CHAPTER 1

INTRODUCTION

1.1 Background

Life cycle assessment (LCA) of HRSG at UTP GDC plant was performed to evaluate the carbon dioxide (CO_2) emission save from coming out to the surroundings. Basically, HRSG uses the exhaust gas from gas turbine to be converted to steam for the usage of cogeneration or combine cycle plant. The waste heat that comes from the gas turbine usually becomes CO_2 emission but since HRSG takes up to 60% of the waste heat and use it to heat up the feed water inside and turns it into steam reduces the CO_2 emission by gas turbine [2]. The CO_2 will cause global warming and endangered the population of earth. Hence, this project was undertaken to evaluate the total potential CO_2 emission and shows that HRSG is an equipment that can reduce the CO_2 emission by gas turbine.

Figure 1.1: HRSG in UTP GDC plant

Heat recovery steam generator (HRSG) is a boiler that consists of economizer and evaporator. In some cases it also consists of a super heater if it is intended for the use in combine cycle plant which consists of a steam turbine. The steam generated in cogeneration mode is being utilized for process applications, while in combine cycle configuration the steam generated is utilized to drive the steam turbine generator for electricity production. There are some advantages by using gas turbine as a power source such as it takes short time to start up, have large power output (3MW to 100MW), comes in modules packaged, easy to assemble and erect, have high efficiencies on low heating value (LHV) basis (25% to 35%) and consume little to no cooling water [1]. UTP GDC plant uses the HRSG to generate steam to support the steam demand by the steam absorption chiller (SAC) in case if the auxiliary boiler cannot generate enough steam [10]. In this case, the HRSG is the main boiler for the SAC.

Recent developments include low emission features with high capacity units up to 250 MW, in addition to high operating temperatures for combustor (in the range of 1205°C), making the Rankine cycle more efficient by having results in higher efficiencies than 35% and the resulting exhaust gas temperature is also higher, that helps to generate high-pressure/high-temperature superheated steam [3].

1.2 Problem Statement

The gas turbine releases exhaust gas during operation and the waste heat that is released to the surroundings will become CO_2 and this may cause air pollution and global warming. The usage of HRSG will use up to 60% of the waste heat from gas turbine to be used for steam generation to drive steam turbine in combine cycle or produce energy (cogeneration) for other purposes such as supply steam for chiller. In UTP GDC plant HRSG is used to support the production of steam for SAC usage. The usage of heat energy from the HRSG operation could reduce carbon dioxide emission. As carbon dioxide released to the surroundings will be accumulated in the atmosphere and leads to global warming, it will affect the future generation. It is thus important to evaluate the amount of CO_2 that can be reduced by HRSG.

1.3 Objectives

The project is performed based on two objectives. These are the following objectives:

- To develop life cycle assessment model for the HRSG.
- To evaluate the saving of carbon dioxide emission through the operation of the HRSG.

1.4 Scope of Study

This project focused on the life cycle assessment of the HRSG at the UTP GDC plant. While there are two HRSGs in UTP GDC plant, but the main focus in this project will be on the HRSG B3030A. The data obtain was based on the performance of HRSG B3030A from January 2016 to June 2016. Based from the data obtained, a LCA model is develop using Microsoft Excel.

CHAPTER 2

LITERATURE REVIEW

2.1 Life Cycle Assessment

Life cycle assessment (LCA) or sometimes known as cradle-to-grave analysis is a tool to assess the potential environmental impacts of industrial processes and consumer products from raw materials to waste removal. The advantage of doing an LCA is to get the understanding of the impacts of a process, product, or activity in order to find an effective way to improve it [2]. LCA is now an important tool which plays a crucial role in the management of environment and essential for sustainability of the environment. LCA consists in shifting of burdens which is the only tool to assess environment that avoids positive ratings for measurement [3].

Based on the ISO 14040 and 14044, there are four basic structures to standardize the LCA which are: 1. Goal and scope, 2. Life cycle inventory, 3. Life cycle impact assessment, 4. Interpretation.

