FEASIBILITY ASSESSMENT OF THE APPLICABILITY OF TRI-GENERATION SYSTEMS IN THE APPAREL INDUSTRY IN SRI LANKA: A CASE STUDY

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List of Abbreviations

TGT	– Tri-generation Technology
TJ	- Tee Jay Lanka PLC
IPZ	– Industrial Processing Zone
HFO	– Heavy Fuel Oil
STG	– Steam Turbine Generator
KTPI	– Key Thermal Performance Indicator
KPI	– Key Performance Indicators
DCS	– Distributed Control System
OEM	– Original Equipment Manufacturer
CEB	– Ceylon Electricity Board
ESP	– Electrostatic Precipitator
GHG	– Greenhouse Gas
PRV	– Pressure Reducing Valve

ABSTRACT

In this study, the technical and financial performances of the first tri-generation plant installed in Sri Lanka were evaluated. This plant was installed at Tee Jay Lanka PLC; a leading knit fabric manufacturer in the local context.

In this tri-generation design, the thermal demand of the process was matched and the technology used was the Rankine cycle with a back-pressure turbine. The overall efficiency, heat to power ratio and the net electrical power were the technical parameters evaluated for the technical feasibility. The net cash flow was evaluated for the financial performance. The evaluation indicates that the TG plant operates below the technical performance of a TG system, which uses the same technology. The failure to operate the steam turbine was identified as the main factor for the underperformance. However, the financial feasibility was observed for the year 2016, indicating a positive cash flow throughout the year.

The detailed study reveals that the process steam flow variation caused the back-pressure variation and therefore, the tripping of the turbine. It was proposed to alter the turbine control mode from load command mode to the back-pressure mode. However, the turbine startups failed due to high vibration. After the dismantling of the turbine, it was found that the rotor had corroded and the turbine blades were loose. It was sent for repairs. Afterwards, the turbine is to be started under back pressure mode. If the operation is successful, the technical parameters which measure the performance will reach nominal levels.

The political factors affecting the performance were also reviewed in brief. The energy efficiency policies of the government are to be strengthened to encourage investment in energy efficiency projects. The policy of importing coal has to be reviewed again to assure a seamless supply chain especially for the small and medium scale users.

1 CHAPTER 1: INTRODUCTION

1.1 Background

The apparel industry is a key component that contributes to the Sri Lankan economy. According to socio-economic data published by the Central Bank of Sri Lanka for the year 2015, the export value of the apparel sector is US$ 4,820 million, which accounts for more than 45% of the total export revenue (Central Bank of Sri Lanka, 2014). However, one of the major issues faced by the apparel industry is the increased production cost of garments. With this, regional competitors, such as Bangladesh, India and Pakistan, are now proving to be a challenge to the Sri Lankan apparel industry. The apparel industry utilizes electrical power, heating and cooling for overall production activities. Electrical power is used to energize the various types of machinery, including the abundantly used sewing machines. Heat is widely used in different functions such as garment washing, dying and ironing among others. Additionally, cooling is required to condition the production atmosphere across the factories. The general practice is that the electrical power requirements, including the cooling via vapour compression, are supplied by the national electricity grid. The required heat load is fulfilled by the boilers installed at the factory. Most boilers utilize heavy fuel oil as the energy input, for steam production. In the recent past, several boilers were converted to biomass fueled boilers, with fire wood commonly used as the fuel material. The apparel industry is highly energy intensive due to the electricity, heating and cooling requirements. As such, tri-generation (TG) would be an attractive technology to implement for the reduction of production costs, in order to compete with other garment industries located within the South Asian region.

Tee Jay (TJ) Lanka PLC is a knit fabric manufacturer located in the Avissawella Industrial Processing Zone (IPZ). A coal fueled TG plant was installed in the year 2014 for the fulfillment of the energy requirements of the factory. This was the first TG plant installed in Sri Lanka.

1.2 Present Status

The TG plant installed at TJ Lanka PLC has been in operation since 2014 intermittently. The electricity generation, which represents one form of output energy, out of three, is hardly generated. Currently, only the boiler is in operation, and the steam generated is being distributed to the process and air conditioning for the production floor of the factory. However, the financial benefit of the installed TG system is seen due to the lower fuel cost of coal compared to expensive heavy fuel oil (HFO), which was utilized as fuel for steam production previously.

1.3 Problem statement

This study expects to identify the problem gaps of the TG plant installed at TJ Lanka PLC, in comparison to a typical TG plant. Following the comparison, suitable solutions are to be proposed, in order to operate the TG plant for optimal performance.

1.4 Aim and Objectives

The aim of this research is to conduct a technical and financial feasibility assessment to identify the gaps of the TG system installed at TJ Lanka PLC against a typical TG plant in operation.

The objectives of the research were:

a) Identification of the parameters affecting the performance of a tri-generation system

b) Deriving the KPIs (Key Performance Indicators) to evaluate and compare the performance of a tri-generation system

c) Evaluation of the tri-generation plant at TJ Lanka PLC with the derived KPIs and identification of the issues affecting the performance

d) Proposed solutions to the identified issues

1.5 Methodology

The methodology to achieve the above-mentioned aim and objectives are given below:

a) Literature review for the understanding of the energy mix of the apparel industry, the tri-generation concept and its various types and performance ratios

Identification of the energy usage and its related cost of the apparel industry is necessary to obtain the contribution margin of the utilities that play in the overall production cost in the industry. There are different types of apparel products and manufacturing methods available within the Sri Lankan context. Through literature, it expected to review widely used manufacturing methods and utilities usage.

The tri-generation concept is expected to be reviewed in detail. The differentiation between co-generation and tri-generation is also compared. The tri-generation architecture is dependent on the application. Commonly used TG concepts are reviewed in detail.

b) Derive KPIs which evaluates the performance of a TG system using the literature reference

Even though, different types of TG architecture are available, the key performance indicators (KPIs) can be used to measure performance across these different types. From this activity, the performance can be compared on a common platform. The identification of the critical parameters is carried out through literature reviews.

c) Site visits and reference of the technical and operation data, manuals to evaluate the TG plant at TJ Lanka PLC based on the derived KPIs.

Site visits were conducted to evaluate the performance of the TG plant located at the Avissawella Industrial Processing Zone. Operational data was obtained from the distributed control system (DCS) and used in the measurement of the performance. Further, spot measurements were taken, using externally fitted equipment, to calculate the heat balance and efficiency of the system. System operation data for the year 2016 was used to evaluate the KPIs of the TG plant. Technical manuals, for boiler and turbine, were critically referred to identify and understand the behavior of those equipment. The technical expertise of the operation crew and original equipment manufacturer (OEM) team was consulted in identifying the issues faced during the operation.

d) Identification of the performance gaps through the comparison of the KPIs against a typical TG plant of same kind.

Comparison of the KPIs obtained through literature review and the real-time performance data was carried out to identify the gaps in the performance of the TG plant, with a typical TG plant of same type. Further, explanations to the performance gaps were drafted which relates in resolving the issues faced.

e) *Reveal the facts that is caused for the performance gaps and propose solutions to optimize the performance*.

The methodology of corrective actions/remedial measures to be taken to obtain the optimal performance of the plant is discussed here. The approach to finding the solutions were proposed using the related literature reference and the technical expertise of the research person and advisors.

2 CHAPTER 2: REVIEW OF LITERATURE

2.1 Apparel Industry Energy Mix

The apparel industry can be divided into several sub industries based on functionality, and are listed below:

I. Fabric manufacturing
   - Woven fabric
   - Knit fabric
   - Synthetic fabric

II. Fabric printing

III. Fabric cutting and sewing

IV. Garments finishing

V. Manufacture of other elements (Buttons, zippers, hangers etc.)

The energy mix required across of all the above functionalities is diverse and difficult to figure out the energy consumption pattern based on the function. However, the requirement of electricity, heating and cooling exists across all of these functions. Apparel manufacturing is the highest energy intensive sector out of the above five components. The identification of the energy mix of these functions has to be carried out through a comprehensive study. Such a study has not been carried out thus far in the national context. In this research, it is expected to carry out the survey for the identification of the energy mix.

The average energy mix of the selected five factories that comprises the above five functionalities were evaluated through the analysis of the energy data of that factories. Since the production is differed from factory to factory, clock hours has been considered for the benefit of the comparison.

Function	Electricity (kWh)	Steam (kWh)	A/C (kWh)	Total energy (kWh)/clock hour
Knit fabric manufacturer	0.56	1.80	0.15	2.52
Fabric printing	0.41	1.54	0.06	2.01
Fabric cutting & sewing	0.01	0.73	0.73	1.48
Garments finishing	0.45	0.25	0.24	0.94
Button manufacturer	0.32	0.33	0.10	0.75

Table 1: Apparel Industry Energy Mix

According to the above table, fabric manufacturing represents the most energy consuming sector. The knit fabric manufacturer (Tee Jay) consumed about 2.52 kWh of energy per clock hour of the production. Therefore, the implementation of TG in to TJ was the most preferable decision.

2.2 Tri-generation technology

The concept of TG can be considered as a further development of co-generation technology. These concepts were initially implemented at thermal power plants in the United States of America (USA) and European Union (EU), to increase overall efficiency, as well as for obtaining energy at a cheaper price (Wikipedia the Free Encyclopedia, 2015). However, with the development of the TGT, this concept was expanded to medium and small-scale power generating facilities. Energy intensive industries, commercial and residential buildings such as super markets and residencies that are of large, medium and even small scale, are now practicing TGT due to the lower energy cost, in combination with a significant reduction of emissions, in comparison to the conventional way of fulfilling the said energy requirements.

There are several factors that need to be considered in designing a TG plant. Primarily, the triple energy requirements (electrical power, heating and cooling) have to be used together in a utility. If these three energy sources are present, the basic design is carried out based on the proportionalities of the said energy requirements. In order to implement the best configuration of the TG design, accurate thermodynamic analysis has to be carried out (E. Miniciuc, O. Le Corre, V. Athanasovici, M. Tazerout, I. Bitir, 2003). Secondly, the primary energy source needs to be considered. Gas turbines, reciprocating internal combustion engines and steam turbines are the widely used energy sources for the TGT. Based on the energy source, the energy harvesting technologies from the waste heat available by the primary energy source vary significantly. The fuel used in the energy source is another key factor that affects the design of a TG plant. The quantity of waste heat extraction from the main energy source is dependent on the sulphur content, moisture content, firing temperature of the fuel and other factors that occur during the combustion processes.

2.2.1 Tri-generation with the Rankine Cycle

Thermal power plants generate electricity through a steam turbine as per the Rankine cycle theory. Typical heat rates vary between 8,000 and 12,000 kJ/kWh$_e$ (U.S. Energy Information Administration, 2012). In general, two types of steam turbines can be utilized within the TG system design. These are the back-pressure steam turbines and extraction steam turbines.

Back Pressure Steam Turbines

At the exit of the turbine, steam exists at a pressure greater than the atmospheric pressure. This pressure is decided by the heat requirement for the process. The following diagram indicates the components of the back-pressure type steam turbine coupled with a tri-generation plant:

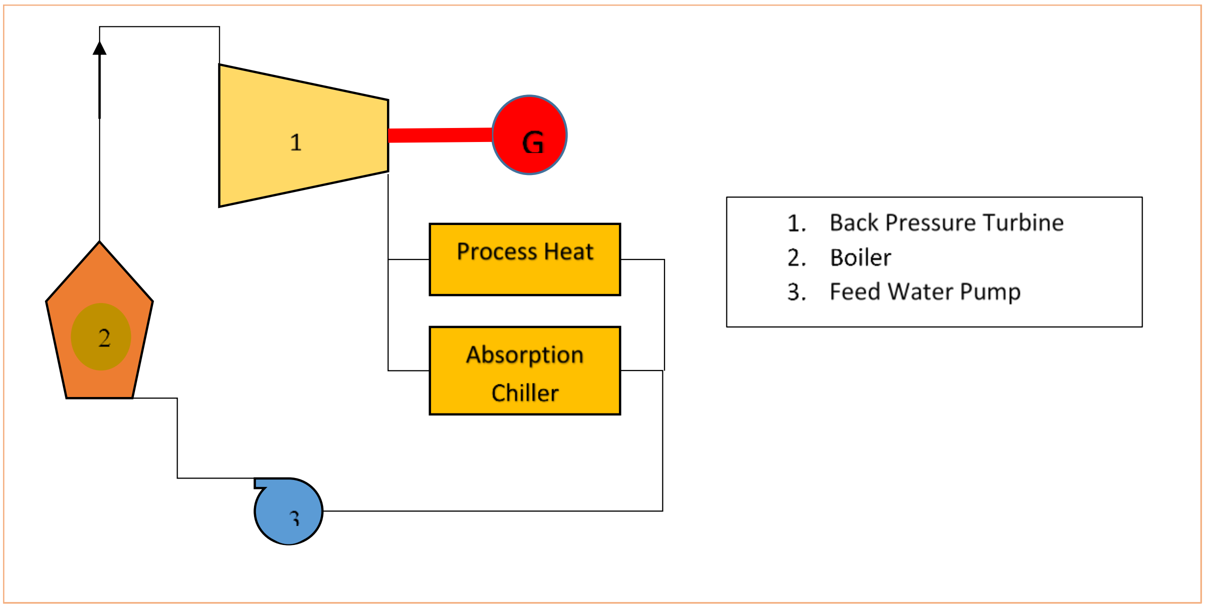


Figure 1: Schematic Diagram of a Back-Pressure Turbine

In this technology, the requirement of the main condenser is minimized, as the steam taken from the turbine is fed directly to the process and the vapour absorption chiller, to produce chilled water. Due to this, the overall efficiency may be increased, which results in a lower heat rate. However, the presence of the main condenser cannot be eliminated from the system, as its function is required during the variations of the process heat load and the cooling load. After the heat is extracted from the process and the absorption chiller, the condensate is collected in a deaerator, following which, the condensate is pumped back to the boiler for steam production.

Extraction Steam Turbines

Steam is extracted at a designed pressure level for the usage of the process. At the exit of the turbine, steam is exhausted at a very low pressure (below the atmospheric pressure). This is to extract more work from the turbine. In this case, the condenser space has to be kept at a vacuum pressure.

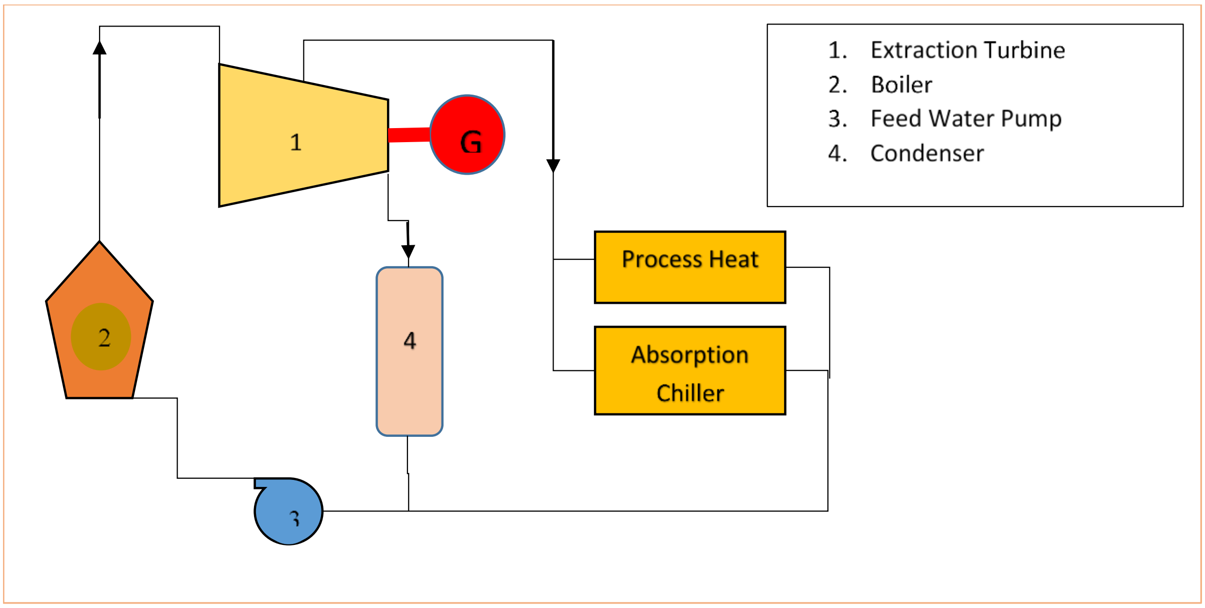


Figure 2: Schematic Diagram of an Extraction Turbine

2.2.2 Tri-generation with the Gas Turbine

Gas turbines represent a set of machines with a lower power density in comparison to the other prime movers present in the world. For an example, the weight of the 17 MWe WÄRTSILÄ Vasa 18V46 diesel engine is approximately equal to the weight of the 100 MWe frame 9171E gas turbine of General Electric Company.

However, the energy conversion efficiency of gas turbines is less compared with reciprocating IC engines. Therefore, the potential of heat recovery at the exhaust of the gas turbines is much higher in comparison to reciprocating engines.

For power generation, gas turbines are operated in two basic modes: open cycle mode and combined cycle mode. In general, open cycle gas turbines have to be operated at a higher heat rate, as they are primarily installed for peak load power generation and for emergency power generation. Combined cycle gas turbines are operated in base load power plants as the heat rate is much lower compared to open cycle gas turbines.

