APPLICABILITY OF KALINA CYCLE FOR WASTE HEAT RECOVERY IN THEMAL POWER STATIONS IN SRI LANKA

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Degree of Master of Engineering in Energy Technology

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February 2017

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Thesis submitted in partial fulfillment of the requirements for the degree
Master of Engineering

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DECLARATION

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ABSTRACT

Energy Crisis is the critical problem faced by the modern world. Day by day the impact is becoming severe with decaying of fossil fuels. Therefore, whole world has paid their attention on Non Conventional Renewable Energy sources. Industrial Waste Heat Recovery is one of them. The main focus of this thesis is to identify the best suited method for recovering low-grade energy from thermal power stations in Sri Lanka. Among few methods, Kalina Cycle System is selected by concerning its viability for usage.

Several attempts were made to assess the available heat energy from thermal power stations in Sri Lanka. The first objective of this research is to assess the thermal energy wasted from thermal power stations operating in Sri Lanka. The next objective was to identify the best suited configuration of Kalina Cycle System for extracting low-grade heat energy. The final objective was to use the said system for harnessing the energy, and quantify them. Simultaneously an economic analysis was carried out to assess its economic feasibility. A literature review was done to identify possibilities of harnessing the energy from flue gas of thermal power stations and to find out the suitable method for extracting energy.

Lakvijaya Power Station and Kelanitissa Combined Cycle Power Station, which have emissions below 200°C, has the ability of generating electricity using the Kalina Cycle. However, as per the analysis, they are not economically feasible. However, with these results, it is suggested to continue the same exercise to other thermal power stations, which has high temperature flue gases. As the next step, it is proposed to identify the best suited Kalina Cycle System for the rest of thermal power stations and expand this exercise throughout CEB owned and private owned thermal power stations, using other suitable configurations of Kalina Cycle System.

Key words: Waste Heat Recovery, Kalina Cycle System, thermal efficiency, flue gas

ACKNOWLEDGEMENT

I am very much grateful to Prof. K.K.C.K. Perera, Senior Lecturer, Department of Mechanical Engineering, University of Moratuwa for giving me his valuable guidance on this research. Sincere gratitude is granted to Dr. R.A.C.P. Ranasinghe - Senior Lecturer for giving his fullest support in every stage of this research. I wish to thank Dr. H.K.G. Punchihewa - Senior Lecturer, Dr.(Mrs.) M.A. Wijewardhana - Senior Lecturer and Mr. S.D.L. Sandanayake - Lab Attendant from Department of Mechanical Engineering, University of Moratuwa and Mr. Rumesh Fernando, Mechanical Engineer, Ceylon Electricity Board. This research was carried out under the supervision of Prof. K.K.C.K. Perera, Senior Lecturer, Department of Mechanical Engineering, University of Moratuwa and Dr. R.A.C.P. Ranasinghe, Senior Lecturer, Department of Mechanical Engineering, University of Moratuwa. I would like to thank my loving wife Ruvini Aberathna to encourage and support me in every step of this endeavor. Finally, I would appreciate everyone, who helped me in numerous ways at various stages of the research, which were of utmost importance in bringing out this effort to a success.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
GDP	Gross Domestic Product
IC	Internal Combustion
IPP	Independent Power Producers
KCCPP	Kelanitissa Combined Cycle Power Plant
KCS	Kalina Cycle System
NCRE	Non-Conventional Renewable Energy
NPV	Net Present Value
ORC	Organic Rankine Cycle
TFC	Trilateral Flash Cycle

CHAPTER 1
INTRODUCTION

1.1 Background

With the rapid development of society and changes in environment, generation of sustainable power has become an essential entity. For a long time, the society was used to fulfill its energy requirement using the energy sources such as solar power, hydro power, biomass. However, with the booming demand for power, it was no longer enough. As a result, the global energy market tends to fulfill its requirement using fossil fuels. With the excessive usage of fossil fuels in an exponential manner for day to day requirements and less efficient generation methods have already lead to many irreversible issues. Due to the crisis of energy [1], the society was interested on finding possible methods for recovering the waste heat as a one method for energy conservation and to find out Non-Conventional Renewable Energy sources (NCRE). Considerable amount of energy is emitted to the environment from Industries, specially from thermal power stations. From recent past, the original equipment manufacturers of thermal power stations were paying their attention on the ways and means of recovering the waste heat. As a result, recovery systems are inbuilt in modern designs. However, recovering of low-grade heat energy is still a challenge for the researchers. At present few cycles have come up as acceptable solutions, which some are still in research level. Some of these technologies are practiced worldwide to recover the low-grade energy.

1.2 Motivation

The power generation in Sri Lanka has started in 19th century. The hydro power was enough to fulfill the demand of country, till 1997. Thereafter, as the power requirement was being increased rapidly, thermal power stations were introduced. Specially few power stations, which used diesel were added to system as a short-term solution. At the end of the year 2015, Ceylon Electricity Board owned 08 major thermal power stations with an installed capacity of 1504 MW and Independent Power Producers owned 04 major thermal power stations with an installed capacity of 511MW [2]. As per the ‘Long term generation expansion plan’ of Ceylon Electricity Board for the period of year 2015-2035 [3], ample amount of thermal power station proposed to be added in next two decades. More importantly, the exhaust gas of all thermal power stations contains lot of energy. Although certain heat recovery methods are practiced in these power stations, there are enough room to develop them further. If more efficient methods are introduced, there is a possibility of harnessing more energy from waste heat. If we assume that we can extract $1^{o}C$ from the exhaust gas from Lakvijaya Power Station, it would yield 3.87 MJ per year and would save about LKR 33M annually. Moreover, since there is a massive flow rate in flue gas, the reduction of temperature will help to reduce the ambient temperature of environment. It is advisable to use these novel technologies for Waste Heat Recovery of local thermal power stations.

1.3 Aim and Objectives

Aim

To conduct a feasibility assessment of usage of Kalina Cycle for recovering low-grade waste heat in Thermal Power Stations under the Ceylon Electricity Board, Sri Lanka.

1. *To assess the amount of waste heat from Ceylon Electricity Board owned Thermal Power Stations in Sri Lanka.*

   Based on the measured data in several thermal power stations, the amount of energy wasted was quantitatively and qualitatively assessed.
2. *To investigate the possibility of using Kalina Cycle for harnessing the low-grade waste heat.*

   It is expected to use the Kalina Cycle for compatible power stations and conduct a sensitivity analysis of the most appropriate parameters relevant to them.
3. *Conduct an economic feasibility analysis in selected power stations.*

   An economic analysis was carried out using current market prices with reference to literature.

1.4 Methodology

The following methodology was used in conducting this thesis.

1. Literature Survey

A literature Survey was conducted to find out the currently used ‘Waste Heat Recovery Methods’. In waste heat recovery, mainly two cycles could be identified as, ‘Topping Cycle’ and ‘Bottoming Cycle’. The WHR in thermal power stations is categorized to ‘Bottoming Cycle’ and further attention was given for harnessing the ‘Low grade heat energy’. Data was collected regarding the existing technologies and its applicability. Fair number of journals and text books were referred in this regard.

2. Collection and analysis of the data received from Thermal Power Stations in Sri Lanka

It was attempted to collect data from thermal power stations owned to both CEB and IPP. Although the data from CEB was received, the data from IPP was hard to obtain. Eventhough temperatures of certain points are required to carry out the analysis, unfortunately they were not being measured and recorded. Data analysis was done to identify the efficiencies of these plants. In the meantime the data were used to identify the amount of energy wasted to environment, which is the first objective of the thesis. Assumptions were made in the situations where necessary. As it was intended to do the thesis on extraction of ‘Low Grade Heat Energy’ focus was given for the heat sources with lower temperatures.

3. Sensitivity analysis to identify the parameters for particular plant.

From literature survey, an appropriate Kalina Cycle System configuration was identified. Then with reasonable assumptions Kalina Cycle was used to different power stations with low grade heat energy sources. Subsequently those possible parameters were changed and checked the efficiency of the Kalina Cycle for waste heat recovery. Finally, a set of best suited parameters were identified for each power station and an economic analysis was conducted to identify its feasibility.

1.5 Contribution to knowledge

- Kalina Cycle System 11 can be adopted to the Sri Lankan Power Stations which the flue gas temperatures are below 200 ^{o}C.
- Best cycle efficiencies of KCS 11 could be gained when ‘Turbine Inlet Pressure’ around 40 bar.

1.6 Structure of the Thesis

Chapter 02 : Discuss the data relevant to the thermal power stations and its priority. The methods used for the waste heat recovery and the explanation of ‘Kalina Cycle System’

Chapter 03 : Analysis of the waste heat from selected thermal power stations in Sri Lanka.

Chapter 04 : Sensitivity analysis of the parameters which is suitable for recovering low grade energy of selected thermal power stations in Sri Lanka and discussion of its financial background.

Chapter 05 : Discussion of the results.

Chapter 06 : Case study by applying the technology for selected power station.

Chapter 07 : Economic analysis of the applicability of the system to the selected power stations.

Chapter 08 : Key findings from the thesis.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Sri Lanka is a country with lot of natural energy sources. The major sources are the bio mass or fire wood, solar power, hydro-power and wind power. Bio mass is being extensively used for domestic purposes and rarely being used for electricity generation in major scale. Except the hydro power, others are still emerging technologies. The electricity generation from Conventional Renewable Energy Sources were more than enough to fulfil the electricity demand till 1997. Thereafter with the rapid increase of demand for electricity, lot of thermal power stations were introduced to Sri Lankan electricity market by both CEB and IPP. In this chapter, details regarding history of power sector, present and future demand for electricity and the attempts for recovering waste heat in general will be discussed using the literature.

2.1 Present Status

With the excessive daily demand for electricity, thermal power stations are contributing more than 50% of total demand. In-fact in the drought season the contribution from the thermal, is more than 80% [4]. Both CEB owned and IPP owned power stations are contributing to generate power as per the system requirement. The ownerships and contribution for generation from each sector as per 2015 is shown in Table 2.1.

As per the Table 2.1, 80% of the total thermal installed capacity is from CEB owned thermal power stations and the rest is from IPP owned thermal power stations. On the other hand, 39 % of the total installed capacity is from CEB owned thermal power stations, while 13% is from IPP owned thermal power stations. Thus, total thermal base installed capacity is more than 50% of total installed capacity. At present, the average daily peak load is about 2200 – 2300 MW. The base load varies from 850-1000 MW [4]. Generally, coal powered thermal power stations are considered as ‘Base Load Power Plants’. So, they are running continuously throughout the day. Peak is catered using the hydro, diesel and gas turbines in which the starting time is less. When operating a Diesel Power Plant, its flue gas temperature ranges from 400-450 °C, which consist lot of heat energy. Similarly, from all other thermal power stations lot of thermal energy is wasted to the environment. It is hard to reduce the heat losses, due to technical constraints of systems. However, it is required to reduce the addition of unnecessary heat energy to the environment to ensure its sustainability, while conserving the energy as well.

Table 2.1: CEB owned power stations and its installed capacities in MW's [2]

Ownership and source of Power Station	**No of Power Stations**	**Installed Capacity in MW (% of contribution)**
CEB - Total	**26**	**2,884 (75%)**
Hydro	17	1,377 (36%)
Thermal-Oil	7	604 (16%)
Thermal-Coal	1	900 (23%)
Wind (NCRE)	1	3 (0.08%)
I.P.P.- Total	**184**	**963 (25%)**
Thermal	4	511 (13%)
NCRE Mini Hydro	154	307 (8%)
NCRE - Wind	15	124 (3%)
NCRE-Other	11	21 (0.5%)
Total	**210**	**3847**

2.2 Historical Data

Bio mass is being used extensively for day to day domestic purposes. Other than that, hydro power, fossil fuels and Non-Conventional Renewable Energy are playing a key role in fulfilling necessity of energy to the society. Figure 2.1 shows the evolution of energy need in Sri Lanka from 1978 to 2014.

Electricity generation is conversion of one form of energy; usually mechanical, chemical or thermal to electrical energy. Before 1996/97, electricity generation through hydro power dominated the electricity sector. Thereafter, thermal power stations were added to the national grid with small time intervals, as short-term solutions. So, figure 2.2 illustrates how each energy source contributes to electricity generation at past. [3]

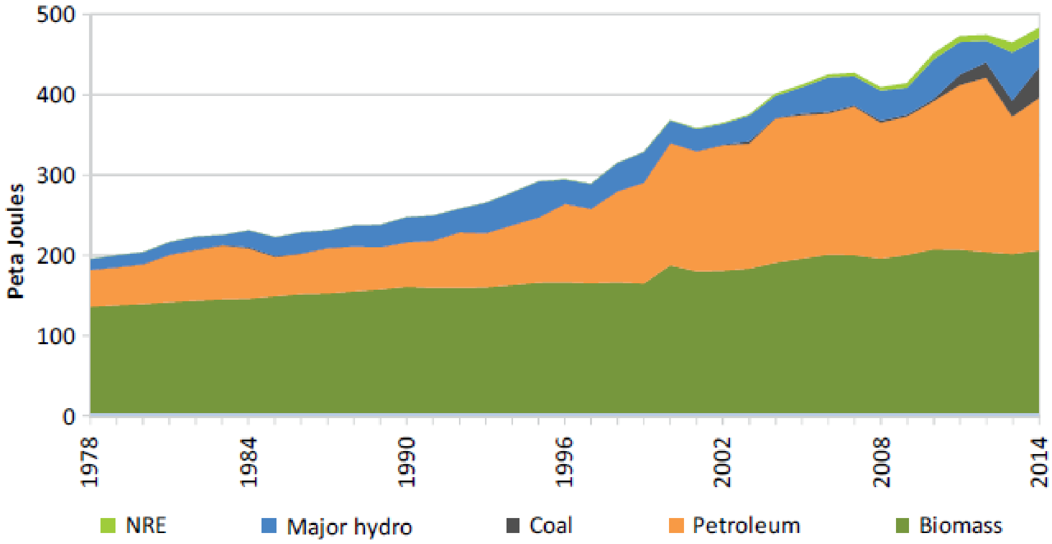

Figure 2.1: Evolution of Energy Supply Forms in Sri Lanka [4]

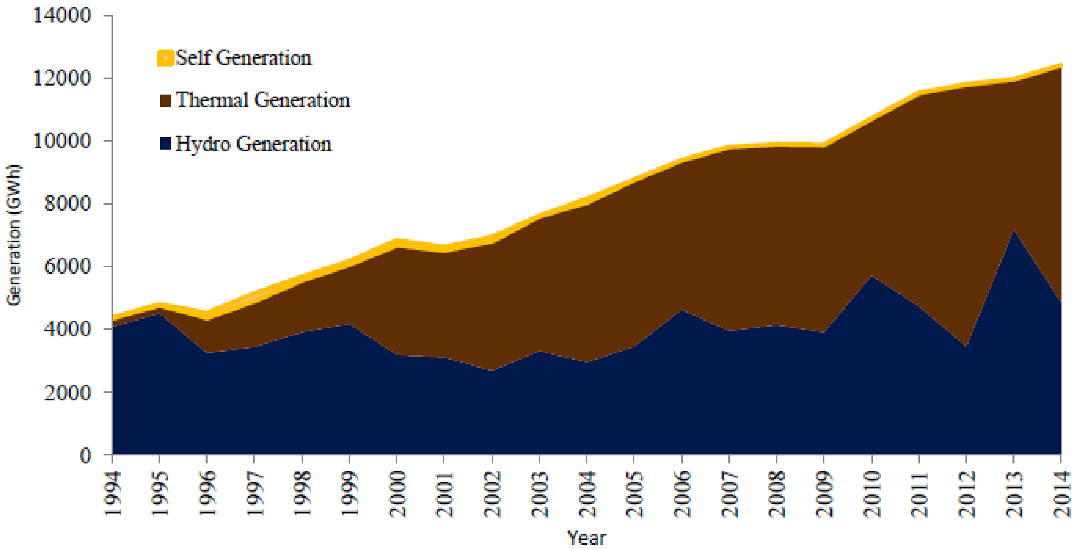

Figure 2.2: Hydro thermal share in recent past [3]

During the periods of high rainfall, the hydro power generation increases while thermal generation reduces. In the year 2013, there was a massive rain fall throughout the year and in figure 2.2, a clear peak in hydro power generation can be seen. As the weather is an unpredictable and uncontrollable factor, excess amount of installed capacity shall be maintained using thermal power stations to face an emergency like; failure of a major power stations, to face a drought. At present, almost all the hydro power sources are utilized and further significant expansion on hydro sector cannot be expected.

Over the last few decades the attention of researches has been focused on inventing and improving the Non-Conventional Renewable Energy sources. For that category, Solar Energy, Wind Energy, Mini-Hydro Energy, Biomass (Dendro) Energy, Agricultural & Industrial Waste Energy, Municipal Waste Energy, Waste Heat Recovery Energy and Wave Energy are included [5]. Lot of Wind Power Plants were built in various parts of the country. It was identified that Puttlam Bay, Jaffna bay, central part of country has enough potential to produce electricity using wind power. Consequently, there are ample amount of proposals to build wind farms in near future.

Power generation from solar is an emerging technology. The technology of solar Photo Voltaic(PV) panels were developing very fast over the years. In-fact this is used for fulfilling part of the requirement of domestic and industrial sectors. As per the geological location of Sri Lanka, we have a productive irradiation level. Further with the policy decisions of the government to face the future energy crisis, government is giving subsidies to domestic customer to enhance the usage of solar PV in Sri Lanka. With the subsidy given to public, there is a huge interest of harnessing energy using PV panels. Few years ago, government introduced the net-metering system to get the contribution of its customers to the national grid. When these unknown loads are added considerably to the system, it may affect the stability of system frequency. At present, there are two solar parks at Hambantota and Kilinochchi. Figure 2.3 shows the generation of solar energy at Hambantota solar park in each month and figure 2.4 shows the generation of solar energy within a year 2015.

