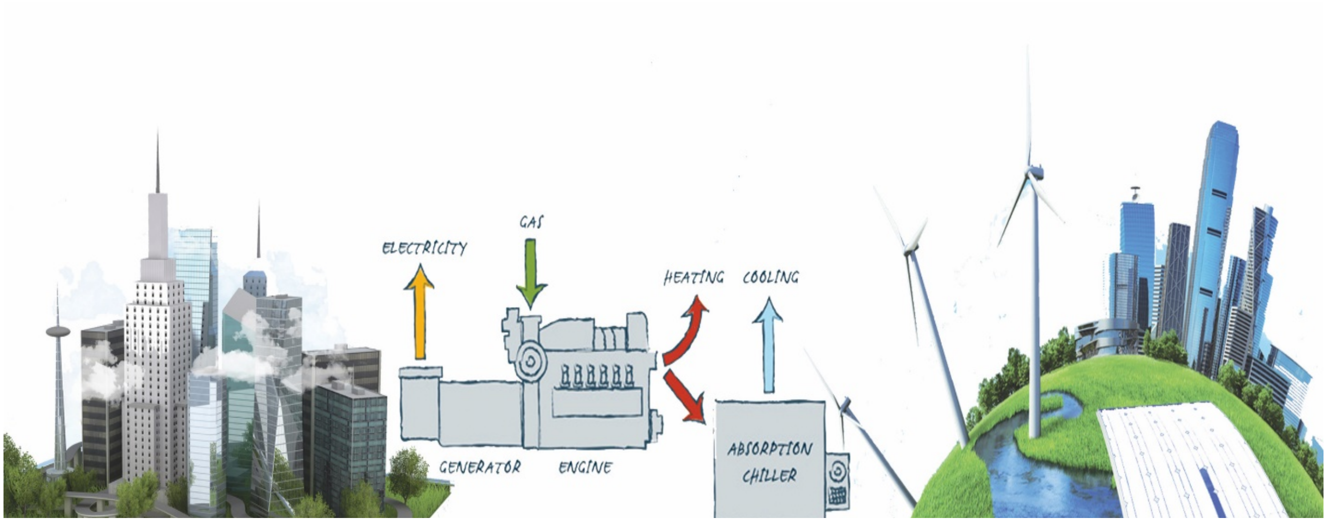
# Feasibility Study for the Implementation of Combined Cooling, Heating and Power (Tri-Generation) System at Biyagama Export Processing Zone- Sri Lanka



SRI LANKA
SUSTAINABLE ENERGY AUTHORITY

# Content

**1 BACKGROUND DATA ........................................ 6**

1.1 Data Collection ........................................ 6

1.2 Acknowledgement ........................................ 6

**2. EXECUTIVE SUMMARY ........................................ 7**

**3. INTRODUCTION ........................................ 9**

**4. ENERGY CONSUMPTION SCeNARIO AT BIYAGAMA EXPORT PROCESSING ZONE ........................................ 12**

4.1 Current Monthly Energy Usage Recorded in Log Books ........................................ 12

4.2 Real-time Energy Usage through Field Measurements ........................................ 18

**5. COMBINED COOLING HEATING AND POWER TECHNOLOGY ........................................ 22**

5.1 Merits and Demerits of CCHP Systems ........................................ 24

5.1.1 Advantages ........................................ 26

5.1.2 Disadvantages ........................................ 26

5.2 Important Aspects to be Considered for the Applicability of CCHP Systems ........................................ 26

**6. CHANGES NEEDED TO THE ENERGY COMPOSITION AT BIYAGAMA EXPORT PROCESSING ZONE (BEPZ) ........................................ 29**

6.1 Proposed Changes to the Existing Energy Supply Systems ........................................ 29

6.1.1 Evading Thermic Oil Heat Supply from the Proposed CCHP System ........................................ 30

6.1.2 Supply of Steam for Hot Water Consumers ........................................ 30

6.1.3Replacement of Vapour Compression Chillers with Vapour Absorption Chillers ........................................ 30

6.2 Maximum Daily Energy Consumption of the Year ........................................ 30

6.3 Replacement of vapour compression chillers with vapour absorption chillers ........................................ 32

6.4 Total Energy Demand Characteristics on a Peak Day ........................................ 33

6.5 Operating Strategies of Combined Cooling Heating and Power Systems ........................................ 35

**7 PROPOSED TRI-GENERATION ARCHITECTUREs FOR BEPZ ........................................ 36**

7.1 CCHP System with Rankine Cycle ........................................ 37

7.1.2 Rankine Cycle with Back Pressure Steam Turbines ........................................ 38

7.1.3 Financial Analysis – CCHP on Back Pressure Steam Turbine ........................................ 43

7.2 Gas Turbine with a Waste Heat Boiler ........................................ 45

7.2.1 Financial analysis of the CCHP system on Gas Turbine and Waste Heat Boiler ........................ 48

7.3 Reciprocating Engine and Waste Heat Boiler ........................................................................ 50

7.3.1 Financial Analysis of CCHP on Reciprocating Engine and Waste Heat Boiler ............................ 53

7.4 The Summary of Sensitivity Analysis of All Five Options ..................................................... 54

**8 EVALUATION OF THE TG TECHNOLOGIES ......................................................55**

8.1 Fuel Selection for the CCHP Plant ........................................................................................ 57

**9 ABBREVIATIONS ..................................................................................................60**

**10 THE ANNEXURES ................................................................................................61**

# List of Tables

Table 1: The sensitivity parameters of different plant configurations for a period of 8 years ..................... 8
Table 2: The industries currently in operation and belong to BEPZ ..................... 10
Table 3: The annual total energy consumption of each energy source including electricity ..................... 13
Table 4: Thermal performance of conventional centralized power systems and decentralized CCHP systems ..................... 24
Table 5: Typical operating ranges of heat-to-power ratio in each CCHP technology ..................... 27
Table 6: Characteristics of cogeneration options ..................... 29
Table 7: Comparison of daily energy (MWh/Day) consumption between measured and peak day in November last year ..................... 31
Table 8: The daily energy consumption scenario with the replacement of electric chillers with absorption chillers ..................... 32
Table 9: The predicted maximum process steam and electricity demand of the cluster with absorption cooling ..................... 33
Table 10: Carbon footprint on the use of different fuel (Source: www.eia.gov) ..................... 37
Table 11: Annual fuel consumption and energy dispatched the CCHP system fired by biomass ..................... 41
Table 12: Annual fuel consumption and energy dispatched of the CCHP system fired by coal ..................... 41
Table 13: Projected capital investment for CCHP System with a Back-Pressure Steam Turbine ..................... 43
Table 14: Projected Profit and Loss Statement for the CCHP system with backpressure steam turbine ..................... 44
Table 15: Projected financial indicators for CCHP System with a back-pressure steam turbine ..................... 44
Table 16: Annual fuel consumption and energy dispatched of the CCHP fired by HFO ..................... 46
Table 17: Annual fuel consumption and energy dispatched of the CCHP fired by LNG ..................... 47
Table 18: Projected capital investment for CCHP system with gas turbine and waste heat boiler ..................... 48
Table 19: Projected profit and loss statement for CCHP System with gas turbine and waste heat boiler ..................... 49
Table 20: Projected financial indicators for CCHP system with gas turbine and waste heat boiler ..................... 49
Table 21: Annual fuel consumption and energy dispatched for the optimum uninstalled capacity of the proposed CCHP ..................... 52
Table 22: Projected capital investment for CCHP System with Reciprocating Engine and Waste Heat Boiler ..................... 53
Table 23: Projected profit and loss statement for the CCHP system with reciprocating engine and waste heat boiler ..................... 54
Table 24: Projected financial indicators for CCHP System with Reciprocating Engine and Waste Heat Boiler ..................... 54
Table 25: The comparison of sensitivity parameters of four different options ..................... 55
Table 26: Capacity of the CCHP plant components ..................... 56
Table 27: Fuel prices and their gross calorific values ..................... 58
Table 28: Current and predicted annual fuel consumptions with additional biomass boilers ..................... 58

# List of Figures

Figure 1: Annual total energy consumption (GWh/year) for lighting and the generation of cooling load, steam, hot water and hot thermic fluid last year.......................................................................... 13
Figure 2: Characteristic total monthly energy consumption of the facility in the year 2018 including electricity, biomass and fuel oil that are used to generate thermic oil, hot water and steam ..................... 14
Figure 3: Characteristic daily average energy consumption of each month  in the year 2018.................. 15
Figure 4: Energy consumption (GWh/Month) scenario in the off-peak month of April last year ............. 16
Figure 5: Energy consumption (GWh/Month) scenario in the peak month of November last year........... 16
Figure 6: Characteristic behaviour of monthly heat-to-electricity ratio last year..................................... 17
Figure 7: Current thermal energy consumption (MWh/Day) scenario obtained from field measurements 19
Figure 8: Characteristic real-time energy demands in 15 minutes intervals for a day (180$^{o}$C < Thermic heat-1 < 210$^{o}$C and 210$^{o}$C < Thermic heat-2 > 250$^{o}$C. (The maximum process steam pressure was 12 barg, process steam represents the hot water and steam demands) ........................................................ 20
Figure 9: Current energy consumption scenario (MWh/Day) for a day (180oC < Thermic heat-1 < 210oC, 210oC < Thermic heat-2 > 250oC and steam pressure  12barg)............................................................ 21
Figure 10: Combined and separate generation of electricity, cooling and heating using CCHP technology and conventional decentralized system ........................................................................................... 22
Figure 11: The phase shift between thermal and electricity demand in Factory A and both of them are in the same phase in Factory B ................................................................................................... 28
Figure 12: Characteristic daily averaged energy consumption of each month last year........................... 31
Figure 13: The calculated electricity and process steam demand including absorption cooling of the selected cluster at BEPZ .................................................................................................................. 32
Figure 14: Predicted process steam and electricity demands with absorption cooling on a peak day of November. The maximum steam pressure is 15barg at the CCHP plant................................................. 33
Figure 15: Predicted characteristic behaviour of heat-to-electricity ratio in a peak day ........................... 35
Figure 16: Schematic diagram of a CCHP with an extraction condensing turbine .................................. 38
Figure 17: Schematic diagram of a CCHP with a backpressure turbine.................................................. 39
Figure 18: The temperature entropy diagram of the proposed CCHP with no additional condenser......... 40
Figure 19: Heat and mass balance diagram of CCHP system with a Back-Pressure Turbine ................... 42
Figure 20: Schematic diagram of the open cycle gas turbine with a waste heat boiler ............................. 45
Figure 21: Heat and mass balance diagram of CCHP system on gas turbine and waste heat boiler.......... 47
Figure 22: Schematic diagram of the reciprocating engine with a waste heat boiler ................................ 50
Figure 23: The percentage of heat recovery from different waste heat channels in the reciprocating engines.......................................................................................................................................... 51
Figure 24: Heat and mass balance diagram of CCHP system on Reciprocating Engine and Waste Heat Boiler ............................................................................................................................................ 52
Figure 25: Schematic diagram of the proposed CCHP plant at BEPZ ................................................... 57
Figure 26: IRR Vs Biomass price of the proposed CCHP plant with a backpressure turbine ................... 59

# 1 BACKGROUND DATA

Sri Lanka Sustainable Energy Authority (SLSEA) awarded the Feasibility Study for the Implementation of Tri–generation System at Biyagama Export Processing Zone (BEPZ) to Industrial Services Bureau (ISB) on 21.06.2018 following the government procurement process.

**The ISB Project Team**

- Consultant Team Leader – Dr. SaliyaJayasekara, Senior Lecturer, Faculty of Engineering, UOM
- Team members
    - Dr. A.C. Vidanapathirana - Electrical Engineering
    - ThilankaAlwis - B. Sc. Chemical Process Engineering
    - Niroshan Abeysinghe - Technical officer
    - Dammika Bandara - Technical officer

## 1.1 Data Collection

The data collection was done in two stages. At the first stage, basic energy use data (installed capacity) was gathered from 59 factories at BEPZ from 19.09.2018 to 19.10.2018.

At the second stage the detailed electrical, thermal, and cooling load data were obtained for a period of 24 hours in 15 minutes interval. More than 50% of the bulk energy consumers (short listed 36 industries) were addressed in the second stage. The detailed energy surveywas carried out for the short-listedgroup of20industriesfrom phase A and 16 industries from phase B at BEPZ from 19.10.2018 to 9.12.2018. None of the industry that utilized heat for their manufacturing process has been left behind. In addition, any industry/office-building that deployed a central air conditioning system with a large cooling load has been included in to thisshort-listedgroup.

## 1.2 Acknowledgement

SLSEA would like to express sincere thanks to Mr. Lawrence, Executive Director (Zones), A.K. Jayasinghe, former Director Zone ( BEPZ) and all Engineers and staff of the BEPZ for extending their cooperation in data collection, during the factory visits of the survey.

Also, SLSEA would like to thank to Industrial Services Bureau (ISB) Team, the selected Consultant and registered Energy Services Company (ESCo), headed by Dr. Saliya Jayasekara, Senior Lecturer of University of Moratuwa (UOM), and Director ISB, Mr. Ajith Vidanapathirana and all staff for successfully completing this assignment.

We would also like to express the sincere thanks to Management and Staff of SLSEA including, Chairman, DG, DDG (DSM), D(EM), Head (EM), Mr. Saman Elvitigala and all Engineers, the Technical Evaluation Committee and the staff for their fullest support extended to complete this study.

## 2. EXECUTIVE SUMMARY

Industrial Services Bureau (ISB)carried outthisfeasibility study on Combined Cooling Heating and Power (CCHP) Technology (Tri-generation)atthe Export Processing Zone Biyagama (BEPZ) Sri Lanka, supported by Sri Lanka Sustainable Energy Authority (SLSEA) with an overall objective of improving the energy efficiency in Free Trade and Industrial Zones in Sri Lanka. The BEPZ is one of the largest industrial zones in Sri Lanka focusing mainly on producing garments and fabrics forthe foreign market. Accordingly, this BEPZ was chosen for the feasibility study on CCHP Technologies, to facilitate maximum replication in other free trade zones and industrial areas in the country. The main energy forms used in BEPZ are grid electricity, biomass, furnace oil,kerosene and diesel oil. In the BEPZ 50% of total energy is usedforhot water, steam and thermic heat generation.

Boilers, thermic fluid and hot water heaters are used to generate these thermal energy carriers and serve the production lines through distribution pipelines. The efficiency of these thermal systems varies from 64.6 to 82.8% based on gross calorific value of the fuel. Majority of the industries of the BEPZ use biomass for the productionprocess heat, whereas very few industries use diesel and kerosene. This Detailed Report on FeasibilityStudy (DRFS) highlights the energy, environment, economic and social benefits of the use of biomass-fired Rankine cycle-based co-generation technology for power generation and utilization of waste heat from the backpressure turbine in steam and hot water production. Rankine cycle-basedco-generation technology, generates electrical energy and thermal energy at the same time by using biomass as a fuel. Partially expanded steam from the turbine at the right pressure is released in two ways;firstly,directly to the industries that utilized steam and secondly through a water heater to the industries that need hot water. Hence, in order to increase the thermal load that increases the combined generation of electricity, the electric chillers are replaced with absorption chillers fired by steam that reduces the electricity consumption of the cluster.

Table 1: The sensitivity parameters of different plant configurations for a period of 8 years

| **Sensitivity parameter** | **Backpressure turbine** | | **Engine** | **Gas turbine** | |
|---|---|---|---|---|---|
| | **Biomass** | **Coal** | | **HFO** | **LNG** |
| NPV at 12% (Millions LKR) | 5,226 | 1,479 | 4,131 | -2,769 | -1,498 |
| IRR | 36% | 20% | 20% | 2% | 7% |
| Simple Payback | 27 Months | 45 Months | 46 Months | 87 Months | 72 Months |

The projected profitability and cash flow statements and technical evaluations indicate that the project implementation i.e. installation of ***steam-based backpressure cogeneration technology will be a financially viable and technically feasible solution for the cluster***.

The proposed option of biomass-fired Rankine cycle is the best option economically as shown in Table 1. Based on the well-establishedRankine cycle technology and results from the technical feasibility study, the proposed system istechnically the second-best among the above options.

The proposed system does not directly contribute to the environment pollution since the biomass is considered as a carbon zero fuel. The strong biomass supply chain currently established at the BEPZ is promising the fuel supply security and assures the benefits of the biomass farmers and suppliers currently enjoying in nearby villages.

NOTE:

The selling and purchasing prices of electricity, heat and fuel for the above CCHP plants configurations were taken as follows

- Electricity selling price: 22Rs/kWh
- Thermal energy selling price: 6.70Rs/kWh
- Biomass purchasing price: 6Rs/kg
- Coal purchasing price: 19Rs/kg
- Furnace oil purchasing price: 80Rs/L
- Liquid Natural Gas (LNG) purchasing price: 77Rs/$m^3$

# 3. INTRODUCTION

Fulfilment of energy needs is a challenge today, and itis likely to remain so in future, as the current energy supply systems (from primary energy sources to final energy services) appear to be unsustainable. A transition to alternative energy supply systems is presently in the spotlight, propelled by concerns on climate change caused by greenhouse gas emissions and dependence on depleting fossil fuel reserves. This transition will certainly involve meeting the future's energy demands with greater efficiency. The improvement of energy utilization efficiencies and the use of renewable energy sources will play a significant role in reducing energy cost as well as the environmental impact.

Sri Lanka Sustainable Energy Authority (SLSEA) and Industrial Services Bureau (ISB) jointly implement this feasibility study. This study mainly focuses on the feasibility of CCHP technology to BEPZwhich consumes electricity for production and HVAC as well as biomass and fossil fuel for process heating in large quantities.

Biyagama ExportProcessing Zone (BEPZ) is one of the largest industrial processing zones in Sri Lanka and mainly famous for the manufacturing of garments and fabrics. The BEPZ is spread throughout about 2km in the Biyagama area. There are approximately 62 companies in this zone, which are engaged in manufacturing of garments, gloves, buttons, ceramicand other products.The main sourcesof energy used by the companies in the zone are Grid Electricity, Biomass, Kerosene and Diesel oil. Major consumptions of energy are thermal energy usingBiomass.