Open Cycle Gas Turbines

The schematic diagram of the TGT implemented in the open cycle gas turbine is given below:

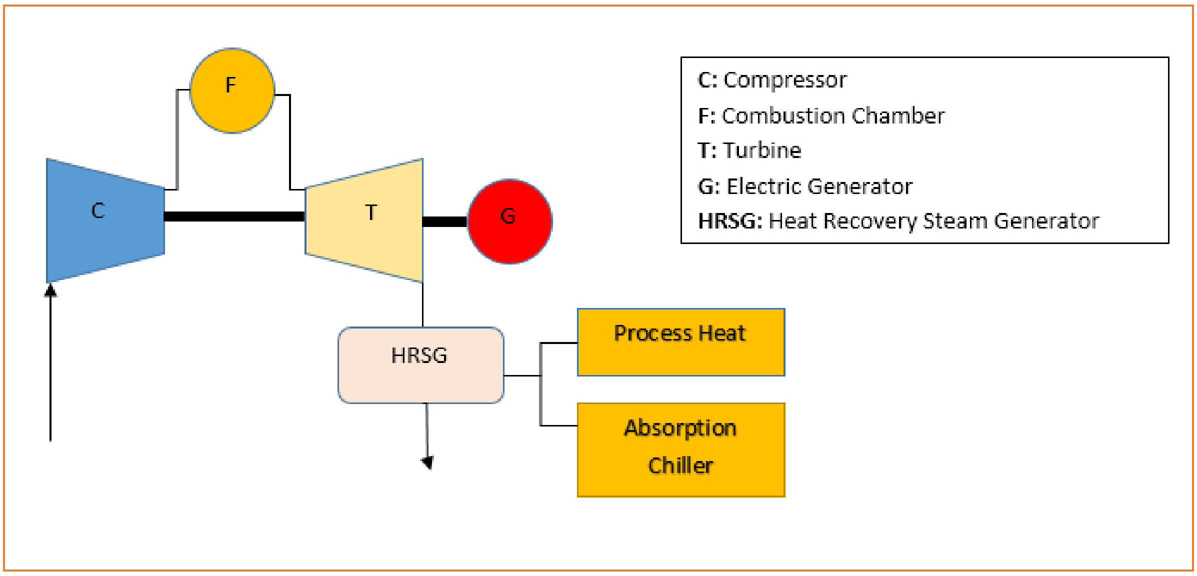


Figure 3: Schematic Diagram of the Open Cycle Gas Turbine

This layout can usually be implemented to an already installed open cycle gas turbine to improve the overall efficiency of the system. Open cycle gas turbines are generally not installed for continuous operations, as the related operational costs are significantly higher, in comparison to other potential technology options that could be considered.

Combined Cycle Gas Turbines

Combined cycle gas turbines incorporate a heat recovery steam generator (HRSG) and the generated steam is connected to a steam turbine to generate more electricity. The overall heat rate in such installations is much lower than the open cycle option. Moreover, the tri-generation can be executed in this configuration, resulting in a further reduction of the overall heat rate. Since the Rankine cycle is applied to the heat recovery process of the combined cycle gas turbines, two types of TG modes are possible if the extraction and back pressure steam turbines are utilized.

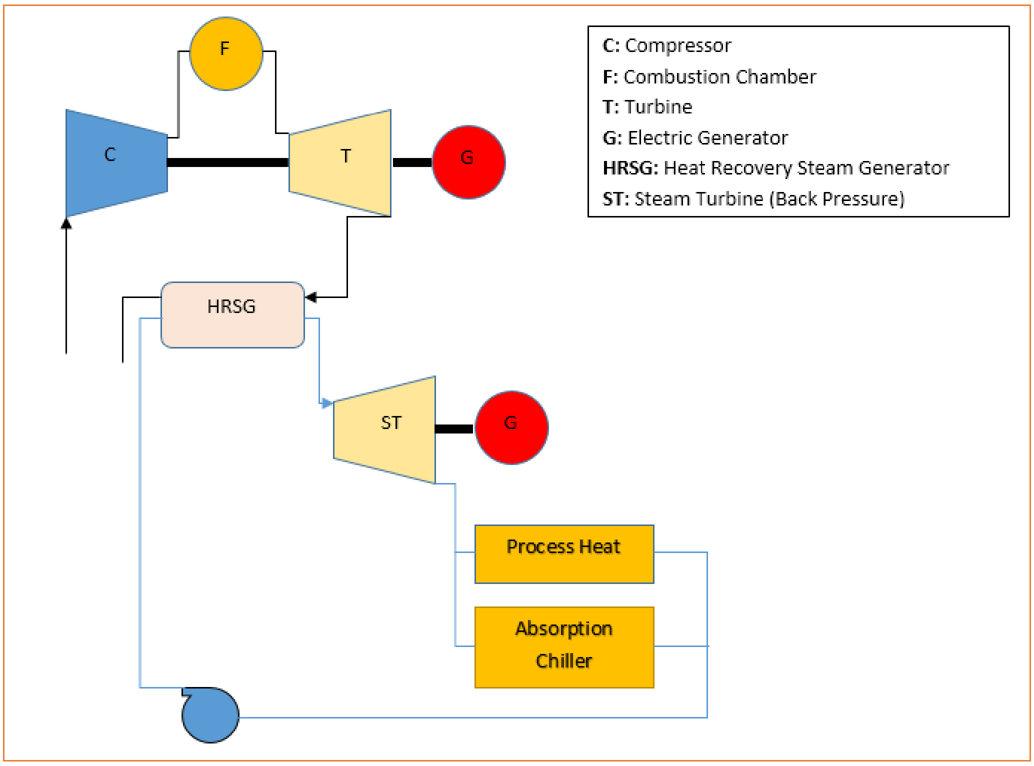


Figure 4: Combined Cycle Gas Turbine with Back Pressure Steam Turbine

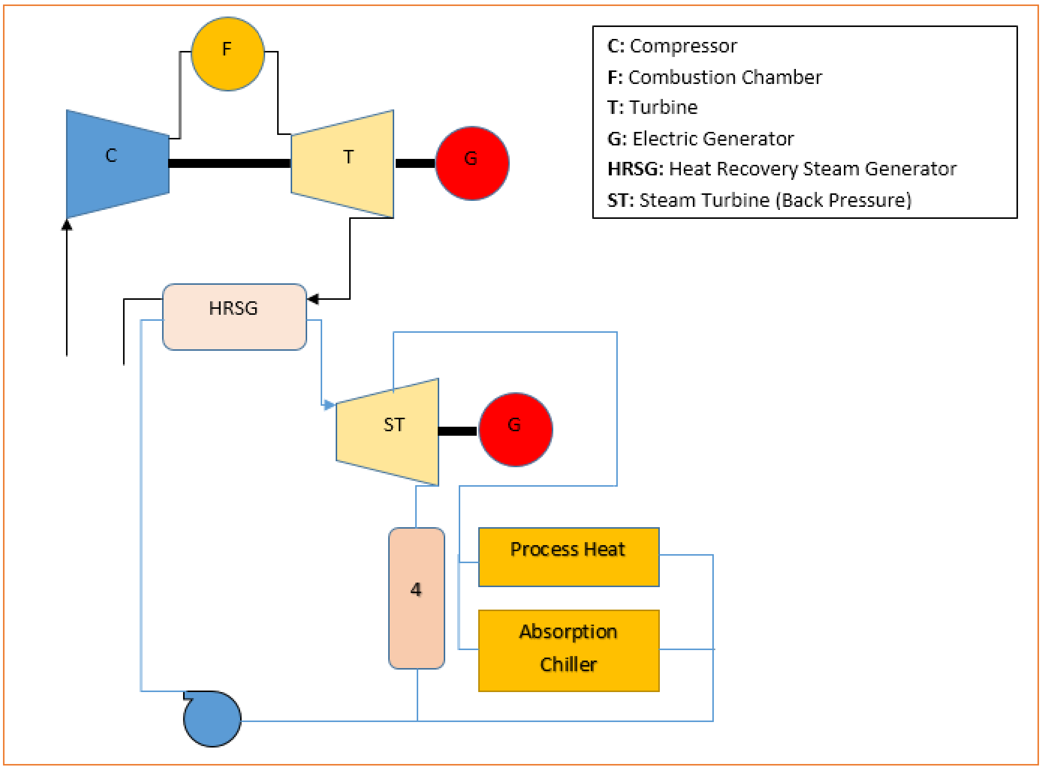


Figure 5: Combined Cycle Gas Turbine with Back Pressure Steam Turbine

2.2.3 Tri-generation with the Reciprocating Engine

For medium and small-scale TG options, reciprocating engines can be utilized. The waste heat available at the engine exhaust constitutes significant potential for energy recovery. Another waste heat source is available in a typical diesel engine; the cooling water system that removes the heat from the cylinder liners, cylinder head, lubricating oil and charged air (in case of a turbocharged engine). In a typical engine, the heat generated from the above components is absorbed by the cooling water system and it is released at the radiator to the atmosphere. Therefore, both waste heat sources can be utilized in designing a TG system.

The energy requirements of the building or utility and the degree of heat recovery should be carefully analyzed in order to achieve greater efficiency. In the case of implementing TG for an existing diesel generator, or in the process of designing a diesel generator with TGT, the power to weight ratio of the utility should be taken in to consideration first. The heat to power ratio of a utility, for a typical small-scale engine should be in the range of 1.3:1 to 2.0:1 (The Charted Institution of Building Services Enginers, 1999) to obtain better efficiencies. For utilities where the heat to power ratio is significantly different to the above range, either the power demand or the heat demand can be matched with a better system efficiency. However, it is difficult to match the heat and power demands with a better overall efficiency. The schematic diagram of a diesel generator is given below with the TG system associated with it:

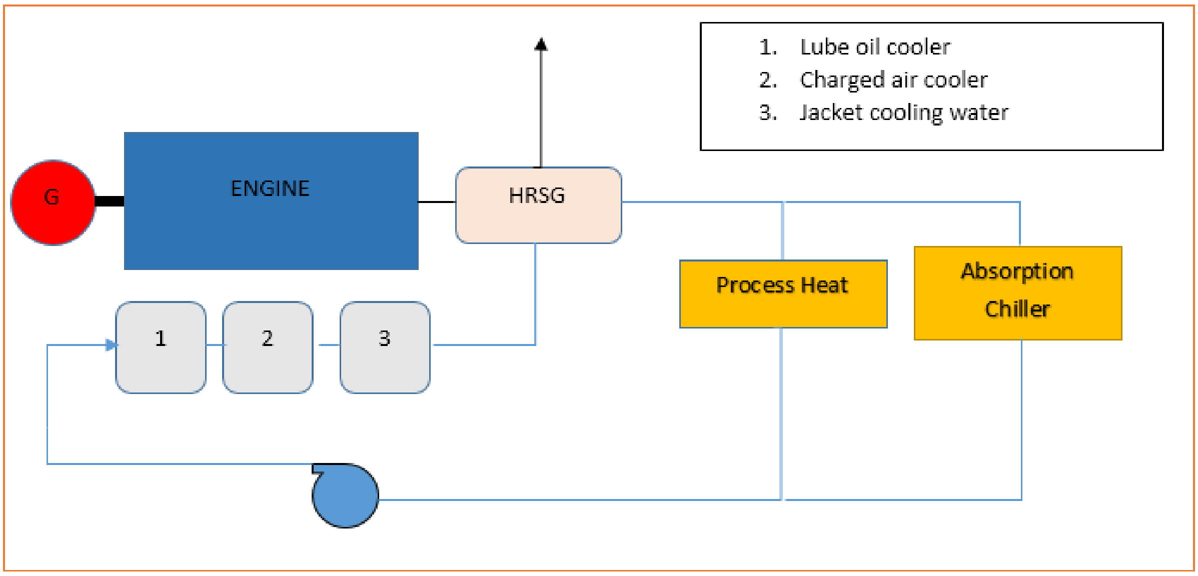


Figure 6: Schematic Diagram of the Reciprocating Engine with TG Technology

2.2.4 Merits and Demerits of Tri-generation

TGT is a technology that improves the overall efficiency of a combined energy requirement of a utility. By doing so, the overall cost of supplying the combined energy requirements is lower, compared to the conventional way of fulfilling said energy requirements. The following table compares the overall efficiencies of an assumed utility with an electrical, heating and cooling demands; with equal distribution of 100kW for each component:

Traditional Method						
Output Energy (kW)	*Energy Source*	*Method*	*Remark*	*Input Energy (kW)*	*Total Energy (kW)*	*Overall Efficiency*
100	Electricity	National Grid	efficiency 35%	286	506	59
100	Process Heat	Boiler	efficiency 80%	125		
100	Cooling	Vapor compression	COP is 3.0	95		
Trgeneration Method by Matching the Thermal Loads						
Output Energy (kW)	*Energy Source*	*Method*	*Remark*	*Input Energy (kW)*	*Total Energy (kW)*	*Overall Efficiency*
100	Electricity	TG plant was designed to match the thermal demand. Vapor absorption chiller	electrical conversion efficiency 30%	408	408	74
100	Process Heat		HRSG efficiency 70%	143		
100	Cooling		COP is 1.0	143		

Table 2: Comparison of TGT and Conventional Systems

Advantages

- The key advantage of a TG system is the reduced energy cost of production to accommodate the total energy requirement. This is achieved through the increase of overall efficiency of the system by introducing TGT.
- In addition, the total emissions from production are less compared to the conventional process. Total equivalent CO_2 emissions are minimized, thus the impact to the environment is also reduced.
- The complete energy requirement is fulfilled under the control of the own utility. Therefore, the dependency on the national electric grid is minimized. Comparatively, lower dependency on the national grid is beneficial for the country as the total power requirement reduces.
- In a complex business environment, it is possible to gain a competitive advantage over similar businesses due to the efficient use of energy.

Disadvantages

- The initial investment of implementing TGT is higher compared to the traditional method. Due to this reason, it is always a challenging decision to switch from the conventional process to the TGT.
- As mentioned above, the total emissions quantity is less compared to the usual method. However, if local emissions are compared, TGT has the higher emission. This is

because, emissions related to the electricity taken from the national grid cannot be considered a local component.

- Another disadvantage is the presence of three energy requirements. Not all the utilities require these three energy requirements at the same time. Due to this fact, certain utilities have to be omitted from consideration.
- The complete energy requirement is fulfilled by a single fuel source. Therefore, the requirement of an alternative energy source (most likely the national grid) is compulsory for the uninterrupted service of energy requirements.

2.2.5 Applications of Tri-generation

Since 1960, the concepts of co-generation and tri-generation were practiced across the USA and the EU at large scale power plants. Later, it was implemented at medium and small-scale industries and commercial buildings.

Andrea Costa et al reviewed the economics of implementing TGT in a paper manufacturing facility in Canada (Andrea Costa, Jean Paris, Michael Towers, Thomas Browne, 2007). Paper manufacturing is a highly energy intensive industry. In this case, steam is required at three different pressure stages for the process. These three stages of steam were fulfilled separately to the conventional way. The TG option Andrea Costa et al proposed has a steam turbine and a vapour absorption heat pump (VAHP) to provide all the steam requirements from a single boiler. Results of this study indicates that a simple payback period (SPB) ranges from 1 to 2.5 years for the tri-generation system, including the VAHP covering the 40% of the low-pressure steam demand.

Sugiartha et al evaluated the energetic, economic and environmental feasibility of a supermarket of 2,800 m^2 floor area, located in Southern England (N. Sugiartha, S.A Tassou, I. Chaer, D. Marriott, 2009). In this selected case, the heat to power ratio is around 1.5:1 which represents a suitable case to implement TGT. The energy mix of the supermarket is denoted below:

Energy Usage	Amount
Lighting and other electrical appliances	237 kWe
Low temperature freezers (for frozen food)	59 kWc
High temperature freezers (for chilled food)	248 kWc
Space heating	55 kWt

Table 3: Power Usage of the Super Market

In relation to the load distribution of the above example, the space heating component is not necessary in a local context, across supermarkets in Sri Lanka. Other energy components occur with some differences with the quantity. From this study, it was proposed to install a micro gas turbine, powered by natural gas and an absorption chiller running on the waste heat produced by the gas turbine. Results indicate that a simple payback period of 3.8 years can be achieved for the electricity to gas price ratio of 4 with the COP of the absorption chiller of 1.0.

2.2.6 **Tri-generation modes**

The type of TG system is based on the ratio of thermal to electrical energy produced within a TG system. In general, there are six types of TG systems are available:

a) Process heat matching mode

Here, the process load of the utility is matched. The electricity is considered as the second benefit. If generated electricity is in excess, it is then sold to the utility. If the generated electricity is insufficient, the balance amount is drawn from the grid.

b) Base thermal load matching mode

The base thermal load is matched through this method, through the supply of balance thermal load by a standby boiler. The prime mover in the TG plant is operated at its base load condition.

c) Electricity matching mode

The generated electricity is equal to the total electrical consumption of the utility. If the process thermal load is greater than the generated thermal load, then a standby boiler is operated. Conversely, if the thermal load is in excess, the extra heat is rejected to the atmosphere.

d) Base electrical load matching mode

The base electrical demand is matched onsite, through the TG plant, and additional demand is met by a standby boiler. Additional power is purchased from the utility.

e) Mixed matching mode

Both thermal and electrical demands are met based on the site requirement. TG plant is constructed to match both requirements.

f) Stand-alone mode

The total supply of the thermal and electrical power is done by the TG plant.