Goal and scope of study of an LCA must be clearly defined. In other words, defining goal and scope of study includes finding the appropriate limits of the analysis [4]. In the ISO standards, it requires the goal and scope of study of an LCA to be clearly stated and consistent with the intended application. There are four technical details to guide goal and scope of study of an LCA which are functional unit, system boundaries, assumptions and limitations and allocation methods.

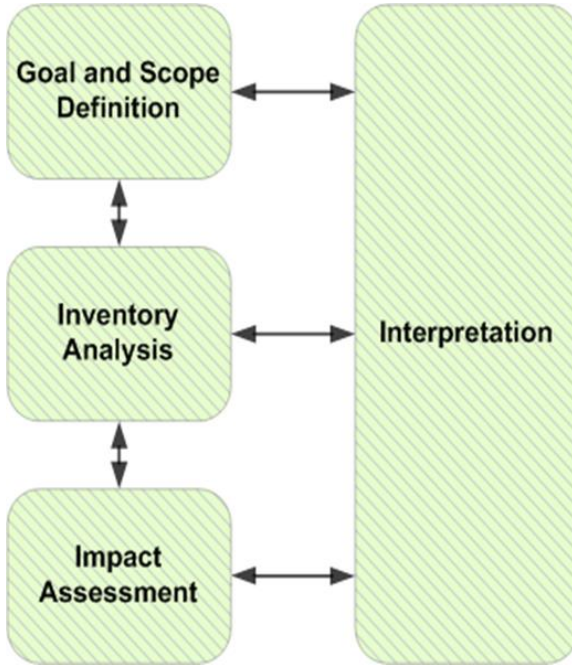

Figure 1.1: Outline of generic LCA procedure [4]

Life cycle inventory (LCI) analysis is to produce flows of inventory for a product system. Flows of inventory include inputs of raw materials and energy. A flow model of the product system is constructed to develop the inventory.

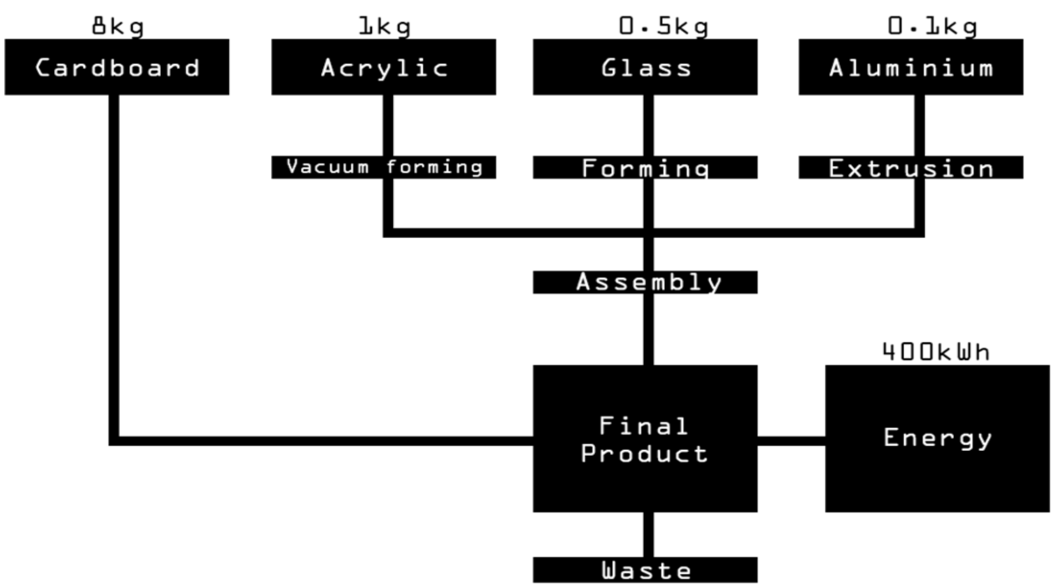

Figure 2.2: Example of LCI diagram [4]

Life cycle impact assessment (LCIA) purpose is to evaluate the significance of potential environmental impacts through the LCI. There are several important steps that must be followed in order to do LCIA which are selection of impact categories follows by the classification stage and finally the impact measurement.