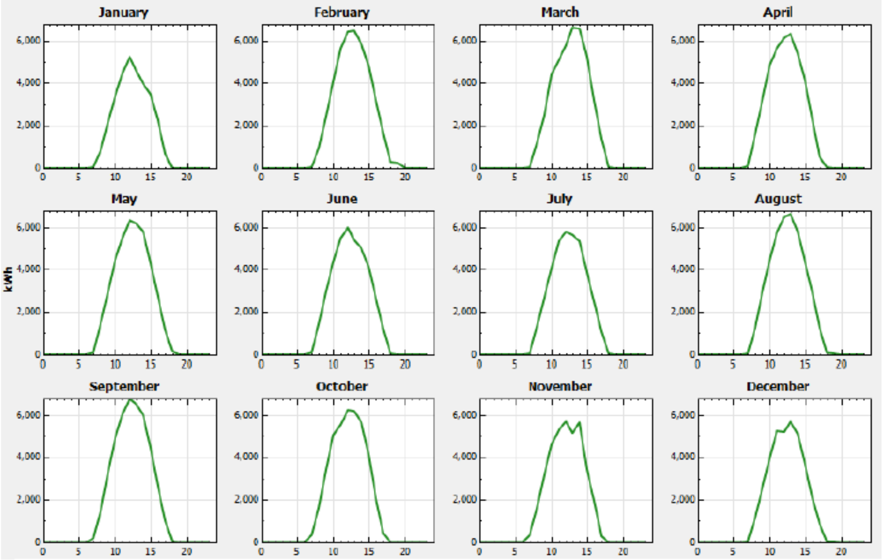

Figure 2.3: Monthly Solar Energy Variation of Hambantota 10MW Plant [3]

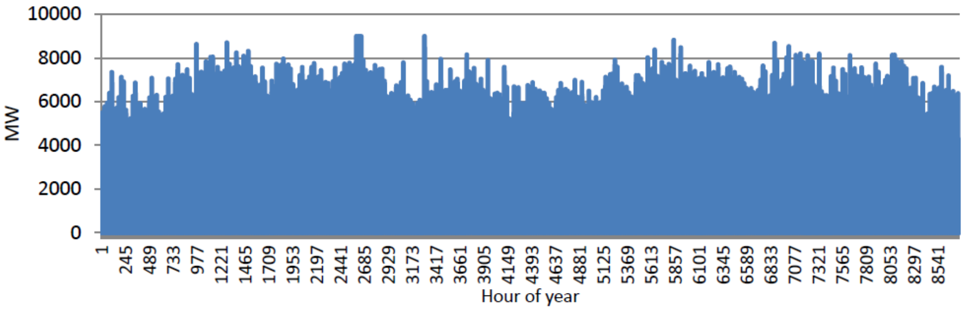

Figure 2.4: Capacity Output of Hambantota 10MW Plant [3]

With increasing usage of the thermal power in the country, petroleum usage also increases proportionately. Petroleum is not only used for power generation, but also for lot of other activities. However huge amount of petroleum is used for power stations, which makes an impact for domestic petroleum market and economy as well. Although in hydro power generation the source is free; whereas petroleum is not. Compared to hydropower, cost of generation through petroleum per unit is very high. The amount paid for purchasing petroleum, directly affects the economy of the country. As the petroleum resource is decaying very fast, the value of it is increasing rapidly [6]. However, time to time due to certain global socio-economic issues, its prices are temporary fluctuating like at present. For last few years this floating fuel prices and increasing fuel consumption had direct adverse impact on the economy of Sri Lanka.

In further analysis of the effect from the electricity generation to the Sri Lankan economy, a direct correlation between Electricity Demand Growth and the GDP Growth Rate can be identified. If both statistics are considered in a single graph, it shows that the variation of these two are almost same. It is shown in the figure 2.5.

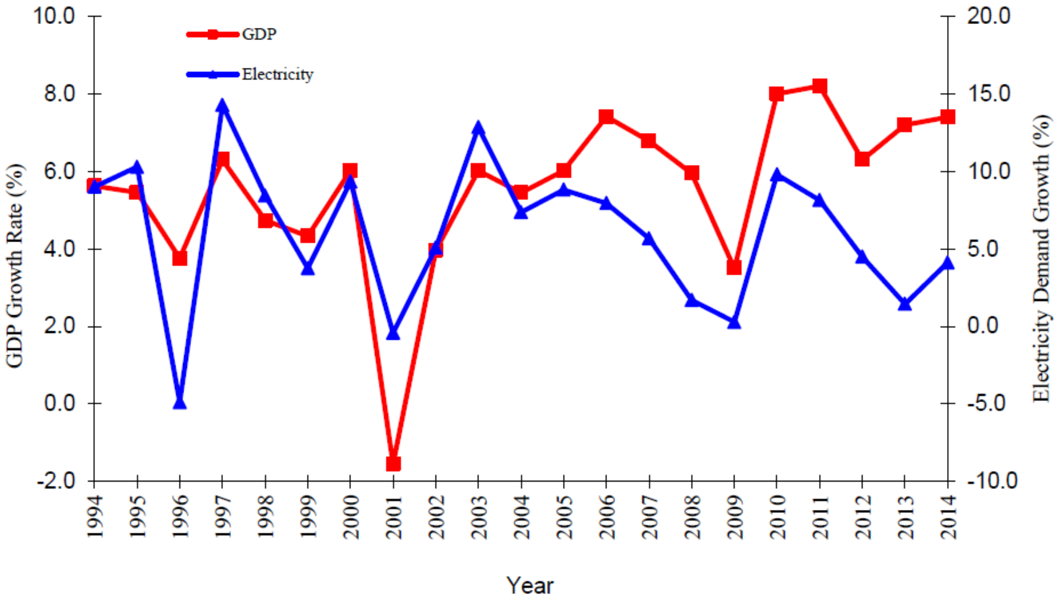

Figure 2.5: Variation of GDP Growth Rate and Electricity Demand Growth with year

2.3 Future Power Demand

When the ‘Long Term Generation Expansion Plan, 2015-2034’ of CEB is considered the base case plan could be summarized as below.

Table 2.2: Results of Generation Expansion Planning Studies –
Base Case Plan 2015-2034

Year	Renewable Additions	Thermal Additions
2015	---	4 x 15MW barge power plant
2016	---	---
2017	35MW Broadland HPP 120 MW Uma Oya HPP	4 X 17MW Kelanitissa Gas Turbines
2018	100 MW Mannar Wind Power Phase I	2 x 35 MW Gas Turbines
2019	---	1 x 35 MW Gas Turbines
		Continued

Year	Renewable Additions	Thermal Additions
2020	31 MW Moragolla HPP 15 MW Thalpitigala HPP 100 MW Mannar Wind Power Phase II	2 x 250 MW Coal Power Plant
2021	50 MW Mannar Wind Park Phase II	---
2022	20 MW Seethawaka HPP 20 MW Gin Ganga HPP 50 MW Mannar Wind Park Phase III	2 x 300 MW Coal Power Plant Trincomalee-1, Phase I
2023	25 MW Mannar Wind Park Phase III	163 MW Combined Cycle Plant
2024	25 MW Mannar Wind Park Phase III	1 x 300MW Coal Power Plant Southern Province
2025	1 x 200MW PSPP 25 MW Mannar Wind Park Phase III	---
2026	2 x 200MW PSPP	---
2027	---	1 x 300 MW Coal Power Plant Southern Province
2028	---	---
2029	---	1 x 300 MW New Coal Power Plant Trincomalee-2, Phase II
2030	---	1 x 300 MW New Coal Power Plant Trincomalee-2, Phase II
2031	---	---
2032	---	2 x 300 MW New Coal Plant Southern Region
2033	---	---
2034	---	1 x 300 MW New Coal Plant Southern Region

As per the table 2.2, 3200 MW of Coal Plants and 105 MW of Gas Turbines are to be added to the system within the next 20 years of time starting from 2015. Which means, there would be significant amount of energy available as waste heat. As per the ‘Long Term Generation Plan 2015-2035’, it is predicted that there will be electricity demand growth rate of 4.6% per annum. However, with technological developments, we can expect much more NCRE power generation contribution which is not predicted in the plan.

2.4 Waste Heat Recovery

2.4.1 Introduction

What is waste heat?

As per the prevailing definitions, the WH is the heat produced by different processes and dumped into environment without utilizing [7].

What is Waste Heat Recovery?

This can be defined as capturing, converting and utilizing the Waste Heat to do a useful work [7]. Further this can be classified depending on the type of Waste Heat usage.

- Waste Heat for heating – Utilize the waste heat for space heating or process heating.
- Waste Heat for refrigeration and space cooling – Utilize the waste heat for the vapour absorption cycle to reduce the cost for refrigeration and space cooling requirements.
- Waste heat for electricity generation – Utilizes the waste heat energy for running steam turbine, Kalina Cycle for reducing the cost of electricity.

2.4.2 Waste Heat Recovery for Thermal Power Stations

In electricity generation, about 50% of fuel energy is emitted from thermal power stations as waste heat to the environment. Lot of technologies have been invented and practiced in recovering the waste heat. The amount of energy recovered depends on many factors. They are the mass flow rate, source temperature, heat capacity of flue gas, system pressure and working fluid. There are two salient features in waste heat, to decide the economic viability to recover the energy. Those are,

1. Quality of Waste Heat
2. Quantity of Waste Heat

Basically, these two depend on the temperature and the mass flow rate of flue gas. Usually when these two factors are high, then obviously it is worth to implement a recovery system.

Figure 2.6 illustrates the type of flue gas temperatures which emits in different industries. The temperature of emissions from different processes varies over a range of temperatures.

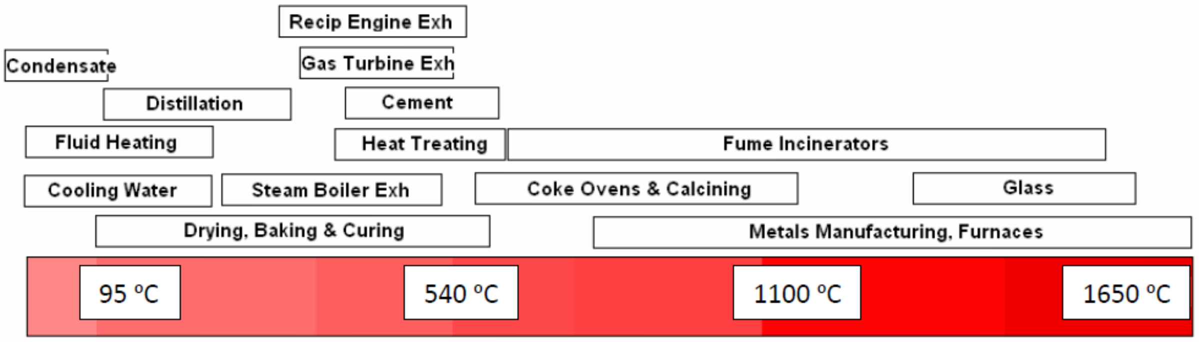

Figure 2.6: Waste heat classification based on Temperature [8]

Basically, the temperature ranges are classified as below [9].

1. High – Above 593°C (1100°F)
2. Medium – 204°C (400°F) to 593°C (1100°F)
3. Low – Below 204°C (400°F)

This classification may slightly different in other literature. Waste heat with high temperatures are emitted in metal manufacturing, furnaces, glass & coke ovens, calcining and fume incinerators. For this range of temperatures, we can use steam turbines to recover the heat. Low to medium temperature flue gases are emitted in different processes like turbine, engine and boiler exhaust, distillation columns, drying and curing processes and cooling towers from industrial processes. Lot of processes with industrial waste heat is categorized to this type.

These types of waste heat are being used for heating, electricity generation, refrigeration and air conditioning. In waste heat recovery technologies, two main concepts are used. They are,

1. Active Waste Heat Recovery Technology
2. Passive Waste Heat Recovery Technology

Waster Heat Recovery Classification

When the heat recovery options are concerned, they are categorized mainly in to three groups.

1. Recycling energy back into the process
2. Recovering energy for other on-site uses
3. Using it to generate electricity in combined heat and power systems.

Basically, the Waste Heat Recovery Technologies are classified in to two groups as,

1. Passive technologies – Technologies which do not use (significant amount of) external energy supply to support energy recovery process
2. Active technologies – Technologies which uses external energies to extract the energy

Passive heat recovery makes use of the heat exchangers which transfer heat between two sources. No significant mechanical or electrical energy is being used, other than for auxiliary plants like pumps and fans.

Active heat recovery makes use of mechanical or electrical energy for upgrading the existing energy. For example, the heat pumps and absorption chillers could be taken.

Heat Recovery Technology Classification [10].

1. Passive heat recovery: Temperatures greater than 95^{o}C
2. Industrial closed-cycle mechanical heat pumps: Temperatures less than 95^{o}C
3. Absorption Chillers and Heat Pumps: Temperatures between 95^{o}C to 200^{o}C
4. Organic Rankine Cycle, Combined Heat and Power (CHP): Typically, 150^{o}C to 400^{o}C
5. Kalina Cycle: 120^{o}C to 400^{o}C

2.3.3 Low Grade Energy Recovery Cycles

Low grade energy is referred to as the heat below 200^{o}C [11]. Generally, it is considered that the extraction of low grade energy is less economical compared to associate investment. It is hard to use the Passive technologies for extracting the low-grade energy. Therefore, Active technologies have been used to extract this type of energy.

Usually it is not possible to use ordinary ‘Steam Rankin Cycle' for generating electricity with low grade energy sources. Therefore, many low-grade heat recovery cycles were invented and developed over the years. Thus, following thermodynamic cycles were introduced for low grade energy recovery.

1. Organic Rankine Cycle
2. Kalina Cycle
3. Tri Lateral Flash Cycle
4. Goswami Cycle

These cycles are performing very well rather than water with much less cost for equipment, higher effectiveness and higher efficiencies. Each of them will be discussed in brief under this section.

Organic Rankine Cycle

Organic Rankine Cycle uses the same principles applied for simple Rankine Cycle. The only difference is, an organic fluid with a low boiling point is used as the working fluid. The cycle comprises with an expansion turbine, a condenser, a pump, a boiler and if needed a super heater. Different kind of organic fluids are used for the ORC depends on the application. Such as Toluene, Benzene, Decane, Pentane, Heptane etc. Organic fluids have many distinct characteristics than water. Therefore, lot of researches have been carried out to study about the suitable organic fluids for ORC. An ORC system is consisted of a single-stage expander, resulting more economical system in terms of capital investment and maintenance costs. The advantage of this cycle is, its extraction of low grade energy from waste heat, which the traditional Rankine cycle cannot do.

Depending on the thermodynamic processes such as heat addition, expansion, heat rejection and compression, the ORC can be categorized in to three types. They are,

1. Subcritical ORC – All four-thermodynamic process at lower pressure than critical pressure
2. Trans-Critical ORC – Heat rejection happens in a lower pressure while the heat addition happens in a higher pressure than the critical pressure. Other two processes are happening between these two pressure levels.
3. Super-Critical ORC- All four processes at higher pressure than critical pressure.

In recent past considerable attention was given for ORC with the depletion of fossil fuels. Worldwide attention has been paid to find out the ways and means for conserving the energy as it will be the next obstacle for the development of the society.

Few advantages of ORC compared to Steam Rankine Cycle;

1. Less amount of heat is required to evaporate the Organic fluid (it happens in lower pressure and temperature)
2. Absence of moisture during the vapour expansion, avoids erosion in blades.
3. As expansion process ends at vapour region, the superheating is not required.
4. Use a simple single expander, as pressure ratio is less.
5. The temperature difference between the evaporator and condenser is less. Therefore, less pressure ratios reduce the cost.

The arrangement of major components of a simple Organic Rankine Cycle could be shown as in figure 2.7.

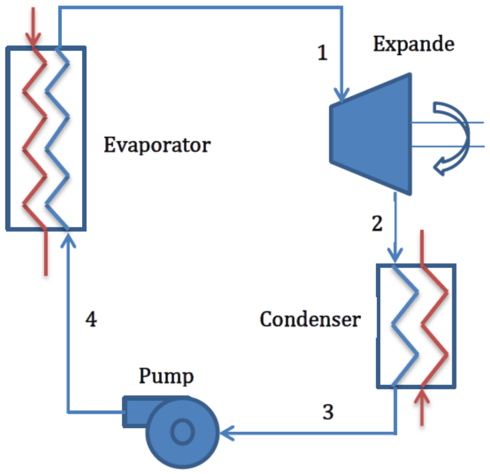

Figure 2.7: Organic Rankine Cycle

The heat of the waste heat is transferred to the Organic Fluid from the evaporator. The liquid entering to the evaporator is in liquid phase at high temperature. After extracting the heat from waste heat, the fluid becomes a vapour. Next it is fed to the turbine and expand, generating electricity while reducing the temperature and pressure. Then, when passing through the condenser the low temperature and pressure organic fluid is cooled. Finally, the pump is used to send the organic fluid to evaporator.

Kalina Cycle

In 1984 Dr. Alexander I. Kalina proposed a new thermodynamic cycle which utilizes binary mixture as working fluid and that cycle configuration was named as Kalina Cycle [9,10,12]. In this cycle binary fluid, typically ammonia-water mixture is used as the working fluid. The main reason for the usage of this binary fluid is to reduce the thermodynamic irreversibility of the fluid and increase efficiency of the cycle. As per literature of Kalina Cycle, it is performing very good for extracting low grade energy which is less than 150 ^{o}C [13,14]. Moreover by using Kalina Cycle, it can be achieved 20%- 40% higher efficiencies than conventional waste heat recovery plants [15]. Simple Kalina Cycle configuration is shown below.

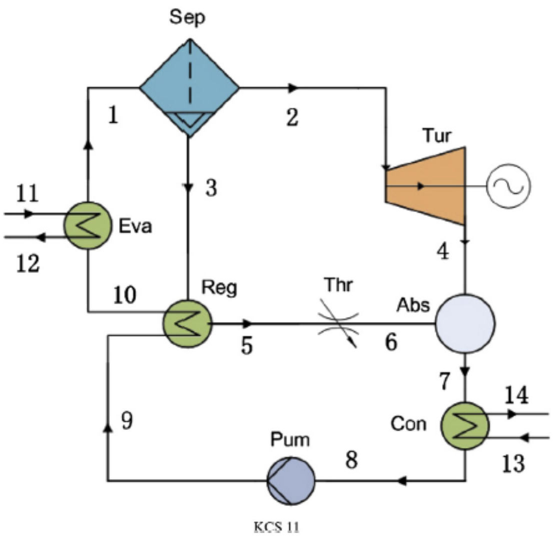

Figure 2.8: Kalina Cycle System [16]

Kalina Cycle configuration comprises of expander (turbine), evaporator, separator, absorber, condenser, recuperator, pump, super heater (optional). The working fluid entering at 10 is heated up using the energy in WH and then sent to the separator. In separator, high concentrated ammonia vapour is sent to the turbine (2) while the ammonia lean fluid mixture is sent via recuperator to reject heat to the stream which goes for the evaporator (10). Non-isothermal boiling takes place in the boiler as the binary fluid has the ability to change its composition while absorbing the heat. As a result, the fluid will have good thermal match [17]. Thus, this is another degree of freedom of Kalina Cycle than ORC. After recuperator, the working fluid is sent via throttle valve to reduce the pressure (5) and mixed with the outlet from the turbine (4) at the absorber. Then it is sent through the condenser and again pump to the evaporator.