The first two TG configurations above are widely used in industry, due to the higher efficiencies provided through these configurations.

2.3 Tri-generation plant at Tee Jay Lanka PLC

Tee Jay Lanka PLC is a knit fabric manufacturer located in the Seethawaka IPZ – Avissawella. The maximum capacity of the factory is 2.5 million meters of knitted fabric. It is a joint venture of Pacific Textiles Holdings Ltd - China and Brandix Lanka Limited. TJ manufactures Viscose, Modal, Micro Modal and Tencel fabrics for tworld renowned brands such as Mark and Spencer and Victoria's Secret among others (Brandix Lanka Limited, n.d.) (Textured Jersey Lanka PLC, n.d.)

TJ utilizes grid electricity, furnace oil and diesel as sources of energy in the manufacturing of knit fabric. Electricity is mainly used for production machines and vapour compression chillers. Furnace oil is utilized for the supply of thermal energy demands in the production. Diesel is used to power up the standby generators. Therefore, the use of diesel is at a minimum quantity. Following table indicates the overall energy usage of TJ.

Energy Source	Equipment	Function
Grid electricity	Production machinery	Production of fabric
	Vapor compression chillers	Air-conditioning of the production space
	Office equipment	Office functionalities
	Light fixtures	Provision of light for production and office
Furnace oil	Steam boilers	Bulk dyeing machines
		Sample dyeing machines
		Baby dyeing machines
		Yarn dyeing machines
		Dye mixing machines
		Dye heating machines
		Drying machines - finishing
		Compactors - finishing
	Thermic oil heaters	Stentors - finishing
Diesel	Standby generators	All functions in the grid electricity usage

Table 4: Energy Consumption of Textured Jersey (W. C. Jagodaarachchi, A. Ekanayake, 2013)

The steam required for overall production is approximately 10,000 kg/hr at 9.0 bar of saturated steam. Approximately 2/3 of the total amount of furnace oil was consumed for the steam boilers and the rest was consumed for the thermic heaters. The process heating demand variation was expected as the demand of process heat is varied upon the type of fabric throughout the day in the factory. The total installed capacity of the chillers and other air conditioning machines was 610 TR. Before the implementation of TGT, the average energy consumption data for the year 2014 is given below:

Grid electricity	Energy (kWh)	2,000,000 per month
	Maximum demand (kVA)	3,265 per month
	Active power (kW)	2,770
Furnace oil	Consumption (litres)	650,000 per month

2.3.1 Tri-generation Architecture of Tee Jay

The electrical energy and/or thermal energy demands can be met through any tri-generation combination. In general, matching both demands is not carried out due to the significant increase in capital cost and in order to enhance the financial benefits. The total electrical energy demand of TJ is approximately 2.7 MW, inclusive of vapour compression air conditioning machines. If the vapour compression chillers were replaced with vapour absorption chillers electrical power demand can be reduced by 0.7MW to 2 MW.

In this factory, the existing chillers' lifetime was approximately 10 years and it was decided to replace the existing chillers with a vapour absorption chiller. The following table compares the previous and present energy mix of the utilities of the factories:

Description (Average)	Unit	Before TG	After TG
Electrical power demand	kW	2,700	2,000
Steam demand	Tons/hour	10	12
Heavy fuel oil demand	litres/hr	1200	400

Table 5: Energy Mix of TJ before and after the TG Implementation

The steam demand was increased by approximately 2 tons/hour due to the steam usage of the vapour absorption chiller. However, the heavy fuel oil demand for the thermic oil heaters remained unaltered. Therefore, by introducing TGT to the factory, the heavy fuel oil consumption does not reduce to zero.

2.3.2 Evaluation of the TG Technologies

The availability of fuel played the major role in selecting the prime mover for the TGT. Natural gas was determined as the most suitable fuel for the gas turbine option. However, natural gas is not available in Sri Lanka. While biomass based gasification options are available for gas turbine electricity, this option was deemed to be unsuitable due to the immaturity of such technology in the Sri Lankan context. As such, the gas turbine option was dropped.

Technical feasibility with IC engine

Reciprocating IC engine technology is an established technology in the local context. Larger scale (greater than 1 MW) prime movers were installed in Sri Lanka for power generation applications. Preferable fuel sources for the reciprocating IC engines are petroleum based oil; diesel, heavy fuel oil or natural gas are convenient fuels in terms of technological advancement. However, if the reciprocating engine was selected, then the electricity demand has to be met through the process load matching process. If the thermal load was matched, then an excess quantity of electricity will be generated and exported to the national grid at a lower cost in comparison to production costs. The higher costs of petroleum based fuels provided negative results to the financial feasibility of this option.

Below table describes the status of a reciprocating IC engine sized to match the power demand of TJ.

Description	**Unit**	**Qty**
TJ Power demand	MW	2.7
TJ Steam Demand	T/hr	12
Engine capacity	MW	3
Fuel consumption	ml/kWh	235
Exhaust temperature	^oC	500
Ambient temperature	^oC	30
Exhaust temperature after heat recovery	^oC	200
Fuel		HFO
Net calorific value	MJ/kg	40
Fuel price	LKR/liter	80
Density	kg/m^3	950
Overall efficiency		40%
Fuel cost of electricity	LKR/kWh	18.80
Possible steam flow rate	T/hr	3.3
Balance to be given by the boilers	T/hr	8.7

From the results, it can be seen that only 3.3 tons/hr steam demand can be produced. This requirement is well below the required steam demand. Below is the simple payback analysis.

As per the simple payback analysis, this technology is not viable.

Cost Calculation per annum	**Unit**	**IC Engine**	**Normal Case**
Electricity cost	LKR	438,566,400	303,264,000
Boiler cost	LKR	480,841,591	663,552,000
Total Utility cost	USD	7,355,264	7,734,528
Investment	USD	3,500,000	
Simple payback	years	9.23	

2.3.2.1 Technical feasibility with Rankine cycle-condensing turbine

The suitability of this option is reviewed with the calculations. In order to supply the process steam demand, there has to a steam extraction from the turbine. The upper limit of power generation limit of ST is the electricity demand of the factory. The reason is the utility (CEB) does not allow to export electricity under the existing contract with TJ. Therefore, the steam turbine power has been sized as 3 MW to match the 2.7 MW factories nominal power demand.

The below table summarizes the calculation:

State	Description	Unit	Capacity
	Max ST power output	MW	3
	ST overall efficiency		52%
	Boiler overall efficiency		88%
a	Boiler output Steam		
	Pressure	barg	35
	Temperature	°C	360
b	Turbine Steam Extraction		
	Pressure	barg	10
	flow rate	Tons/hr	20
c	Turbine end		
	Pressure	bara	0.05
	flow rate	Tons/hr	x
	x	kg/s	7
		Tons/hr	25
	Boiler Capacity	Tons/hr	20 + x
		Tons/hr	**45**
	Fuel rate calculation		
	Net calorific value-coal	MJ/kg	26
	Coal consumption rate	Tons/hr	4.13

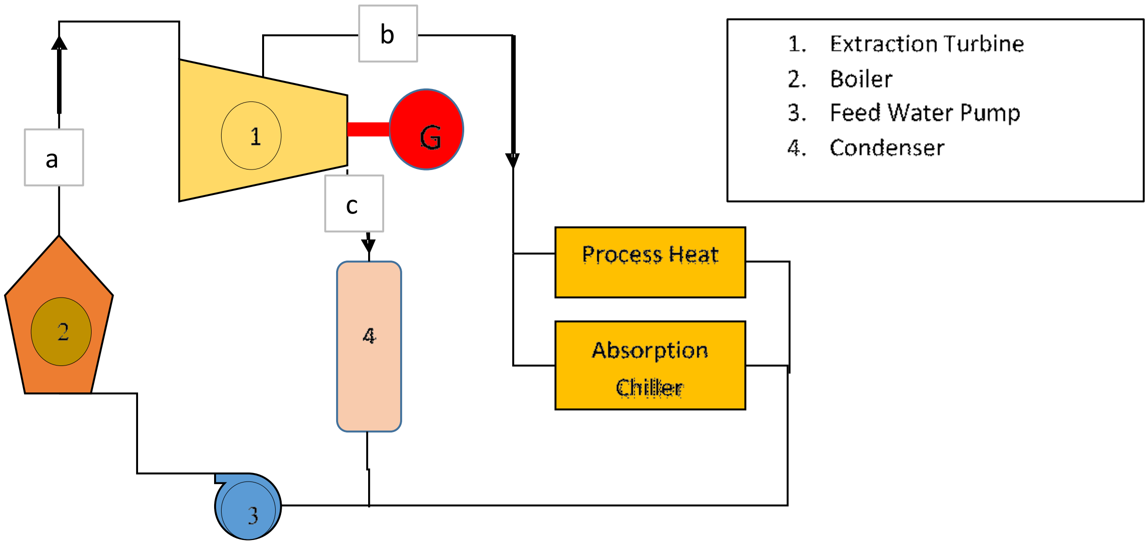


Figure 7: Schematic diagram of tri-generation option with extraction turbine

To match the 3 MW power generation by the ST, the boiler has to be sized at 45 Tons /hr at 35 barg steam pressure and 360°C steam temperature. The capital investment should be increased with the increased capacity of the boiler and the turbine. Also, additional condenser has to be fixed to accommodate the Rankine cycle whereas in the back-pressure mode, the function of the condenser is eliminated. Following table describes the increase of the capital investment. The increased capital expenditure for the condensing turbine option is a major drawback when comparing the suitable TJ options. Also the related simple payback has been calculated. The condensing turbine option has a financial payback of 46 months and the back pressure mode has only 18 months payback. Therefore, the most suitable option is the Rankine cycle with the back pressure mode.

DESCRIPTION	Condensing Turbine		Back Pressure Turbine	
	Local	Foreign	Local	Foreign
Plant Equipment Cost		**$3,800,000**		**$1,900,000**
Dust Proof System		**$200,000**		**$150,000**
Cost of Accessories		**$565,000**		**$310,000**
Fire Bricks	$170,000		$100,000	
Valves, Structural Steel & Pipes	$250,000		$120,000	
Chimney & Duct Work	$100,000		$60,000	
Tools	$45,000		$30,000	
Land & Buildings	**$215,000**		**$140,000**	
Coal Storage	$50,000		$30,000	
Boiler, Cooling Tower & Turbine Foundations	$45,000		$30,000	
Boiler & Turbine Room Buildings	$75,000		$50,000	
Earth Work & Roadworks	$20,000		$10,000	
Water Line	$25,000		$20,000	
Synchronizing & Switch Gear Equipment, Electrical		**$300,000**		**$200,000**
Transport of Equipment	**$75,000**		**$50,000**	
Project Consultancy Cost	**$175,000**		**$150,000**	
Contingency	**$200,000**		**$200,000**	
Total		**$5,530,000**		**$3,100,000**

Table 6: Capital expenditure of both options

The increased capital expenditure for the condensing turbine option is a major drawback when comparing the suitable TJ options. The related simple payback has been calculated. The condensing turbine option has a financial payback of 46 months and the back-pressure mode has only 18 months payback. Therefore, the most suitable option is the Rankine cycle with the back-pressure mode.

Technical feasibility with Rankine cycle-Back pressure turbine

The next available option is the generation of power using a steam turbine based on the Rankine cycle. The fuels can be either biomass or coal. Both fuel sources are less expensive compared to petroleum based fuels. Therefore, the financial viability of this technology made the investment more attractive. However, this option requires more land area for the storage of fuel and the installation of the boiler and related equipment, which is comparatively larger than the two technologies mentioned above. However, in this case, the factory had adequate space to accommodate the set of equipment to be installed with the TG plant.

Next option is the sizing of the plant capacity. As mentioned in Table 7, the total power demand is 2 MW and the thermal energy demand including the vapour absorption AC system is 12 Tons/hour. The total thermal power demand is to be matched in the TG combination. By considering the future expansion work of the factory, it was decided to increase the capacity of the boiler to 20 Tons/hour. After the steam turbine, the steam pressure has to be at 12.0 bar allowing a 1.0 bar loss for the 50 m length pipe transportation. With above thermal demand conditions, the turbine capacity was selected as 1,000 kW.

Description	Unit	Required quantity	Supplied Quantity	Balance
Electrical power	kW	2,000	1,000	1,000
Steam demand	Tons/hour	12	20	(-8)
Heavy fuel oil demand	liters/hour	400	-	400

Table 7: Summary of Energy Supplied by the Tri-generation Plant

The electrical power demand is partially met through this combination. Approximately, 1,000 kW of power must be imported from the national grid. This represents a 62% reduction in electricity drawn from the national grid, in comparison to the initial situation at TJ.

The following schematic diagram describes the layout of the TG plant:

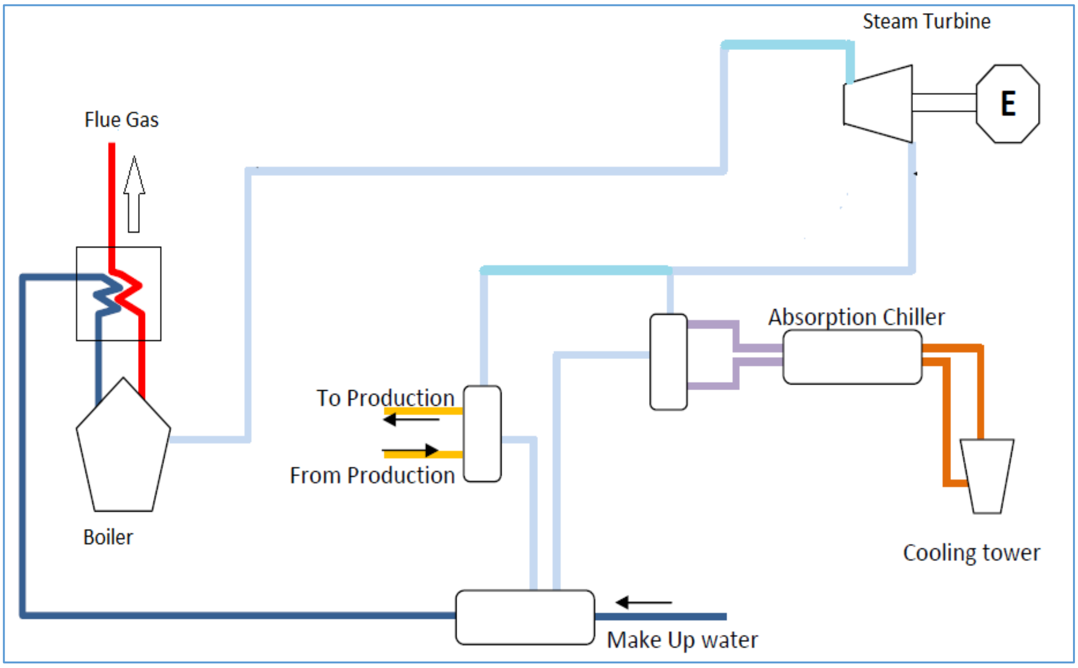


Table 8: Schematic Diagram of the Tri-generation Plant at Tee Jay

Fuel Selection for the Tri-generation Plant

Biomass and coal were the short-listed fuel sources to be used in the TG plant. The supply of biomass had to be fulfilled from local suppliers. The supply of coal had to be fulfilled from Holcim Lanka Ltd.

The price and energy comparison table of the two fuel sources are denoted in the below table:

Fuel Source	**Price at site (US$/Ton)**	**Avg. Energy content (MJ/kg)**	**Specific cost (US$/MJ)**
Biomass 20% moisture WB	42.31	13	0.00325
Coal	115	25	0.00460

Table 9: Comparison of Fuel Cost

From above comparison, it is understood that coal is the most expensive option compared to the biomass. When the supply chain of the coal is considered, only two bulk importers were present in Sri Lanka: Ceylon Electricity Board (CEB) and Holcim

Lanka PLC. Coal has been imported by CEB to power up the 900 MW Norochcholai thermal power station. Holcim Lanka PLC being the largest cement manufacturer, have been using coal for their production purposes. For medium scale coal consumers (less than 5,000 tons) direct import of coal was possible and to be purchased from either CEB or Holcim. CEB being a government entity did not encourage TeeJay Lanka to purchase from them, leaving Holcim as the only available option.

Biomass supply is fulfilled through the external environment, such as plantations, which requires transportation from a significant distance. In Sri Lanka, currently there is a lack of entities guaranteeing a sustainable supply of biomass. As such, the selection of biomass would have caused undue inconvenience to the management of TJ during the operation of the TG plant. Due to these reasons, it was decided to use coal as fuel for the TG plant.

Emission Control Technique

For the maintenance of dust concentrations below recommended levels at the stack, an emission monitoring technique had to be used at the plant. TJ used an electrostatic precipitator (ESP) for this purpose. An ESP removes dust from a moving gas stream through an induced electrostatic charge. ESPs are one of the most effective devices in dust control. In comparison to wet scrubbers, the energy usage is minimal as ESP applies energy only to the particles being collected. Further, the ESPs do not produce acidic water and slurry, which is hazardous to dispose of directly to the environment.