Based on the ISO 14040:2006, the life cycle explanation includes significant topic identification based on the LCI and LCIA phases of an LCA results, evaluation of the subject area considering sensitivity and consistency checks, completeness and limitations, conclusions and recommendations.

LCA consists of three basic levels which are matrix LCA, screening LCA and also full LCA. matrix LCA is by using the quantitative or semi-quantitative data, while screening LCA is by using data that is already available whereas full LCA which uses new data inventory [5].

There are two simplified way to do LCA which are MECO and ERPA [6]. The right method must be chosen in order to get the right result for the LCA. There will never be a complete LCA because it has never been accomplished before [7]. It is better to start from a progressive study, less detailed towards more detailed [8].

2.2 UTP GDC Plant

Universiti Teknologi PETRONAS (UTP) is a private university, 92,600 m^2 in area, with approximately population of 6,000 fully residential [9]. The UTP GDC plant was constructed in 2001 and was fully operational in 2003. It has the purpose of supplying both chilled water and electricity to UTP campus in Tronoh, Perak. The plant initially supply 4000RT of chilled water and generate 8.4MW of electricity. Nowadays, the loads have been increase further to 11000RT and 20MW in order to meet the higher demand as the student population increases [10]. UTP GDC plant is essentially a centralized plant generating thermal media (chilled water) for air-conditioning requirements of several buildings within a district. It is operated by Makhostia Sdn Bhd. The plant consist major equipment in order to be operated for a big output. The equipments are; two units of Solar Taurus gas turbines, two units of Vickers Hoskin

HRSGs, Carrier steam absorption chiller, Dunham Bush electrical chiller and Vickers Hoskin auxiliary gas boiler.

Cogeneration system is also implemented in Gas District Cooling (GDC) at Universiti Teknologi PETRONAS (UTP) where the absorption system comprises of 2 units of Gas Turbine Generators (GTG with 4.2 MW each), 2 units of Heat recovery Steam Generators (HRSG with 10 Tonne/hr each), and 2 units of Steam Absorption Chiller (SAC with 1250 RT/hr each). The plant use natural gas a fuel for combustion gas turbine generators. The power generated (from gas turbine generators) and chilled water generated (from SAC) are supplied to the facilities of Universiti Teknologi PETRONAS (UTP).

The plant operates on a 24 hour basis where during the peak periods, the absorption system is operated with full load capacity. The unique configuration of the overall system enables the plant to achieve the high effective operation due to peak cut of both daily peal demands of power and chilled water. The presence of chilled water Thermal Energy Storage Tank (TES Tank) enables to effectively leveling the power generation.