There are numerous studies to identify the appropriate binary fluids for the use of KCS 11. However, all of them are still in experimental level other than the mixture of ammonia-water [11]. In Kalina Cycle the ammonia-water mixture entering the separator exist in two phase region. The high pressure and high concentrated ammonia which comes through the separator is passed through the turbine to generate electric power. According to different temperature ranges and applications of Kalina Cycle, few configurations have been defined. For example, Kalina Cycle System 5 (KCS 5) for direct fired power plants, KCS 6 for a gas turbine based combined cycles, KCS 11 for geothermal temperatures from about 121°C to 204°C. Similarly, KCS 34 is suitable for temperatures below 124°C [18,19].

Hettiarachchi et al. [20] defined five parameters of KCS 11 and concluded that KCS 11 has better performance than ORC in moderate pressures. Nag and Gupta et al. [21] pointed out that the Turbine Inlet Conditions (Temperature and Concentration) and the Separator Temperatures are the critical factors for the cycle efficiency.

Goswami Cycle

This cycle was proposed by Dr. Yogi Goswami (1998) which uses binary mixture to produce power and refrigeration simultaneously [22]. This is a cycle which uses two thermodynamic cycles known as the Rankine Cycle and the Ammonia-absorption refrigeration cycle. The working fluid of the cycle is ammonia-water combination. The main advantages of this system could be shown as below.

1. Production of power and refrigeration at the same cycle
2. Design flexibility of producing any combination of power and cooling requirement
3. Efficient conversion of moderate energy sources to power
4. Possibility of improved resource utilization compared to separator power and cooling

The cycle configuration could be shown as in figure 2.9 below.

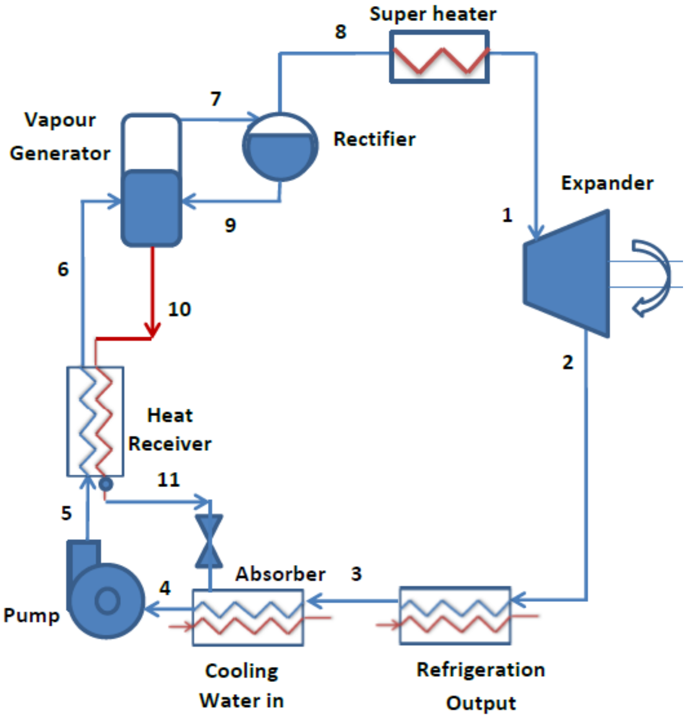

Figure 2.9: Goswami Cycle

Ammonia rich mixture is pumped to the vapour generator (4-6) and the vapour from the vapour generator is fed to the rectifier (7). If any condensed water exists, then it is again fed to the vapour generator (9). The vapour is super-heated using the super heater (8-1). Then it is expanded to produce the electricity. Then the working fluid is sent via a condenser and phase is changed to saturated liquid.

Trilateral Flash Cycle

Tri Lateral Flash Cycle is a cycle in which the expansion happens in the saturated liquid phase rather than the saturated vapour phase. As the heat absorption is done in the liquid phase a perfect temperature matching is achieved. Thus the irreversibly is minimized. Potential heat recovery of Trilateral Flash Cycle is 14-85% which is more than in comparison to ORC or Flash steam cycle. The general configuration of TFC is shown 2.10 below.

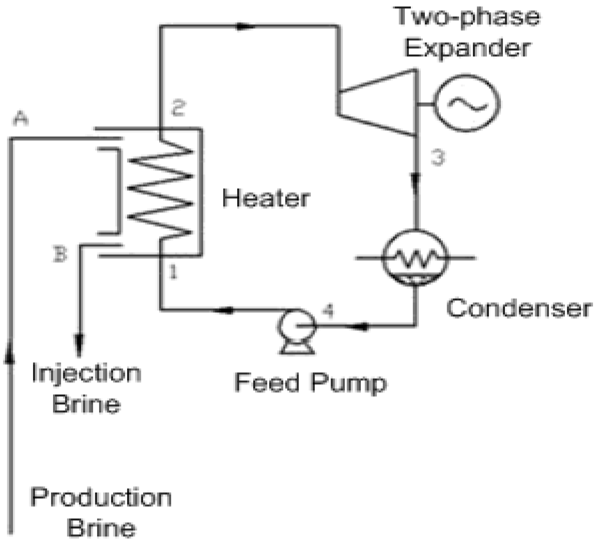

Figure 2.10: Tri Lateral Flash Cycle [23]

The TS diagram of the above cycle can be identified as shown 2.11 below.

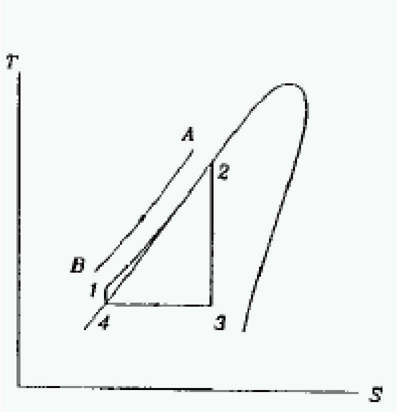

Figure 2.11: TS diagram of Tri Lateral Flash Cycle [23]

The working fluid is heated up to its boiling point under pressure. The expansion phase in the expander starts from saturated liquid state and flashes to the condenser pressure. Eventhough TFC has some significant features, the difficulty in finding expander, working under two phase working fluid are the present main drawbacks of this technology.

2.3.4 Selection of appropriate technology

As explained above, several technologies have been used for recovering waste heat. This study is done to find out the possibility of recovering the waste heat of thermal power stations operating in Sri Lanka. It is obvious that if the temperature of the flue gas is high, the potential of recovery is high. However, in recovering the low-grade energy, it’s crucial to select the appropriate technology to succeed.

In above explained technologies, the Trilateral Flash Cycle is not still feasible, since it is not consisted of an expander which can work in both phases. So, it is impractical in prevailing scenario. Although Goswami Cycle is a promising technology, still it is in research level. Lot of studies are being proceeded to find out the ability to make it practical, yet it is not feasible. KCS and the ORC are the other two technically viable methods, while both show similar performances. ORC is a well-established technology over the years and lot of practical examples could be seen all over the world. In fact, lot of reaches are being carried out to find out the methods to make the cycle more efficient. Similarly, KCS is a promising technology and it is being used in several geothermal power plants operating in various parts of the world. Although it is not that much established as ORC, with the characteristics of binary fluid the technology is getting more and more popular.

It is necessary to decide which technology is suited for the low-grade energy extraction. ORC is known to be performing well from 150^{o}C to 400^{o}C and researches were done to identify suitability on thermal power station in Sri Lanka [24]. Similarly, the KCS is appropriate from 120^{o}C to 400^{o}C. Further it is said that KCS has much good efficiencies in temperature lower than 200^{o}C. [19] So this study mainly aims on the techno economic feasibility analysis of extracting energy from the low-grade waste heat using the KCS. Mainly two plants were identified. i.e. Lakvijaya Coal Power Plant and Kelanithissa Combined Cycle Power Plant. Further analysis will be done basically focusing on these two plants.

CHAPTER 3
KALINA CYCLE

The basic cycle which uses for power generation in thermal power stations is the Conventional Rankine Cycle. Water is the working fluid in the system. However, with time and development of the technology, lot of researches and studies were done to find more efficient working fluids. As a result, Organic fluids and binary fluids were introduced and subsequently Organic Rankine Cycle and Kalina Cycle were started to use for Waste Heat Recovery. In this Chapter, it is expected to discuss the details of the Kalina Cycle. Its developments, configurations, mathematical modeling, properties of working fluid are being discussed.

With the shortage of energy, there is a huge interest on inventing the technologies for recovering Waste Heat. Steam Rankine Cycle is known as the most efficient cycle for power generation. However, it can be used only for temperatures of high values. Later different technologies were introduced to extract low grade energy with modifications to the Rankine Cycle. In this chapter, the details of the Kalina Cycle is discussed.

3.1 What is Kalina Cycle

Kalina Cycle was first invented by a Russian Engineer, Aleksandr Kalina in the year 1984 [25]. Ammonia water mixture had been used in the industry for the refrigeration cycle for more than 100 years. However, this was the first time of attempting it to use for power generation. In the principle of Kalina Cycle, it uses a binary fluid to convert the thermal energy to mechanical energy. By using the ability of changing the composition of the working fluid upon its temperature, which means the non-azeotropic property of water-ammonia mixture, Kalina Cycle is known as a cycle with a perfect temperature matching. Further, by varying the concentration in the different locations of the cycle, it increases the thermodynamic reversibility and therefore increases the overall thermodynamic efficiency. Further there are numerous benefits of using water-ammonia mixture as the working fluid, rather than the other types of fluids. Experimental results adduce that it was identified that the Kalina Cycle is 20% - 40% high efficient than the conventional Rankine Cycle. [15]

This cycle was designed to replace the previously used Rankine Cycle which is used as a bottoming cycle for a combined-cycle energy system. In a plant, which uses steam, boiling essentially happens at a constant pressure and a temperature. Therefore, perfect matching with the temperature profile (perfect extraction of waste heat energy) of the exhaust flue gas is not achieved. Further, when using the binary fluid of water-ammonia mixture, first of all ammonia vaporized as its boiling point is far less than water and then starts the boiling of water. This feature paves the way to match the temperature profile of the flue gas much better. Basically, this is more suited for medium-low grade energy recovery systems which have temperature range from 90°C to 500°C.

Lot of researches have been done to identify the suitable applications by changing the original configuration of the cycle. The first design presented by Dr.Kalina was known as the KCS1 [27]. It was suited for small units such as the total generation below 20MW or bottoming cycles less than 8MW. Then with a modification to original cycle the KCS6 was introduced with improved features of harnessing the energy which was suitable for larger power generating units. Similarly, KCS11 system is adopted to suit the geothermal applications where the heat source temperature is between 121°C to 204°C. For the applications where the source temperature is less than 121°C, KCS34 is being used [16,19]. More details are shown in table 3.1.

Table 3.1: Kalina cycle development status

Cycle No	**Application**	**Development Status**
1	Bottoming cycle small plants	Design completed for Canoga Park Demonstration
2	Low temperature geothermal	Design completed, under development and planning
3	High temperature geothermal and waste heat	Design completed, under development and planning
4	Cogeneration	Design completed, under development and planning
5	Direct fired for coal and other solid fuels	Design Completed
		Continued

Cycle No	**Application**	**Development Status**
5n	High temperature gas-cooled nuclear reactor	Design Completed
6	Bottoming for utility combined cycle	Design Completed
7	Direct fired, split cycle	Under development
8	Bottoming cycle, split cycle	Under development
9	Retrofit subsystems for existing plants	Under development
12	Low temperature geothermal	Design completed

By changing the No. of heat exchangers, separators and absorbers the cycle could be altered according to the application, specially it depends on the source temperature. Such few configurations are shown in figure 3.1.

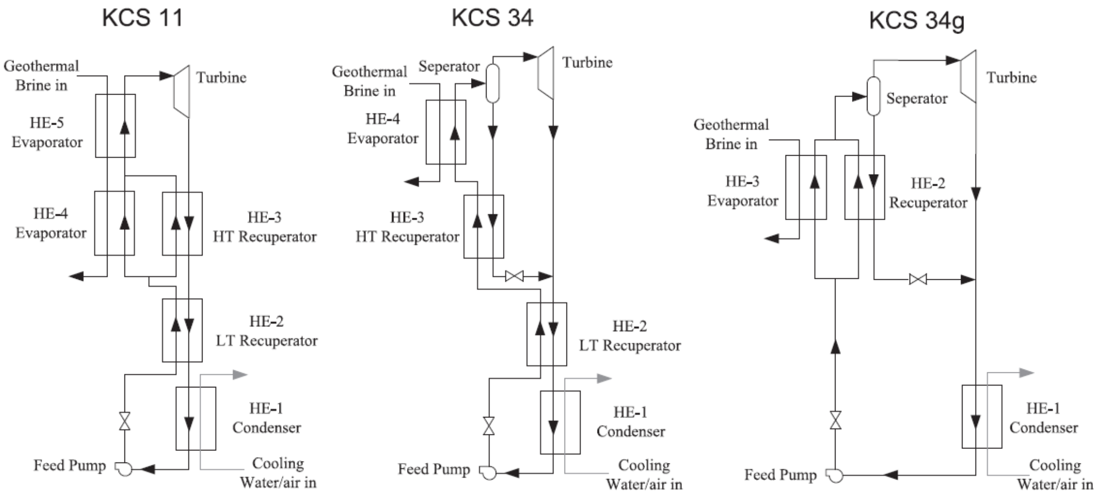

Figure 3.1: Kalina Cycle System configurations [19]

In this work, mainly the feasibility of KCS11 is studied as it is considered to be the best suited for low and moderate temperatures ranging from 121°C to 204°C. The basic configuration of the KCS 11 is shown below3.2.

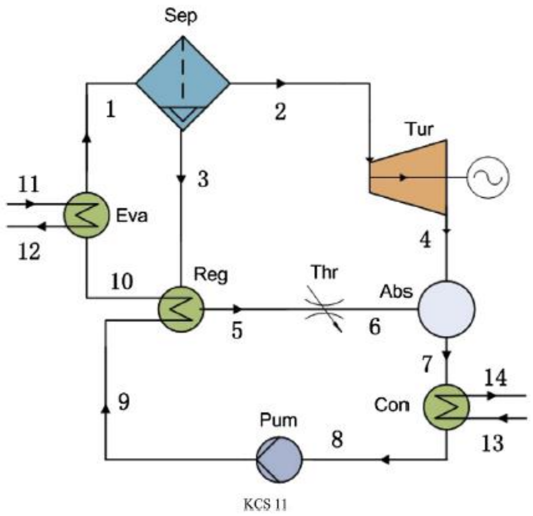

Figure 3.2: Configuration of KCS11 [16]

The energy in flue gas which comes from power station (11) is exchanged as heat via the evaporator and returned back (12). The heated wet vapour (1) is then entered to the Separator. The ammonia lean mixture (3) and ammonia rich vapour (2) is separated by the Separator. High pressure, high temperature and ammonia rich solution (2) is fed to the turbine to expand and generate electricity. The solution after expansion (4) and the throttled lean solution (5-6) is mixed at the Absorber. The mixture with original concentration (7) is circulated through a condenser and saturated liquid (8) is pressurized by the pump (9). The heat in the lean mixture after separator (3) is exchanged to the mixture from the pump. The heated solution is then fed in to the evaporator. The ammonia mass fraction vs enthalpy diagram, which is related to the figure 3.2 is shown in figure 3.3. Both saturated liquid and saturated vapour lines are shown in the diagram and the binary fluid which enters to the evaporator is having a concentration of 0.8. At the Separator, the ammonia rich mixture is directed to the expander and lean mixture is going through a recuperator and a throttle valve. Then at absorber both are mixed together.

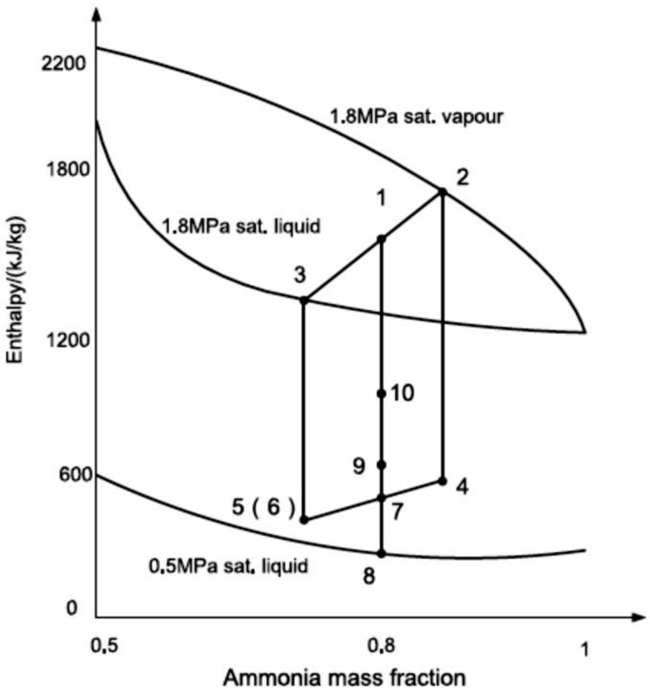

Figure 3.3: Enthalpy vs ammonia mass fraction graph [16]

3.2 Thermodynamic modeling of the Kalina Cycle 11(KCS 11)

The modeling equations with reference to the figure 3.2, for the Kalina Cycle System 11 could be shown as below.