Tri-generation Plant Equipment

A fluidized bed type was selected due to the compactness in comparison to the moving grate type. Pulverized coal is also to be utilized for the boiler. The construction and commissioning of the TG plant was carried out by a local engineering company under the supervision of Thermax Limited – India. Key equipment such as the main boiler unit, electrostatic precipitator (ESP) and coal preparation unit were constructed by Thermax Limited. The steam turbine was manufactured by Triveni Engineers and Industries Ltd – India. The study will discuss the boiler and turbine in further detail in a later section.

Figure 8: Picture of the Tri-generation Plant

2.3.3 Tri-generation Plant Construction Review

Plant construction was carried out during the time frame of the project. However, some issues occurred at the time of commissioning. During the initial firing of the boiler, the electrostatic precipitator had to be switched on after reaching an exhaust temperature of 120^{o}C. Due to this reason, there was a time lag of approximately three hours from the start-up of the boiler. During this time, there were smoke emissions into the atmosphere. To arrest this situation, the ESP switch on temperature was decreased to 90^{o}C and electrical heaters were installed at the cold air purge pipes of the ESP. A wet scrubber was also installed to facilitate the startup of the boiler.

To reduce the noise emanating from the plant, sound proof barriers were installed at the main noise generating equipment, such as induced draft, forced draft fans and boiler feed pumps. All steam vents were fixed with silencers to suppress noise emitting when flash steam is released. The coal yard, coal crushing unit and the complete path of coal delivery have been kept at a negative pressure to assure no coal dust is evacuated to the atmosphere.

2.3.4 Boiler

This section will discuss the boiler in further detail. The boiler type is indoor, water tube, natural circulation, bi-drum, balanced draft, atmospheric fluidized bed combustion, and under bed fired. Following are the parameters:

Steam output: - 20,000 kg/hr

Steam pressure at boiler outlet: - 36 kg/cm^{2}g

Steam temperature at boiler outlet: - 385 +/- 5°C

The fuel specification for the boiler is given below.

Composition	Percentage
Carbon	60.95
Hydrogen	4.49
Nitrogen	0.53
Sulphur	0.64
Oxygen	10.76
Moisture	16
Ash	6.64
GCV (kcal/kg)	6022

Source: Thermax boiler manual

The particle size of the coal is as below:

The particle size: - Maximum 30% of having the size of 2 mm

Rest is equally distributed between 3 mm and 6 mm

The boiler is associated with fluidized bed combustion technology. A mixture of fuel particles is suspended in an upward flowing air stream callusing the characteristics of a moving fluid. In the bed, combustion occurs at a comparatively low temperature. In this case, the bed temperature varies between 800 – 900°C, which results in lower emissions; mainly the nitrogen oxides. The presence of sand in the combustion bed acts as the fluidized bed.

During the startup of the boiler, the air flow rate is gradually increased by the forced draft and induced draft fans, resulting in a shift of the bed state from static bed to fluidized bed. This state is called the “bubbling of the bed”. Initial fuel is introduced at this state. During the initial startup, a pilot fire has to be introduced through the use of charcoal. Charcoal is fired and the bed temperature is approximately 500°C. After the pilot ignition, the coal dust is introduced to the bed which results in propagating the combustion further up to the final bed temperature.

Water, which is conditioning at the deaerator, is fed to the water drum through boiler feed water pumps. Prior to that, an economizer preheats the condensate. The most important energy saving factor in this boiler is the natural circulation of water. This feature eliminates the pumping requirement of water from the water drum to the steam drum. The saturated steam generated from the evaporator coil is fed to the super heater, located near the combustor. From the super heater, the steam is fed to the back-pressure turbine to generate work.

The atmospheric air is drawn by the forced draft fan to the combustor through an air pre- heater.

Oxygen is supplied for the combustion. Following the combustion process, exhaust gasses are drawn by the induced draft fan and then diverted to the ESP for removal of fly ash and unburnt hydrocarbons. During start-up, air is supplied through a primary air fan, which is shut off after combustion is completed. The ESP can be started after the exhaust gas temperature reaches approximately 100°C. Until temperature reaches this point, a wet scrubber is in operation to remove any unburnt fuel and fly ash.

Following is the startup sequence of the boiler:

- Induced draft fan
- Primary air fan
- Forced draft fan
- Fuel feeders
- Boiler feed water pump
- Chemical dosing pumps
- Ash handling system
- Electrostatic precipitator

Deaerator

A deaerator is installed in the system to evacuate air and other gases, apart from steam, from the water/steam circuit. Live steam at 3 bar, is fed to the deaerator to remove the air and gases. The makeup water from the demineralized water tank is fed to the deaerator to accommodate the losses of water in the system. The vent of the deaerator is important as it controls the extent of evacuation of air and gases. A phenomenon called ‘air blanketing’ occurs when the vent is too throttled. Conversely, if the vent is too open, the steam loss is high.

2.3.5 Steam Turbine

The turbine installed in the TG plant is a back-pressure type turbine and the capacity is 1 MWe.

The following are the key operation parameters of the turbine:

a) Steam inlet pressure : 35 bar

b) Steam inlet temperature : 380°C

c) Max steam inlet flow : 19,800 kg/hour

d) Exhaust Pressure : 10 bar

The steam turbine converts the thermal energy of the steam into the work. This action occurs by the expansion of steam through the stator blades (nozzles), giving a higher kinetic energy to the steam. Work is then created by that steam impinging in to the rotor blades (buckets). While converting a large amount of thermal energy to work, the use of several stages of nozzles and buckets is necessary to optimize the conversion efficiency. Through this action, the pressure energy in steam is expanded through several steps. This turbine has three stages for the energy conversion. First, the superheated steam enters the steam end of the turbine and is flown axially to the exhaust end. The efficiency of the turbine can be maximized when the rotational speed is maximized. However, the speed is matched by using a gear box to cater the electric generator. The rotor is supported by two axial bearings on the steam and exhaust ends of the turbine and a thrust bearing to oppose the axial movement of the rotor.

The nozzles are fixed at the outer covering which is built to contain the steam around the rotor. The labyrinth seals are present both sides of the rotor, which controls the leak of steam which can be happened to atmosphere.

To accommodate the thermal expansion of the steam turbine and ensuring the correct meshing of the gearbox, a flexible coupling is incorporated between the steam turbine and the gear box.

These are essential accessories fitted to the turbine:

a) Speed governor

This is fixed to control the amount of steam fed to the turbine to match the load requirement and therefore, to maintain the fixed speed.

b) Lubrication system

Lubricating oil is to be supplied to the main bearing and thrust bearings to generate the axial loading and the required thrust through lube oil film. The heat exerted in to the bearings will be taken by lube oil and the bearing is kept at the right temperature. There is a separate lube oil circuit to remove the heat through a water condenser and pump back to the bearings.

c) Gland condenser

This is used to evacuate the steam leak offs from the labyrinth seals and valve spindle. Gland steam condenser is used as steam conserving equipment.

Steam purity

Steam purity is considered as an important concept in operating the steam turbine for long term use. Good quality steam will not be affect the turbine life. If the steam quality is maintained at the recommended level, then deposits could form around the turbine equipment, which diminishes the operational status of the turbine. The recommended purity levels are mentioned in the below table:

Parameter	**Unit**	**Recommended value**	**Limit value**
Specific electrical conductivity at 25°C	µS/cm	0.3	1
Silicon dioxide (SiO_2)	µg/l	20	
Sodium + Potassium (Na + K)	µg/l	10	35
Total iron (Fe) content	µg/l	20	
Ammonia (NH_3)	mg/l	1	
Total Copper content (Cu)	µg/kg	3	

Table 10: Allowed steam quality parameters for Steam Turbine

Speed and load controlling of the steam turbine

A governor was installed in the steam turbine control mechanism to control the speed by regulating the steam flow to the turbine. This governor is called a Woodward governor and comprises of three key components:

1. Speed sensing unit
2. Hydraulic relay
3. Steam control valve

The speed sensing unit comprises of three magnetic pickup sensors for sensing of the turbine speed. The electronic signals generated through the sensing unit is transmitted to the hydraulic relay, where the electronic signal is converted to a hydraulic fluid flow and then amplified. The amplified hydraulic oil flow passes through the actuator of the steam control valve, which is a spring-loaded control valve. It alters the steam flow directed to the steam turbine. The controlled flow of steam is directed to the turbine, resulting in the controlled speed of the turbine.

The same mechanism is used to control the load of the turbine. As a rule, for grid connected systems, the speed of a turbine remains constant and is proportional to the grid electrical frequency. The grid frequency of the local electric grid is 50 Hz. Therefore, in a grid synchronized system, the load of a steam turbine of any prime mover is directly proportional to the torque generated in the turbine. Therefore, the torque is controlled by controlling the steam flow.

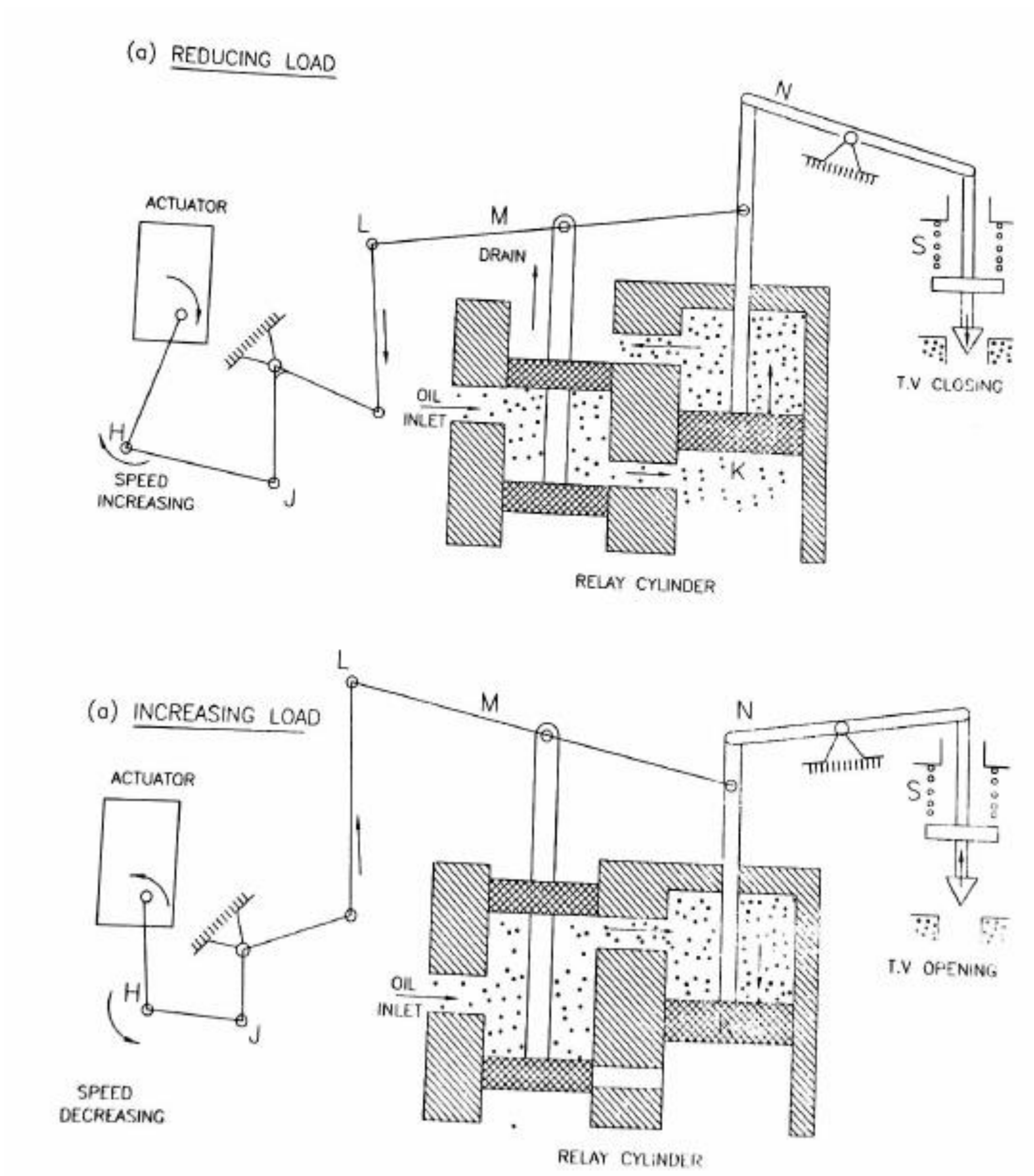


Figure 9: Speed controlling mechanism of the steam turbine

(Source: - Triveni turbine operation manual)

Steam turbine trip conditions

The conditions for the trip is defined to protect the turbine from the undesirable working conditions. The conditions that result in the tripping of the steam turbine are:

a) Over speed trip

b) High back pressure trip

c) High inlet steam pressure trip

d) Thrust wear trip

e) Lube oil conditions trip (temperature and pressure)

f) Manual trip (Actuator and solenoid)

g) Vibration high trip

Steam turbine load capability

As described earlier, the steam demand of the process was matched in this tri-generation plant. The steam flow is dependent upon the requirement of the production. The turbine power curve based on the steam flow is denoted below graph. This graph was produced by the turbine manufacturer. From this, the turbine operating point in relation to any process load can be found.

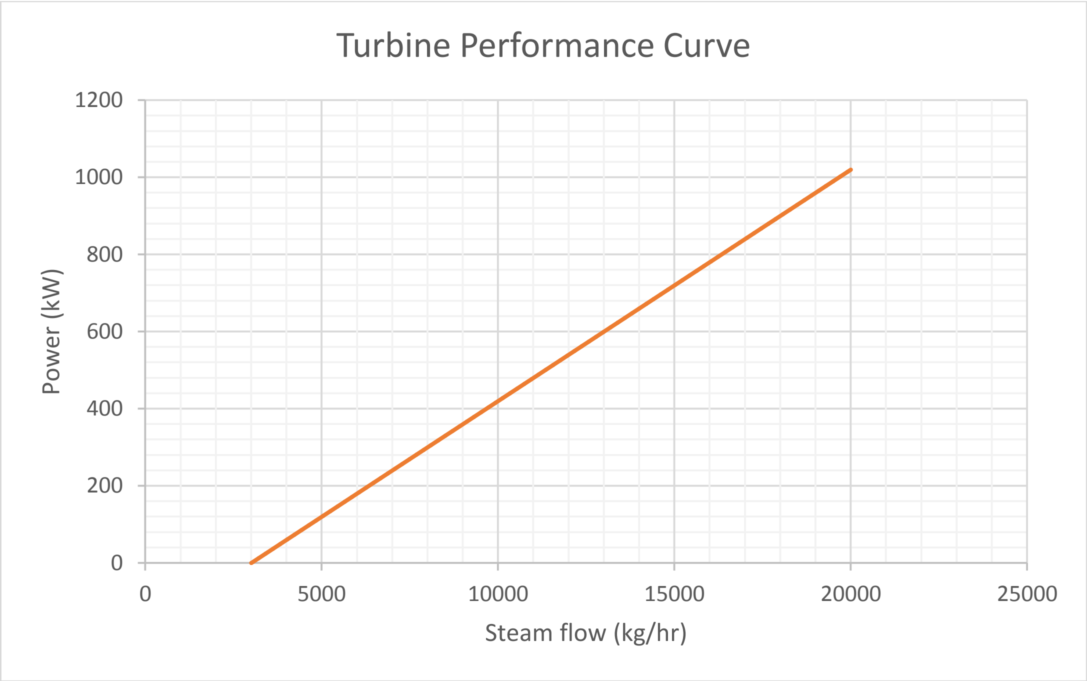


Figure 10: Turbine performance curve

(Source: - Triveni turbine manual)

3 CHAPTER 3: RESEARCH METHODOLOGY

3.1 Identification of the parameters

The identification of the key parameters affecting the performance of a TG plant is discussed here. The relevant literature was referred for this purpose.

Heat-to-power ratio is one of the most important technical parameters influencing the selection of the type of co-generation system. (South African National Energy Development Institute, 2014). This ratio represents the ratio of heat energy to the electrical energy produced. The nominal heat to power ratios of different types of tri-generation plants are given below:

HEAT TO POWER RATIOS FOR DIFFERENT COGENERATION SYSTEMS			
Cogeneration system	Heat-to-power ratio (kWth/kWe)	Power Output (% of fuel input)	Overall efficiency (%)
Back-pressure steam turbine	4.0 - 14.3	14 - 28	84 - 92
Extraction-condensing steam turbine	2.0 - 10.0	22 - 40	60 - 80
Gas turbine	1.3 - 2.0	24 - 35	70 - 85
Combined cycle	1.0 - 1.7	34 - 40	69 - 83
Reciprocating engine	1.1 - 2.5	33 - 53	75 - 85

Table 11: Heat to power ratio of different TG types

(South African National Energy Development Institute, 2014)

The electrical power output and thermal efficiency are the other performance parameters mentioned in the above table. The comparison of different prime mover types that TG technology can be implemented were indicated here. As the authors have indicated, the above figures were obtained by evaluating the different types of TG systems already in operation in South Africa.

Energy efficiency, net electrical power, electrical to heating and cooling ratios, and greenhouse gas (GHG) emissions were tested across three different tri-generation systems that use the organic Rankine cycle (Fahad A. Al-Sulaiman, 2011). In this thesis, a solid oxide fuel cell (SOFC) based tri-generation, biomass gasifier based TG system and solar heat based TG system were compared based on above mentioned parameters.

