_u}{R}=\frac{8760\alpha}{R}}\left(C_e + \frac{C_h\eta_h}{\eta_e} - \frac{C_f}{\eta_e}\right) \qquad (3.3)$$

The definition of the I_p is identical to that of the profit index, which has been derived by (Pak, and Suzuki, 1988) . Therefore, for the CGS to be economically feasible, it is required that

$$I_p > X \qquad (3.4)$$

It should be noted that the unit of I_p is currency per watt [17].

3.4.1 General strategies to improve economics of CGS

In this section, the strategy to improve the economics of a CGS is generally discussed based on the profit index.

1. If capacity factor α of the CGS system becomes large, the condition (equation (3.4)) becomes easy to hold, because the value of I_p increases when α increases.
2. Let us assume that the capital recovery factor can be used in place of the annual cost rate for the construction cost R. Then, R may be calculated by

$$R = \frac{r}{(1-(1+r)^{-n})} \qquad (3.5)$$

Where r denotes the annual interest rate and n the pay-out period. I_p is proportional to the reciprocal of R, thus I_p becomes large when r becomes small or n becomes large.

3. When C_e and C_h become high, or when C_f becomes low, I_p becomes large.
4. When the value of η_h is improved, I_p becomes large. The term related with η_e in equation (3.3),$(C_h\eta_h - C_f)/\eta_e$, usually takes a negative value, since $1/\eta_h > 1/0.6$ and $C_h/C_f < 1.67$ in most cases. Therefore, improvement in ηe usually makes I_p large.
5. Smaller X contributes directly to hold the condition (equation (3.4)).

The following facts should also be noted.

1. The factor α is a parameter whose value becomes large in general when the ratio of heat

demand to power demand increases. This fact explains the reason why CGS has been installed in many energy intensive manufacturing plants such as chemical, paper etc.

2. The capital recovery factor R is related to the durability of the CGS. The extension of its durability generally leads to larger n.

As one of national energy policies, it might be planned to aid the construction of CGSs with low interest rate financing in order to realize the systems with high total energy utilization efficiency. Such a policy contributes to make r low.

3. In Japan, there exist various legislative regulations for a heat supply company with regard to the supply of electricity in the territory of a power company, for the purpose of securing a stable supply of electricity by the power company. These regulations prohibit the selling of surplus power of the CGSs directly to consumers, so that the surplus power should be sent to the power company only. Since the price leadership is held by the power company, these regulations act to make the value of C_e very small, and this is one of the main causes for degrading the economics of the CGSs. However, a policy to deregulate these regulations to a large extent is now being discussed. If such a policy is adopted, it will contribute largely to the improvement of the economics of the CGSs.

The fuel cost C_f has a great influence on the economics of CGSs. One of the main reasons why CGSs have been installed in many iron mills is explained by the fact that the waste gas usable as fuel can be obtained as a by-product from these plants. It is also expected that the positive utilization of recovered gaseous waste fuel might be one of the significant methods to make the fuel cost cheap (such as a fermentation gas of the sewage sludge and a pyrolysis gas of the municipal refuse).

4. Improvements in η_e and η_h are related to technological advances in the efficiencies of the CGS, and their improvements are considered one of key factors of wider use of CGSs. In a CGS composed of gas turbines, it is expected that remarkable improvements of its efficiencies can be attained by making the turbine inlet temperature higher through improvements in turbine blade cooling systems or by making use of fine ceramics.

5. The unit construction cost X depends on the capacity of the CGS, and the determination of its optimal capacity has been one of important problems to be investigated. It is considered that CGS is a system in which great technological developments to reduce the construction

cost can be attained as compared with conventional thermal power plants. A considerable reduction in X would be realized through the wider use and/or standardization of CGSs in the future [16].

3.5 Economic and technical parameters data

To evaluate the computer program the economic and technical parameters values that used by (Suzuki et al., 1984) in order to ascertain the effectiveness of the profit index used. Table 3.1 summarized the basic values used in this study for economical and technical evaluation of combined heat and power.

Table 3.1: Basic values of the various parameters for evaluating the economics of a CGS

No.	Parameter	Value
1	Construction cost X	170 currency
2	Capacity factor α	0.25
3	Annual cost rate for construction cost * R	0.1627
4	Average unit selling price of electricity C_e	22.5 currency/kWh
5	Average unit selling price of heat C_h	6.88 currency/kWh
6	Unit cost of the fuel C_f	6.02 currency/kWh
7	Average power generating efficiency η_e	0.27
8	Average heat generating efficiency η_h	0.48

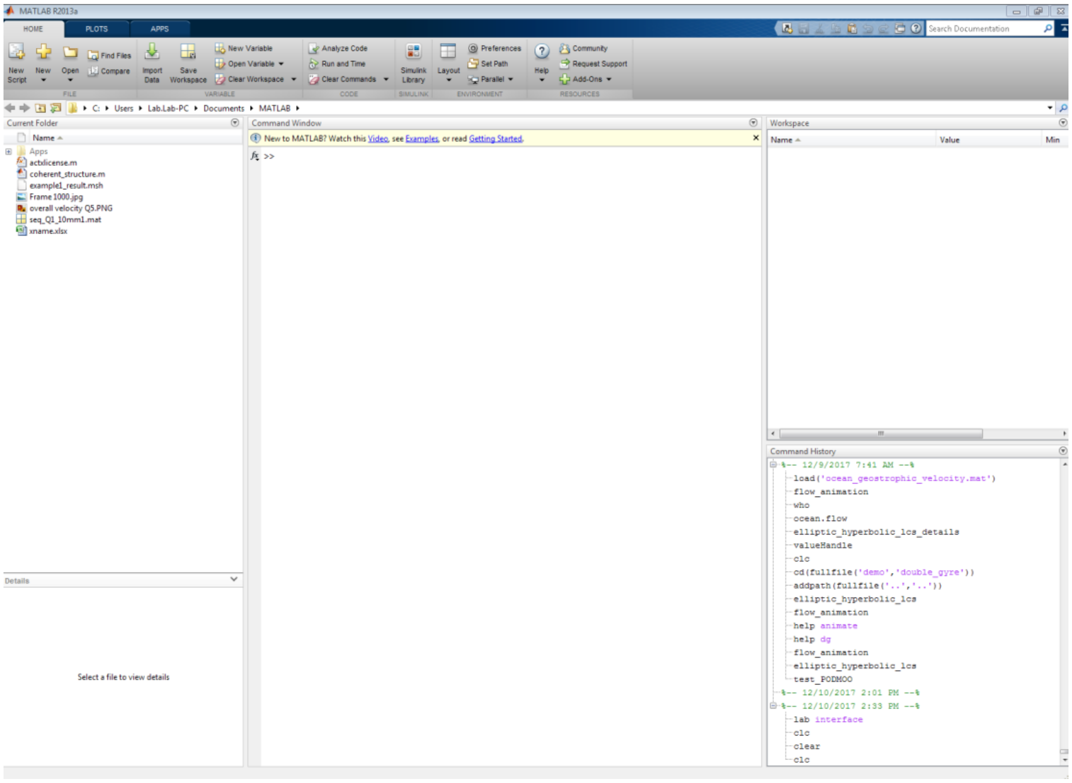
* Note that the annual interest rate r = 0.1, pay-out period n = 10 year

3.6 Numerical Solution Using Matlab

MATLAB® is a high-performance language for technical computing. Figure 3.2 shows the Matlab interface which consist of several windows including, command window, command history, workspace as well as window to present current folder.