The feasibility study was initiated with the Walk-ThroughEnergy Audit (WTEA) covering all the 62 industries in the BEPZ. During the WTEA basic energy and production data were gathered from each factory for a period of three years (approximately). These data were then analyzed and shortlisted the industries that consume energy in large quantities as bulk energy consumers for the detailed energy survey. To targetall most all the thermal energy consumers, 36 industries (20 from Zone A and 16 from Zone B) were selected for the detailed study.

For this short-listed group detailed electrical, thermal and cooling load data were taken for a period of 24 hours. The industries currently operating in Zone A and Zone B are shown in Table 2. The 36 number of industries shortlisted for the detailed analysis are shown in ***green colour***in Table 2. Basically, these factories are engaged in manufacturing apparel, gloves, knitting, vegetable processing and packaging, solid tyres, chemicals, tobacco processing and, etc. (The production and energy details of BEPZ are shown in the Annexure B).

Table 2: The industries currently in operation and belong to BEPZ

|  | **No** | **Name of the Industry** | **Electrical** | **Heating** | **Cooling** |
|---|---|---|---|---|---|
| **Phase A** | 1 | Ansell Lanka ( Pvt)Ltd | √ | √ | √ |
|  | 2 | MAS Active (Pvt) Ltd | √ | √ | √ |
|  | 3 | Lumiere Textiles Ltd | √ | √ |  |
|  | 4 | Mas Active-Linea Intimo | √ | √ | √ |
|  | 5 | Central Rubber (Pvt) Ltd | √ | √ | √ |
|  | 6 | Silueta(Pvt ) Ltd | √ |  | √ |
|  | 7 | Workwear Lanka (Pvt) Ltd | √ | √ |  |
|  | 8 | Richard Peiris Natural forms Ltd | √ | √ | √ |
|  | 9 | Noyon Lanka | √ | √ | √ |
|  | 10 | DPL Universal Glove Ltd | √ | √ |  |
|  | 11 | H.J.S Conddiments Ltd | √ | √ |  |
|  | 12 | MapaLalan Rubbers (Pvt ) Ltd | √ | √ |  |
|  | 13 | Noth Manufacturing (Pvt ) Ltd | √ |  | √ |
|  | 14 | Starco Lanka (Pvt) Ltd | √ | √ |  |
|  | 15 | S & D Chemical (Pvt) Ltd | √ | √ |  |
|  | 16 | Southern spars International (Pvt) Ltd | √ |  |  |
|  | 17 | De La rue Lanka Currancy&Scurity print Ltd | √ |  |  |
|  | 18 | Agio Tobacco Processing Co Ltd | √ | √ |  |
|  | 19 | Unichela (pvt) Ltd (Unichela(Pvt) Ltd | √ |  |  |
|  | 20 | MAS Aayathi | √ |  | √ |
|  | 21 | Rainwear (Pvt) Ltd | √ |  |  |

| | | | | | |
|---|---|---|---|---|---|
| | 22 | Industrial Gloves & House hold Gloves | √ | | √ |
| | 23 | Stretchline (Pvt) Ltd - Main Plant | √ | √ | √ |
| | 24 | Stretchline (Pvt) Ltd - Knitting Plant | √ | | |
| | 25 | Stretchline (Pvt) Ltd - Dye Plant | √ | √ | √ |
| | 26 | Dyna Wash (Pvt) Ltd | √ | √ | |
| | 27 | Prym Intimates Lanka (Pvt) Ltd | √ | | √ |
| | 28 | Lalan Rubber (Pvt) Ltd | √ | √ | |
| | 29 | Reliance Diamond Tools (Pvt) Ltd | √ | | |
| | 30 | The Wheelwork (Pvt) Ltd | √ | √ | |
| | 31 | MAS Fabric Park (Pvt) Ltd | √ | | |
| | 32 | Seylon Industries (Pvt)) Ltd | √ | | |
| | 33 | Ardmel Manufacturing (Pvt) Ltd | √ | | |
| | 34 | Snackings(Pvt) Ltd | √ | | |
| | 35 | Modern Printing Design Lanka Limited | √ | | |
| | 36 | Multichemi Exports (Pvt) Ltd | √ | | |
| | 37 | Verora Lanka Power panels (Pvt) Ltd | √ | | |
| | 38 | Ceramic World (Pvt) Ltd | √ | | |
| | 39 | EDUENG (Pvt) Ltd | √ | | |
| | 40 | Stretchline (Pvt) Ltd - Covering Plant | √ | √ | |
| | 41 | Trelleborg Wheel System Ltd | √ | √ | |
| | 42 | ACE Container pvt ltd | √ | | |
| | 43 | Global Baggage(Pvt) Ltd | √ | | |
| | 44 | South Asia G & M (Pvt) Ltd | √ | | |
| | 45 | Young An International Lanka (Pvt) Ltd | √ | | |
| | 46 | Trelleborg Wheel System Ltd | √ | √ | |
| | 47 | Esika (Pvt) Ltd. | √ | | |
| **Phase B** | 1 | Marangoni Industrial Tyres Lanka (Pvt) Ltd | √ | √ | |
| | 2 | Ocean Lanka (Pvt) Ltd | √ | √ | √ |
| | 3 | DPL Premier Gloves Ltd (Pvt)Ltd | √ | √ | |

| | | | | | |
|---|---|---|---|---|---|
| | 4 | Lalan Rubber (Pvt) Ltd | √ | √ | √ |
| | 5 | Arpitalian compact sales (Pvt)Ltd | √ | √ | √ |
| | 6 | Avery dennison Lanka (Pvt)Ltd | √ | | |
| | 7 | T & S Buttons lanka (Pvt) Ltd | √ | √ | √ |
| | 8 | Techstar Packing (Pvt) Ltd | √ | | |
| | 9 | Lanka Harness co; (Pvt) Ltd | √ | | |
| | 10 | Sundaram Lanka Tyres (Pvt) Ltd | √ | √ | |
| | 11 | TOS Lanka (Pvt) Ltd | √ | | |
| | 12 | Brandix Apparel Solutions Limited | √ | | √ |
| | 13 | Bslt Ventures(Pvt) Ltd | √ | | |
| | 14 | Esika (Pvt) Ltd | √ | | |
| | 15 | Global Clothing intl ltd | √ | | |

# 4. ENERGY CONSUMPTION SCENARIO AT BIYAGAMA EXPORT PROCESSING ZONE

## 4.1 Current Monthly Energy UsageRecorded in LogBooks

All the companies selected (36 potential bulk energy consumers) for the study have provided monthly energy consumption data from their electricity bills and fuel supply inventories except for few companies (namely 3) that provided only for few months of energy consumption data for the year considered (September 2017 to August 2018). The energy consumption data of the companies that have not provided the information werecalculated using the data obtained from field measurements and the number of working days of that company. Since only a few numbers of companies have provided the complete manufacturing data for the 12 months, the Specific Energy Consumption (SEC) data of each company in the cluster based on the product is not presented.

Steam, hot water and thermic fluid are the main thermal energy commodities in this selected cluster. Therefore, boilers, thermic fluid and hot water heaters are in operation to provide these services at elevated temperatures. Some of the services need relatively high temperature, therefore they run thermic fluid heaters above 180$^{o}$C most of the time. Similarly, hot water heaters and steam boilers are used to cater for low-temperature heat applications typically on or bellow 180$^{o}$C.

The monthly electricity consumption of the cluster companies ranges from 18GWh to 22GWh depending on the seasonal demand. In thermal energy, solid and liquid fuels such as biomass, furnace oil-800, furnace oil-1500, diesel, kerosene are used in the selected factories and none of the companies use LPG, Natural Gas (LNG) or Coalas an industrial fuel currently.Monthly biomass consumption in the cluster companies ranges from 14,166 to 20,023Ton.Monthly furnace oil, kerosene and diesel consumption in the companies varies from 1,068 to 1,614$m^3$. The annual use of each energy source including electricity are shown in Table 3.On average BEPZ consumes 617MT of biomass and 190 Barrels of fuel oil daily.

Table 3: The annual total energy consumption of each energy source including electricity

| | Electricity (MWh/Year) | Biomass (MT/Year) | Fossil fuel ($m^3$/year) | | |
|---|---|---|---|---|---|
| | | | Furnace oil | Diesel | Kerosene |
| Consumption | 248,080 | 209,717 | 14,594 | 9 | 49 |

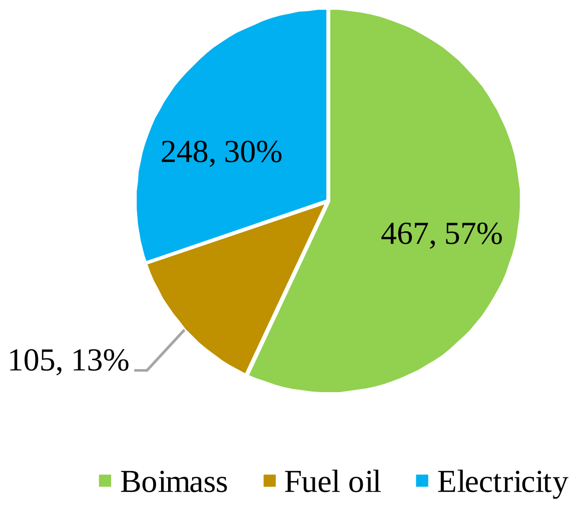


Figure 1: Annual total energy consumption (GWh/year) for lighting and the generation of cooling load, steam, hot water and hot thermic fluid last year

The average gross calorific value (GCV) of biomass and fuel oil were determined as 14.4MJ/kg and 42.67MJ/kg respectively.The maximum operating pressure of the boilers are 12 bargand the maximum supply temperature of hot water from the water heatersare 180$^{o}$C. Most of the steam distribution systems are equipped with condensate returns pipe networks. The supply temperature of thermic fluids varies from 180$^{o}$C to 250$^{o}$C. The supply and return temperature difference of the working fluid of almost all the hot water and thermic fluid heaters havenot exceeded 20$^{o}$C. The thermal efficiency of biomass systems varies from 64.6 to 71.5% when the thermal efficiency of fuel oil systems varies from 80 to 82.8%. Based on these systems' performance parameters and the annual fuel consumption data recorded, the annual consumptions($E_y$) of electricity, biomass and fuel oil last year were determined and shown in Figure 1.

$$E_y = \sum_1^{36} \dot{m}_\iota . GCV . \eta_i$$

where GCV-gross calorific value of fuel, $\dot{m}_\iota\, and \eta_i$ – annual fuel consumption and thermal efficiency of the system at i$^{th}$industry

The total annual thermal energy (heat for the process) consumption has recorded as 467,370MWht with the use of biomass, furnace oil-800, furnace oil-1500, kerosene and diesel. The annual electricity consumption is about 248,080MWhe and accounting for 30% of the total energy consumption.

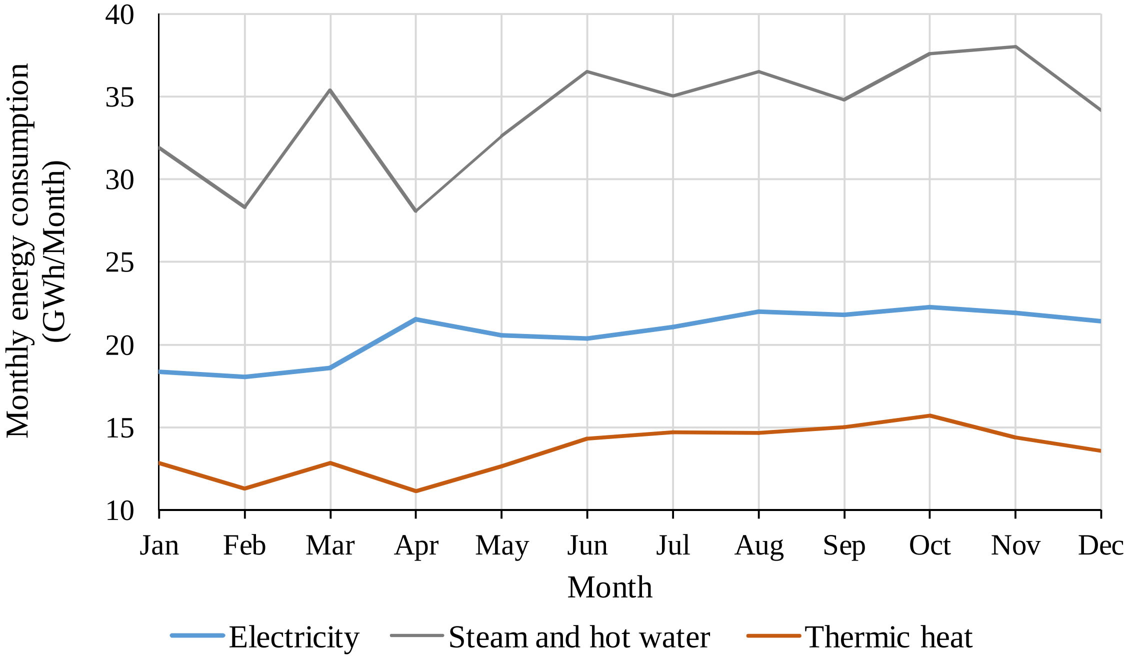


Figure 2: Characteristic total monthly energy consumption of the facility in the year 2018 including electricity, biomass and fuel oil that are used to generate thermic oil, hot water and steam

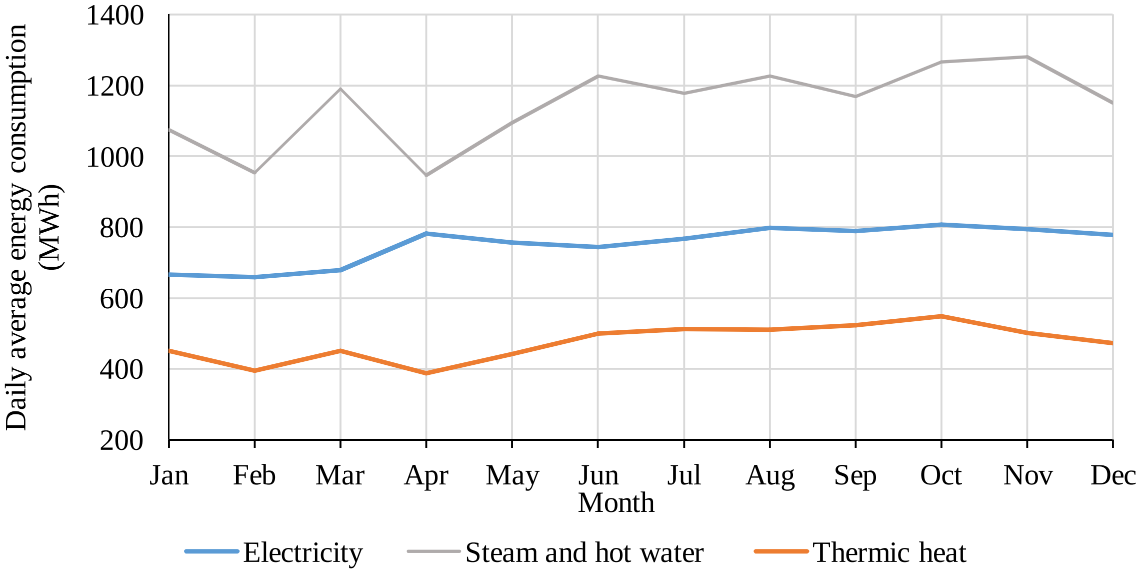


Figure 3: Characteristic daily average energy consumption of each month inthe year 2018

The biomass and fuel oil are only used for the thermal applications while electricity is used for lighting, air conditioning and refrigeration. The average efficienciesof biomass-fired and fuel oil fired boiler/thermic/water heaters were evaluated during the detailed energy audit and determined as 66.2% and 80.7% (GCV base) respectively.

The characteristic monthly energy consumption profiles of the above three energy commodities are shown in Fig. 2. The monthly electricity and total thermal energy consumptions (steam, hot water and thermic heat) of the cluster varies from 18.07 to 22.29GWh and 28.08 to 38GWh respectively. Some of the companies in the cluster have been backed up by their own generators to minimize the downtime during the power cuts of the national grid they are being served. However, based on the lack of properly recorded data, the in-house generation data of electricity is not included in this assessment. Figure 3 shows the average daily energy consumption in each month last year. Number of working days ($D_i$)per month in each company and the monthly energy consumption ($E_{month.i}$) data from logbooksand databasesof each company are used to calculate the average daily energy consumption ($E_{daily}$) of the facility.

$$E_{daily} = \sum_{1}^{36} \frac{E_{month,i}}{D_i} \text{where i denotes the} i^{th} \text{ industry}$$

In Figure 3, the month with the highest daily thermal energy consumption was considered as the peak month as well as the month with the lowest thermal energy consumption as the off-peakmonth. The relative energy consumptions in off-peak and peak months based on fuel sources are shown in Fig. 4 and 5.

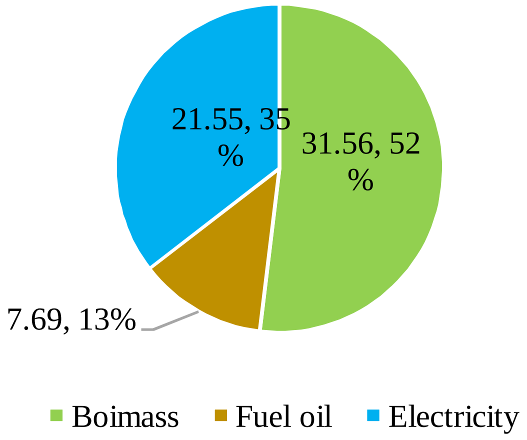


Figure 4: Energy consumption (GWh/Month) scenario in the off-peak month of April last year

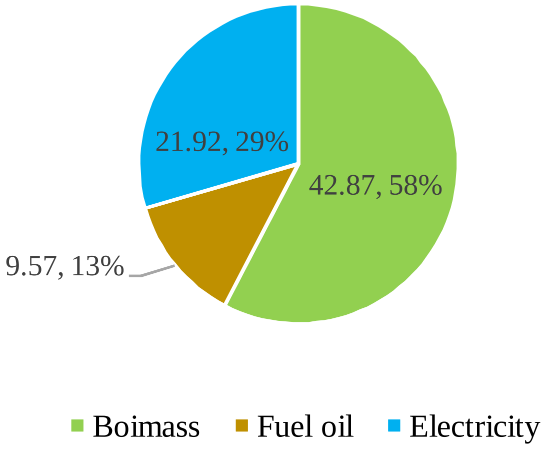


Figure 5: Energy consumption (GWh/Month) scenario in the peak month of November last year

During the peak month, the total thermal energy consumption has increased by 10.6% compared to the average monthly consumption. Similarly, during the off-peakmonth, the total thermal energy consumption has dropped by 15.6%.