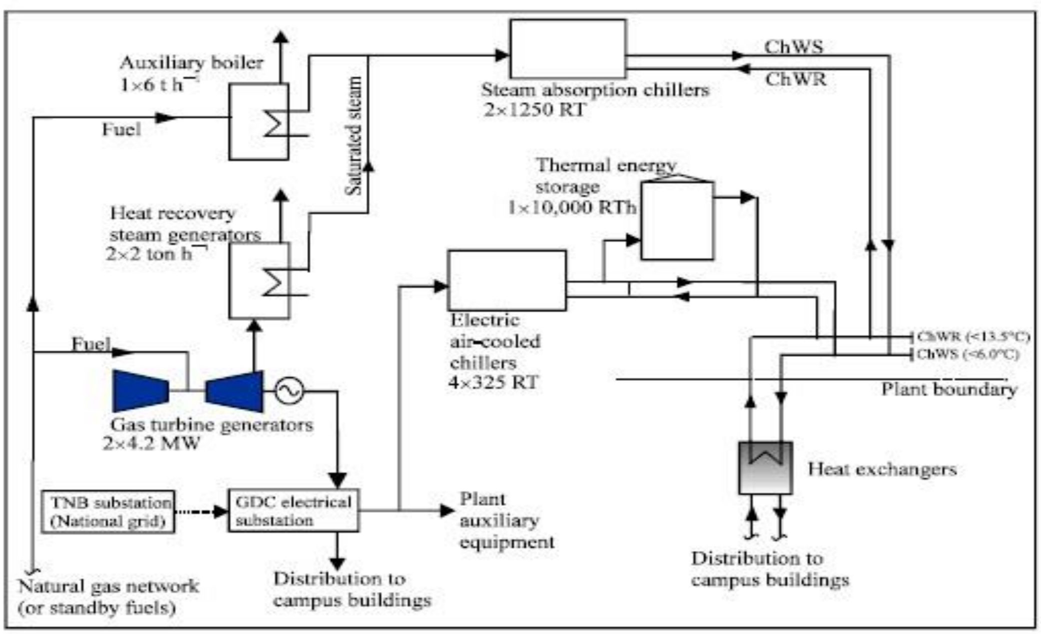

Figure 2.3: UTP GDC plant process flow [22]

2.3 Heat Recovery Steam Generator

The HRSG is basically a heat exchanger that extracts the remaining heat energy of the flue gas from gas turbine exhaust and uses the energy to produce saturated steam to be used by the steam absorption chiller unit, hence increasing the efficiency of the power plant [11].

The HRSG consist of Steam Drum and banks of Economizer tubes. The tubes are made of carbon steel to withstand the high temperatures in the HRSG. From the data obtained related to GDC-UTP operations, only 66.6% of the heat from exhaust gas of GTG is captured by HRSG to produce steam while remaining 33.4% is emitted and loss to environment [10].

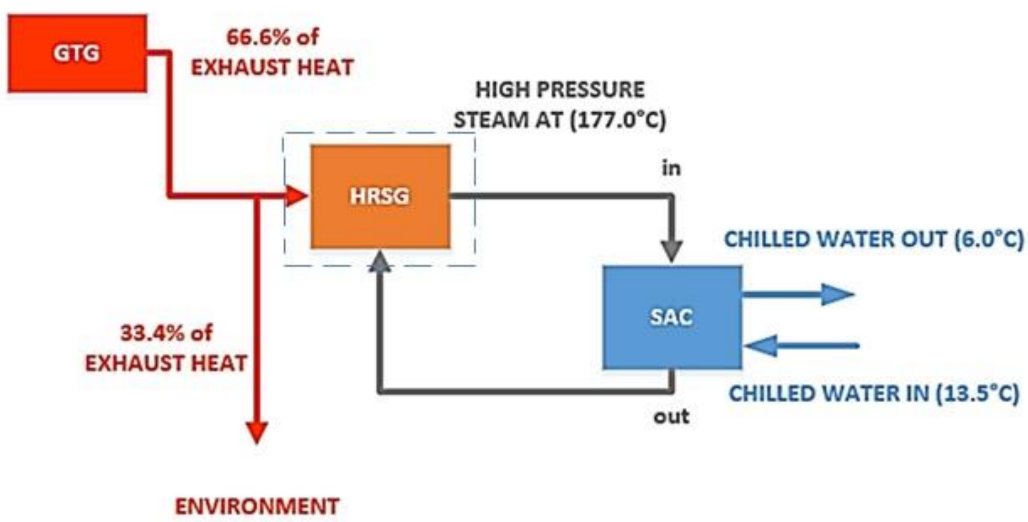

Figure 2.4: Energy circulation in absorption system in UTP-GDC plant

CHAPTER 3

METHODOLOGY

3.1 Project Flowchart

Figure 3.1 portrays the project flowchart that need to be followed in order to complete the project. In this flow chart, it shows the steps of the project from the assignment of the project which is the LCA model of HRSG to evaluate CO_2 emission until the validation of the LCA model.