Matlab software integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

- Math and computation.
- Algorithm development.
- Modeling, simulation, and prototyping.
- Data analysis, exploration, and visualization [18].



New to MATLAB? Watch this Video, see Examples, or read Getting Started.

Select a file to view details

```
%-- 12/9/2017 7:41 AM --%
  load('ocean_geostrophic_velocity.mat')
  flow_animation
  who
  ocean.flow
  elliptic_hyperbolic_lcs_details
  valueHandle
  clc
  cd(fullfile('demo','double_gyre'))
  addpath(fullfile('..','..'))
  elliptic_hyperbolic_lcs
  flow_animation
  help animate
  help dg
  flow_animation
  elliptic_hyperbolic_lcs
  test_PODMOO
%-- 12/10/2017 2:01 PM --%
%-- 12/10/2017 2:33 PM --%
  lab interface
  clc
  clear
  clc
```

Figure 3.2: Matlab interface[19]

- Scientific and engineering graphics.
- Application development, including graphical user interface buildin.g

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non interactive language such as C or Fortran. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects. Today, MATLAB uses software developed by the LAPACK and ARPACK projects, which together represent the state-of-the-art in software for matrix computation. MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis. MATLAB features a family of application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology.

Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others [18].

3.7 Matlab programming

In this work Matlab software was applied to program the economic and technical evaluation models. Figure 3.3 shows the flow chart for Matlab programming.

The developed Matlab code was used the economic and technical models described in the previous section. All Matlab codes can be found in Appendix. The input parameters for the codes as follow:

- The construction cost of the CHP system per unit electric output currency/w.
- The annual capacity factor.
- The average unit selling price of electricity currency/kWh.
- The average unit selling price of heat currency/kWh.
- The unit cost of the fuel currency/kWh.
- The average power generating efficiency.
- The average heat generating efficiency.
- The annual interest rate.
- The pay-out period.

The code was designed to calculate all relevant parameters for the economic and technical evaluation of CHP system. Moreover, the code designed to plot all parameters that effect in the profit index of CHP system evaluation.

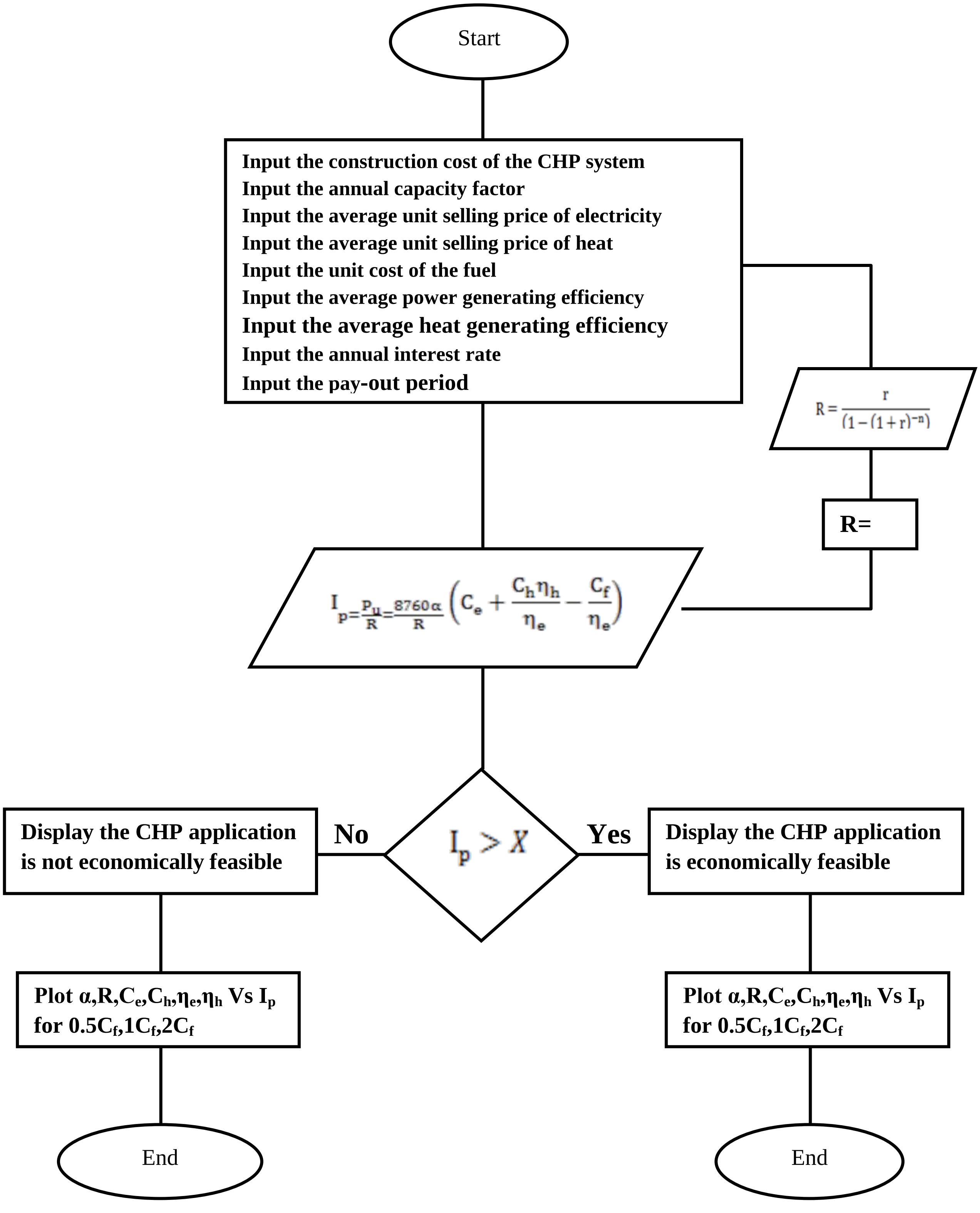


Figure 3.3 shows the flow chart for Matlab programming

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Chapter Overview

This chapter presents the results and discussion for the model proposed for economic and technical evaluation of combined heat and power (CHP) applications. The effect of several factors that influence the profit index of CHP system were included and discussed in detail. These factors includes, capacity factor, annual cost rate for construction cost, the average unit selling price of electricity, the average unit selling price of heat, the average power generating efficiency and the average heat generating efficiency.