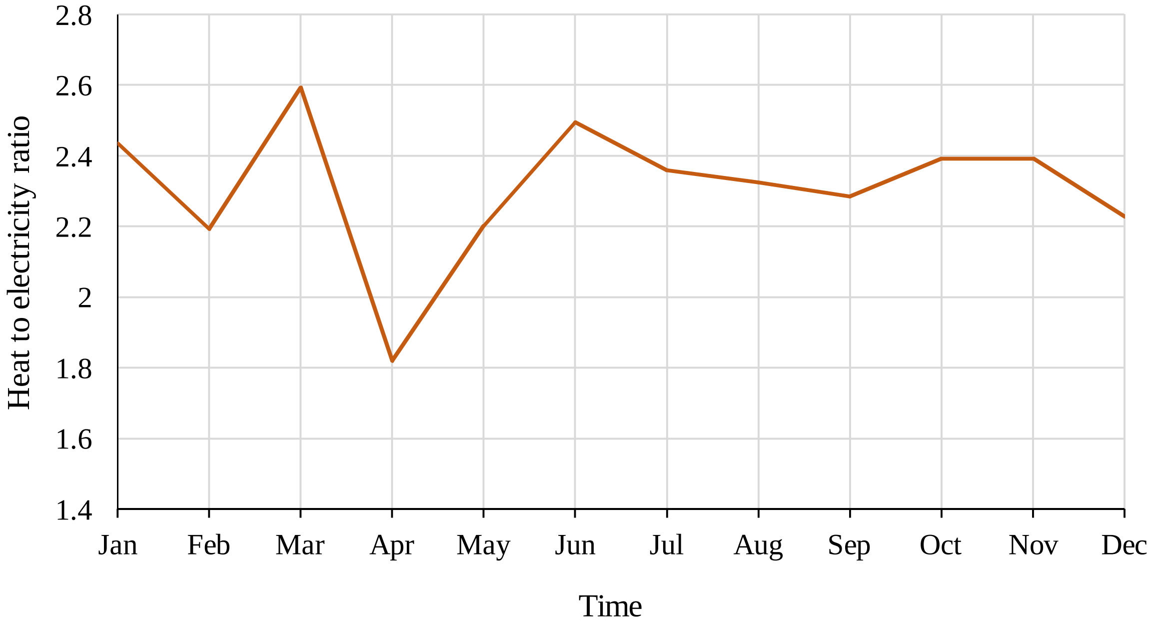


Figure 6: Characteristic behaviour of monthly heat-to-electricity ratio last year

The relative consumption of thermal energy to electricity was analyzed in the cluster and the characteristic behaviour is shown in Fig. 6. The monthly heat-to-electricity ratio varies between 1.82 and 2.59.However, the monthly heat to electricity ratio doesn’t reflect the relative consumption of each commodity for a given moment. Therefore, the information obtained from databases and logbooks provided limited information for the CCHP system sizing.

Since the data available in above records in all the industrieswere limited to the monthly consumption data of each fuel source and the production process of these companies need the heat at different temperature levels, for a detailed investigation, the thermal energy consumption data mentionedabove should be decomposed into different commodities based on the working fluid. Nevertheless, lack of detailed energy consumption data recorded in the cluster companies for several years could limit the study based on several assumptions.

For example, including the thermic fluid systems that need relatively high temperature compared to steam or hot water systems in the cogeneration concept could hamper the expected performance of such technologies. Either investment on duel commodity (steam and thermic fluid) thermal energy supply and distribution pipe networks or conversion of such thermic oil systems in the cluster companies into hot water or steam-driven system would not be economically attractive. So, for such a decision based on technical or economic feasibility during this study, we need to categorize the thermal energy consumption data and understand the nature of the heat demand of each commodity based on a real-time observation. The operating capacities of most of the thermal systems deviate from its nameplate data. Some of the manufacturing systems demand thermal energy in large quantities only for a short period leading to peak overshoots in the characteristic thermal energy demand curve of the system. In such cases, the real-time monitoring energy demand is vital to determine the exact installation capacity required for such thermal systems. Besides, the study of the share of all the energy commodities (steam, hot water and thermic) in the total thermal load is an important activity to cover up all the heat need in the cluster from a cogeneration facility.

Therefore, to enhance the accuracy of assessment and deliver a robust outcome, a detailed energy study was carried out in each company within the cluster. A dedicated team of experts have involved in obtaining the real-time energy demand data of each commodityin 15 minutes interval for a day.

## 4.2 Real-time Energy Usage throughField Measurements

The thermal/electrical energy supply and consumption data from chillers, boiler and heaters were obtained at 15 minutes intervals for a period of one day (from 7.00AM to 7.00PM) for all the commodities. Since 36 number of industries to be covered in the detailed energy study, obtaining field data simultaneously was almost impossible due to the limited availability of instruments such as data loggers and flow rate measuring devices. Therefore, all these 36 industries were divided into 10 sub-groups having 3-4 industries in eachgroup before carrying out the detailed energy audits from 7.00AM to 7.00 for 10 days from 2nd November 2018 to 13th November 2018.The system operating parameters were also obtained at the same time to investigate the operating thermal performance such as efficiency, COP, effectiveness etc. of the systems included in the study.The total electricity demand data was also obtained from the Ceylon Electricity Board in parallel with the measured data.

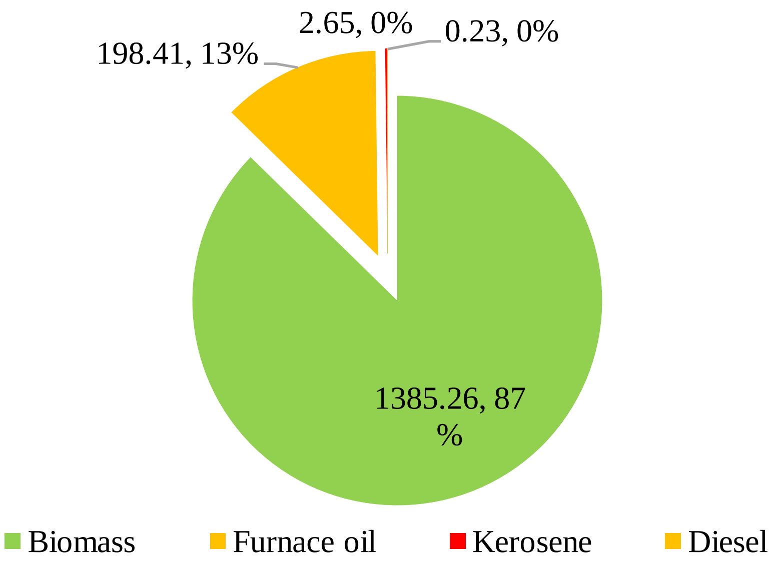


Figure 7: Current thermal energy consumption (MWh/Day) scenario obtained from field measurements

Figure 7: demonstrates the thermal energy share between biomass, furnace oil, kerosene and diesel obtained from the field measurements carried out for aday. Biomass was accounting for a major share of 87% of the total thermal load,second largest being the furnace oil of the 800 and 1500 grades. This would simply indicate that the use of biomass has benefited the companies economically as well as environmentally. This would also ascertain that there is an already developed biomass supply chain around the cluster.

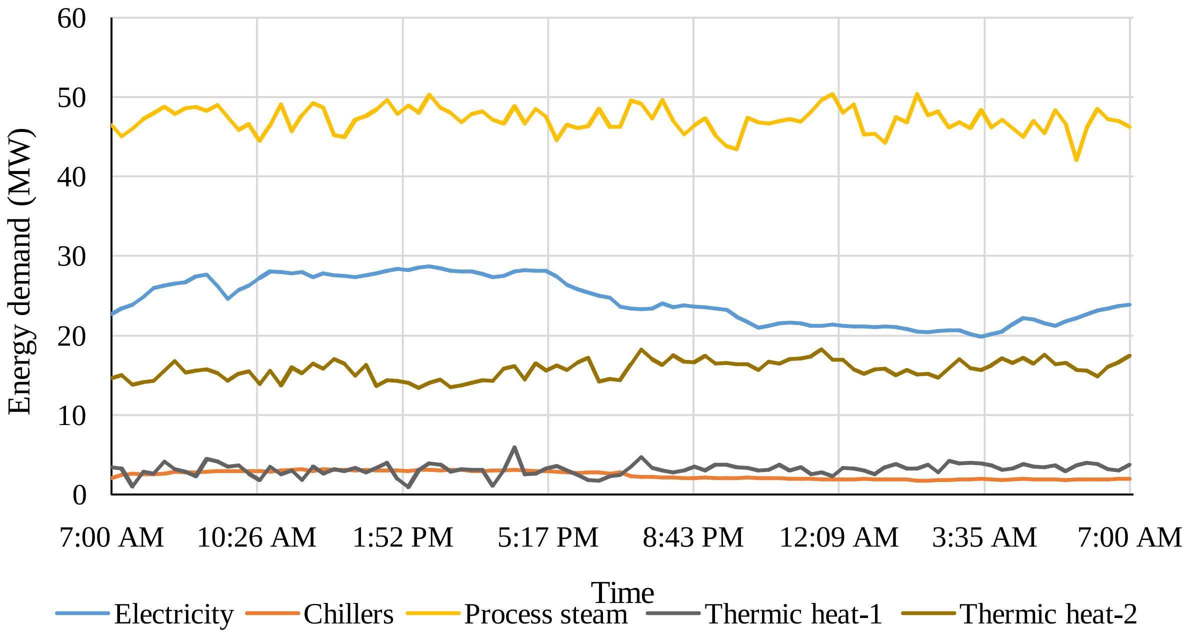


Figure 8: Characteristic real-time energy demands in 15 minutes intervals for a day ($180^{o}$C < Thermic heat-1 < $210^{o}$C and $210^{o}$C < Thermic heat-2 > $250^{o}$C. (The maximum process steam pressure was 12barg, process steam represents the hot water and steam demands)

Figure 8: shows the characteristic behaviour of the demand of each energy commodity in the facility measured in 15 minutes interval for 24 hours from 7.00AM to 7.00AM. This would also help to understand the maximum capacity needed for a thermal system for a smooth operation of the facility. So, we mainly collected the data from five separate energy commodities namely, total electricity, chillers’ electricity consumption, process steam, low and high-temperature thermic fluids.

Since absorption-cooling technology is well proven in the world today, and low-grade heat such as steam can drive the absorption chillers, the replacement of electric vapour compression chillers would also be a financially attractive investment. Therefore, the electricity demand pattern and the real-time consumption data of the electric chillers were also separately obtained as shown in Fig. 8. The total electricity demand of the facility varies from 19.87to28.71MW while the electricity demand of chillersvaries from 1.76 to 3.17MW.So, on average chillers consumes 10% of the total electricity consumption.

Thermic fluid heat is also contributing to the total thermal energy demand of the cluster with relatively smooth and flat demand throughout the day.Thermal demand for thermic fluid is divided into two groups based on the temperature levels. The low-temperature heat utilized through thermic fluid may be replaced with hot water in near future with a mutual agreement of the factory management.  This may involve a significantly high investment for the installation of pressure pipe network and retrofitting of machineries to withstand the pressure of steam or hot water.

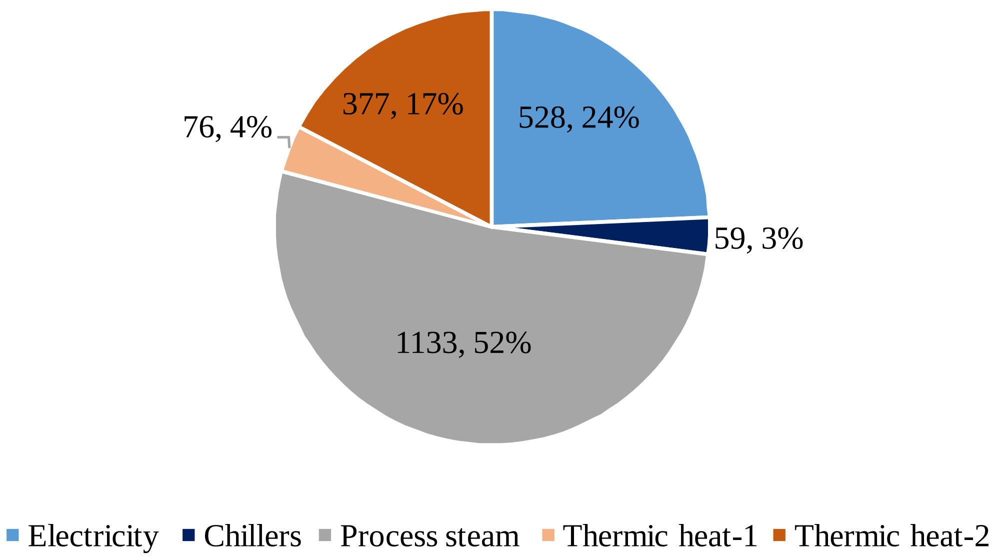


Figure 9: Current energy consumption scenario (MWh/Day) for a day (180oC < Thermic heat-1 < 210oC, 210oC < Thermic heat-2 > 250oC and steam pressure 12barg)

Nevertheless, the replacement of high-temperature thermic fluid heat (>$210^{o}$C) from steam or hot water will incur large investments and hamper the expected thermal performance of a combined generation system. The thermic heat demand is less than 34% of the total thermal demand of the facility and therefore, such high-temperature thermic oil heat demands are also categorized into a separate group and disregarded from the analysis hereafter.

All the steam and hot water driven systems in the cluster companies are operating at or below $180^{o}$C. Since the hot water production, using steam at the site is technically and economically feasible and avoid unnecessary repetition of separate transmission pipe networks for steam and hot water, this report hereafter considers hot water and steam as a single commodity named “process steam”. Major portion of the daily thermal energy consumption is dominated by the process steam that can be economically generated from the left overheat of the electricity production using a topping thermal power cycle. This also highlights the factsthat the process steam consumption is more than twice the electricity consumption of the cluster for a day as shown in Fig. 9.

This process steam demand varies from 54.84 to 68.64MWin the facility with no erratic peak demands.The process steam account for 52% of the total daily energy demand of the facility as shown in Fig. 9.So, it is interesting to see in Fig. 8 and 9 that there is a large low-grade thermal energy demand in the cluster in phase with a reasonable electricity demand.

Electricity demand that includes the electricity consumption of the chillers has been slightly shaped up by the cooling demand that is well-aligned with the ambient temperature profile of the day. Since the cooling load is represented in terms of electricity, it is rationally small compared to the other demands, however, if converted into low-grade heat, this would also play a significant role in shaping up the thermal energy demand. Therefore, a nearly smooth electricity load with a spatial variation (not peak overshoots) aligned with the cooling load can be seen in the cluster. The thermal energy demand of the process steam can be considered as a flat demand with minor ups and downs and being the dominating commodity of the present energy scenario.

Concurrent generation of electricity and heat from a single energy source is a well-known fact that reduces the energy cost of a production facility.The increased capacity of thermal demand through absorption chiller would increase the electricity generation capacity at its maximum efficiency as well as the useful consumption of the fuel leading to a reduction of $CO_2$ footprint of the process. Since the demand data of the cluster shows a simultaneous consumption of electricity and heat the concurrent generation of electricity, cooling and heat using Combined Cooling Heating and Power System (CCHP) or known as Tri-generation Systemswill be technically feasible.

## 5. COMBINED COOLING HEATING AND POWER TECHNOLOGY

The concept of Combined Cooling Heating and Power (CCHP) systems 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 Europe to increase overall efficiency, as well as to obtain energy at a cheaper price.

CCHP systems have important socio-economic benefits related to their efficient use of energy resources and the relative economic benefits of the three energy commodities (cooling, heating and power) obtained.

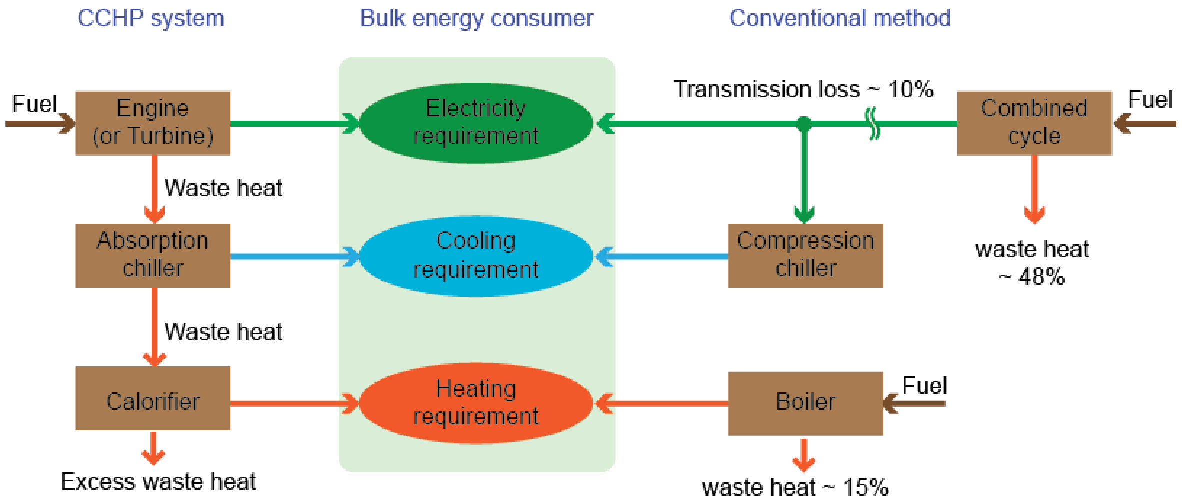


Figure 10: Combined and separate generation of electricity, cooling and heating using CCHP technology and conventionaldecentralized system

CCHP is defined as the concurrent supply of these energy commodities for services and/or manufactured products that benefit from the energy integration of the processes in its equipment, extracts the maximum thermodynamic potential of the resources consumed.