The thermal efficiency of a 630 MW coal power plant in Turkey before and after the feasibility of implanting the TG technology was reviewed (Hasan Huseyin Erdem, 2010). The results of the study indicate that the plant thermal efficiency can be increased from 36% to 44.2%, if heat is extracted for the process heating.

The overall thermal efficiency and electrical to thermal ratios were critically evaluated in different TG prime mover options (M. Jradi n, 2013). They identified that the thermal efficiency and electricity to thermal load ratio were the critical parameters that govern the operational performance of TG systems.

	IC engines	**Gas turbines**	**Sterling engines**	**Fuel cell**	**Rankine cycle**
Thermal efficiency	65-80%	65-75%	60-80%	55-80%	80%
E to T ratio	0.5 – 1.0	0.4 – 0.7	0.15 – 0.40	0.5 – 2.0	0.15 – 0.40

Table 12: Performance of different Tri-generation options

3.2 Development of KPIs

From the literature review for the identification of the key performance indicators, three indicators were clearly identified as the most significant factors:

a) Overall efficiency
b) Heat to power ratio
c) Net electrical power

3.2.1 Overall thermal efficiency

The theoretical formulae for the calculation of the overall efficiency was indicated. The overall efficiency is calculated as the energetic form. The exegetic efficiency of the system can also be used.

$$\eta_{p=} \frac{W_s}{H_f} = \frac{W_s}{m_f LHV}$$

The efficiency of the prime mover (η_p) is the ratio between shaft power (W_s) and energy content of the fuel flow (H_f) which is equal to the multiplication of fuel flow rate and the lower calorific value of the fuel (LHV).

The electrical efficiency is given by below formula:

$$\eta_{e=} \frac{W_e}{H_f} = \frac{W_e}{m_f LHV}$$

W_e is the net electrical power generated. Internal electricity consumption for the tri-generation system is to be deducted by the total electricity generation to obtain the net electrical power.

Thermal efficiency of the system is given by,

$$\eta_{T=} \frac{Q_i}{H_f} = \frac{Q_i}{m_f LHV}$$

Q_i is the useful thermal energy generated by the TG plant.

Overall efficiency of the system can be calculated as follows,

$$\eta = \eta_e + \eta_T$$

$$\eta = (W_e + Q_i)/ m_f LHV$$

Heat to Power ratio (HPR)

The heat to power ratio can be defined as the ratio between the useful heat input and net electrical power generated by the TG system.

$$HPR = \frac{Q_i}{W_e}$$

3.3 Evaluation of the performance

The evaluation of the TG system as per the identified KPIs is denoted here. In order to do so, operational data, onsite measurements, and the DCS data were used. The data was captured for the year 2016. The operation data has been obtained through the log sheets of the different operators. The parameters obtained were given below.

a) Daily steam consumption (tons)
b) Daily coal consumption (tons)
c) Running hours of the boiler (hours)
d) Internal electricity consumption (kWh)
e) Demineralized water consumption (m^3)

From the DCS data sheets real- time values were obtained to measure the steam pressure of the delivery point to the process.

To evaluate the lower calorific value of the coal, the test reports were collected which were carried out at independent certification laboratories such as SGS and Bureau Veritas.

For the evaluation of the financial performance, the cash flow of the project during the year 2016 was considered. Following cost factors were considered in the cash flow analysis.

a) Cost of coal was calculated as per the agreement with Holcim Lanka PLC.

b) Savings gained by not operating oil boilers were calculated.

   i. Steam to oil ratio was taken as 12.
   ii. Density of heavy fuel oil was taken as 950 kg/m^3
   iii. Price of heavy fuel oil was taken as 80 LKR/liter

c) The depreciation was taken as 10 years of the total project life

   i. Total investment for the project is taken as 4.2 million USD

d) The salaries of the crew were taken as the overhead of the project.

After the comparison of the technical and financial KPIs, the gaps can be identified. The reasons for the performance gaps are to be figured out by comparing the typical parameters of a TG plant of a same technology.

Once the gaps were identified, the root cause of the issue is to be figured out. For that the careful analysis of the operations data, reference of the literature including the technical manuals etc. Then the process of mitigating the gaps are to be denoted. This section is described in the results and discussion.

4 CHAPTER 4: RESULTS AND DISCUSSION

4.1 Evaluation of the performance

4.1.1 Evaluation of the overall efficiency

For this, the daily data for the afore mentioned year was averaged to a monthly data set. Then the efficiencies were calculated for last twelve months. Therefore, the efficiency figure gives a rational number.

Month	Steam consumption (Tons)	Steam latent heat (kJ/kg) at 10 barg	Coal Consumption (Tons)	Coal LHV (kJ/kg)	Thermal efficiency
January	5,379	1,999	647	28,032	59.29%
February	5,671	1,999	721	28,032	56.10%
March	6,755	1,999	870	28,032	55.38%
April	4,644	1,999	602	26,752	57.65%
May	7,956	1,999	1,034	26,752	57.50%
June	6,799	1,999	903	26,752	56.27%
July	5,596	1,999	764	26,752	54.74%
August	8,841	1,999	1,154	26,360	58.11%
September	8,446	1,999	1,122	26,360	57.09%
October	6,996	1,999	967	26,360	54.87%
November	858	1,999	124	26,360	52.48%
December	-	1,999	-	26,360	
Total	**67,941**	**1,999**	**8,908**	**26,909**	**56.67%**

Table 13: Average thermal efficiency for year 2016

4.1.2 Evaluation of the Heat to Power ratio

The evaluation of heat to power ratio is denoted in below table. The related data set and the calculation table is given in the appendix.

Month	Steam consumption (Tons)	Total hours	Steam latent heat (kJ/kg) at 10 barg	Net Electricity generation (kWh)	Average heat generation(kW_{th})	Average electricity generation(kWe)	Heat to power ratio (kW_{th}/kWe)
January	5,379	509	1,999	-	5,869	-	Infinity
February	5,671	532	1,999	-	5,920	-	Infinity
March	6,755	633	1,999	-	5,926	-	Infinity
April	4,644	428	1,999	-	6,026	-	Infinity
May	7,956	724	1,999	-	6,103	-	Infinity
June	6,799	664	1,999	-	5,687	-	Infinity
July	5,596	555	1,999	-	5,600	-	Infinity
August	8,841	744	1,999	-	6,599	-	Infinity
September	8,446	708	1,999	-	6,625	-	Infinity
October	6,996	602	1,999	-	6,454	-	Infinity
November	858	80	1,999	-	5,956	-	Infinity
December	-	-	1,999	-			Infinity
Total	**67,941**		**1,999**	**-**	6,070	-	Infinity

Table 14: Heat to Power ratios for the year 2016

The main fact to be noted is that the electrical power generation was not being performed in this TG plant throughout the year 2016. As such, the heat to power ratio becomes infinity.

The summary of the comparison of the performance of the TG plant is denoted below.

KPI	TJ Lanka PLC	Typical other plant with Back pressure turbine
Overall efficiency	56.67%	84 – 92%
Heat to Power ratio	Infinity	4 - 14
Net Power output (as a percentage of fuel input)	Zero	14 – 28 %

Table 15: Comparison of the KPIs with a typical TG plant

4.1.3 Financial Performance of year 2016

Apart from the technical feasibility of the TG plant, the financial status for the year 2016 was reviewed. The cost of steam produced was compared against the previous option (through oil fired boilers.)

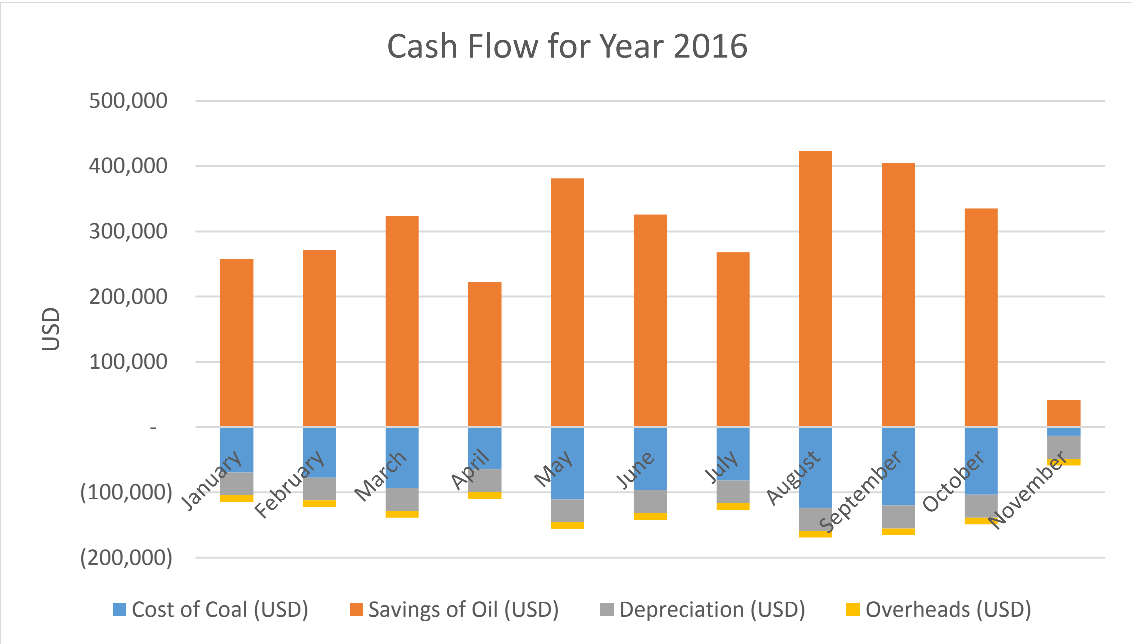


Figure 11: Cash Flow for Year 2016

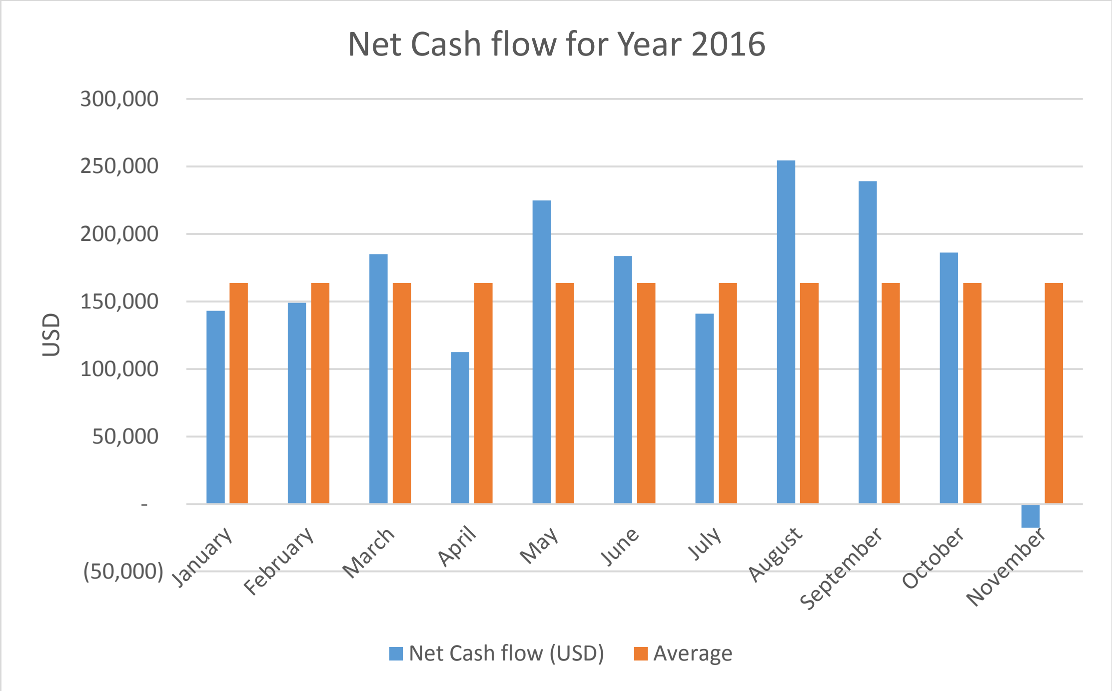


Figure 12: Net Cash Flow for Year 2016

The two graphs clearly showed the results of the financial analysis. Other than the month November, the cash flow has been positive by about 163,731 USD per month. The reason for the negative cash flow is that the closure of the TG plant due to the unavailability of coal.

4.2 Forecasting of the performance in the ideal case

If the TG plant were operated with full performance, the related parameters were calculated in this section. In this case the figures were obtained assuming the steam turbine was in operation.

4.2.1 Evaluation of the overall efficiency

The ideal electrical power generation was calculated based on the steam turbine performance curve which the manufacturer provided. Therefore the electrical power efficiency can be added to the overall efficiency formula.

Month	Steam consumption (Tons)	Total hours (hours)	Steam flow rate (kg/hr)	Related Net electrical power (kW)	electrical energy (kWh)	Steam latent heat (kJ/kg) at 10 barg	Coal Consumption (Tons)	Coal LHV (kJ/kg)	Average heat generation(kW_{th})	Overall Efficiency
January	5,379	509	10,568	454	231,120	1,999	647	28,032	5,869	63.88%
February	5,671	532	10,660	460	244,500	1,999	721	28,032	5,920	60.45%
March	6,755	633	10,671	460	291,360	1,999	870	28,032	5,926	59.68%
April	4,644	428	10,850	471	201,600	1,999	602	26,752	6,026	62.16%
May	7,956	724	10,989	479	347,040	1,999	1,034	26,752	6,103	62.02%
June	6,799	664	10,239	434	288,420	1,999	903	26,752	5,687	60.57%
July	5,596	555	10,083	425	235,860	1,999	764	26,752	5,600	58.89%
August	8,841	744	11,883	533	396,540	1,999	1,154	26,360	6,599	62.80%
September	8,446	708	11,929	536	379,320	1,999	1,122	26,360	6,625	61.71%
October	6,996	602	11,621	517	311,400	1,999	967	26,360	6,454	59.27%
November	858	80	10,725	464	37,080	1,999	124	26,360	5,956	56.56%
December	-	-				1,999	-	26,360		
Total/Average	**67,941**		**10,929**	**476**		**1,999**	**8,908**	**26,909**	**6,070**	**60.73%**

Table 16: Average thermal efficiency for year 2016 for the ideal case

4.2.2 Evaluation of the Heat to Power ratio

Month	Steam consumption (Tons)	Total hours (hours)	Steam flow rate (kg/hr)	Related Net electrical power (kW)	electrical energy (kWh)	Steam latent heat (kJ/kg) at 10 barg	Coal Consumption (Tons)	Coal LHV (kJ/kg)	Average heat generation(kW_{th})	Ideal Heat to power ratio (kW_{th}/kWe)
January	5,379	509	10,568	454	231,120	1,999	647	28,032	5,869	12.9
February	5,671	532	10,660	460	244,500	1,999	721	28,032	5,920	12.9
March	6,755	633	10,671	460	291,360	1,999	870	28,032	5,926	12.9
April	4,644	428	10,850	471	201,600	1,999	602	26,752	6,026	12.8
May	7,956	724	10,989	479	347,040	1,999	1,034	26,752	6,103	12.7
June	6,799	664	10,239	434	288,420	1,999	903	26,752	5,687	13.1
July	5,596	555	10,083	425	235,860	1,999	764	26,752	5,600	13.2
August	8,841	744	11,883	533	396,540	1,999	1,154	26,360	6,599	12.4
September	8,446	708	11,929	536	379,320	1,999	1,122	26,360	6,625	12.4
October	6,996	602	11,621	517	311,400	1,999	967	26,360	6,454	12.5
November	858	80	10,725	464	37,080	1,999	124	26,360	5,956	12.9
December	-	-				1,999	-	26,360		
Total/Average	**67,941**		**10,929**	**476**		**1,999**	**8,908**	**26,909**	**6,070**	**12.8**

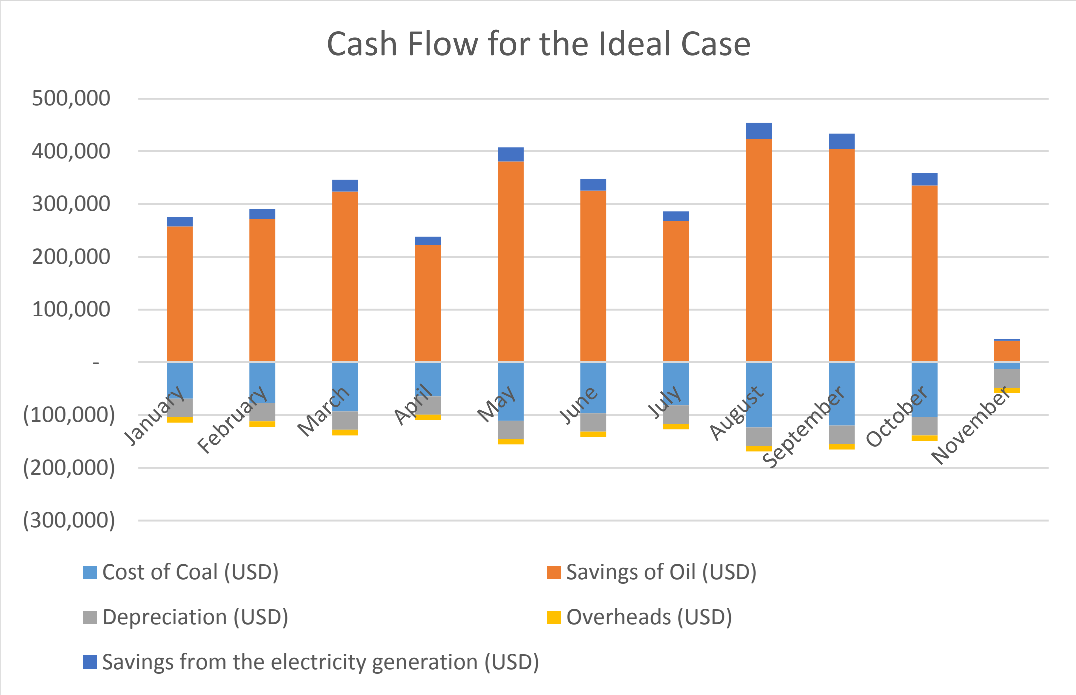
Table 17: Average thermal efficiency for year 2016 for the ideal case