4.2 Effect of Capacity Factor

Figure 4.1 shows the effect of capacity factor on the profit index for three cases of fuel cost, including 0.5, 1 and 2 times of fuel cost. In all cases, a linear relationship was observed either positively or negatively. However, for high fuel cost of $2C_f$, an inverse linear relationship was obtained, whereby increasing the capacity factor resulted in profit index reduction. While by decreasing the fuel cost, the response of linearity was changed to positive direction, where the increases of capacity factor lead to increase the profit index with strong linear relationship. Therefore, the fuel cost factor had a significant effect on controlling the profit index changes.

In order to evaluate the economics of CHP systems, a construction cost line was plotted as ground-truth (see the red dash-line in Figure 4.1). The greater the profit index over the construction cost line, the more the system becomes economic and more profit can be gained. As a result, two cases of fuel cost were partially economic including $0.5C_f$ and $1C_f$ cases, while $2C_f$ case was un-economic. Again, for high fuel cost case (i.e. $2C_f$) it was totally un-economic, while by reducing the fuel cost, the system becomes partially economic. This was expected since the decreases in fuel cost usually lead to increase the profit of any system. The economics of the CHP system is also depend on the value of capacity factor. By using the smaller capacity factor, the system can be described as un-economic, while the larger the capacity factor value, the more the system becomes economics. Specifically, by increasing the capacity factor more than 0.13 for $0.5C_f$ fuel cost case, and greater than 0.27 for $1C_f$ fuel cost case, the system is an economic. Therefore, to improve the economics of any CHP system the fuel cost should be minimized while the capacity factor should maximized. The latter conclusion was also found by Suzuki et al.[16].

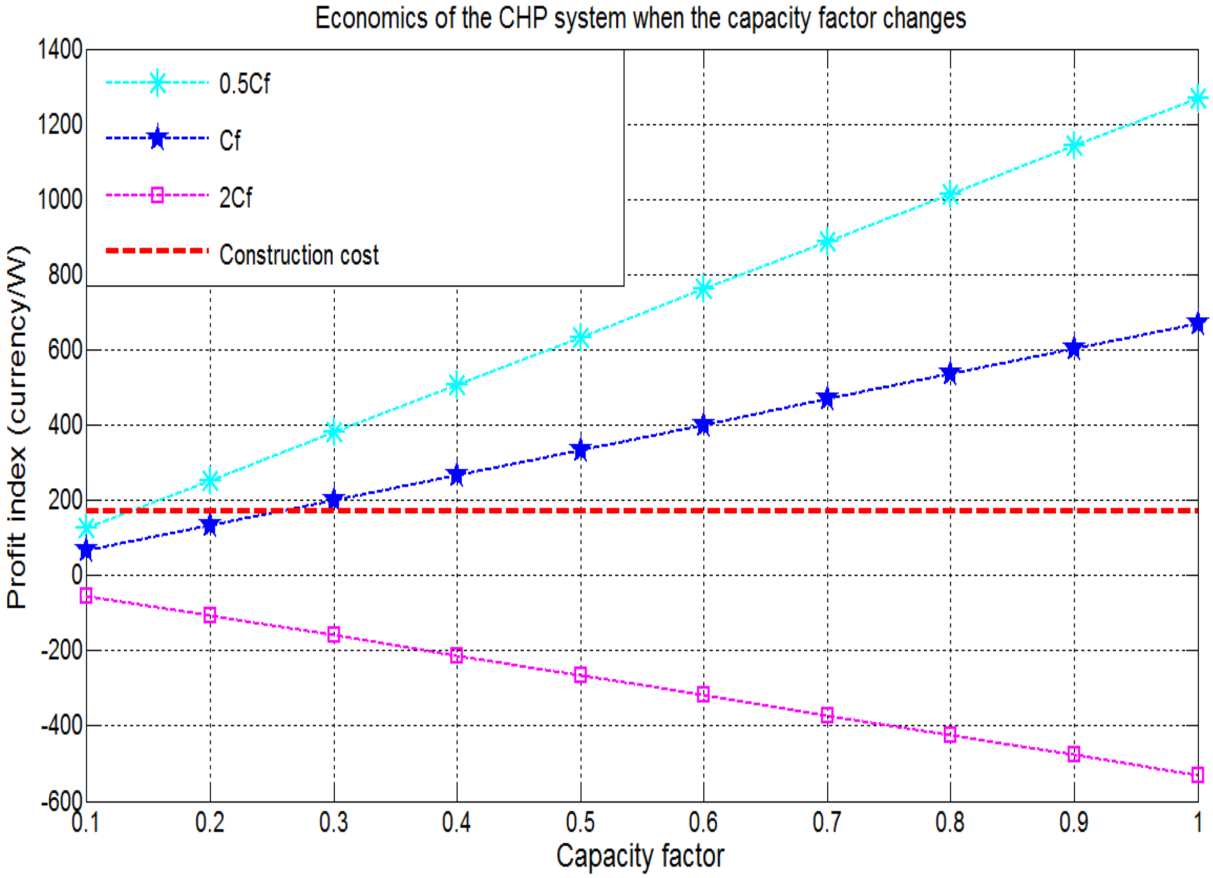


Figure 4.1: Effect of capacity factor on profit index of CHP system

4.3 Effect of Annual Cost Rate for Construction Cost

Figure 4.2 shows the effect of annual cost rate for construction cost on profit index of CHP system for three cases of fuel cost, including 0.5, 1 and 2 times of fuel cost. As shown in this figure, a non-linear relationship was observed between the annual cost rate for construction cost and the profit index of CHP system. Moreover, the fuel cost had a significant effect on this non-linear relationship. For high fuel cost, the profit index increases with increasing the system annual cost rate for construction cost. However, the higher fuel cost lead to un-economic system. By reducing the fuel cost, a negative non-linear relation was obtained between annual cost rate for construction cost and profit index. In this case, as increasing the annual cost rate for construction cost the profit index reduced gradually. For medium fuel cost (i.e. C_f), the CHP system becomes economic in case the annual cost rate for construction cost remains low with a value less than 0.16. While by increasing the annual cost rate for construction cost greater than 0.16, the system was un-economic. Furthermore, for low fuel cost case (i.e. $0.5C_f$) the system seems economic, with the negative effect of increasing the annual cost rate for construction cost.