In recent years, the analysis and design tools for energy systems have undergone important developments. Particularly, the synthesis and design of CCHP systems in the commercial and industrial sector have become increasingly elaborated with numerous possibilities for energy sources and technological options. Figure 10 schematically represent the supply of electricity, cooling and heating simultaneously using CCHP technology and conventional centralized power systems. Since the waste heat or steam cannot be economically transmitted, the conventional centralized power generation from fossil fuel is less productive. The cogeneration of electricity and heat/steam with decentralized power generation technology helps in utilizing waste heat where electricity and fuel would otherwise have been used.Cascading energy systems that have different operating temperatures into descending order along the hot flue gas stream from the generator enhances the productivity of the energy conversion process. However, with the development of the CCHP, this concept was expanded to medium and small-scale power generating facilities. Energy-intensive industries, commercial and residential buildings such as supermarkets and residencies that are of large, medium and even small scale, are now practising CCHP 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.

The process can utilize the input energy efficiently and may result in economic savings, reduced emissions, reduced overall Primary Energy Consumption (PEC), and other benefits for the energy consumption when compared with a traditional separate heat and power system, whereby electricity is produced at a central power plant and thermal demand is met using separate on-site equipment.

The ability to gain the benefits described above by using CCHP systems depends on the type of prime mover used to generate power, the characteristics of a variety of system components, the method of operation, and the location of the system. The different prime movers and cooling technologies that can be used on these systems, therefore the CCHP technologyshould be evaluated separately for an optimum use of the energy source based on the quantity and the quality of the energy demand of the facility.

There are several factorswhich need to be considered in designing a CCHP plant. Primarily, the Triple Energy Requirements (Electrical Power, Heating and Cooling) have to be used together in a utility. If these three energy commodities are present, the basic design is carried out based on the proportionalities of the said energy requirements. To implement the best configuration of the

CCHP plant design, accurate thermodynamic analysis should be carried out. Secondly, the primary energy source needs to be considered.

Gas turbines, reciprocating internal combustion engines and steam turbines are the widely used prime movers for the CCHP. Based on the energy source, the energy harvesting technologies from the waste heat available in the prime mover vary significantly. The quality, quantity, price and the availability of the fuel used in the prime mover are theother key factors that affect the design of CCHP plants. The quantity of waste heat extractedfrom the flue gas stream of the prime mover is limited by the sulphurcontent, moisture content and the gas temperature.

Besides, the system's operational strategies such as operating following the electric load, thermal load, base loading, or a combination of them are also important to achieve the real-world goal of the CCHP technology. Finally, state-of-the-art ideas for improving and optimizing CCHP systems are considered for their potential toward further development of the technology in free trade zones around Sri Lanka.

### 5.1 Merits and Demerits of CCHP Systems

CCHP 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 becomes lower, compared to the conventional way of fulfilling said energy requirements. However, other than the benefits discussed here, several aspects may affect the smooth operation of the production facility if the right technology is not properly matched. The prime concern of the introduction of the technology should be the uninterrupted operation of the core business. Secondly applicability of cutting-edge technologies that minimize the energy cost of the facility with improved reliability, safety and reduced environmental impact. The conventional centralized thermal power plants operate from long distancesand most of the time in isolated areas due to noise and environmental pollution from emissions. So, the losses of electricity transmission and distribution for long distances together with the thermal loses to the environment, the overall efficiency of conventional centralized power generation systems have shown inherently low value at the inception.

Table 4: Thermal performance of conventional centralized power systems and decentralized CCHP systems

| **Centralized Power System** | | | | | | |
|---|---|---|---|---|---|---|
| Output (kWh) | Energy Commodity | Method | Individual Efficiency (%) | Input energy (kWh) | Total energy (kWh) | Overall Efficiency (%) |
| 100 | Electricity | Power Plant | 35 | 286 | | |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 100 | Process heat | Boiler | 83 | 120 | 501 | 60 |
| 100 | Cooling | Electric chillers | COP-3 | 95 |  |  |
| **Decentralized CCHP System** |  |  |  |  |  |  |
| Output (kWh) | Energy source | Method | Individual efficiency | Input energy (kWh) | Total energy | Overall Efficiency |
| 100 | Electricity | CCHP | 30 | 333 | 333 | 90 |
| 100 | Process heat |  | 70 | 143 |  |  |
| 100 | Cooling |  | COP-1.2 | 83 |  |  |

With the advantage of being close to the bulk energy consumers which make the utilization of waste heat from thermal power systems technically and economically feasible, the decentralized CCHP systems offer relatively improved thermal performances compared to the conventional centralized systems.

Table 4 compares the overall efficiencies of assumed utilities of heating, cooling and power demands distributed equal quantities of 100kW for each commodity. Other than the quantitative benefits shown in Table 4, following additional merits and demerits may be observed from the CCHP technology.

### 5.1.1 Advantages

- The key advantage of a Tri-generation (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 TG.
- In addition, the total emissions from production are less compared to the conventional process. Total equivalent $CO_2$ emissions are minimized, thus the impact on the environment is also reduced.
- The complete energy requirement is fulfilled under the control of their 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.

### 5.1.2 Disadvantages

- The initial investment of implementing CCHP 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 CCHP.
- As mentioned above, the total emissions quantity is less compared to the usual method. However, if local emissions are compared, CCHP has a 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.

## 5.2 Important Aspects to be Considered for the Applicability of CCHPSystems

While selecting CCHP systems, one should consider some important technical parameters that assist in defining the type and operating scheme of different alternative cogeneration systems to be selected. The most important thing is the size and the available space close to the bulk energy consumer. In an areaof environmental concerns is on the topmost place, the environmental impact of such CCHP technologies should be considered at the design stage. Not only the systems but also the nature of the fuel and the requirement of fuel pre-processing may lead to a significant change in the fuel as well as the system design. Another important aspect is the maximumlevel of particulate emission required in the proposed area and the cost of related downstream pollution control technologies that reduce the emission up to the maximum level accepted by Sri Lanka Environmental Authority.

Heat-to-power ratio is one of the most important technical parameters influencing the selection of the type of cogeneration system. The heat-to-power ratio of a facility should match with the characteristics of the CCHP system to be installed. It is defined as the ratio of thermal energy to electricity required by the energy-consuming facility. Though it can be expressed in different units such as Btu/kWh, kCal/kWh, etc., here it is presented based on the same energy unit (kW) so that the heat to electricity ratio goes dimensionless. Basic heat-to-power ratios of the different cogeneration systems are shown in Table 5along with some technical parameters. The steam turbine-basedcogeneration systems can offer a large range of heat-to-power ratios.

Table 5: Typical operating ranges of heat-to-power ratio in each CCHP technology

| **Cogeneration system** | **Heat to power ratio (kWt/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 |
| Reciprocating engine | 1.1 – 2.5 | 33 – 53 | 75 – 85 |

CCHP uses a single process to generate both electricity and usable heat or cooling. The proportions of heat and power needed tovary from site to site, so the type of plant must be selected carefully and appropriate operating schemes must be established to match demands as closely as possible. The plant may therefore be set up to supply part or all of the site heat and electricity loads, or an excess may be exported if a suitable customer is available.

Cogeneration is likely to be most attractive under the following circumstances:

(a) The demands of both steam and power are balanced i.e. consistent with the range of heat to power output ratios that can be obtained from a suitable cogeneration plant.

(b) A single plant or group of plants has a sufficient demand for heat and power to permit economies of scale to be achieved.

(c) Peaks and troughs in demand can be managed or, in the case of electricity, adequate backup supplies can be obtained from the utility company. The ratio of heat to power required by a site may vary during different times of the day and seasons of the year. Importing power from the grid can make up a shortfall in electrical output from the cogeneration unit and firing standby boilers can satisfy additional heat demand. Many large cogeneration units utilize supplementary or boost firing of the exhaust gases in order to modify the heat to power ratio of the system to match site loads.

(d) Quality of thermal energy needed: The quality of thermal energy required (temperature and pressure) also determines the type of cogeneration system. For a sugar mill needing thermal energy at about 120°C, a topping cycle cogeneration system can meet the heat demand. On the other hand, for a cement plant requiring thermal energy at about 1450°C, a bottoming cycle cogeneration system can meet both high-quality thermal energy and electricity demands of the plant.

(e) Load patterns: The heat and power demand patterns of the user affect the selection (type and size) of the cogeneration system. For instance, the load patterns of two energy-consuming facilities are shown in Figure 11. Since the prime movers generate heat and electricity simultaneously, the energy demand characteristics shown in Fig. 11A would require additional heat storages to get the demand pattern in phase. Therefore, the Fig. 11B would be the best load pattern for CCHP application.

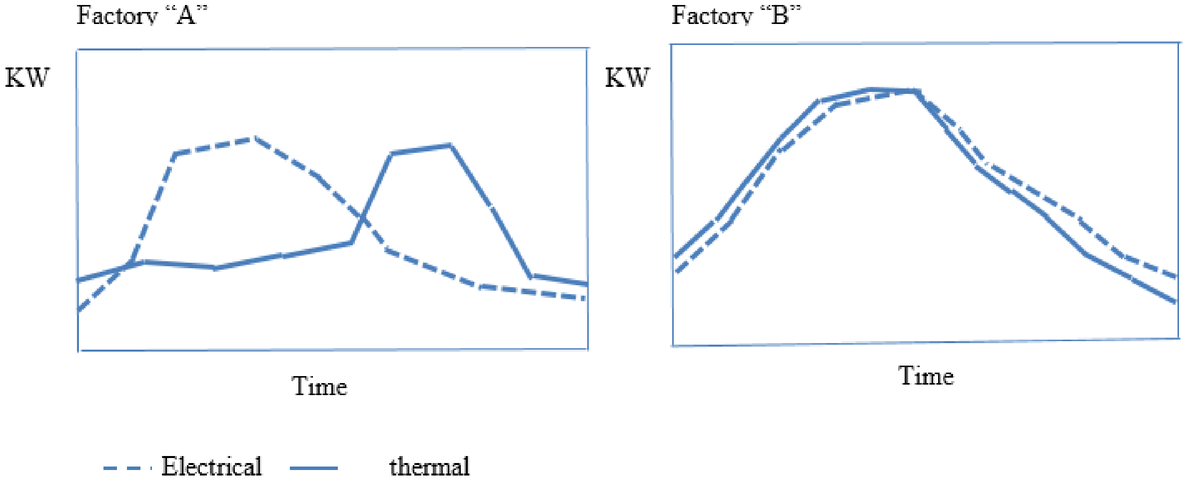


Figure 11: The phase shift between thermal and electricity demand in Factory A and both of them are in the same phase in Factory B

Some of the additional important aspects that should be considered in the selection of the right CCHP configuration are listed down in Table 6.

Table 6: Characteristics of cogeneration options

| Technology | Advantages | Disadvantages |
|---|---|---|
| Steam turbines and boiler | • Long life (~ 40 years)<br>• Can burn coal and other non-premium fuels<br>• Established, well-understood technology | • Low electric efficiency (<30%)<br>• Not easily operated at part load<br>• Un-economical at small capacities<br>• Plant cannot be operated unattended<br>• Overall efficiency is low (50-60%)<br>• Air pollution problems |
| Gas turbines | • High-temperature heat<br>• High ratio of recoverable heat and overall thermal efficiency<br>• Compact, lightweight<br>• Easily set up<br>• Low maintenance requirements<br>• Short lead time<br>• Good flexibility | • Natural gas or petroleum-based fuels required<br>• Noisy (Siting restraints)<br>• Need skilled labourer |
| Diesel and gas engines | • Reliability<br>• High electrical efficiency<br>• Small/intermediate size<br>• Low initial cost | • Low-grade waste heat<br>• Natural gas or petroleum-based fuels required<br>• Air pollution problems<br>• Overall efficiency based on the temperature of the waste heat requires |

In addition to the careful selection of the technology for a particular application, the availability of the required competencies for operation and maintenance, social and environmental impact should be carefully addressed for the technology to be best suited for the purpose.

# 6. CHANGES NEEDED TO THE ENERGY COMPOSITION AT BIYAGAMA EXPORT PROCESSING ZONE (BEPZ)

## 6.1 Proposed Changes to the Existing Energy Supply Systems

BEPZ consumes electricity from the national grid, biomass and fuel oil in conjunction or alone to meet the process thermal demand. Boilers, thermic fluid heaters and hot water heaters are fired to generate the required thermal energy from the primary sources. Following engineering decisions are taken to maximise the benefits from a CCHP system as well as make the project technically and financially viable.

### 6.1.1Evading Thermic Oil Heat Supply from the ProposedCCHP System

The recovery and transmission of high-temperature thermal energy that utilizesthermic fluid is not considered for the proposed CCHP system, since they need either separate thermic fluid transmission and distribution pipe networks or a retrofit existing system in the member companies to steam or hot water systems. However, the supply of high-pressure steam /hot water from the CCHP system degrades their thermal performance. Therefore, considering the practical difficulty in developing multiple pipe networks and huge investment on such changes to the thermic fluid systems, the thermal demands that use thermic oil are simply ignored. Therefore, the thermic fluid heat is not considered in the thermal analysis of the system hereafter.

### 6.1.2 Supply of Steam for Hot Water Consumers

Since the operating temperature range of the hot water alike the temperature of process steam, the hot water supply can also be economically considered and predict the total thermal demand together with steam for the development of CCHP technology accordingly. Considering, the laying of two different pipelines for hot water and steam needs additional space, hot water needs relatively large diameter pipes compared to steam for the transmission of the same energy quantity and the increased investment and maintenance cost of energy transition pipe network, the only supply of adequately pressurised steam to each company from the CCHP system is considered. Secondly, injecting pressurised steam in right quantities into the existing hot water supply system to generate the required temperature difference between hot water supply and return is considered. Therefore, the cumulative thermal energy demand arose from both hot water and steam demands is considered for the analysis and named as the process steam.

### 6.1.3 Replacement ofVapour CompressionChillers with Vapour Absorption Chillers

Currently, vapour compression chillers that consume electrical energy drive all the HVAC systems. Since the pressurized steam is supposed to be provided to the doorstep of all the companies in the cluster, the electric chillers can be replaced with absorption chillers expecting an additional thermal energy supply for the proposed CCHP system. This would reduce the electrical energy demand and consumption as well as the cost of air conditioning. The industries with large cooling loads and chilled water systems will be considered in this study.

## 6.2 Maximum Daily Energy Consumption of the Year

The steam and hot water demands obtained from the field measurements for a limited period may not provide the maximum demand throughout the year. However, with the limited availability of at least hourly, daily or weekly energy consumption data, the monthly energy consumption data were collected from the logbooks in each factory belong to the cluster. Since daily thermal energy consumption data are not available in each company,we calculated the daily average consumption of process steam and electrical energy in each month using the monthly energy consumption data and the number of operating days of the relevant month.The characteristic behaviour of daily averagedelectricity, and steamand hot water (process heat) consumptions of each month in the cluster is shown in Fig. 12. The daily averaged maximum energy demands calculated have shown an increase compared to the measured quantity as shown in Table 7.

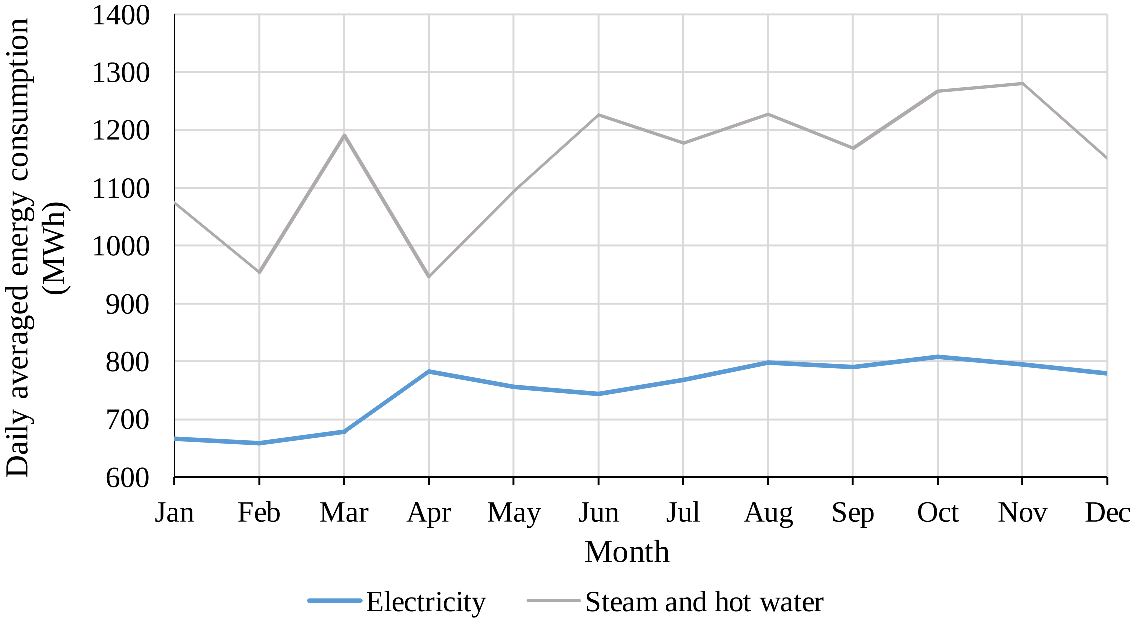


Figure 12: Characteristic daily averaged energy consumption of each month last year

However, as we mentioned earlier, we consider the thermal energy consumption for prioritizing the months as peak or off-peak. So, November can be considered as the month of peak daily thermal energy consumption as shown in Fig. 12. So, electrical and thermal energy consumption data in a day in November is considered for further analysis of data for system sizing. The share of process steam and electricity consumption in a peak demand day is shown in Fig. 13.