4.2.3 Evaluation of the net power output

Month	Steam consumption (Tons)	Total hours (hours)	Steam flow rate (kg/hr)	Related Net electrical power (kW)	electrical energy (kWh)	Steam latent heat (kJ/kg) at 10 barg	Coal Consumption (Tons)	Coal LHV (kJ/kg)	Average heat generation(kW_{th})	Net Power output
January	5,379	509	10,568	454	231,120	1,999	647	28,032	5,869	5%
February	5,671	532	10,660	460	244,500	1,999	721	28,032	5,920	4%
March	6,755	633	10,671	460	291,360	1,999	870	28,032	5,926	4%
April	4,644	428	10,850	471	201,600	1,999	602	26,752	6,026	5%
May	7,956	724	10,989	479	347,040	1,999	1,034	26,752	6,103	5%
June	6,799	664	10,239	434	288,420	1,999	903	26,752	5,687	4%
July	5,596	555	10,083	425	235,860	1,999	764	26,752	5,600	4%
August	8,841	744	11,883	533	396,540	1,999	1,154	26,360	6,599	5%
September	8,446	708	11,929	536	379,320	1,999	1,122	26,360	6,625	5%
October	6,996	602	11,621	517	311,400	1,999	967	26,360	6,454	4%
November	858	80	10,725	464	37,080	1,999	124	26,360	5,956	4%
December	-	-				1,999	-	26,360		
Total/Average	**67,941**		**10,929**	**476**		**1,999**	**8,908**	**26,909**	**6,070**	**4%**

Table 18: Net power output for year 2016 for the ideal case (as a percentage of the energy of fuel intake)

4.2.4 Financial Performance of the Ideal Case



The benefit obtained through the generation of the electricity is added to the cash flow resulting the increase of average cash flow to 184,546 USD per month. The performance comparison of the ideal case compared to a typical TG plant with back pressure turbine is given in below table.

KPI	TJ Lanka PLC Actual case	TJ Lanka PLC Ideal case	Typical other plant with Back pressure turbine
Overall efficiency	56.67%	60.73%	84 – 92%
Heat to Power ratio	Infinity	12.8	4 - 14
Net Power output (as a percentage of fuel input)	Zero	4%	14 – 28 %

Table 19: Overall review of the performance

4.2.5 Financial feasibility of the back- pressure turbine with and without Steam Turbine

The financial feasibility of the trigeneration proposal has been changed due to the non-functionality of the steam turbine. The variation has been calculated and the summary is given below.

<u>Financial feasibility with ST operation</u>

	2012	2013	2014	2015	2016	2017	2018	2019	2020
	0	1	2	3	4	5	6	7	8
Electricity									
Potential energy consumption (MWh)		24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Energy generation from Coal plant (MWh)		7,446	7,446	7,446	7,446	7,446	7,446	7,446	7,446
Energy Consumption for Chillers (MWh)		2,681	2,681	2,681	2,681	2,681	2,681	2,681	2,681
Total Energy Exported (MWh)		6,701	6,701	6,701	6,701	6,701	6,701	6,701	6,701
Total Energy Saving (MWh)		9,382	9,382	9,382	9,382	9,382	9,382	9,382	9,382
Furnace Oil (FO)									
Potential FO consumption (L)		8,900,000	8,900,000	8,900,000	8,900,000	8,900,000	8,900,000	8,900,000	8,900,000
FO Consumption for Thermic Heaters (L)		3,560,000	3,560,000	3,560,000	3,560,000	3,560,000	3,560,000	3,560,000	3,560,000
FO Consumption for Boilers (L)		5,340,000	5,340,000	5,340,000	5,340,000	5,340,000	5,340,000	5,340,000	5,340,000
Steam generation (MT)		66,750	66,750	66,750	66,750	66,750	66,750	66,750	66,750
,000 USD									
Investment	**(4,000)**								
Cash Out Flow for CHP Plant									
Cost of Coal		2,075	2,283	2,511	2,762	3,039	3,342	3,677	4,044
Cost of Spares		74	80	85	91	98	104	112	120
Cost of water		37	39	41	43	45	48	50	52
Admin Cost		105	116	127	140	154	169	186	205
Total cost		2,292	2,517	2,765	3,037	3,335	3,664	4,025	4,421
Cost Saving from CHP Plant									
From Electricity		1,010	1,010	1,010	1,010	1,010	1,010	1,010	1,010
From FO		3,286	4,108	5,135	6,418	8,023	10,029	12,536	15,670
Net	(4,000)	2,004	2,601	3,380	4,392	5,698	7,375	9,521	12,259
Simple Payback Period (Months)	**23.95**								

Financial Feasibility without ST operation

	2012	2013	2014	2015	2016	2017	2018	2019
	0	1	2	3	4	5	6	7
Electricity								
Potential energy consumption (MWh)		24,000	24,000	24,000	24,000	24,000	24,000	24,000
Energy generation from Coal plant (MWh)		-	-	-	-	-	-	-
Energy Consumption for Chillers (MWh)		2,681	2,681	2,681	2,681	2,681	2,681	2,681
Total Energy Exported (MWh)		-	-	-	-	-	-	-
Total Energy Saving (MWh)		2,681	2,681	2,681	2,681	2,681	2,681	2,681
Furnace Oil (FO)								
Potential FO consumption (L)		8,900,000	8,900,000	8,900,000	8,900,000	8,900,000	8,900,000	8,900,000
FO Consumption for Thermic Heaters (L)		3,560,000	3,560,000	3,560,000	3,560,000	3,560,000	3,560,000	3,560,000
FO Consumption for Boilers (L)		5,340,000	5,340,000	5,340,000	5,340,000	5,340,000	5,340,000	5,340,000
Steam generation (MT)		66,750	66,750	66,750	66,750	66,750	66,750	66,750
,000 USD								
Investment	(4,000)							
Cash Out Flow for CHP Plant								
Cost of Coal		2,075	2,283	2,511	2,762	3,039	3,342	3,677
Cost of Spares		74	80	85	91	98	104	112
Cost of water		37	39	41	43	45	48	50
Admin Cost		91	100	110	121	134	147	162
Total cost		2,278	2,502	2,748	3,018	3,315	3,641	4,000
Cost Saving from CHP Plant								
From Electricity		289	289	289	289	289	289	289
From FO		3,286	4,108	5,135	6,418	8,023	10,029	12,536
Net	(4,000)	1,297	1,895	2,676	3,689	4,996	6,676	8,824
Simple Payback Period (Months)	37.02							

The main reason to the increased payback is the power generation benefit does not exist without ST operation. However other overheads also will be remained the same for both options.

4.3 Root Cause Analysis of the Issue

The main issue affecting performance was identified as the inability to operate the steam turbine. Therefore, the turbine has been bypassed through a pressure reducing valve (PRV) that reduces the pressure from 35 barg to 10 barg, with the delivery of steam to the process. Evaluating the operational data for 2016, it was identified that the steam turbine was operated only at two instances. Afterwards the ST operation has been abandoned.

The reason to the isolation of the steam turbine has been discussed. The operations crew was interviewed to find out the root cause. During the operation of the steam turbine, it was tripped due to higher back pressure at the turbine exit. It was notified that the steam turbine was loaded to its' full capacity (1 MWe) during the commissioning of the plant. After the commissioning work the turbine has not been operated due this tripping incident occurred. The following table indicated the back pressure trip limit for the turbine.

Description	**Limit**
Back pressure high	10.3 barg
Back pressure low	No trip limit

Table 20: Back pressure trip limit for the steam turbine

Even though the back pressure is maintained at 9.5 barg to feed to the production, the trip limit is marginal at 10.3 barg. Therefore, the tolerance level for the operation of the back pressure is narrow. There is only 0.8 barg of pressure difference can be allowed as the variation of the process steam flow rate. For the low back pressure, there is no trip limit, however it is not recommended to operate too low steam pressures as the water droplets can be formed and it can be caused the damages to the steam turbine.

The factory operates 24 hours for 360 days annually, producing the knit fabrics. The process steam flow variations can be minimal. The first impression on the steam demand is what is mentioned here. However, the process steam pressure variation for the year 2016 has been graphed as a day by day for 360 days of continuous operation. The actual variation of the steam flow can be interpreted.

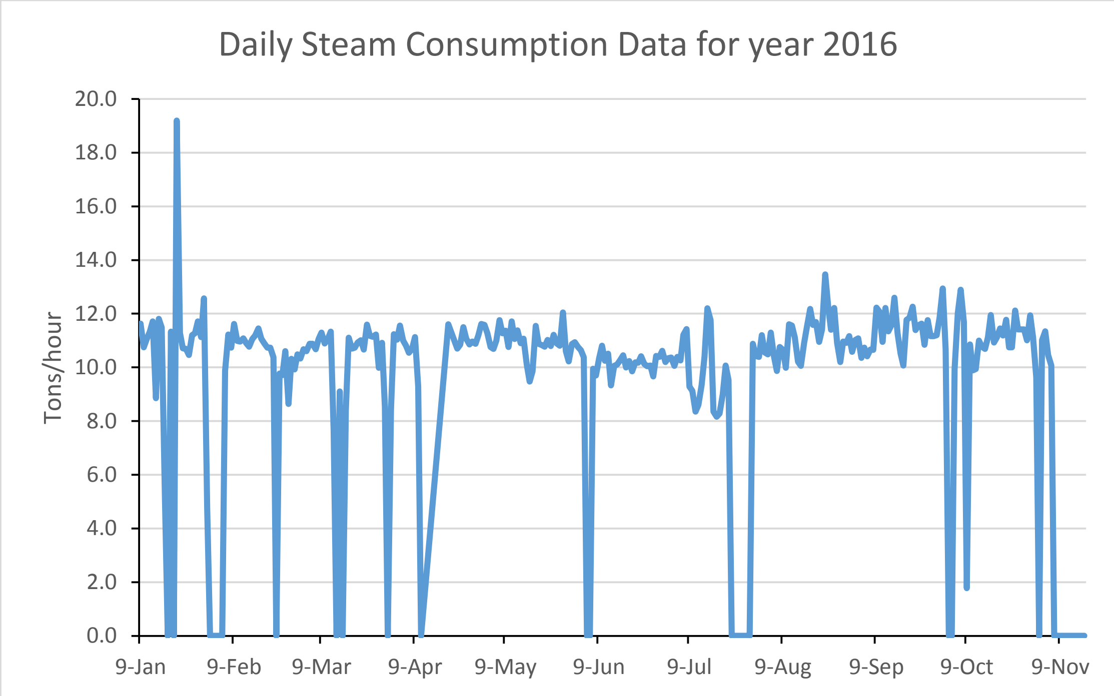


Figure 13: Daily steam flow variation

By looking at the graph, there were 9 days that the TG plant was not operated. Breakdowns of the plant were caused the downtime.

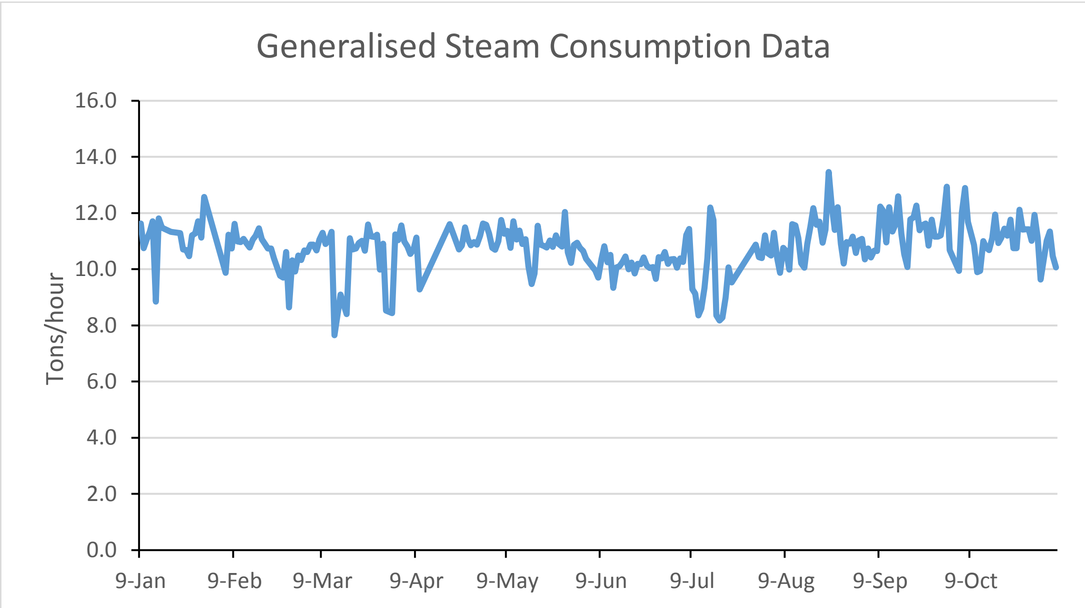


Figure 14: Generalized Steam consumption data

Second curve denotes the steam consumption pattern after disregarding the peaks and breakdowns. The trend showed in this table indicates the real pattern of the steam consumption data by the factory. The steam demand variation was occurred between 8.0 – 13.0 barg. Also, the steam variation of a typical day operation was indicated in below graphs.

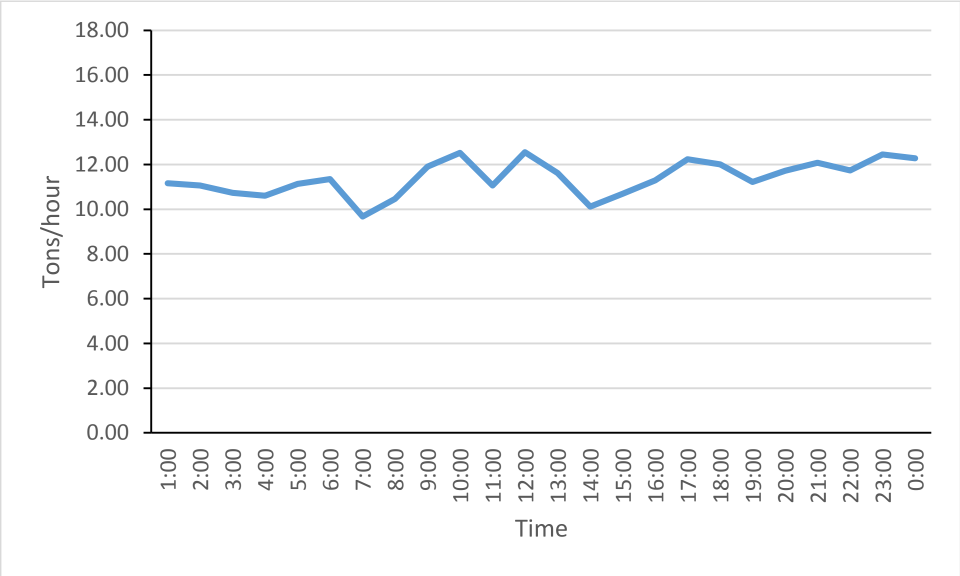


Figure 15: Steam consumption variation on 2016/10/20

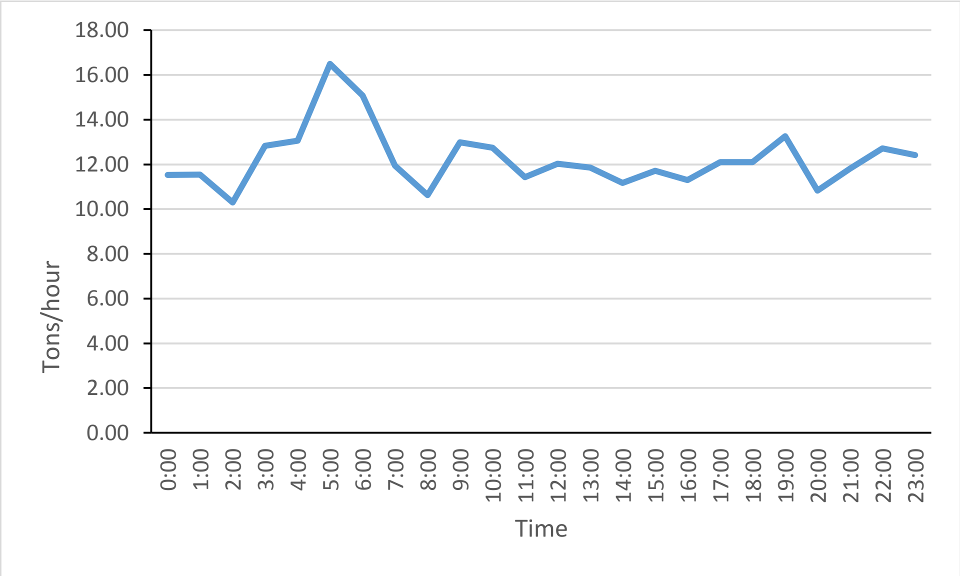


Figure 16: Steam consumption variation on 2016/10/25

From the above four graphs, it is observed that there is a steam variation present at the process. Even though the production is carried out seamless throughout the year, the steam flow requirement tends to vary. On average, the steam flow variation between 8 – 13 tons/hour can be observed. The major reason to the variation has been overlooked. It was identified that, the type of fabric, the graphics of the fabric and the colour are the three main factors that affects to the variations of the steam flow. The flexibility of the process plays a significant role in determining the capability of a textile mill. The apparel industry today is all about catering to the change of the customer demand. Conventional apparel industry catered to a seasonal based customer demand which is no longer valid due to the reasons such as the climate change and online sales of the apparels.