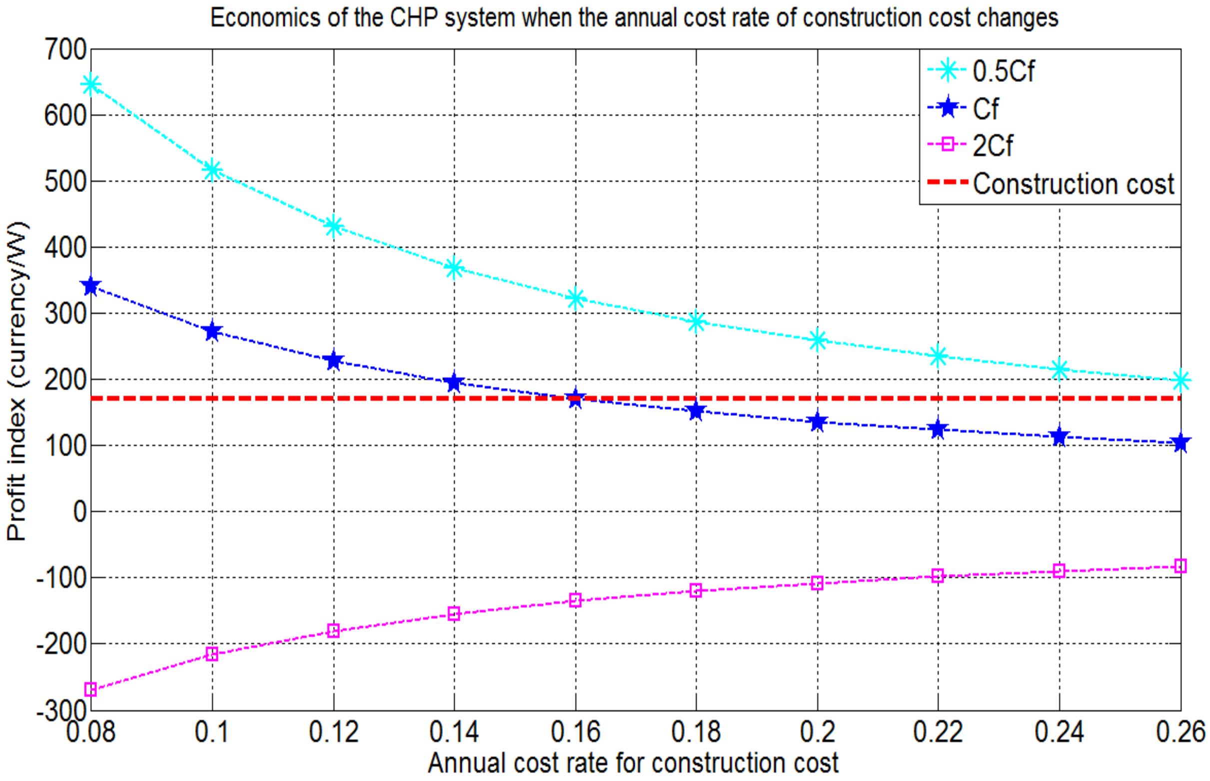


Figure 4.2: Effect of annual cost rate for construction cost on profit index of CHP system

4.4 Effect of average unit selling price of electricity

Figure 4.3 shows the effect of average unit selling price of electricity on the profit index of CHP system including the three different cases of fuel cost that considered in this study. The profit of CHP system depends on average unit selling price of electricity as well as the fuel cost. For all cases of fuel cost, increases of average unit selling price of electricity increased linearly the profit index. A construction cost line was plotted (see red line) in order to evaluate the economics of CHP system. High fuel cost lead in un-economic system while by reducing the fuel cost the system becomes economics. The fuel cost had a significant effect on the profit index as compared to the factor of average unit selling price of electricity. For the case of higher fuel cost (i.e. $2C_f$), the project was un-economic for all value of average unit selling price of electricity. While by reducing the fuel cost by factor two, the project was still un-economic for average unit selling price of electricity ranging from 8 to 23 currency/kWh, and becomes economic with using average unit selling price of electricity greater than 23 currency/kWh. Finally, by reducing the fuel cost to the minimum range (i.e. $0.5C_f$), the project becomes economic, in which the profit index increases with the increasing of average unit selling price of electricity up to 11.5 currency/kWh.