Table 7: Comparison of daily energy (MWh/Day) consumption between measured and peak day in November last year

| **Energy (MWh/Day)** | **Measured** | **Peak day** |
|---|---|---|
| Electricity | 587 | 795 |

| | | |
|---|---|---|
| Heat | 1133 | 1281 |

### 6.3Replacement of vapour compression chillers with vapour absorption chillers

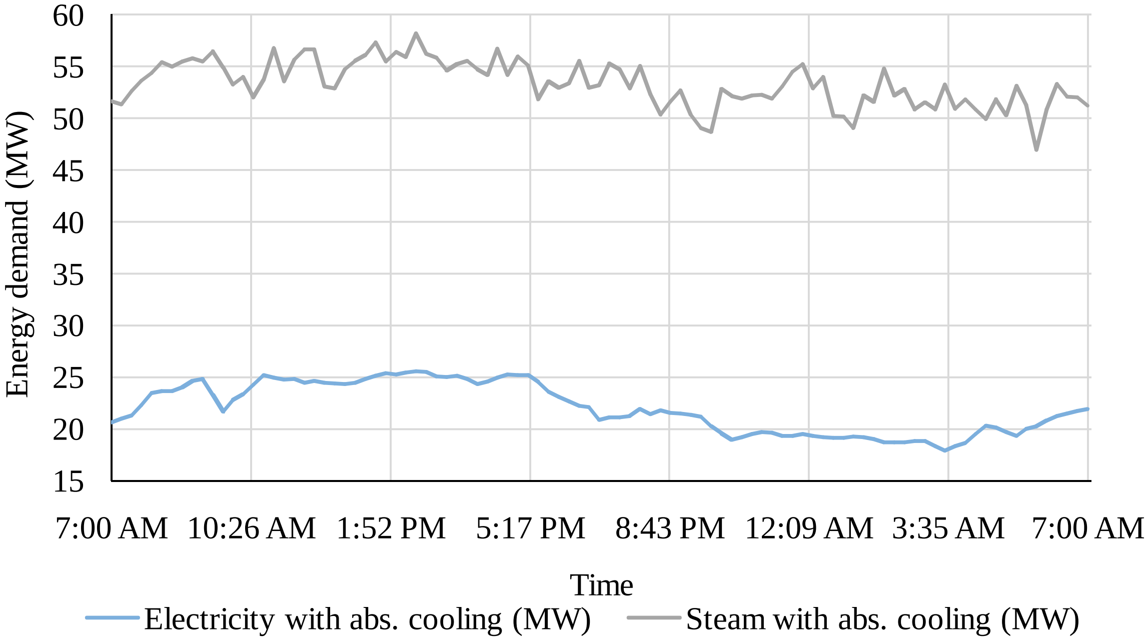


Figure 13: The calculated electricity and process steam demand including absorption cooling of the selected cluster at BEPZ

If the companies belong to the cluster from which the data were obtained will take a corporate decision to replace their electric chillers with double-acting absorption chillers the predicted demand of electricity and process steam are shown in Fig.13. Based on the electricity consumption data and thermal performance parameters (COP = 3) obtained from vapour compression chillers, the predicted percentage reduction of total electricity consumption is 10%. Simultaneously, the process steam consumption of the facility increases by 13% as shown in Table 8. The coefficient of performance (COP) of the commercially available absorption chillers was taken as 1.2.

Table 8: The daily energy consumption scenario with the replacement of electric chillers with absorption chillers

| **Daily energy consumption (MWh/Day)** | **Chiller type** | | **Increase (%)** |
|---|---|---|---|
| | **Compression** | **Absorption** | |

| | | | |
|---|---|---|---|
| Electricity consumption | 587 | 528 | -10 |
| Process steam <12barg | 1133 | 1281 | 13 |

## 6.4Total Energy Demand Characteristics on a Peak Day

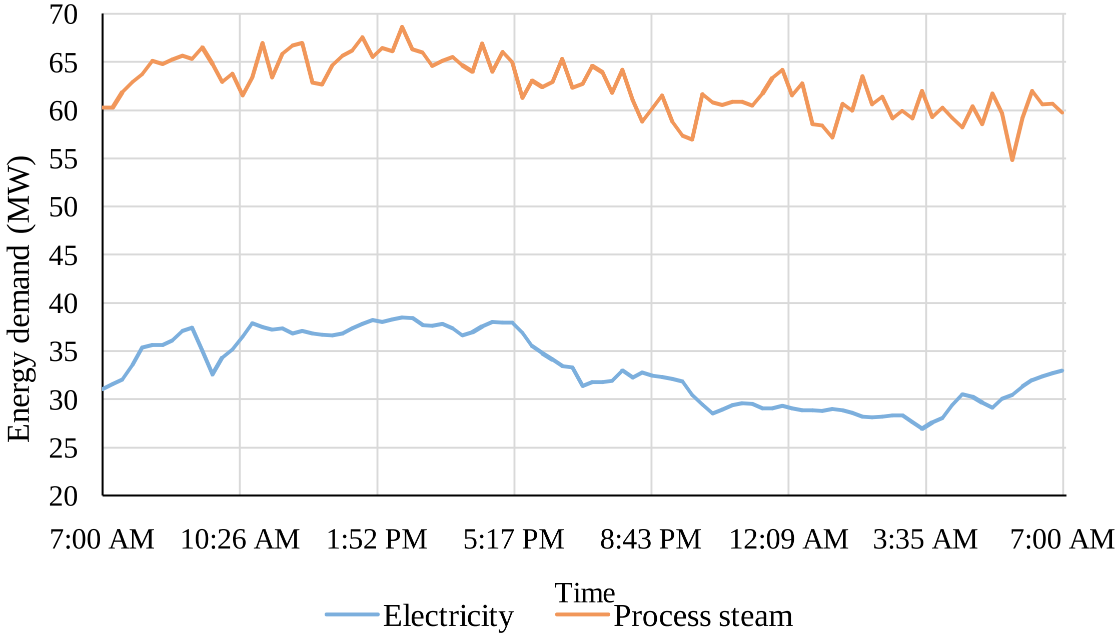


Figure 14: Predicted process steam and electricity demands with absorption cooling on a peak day of November. The maximum steam pressure is 15barg at the CCHP plant

However, using the predicted 15-minute demand data (Fig. 14) obtained from field measurements including the adjustments for the replacement of electric chillers with absorption chillers, the total energy consumption of the peak day was discretized into 15minutes interval and treated as the process steam and electrical power demands in each 15 minutes interval throughout the day. Nevertheless, the predicted characteristic behaviour of the total process steam and electricity demand in a peak day of November are shown in Fig. 14. The predicted maximum demand of the same in a peak day in November last year is shown in Table 9.

Table 9: The predicted maximum process steam and electricity demand of the cluster with absorption cooling

| **Energy demands** | **Max operating capacity (MW)** |
|---|---|
| Electric machineries and lightings | 38.52 |
| Process steam <12barg | 68.64 |

The nearly flat average demand of process steam with minor ups and downs at the cluster currently operating aligns with the electricity demand right after the installation of absorption chillers (Fig. 13).Figure 14 also shows that the total electricity and process steam demands in a peak day of the installation are in phase. Figure 13 and 14 compare the characteristic behaviour of total process steam demand and electricity demands on the day we conducted the energy audit and a peak day in November. Therefore, the characteristics of these two commodities can be taken in phase after the installation of the absorption chillers. The thermal power demand varies between 54.84MW and 68.64MW while electricity demand varies between 26.99MW and 38.52MW (Fig. 14). All the power demand data have clearly shown that there are no significant peak overshoots in the demand and are nearly flat with spatial variation with minor ups and downs.

Table 9:shows the expected maximum operating capacity in a peak day. Since we mainly focus on maximum waste heat recovery, both electrical and thermal capacities are obtained from the day the cluster utilised maximum amount of process heat. Therefore, the maximum operating capacity of thermal energy in last year shown in Table 9 is the maximum possible in the last year but the electricity demand indicated is not the maximum possible last year.

Figure 15: shows the characteristic behaviour of thermal energy into electricity ratio ($\gamma$) for two different scenarios of with absorption chillers and with electric chillers. The replacement of electric chillers with absorption chillers has significantly increased the thermal energy consumption as steam, and reduced the total electricity consumption of the cluster leading to a significant increase of heat to electricity ratio by 0.51 on average. The minimum value of $\gamma$ shown with electric chillers is above 1.22. The recorded highest is 1.84. So, the heat to electricity ratio with electric chillers varies between 1.22 and 1.84 as shown in Fig.16. However, with the replacement of electric chillers with absorption has enhanced the heat to electricity ration by 23% on average. The predicted minimum value of $\gamma = 1.66$ with absorption cooling while the maximum being $\gamma = 2.29$

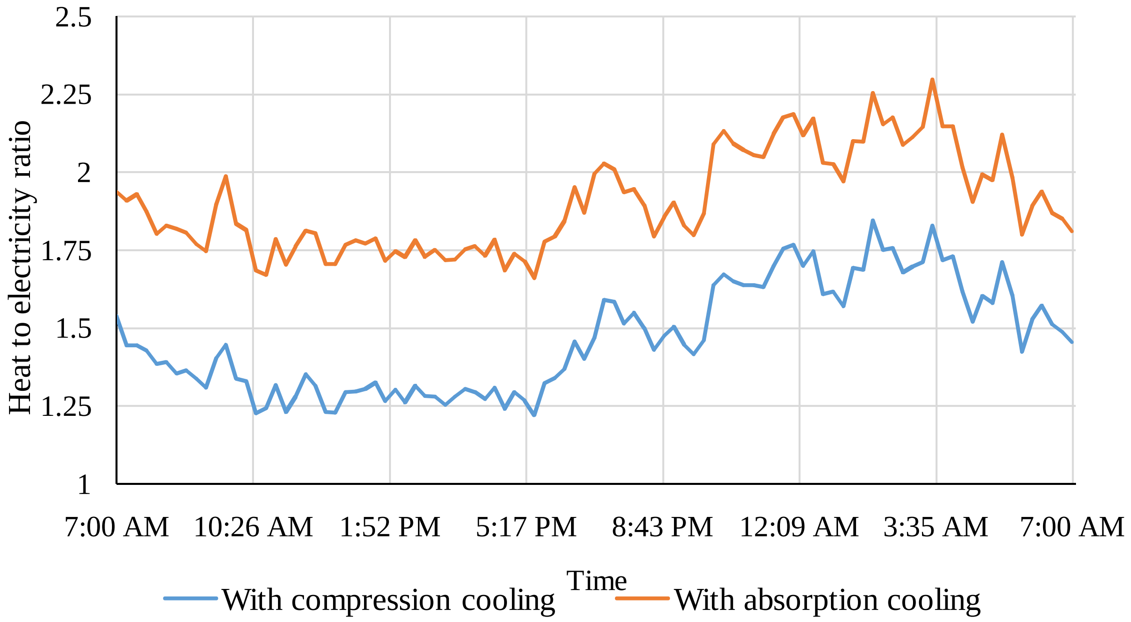


Figure 15: Predicted characteristic behaviour of heat-to-electricity ratio in a peak day

When the heat to electricity ratio reaches top the heat and electricity demands are 62.00MWt and 26.99MWe respectively. When γ reaches minimum the thermal and electricity demands are 61.26MWt and 36.92MWe respectively.

### 6.5OperatingStrategies of Combined Cooling Heating and Power Systems

Mostly the type of CCHP system is based on the ratio of thermal to electrical power consumedby the bulk energy consumer. In general, following broadly mentioned six (06) types of different strategies which are applicable to maximize the benefit from the energy transaction based on the fuel type, electricity market and tariff, grid power availability for both buying and selling, location, heat to electricity ratio and the system architecture etc.

a) Process heat matching mode

Here, the thermal 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. CCHP 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.

# 7 PROPOSED TRI-GENERATION ARCHITECTURES FOR BEPZ

The electrical energy and/or thermal energy demands can be met through any tri-generation system. Since a major share of the annual thermal energy consumption of the companies belong to the selected cluster is at low temperature (typically less than 180$^{o}$C) the topping cycle CCHP systems are more suitable rather than bottoming cycle CCHP systems. Topping cycle CCHP systems properly utilize the available heat (Exergy) at a greater extent as it utilizes high-temperature heat directly from the fuel combustion. So, the transaction between heat and work is relatively efficient in topping cycle CCHP than that of the bottoming cycle.

The manufacturing processes in the cluster use relatively low-temperature thermal energy, therefore the waste heat from the power cycle can directly be used for low-pressure steam generation through a waste heat boiler. Therefore, the use of toping cycle (see Section (d)) CCHP systems are more attractive for these types of energy qualities and quantities.In general, matching both demands are not carried out due to the significant increase in capital cost and reduced financial benefits. Current maximumelectricity demandat BEPZ is approximately 43.23MW, inclusive of vapourcompression electric chillers.

In some of the industries, the existing vapour compression chillers' lifetime exceedsabove 10 years and it may be decided to replace the existing chillers with a vapour absorption chiller. If the vapour compression chillers were replaced with vapour absorption chillers, the electric power demand could be reduced from 43.23MWe to 34.64 MWe. The maximum process steam demand will increase up to 68.64MWt with the addition of approximately10.46MWtdue to the steam usage of the vapour absorption chiller. However, the heavy fuel oil and biomass demand for the thermic oil heaters remained unaltered. Therefore, by introducing CCHP to the cluster, the heavy fuel oil consumption does not reduce to zero.

Since the characteristic demand of electricity and heat are nearly flat with minor ups and downs of less than 20% of the mean as shown in Fig. 3, the efficiency variation of the engines is not considered in all the assessments. Gross calorific value of biomass was considered as 14400kJ/kg while HFO and LNG being 42676kJ/kg and 38700kJ/m$^3$ respectively, the density of HFO and standard operating pressure LNG are 0.94kg/m$^3$and 140kPa respectively. The biomass boilers with combustion air pre-heaters usually show an efficiency of about 70% based on gross calorific value.

The carbon footprint of each thermal system proposed was evaluated based on the specific $CO_2$ emission from the use of each fuel. The carbon footprint of electricity supplied by the national electricity grid was obtained from SLSEA and as shown in Table 10. Biomass is considered as carbon-free due to its short cycle time.

Table 10:Carbon footprint on the use of different fuel (Source: www.eia.gov)

| Fuel | Carbon footprint |
|---|---|
| Electricity | 0.585 kg/kWh |
| Coal (lignite) | 2.44 kg/kgfuel |
| Diesel and HFO | 2.96 kg/kgfuel |
| Natural gas | 1.95 kg/m$^3$ |

## 7.1 CCHP System with Rankine Cycle

Thermal power plants generate electricity through a steam turbine as per the Rankine cycle theory. In general, two types of steam turbines can be utilized within the CCHP system design. These are theextraction condensing steam turbines and backpressure steam turbines. Since there exists a well-established biomass supply chain, biomass with a gross calorific value of 14,400kJ/kg at 25% moisture content was selected as the fuel. In addition to that, the financial feasibility of the same system fired by coal was also studied. The gross calorific value of coal considered was 26365kJ/kg

### 7.1.1 Rankine Cycle with Extraction Condensing Steam Turbines

The schematic configuration of a CCHP system with extraction condensing steam turbine is shown in Fig16. 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 pressure is below atmospheric pressure and part of the heat is wasted to the environment through the condenser. Therefore, this type of configuration is not suitable for the proposed CCHP plant at BEPZ.

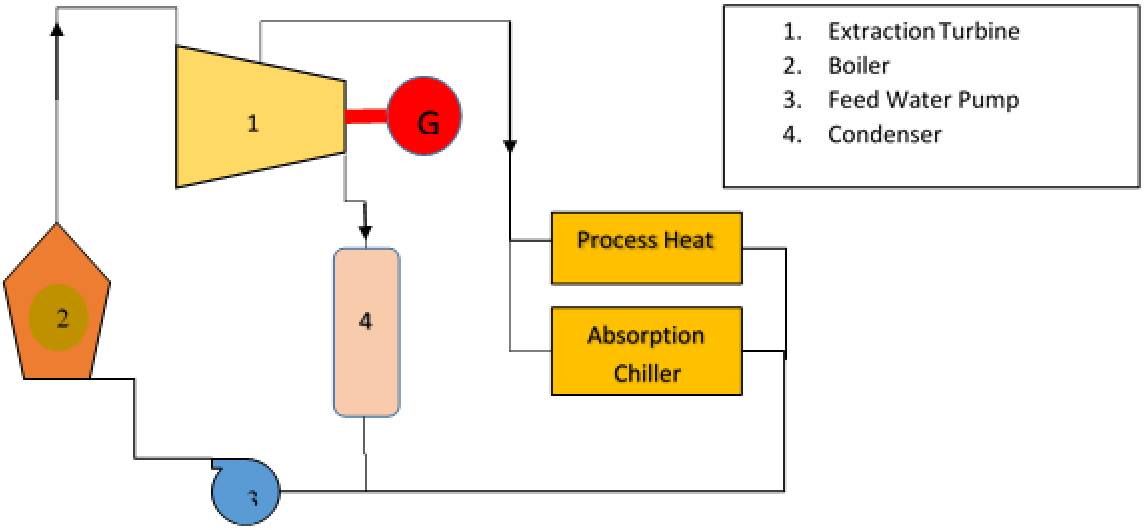


Figure 16: Schematic diagram of a CCHP with an extraction condensing turbine

### 7.1.2 Rankine Cycle with Back Pressure Steam Turbines

In cases where steam is supplied for process heating, a backpressure turbine can be installed instead of the usual pressure-reducing valve if delivered steam pressures are high enough. At the exit of the turbine, the steam pressureis greater than the atmospheric pressure. This pressure is decided by the temperature requirement of the process. Figure 17shows the main components of the back-pressure type steam turbine coupled with a CCHP plant.