$\dot{Q}_{HRVG}$ - Heat energy input to Heat Recovery Vapour Generator

W_t - Useful work from turbine

W_p - Work input to the pump

W_{net} - Net work output

η - Efficiency of the cycle

η_t - Isentropic efficiency of turbine

η_g - Efficiency of generator

η_p - Isentropic efficiency of pump

m_a - Mass flow rate of each stage, where a=1,2,3,4,5,6,7,8,9,10,11,12

h_b - Enthalpy of each stage , where b=1,2,3,4,5,6,7,8,9,10,11,12

Heat energy absorbed by the Heat recovery vapour generator per m_1 could be calculate by the enthalpy difference at inlet and outlet of HRVG,

$$\dot{Q}_{HRVG} = m_1(h_1 - h_{10}) \qquad \ldots\ldots\ldots\ldots\ldots 3.1$$

Separator work can find by applying the conservation of energy,

$$m_1 \times h_1 = m_2 \times h_2 + m_3 \times h_3 \qquad \ldots\ldots\ldots\ldots\ldots 3.2$$

Useful work of the turbine is calculated by multiplying the isentropic efficiencies of turbine and generator from the enthalpy difference at inlet and outlet of expander per m_2 mass,

$$W_t = m_2(h_2 - h_4)\eta_t\eta_g \qquad \ldots\ldots\ldots\ldots\ldots 3.3$$

By applying the conservation of energy to the recuperator;

$$m_3(h_3 - h_5) = m_9(m_{10} - m_9) \qquad \ldots\ldots\ldots\ldots\ldots 3.4$$

Energy balance for the throttle valve;

$$m_5 \times h_5 = m_6 \times h_6 \qquad \ldots\ldots\ldots\ldots\ldots 3.5$$

The work input to the pump is taken from;

$$W_p = m_8(h_9 - h_8)/\eta_p \qquad \ldots\ldots\ldots\ldots\ldots 3.6$$

Net output of the cycle;

$$W_{net} = \left(W_t - W_p\right) \qquad \ldots\ldots\ldots\ldots\ldots 3.7$$

Therefore, the cycle efficiency;

$$\eta = \frac{(W_t - W_p)}{\dot{Q}_{HRVG}} \qquad \ldots\ldots\ldots\ldots\ldots 3.8$$

The figure 3.4 shows, how does the heat acquisition of Rankine Cycle and Kalina Cycle happen with compared to the heat source.

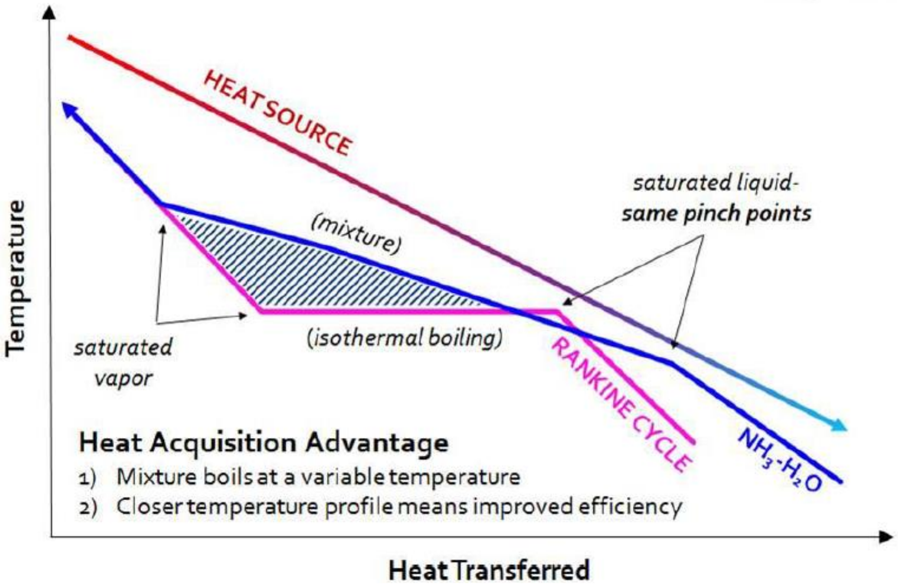

Figure 3.4: Heat acquisition comparison between Rankine Cycle and NH_3-H_2O [15]

It is clearly shown that due to the non-azeotropic nature of water-ammonia mixture, the boiling happens at different temperatures in different compositions. Therefore, heat absorption from the source is more efficient than the Rankine Cycle [28]. When the binary fluid in Kalina Cycle is boiled, a separation in two components is taken place. At the most beginning, more volatile ammonia starts to vaporize. As the ammonia concentration in the remaining mixture reduces, saturation temperature rises, providing a better match with the flue gas temperatures.

N.S. Ganesh, T. Srinivas [29] state that the Kalina Cycle turbine is less expensive than the steam turbine, since the volumetric flow rate in the low-pressure part of the ammonia-water turbine is much smaller than in the steam turbine, while the expenses for the Kalina Cycle is much higher than steam. However, certain literature shows that, same steam cycle components could be used because of the molecular mass equality of both water and ammonia [30].

Although Kalina Cycle system was introduced in 1984, it became popular in late nineties. Some of the successfully built power stations based on this technology is shown below.

Table 3.2: Kalina Cycle System based power stations, worldwide [27]

No	Plant Name	Capacity	Commissioned Date
01	Husavik	2 MW	2000
02	Canoga Park	6.5 MW	1992
03	Unterhaching	3.4 MW	2009
04	Bruschel	0.6 MW	2009
05	DG Khan cement	8.6 MW	2016
06	Start Cement	4.75 MW	Under Construction
07	Fuji Oil	4 MW	2005
08	Sumitomo Metals	3.5 MW	1999
09	Sinopec Hainan	4 MW	Under Construction
10	Fukuoka	4 MW	1998
11	Shanghai Expo	0.05 MW	2010
12	Quingshui	0.05 MW	2011

3.3 Properties of Water and Ammonia

For this cycle, ammonia-water mixture is used as a binary fluid. Generally, both ammonia and water have same molecular structure including Hydrogen bonds. However, the bonds between O-H are stronger in water than the N-H bonds in ammonia. The molecular weight of both these substances are almost same. Some of the properties of them are shown below in table 3.3[28].

Table 3.3: Properties of Ammonia and water [28]

Property	Ammonia	Water
Molar Weight, (g/mol)	17.031	18.015
Boiling Point (at 0.101 MPa), (^{o}C)	-33.4	100.0
Critical Temperature, (^{o}C)	132.3	374.1
Critical Pressure, (MPa)	11.35	22.12

Number of experiments were done in the past to find the most suited binary fluid to increase efficiency of the cycle. Mercury, aluminum bromide, zinc ammonium chloride and diphenyl oxide were used and checked its performances [26]. However, due to metalogical and safety reasons all those fluids were not used consistently. In the cycle, when the heat is absorbed, ammonia starts boiling and later water starts to boil. Therefore, the boiling temperature changes with the composition and it is an advantage in harnessing the energy. Although ammonia and water are two fluids with different features, when they mix together it behaves completely different than pure fluids. As per literature there are four (04) primary differences. [19]

1. An ammonia-water mixture has a varying boiling and condensing temperatures.
2. The thermo-physical properties of an ammonia-water mixture can be altered by changing the ammonia concentration.
3. The temperature of the mixture could be increased or decreased without changing the heat content as a result of thermos-physical properties of the mixture.
4. Water freezes at 0^{o}C which is a high temperature compared to the freezing temperature of ammonia, which is -78^{o}C. Consequently keep the mixture in a low freezing temperature.

Also, it is important to find the reasons for using water-ammonia mixture as the binary fluid rather than going for other organic fluids. The advantages of using ammonia for the binary fluid are shown below. [15,19]

1. Fluid is less hazardous and flammable compared to the Organic Cycle working fluids.
2. Ammonia is very much volatile and also self-alarming.
3. Environmentally friendly and could be identified as one of the most common compounds found on nature.
4. It has proven records of usage in refrigeration plants, power plants and ammonia synthesis.

5. The lighter component (ammonia), provides efficient waste heat recovery at high pressure by causing boiling to start at lower temperature.
6. The mixture allows the composition to be varied through the use of distillation. Thereby, higher efficiency could be achieved with the better temperature matching.
7. As the molecular weights of both ammonia and water are same, the behavior of water-ammonia mixture behaves same as steam, which allows to use the same components used for steam turbines.
8. Standard materials such as Carbon Steel and standard high-temperature alloys can be used.
9. Ammonia is inexpensive in market.

CHAPTER 4
WASTE HEAT FROM THERMAL POWER STATIONS IN SRI LANKA

Thermal power station is a place where heat energy is converted to electrical energy by using mechanical components. Usually in a thermal power station considerable amount of energy is emitted to the environment as waste heat. The heat recovery technologies are introduced to minimize the losses as much as possible. However, there are limitations and constrains in which the temperature could be reduced due to external factors. At present the total installed capacity of thermal power plants in Sri Lanka is 3,300 MW. However due to the less efficiencies of the power generating cycles lot of energy is emitted to the environment as waste heat. They may be in the form of flue gas, hot water or steam. Few technics are used at present to recover some of this waste heat: for example, steam generators, pre-heaters etc. At this situation, it is worth to get an idea of the amount of energy wasted to the environment.

The objective of this chapter is to identify the efficiencies of thermal power stations and assess the amount of heat energy wasted to environment from Thermal Power Stations in Sri Lanka. Relevant data was collected from existing literature and by inquiring the power stations.

4.1 Efficiencies of Power Plants

At present, there are 08 major thermal power stations owned by Ceylon Electricity Board, with an installed capacity of 1504 MW. Also, there are 04 IPP owned thermal power stations, with an installed capacity of 511 MW. The details of those power stations are shown below.

As shown in table 4.1, there is a huge contribution from Lakvijaya Power Station for fulfilling the annual electricity requirement. Year 2014 was a year which had an average amount of rain. Thus, the values shown can be considered as average values of annual thermal generation. CEB owned thermal power stations generated 5269.1 GWh which is equal to 66.2% of total contribution.

Table 4.1: Details of CEB owned thermal power stations [4]

Name of the Power Station	Technology Type	Fuel Type	Capacity (MW)	Gross Generation (GWh)	Share in Generation %
CEB					
Kelanithissa Power Station	GT Stage 2	Auto Diesel	115	208.3	2.6
	GT Stage 3	Auto Diesel	80	33.6	0.4
Sapugaskanda Power Station	Diesel Engine	Auto Diesel	80	5.7	0.1
		HSFO 380 cst		231.4	2.9
Sapugaskanda Extension Plant	Diesel Engine	Auto Diesel	80	3.5	-
		HSFO 380 cst (FO 3500)		415.7	5.2
Kelanitissa Power Station	Combined Cycle Plant	Auto Diesel	165	284.6	3.6
		Naptha		465.5	5.9
Uthuru Janani	Diesel Engine	Auto Diesel	24	0.1	-
		HSFO 180 cst		95.7	1.2
Lakvijaya Power Station	Steam	Auto Diesel	900	19.4	0.2
		Coal		3505.60	44.1
Total from CEB			1464	5269.1	66.2

The figures in table 4.2 is related to the year 2014. At present 'Colombo Power' is owned to CEB. Heladanavi Power Station was retired as its agreement period was expired. The rest of the power stations are still in operation.

Table 4.2: IPP owned thermal power plants and respective generations, 2014

Name of the Power Station	Technology Type	Fuel Type	Capacity (MW)	Gross Generation (GWh)	Share in Generation%
Asia Power	Diesel Engine	HSFO 380 cst (FO 3500)	49	184.2	2.3
Colombo Power	Diesel Engine	HSFO 180 cst (FO 1500)	60	294.7	3.7
AES - Kelanitissa	Combined Cycle	Auto Diesel	110	500	6.3
Heladanavi	Diesel Engine	HSFO 180 cst (FO 1500)	100	489.7	6.2
Ace Power Ambilipitiya	Diesel Engine	HSFO 180 cst (FO 1500)	100	488.9	6.2
Yugadhanavi - Kerawalapitiya	Combined Cycle	LSFO 180 cst	270	657.6	8.3
					Continued

Name of the Power Station	Technology Type	Fuel Type	Capacity (MW)	Gross Generation (GWh)	Share in Generation%
Northern Power	Diesel Engine	HSFO 180 cst (FO 1500)	27	60.2	0.8
Total			2160	2675.3	33.8

A set of data was considered for the month of November 2016 and calculations were done to assess the efficiencies of 'Sapugaskanda Power Station'. Table 4.3 shows those efficiencies.

Table 4.3: Operational data of Sapugaskanda Power Station

Engine No	**Used Diesel (m^3)**	**Used Heavy Furnace Oil Qty (m^3)**	**Total input energy**	**Generation (MWh)**	**Energy Output**	**Overall Efficiency**
Scheme A						
E 01	50.7	2305.5	100448290	9910	35676000	35.52%
E 02	57.1	2407.4	105148500	10015	36054000	24.29%
E 03	46.8	2321.2	101043400	9619	34628400	34.27%
E 04	34.8	2713.5	117300210	11283	40618800	34.63%
Scheme B						
E01	6.8	1371.8	58856020	5921.78	21318408	36.22%
E 02	3.0	1295.4	55437180	5962.11	21463596	38.72%
E 03	3.8	1343.9	57541090	6086.18	21910248	38.08%
E 04	10.8	1330.5	57257310	6012.38	21644518	37.80%
E 05	5.4	104.2	4671820	468.13	1685268	36.07%
E 06	5.6	1372.5	58836470	5949.23	21417228	36.40%
E 07	3.4	1366.6	58493900	6231.78	22434408	38.35%
E 08	1.7	1376.4	58842320	6268.58	22566888	38.35%

Following data were used for the above calculations

Calorific Value of Heavy Furnace Oil – 41.2 MJ/l

Calorific Value of Diesel – 42.7 MJ/l

Density of Heavy Furnace Oil – 870 m^3/kg

Density of Diesel – 930 m^3/kg

As per the above calculated values, the efficiency of the Diesel Generators in Scheme A is about 34% while in Scheme B is around 38%. Typical temperature of exhaust gas is around 250-300 ^{o}C.

Similarly depending on the statistics of the month of November,2016 at Kelanitissa Power Plant and Kelanitissa Combined Cycle Power Plant the calculations were done to find the relative efficiencies of the power plants. They are shown in table 4.4.

Table 4.4: Operation data of Kelanitissa Power Plant and KCCPP

Serial No	Plant	Capacity	Fuel	Efficiency
01	GT Frame02	20 MW	Diesel	19.90%
02	GT Frame03	20 MW	Diesel	20.81%
03	GT Frame04	20 MW	Diesel	21.39%
04	GT Frame05	20 MW	Diesel	21.28%
05	GT Frame07	115MW	Diesel	28.00%
06	Combined Cycle			
	GT	105 MW	Naptha & Diesel	29.73 %
	ST	60 MW	Naptha & Diesel	44.14 %

According to table 4.4, efficiencies of Diesel Power Plants varying from 19-30%. Table 4.5 shows the efficiencies of Kelanitissa Power Plant and Kelanitissa Combined Cycle Power Plant depend on rated heat rates [31].

Table 4.5: Heat rates of Kelanitissa Power Plant and KCCPP

Unit no	Capacity	Heat Rate (kCal/kWh)	Efficiency
GT 02	17 MW	4277.92	20.04%
GT 03	17 MW	4084.59	20.98%
GT 04	17 MW	3980.79	21.53%
GT 05	17 MW	3992.06	21.47%
KCCPP	165 MW	2020 (At 153.7 MW)	42.58%

As per the collected data, technically the temperature of the flue gas from the Kelanitissa Combined Cycle Power Station could be maintained below 120^{o}C with its optimum efficiency level. However, due to external constrains, practically the exhaust temperature is being maintained at about 150^{o}C.

The thermal efficiencies of each unit at Uthuru Janani Power Station are shown below.

Table 4.6: Heat rates and efficiencies of Uthuru Janani Power Station [31]

Unit no.	Specific Fuel Consumption (kg/kWh)	Heat Rate (kCal/kWh)	Efficiency
01	0.2068	2185.43	39.4%
02	0.2052	2168.53	39.7%
03	0.2063	2180.15	39.4%
Total Plant	0.2061	2178.04	39.5%

Density of Heavy Fuel Oil = 985 kgm^{-3}

Calorific Value = 10568 kCal/kg

At Uthuru Janani Power Station the exhaust temperature of the flue gas just after the IC engine is around 400^{o}C, which is a high value. That heat energy is used for steam generation and then used to heat Heavy Fuel Oil. This is an instance of waste heat recovery. However, due to various constrains their flue gas temperature, which is emitting to the environment is prevailing at above 200^{o}C.

As far as the Lakvijaya Power Station is concerned, it is consisted of 03 machines and each with 300MW capacity. The flue gas temperature just after the boiler is about 340 ^{o}C. Then it is sent through a ‘gas to gas’ heat exchanger and the hot gas is used for pre-heating the intake air. Then again it goes through a bundle of heat exchangers and bubbled at water to dissolve Sulphur. Then again with the last heat exchanger bundle, the flue gas is heated to emit to the environment. Thus, in this process heat is recovered using, gas to gas heat exchangers to enhance the efficiency.

For comparison, few more data relevant to AES Kelanitissa Plant and West Coast Power Plant were considered. They are tabulated in table 4.7 & 4.8.

Table 4.7: Heat rates and efficiency of AES Kelanitissa Power Station

Loading (MW)	Hear Rate (kcal/kWh)	Efficiency
101 (65%)	3038.36	28%
118 (75%)	2739.81	31%
136 (85%)	2502.18	34%
157 (100%)	2027.57	42%

Table 4.8: Heat Rates and efficiencies of West Coast Power Plant [31]

Combined Cycle Gas Turbine Plant		Capacity: 270 MW
Loading (MW)	**Heat Rate (kcal/kWh)**	**Efficiency (%)**
108 (40%)	2745.70	31%
135 (50%)	2483.94	35%
270 (100%)	2083.46	41%

Based on the above calculated and collected data, we can summarize the thermal efficiencies of the power plants depends of their types, as shown below.

Gas Turbine Power Plant efficiency range	:	18~29 %
Diesel Engine Power Plant efficiency range	:	33~41 %
Combined Cycle Power Plant efficiency range	:	40~43 %

4.2 Exhaust data of Thermal Power Stations

As explained above, efficiencies of the existing power stations are ranging from 18 ~ 43 % which is less than 50%. As a result, lot of energy is emitted to the environment as waste heat. Following tables illustrate the properties of flue gas at the thermal power stations belong to CEB.