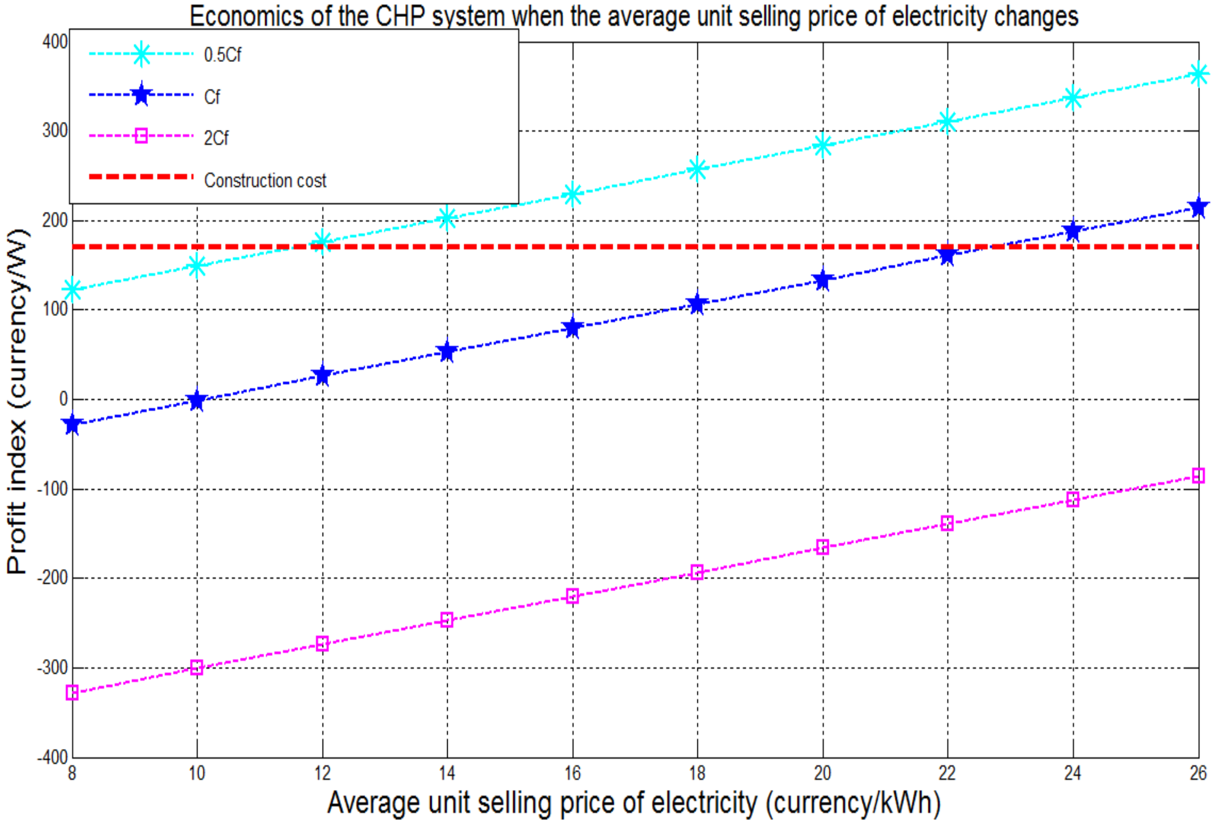


Figure 4.3: Effect of average unit selling price of electricity on profit index of CHP system.

4.5 Effect of average unit selling price of heat

Figure 4.4 shows the effect of average unit selling price of heat on the profit index of CHP system including the three different cases of fuel cost that considered in this study. The profit of CHP system depends on average unit selling price of heat as well as the fuel cost. For all cases of fuel cost, increases of average unit selling price of heat increased the profit index with strong linear relationship. A construction cost line was plotted (see red line) in order to evaluate the economics of CHP system. High fuel cost lead in un-economic system while by reducing the fuel cost the system becomes economics. The fuel cost had a significant effect on the profit index as compared to the factor of average unit selling price of heat. For the case of higher fuel cost (i.e. $2C_f$), the system was un-economic for all value of average unit selling price of heat. While by reducing the fuel cost by factor two, the system was still un-economic for average unit selling price of heat ranging from 3 to 7currency/kWh, and becomes economic with using average unit selling price of heat greater than 7 currency/kWh. Finally, by reducing the fuel cost to the minimum range (i.e. $0.5C_f$), the system becomes economic for all values of average unit selling price of heat considered in this study.

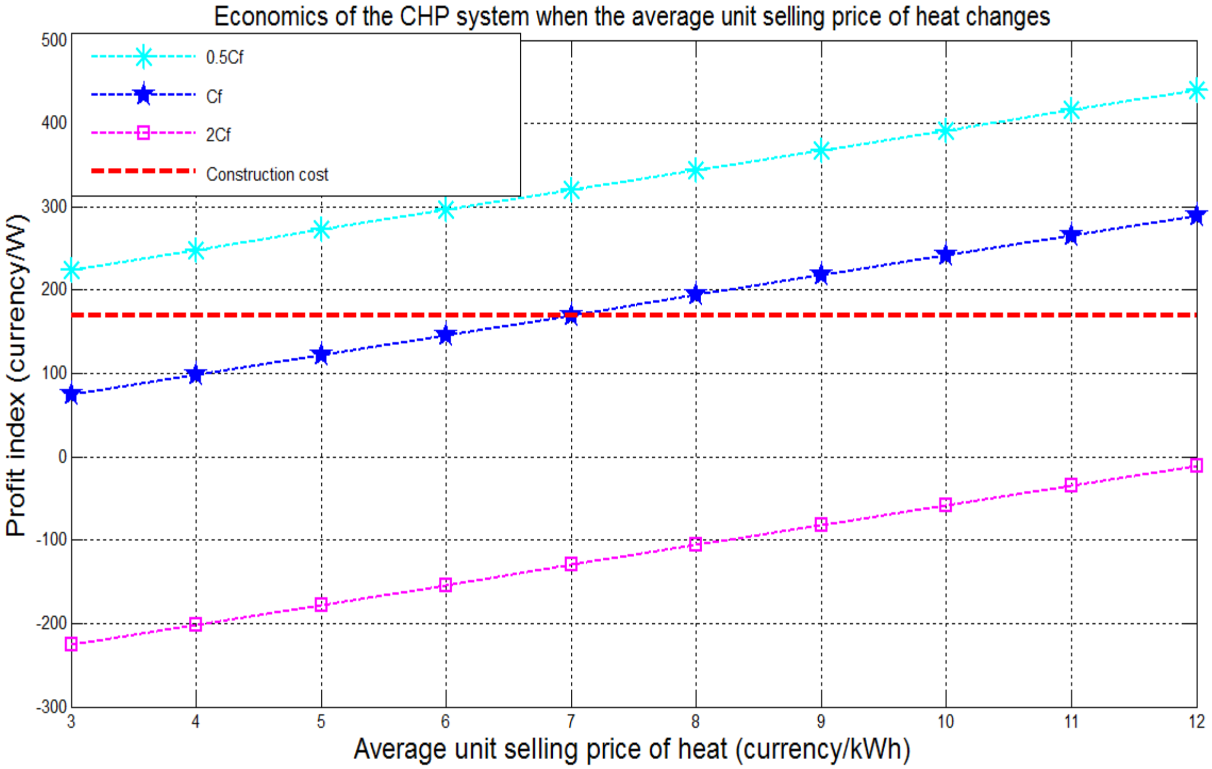


Figure 4.4: Effect of average unit selling price of heat on profit index of CHP system

4.6 Effect of average power generating efficiency

Figure 4.5 shows the effect of average power generating efficiency on the profit index of CHP system for the three different cases of fuel cost considered in this study. The profit of CHP system depends on average power generating efficiency as well as the fuel cost. A non-linear relationship between the average power generating efficiency and the profit index was observed for the cases of fuel cost of $2C_f$ and $1C_f$. In these cases the profit index rapidly increased with the increases of average power generating efficiency and then slightly continues increasing. However, very low profit was obtained for low efficiency, while reducing the fuel cost improved the overall average power generating efficiency. In case of fuel cost $1C_f$, the system was economic when using a value of average power generating efficiency greater than 30%. Almost linear relationship between average power generating efficiency and the profit index was obtained by reducing the fuel cost to a value of $0.5C_f$. The latter case (i.e. $0.5C_f$) fuel cost, the project was totally economic with no significant effect of average power generating efficiency factor.