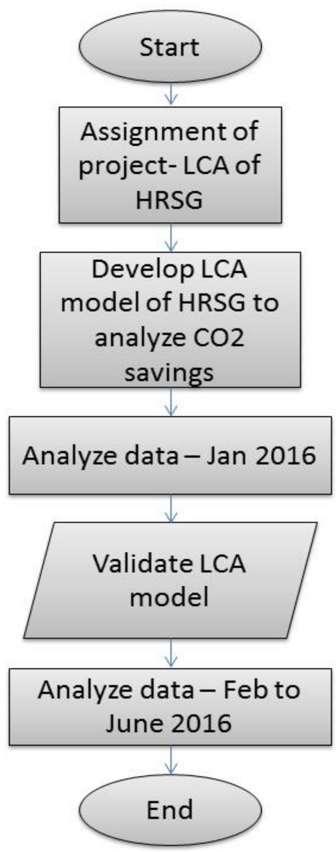

Figure 3.1: Project flowchart for FYP

3.2 Gantt Charts

Table 3.1: Gantt chart for FYP 1

No.	Detail work	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Assignment of project – LCA model for HRSG to evaluate CO_2 emission	■	■												
2	Literature review for LCA & HRSG		■	■											
3	Data acquisition for one month (January 2016)			■	■										
4	Writing extended proposal report				■										
5	Submission of extended proposal report				■										
6	Proposal defense					■	■								
7	Develop LCA Model							■	■	■					
8	Data analysis January 2016									■	■	■			
9	Validation of LCA model											■	■		
10	Writing of interim report												■	■	
11	Submission of interim draft report													■	
12	Submission of interim report														■

Table 3.2: Gantt chart for FYP 2

No.	Detail work	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Data acquisition for another six months (February – June 2016)	■	■	■											
2	Continuation on spreadsheet				■	■	■								
3	Data analysis							■							
4	Validation of data obtained							■							
5	Develop spreadsheet template using Microsoft Excel	■	■	■	■	■	■	■							
6	Writing of progress report	■	■	■	■	■	■	■							
7	Submission of progress report							■							
8	Continuation on presentation poster								■	■	■				
9	Pre- SEDEX										■				
10	Submission of draft final report											■			
11	Submission of final report												■		
12	Viva													■	■

3.3 Project Key Milestones

Figure 3.2 and figure 3.3 shows the key milestones that needed to be followed in order to keep track of the project so it will be completed in time.