Table 4.9: Flue gas data of Thermal Power Stations

Power Plant	**Capacity (MW)**	**Exhaust Gas Temperature (^oC)**	**Flue gas flow rate (tons/hour)**
Kelanitissa Power Plant			
Combined Cycle	165	145 ~ 160	410
Gas Turbine	20	440 ~ 470	14400
Sapugaskanda Plant			
Sapugaskanda A	20	250 ~ 300	140 ~ 160
Sapugaskanda B	10	250 ~ 300	70 ~ 80
Lakvijaya Power Plant			
Stage 01	300	125 ~ 140	1000
Stage 02	600	125 ~ 140	2000
Uthuru Janani Diesel Power Station			
Uthuru Janani PS	23	250 ~ 270	-

There are only two thermal power stations which is operating below 200^oC in actual operating conditions. i.e. Kelanitissa Combined Cycle Power Station and the Lakvijaya Power Station. From the rest of power plants, the Gas Turbines in Kelanitissa Power Station has huge amount of energy potential which is with high temperature (440 – 470 ^oC) and with a massive flue gas flow rate (14,400 tons/hour). Rest of the power stations have moderate temperatures and mass flow rates.

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, it is expected to identify the impact of each critical parameter on the system. The main parameters which affect the system performances are turbine inlet pressure, turbine outlet pressure, separator temperature and concentration of NH_3 at separator. It is intended to identify the impact of these parameters in a model system.

5.1 Mixture for the cycle

From the beginning of 1900’s there was a discussion for finding proper binary fluids which suit for waste heat recovery systems. However, very recently the binary fluid, ammonia-water mixture was successfully used for the Kalina Cycle System.

The variation of the enthalpy values against the concentration of the mixture could be identified as below. Basically these graphs were built up using the Gibbs Free Energy Equations.

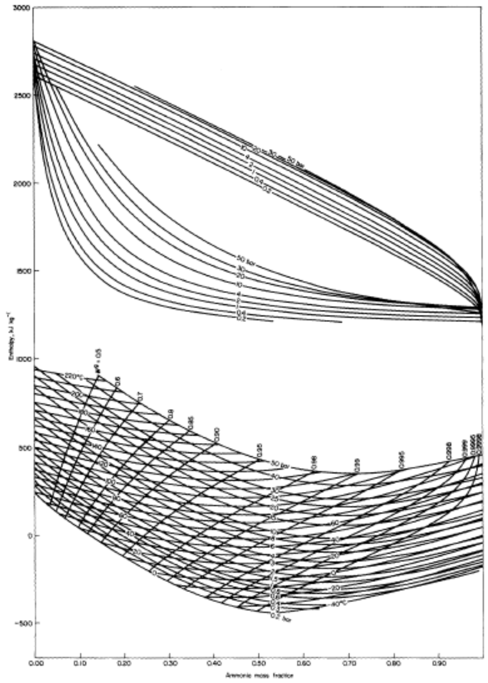

Figure 5.1: Ammonia-water mixture and enthalpy diagram [33]

In addition, the property table of 100% concentrated Ammonia diagrams was used for the calculations. They were generated by using the *RefProp®* software. A generated diagram is shown below.

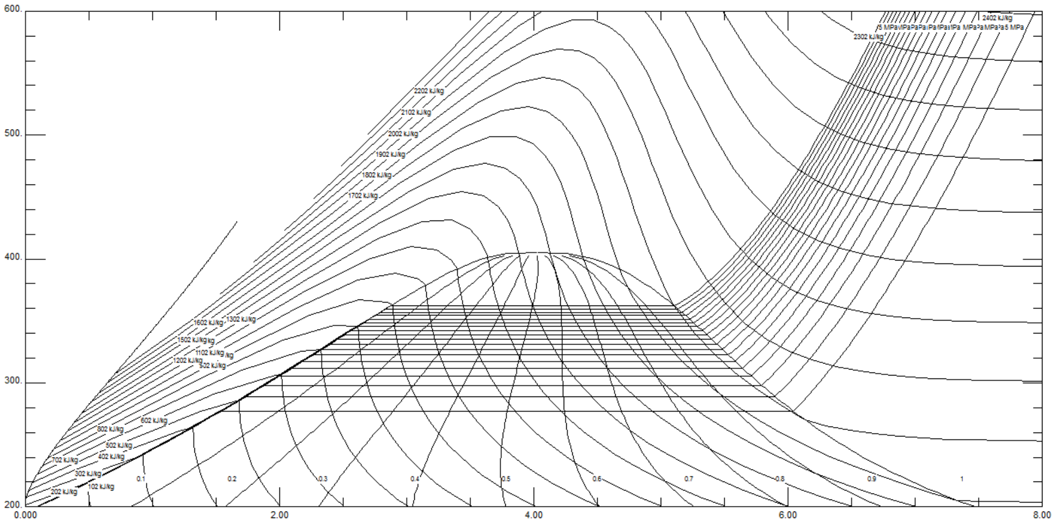

Figure 5.2: Entropy vs Temperature diagram of Ammonia

In this sensitivity analysis, it is expected to see the variation of the cycle efficiency with varying critical parameters.

5.2 Variables of the system

As per the knowledge gained through the literature survey, 04 critical parameters which affect significantly to the efficiency of Kalina Cycle were identified [19]. They are shown below.

1. Turbine Inlet Pressure
2. Turbine Inlet Temperature
3. Turbine Outlet Pressure
4. Separator Temperature

This analysis will look at the impact of the above parameters for the efficiency of the KCS 11. KCS 11 is extensively used in Geothermal applications as it is most appropriate for extracting low-grade energy. The conditions of the separator and the turbine are affecting both first and second low thermodynamic efficiencies [19]. In addition, the impact from power rating of feed water pump was also taken in to consideration.

It is expected to identify the impact of the above factors upon the cycle, step by step.

5.3 Analysis

This analysis was carried out for a KCS 11 based on the following assumptions.

1. The Kalina Cycle System is in steady state and in thermal equilibrium.
2. It is taken the isentropic efficiency of the turbine as 80%.
3. The isentropic efficiency of the feed pump as 80%.
4. The efficiency of the generator is taken as 90%.
5. With reference to the research papers the ‘Turbine Outlet Pressure’ is taken as 7.5 bar.
6. The losses at the pipe lines and its junctions are negligible.
7. Ignore the pressure losses at each component.
8. It is assumed that all heat exchanger and cooler devices are using external insulations.
9. There is no absorption or incomplete boiling.
10. The Ammonia concentration at the turbine inlet is considered as 100% due to inconvenience of finding a proper table for calculation.

As explained in the Chapter 03, compared to the water the boiling point of the Ammonia is very low. Due to the zeotropic nature of this mixture more efficient energy harvesting could be done.

Following system specifications were assumed for the model.

1. Source Fluid Temperature - 125°C
2. Ambient Temperature - 27°C
3. Flue gas flow rate - 50 kg/s
4. Inlet temperature of water - 30°C
5. Power rating of the feed pump - 7.5 kW

In this analysis, the following were considered.

- As per the literature referred, in most cases the 'Turbine Inlet Pressure' was varied between 30 – 50 bar. Therefore, the analysis was carried at the range 20-50 bar.
- As KCS11 was used for the analysis, it is expected to use it for harnessing the low-grade heat energy. Therefore, the separator temperature range used for this analysis was 100 – 160 °C.
- As per literature, practically 'Turbine Outlet Pressure' is being maintained less than 10 bar. Mostly between 5-8 bar. Therefore, the analysis was done by varying the 'Turbine Outlet Pressure' from 4-10 bar.
- The feed water pump power was gradually increased from 2 – 16 kW.

Relationship between the 'Separator Temperature' and 'Cycle Efficiency'

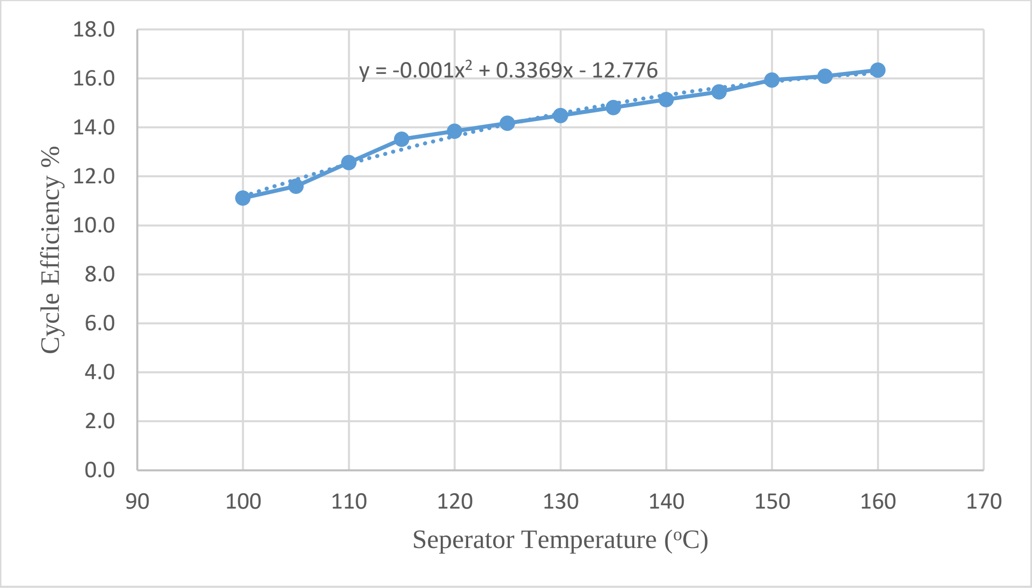

Figure 5.3: Variation of Cycle Efficiency with Separator Temperature

Following key points could be identified from figure 5.3;

- Cycle Efficiency is increasing with the increasing 'Separator Temperature'. The ammonia-water mass flow rate was kept as 1 kg/s.

- As the gradient is lowering with the increasing temperature, we can assume that within shorter period the maximum efficiency will be stabilized.
- The predicted equation for the trend line is $y = -0.001x^2 + 0.3369x – 12.776$, which is a polynomial.
- By solving the equation, the ‘Separator Temperature’ which achieves the maximum efficiency of 15.6% is 168.45°C.

Relationship between the ‘Turbine Inlet Pressure’ and ‘Cycle Efficiency’

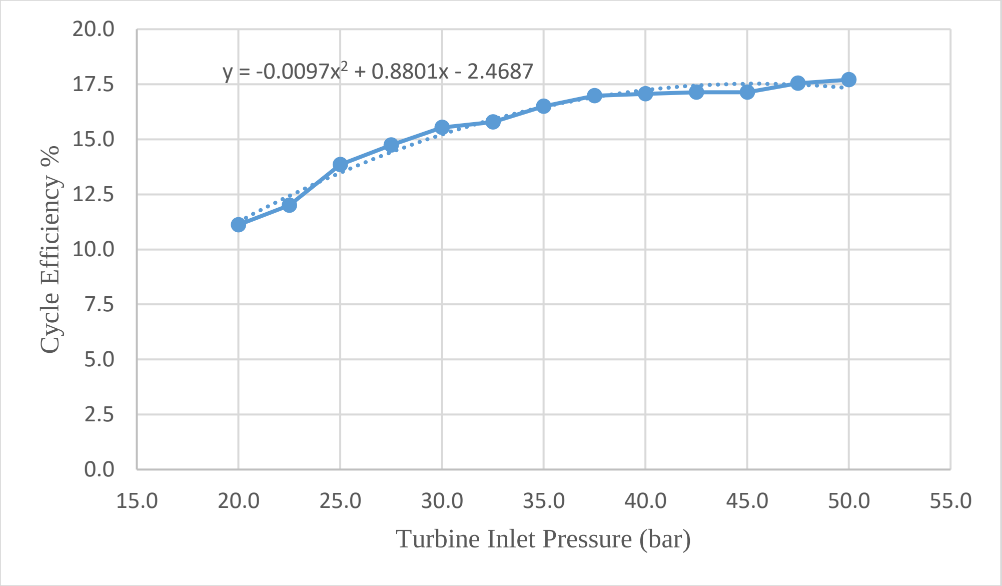

Figure 5.4: Cycle Efficiency variation with Turbine Inlet Pressure

Following key points could be identified from figure 5.4;

- The cycle efficiency is increased gradually with increasing ‘Turbine Inlet Temperature’.
- From 20 bar to 37.5 bar the rate of increasing the cycle efficiency is higher than the rest and then it is stabilized thereof.
- As per the literature survey most of the times the highest practical efficiencies were gained between 30-45 bar range.
- The predicted equation for the trend line is $y = -0.0097x^2 + 0.8801x - 2.4687$, which is a polynomial.

- By solving the equation, the maximum cycle efficiency of 17.5% is achieved at the 'Turbine Inlet Pressure' of 45.36 bar.

Relationship between the 'Turbine Outlet Pressure' and 'Cycle Efficiency'

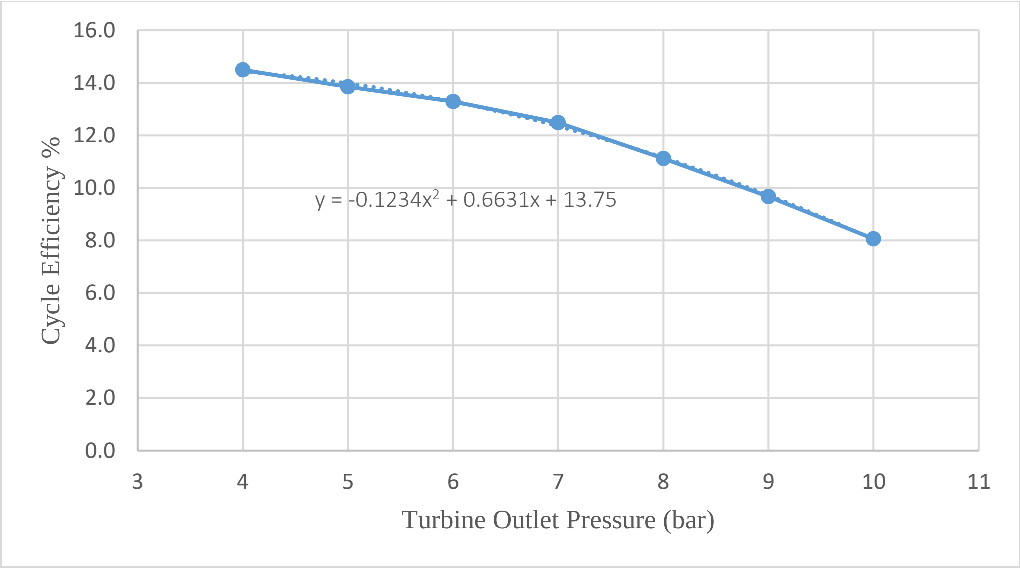

Figure 5.5: Variation of Cycle Efficiency with Turbine Outlet Pressure

Following key points could be identified from figure 5.5;

- As shown in the figure the cycle efficiency is decreased with the increasing 'Turbine Outlet Pressure'. This is severe in the higher pressures.
- Typically, in real applications the pressure range which is being used for the 'Turbine Outlet' is 6-8 bar.
- The trend line equation for the above polynomial is $y = -0.1234x^2 + 0.6631x + 13.75$, which has a peak.
- By solving the equation, the maximum efficiency of 14.64% is achieved at the 'Turbine Outlet Pressure' of 2.69 bar.

Relationship between the 'Feed Water Pump Power' and 'Cycle Efficiency'

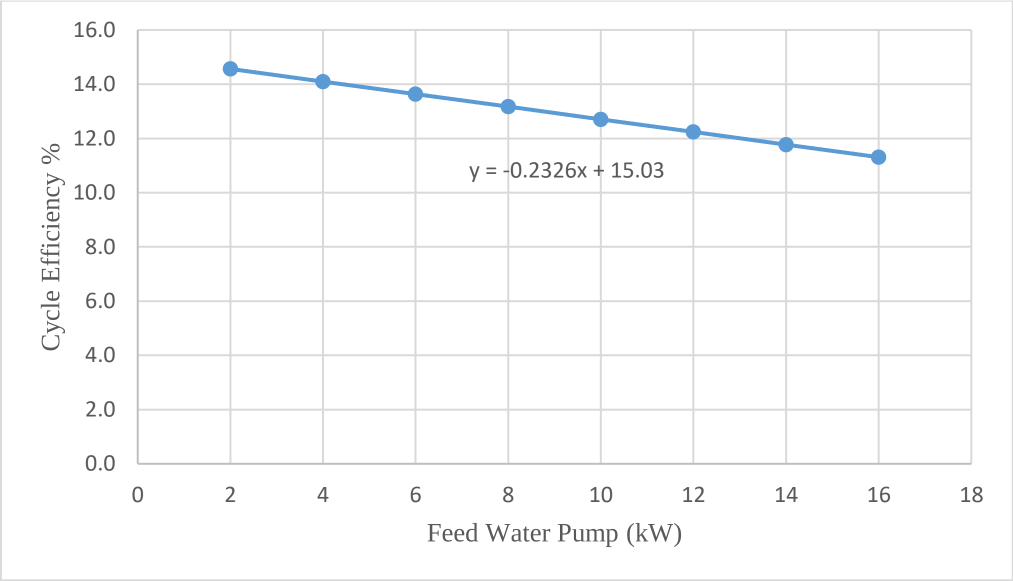

Figure 5.6: Variation of the Cycle Efficiency with Feed Water Pump power consumption

Following key points could be identified from figure 5.6;

- The cycle efficiency is reduced in a linear manner with the increasing 'Feed water pump power'.
- Generally, as a rule of thumb, it is kept as 10% of the Turbine Power.
- The trend equation predicted is $y = -0.2326x + 15.03$.

As there are lot of variations in 'Cycle efficiency' referred to different parameters, it is required to find the optimized point concerning all.

CHAPTER 6

CASE STUDY

In this chapter, it is expected to adopt the analysis for the power stations which generate low grade heat energy which is below 200^{o}C. From the data analysis at Chapter 4, it was identified that there are only two (02) power stations which generate low grade heat energy. They are,

1. Kelanitissa Combined Cycle Power Plant
2. Lakvijaya Power Plant

The flue gas temperatures of all other thermal power stations are greater than 200^{o}C. Therefore, within the defined scope of the analysis was carried out only for above two power stations.

6.1 Kelanitissa Combined Cycle Power Plant

Kelanitissa Combined Cycle Power Plant was commissioned and connected to the national grid in the year 2002. The capacity of the plant at full load is 165 MW. It is a combination of a gas turbine and a steam turbine with a good thermal efficiency. There are certain environmental regulations which controls the emission factors depends on the ambient condition. However, the flue gas conditions of KCCP is shown below.