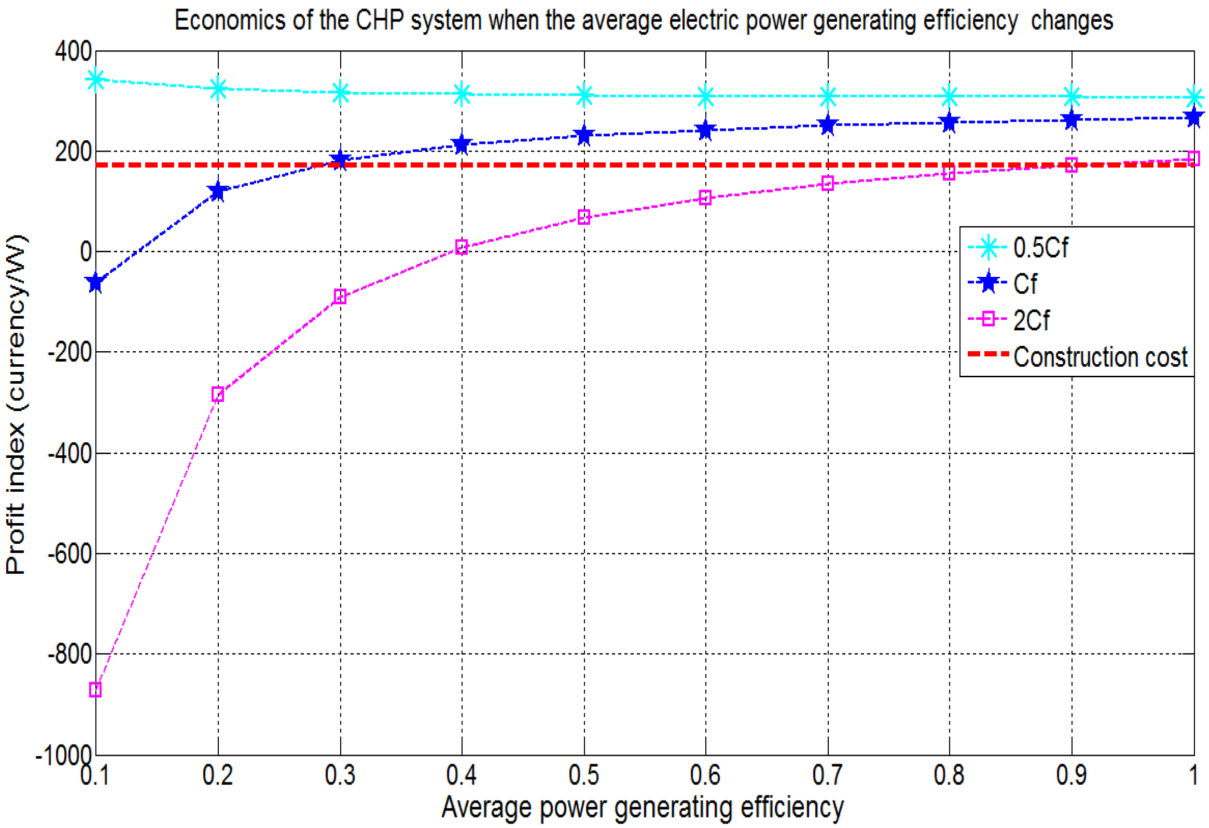


Figure 4.5: Effect of average power generating efficiency on profit index of CHP system

4.7 Effect of average heat generating efficiency

Figure 4.6 shows the effect of average heat generating efficiency on the profit index of CHP system for the three different cases of fuel cost that considered in this study. The profit of CHP system depends on average heat generating efficiency as well as the fuel cost. For all cases of fuel cost, increases of average heat generating efficiency increased the profit index with strong linear relationship. A construction cost line was plotted (see red line) in order to evaluate the economics of CHP system. High fuel cost lead in un-economic project while by reducing the fuel cost, the project becomes economic. The fuel cost had a significant effect on the profit index as compared to the factor of average heat generating efficiency. For the case of higher fuel cost (i.e. $2C_f$), the project was un-economic for all value of average heat generating efficiency. While by reducing the fuel cost by factor two, the system was still un-economic for average heat generating efficiency ranging from 10% to 50%, and becomes economic with using average heat generating efficiency greater than 50%. Finally, by reducing the fuel cost to the minimum range (i.e. $0.5C_f$), the project becomes economic for all values of average heat generating efficiency considered in this study.