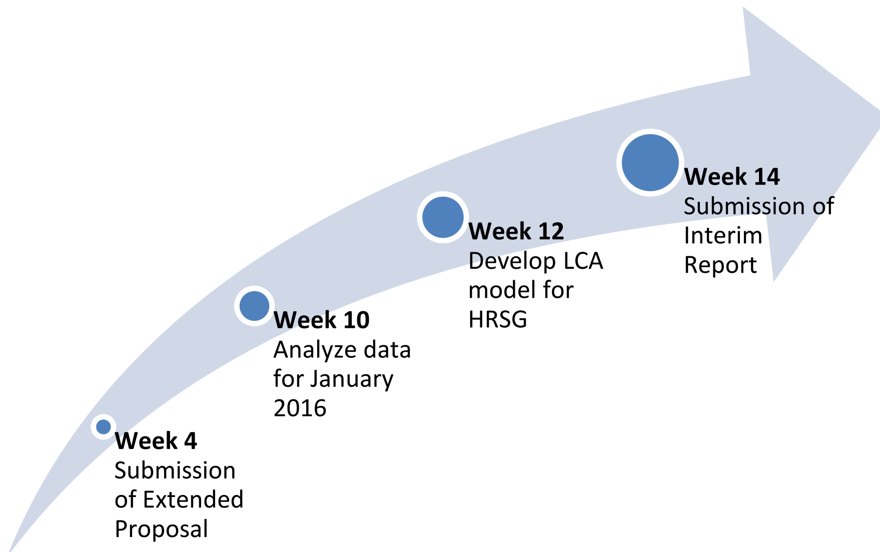

Figure 3.2: Project Key Milestones for FYP 1

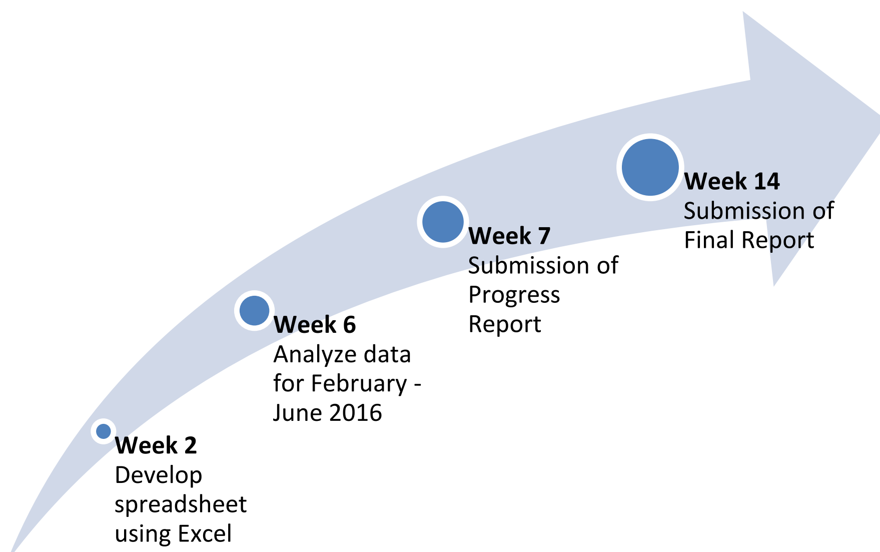

Figure 3.3: Project Key Milestones for FYP 2

3.4 HRSG Formula

Based on figure 3.4, the profiles of the steam temperature and gas temperature in a HRSG which consist of economizer and evaporator are shown. The HRSG is operating at a single pressure. Initially, exhaust heat, T_{g1} enters the evaporator. It then entered into the evaporator and economizer and being released to the environment by the HRSG at T_{g3}. Refrigerant entered into the economizer at temperature T_{w1} and was heated sensibly at T_{w2}, after it went through the evaporator. In the evaporator, the water boiled at saturation temperature, T_s and then exits the evaporator as saturated steam at T_{s4}. The generated steam was then being used by absorption chiller to generate chilled water.

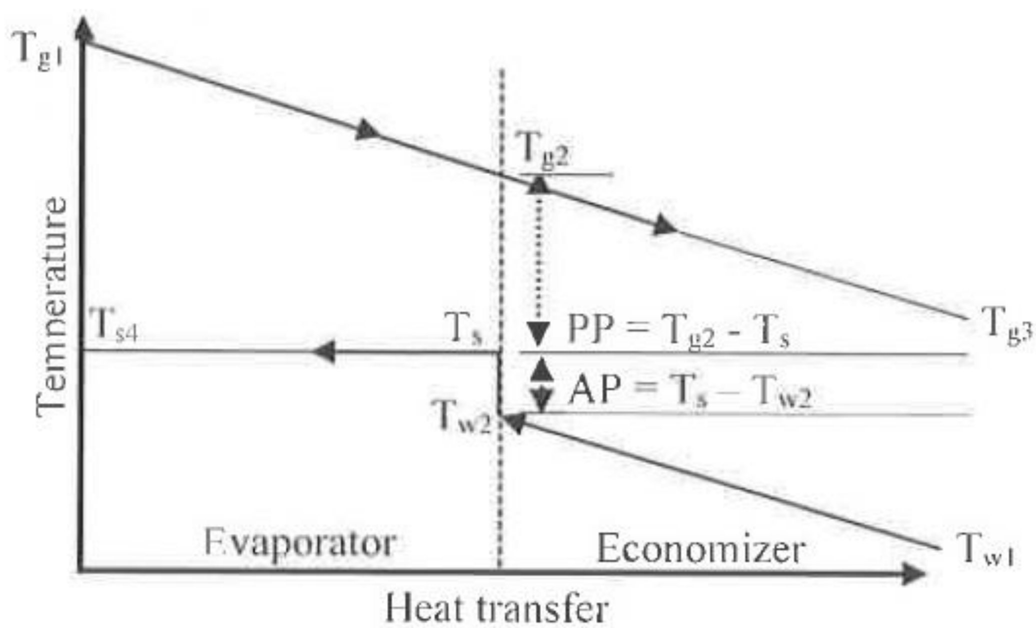

Figure 3.4: HRSG gas and steam temperature profile

Eq. (1) and Eq. (2) show the relationship of pinch point (PP) and approach point (AP) to T_{g2}, T_s and T_{w2}. By knowing the PP, AP and T_s, the value of T_{g2} and T_{w2} were obtained. The value of T_{g2} and T_{w2} is then used in Eq. (4) and Eq. (6).