- Flue gas mass flow rate : 110 kg/s
- Flue gas temperature : 150^{o}C

Relationship between the 'Turbine Inlet Pressure' vs 'Cycle Efficiency'

Following key points could be identified from figure 6.1;

- The cycle efficiency of the KCCP is gradually increased and the equation of the polynomial is $y = -0.012\ x^2 + 1.0245\ x – 4.163$.
- By solving the equation, the optimum cycle efficiency of 17.7 % is achieved at the 'Turbine Inlet Pressure' of 42.7 bar, which is a good pressure rating which matches with the other research results.

- Although the cycle efficiency is rapidly increasing from 20 bar to 35 bar, it is settled to a stable value within the range from 35 bar to 45 bar, and then gradually starting to reduce.
- The analysis was done for a flow rate of 2 kg/s of ammonia-water mix which is a moderate value.

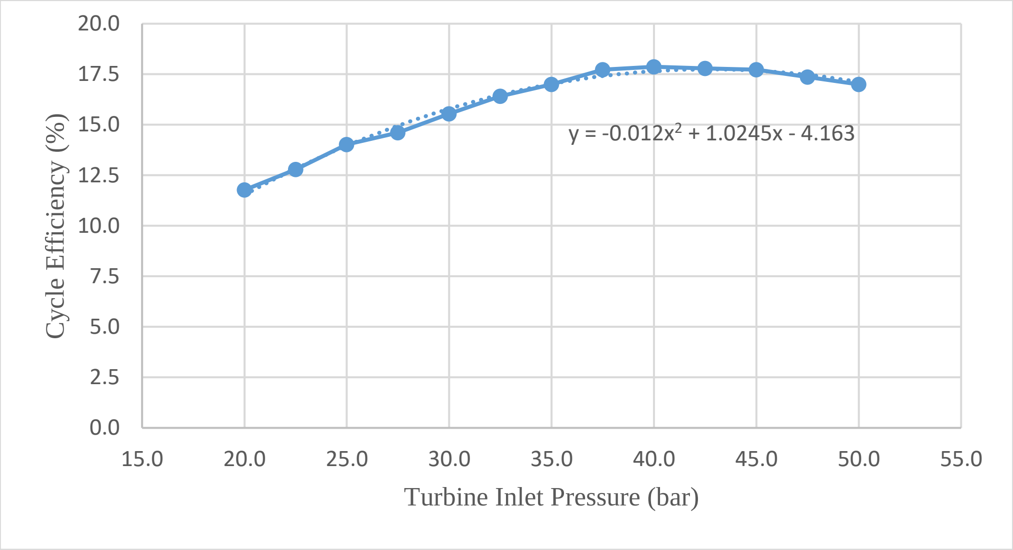

Figure 6.1: Turbine Inlet Pressure Vs Cycle Efficiency of KCCPP

Relationship between the 'Turbine Outlet Pressure' and 'Cycle Efficiency'

Following key points could be identified from figure 6.2;

- Similar to the model results, the 'Cycle Efficiency' is dropped down with the increase of the turbine outlet pressure.
- The frequency where the efficiency drop is almost in a leaner pattern.
- There is a requirement of maintaining the minimum 'Turbine Outlet Pressure' above the atmospheric pressure.
- When the pressure drop through the turbine is high, proportionate amount of energy is fed to the pump to build up the rated 'Turbine Inlet Pressure'.
- Therefore, most occasions moderate values like 5-7 bar are used for the KCS11.

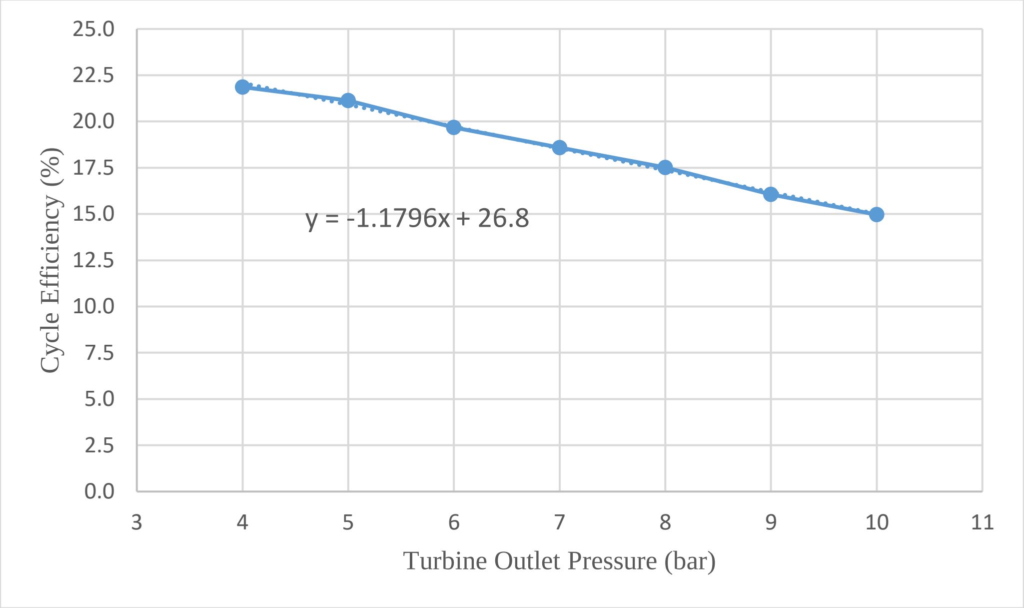

Figure 6.2: Turbine Outlet Pressure vs Cycle Efficiency of KCCPP

Relationship between the 'Turbine Outlet Pressure' and 'Cycle Efficiency'

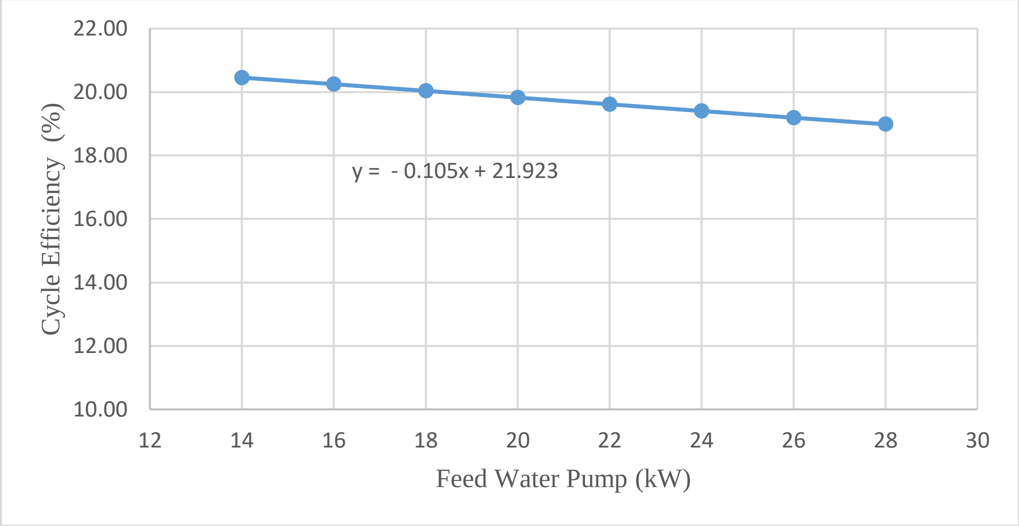

Figure 6.3: Variation of Cycle Efficiency over the Feed water pump work at KCCPP

Following key points could be identified from figure 6.3;

- Similar to the study of the model, the variation of the 'Cycle Efficiency' has a linear correlation with the power consumption of the feed pump. As per the documents the power consumption of the feed pump is around 10% from the power generated from the turbine.

By considering above variations with the practical scenarios, it can be concluded that the best operating conditions for the Kelanitissa Combine Cycle Power Plant are,

- Separator Temperature : 150^{o}C
- Turbine Input Pressure : 40 bar
- Turbine Output Pressure : 5 bar
- Concentration at Turbine Inlet : 1.0
- Feed Water Pump Work : 20 kW
- Mass flow rate of NH_3-H_2O mix : 2 kg/s
- Kalina Cycle Efficiency : 19.82%
- Work output from turbine : 208.74 kW

6.2 Lakvijaya Power Plant

Lakvijaya Power Station comprises of three (03) generating units of each 300MW. The first machine was commissioned in July 2011. The next two were in May 2014 and October 2014 respectively. These machines are the most critical machines for generating the daily power requirement of country and because of its importance, the operational condition of Lakvijaya Power Station is included as a Key Performance Indicator in the field of State Power Generation sector. The fuel used for the power station is Coal. However, at starting and low operating loads diesel is used. The general flue gas data of a one unit of Lakvijaya Power Plant Could be shown as below.

- Flue gas mass flow rate : 275 kg/s
- Flue gas temperature : 125^{o}C

Relationship between the 'Turbine Inlet Pressure' vs 'Cycle Efficiency'

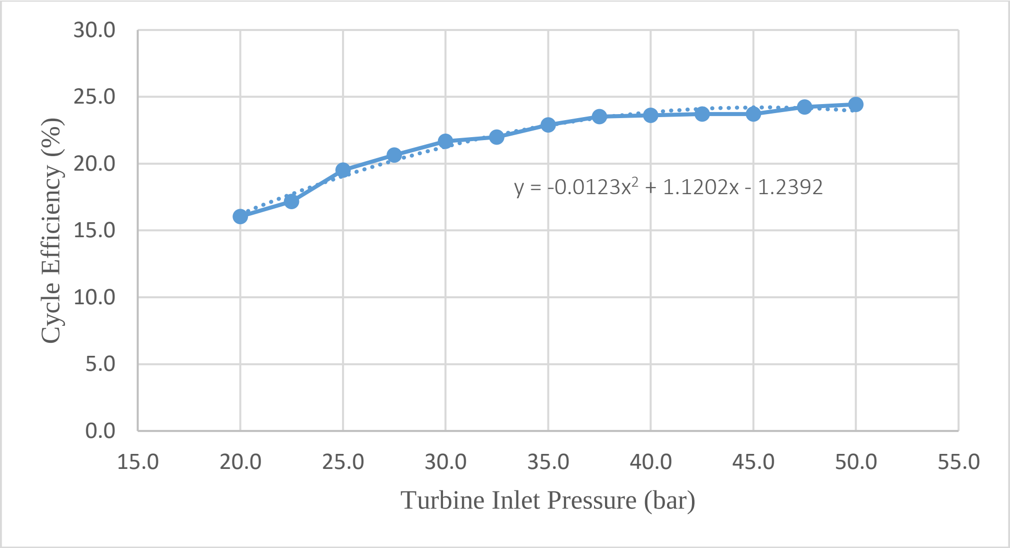

Figure 6.4: Cycle Efficiency over the Turbine Inlet Pressure of Lakvijaya Power Plant

Following key points could be identified from figure 6.4;

- Till 37.5 bar the cycle efficiency is rapidly increased and started to stabilize around 24%. Eventhough the Turbine Inlet Pressure is increased further, considerable increase could not be seen in the Cycle Efficiency.
- The cycle efficiency of the Lakvijaya Power Plant is gradually increased and the equation of the polynomial is $y = -0.0123\ x^2 + 1.1202\ x - 1.2392$.
- By solving the equation, the optimum cycle efficiency of 24.26 % is achieved at the 'Turbine Inlet Pressure' of 45.5 bar, which is a good pressure rating which matches with the other research results.

Relationship between the 'Turbine Outlet Pressure' vs 'Cycle Efficiency'

Following key points could be identified from figure 6.5;

- When increasing the 'Turbine Outlet Pressure', the 'Cycle Efficiency' started to drop 18 % to 12%.

- The rate at which the cycle efficiency drop from 7-10 bar is much greater than 4-7 bar.
- With the practical applicability after considering all external factors, the value of 7.5 bar is selected for the cycle as the ‘Turbine Outlet Pressure’.

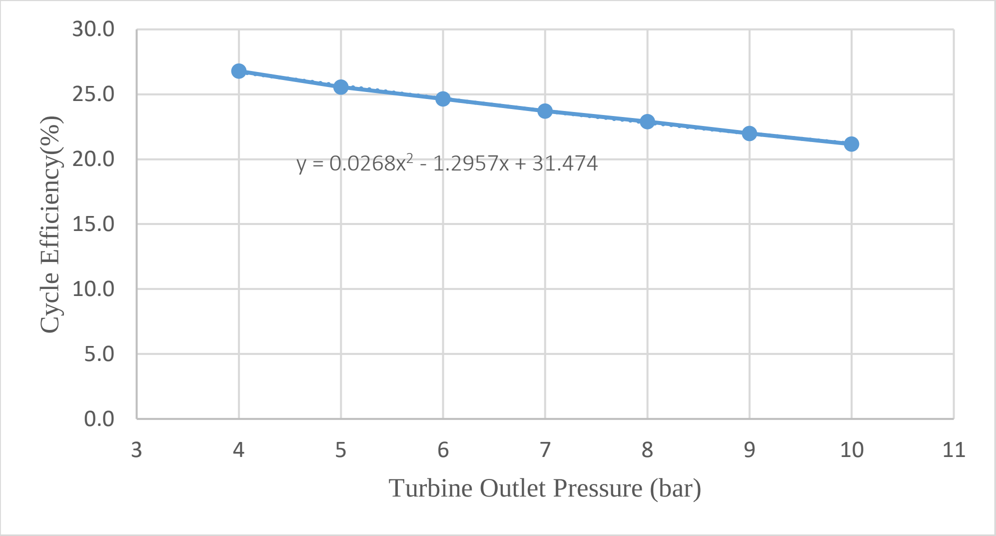

Figure 6.5 : Cycle Efficiency with the Turbine Inlet Pressure of Lakvijaya PP

Relationship between the ‘Turbine Inlet Pressure’ vs ‘Cycle Efficiency’

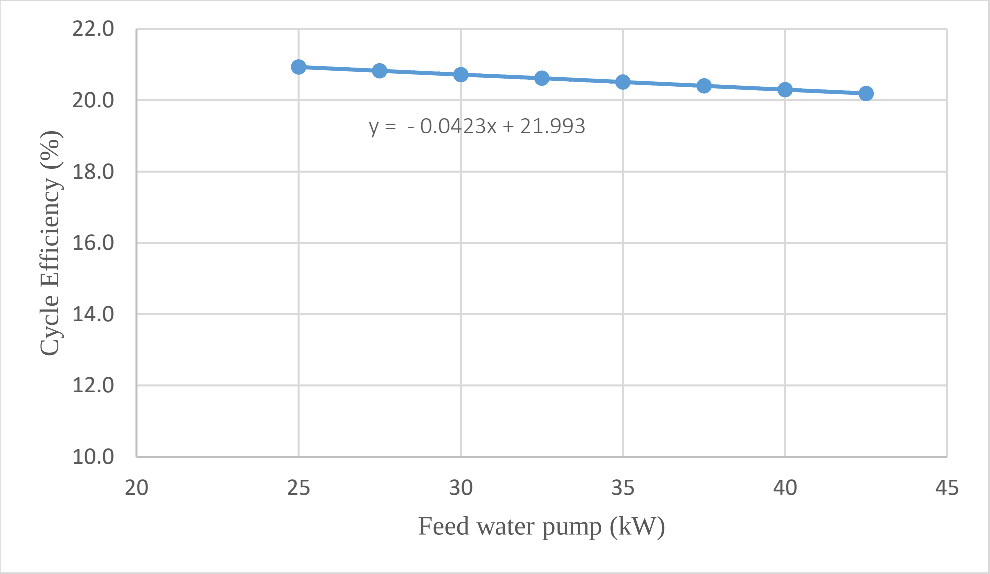

Figure 6.6: Cycle Efficiency over the Feed Water Pump Power at Lakvijaya PP

Following key points could be identified from figure 6.6;

- When the Feed water pump power increases, it shows a linear correlation with the cycle efficiency.
- The cycle efficiency is varied between 16% -17 % throughout the series.
- We can understand that, when pump power is increased the losses simultaneously increased.
- However, to match the cycle performance a pump with a rating of 10 kW is selected.

By considering above variations with the practical scenarios, it can be concluded that the best operating conditions for the Lakvijaya Power Plant are,

- Separator Temperature : 125^{o}C
- Turbine Input Pressure : 40 bar
- Turbine Output Pressure : 6 bar
- Concentration at Turbine Inlet : 1.0
- Feed Water Pump Work : 30 kW
- Mass flow rate of NH_3-H_2O mix : 7 kg/s
- Kalina Cycle Efficiency : 20.7 %
- Work output by the turbine : 520.12 kW

CHAPTER 7

ECONOMIC ANALYSIS

Economic analysis was carried for the selected two power stations. Method of Net Present Value (NPV) was adopted for the project investment evaluation.

7.1 Investment Cost for KCS11

Generally, the capital investment of a project includes lands, buildings, equipment's, technologies, design, consultancy, construction and commissioning. As these projects are to be configured within the system, no much of building or lands are required. Instead huge cost of involved due to sophisticated designs and consultancy is involved. Also, the component used for the binary fluid system are different from the components used for steam.

As stated before, lot of technical aspects are linked with these projects. Most of the suppliers are reluctant to elaborate their financial and technical figures to the public. Therefore, it is a barrier to conduct a successful analysis, which matches the actual situation. Following estimated investment cost could be found through literature. As per the available figures the investment for a 500 kW power plant is around USD 720,000, which means USD 1,440 in the year 2003 [34]. With the inflation and time factor we assume that the price has increased from 1.4 times. Therefore, the current investment for 1kW is USD 2016.

Note: It is considered that the cost for lesser values of MW is from the same rates shown above. The exchange rate was considered as, 1 USD = Rs. 150.00

7.2 Net Present Value

The Net Present Value (NPV) is the present value of all expected cash flows. Which means the 'difference between the present value of cash inflow and the present value of cash outflow'. Here the cash inflows are cash generated from investment and cash outflows are the expenditures for such investments. NPV is a of tool used for analyzing the profitability of a project in capital budgeting.

The NPV relationship between inflows and outflows are shown below.

$$NPV = \sum_{i=1}^{n} (B - C)i * Ai$$

Where,

NPV	-	Net Present Value
B	-	Cash inflow or benefit
C	-	Cash outflow or investment
A	-	Discount rate

The discount rate is the rate of return used in a discounted cash flow analysis to determine the present value of future cash flows. The discount rate takes in to account not only the time value of money, also the risk or uncertainty of future cash flows. Hence, greater the uncertainty of future cash flows, the higher the discount rate.