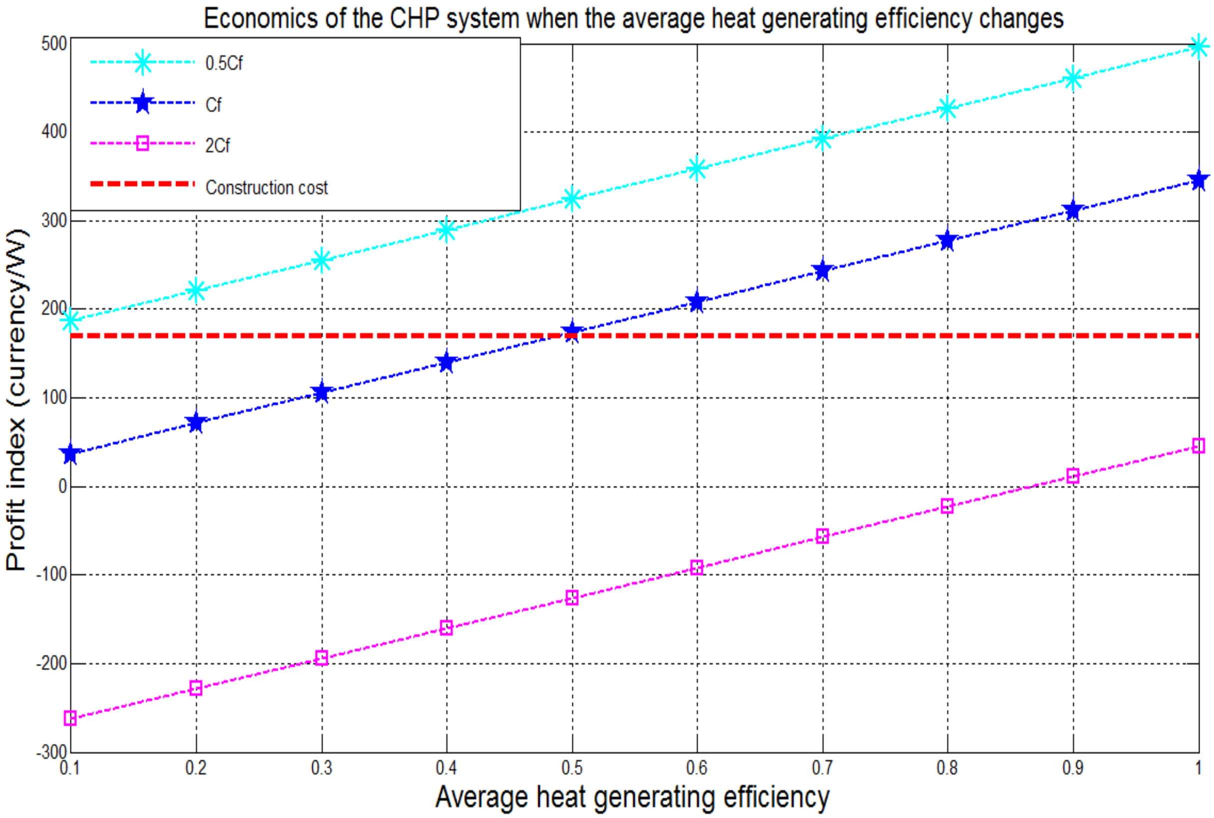


Figure 4.6: Effect of average heat generating efficiency on the profit index of CHP system

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this work, economic and technical evaluation was conducted for CHP applications. The overall conclusions of this study are summarized as follows:

1. A computer program was developed for easy evaluation of CHP applications.
2. The effects of several parameters on the CHP system economic were studied in detail. The effect of these parameters can be summarized as:
    - The effect of capacity factor on the profit index of CHP system had a linear relationship either positively or negatively.
    - The effect of annual cost rate for construction cost on profit index of CHP system showed a non-linear relationship to the profit index of CHP system.
    - The increases of average unit selling price of electricity and average unit selling price of heat increased linearly the profit index.
    - A non-linear relationship between the average power generating efficiency and the profit index was observed for all cases of fuel cost considered in this study. However, very low profit was obtained for low efficiency, while reducing the fuel cost improved the overall electrical power generating efficiency.
    - Finally, increases of heat power generating efficiency was directly increased the profit index with strong linear relationship.

5.2 Recommendations

The following recommendations are suggested for possible future studies:

- To extend the computer program by including large range for the parameters that effect directly on the CHP system.
- Build a Graphical User Interface (GUI) for interactive platform for economic and technical evaluation of any CHP system.

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Appendix:

Matlab Codes:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%This program is devoloped by Mojtaba Alfadil Defa Allah%%%
%%%to evaluate the economic of cogeneration applications  %%%
%%%based on the profit index method                       %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear all
close all
X=input('inter the construction cost of the CHP system per unit
electric output currency/W =');
alpha=input('inter the annual capacity factor =');
Ce=input('inter the average unit selling price of electricity
currency/kWh =');
Ch=input('inter the average unit selling price of heat
currency/kWh =');
Cf=input('inter the unit cost of the fuel currency/kWh=');
etae=input('inter the average power generating efficiency =');
etah=input('inter the average heat generating efficiency =');
r=input('inter the annual interest rate =');
n=input('inter the pay-out period =');
%%R is the annual cost rate for the construction cost
R=r/(1-(1+r)^-n)
%% Economic test..
Ip=((8760*alpha/R)*(Ce+(Ch*etah/etae)-(Cf/etae)))/1000
%% the obove equation divided by 1000 in order to change Ip
unit to
%% currency per watt to compate with X in currency per watt
if Ip>X
     disp('The CHP application is economically feasible')
else
    disp('The CHP application is not economically feasible')
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure('color','white')
alphadot=[0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1];
Cf1=0.5*Cf;
```

```
Ip=((8760*alphadot/R)*(Ce+(Ch*etah/etae)-(Cf1/etae)))/1000;
plot(alphadot,Ip,'color','c','MarkerSize',15,'Marker','*','Line
Width'...
,2,'LineStyle','--','MarkerEdgeColor','c');
hold on
Cf2=Cf;
Ip=((8760*alphadot/R)*(Ce+(Ch*etah/etae)-(Cf2/etae)))/1000;
plot(alphadot,Ip,'color','b','MarkerSize',12,'Marker','pentagra
m',...
'LineWidth',2,'LineStyle','--
','MarkerFaceColor','b','MarkerEdgeColor','b');
Cf3=2*Cf;
Ip=((8760*alphadot/R)*(Ce+(Ch*etah/etae)-(Cf3/etae)))/1000;
plot(alphadot,Ip,'Color','m','Marker','square','MarkerSize',10,
...
'LineStyle','--','LineWidth',2,'MarkerEdgeColor','m');
x = X.*ones(1,length(alphadot));
plot(alphadot,x,'LineWidth',3,'LineStyle','--','Color','r')
set(gca,'fontsize',15)
xlabel('Capacity factor','FontSize',18)
ylabel('Profit index (currency/W)','FontSize',18)
title('Economics of the CHP system when the capacity factor
changes',...
'FontSize',16)
legend('0.5Cf','Cf','2Cf','Construction cost')
set(legend,'Position',[0.213319624459951 0.667626023039878
0.225324027916251 0.176078414501229]);
grid on
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure('color','white')
Rdot=[0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24 0.26];
Cf1=0.5*Cf;
Ip=((8760*alpha./Rdot)*(Ce+(Ch*etah/etae)-(Cf1/etae)))/1000;
plot(Rdot,Ip,'color','c','MarkerSize',15,'Marker','*','LineWidt
h',2,...
'LineStyle','--','MarkerEdgeColor','c');
hold on
Cf2=Cf;
Ip=((8760*alpha./Rdot)*(Ce+(Ch*etah/etae)-(Cf2/etae)))/1000;
```