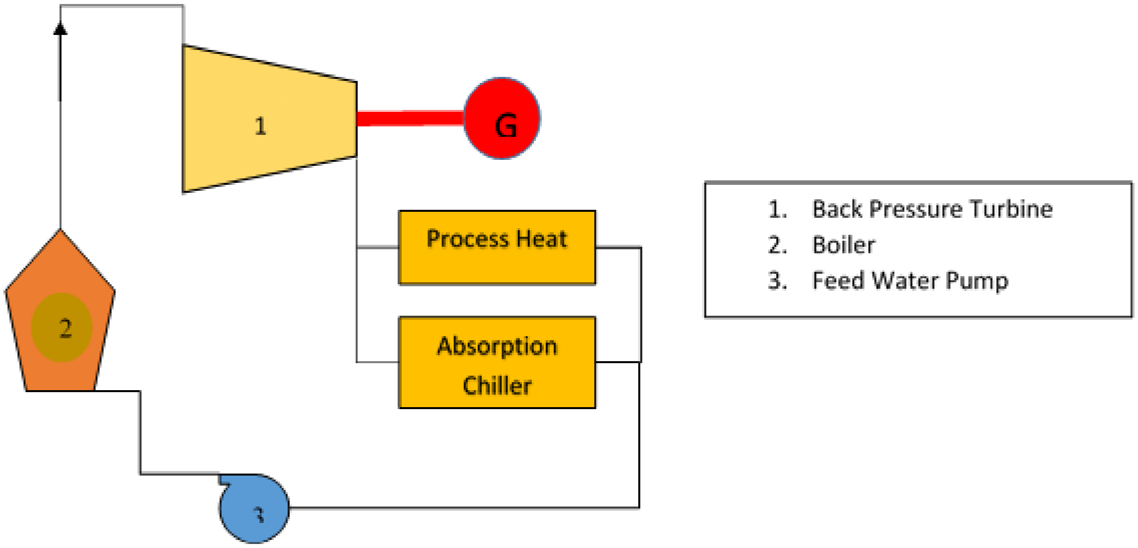


Figure 17: Schematic diagram of a CCHP with a backpressure turbine

In this technology, the requirement of the main condenser is minimized, as the steam is taken from the turbine is fed directly to the process and the vapour absorption chiller, for the process heat and production of chilled water. Due to this, the overall efficiency isenhancedresulting in a lower heat rate. However, the presence of the main condenser cannot be completely 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 to the deaerator, following which, the condensate is pumped back to the boiler for steam production.

The potential power output by the turbine generator is calculated by comparing the inlet and exhaust pressures at the turbine. Depending on pressure differentials, anywhere from 20 to 50 kWh per ton of steam can be produced.Since a boiler turns the chemical energy in biomass/coalto heat, this type of power plant can accommodate any type of fuel independent of nature. Higher the boiler pressure better the thermal performance of the electrical power generation is, since the manufacturing processes in the bulk energy consumer can utilize all the heat losses during the powergeneration in the steam turbine, the specific steam consumption (SSC) of the turbine has less impact on the overall system performance. In general, during part load operations, reduced SSC decreases the power output of the turbine apart from increased utilization of fuel for power production.

The traces of Na, K and Clmaterials accelerate the corrosion of hi-temperature part as well as fouling. Thislimits the maximum operating pressure of the boiler.The typical maximum operating pressure and temperature of such utility boilers fired by the biomass available in Sri Lanka is about 48barg and 440$^{o}$C to reduce the accelerated corrosion and fouling in the boiler pressure parts. If such materials had not been a presence in the fuel, the boiler pressure could have been increased to maximize the power generation efficiency of the proposed CCHP. The coal-fired boilers can be operated at relatively high pressure compared to biomass (since no Cl and low K, Na contents in coal) fired boilers to increase the overall power plant efficiency. However, in this assessment, we considered the same maximum operating pressure of the boilers irrespective of the fuel.

Unlike power generating systems, the boiler efficiency doesn't vary significantly around the maximum continuous rating (MCR), so the capacity of the proposed boiler is based on the maximum process steam (steam + hot water) demand calculated from the peak month last year. Since the processes need minimum of 12barg, the expected backpressure of the turbine was set at 14bargincluding the pressure losses for 2km distance during steam transmission.

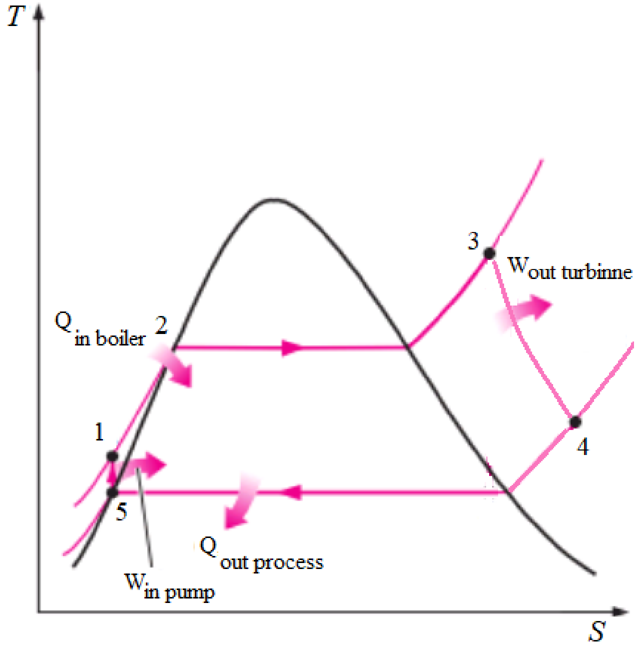


Figure 18: The temperature entropy diagram of the proposed CCHP with no additional condenser

The exhaust steam from the back-pressure turbine is superheated as shown in Fig 18,however, the process needssaturated steam at 12bargmaximum, so de-superheating technology is applied and the saturated liquid water is taken from the condensate return.This has reduced the boiler capacity less than the steam flow rate needed for the process.The heat and mass balance diagram for the proposed CCHP plant at BEPZ is shown in Fig. 19.The plant input and outputparameters when fired by Biomass and Coal separately are shown in Table 11and 12.

Table 11: Annual fuel consumption and energy dispatched the CCHP system fired by biomass

| **Parameter** | **Electricity (MWh/Year)** | **Steam (MWh/Year)** |
|---|---|---|
| Energy consumed by the cluster | 248,080 | 408,902 |
| Energy supplied by CCHP | 41,871 | 408,902 |
| Biomass consumption | 187,720Tons/Year | |
| Boiler capacity | 110 TPH | |
| Boiler operating pres. and temp. | 48barsand 440°C | |
| Steam turbine capacity | 7 MWe | |
| Overall thermal performance | 60% | |
| $CO_2$ Savings (MT/Y) | 30,568 | |

Table 12: Annual fuel consumption and energy dispatched of the CCHP system fired by coal

| **Parameter** | **Electricity (MWh/Year)** | **Steam (MWh/Year)** |
|---|---|---|
| Energy consumed by the cluster | 248,080 | 408,902 |
| Energy supply by CCHP | 41,871 | 408,902 |
| Coal consumption | 102,527Tons/Year | |
| Boiler capacity | 110 TPH | |
| Boiler operating pres. and temp. | 48bars and 440°C | |
| Steam turbine capacity | 7 MWe | |
| Overall thermal performance | 60% | |
| Additional $CO_2$generation (MT/Y) | 217,516 | |

- Note: The operating pressure and temperature of coal-fired boiler can be increased to increase the power generation efficiency and thereby the output electrical capacity of the CCHP plant

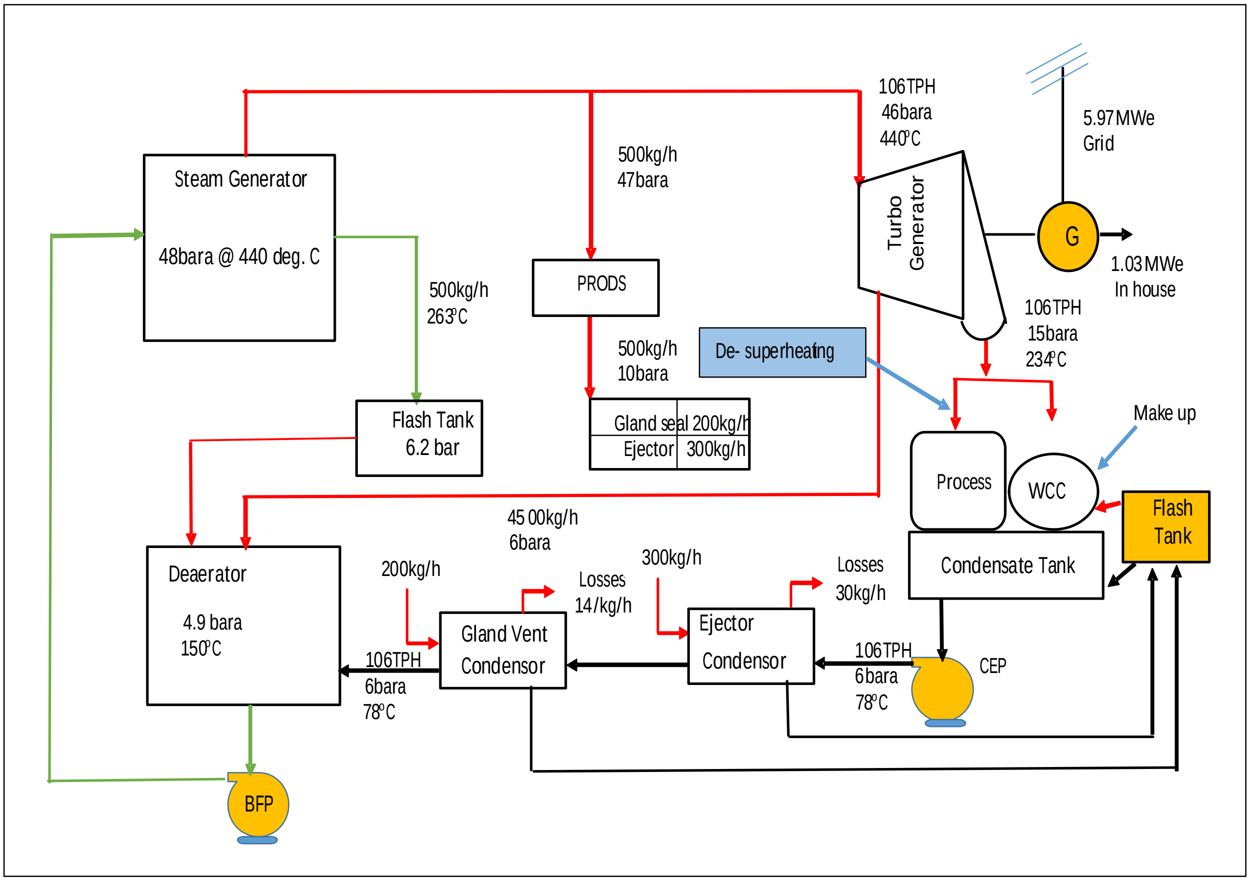


Figure 19: Heat and mass balance diagram of CCHP system with a Back-Pressure Turbine

### 7.1.3 Financial Analysis – CCHP on Back Pressure Steam Turbine

Table 13: Projected capital investment for CCHP System with a Back-Pressure Steam Turbine

| **Fixed assets** | ***Investment (millions of LKR)*** | | |
|---|---|---|---|
| | ***Equity*** | ***Loan*** | ***Total*** |
| Land - 4 Acres @ 1Mns per perch | 300 | 340 | 640 |
| Buildings - 100,000 sq. ft | 165 | 300 | 465 |
| Plant and Machinery (7 MWe Turbine, 110 TPH Steam Generator and other related accessories) | 1,387.50 | 3,237.50 | 4,625 |
| Transport and Installation | 92.50 | 138.75 | 231.25 |
| 12" and 6" steam and condensate pipes for 2Kms | 60 | 140 | 200 |
| Water treatment | 30 | 70 | 100 |
| Commissioning | 15 | 35 | 50 |
| Vehicle | 21.50 | 50.75 | 72.25 |
| Office equipment | 3 | 7 | 10 |
| Pre operating expenses<br>working capital | 100 | | 100 |
| ***Total*** | ***2,174.50*** | ***4,319.00*** | ***6,493.50*** |

Table 14: Projected Profit and Loss Statement for the CCHP system with backpressure steam turbine

| **Income & expenditure (LKR millions)** | **Year** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| Revenue | 3,661 | 3,661 | 3,661 | 3,661 | 3,661 | 3,661 | 3,661 | 3,661 |
| Material (Bio mass Cost /Inputs | 1,126 | 1,183 | 1,242 | 1,304 | 1,369 | 1,438 | 1,509 | 1,585 |
| Labour/Supervisory Inputs | 25 | 26 | 28 | 29 | 30 | 32 | 34 | 35 |
| Over Head Expenses | 15 | 16 | 17 | 17 | 18 | 19 | 20 | 21 |
| **Operating Profit** | 2,494 | 2,436 | 2,375 | 2,311 | 2,243 | 2,172 | 2,098 | 2,020 |
| **Less** | 20 | 21 | 22 | 23 | 24 | 26 | 27 | 28 |
| **Gross Profit** | 2,474 | 2,415 | 2,353 | 2,287 | 2,219 | 2,147 | 2,071 | 1,992 |
| Less Loan Instalment | 442 | 396 | 349 | 303 | 256 | 210 | 163 | 29 |
| Depreciation | 233 | 233 | 233 | 233 | 233 | 233 | 233 | 233 |
| **Net Profit Before Tax** | 1,799 | 1,786 | 1,771 | 1,752 | 1,730 | 1,704 | 1,675 | 1,596 |
| Less 15 % Tax | 270 | 268 | 266 | 263 | 259 | 256 | 251 | 239 |
| **Net Profit After Tax** | 1529 | 1518 | 1505 | 1489 | 1470 | 1449 | 1424 | 1356 |
| **Cumulative *Profit*** | 1529 | 3048 | 4553 | 6042 | 7512 | 8961 | 10385 | 11853 |

***(Inmillion LKR)***

Table 15: Projected financial indicators for CCHP System with a back-pressure steam turbine

| ***Financial Indicators*** | **Year** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| ***Debt Service Coverage Ratio DCSR*** | 2.98 | 3.08 | 3.19 | 3.31 | 3.44 | 3.59 | 3.76 | 3.95 |
| ***Profit Margin PM (%)*** | 49.15 | 48.80 | 48.37 | 47.85 | 47.25 | 46.55 | 45.76 | 43.59 |
| ***Return On Equity ROE (%)*** | 90.75 | 90.11 | 89.32 | 88.37 | 87.25 | 85.96 | 84.49 | 80.48 |
| ***Return On Investment ROI (%)*** | 26.08 | 25.90 | 25.67 | 25.40 | 25.08 | 24.71 | 24.28 | 23.13 |

## 7.2 Gas Turbinewith a Waste Heat Boiler

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 for heat recovery at the exhaust of the gas turbines is much higher in comparison to reciprocating engines. Besides, most of the waste heat can be recovered at relatively high temperature where the quality of heat has not deteriorated unlike the low-temperature heat released through the jacket water in reciprocating engine.

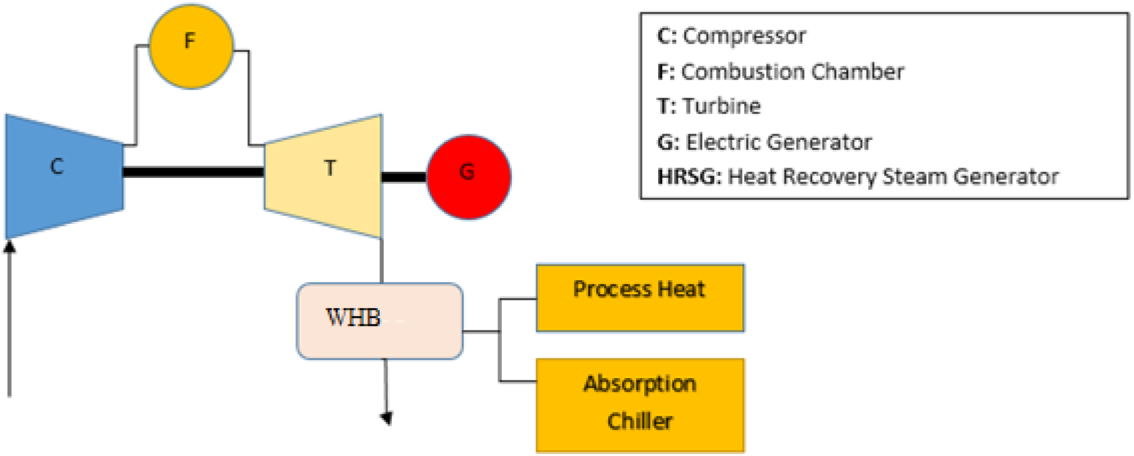


Figure 20: Schematic diagram of the open cycle gas turbine with a waste heat boiler

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.