The discount rate can be calculated as below;

$$A = \frac{1}{(1 + i)^p}$$

i	-	Interest rate
p	-	Period or years

Approximate capital investment calculations were done based the turbine work output calculations in Chapter 06.

Table 7.1: Technical and financial details of selected power stations

Waste Heat Recover Opportunity	Expected Electric Output (kW)	Estimated Plant Capacity (kW)	Investment Cost (USD) per kW	Total Investment Rs.
KCCP	208.74	210	2016	63,504,000.00
Lakvijaya Power Plant	520.12	520	2016	157,248,000.00

The most of the thermal power stations operating all over the world are maintaining higher plant factors. That is because most of the thermal power stations are operated as ‘Base Load’ plants which are being operated for 24 hrs. Normally, due to the nature of operation of thermal power stations, it could not be started and stopped within short period of time. For example, Lakvijaya Power Station operating in Sri Lanka maintain plant factor more than 70% which will directly reduce the power purchasing from Independent Power Producers (IPP). For these calculations, it is assumed that Lakvijaya Power Station is operating with Plant Factor of 70%. The operation of the Kelanitissa Combined Cycle Power Station is not operated in regular manner. Its operating hours are much more less and it is about 40% of total running hours. For the calculation purposes, it is assumed that these patterns will exist for next 05 years.

Due to the fluctuation in electricity tariff and varying inflation, it has become complex part in analysis the financial perspectives. However due to unsteady economic condition have push us to evaluate the investment under different scenarios. By using these different scenarios, it helps to build up a picture of the future and to identify different future threats and adopt accordingly.

Seven (07) different scenarios were defined as shown in table 7.2 were analyzed using the existing bank interest rates and electricity tariff rates.

Table 7.2: Different Scenarios for Financial Evaluation

Practical Scenario	**Average Unit Selling Rate**	**Bank Interest**
Scenario 01	14.00	8 %
Scenario 02	15.00	8 %
Scenario 03	15.40	8 %
Scenario 04	14.00	10 %
Scenario 05	15.00	10 %
Scenario 06	15.00	12 %
Scenario 07	Refer to the table 7.5	

Table 7.3: Plant running hours and interests rate for scenario 7

Waste heat recovery opportunity	**Average Annual Running**	**Exp. Running hours per year**	**Average Unit Selling Rate (Rs.)**	**Interest Rate**
Lakvijaya Power Plant	70 %	6132	15.00	10%
KCCPP	40 %	3504	15.00	10%

The table 7.3 shows some realistic figures relevant to Lakvijaya and Kelanitissa Power Plants. Kelanitiss Combined Cycle Power Plant is operated when relatively cheaper power generating units are not available. However, in recent past with the draught conditions of environment, even expensive thermal power stations became critical in fulfilling the necessity. Generally, the actual selling cost is Rs.15.40, however for the scenario 07 the unit operating cost was considered as Rs.15.00. Thus, it is expected to have a price reduction in future. At present the bank interest rates are slightly high as 11-12%. However, in long term it is assumed that 10% is a reasonably acceptable rate. Thus, with these approximations, it is expected to get a close practical value from the scenario 07.

Further, it is assumed that the total overheads including operation and maintenance, spares, labour cost are 1% of total investment for the next 5 years.

6.3 NPV Results

The calculations were done for 07 scenarios to identify the feasibility of the Kalina Cycle System 11. Following table shows the NPV calculations.

Table 7.4: Net Positive Value for different waste heat opportunity

WHR Opportunity	Net Cash Flow after 05 year's						
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**
KCCP	(4,711,807)	(331,256)	1,420,965	(7,685,104)	(3,526,090)	(10,424,088)	12,664,381
Lakvijaya Power Plant	(10,715,422)	199,652	4,565,682	(18,126,012)	(7,762,945)	(24,952,605)	(51,465,031)

The letters shown in 'Red' colour are the negative incomes. The final outcomes are shown below.

Table 7.5: Summery of feasibility of investment

WHR Opportunity	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**
KCCP	x	x	√	x	x	x	x
Lakvijaya PS	x	√	√	x	x	x	√

Referring to the above summery key points could be addressed as,

- The scenario 1,4,5 and 6 are not economically feasible.
- Scenario 2 and 7 is feasible for Lakvijaya Power Station.
- Scenario 3 is feasible for both power stations.

Selected scenario for the power station;

- Scenario 7 is the most realistic scenario and it is applicable for Lakvijaya Power Plant.
- Scenario 3 is the only matching scenario for the Kelanitissa Combined Cycle Power Plant.

CHAPTER 8
CONCLUSIONS

In a technical application, the utmost important thing is to understand opportunity. Subsequently when there are few alternatives the selection of the suitable, practical, economical solution is very much vital. However, in some instances, we have to practice some of the solutions and get to know its applicability through the results. Evaluation of the solutions both technically and economically is important.

In this thesis, the main focus was given for understanding the waste heat opportunities through the thermal power stations operating under CEB. Then the applicable waste heat recover systems for low-grade heat energy was analyzed and based on literature Kalina Cycle was selected as the appropriate technology. As there are different configurations in Kalina Cycle Systems, KCS 11 was selected to carry-on the thesis as its temperature range captures the most critical power station in Sri Lanka, Lakvijaya Power Plant for evaluation. Then and there, technical and financial evaluation was done.

From this thesis following points can be abstracted as conclusion.

8.1 Theoretical Evaluation

- The selection of the appropriate ‘Kalina Cycle System’ depends on the source temperature.
- As the waste heat is free, it is important to pay attention on ‘Work Output’ than the ‘Cycle Efficiency’.
- There is a correlation between the ‘Separator Temperature’ and the ‘Cycle Efficiency’. The ‘Separator Temperature’ is directly proportionate to the ‘Cycle Efficiency’.
- When the ‘Turbine Inlet Pressure’ increases at lower pressures, ‘Cycle Efficiency’ increases in a rapid manner and after 35 bar it tries to settle. It is expected that in higher pressures, again the ‘Cycle Efficiency’ tends to drop.

- When the 'Turbine Outlet Pressure' is increased, the 'Cycle efficiency' is dropped rapidly.
- There is a liner relationship in 'Pump Power' with the 'Cycle Efficiency'.

8.2 Case Study & Economical Evaluation

- Best operating parameters and outputs from Kelanitissa Combined Cycle Power Station are,
  - Separator Temperature : 150^{o}C
  - Turbine Input Pressure : 40 bar
  - Turbine Output Pressure : 5 bar
  - Concentration at Turbine Inlet : 1.0
  - Feed Water Pump Work : 20 kW
  - Mass flow rate of NH_3-H_2O mix : 2 kg/s
  - Kalina Cycle Efficiency : 19.82%
  - Work output from turbine : 208.74 kW
- Best operating parameters and outputs from Lakvijaya Combined Cycle Power Station (for 300 MW) are,
  - Separator Temperature : 125^{o}C
  - Turbine Input Pressure : 40 bar
  - Turbine Output Pressure : 6 bar
  - Concentration at Turbine Inlet : 1.0
  - Feed Water Pump Work : 30 kW
  - Mass flow rate of NH_3-H_2O mix : 7 kg/s
  - Kalina Cycle Efficiency : 20.7 %
  - Work output by the turbine : 520.12 kW
- As per the economic analysis, 07 scenarios were analyzed and Net Present Values for 05 years were calculated. Due to the high investment, it shows that the application of KCS 11 is not feasible.

8.3 Research Limitations

- As the literature, relevant to isentropic events in different mass fraction was not available, it was assumed that the ‘Turbine Inlet’ is 100% ammonia concentrated.
- Due to the non-availability of details the research was limited to ammonia-water mixture.
- Efficiencies of the recuperators, turbine, generator, working fluid pump were assumed. Moreover, it was considered that the external heat losses from the cycle is zero.

8.4 Future Work

- It is needed to find out other suitable binary fluids for the system and carryout the same analysis.
- Find literature relevant to ammonia-water mass fraction and proceed with varying fractions to the ‘Turbine Inlet’.
- The same practice can be expanded to cover all other thermal power stations using other Kalina Cycle Systems.
- Extensive investigations are required on the expander which work with ammonia-water mixture at different conditions.

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APPENDIX A: TEST RESULTS

Results for Model Test:

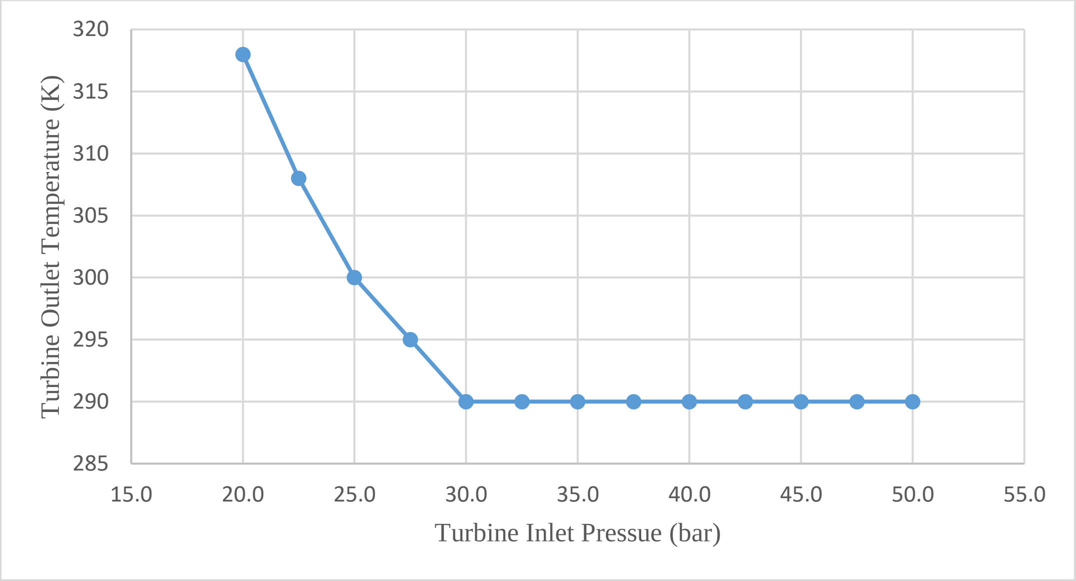

Figure A.1: Turbine Inlet Pressure vs Turbine Outlet Temperature of the model

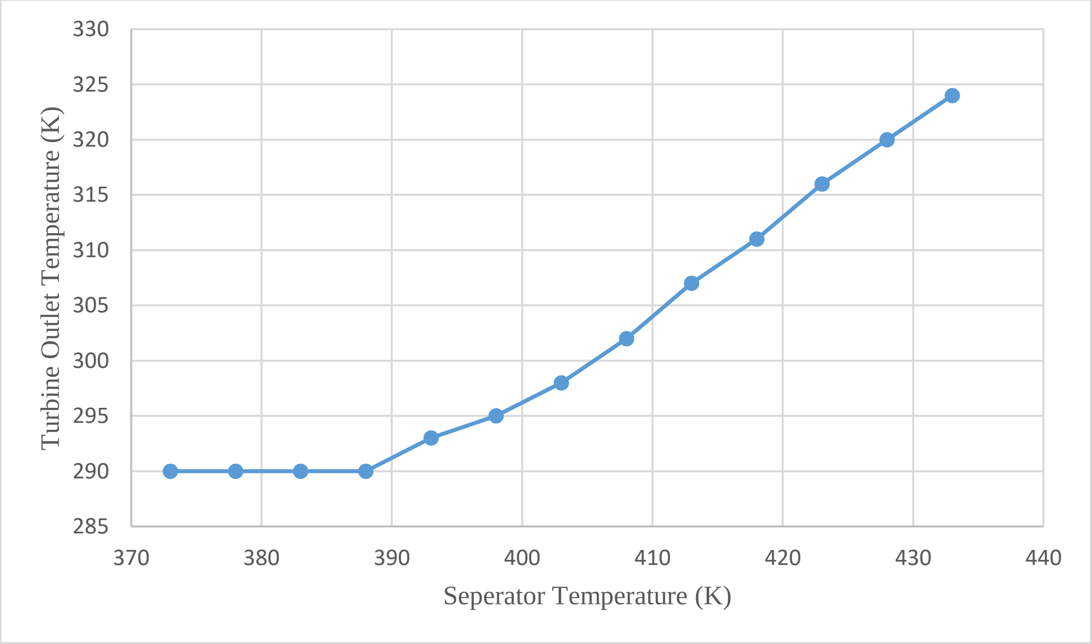

Figure A.2: Separator Temperature vs Turbine Outlet Temperature of the model

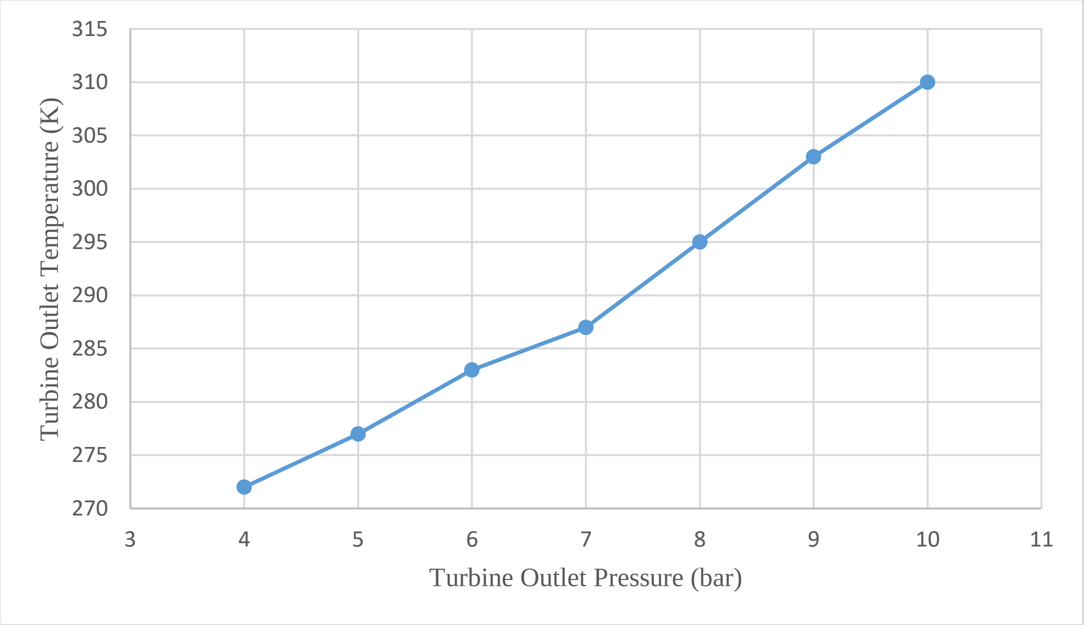

Figure A.3: Turbine Outlet Pressure vs Turbine Outlet Temperature of the model

Results for Kelanitissa Combined Cycle Power Plant:

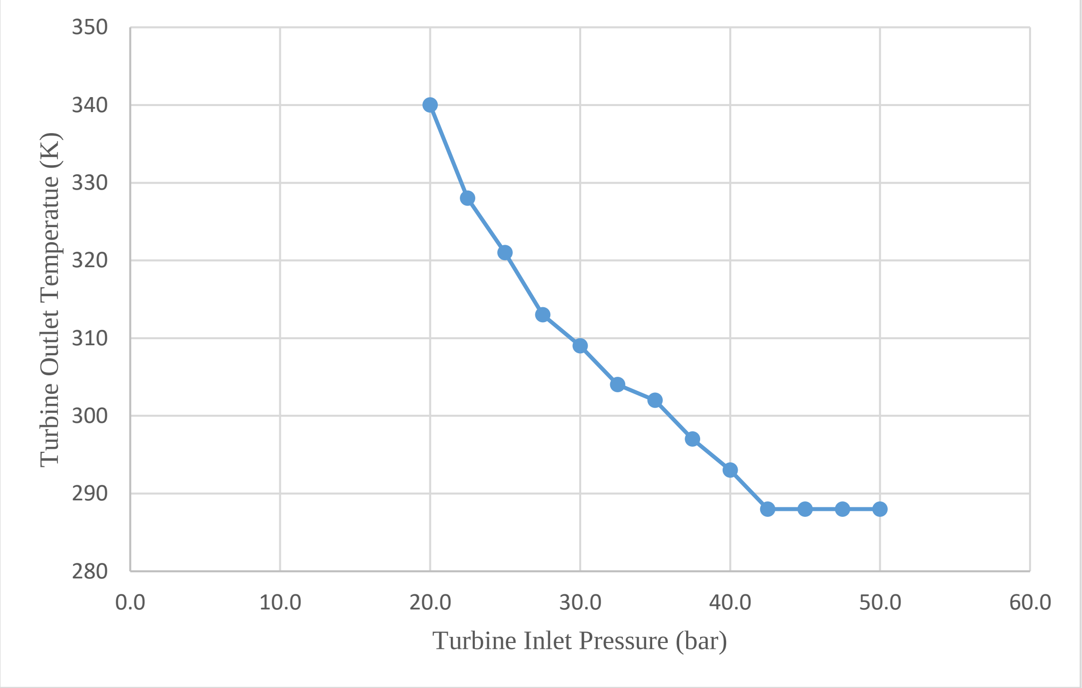

Figure A.4: Turbine Inlet Pressure vs Turbine Outlet Temperature at KCCPP

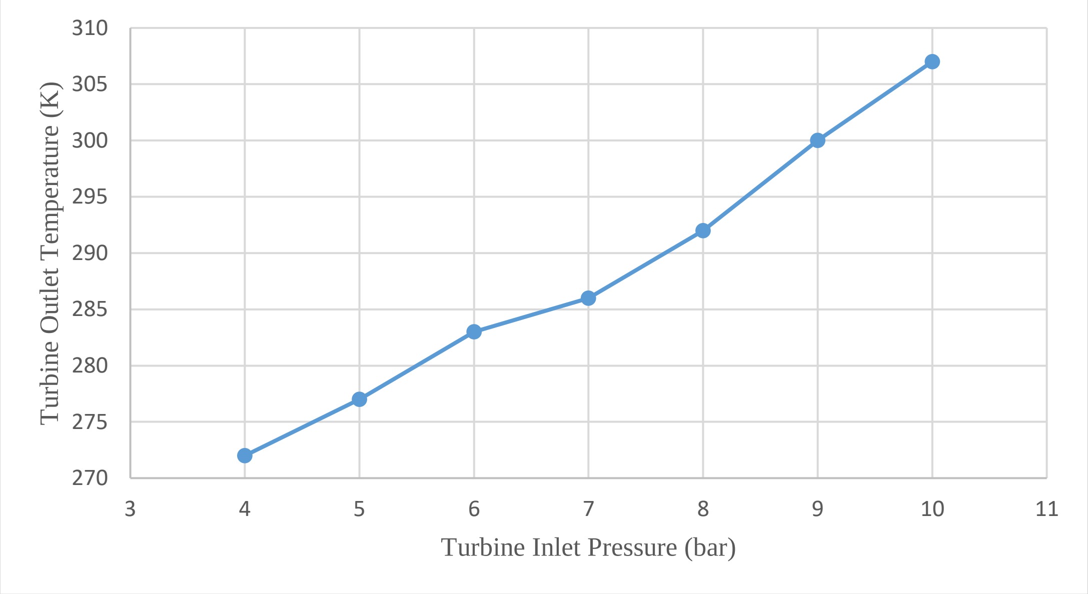

Figure A.5: Turbine Outlet Pressure vs Turbine Outlet Temperature of KCCPP

Results for Lakvijaya Power Plant:

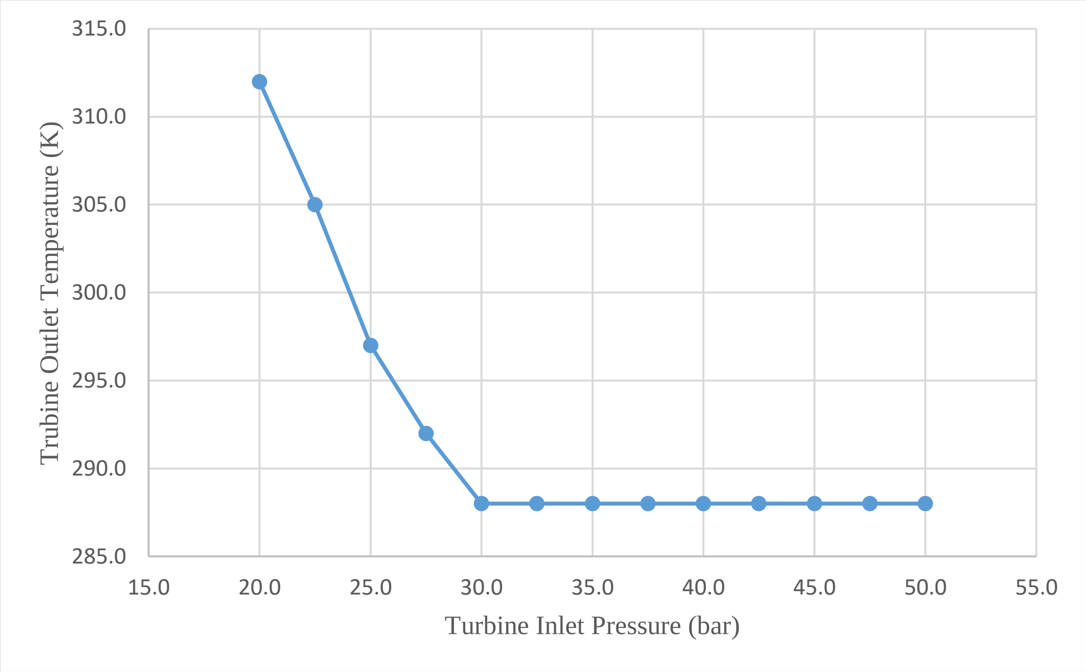

Figure A.6: Turbine Inlet Pressure vs Turbine Outlet Temperature of Lakvijaya Power Plant

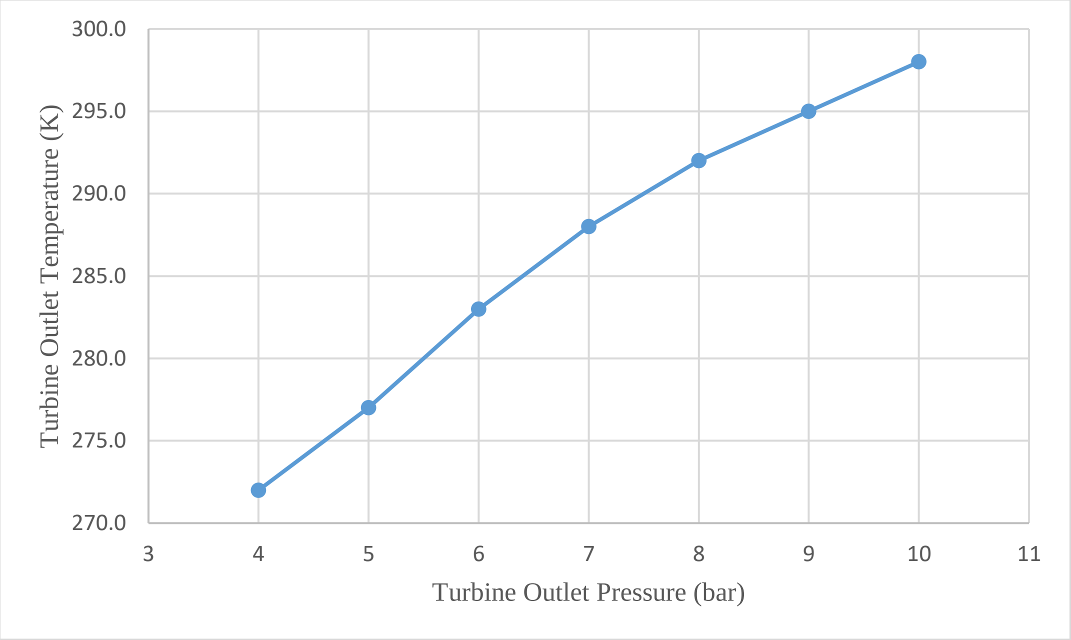

Figure A.7: Turbine Outlet Pressure vs Turbine Outlet Temperature of Lakvijaya Power Plant

APPENDIX B: RELEVENT DIAGRAMS

Ammonia mass fraction Vs Enthalpy diagram

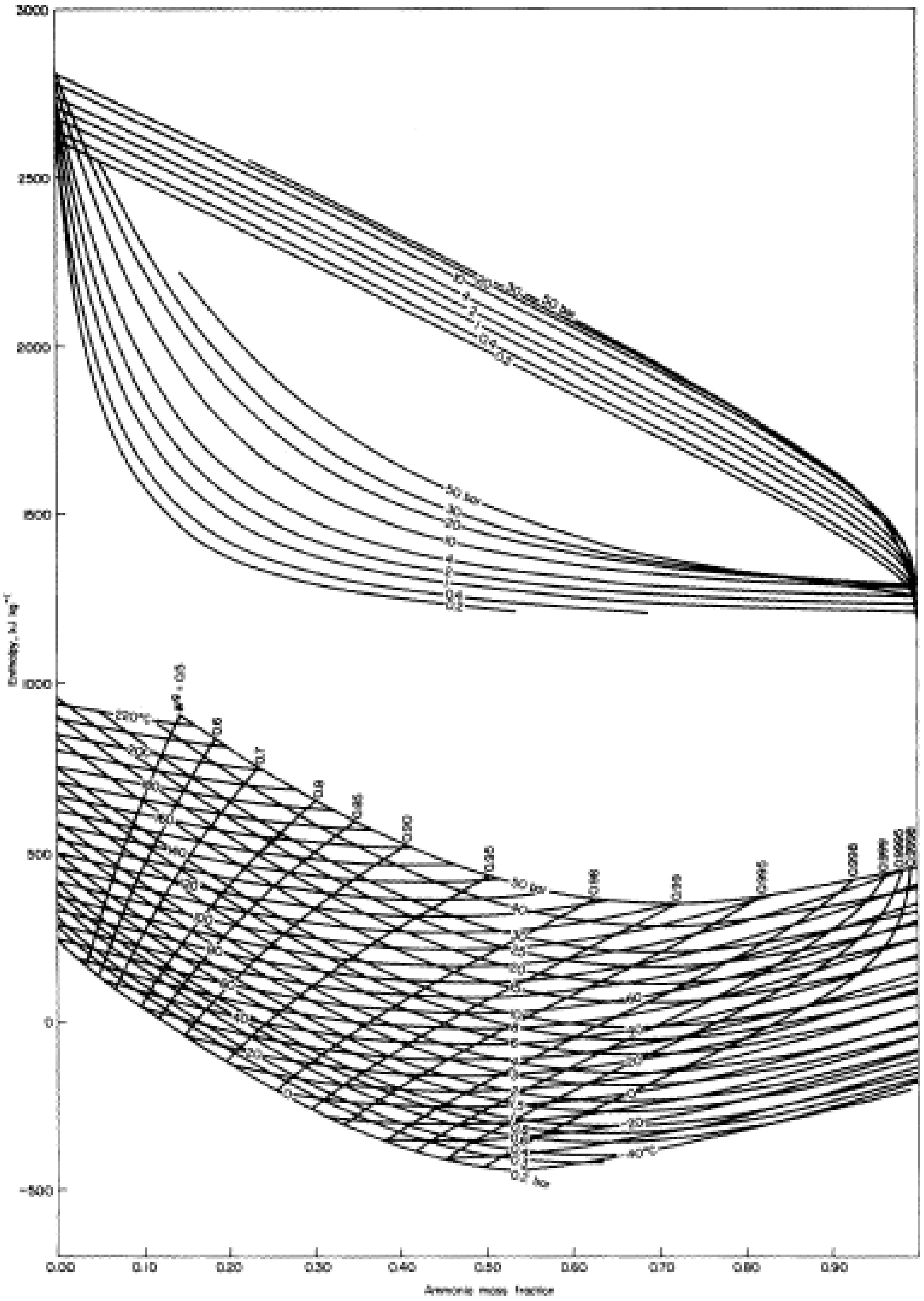

Figure B.1

Temperature Vs Engtropy graph for Ammonia

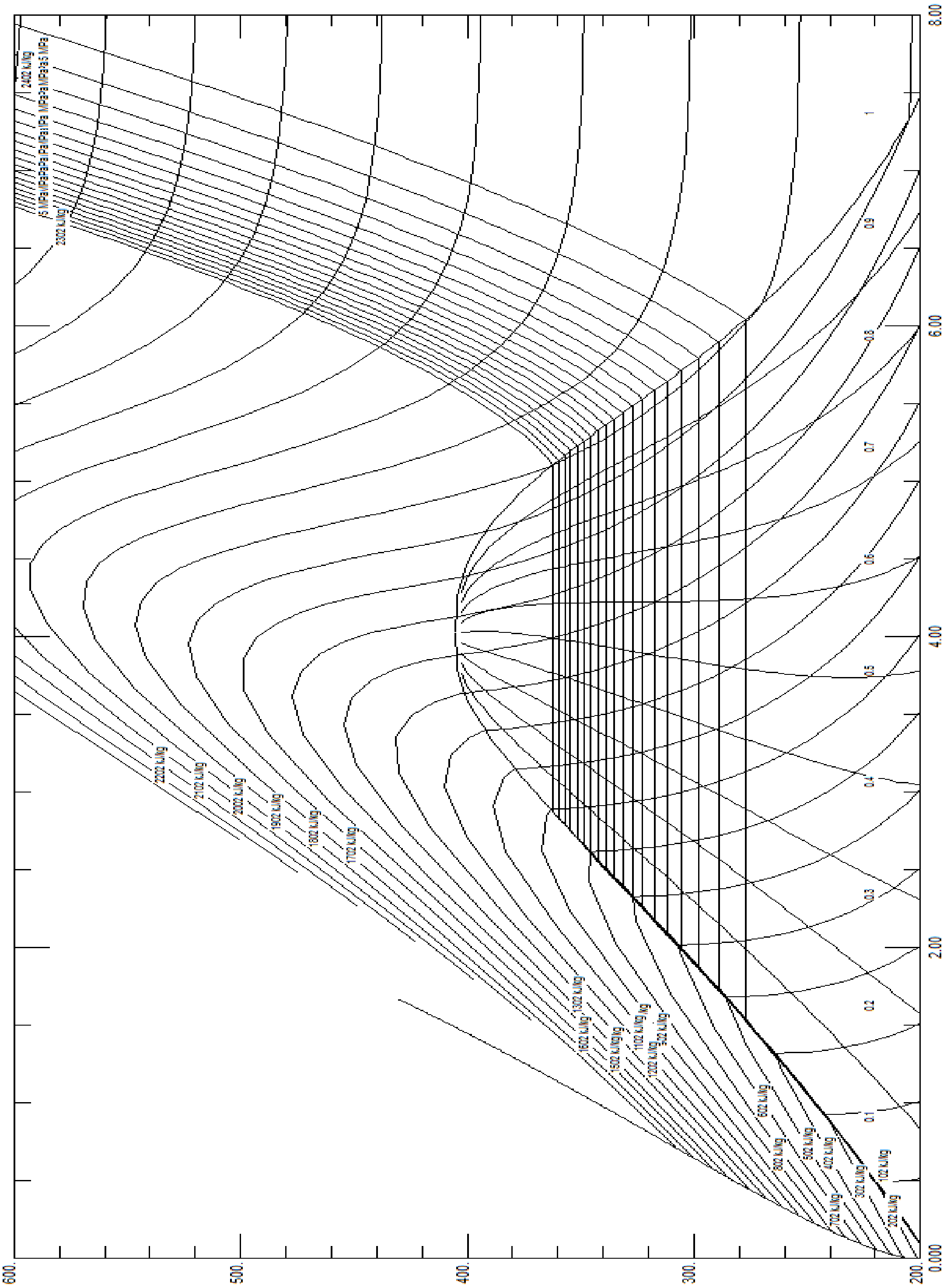

Figure B.2

APPENDIX C: NET POSITIVE VALUE CALCULATIONS

Depends on the different tariff rates and expected running hours, the annual turnover would be changed. Following tables will illustrate the annual turnover of the selected plants under different scenarios.

Table C.1: Expected annual turnover at 60% running hours & Rs. 14.00/kWh

Waste Heat Recovery Opportunity	Exp. Elec. Output (kW)	Exp. Running Hours per year	Exp. Generation kW/yr	Unit Selling Price (Rs.)	Exp. Annual Turnover (Rs.)
KCCP	208.74	5256	1,097,137.44	14.00	15,359,924.16
Lakvijaya PS	520.12	5256	2,733,750.72	14.00	38,272,510.08

Table C.2: Expected annual turnover at 60% running hours & Rs. 15.00/kWh

Waste Heat Recovery Opportunity	Exp. Elec. Output (kW)	Exp. Running Hours per year	Exp. Generation kW/yr	Unit Selling Price (Rs.)	Exp. Annual Turnover (Rs.)
KCCP	208.74	5256	1,097,137.44	15.00	16,457,061.60
Lakvijaya PS	520.12	5256	2,733,750.72	15.00	41,006,260.80

Table C.3: Expected annual turnover at 60% running hours & Rs. 15.40/kWh

Waste Heat Recovery Opportunity	Exp. Elec. Output (kW)	Exp. Running Hours per year	Exp. Generation kW/yr	Unit Selling Price (Rs.)	Exp. Annual Turnover (Rs.)
KCCP	208.74	5256	1,097,137.44	15.40	16,895,916.58
Lakvijaya PS	520.12	5256	2,733,750.72	15.40	42,099,761.09

Table C.4: Expected annual turnover at actual running hours & Rs. 15.00/kWh

Waste Heat Recovery Opportunity	Exp. Elec. Output (kW)	Exp. Running Hours per year	Exp. Generation kW/yr	Unit Selling Price (Rs.)	Exp. Annual Turnover (Rs.)
KCCP	208.74	3504	731,424.96	15.00	10,971,374.40
Lakvijaya PS	520.12	7895	4,106,347.40	15.00	61,595,211.00

Net Positive Value (NPV) Calculations

NPV calculations were done under 07 scenarios to investigate the feasibility of implementing WHR systems in identified heat sources. The calculations are shown below.

Table C.5: Scenario 1 – Electricity unit selling price Rs. 14.00, Interest Rate 8%

WHR Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	15,359,924	14,724,884	0.08	58,792,193	(4,711,807)
Lakvijaya PS	157,248,000	1,572,480	38,272,510	36,700,030	0.08	146,532,578	(10,715,422)

Table C.6: Scenario 2 – Electricity unit selling price Rs. 15.00, Interest Rate 8%

WHR Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	16,457,062	15,822,022	0.08	63,172,744	(331,256)
Lakvijaya PS	157,248,000	1,572,480	41,006,261	39,433,781	0.08	157,447,652	199,652

Table C.7: Scenario 3 – Electricity unit selling price Rs. 15.40, Interest Rate 8%

WHR Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	16,895,917	16,260,877	0.08	64,924,965	1,420,965
Lakvijaya PS	157,248,000	1,572,480	42,099,761	40,527,281	0.08	161,813,682	4,565,682

Table C.8: Scenario 4 – Electricity unit selling price Rs. 14.00, Interest Rate 10%

WHR Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	15,359,924	14,724,884	0.10	55,818,896	(7,685,104)
Lakvijaya PS	157,248,000	1,572,480	38,272,510	36,700,030	0.10	139,121,988	(18,126,012)

Table C.9: Scenario 5 – Electricity unit selling price Rs. 15.00, Interest Rate 10%

Waste Heat Recovery Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	16,457,062	15,822,022	0.10	59,977,910	(3,526,090)
Lakvijaya PS	157,248,000	1,572,480	41,006,261	39,433,781	0.10	149,485,055	(7,762,945)

Table C.10: Scenario 6 – Electricity unit selling price Rs. 15.00, Interest Rate 10%

WHR Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	15,359,924	14,724,884	0.12	53,079,912	(10,424,088)
Lakvijaya PS	157,248,000	1,572,480	38,272,510	36,700,030	0.12	132,295,395	(24,952,605)

Table C.11: Scenario 7 – Electricity unit selling price Rs. 15.40, Interest Rate 8%

WHR Opportunity	Total Investment Rs.	Total Overhead(OH) Cost 0.1% from Inv.	Exp. Turnover (TO) Rs.	Annual Return (TO-OH) Rs.	Interest Rate %	NPV of Income	PV of Inv. After 5 years
KCCP	63,504,000	635,040	11,263,944	10,628,904	0.08	42,438,133	(21,065,867)
Lakvijaya PS	157,248,000	1,572,480	63,237,750	61,665,270	0.08	246,211,542	88,963,542