Therefore, more flexibility in steam flow is to be allocated to the production so that the capability of the manufacturing of fabrics with more options such as color, fabric type and etc is enhanced.

4.3.1 Steam Turbine back pressure control

As per the given steam flow variation, the back pressure at the turbine was to be controlled more precisely. The turbine is to be operated within a 0.8 bar of pressure. The steam turbine can be operated in two different control modes. Those are,

a) Load command mode

b) Back pressure mode

In the load command mode, a desired set point can be given from the turbine control interface and the governance of the main steam control valve is carried out based on the load command. During the commissioning of the steam turbine, the team operated the turbine in this mode. When the load command is given to the system, the steam control valve operates to reach the set load command. The demand of the steam flow is calculated as per the load set point. As a result, the boiler starts to generate steam as per the turbine load command.

This amount of steam has to be passed through the turbine and to be fed to the process. However, the amount of steam required to the production is determined by the production machineries and has no inter connection with the TG plant.

The result of this operation mode is that the undesirable pressure variation at the turbine back end causing the tripping of the turbine. As a corrective action, the operations crew maintain the back-end pressure by dumping the excess steam to the atmosphere. By this method, the turbine can be operated with the controlling of the back pressure. However, the steam is wasted in higher quantities causing the waste of energy. The noise emanated by dumping the live steam was very high. Due to above two reasons, the operation of the turbine has been abandoned.

The TG plant has been operating without the steam turbine for more than a year. However, the steam for the process has been supplied throughout. The financial status of the plant was maintained healthy with a positive cash flow of around 160,000 USD per month. As seen in the financial analysis, more than 2 million dollars were saved during the year of 2016 by the TG plant.

Turbine operation with back pressure control

As mentioned in the study, the TG plant architecture was to match the thermal demand of the process. The electricity generation is considered as the result of the thermal demand. The best suitable operating mode is the turbine operation with back pressure control. In this case, the turbine main steam control is operated as per the pressure variation given by the turbine back pressure resulting a smooth operation.

Two trial runs were tested by changing the operation mode of the operation during the month December 2016. In both cases the turbine was tripped during the start-up while ramping to the full speed no load (FSNL) condition. (The turbine is to be ramped up to 7500 rpm). The turbine was tripped by the high vibration at both journal bearings. The vibrations sensors, terminals, cables were tested and they were found in normal condition. This indication clearly showed that the vibration of the turbine is a real case. It was decided to open the turbine upper shell and see the abnormalities physically. The following pictures were taken after opening the turbine upper half.

Figure 17: Steam turbine upper half opened for inspection

Figure 18: Corrosion at the labyrinth seal

The turbine rotor and the casing was found corroded with rust. The labyrinth seal was also found considerably corroded. The rivets of the turbine blades were eroded. As a result, turbine blades were found loosened. This was the reason to cause high vibration. Afterwards, the turbine rotor was removed and sent for the repair.

After the repair work at the turbine rotor, it is expected to carry out the start-up with back pressure control mode. If the trial runs will be succeeded, the TG plant will be operated with its complete performance.

If the back-pressure control mode operation fails after the trial runs, then an additional back pressure control system is to be installed to regulate the pressure at 9.0 barg. In this system, the excess steam coming out of the system is to be condensed through a heat exchanger and should be recovered. The detailed design work will be carried out after the results of the trial run.

4.4 Political Factors

During the TG plant project, there were several occasions that the overall performance affected significantly due to the influence of the stakeholders. Most of the time, the performance was affected negatively. In this paragraph, those cases were mentioned for the purpose of learning the lessons from the first TG project in Sri Lanka.

4.4.1 Social Influence

The emission and the noise regulations to be met in a BOI zone in Sri Lanka are well established and the environment protection licences (EPL) are issued on annual basis after the environmental audits. During the commissioning stage of the TG plant, concerns were raised by the public on the dust and the noise emanated from the system during start-ups. Management should incur additional amount of money to install noise barriers and an additional wet scrubber to mitigate the issues raised by the public. The fact is to be considered that the plant was designed to run 360 days per year and therefore the start-ups are not a continuous process. However, about 16% of initial capital expenditure has been incurred to mitigate it. This example clearly shows that the lack of interest on the government authorities to support the businesses that intend to conserve energy as well as to improve the business portfolio.

4.4.2 Coal Import Authority

As mentioned in the early pages, the authority of importing coal was not eligible for the company. There were few factors to be fulfilled such as minimum quantity of 10000 tons, independent operation of the port. These two factors are such that a small or medium scale user is not eligible for the import of coal. This factor affects the flawless supply of coal. As an example, operations at this plant were halted for two months, December 2016 and January 2017, due to the unavailability of coal leading the company to use the alternative of burning expensive oil, for the supply of steam to meet the demands.

5 CHAPTER 5: CONCLUSION

Tri-generation technology is the fulfilment of multiple energy requirements such as electricity, heating and cooling from a single energy source. Implementation of tri-generation after a proper design of the overall energy system attributes certain financial benefits over the conventional fulfilment of the basic energy requirements. Even though the TG technology is being practiced in other countries in the region and worldwide, it is still at a primitive stage in the Sri Lankan context.

Three main technologies of power generation are involved with the TG technology. They are steam turbine technology, gas turbine and the reciprocating internal combustion engine technologies. The tri-generation options associated with these three technologies were reviewed in detail. Mostly, the technology is dependent upon the availability of the fuel. Use of steam turbines and internal combustion engines is preferred in the local context as natural gas, which is the best fuel source for the gas turbines is not available in Sri Lanka. Properly designed tri-generation plant can achieve certain financial benefits while in some cases, net emission reduction can also be achieved. The initial cost of investment for the tri-generation is more compared to the conventional method of fulfilment of the energy requirements.

The apparel industry is the backbone of the industrial export sector in Sri Lanka. Moreover, almost all the sub functionalities of the apparel sector, the use of electricity, heat and air conditioning is involved. Hence, there is a potential of implementing TG Technology for the apparel related industries and thereby gaining of lower cost of operation to be competitive among the regional apparel industries.

Out of the main functionalities of the apparel sector, fabric manufacturing is the highest energy intensive process in which the energy conservative options such as the TGT can be implemented with desirable financial benefits. Textured Jersey Lanka PLC is a knit fabric manufacturer located in Avissawella IPZ that implemented the first tri-generation plant running on coal. The atmospheric fluidized bed boiler uses pulverized coal as the fuel and has a capacity of 20 TPH. The back-pressure steam turbine power is having a capacity of 1 MW_e. In this plant design, the total thermal energy demand was matched. The refrigeration system has a capacity of 610 TR and it was replaced by a vapour absorption system which consumes steam as energy input.

In order to evaluate the performance of the TG plant, critical parameters affecting the performance were evaluated. Following indicators were identified as the most significant KPIs in order to evaluate the performance.

a) Overall efficiency
b) Heat to power ratio
c) Net electrical power

Above parameters were calculated using the operations data for the year 2016. It was found that the TG plant performance is below the accepted performance level compared to a similar TG plant using the back-pressure turbine design. However, the financial performance for year 2016 was highly favourable. Throughout the year, the cash flow was positively maintained. As a total around 2.3 million USD savings have been achieved by mitigating the use of heavy fuel oil.

The key point highlighted was the failure of steam turbine operation. Investigations were carried out and it was found that the steam turbine tripped due to the failure of maintaining the back pressure at the turbine. With the process steam flow variation, the back pressure was not maintained at the narrow 0.8 bar tolerance level.

As a solution, it was proposed to operate the turbine at back pressure control mode. During the trial run the turbine was tripped due to higher vibration and it was later found that the turbine rotor was corroded and turbine blades were found loosened. The rotor was sent back to the repair. After the reassembly, the trial runs are expected to carry out switching to the back-pressure control mode.

If the turbine was operated in correct order without the performance indicators were evaluated using the power curve provided by the manufacturer. The results indicate the performance is within the limits of a typical TG plant design using a back-pressure turbine.

Other than the technical and financial performance, few reasons were highlighted which affected the operation and performance. The lack of policies of the government for the energy efficiency projects were highlighted and the dependency of large scale coal importers, affected negative way to the reliability of the seamless coal supply.

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APPENDIX A: OPERATIONAL DATA

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Steam Consumption (Tons)	Running Hours.
1-Jan	0	108	3790	132	12
2-Jan	0	32	2741	0	0
3-Jan	0	108	7079	258	24
4-Jan	0	117	5931	140	15
5-Jan	0	50	1850	0	0
6-Jan	0	28	1846	0	0
7-Jan	0	0	2168	0	0
11-Jan	41	23	5854	265	24
12-Jan	43	0	5685	272	24
13-Jan	39	27	5665	281	24
14-Jan	40	38	5720	212	24
15-Jan	38	41	5794	283	24
16-Jan	36	45	5399	276	24
17-Jan	17	42	4465	126	24
18-Jan	0	69	2316	0	24
19-Jan	18	35	4398	136	24
20-Jan	28	88	5478	256	12
21-Jan	26	90	5818	269	0
22-Jan	30	95	6022	271	14
23-Jan	35	91	5612	257	24
24-Jan	34	117	5783	256	24
25-Jan	33	148	5903	251	24
26-Jan	36	138	5813	269	24
27-Jan	34	141	5877	270	24
28-Jan	35	126	5902	281	24
29-Jan	34	132	5704	267	24
30-Jan	43	132	5567	302	24
31-Jan	7	105	3087	48	24
January Data	**647**	**2166**	**137267**	**5379**	**509**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Steam Consumption (Tons)	Running hrs.
1-Feb	0	70	1242	0	0
2-Feb	0	63	1125	0	0
3-Feb	0	34	1069	0	0
4-Feb	0	21	2414	0	0
5-Feb	0	42	1223	0	0
6-Feb	31	48	3480	237	24
7-Feb	35	54	5506	270	24
8-Feb	33	63	5201	258	24
9-Feb	35	61	5899	279	24
10-Feb	33	103	5561	264	24
11-Feb	34	84	5398	263	24
12-Feb	31	41	5162	266	24
13-Feb	31	81	5224	262	24
14-Feb	31	94	5350	259	24
15-Feb	34	77	5356	265	24
16-Feb	32	94	5411	269	24
17-Feb	35	36	5216	275	24
18-Feb	34	86	5493	266	24
19-Feb	33	68	5513	262	24
20-Feb	33	107	5265	258	24
21-Feb	33	107	5273	258	24
22-Feb	19	96	2344	145	14
23-Feb	0	97	1310	0	0
24-Feb	23	127	0	176	18
25-Feb	26	90	4100	194	20
26-Feb	33	57	5140	255	24
27-Feb	27	60	4813	207	24
28-Feb	33	107	5211	248	24
29-Feb	32	35	5169	238	24
February Data	**721**	**2103**	**119468**	**5671**	532

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Steam Consumption (Tons)	Running hrs.
1-Mar	34	54	5212	252	24
2-Mar	34	82	5189	248	24
3-Mar	35	47	5215	256	24
4-Mar	35	124	5190	255	24
5-Mar	36	116	6153	261	24
6-Mar	36	100	4160	261	24
7-Mar	35	115	5209	256	24
8-Mar	36	111	5237	265	24
9-Mar	37	124	5298	271	24
10-Mar	36	113	5279	262	24
11-Mar	36	89	5219	265	24
12-Mar	36	59	5124	272	24
13-Mar	11	44	1241	77	10
14-Mar	0	51	0	0	0
15-Mar	17	57	191	127	14
16-Mar	0	4	219	0	0
17-Mar	21	109	4211	160	19
18-Mar	25	90	4504	266	24
19-Mar	35	86	5087	257	24
20-Mar	33	129	3605	258	24
21-Mar	30	126	5192	262	24
22-Mar	31	106	5178	264	24
23-Mar	31	117	5116	256	24
24-Mar	34	111	5266	278	24
25-Mar	33	127	5279	268	24
26-Mar	33	110	5185	267	24
27-Mar	33	111	5182	269	24
28-Mar	29	105	4545	240	24
29-Mar	33	151	5258	262	24
30-Mar	15	102	3606	119	14
31-Mar	0	75	1514	0	0
March Data	**870**	**2945**	**132864**	**6755**	**633**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Steam Consumption (Tons)	Running Hrs.
1-Apr	12	72	3218	93	11
2-Apr	33	107	5487	270	24
3-Apr	33	183	5295	265	24
4-Apr	36	216	5460	277	24
5-Apr	34	137	5329	264	24
6-Apr	34	64	5277	259	24
7-Apr	34	174	5273	253	24
8-Apr	34	188	5169	257	24
9-Apr	35	167	5359	267	24
10-Apr	29	149	5525	223	24
11-Apr	0	0	0	0	0
12-Apr	0	0	0	0	0
13-Apr	0	0	0	0	0
14-Apr	0	0	0	0	0
15-Apr	0	0	0	0	0
16-Apr	0	0	0	0	0
17-Apr	0	0	0	0	0
18-Apr	0	0	0	0	0
19-Apr	0	0	0	0	0
20-Apr	0	273	8561	0	0
21-Apr	0	0	0	0	0
22-Apr	14	38	7018	104	9
23-Apr	35	141	5490	257	24
24-Apr	34	180	5371	260	24
25-Apr	35	243	5522	276	24
26-Apr	34	158	5291	266	24
27-Apr	34	105	5254	261	24
28-Apr	34	81	5277	263	24
29-Apr	34	14	5178	261	24
30-Apr	34	111	4816	269	24
April Data	**602**	**2801**	**109170**	**4644**	**428**