```
plot(Rdot,Ip,'color','b','MarkerSize',12,'Marker','pentagram','
LineWidth'...
,2,'LineStyle','--
','MarkerFaceColor','b','MarkerEdgeColor','b');
Cf3=2*Cf;
Ip=((8760*alpha./Rdot)*(Ce+(Ch*etah/etae)-(Cf3/etae)))/1000;
plot(Rdot,Ip,'Color','m','Marker','square','MarkerSize',10,'Lin
eStyle',...
'--','LineWidth',2,'MarkerEdgeColor','m');
x = X.*ones(1,length(Rdot));
plot(Rdot,x,'LineWidth',3,'LineStyle','--','Color','r')
set(gca,'fontsize',19)
xlabel('Annual cost rate for construction cost','FontSize',18)
ylabel('Profit index (currency/W)','FontSize',18)
title('Economics of the CHP system when the annual cost rate of
construction cost changes','fontsize',16)
legend('0.5Cf','Cf','2Cf','Construction cost')
grid on
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure('color','white')
Cedot=[8 10 12 14 16 18 20 22 24 26];
Cf1=0.5*Cf;
Ip=((8760*alpha/R)*(Cedot+(Ch*etah/etae)-(Cf1/etae)))/1000;
plot(Cedot,Ip,'color','c','MarkerSize',15,'Marker','*','LineWid
th',2,...
'LineStyle','--','MarkerEdgeColor','c');
hold on
Cf2=Cf;
Ip=((8760*alpha/R)*(Cedot+(Ch*etah/etae)-(Cf2/etae)))/1000;
plot(Cedot,Ip,'color','b','MarkerSize',12,'Marker','pentagram',
...
'LineWidth',2,'LineStyle','--
','MarkerFaceColor','b','MarkerEdgeColor','b');
Cf3=2*Cf;
Ip=((8760*alpha/R)*(Cedot+(Ch*etah/etae)-(Cf3/etae)))/1000;
plot(Cedot,Ip,'Color','m','Marker','square','MarkerSize',10,'Li
neStyle',...
'--','LineWidth',2,'MarkerEdgeColor','m');
x = X.*ones(1,length(Cedot));
```

```
plot(Cedot,x,'LineWidth',3,'LineStyle','--','Color','r')
set(gca,'fontsize',11)
xlabel('Average unit selling price of electricity
(currency/kWh)','FontSize',18)
ylabel('Profit index (currency/W)','FontSize',18)
title('Economics of the CHP system when the average unit
selling price of electricity changes','fontsize',16)
legend('0.5Cf','Cf','2Cf','Construction cost')
set(legend,'Position',[0.213319624459951 0.667626023039878
0.225324027916251 0.176078414501229]);
grid on
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure('color','white')
Chdot=[3 4 5 6 7 8 9 10 11 12];
Cf1=0.5*Cf;
Ip=((8760*alpha/R)*(Ce+(Chdot*etah/etae)-(Cf1/etae)))/1000;
plot(Chdot,Ip,'color','c','MarkerSize',15,'Marker','*','LineWid
th',2,...
'LineStyle','--','MarkerEdgeColor','c');
hold on
Cf2=Cf;
Ip=((8760*alpha/R)*(Ce+(Chdot*etah/etae)-(Cf2/etae)))/1000;
plot(Chdot,Ip,'color','b','MarkerSize',12,'Marker','pentagram',
...
'LineWidth',2,'LineStyle','--
','MarkerFaceColor','b','MarkerEdgeColor','b');
Cf3=2*Cf;
Ip=((8760*alpha/R)*(Ce+(Chdot*etah/etae)-(Cf3/etae)))/1000;
plot(Chdot,Ip,'Color','m','Marker','square','MarkerSize',10,'Li
neStyle',...
'--','LineWidth',2,'MarkerEdgeColor','m');
x = X.*ones(1,length(Chdot));
plot(Chdot,x,'LineWidth',3,'LineStyle','--','Color','r')
set(gca,'fontsize',11)
xlabel('Average unit selling price of heat
(currency/kWh)','FontSize',18)
ylabel('Profit index (currency/W)','FontSize',18)
title('Economics of the CHP system when the average unit
selling price of heat changes','fontsize',16)
```

```
legend('0.5Cf','Cf','2Cf','Construction cost')
set(legend,'Position',[0.213319624459951 0.667626023039878
0.225324027916251 0.176078414501229]);
grid on
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure('color','white')
etaedot=[0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1];
Cf1=0.5*Cf;
Ip=((8760*alpha/R)*(Ce+(Ch*etah./etaedot)-
(Cf1./etaedot)))/1000;
plot(etaedot,Ip,'color','c','MarkerSize',15,'Marker','*','LineW
idth',2,...
'LineStyle','--','MarkerEdgeColor','c');
hold on
Cf2=Cf;
Ip=((8760*alpha/R)*(Ce+(Ch*etah./etaedot)-
(Cf2./etaedot)))/1000;
plot(etaedot,Ip,'color','b','MarkerSize',12,'Marker','pentagram
',...
'LineWidth',2,'LineStyle','--
','MarkerFaceColor','b','MarkerEdgeColor','b');
Cf3=2*Cf;
Ip=((8760*alpha/R)*(Ce+(Ch*etah./etaedot)-
(Cf3./etaedot)))/1000;
plot(etaedot,Ip,'Color','m','Marker','square','MarkerSize',10,'
LineStyle',...
'--','LineWidth',2,'MarkerEdgeColor','m');
x = X.*ones(1,length(etaedot));
plot(etaedot,x,'LineWidth',3,'LineStyle','--','Color','r')
set(gca,'fontsize',16)
xlabel('Average power generating efficiency','FontSize',18)
ylabel('Profit index (currency/W)','FontSize',18)
title('Economics of the CHP system when the average electric
power generating efficiency  changes','FontSize',16)
legend('0.5Cf','Cf','2Cf','Construction cost')
grid on
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
figure('color','white')
etahdot=[0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1];
Cf1=0.5*Cf;
Ip=((8760*alpha/R)*(Ce+(Ch*etahdot./etae)-(Cf1./etae)))/1000;
plot(etahdot,Ip,'color','c','MarkerSize',15,'Marker','*','LineW
idth',2,...
'LineStyle','--','MarkerEdgeColor','c');
hold on
Cf2=Cf;
Ip=((8760*alpha/R)*(Ce+(Ch*etahdot./etae)-(Cf2./etae)))/1000;
plot(etahdot,Ip,'color','b','MarkerSize',12,'Marker','pentagram
',...
'LineWidth',2,'LineStyle','--
','MarkerFaceColor','b','MarkerEdgeColor','b');
Cf3=2*Cf;
Ip=((8760*alpha/R)*(Ce+(Ch*etahdot./etae)-(Cf3./etae)))/1000;
plot(etahdot,Ip,'Color','m','Marker','square','MarkerSize',10,'
LineStyle',...
'--','LineWidth',2,'MarkerEdgeColor','m');
x = X.*ones(1,length(etahdot));
plot(etahdot,x,'LineWidth',3,'LineStyle','--','Color','r')
set(gca,'fontsize',11)
xlabel('Average heat generating efficiency','FontSize',18)
ylabel('Profit index (currency/W)','FontSize',18)
title('Economics of the CHP system when the average heat
generating efficiency changes','FontSize',16)
legend('0.5Cf','Cf','2Cf','Construction cost')
set(legend,'Position',[0.213319624459951 0.667626023039878
0.225324027916251 0.176078414501229]);
grid on
```