For the purpose of 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 emergency power generation. Combined cycle gas turbines are operated in baseload power plants as the heat rate is much lower compared to open cycle gas turbines. However, with the recovery of waste heat in the open cycle using a waste heat boiler the overall efficiency of the system can be increased. The schematic diagram of the proposed CCHP with open cycle gas turbine and a waste heat boiler is shown in Fig. 20. This layout can usually be implemented with a package type gas turbine and site erected waste heat boiler. The turbine electrical capacityis determined by the required amount of process heat through the waste heat boiler. However, in this type of plant configuration, the varying thermal load can be smooth, managed with the use of supplementary firing in between the gas turbine and the waste heat boiler with the help of duct burner. Since the load variation at the proposed cluster at BEPZ is minimum the use of supplementary firing could be minimized and the turbine has been selected for the maximum process steam demand of 106.6TPH at 15bara. The financially competitive fuel in Sri Lanka for this type of engines could be the heavy fuel oil (HFO) used with can type gas turbines. However, the financial feasibility of a Liquefied Natural Gas (LNG) fired system is also assessed in this assignment.The gross calorific values of HFO and LNG considered here is 42676kJ/kg and 38700kJ/$m^3$respectively at the standard gas pressure of 140kPa. The efficiency of gas turbines does not change significantly with the change of fuel type from liquid to gaseous. Since the minimum percentage part load based on the capacity calculated from the maximumprocess steam demand throughout the year is greater than 26%, the turbine capacity was selected based on the maximum process heat demand calculated for the year to maximize the power generation efficiency and minimize the waste heat produced during the day. The heat and mass balance diagram of the plant is shown in Fig.21. The key performance parameters of the CCHP fired by HFO and LNG are shown in Table 16and 17 respectively.

Table 16: Annual fuel consumption and energy dispatched of the CCHP fired by HFO

| **Parameter** | **Electricity (MWh/Year)** | **Steam (MWh/Year)** |
|---|---|---|
| Energy consumed by the cluster | 248,080 | 408,902 |
| Energy supplied by CCHP | 239,144 | 408,902 |
| HFO consumption | 80,053 $m^3$/Year | |
| Waste heat boiler capacity | 125 TPH | |
| Generator capacity | 40 MWe | |
| Overall thermal performance | 72.6% | |
| Additional $CO_2$ generation (MT/Y) | 74,685 | |

Table 17: Annual fuel consumption and energy dispatched of the CCHP fired by LNG

| **Parameter** | **Electricity (MWh/Year)** | **Steam (MWh/Year)** |
|---|---|---|
| Energy consumed by the cluster | 248,080 | 408,902 |
| Energy supplied by CCHP | 239,144 | 408,902 |
| LNG consumption | 79,450,350m$^3$/Year | |
| Waste heat boiler capacity | 125 TPH | |
| Generator capacity | 40 MWe | |
| Overall thermal performance | 72.6% | |
| Additional $CO_2$ generation (MT/Y) | 6,874 | |

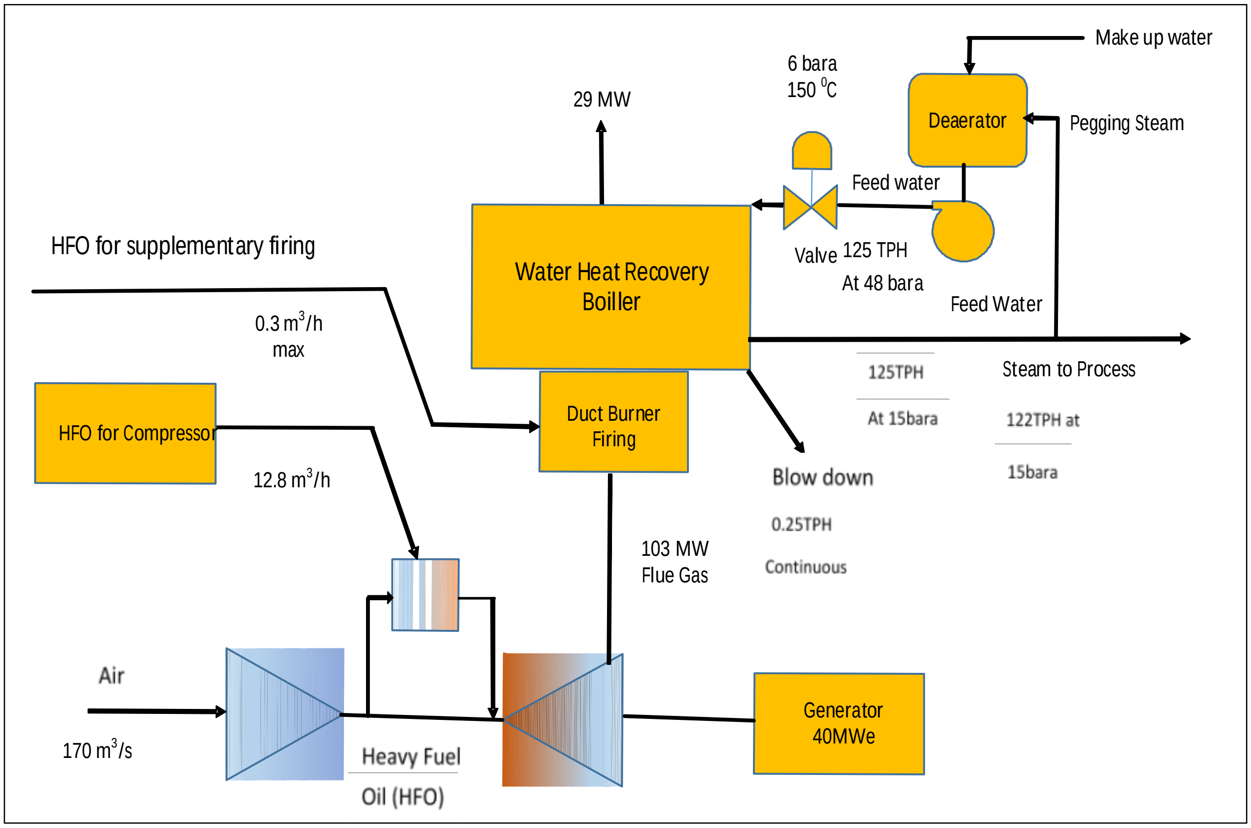


Figure 21: Heat and mass balance diagram of CCHP system on gas turbine and waste heat boiler

### 7.2.1 Financial analysis of the CCHP system on Gas Turbine and Waste Heat Boiler

Table 18: Projected capital investment for CCHP system with gas turbine and waste heat boiler

| **Fixed assets** | ***Investment (millions of LKR)*** | | |
|---|---|---|---|
| | ***Equity*** | ***Loan*** | ***Total*** |
| Land - 4 Acres @ 1Mns per perch | 300 | 340 | 640 |
| Buildings - 100,000 sq. ft | 165 | 300 | 465 |
| Plant and Machinery (40 MWe Generator, 125 TPH Waste Heat boiler and other related accessories) | 2,275.50 | 5,309.50 | 7,585 |
| Transport and Installation | 151.70 | 227.55 | 379.25 |
| 12" and 6" steam and condensate pipes for 2Kms | 60 | 140 | 200 |
| Water treatment | 30 | 70 | 100 |
| Commissioning | 15 | 35 | 50 |
| Vehicle | 21.75 | 50.75 | 72.50 |
| Office equipment | 3 | 7 | 10 |
| Pre operating expenses<br>working capital | 100 | | 100 |
| ***Total*** | ***3,121.95*** | ***6,479.80*** | ***9,601.75*** |

Table 19: Projected profit and loss statement for CCHP System with gas turbine and waste heat boiler

| ***Income and expenditure (LKR millions)*** | **Year** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| Revenue | 8,001 | 8,001 | 8,001 | 8,001 | 8,001 | 8,001 | 8,001 | 8,001 |
| Material (HFO Cost /Inputs | 6,404 | 6,468 | 6,533 | 6,598 | 6,664 | 6,731 | 6,798 | 6,866 |
| Labour/Supervisory Inputs | 25 | 25 | 26 | 26 | 26 | 26 | 27 | 27 |
| Over Head Expenses | 15 | 15 | 15 | 15 | 16 | 16 | 16 | 16 |
| **Operating Profit** | 1,557 | 1,492 | 1,427 | 1,361 | 1,295 | 1,228 | 1,160 | 1,092 |
| **Less** | 20 | 21 | 22 | 23 | 24 | 26 | 27 | 28 |
| **Gross Profit** | 1,537 | 1,471 | 1,405 | 1,338 | 1,271 | 1,202 | 1,133 | 1,064 |
| Less Loan Instalment | 722 | 611 | 500 | 389 | 278 | 167 | 56 | 0 |
| Depreciation | 420 | 420 | 420 | 420 | 420 | 420 | 420 | 420 |
| **Net Profit Before Tax** | 395 | 440 | 485 | 530 | 573 | 616 | 658 | 644 |
| Less 15% Tax | 59 | 66 | 73 | 79 | 86 | 92 | 99 | 97 |
| **Net Profit After Tax** | 335 | 374 | 412 | 450 | 487 | 523 | 559 | 547 |
| **Cumulative *Profit*** | *335* | *710* | *1,122* | *1,572* | *2,059* | *2,583* | *3,142* | *3,689* |

***(In million LKR)***

Table 20: Projected financial indicators for CCHP system with gas turbine and waste heat boiler

| ***Financial Indicators*** | ***Year*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| ***Debt Service Coverage Ratio DCSR*** | 0.93 | 0.96 | 0.99 | 1.02 | 1.06 | 1.10 | 1.16 | 0.00 |
| ***Profit Margin PM (%)*** | 4.93 | 5.50 | 6.07 | 6.62 | 7.16 | 7.70 | 8.22 | 8.05 |
| ***Return onEquity ROE (%)*** | 12.64 | 14.10 | 15.54 | 16.96 | 18.36 | 19.73 | 21.07 | 20.62 |
| ***Return onInvestment ROI (%)*** | 3.49 | 3.90 | 4.30 | 4.69 | 5.07 | 5.45 | 5.82 | 5.70 |

### 7.3 Reciprocating Engine and Waste Heat Boiler

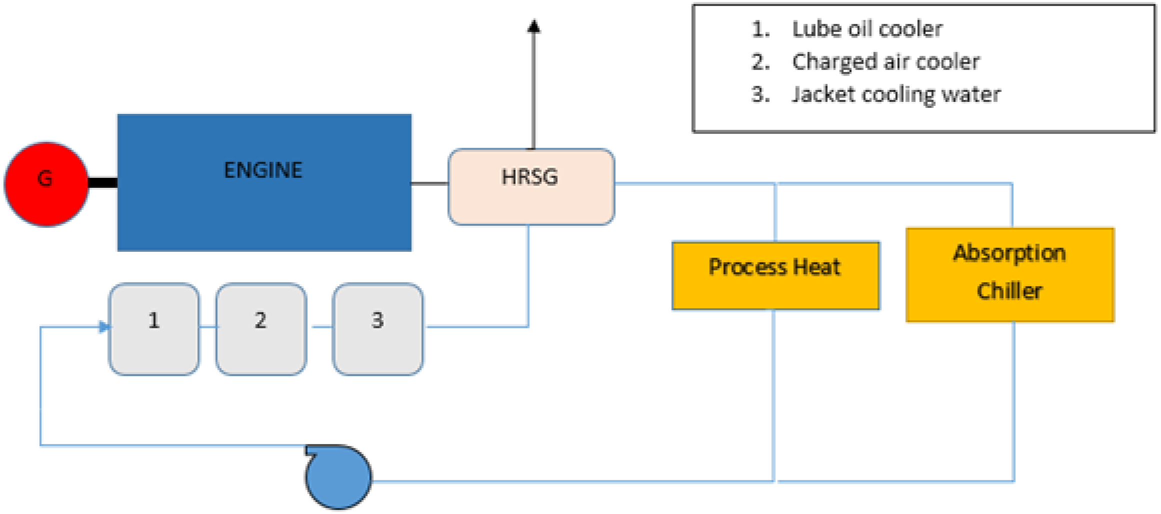


Figure 22: Schematic diagram of the reciprocating engine with a waste heat boiler

For medium and small scale CCHP 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 CCHP system. The configuration of the proposed CCHP plant is shown in Fig. 22.

However, based on the temperature of the heat required in the process, some of the waste heat channels from the reciprocating engines should be disregarded. The temperature of the process steam required for cluster at the BEPZ should not be below 180$^{o}$C and expected maximum temperature of the condensate return is less than 80$^{o}$C. The maximum jacket water temperature available is less than 112$^{o}$C. Since a waste heat exchanger usually needs a minimum pinch difference of 20$^{o}$C to be economically competitive, the heat recovery from all the other channels apart from direct flue gas exhaust may be nearly uneconomical. Figure 23 shows the percentage heat recovery from each waste heat channel of the reciprocating engines.

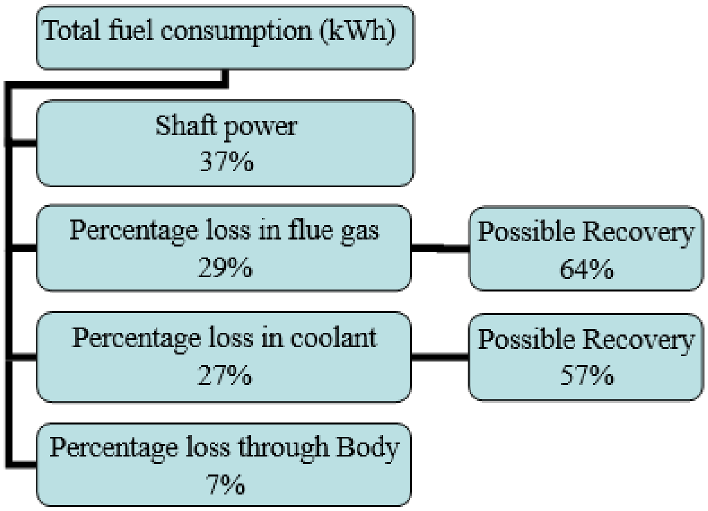


Figure 23: The percentage of heat recovery from different waste heat channels in the reciprocating engines

The energy requirements of the building or utility and the degree of heat recovery has to be carefully analyzedto achieve greater efficiency. 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, however, we have a heat to power ratio (minimum of 1.66) within the range but heat is at an elevated temperature. For utilities where the heat to power ratio is significantly higher than the above range, a surplus electricity should be generated to satisfy the process steam demand completely. This increases the capacity of the generator unnecessary.However, reciprocating engines operate with relatively higher performance compared to the other two systems at partial load operating and there are no limitations for the minimum part-load unlike in steam and gas turbines. The financially competitive fuel in Sri Lanka for this type of engines could be the heavy fuel oil (HFO) used with medium speed engines.The gross calorific value of HFO considered here is 42676kJ/kg. The heat and mass balance diagram of anHFO generator for the proposed CCHP plant at BEPZ is shown in Fig. 24. The plant input and out parameters including the thermal performance are shown in Table 21.

Table 21: Annual fuel consumption and energy dispatched for the optimum uninstalled capacity of the proposed CCHP

| **Item** | **Electricity (MWh/Year)** | **Steam (MWh/Year)** |
|---|---|---|
| Energy consumed by the cluster | 248,080 | 408,902 |
| Energy supplied by CCHP | 943,018 | 408,902 |
| HFO consumption | 235,076 $m^3$/Year | |
| Waste heat boiler capacity | 125 TPH | |
| Generator capacity | 160 MWe | |
| Overall thermal performance | 48.5% | |
| Additional $CO_2$ generation (MT/Y) | 94,255 | |

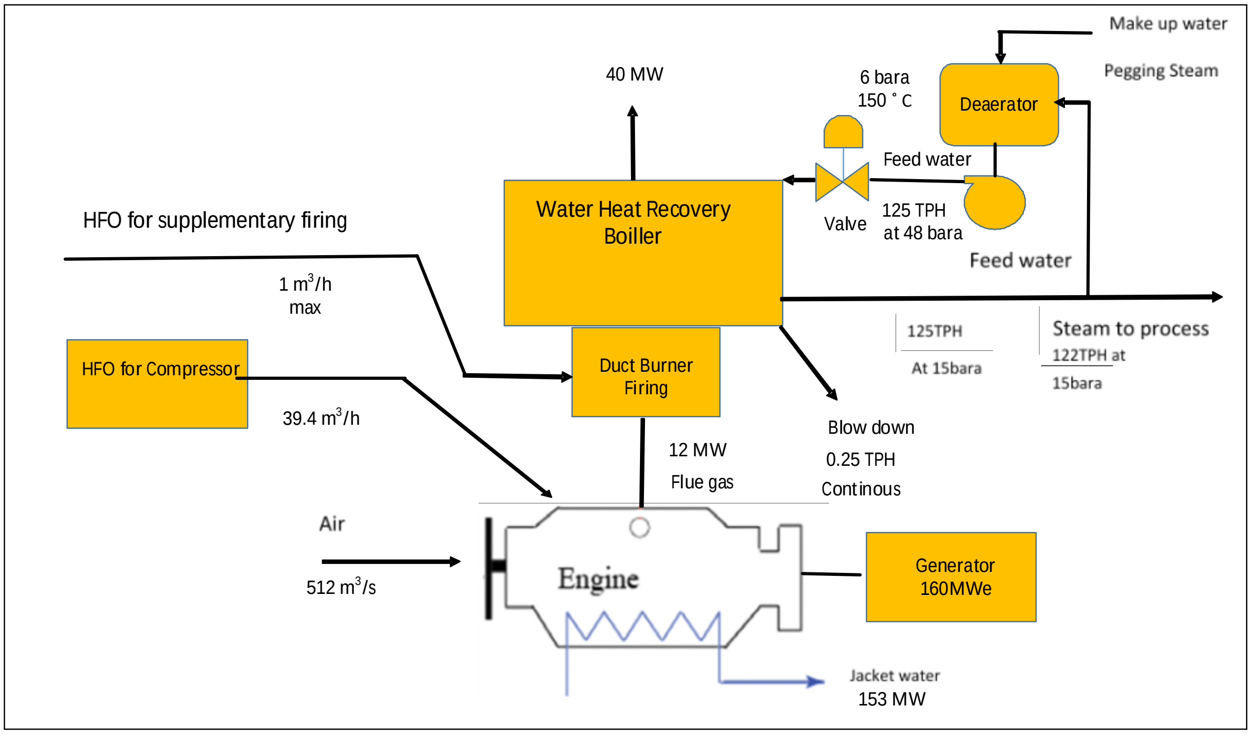


Figure 24: Heat and mass balance diagram of CCHP system on Reciprocating Engine and Waste Heat Boiler