Date	Coal Consumption (Tons)	Electricity Consumption (Kwh)	Steam Consumption (Tons)	Running Hrs.
1-May	36	5461	279	24
2-May	36	5415	278	24
3-May	36	5383	271	24
4-May	36	5412	258	24
5-May	35	5256	257	24
6-May	34	5479	264	24
7-May	36	4944	282	24
8-May	35	3051	270	24
9-May	35	5603	273	24
10-May	34	5536	258	24
11-May	34	5718	281	24
12-May	34	5358	265	24
13-May	35	5774	273	24
14-May	34	5638	262	24
15-May	34	5422	266	24
16-May	33	5612	243	24
17-May	29	5751	227	24
18-May	29	4666	236	24
19-May	35	5853	277	24
20-May	34	5709	261	24
21-May	34	5672	260	24
22-May	34	5790	259	24
23-May	35	5826	265	24
24-May	35	5770	259	24
25-May	36	5758	269	24
26-May	35	5687	261	24
27-May	35	5784	260	24
28-May	37	5693	289	24
29-May	20	5018	180	17
30-May	14	4203	112	11
31-May	35	5623	261	24
May Data	**1034**	**167865**	**7956**	**724**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Steam Consumption (Tons)	Running Hours.
1-Jun	35	117	5694	263	24
2-Jun	35	51	5484	258	24
3-Jun	35	54	5838	255	24
4-Jun	20	70	5707	187	18
5-Jun	0	35	1857	0	0
6-Jun	0	33	1162	0	0
7-Jun	28	140	5173	219	22
8-Jun	29	90	5594	233	24
9-Jun	32	91	5753	248	24
10-Jun	35	157	5754	260	24
11-Jun	32	114	5641	246	24
12-Jun	32	98	5894	252	24
13-Jun	28	161	5678	224	24
14-Jun	32	145	5589	241	24
15-Jun	32	160	5763	243	24
16-Jun	33	202	5648	246	24
17-Jun	32	250	5962	251	24
18-Jun	32	213	5638	240	24
19-Jun	33	205	5715	246	24
20-Jun	31	149	5658	236	24
21-Jun	33	148	5692	245	24
22-Jun	33	156	5616	244	24
23-Jun	34	167	5764	250	24
24-Jun	34	173	5698	243	24
25-Jun	34	190	5661	241	24
26-Jun	34	181	5658	242	24
27-Jun	32	221	5884	232	24
28-Jun	34	254	5873	250	24
29-Jun	34	176	5968	249	24
30-Jun	35	246	5993	255	24
June Data	**903**	**4447**	**163009**	**6799**	**664**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Total Steam Generation (Tons)	Quenby Steam (Tons)	Running Hours
1-Jul	34	131	5756	245		24
2-Jul	34	199	5988	248		24
3-Jul	34	225	5980	249		24
4-Jul	34	239	6030	241		24
5-Jul	34	161	5768	249		24
6-Jul	34	125	5766	246		24
7-Jul	37	125	6028	269	19	24
8-Jul	37	170	6191	274	23	24
9-Jul	31	150	6152	223	9	24
10-Jul	31	163	6189	219	0	24
11-Jul	28	146	6135	200	0	24
12-Jul	28	199	6130	206	0	24
13-Jul	31	142	6107	224	0	24
14-Jul	34	143	5766	249	0	24
15-Jul	39	161	6400	293	29	24
16-Jul	38	155	6322	282	10	24
17-Jul	28	150	6191	201	0	24
18-Jul	24	153	6142	172	0	21
19-Jul	27	194	6074	199	0	24
20-Jul	31	117	6060	216	0	24
21-Jul	34	92	5883	242	0	24
22-Jul	20	38	5653	133	0	14
23-Jul	0	8	2781	0	0	0
24-Jul	0	0	3107	0	0	0
25-Jul	0	0	2481	0	0	0
26-Jul	0	6	2056	0	0	0
27-Jul	0	118	1804	0	0	0
28-Jul	0	40	2045	0	0	0
29-Jul	0	34	2443	0	0	0
30-Jul	24	90	5279	174	0	16
31-Jul	38	151	5838	250	0	24
July Data	**764**	**3825**	**160545**	**5506**	**90**	**555**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Total Steam Generation (Tons)	Quenby Steam (Tons)	Running Hrs.
1-Aug	38	158	6069	249	0	24
2-Aug	38	107	5987	269	14	24
3-Aug	35	55	5932	254	12	24
4-Aug	35	66	6050	252	0	24
5-Aug	38	59	6256	271	12	24
6-Aug	35	118	5791	250	8	24
7-Aug	33	163	5913	237	0	24
8-Aug	36	167	5980	258	5	24
9-Aug	36	103	6130	256	0	24
10-Aug	34	130	6001	240	0	24
11-Aug	39	115	6154	279	29	24
12-Aug	39	71	5703	277	24	24
13-Aug	37	135	5610	267	16	24
14-Aug	34	65	6142	245	0	24
15-Aug	34	124	5361	241	0	24
16-Aug	37	123	5606	262	21	24
17-Aug	39	131	5616	277	28	24
18-Aug	40	145	5771	292	39	24
19-Aug	39	133	4240	278	36	24
20-Aug	39	150	5447	281	33	24
21-Aug	37	98	5285	263	21	24
22-Aug	38	101	5390	274	35	24
23-Aug	45	146	938	323	27	24
24-Aug	41	110	2894	295	27	24
25-Aug	38	136	5383	274	38	24
26-Aug	41	171	5732	293	37	24
27-Aug	36	174	5489	262	27	24
28-Aug	34	125	2460	245	19	24
29-Aug	36	120	4837	263	25	24
30-Aug	36	130	5496	262	31	24
31-Aug	37	134	5640	268	23	24
August Data	**1154**	**3763**	**165303**	**8254**	**587**	**744**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Total Steam Generation (Tons)	Quen by Steam (Tons)	Balance Coal Stock (Tons)	Running Hrs.
1-Sep	35	102	5673	254	5		24
2-Sep	37	59	5472	265	0		24
3-Sep	37	120	5682	266	0		24
4-Sep	35	103	5448	249	0		24
5-Sep	36	100	5206	258	0		24
6-Sep	35	87	5720	250	0		24
7-Sep	36	80	5491	256	0		24
8-Sep	36	35	5525	256	0		24
9-Sep	41	96	5763	294	29		24
10-Sep	41	75	5559	290	27		24
11-Sep	37	71	5657	263	2		24
12-Sep	41	119	5921	293	28		24
13-Sep	38	110	5678	272	23		24
14-Sep	39	116	5807	278	28		24
15-Sep	37	114	5727	264	36		21
16-Sep	38	157	5871	270	21		24
17-Sep	35	121	5744	253	5		24
18-Sep	34	102	5897	242	0		24
19-Sep	40	77	6230	283	23		24
20-Sep	40	73	5831	284	37		24
21-Sep	41	126	5852	294	34		24
22-Sep	39	129	5669	273	32		24
23-Sep	39	137	5875	278	31	**500**	24
24-Sep	39	149	6094	279	30	**461**	24
25-Sep	34	143	5154	238	0	**427**	22
26-Sep	28	143	5426	200	14	**399**	17
27-Sep	38	226	5927	268	18	**361**	24
28-Sep	38	148	5857	268	5	**323**	24
29-Sep	38	81	5044	269	0	**285**	24
30-Sep	40	125	6416	284	28	**245**	24
Sep Data	**1122**	**3324**	**171216**	**7990**	**456**		**708**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Total Steam Generation (Tons)	Quenby Steam (Tons)	Running Hrs.
1-Oct	44	142	5946	311	29	24
2-Oct	27	112	5596	192	0	18
3-Oct	0	49	1343	0	0	0
4-Oct	0	2	1388	0	0	0
5-Oct	10	122	3191	80	0	8
6-Oct	41	246	5174	288	51	24
7-Oct	44	189	5395	309	99	24
8-Oct	15	153	3734	105	19	9
9-Oct	0	50	2040	4	0	2
10-Oct	28	94	4184	195	0	18
11-Oct	34	142	5213	237	0	24
12-Oct	7	67	3631	50	0	5
13-Oct	38	178	5260	264	0	24
14-Oct	31	233	5762	215	0	20
15-Oct	28	150	4596	192	0	18
16-Oct	38	174	5328	267	0	24
17-Oct	40	253	4245	287	0	24
18-Oct	38	159	5361	262	0	24
19-Oct	38	185	5284	267	0	24
20-Oct	39	158	5369	275	0	24
21-Oct	38	157	5195	269	0	24
22-Oct	40	163	5323	282	0	24
23-Oct	37	168	3672	258	0	24
24-Oct	37	162	5255	258	0	24
25-Oct	41	151	5337	291	0	24
26-Oct	39	184	5367	274	0	24
27-Oct	39	162	5173	274	0	24
28-Oct	39	179	5368	274	0	24
29-Oct	38	184	5290	264	0	24
30-Oct	41	171	4576	287	0	24
31-Oct	38	172	5942	267	0	24
October Data	**967**	**4711**	**144538**	**6798**	**198**	**602**

Date	Coal Consumption (Tons)	Process Water Meter (m^3)	Electricity Consumption (Kwh)	Total Steam Generation (Tons)	Quen by Steam (Ton)	Balance Coal Stock (Ton)	Running Hours
1-Nov	17	151	4633	116			12
2-Nov	0	41	2269	0			0
3-Nov	25	99	4465	176	0		16
4-Nov	39	169	5243	272	0		24
5-Nov	37	165	5535	251	0		24
6-Nov	6	100	3211	40	0	**0**	4
Nov till date	**124**	**725**	**25356**	**855**			**80**

APPENDIX B: TECHNICAL DATA OF THE BOILER

EQUIPMENT DATA

GENERAL

Type of System	: Atmospheric Fluidized Bed Combustion
Type of Boiler	: Bi drum, Water tube
Type of Furnace	: Membrane wall
Type of feeding system	: Under Bed for coal
Type of water circulation	: Natural
Type of draft system	: Balanced
Type of support	: Bottom Supported
No. of units	: One

PARAMETERS OF BOILER

Ambient Temperature	: 40 ^{0}C (design and performance)
Relative Humidity	: 60%
Flue gas temperature leaving at APH	: 160-170 ^{0}C

INBED COILS

Tube size	: 50.8mm O.D × 6.35 mm thk
Tube material specification	: SA 210 GR A1, SEAMLESS

FURNACE

Water wall construction	: Membrane panel
Water wall tube size	: 63.5mm OD × 4.06 mm thk
Water wall tube material	: BS 3059 PART1 ERW GR 320
Water wall fin thickness	: 6.0 mm
Water wall fin material	: I 2062
Header Size	: OD 219.1 mm × 12.7 mm thk
Header material	: SA 106 Gr.B

DRUMS

	Steam Drum	Water Drum
Internal diameter-mm	1234	750
Material of construction	SA 516 Gr. 70	SA 516 Gr. 70
Type of dished ends	Semi Ellipsoidal	Semi Ellipsoidal
Length (approx.)-mm	3900	3000
Thickness of shell mm	40	28

AIR PRE HEATER

Arrangement and type : staggered tubes cross counter flow

Tube size : 63.5 mm O. D ×2.04 mm thk

Tube material specification : BS 6323 ERW Part V

Flow medium

- Inside tubes : Flue Gas
- Outside tubes : Air

Casting material specification : 4 mm thk, IS 2062

DUCTING

Air ducting thickness : 3mm thk

Flue gas ducting thickness : 4mm thk

Plate material specification : IS 2062 Gr. A

PAINTING OF FCTORY SUPPLIED ITEMS

Painting specification : As per Thermax Export painting Quality Standard

FORCED DRAFT FAN

Fan Make	: Solyvent Flakt (India) Pvt. Ltd
Fan Model	: HF 3S SLIA 14l S8 (SPL.)
Qty Nos	: 1 (One)
Flow m3/sec	: 8.47
Static head (mmWG)	: 760@45^{0}C
Medium	: Air
Temperature ^{0}C Operating	: 45
Fan speed rpm	: 1440
Connected Power	: 110 kW

PRIMARY AIR FAN

Fan Make		: Solyvent Flakt (India) Pvt. Ltd.
Fan Model		: HF 12S SLIA 77 S8 (Spl.)
Qty	Nos	: 1 (One)
Flow	m3/sec	: 1.3 l
Static head	(mmWG)	: 700@160^{0}C
Medium		: Air
Temperature ^{0}C Operating		: 160
Fan speed	rpm	: 2910
Connected power		: 22kw

INDUCTED DRAFT FAN

Fan Make		: Solyvent Flakt (India) Pvt. Ltd
Fan Model		: FL TSR 136 3TS8A (SPL.)
Qty	Nos.	: 1 (One)
Flow	m3/sec	: 12.64
Static head	(mm WG)	: 200@ 160^{0}C
Medium		: flue gas

Temperature ^0C Oper/Design		: 160
Fan speed	rpm	: 970
Connected Power		: 45 kW

FEED PUMP

Quantity	Nos.	: 2 (One working, one standby)
Make		: KSB
Capacity	m3/hr	: 26
Pressure head	m	: 535
Medium		: Boiler feed water
Feed water temp ^0C		: 130
Connected Load kW		: 75kw

SAFETY VALVES- SD & SH

Make	: TYCO SANMAR LTD
Size (Inlet/orifice/Outlet)	: 1.5 H2 3.0
SD SV-1 Set pressure (Kg/ sq.cm)	: 43.5
Relieving capacity Actual	: 8063 Kg/hr
Safety Valve (Model)	: HCI-R-46W-IBR
SD SV-2 Set pressure (Kg/ sq.cm)	: 44.2
Relieving capacity Actual	: 8191 Kg/hr
Safety Valve (Model)	: HCI-R-46W-IBR
SH SV Set pressure (Kg/sq.cm)	: 39
Relieving capacity Actual	: 5412 Kg/hr
Safety Valve (Model)	: HCI-R-46W-IBR
SV Qty	: 2No on stream drum & 1 No on SH

DEAERATOR AND DEAERATED WATER STORAGE TANK

Make : RAVI INDUSTRIES.

Design code : IBR

Design pressure and temperature : 3kg/cm2g at 175^{0}C

Operating pressure and temperature : 1,74kg/cm2g at 130^{0}C

Design capacity : 22m3/hr

Storage tank capacity (NWL to LLWL) : 7.5 m3

Steam press. & temp. at deaerator I/L : 2.75 kg/cm2 at 240^{0}C

Make up Water inlet Pressure/Temp : 70^{0}C

Material of Construction

Shell and Tower : SA 516 GR. 70

Spray Nozzles & Trays : SS 304

APPENDIX C: TECHNICAL DATA OF THE STEAM TURBINE

TECHNICAL DATA

1. **TURBINE**

Power Normal	KW	1000
Inlet Steam Pressure	ATA	35
Inlet Steam Temperature	^{0}C	380
Inlet Steam Flow	Kg/Hr	19800
Exhaust Pressure	ATA	10
Turbine Speed	RPM	7558
Alternator Speed	RPM	1500
Turbine Trip Speed Range	RPM	8250/8625
First Critical Sped Range	RPM	11250/11750
Steam Inlet size		8” NB 600# RF
Direction of Rotation From Output end		Counter Clockwise

2. GEAR BOX

Type		Single Helical
Model		HSG 320
Speed/Input	RPM	7558-1500

3. OIL SYSTEM

Lubricating Oil		ISO-VG-46
Oil Reservoir Capacity	LTR	1000
1st Fill Oil Requirement	LTR	1100
Flushing Oil Requirement	LTR	1000
Lube Oil Pressure Range	Bar(g)	1.8-2
Control Oil Pressure	Bar(g)	5.0-5.5

A. MAIN LUBRICATING OIL PUMP

Type		Geared
Capacity	LPM	227
Driver		Gear Box

B. A.C. AUXILLARY OIL PUMP

Type		Geared
Capacity	LPM	250
Speed	RPM	1440
Motor	HP	7.5, 400V

C. EMERGENCY OIL PUMP

Type		Geared
Capacity	LPM	73
Discharge Pressure	Bar(g)	2
Motor	HP	110 V AC

D. OIL COOLER

Type		Horizontal Duplex
Capacity	LPM	250
Oil Temperature Inlet	^{0}C	60
Oil Temperature Outlet	^{0}C	45
No. of Tubes	-	188-1/2” O/D ×20 BWG
Cooling Water Temp. Inlet	^{0}C	35
Cooling Water Temp. Outlet	^{0}C	38
Cooling Water Flow	LPM	510

E. OIL FILTER (LUBE OIL)

Type		Duplex
Capacity	LPM	205
Grade of Filtration	Microns	10-15

F. CONTROL OIL FILTER

Model		Vertical mounting
Capacity	LPM	36
Grade of Filtration	Microns	15

G. PRESSURE RELIEF VALVE (MOP)

Duty		Lube Oil
Size Inlet/ Outlet		40 NB
Set Pressure	Bar(g)	5.6

H. PRESSURE RELIEF VALVE (AOP)

Duty		Lube Oil
Size Inlet/Outlet		40 NB-ANSI 150# RF
Set Pressure	Bar(g)	5.5
Discharge Capacity	LPM	410

I. PRESURE RELIEF VALVE (LUBE OIL)

Duty		Lube Oil
Size Inlet/Outlet		1” NB
Set Pressure	Bar(g)	2.10
Discharge Capacity	LPM	3

J. ACCUMULATOR

Pre Changed Pr.	Bar(g)	3.9-4.0
Capacity	Ltr	4.0

K. 2-WAY SOLENOID VALVE

Volts	110 V DC
Connection	¾” BSP (F)
Action	De Energize to Trip

L. 3-WAY SOLENOID VALVE

Volts	110 V DC
Connection	¾ “ BSP (F)
Action	Normally closed

M. SENTINAL RELIEF VALVE

Duty		Steam
Set Pressure	Bara	9.9-10.35
Connection	NPT	¾”

4. THROTTLE VALVE LIFT

Throttle Valve Lift N0.1	mm	38 max

5. GENERAL

A. High Speed Coupling

Model	6GBL-160
Drawing no.	120756-00

B. Low Speed Coupling

Type	Geared
Drawing no.	GA 100701

C. Governor

Type	Woodward (505 Model)
Model	Digital

D. Actuator (HP)

Manufacturer	Woodward
Type	TG 17E

E. GLAND VENT CONDENSER

Type		Horizontal, Shell & Tube
Steam Flow	Kg/Hr	700
Cooling Water Flow	Kg/Hr	64000
C. W. Tem. Inlet/Outlet	^{0}C	32/40
C. W. Pressure	Kg/cm^2(g)	2.0
Surface Area	m^2	7
Blower Capacity	CFM	650bAir at 2” WC
Blower Motor	HP	3.0

6. INSTRUMENT SETTINGS

Description	Service	Recommended settings	Range available
Pressure Switch	AOP auto ON/OFF	1.4 Bar (g) for cur-in, 2.2 Bar(g) for cut-off	0.4 to 4.0Bar(g)
Pressure Switch	EOP auto ON/OFF	1.0 Bar (g) for cur-in, 1.4 Bar(g) for cut-off	0.4 to 4.0Bar(g)
Pressure Switch	Lube oil pressure low alarm	1.4 Bar(g)	0.2 to 2.0 Bar(g)
Pressure Switch	Lube oil pressure very low alarm	1.2 Bar(g)	0.2 to 2.0 Bar(g)
Pressure Switch	Control oil pressure low alarm	3.5 Bar(g)	0.6 to 6.0 Bar(g)
Casing Vibration	Turbine/Gearbox	Alarm-8mm/sec and trip-10mm/sec	Programmable
RTD	Turbine bearings	Alarm 95 ^{0}C, Trip 100^{0}C	Programmable
RTD	Gearbox bearings	Alarm 95 ^{0}C, Trip 100^{0}C	Programmable
RTD	Generator winding	Alarm 120 ^{0}C, Trip 130^{0}C	Programmable