### 7.3.1 Financial Analysis of CCHP on Reciprocating Engine and Waste Heat Boiler

Table 22: Projected capital investment for CCHP System with Reciprocating Engine and Waste Heat Boiler

| **Fixed assets** | ***Investment (millions of LKR)*** | | |
|---|---|---|---|
| | ***Equity*** | ***Loan*** | ***Total*** |
| Land - 4 Acres @ 1Mns per perch | 300 | 340 | 640 |
| Buildings - 100,000 sq. ft | 165 | 300 | 465 |
| Plant and Machinery (IC Enginebased 160 MWe Generator, 125 TPH Steam Generator and other related accessories) | 4,162.50 | 9,712.50 | 13,875 |
| Transport and Installation | 277.5 | 416.25 | 693.75 |
| 12" and 6" steam and condensate pipes for 2Kms | 60 | 140 | 200 |
| Water treatment | 30 | 70 | 100 |
| Commissioning | 15 | 35 | 50 |
| Vehicle | 21.75 | 50.75 | 72.5 |
| Office equipment | 3 | 7 | 10 |
| Pre operating expenses<br>working capital | 100 | | 100 |
| ***Total*** | ***5,134.75*** | ***11,071.50*** | ***16,206.25*** |

Table 23: Projected profit and loss statement for the CCHP system with reciprocating engine and waste heat boiler

| ***Income & expenditure*** | **Year** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | ***3*** | **4** | **5** | **6** | **7** | **8** |
| Revenue | 23,486 | 23,486 | 23,486 | 23,486 | 23,486 | 23,486 | 23,486 | 23,486 |
| Material (HFO Cost /Inputs) | 18,806 | 18,994 | 19,184 | 19,376 | 19,570 | 19,765 | 19,963 | 20,163 |
| Labour/Supervisory Inputs | 25 | 26 | 28 | 29 | 30 | 32 | 34 | 35 |
| Over Head Expenses | 15 | 16 | 17 | 17 | 18 | 19 | 20 | 21 |
| **Operating Profit** | 4,640 | 4,450 | 4,258 | 4,064 | 3,868 | 3,670 | 3,469 | 3,267 |
| **Less** | 20 | 21 | 22 | 23 | 24 | 26 | 27 | 28 |
| **Gross Profit** | 4,620 | 4,429 | 4,236 | 4,041 | 3,843 | 3,644 | 3,443 | 3,239 |
| Less Loan Instalment | 1,234 | 1,044 | 854 | 664 | 474 | 285 | 95 | 0 |
| Depreciation | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 |
| **Net Profit Before Tax** | 2,636 | 2,635 | 2,632 | 2,626 | 2,619 | 2,609 | 2,598 | 2,489 |
| Less 15% Tax | 395 | 395 | 395 | 394 | 393 | 391 | 390 | 373 |
| **Net Profit After Tax** | 2,241 | 2,240 | 2,237 | 2,232 | 2,226 | 2,218 | 2,208 | 2,116 |
| **Cumulative**Profit | 2,241 | 4,480 | 6,717 | 8,950 | 11,176 | 13,394 | 15,602 | 17,717 |

***(In million LKR)***

Table 24: Projected financial indicators for CCHP System with Reciprocating Engine and Waste Heat Boiler

| **Financial Indicators** | ***Year*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| ***Debt Service Coverage Ratio DCSR*** | 1.64 | 1.69 | 1.74 | 1.80 | 1.87 | 1.95 | 2.05 | 0.00 |
| ***Profit Margin PM (%)*** | 11.22 | 11.22 | 11.21 | 11.18 | 11.15 | 11.11 | 11.06 | 10.60 |
| ***Return on Equity ROE (%)*** | 51.34 | 51.32 | 51.25 | 51.15 | 51.00 | 50.82 | 50.59 | 48.47 |
| ***Return On Investment ROI (%)*** | 13.83 | 13.82 | 13.80 | 13.77 | 13.74 | 13.69 | 13.62 | 13.05 |

## 7.4 The Summary of Sensitivity Analysis of All Five Options

Since all four options are technically feasible, the sensitivity analysis was carried out for each option. Table 25compares three significant financial parameters of four option for a financial period of 8 years at 12% interest rate. The selling and purchasing prices of electricity, heat and fuel are furnished bellow

- For a financial period of 8 years at 12% interest rate
- Electricity selling price: 22Rs/kWh
- Thermal energy selling price: 6.70Rs/kWh
- Biomass buying price: 6Rs/kg
- Furnace oil purchasing price: 80Rs/L
- Natural purchasing price: 77Rs/m$^3$

Table 25: The comparison of sensitivity parameters of four different options

| **Sensitivity parameter** | **Steam turbine** | | **Engine** | **Gas turbine** | |
|---|---|---|---|---|---|
| | **Biomass** | **Coal** | | **HFO** | **LNG** |
| NPV at 12% (millions LKR) | 5,226 | 1,479 | 4,131 | -2,769 | -1,498 |
| IRR | 36% | 20% | 20% | 2% | 7% |
| Simple Payback | 27 Months | 45 Months | 46 Months | 87 Months | 72 Months |

# 8 EVALUATION OF THE TG TECHNOLOGIES

The availability of fuel playsa major role in selecting the prime mover for the CCHP. Natural gas isdetermined as the most suitable fuel for the gas turbine option. However, natural gas is not currently available in Sri Lanka. While biomass-basedgasification, options are available for gas turbine electricity, this option isdeemed to be unsuitable due to the immaturity of such technology in the Sri Lankan context.Another option is the operation of gas turbine with Heavy Fuel Oil (HFO) that is readily available in Ceylon Petroleum Cooperation, and the generation of electricity and process steam is well aligned with the demand of these commodities in the cluster. Therefore, the option with the gas turbine is the technically best option for the proposed CCHP at BEPZ. However, the higher costs of petroleum-based fuels and investment haveprovided negative results to the financial feasibility of this option. The carbon footprint and the environmental impactare not comparable with backpressure steam turbine. As such, the gas turbine option was dropped.

The next option is to incorporate a reciprocating internal combustion engine for the CCHP. Reciprocating IC engine technology is an established technology in the local context. Larger scale (about 18MWe) prime movers have beeninstalled 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. Since the prime objective of this project is to minimize the waste heat generation,so the thermal load matching has been proposed, then a relatively large amount of excess quantity of electricity compared to the backpressure turbine and the gas turbinewill be exported to the national grid. Therefore, the system planning of the national grid in this area will have to be studied and upgraded accordingly. The higher costs of petroleum-based fuels and the investmenthave also affected the financial feasibility of this option. The internal rate of return of 20% of this investment would be attractive in a very stable electricity market. However, considering highly excessive electricity generation (more than 280% of the BEPZ demand) and the environmental impact on the use of fossil fuelespecially the additional carbon footprint of 124823MT/Y compared to the biomass option, this option is also disregarded.

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.

The biomass-fired Rankine cycle option has shown the best financial feasibility with relatively low fuel cost. The technology is also well established internationally as well as locally. Coal as the fuel in the same configuration has relatively fewer financial benefits compared to the biomass as indicated in Table 25. Considering the environmental impact with the use of fossil fuel and current legal framework on Coal imports, the biomass-fired Rankine cycle is proposed for the CCHP at BEPZ

Table 26: Capacity of the CCHP plant components

| Description | Remarks | Capacity |
|---|---|---|
| Turbine gross power | Gross power | 7MWe |
| | Net power | 5.97MW |
| Boiler capacity | MCR | 110TPH |
| Overall thermal efficiency | Elec. + heat | 60% |
| Annual biomass consumption | 25% moisture | 187,720Ton |

As mentioned in Table 9, the maximum possible process steam demand of 68.64 MW has been recorded in November including the vapour absorption cooling system. In addition to that, the transmission and distribution loss of heat considered was 5%. The total process steam demand is to be matched in the CCHP operation. Therefore, the sizes of the turbine and the boiler have been selected accordingly. After the steam turbine, the steam pressure has to be at 14 bargallowing a 1.7 bar loss for the 2km length pipe transportation. With the above thermal demand conditions, the turbine capacity selected was 7MWe as shown in Table 26. The schematic representation of the CCHP plant layout is shown in Fig. 25

The electrical power demand is partially met through this combination of national grid and the CCHP system. Approximately, 206,209MWh/year of electricity has to be imported from the national grid. This represents a 16.87% reduction in electricity drawn from the national grid, in comparison to the current situation at BEPZ.

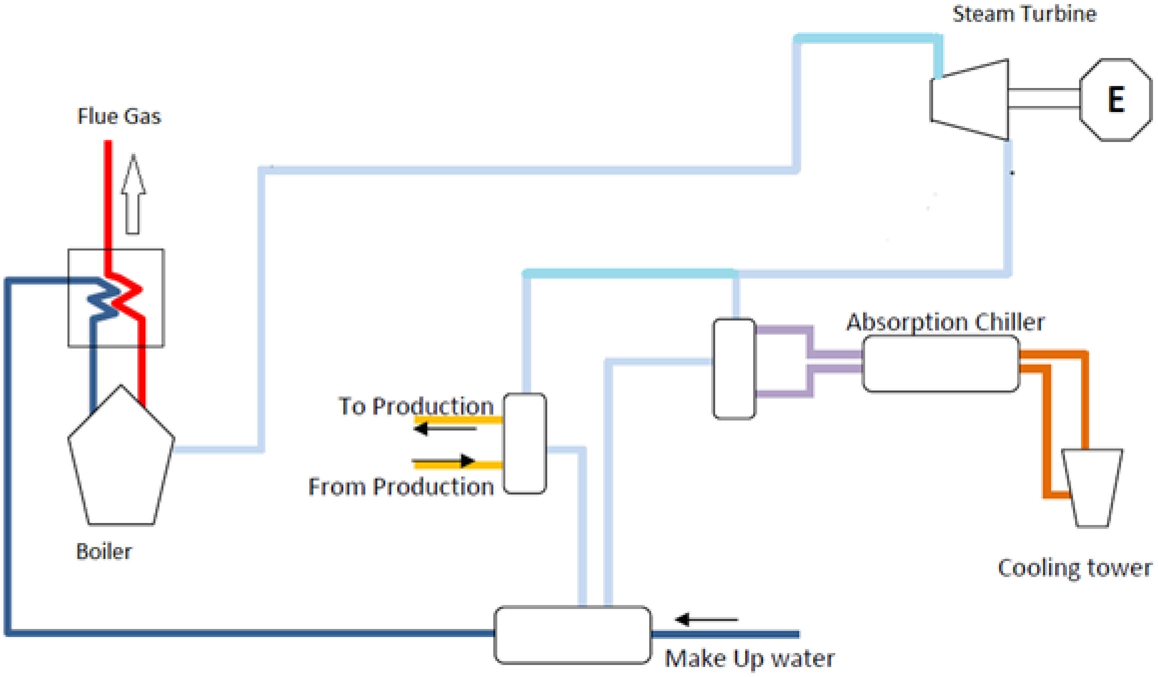


Figure 25: Schematic diagram of the proposed CCHP plant at BEPZ

### 8.1 Fuel Selection for the CCHP Plant

Biomass and coal arethe short-listed fuel sources to be used in the CCHP plant. The supply of biomass has to be fulfilled from local suppliers. The supply of coal may be fulfilled from either CEB or Holcim Lanka Ltd. The price and energy comparison table of the two fuel sources are denoted in Table 27.

Table 27: Fuel prices and their gross calorific values

| Fuel Source | Price (US$/Ton) | GCV (MJ/kg) | Energy cost (US$/MJ) |
|---|---|---|---|
| Biomass at 25% moisture WB | 33.33 | 14.4 | 0.00231 |
| Coal | 106 | 26.365 | 0.00402 |

From the above comparison, it is understood that coal is relativelyexpensive compared to the biomass. When the supply chain of coal is considered, only two bulk importers are present in Sri Lanka: Ceylon Electricity Board (CEB) and Holcim Lanka PLC. Coal is imported by CEB to power up the 900 MW NorochcholaiThermal Power Plant. Holcim Lanka PLC is the largest cement manufacturer, hasbeen using coal for their production purposes. For medium scale coal consumers (less than 5000 tons) direct import of coal was very difficultand has to be purchased from either CEB or Holcim.

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 well-stablished biomass supply chain at BEPZ but the sustainability should be further investigated. As such, the selection of biomass as the fuel would notcause undue inconvenience for the smooth operation of the biomass-fired CCHP at BEPZ.

Table 28: Current and predicted annual fuel consumptions with additional biomass boilers

|  | Electricity (MWh/Year) | Biomass (MT/Year) | Fossil fuel ($m^3$/year) |  |  |
|---|---|---|---|---|---|
|  |  |  | Furnace oil | Diesel | Kerosene |
| Current total consumption | 248,080 | 209,717 | 14,594 | 9 | 49 |
| Fuel for steam and hot water | - | 147,187 | 2814 | 9 | 49 |
| Predicted consumption with CCHP | 223,272 | 233,210 | 11,721 | 0 |  |

Table 28:shows the rationally of current and predicted energy consumption scenarios. The predicted consumptions are based on the current operating efficiencies of the thermal systems

and the existing vapor compression chillers. The electricity consumption of the absorption chillers is considered as negligible. The total fuel consumption refers to the total thermal demand including for the thermic fluid heaters. Currently, these biomass thermic fluid heaters consume about 62531Ton every year while steam and hot water systems consumeabout 147,187Ton/Year. Separate consumption of furnace oil only for steam and hot water is also shown in Table 03. The proposed CCHP system with the replacement electric chillers with absorption chillers has increased the annual biomass consumption by 15% while annual electricity consumption has been dropped by 9% on a peak day. The biomass consumption of the thermic oil heaters hasdecreased from 30% to 27% of the total biomass consumption. However, the contribution of furnace oil consumption to the thermic oil heaters has decreased by 19%. All the forecasted and current furnace oil consumptions are based on the performance of existing systems. Figure 25 shows the variation of IRR of the project compared to escalating biomass price. The current price of biomass is considered as 6Rs/kg

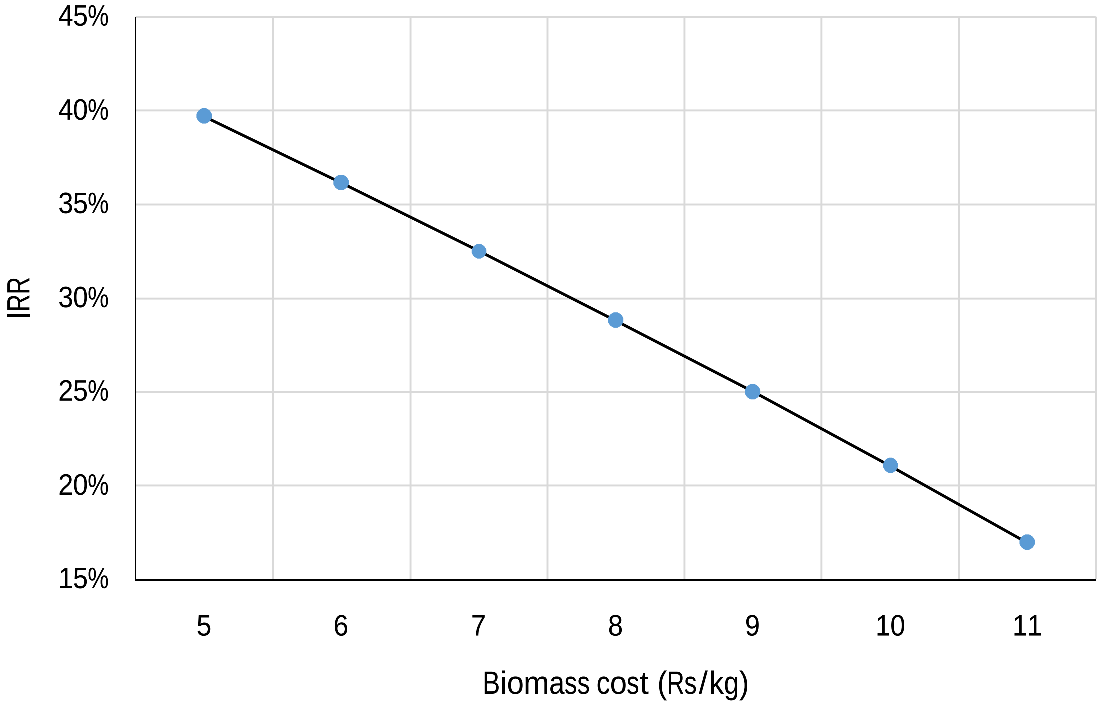


Figure 26: IRR Vs Biomass price of the proposed CCHP plant with a backpressure turbine

# 9 ABBREVIATIONS

BEPZ - Biyagama Export Processing Zone
CCHP - Combined Cooling Heating and Power
COP - Coefficient of Performance
DCSR - Debt Service Coverage Ratio
DPR - Detailed Project Report
GCV - Gross Calorific Value
GW - Giga Watt
GWh - Giga Watt Hour
HFO - Heavy Fuel Oil
HVAC - Heating Ventilation and Air Conditioning
ISB - Industrial Services Bureau
kW - Kilowatt
kWh - Kilowatt Hour
MCR - Maximum Continuous Rating
MT - Metric Tons
MW - Mega Watt
MWh - Megawatt Hour
PM - Profit Margin
ROE - Return on Equity
ROI - Return on Investment
SLSEA - Sri Lanka Sustainable Energy Authority
TG - Tri Generation
TGT - Tri Generation Technology
TPH - Tons Per Hour

| | | |
|---|---|---|
| DRFS | - | Detailed Report on Feasibility Study |
| WTEA | - | Walk ThroughEnergy Audit |

# 10 THE ANNEXURES

The annexures are included in an accompanying soft file.

Filename:Annexures - Feasibility study on Tri Generation systems

A. The contact details of the industries in the BEPZ
B. Production, Energy and related background data of the industries in the BEPZ
C. The electrical load data of the industries
D. The detailed energy load curve data (electrical, thermal, cooling) of selected 36 factories
E. The questionnaire used for the data collection in stage one
F. The map of the BEPZ
G. The proposed steam supply and condensate return piping system
H. The quotations received for the commercial CCHP plants
I. Some photographs representing data collection activates in BEPZ