$$PP = T_{g2} - T_s \tag{1}$$

$$AP = T_s - T_{w2} \tag{2}$$

Mass flow rate of generated steam is determined by using Eq. (3);

$$\text{Mass flow rate of steam generated} = \frac{\text{Evaporator duty}}{\text{Enthalpy absorbed by steam in evaporator}} \quad (3)$$

Evaporator duty is required to be calculated to determine the mass flow rate of the generated steam. The evaporator duty is quantify as;

$$\text{Evaporator duty} = \dot{m}_{\text{exhaust gas}} \times (1 - \text{hl}) \times Cp_{g(\text{evap})@Tg1} \times \left(T_{g1} - T_{g2}\right) \quad (4)$$

where $m_{\text{exhaust gas}}$ is the mass flow rate of exhaust heat from GT, hl is heat loss percentage, T_{g1} is the GT temperature of exhaust heat and T_{g2} is the exhaust heat temperature enters the economizer. $Cp_{g(\text{evap})}$ is the specific heat gas of evaporator and it is quantify as;

$$Cp_g = 0.991615 + (6.99703 \times 10^{-5} \times T) + (2.7129 \times 10^{-7} \times T^2) - (1.22442 \times 10^{-10} \times T^3 \quad (5)$$

Eq. (6) is used to evaluate enthalpy absorbed by steam in evaporator;

$$\text{Enthalpy absorbed by steam in evaporator} = \left(h_s - h_{w@Tw2(\text{fluid})} + \text{bl} \times \left(h_{w@Tw2(\text{vapor})} - h_{w@Tw2(\text{fluid})}\right)\right) \quad (6)$$

For the evaluation of gas temperature leaving HRSG, Eq. (7) is used;

$$T_{g3} = T_{g2} - \text{Gas temperature drop} \quad (7)$$

where the T_{g2} is obtained from Eq. (1). The temperature drop is determined by;

$$\text{Gas temperature drop} = \frac{\text{Economizer duty}}{\left(\dot{m}_{\text{exhaust gas}} \times Cp_{g(econ)} \times (1 - hl)\right)} \quad (8)$$

$$\text{Economizer duty} = \dot{m}_{steam} \times (1 + bl) \times \left(h_{w@Tw2(fluid)} - h_{w@Tw1}\right) \quad (9)$$

where m_{steam} is the mass flow rate of steam gained from Eq. (3), $h_{w@Tw1}$ is enthalpy of feed water.

The efficiency of the HRSG is one of the important factors which influence the efficiency of GDC plant. Using mass and energy balance equations, Eq. (10) is used to determine the HRSG efficiency;

$$\eta_{HRSG} = \frac{\text{Energy given to steam}}{(\text{gas flow} \times \text{inlet enthalpy}) + \text{fuel input on LHV basis}} \quad (10)$$

Eq. (10) is simplified as;

$$\eta_{HRSG} = \frac{\dot{m}_{steam}\left(h_{steam} - h_{w@Tw1}\right)}{\left(\dot{m}_{\text{exhaust gas}} Cp_g\left(T_{g1} - T_{g3}\right)\right) + \left(\dot{m}_{fuel} \times LHV\right)} \quad (11)$$

where m_{fuel} is the mass flow rate of fuel and LHV I the Low heating Value of the GT fuel.

In this study, the efficiency of HRSG, the temperature of exhaust gas leaving HRSG and mass flow rate of steam are determined by varying the value of PP and AP. The results are used to determine the value of PP and AP that generate the maximum steam rate, the lowest temperature of exhaust heat leaving HRSG and the highest efficiency of HRSG.

3.5 LCA Procedure

Based on the ISO 14040 and 14044, there are four basic structures to standardize the LCA which are starting with goal and scope, life cycle inventory, life cycle impact and lastly, interpretation [4]. The details of the LCA procedures are:

- Goal and scope – the goal and scope of the project is to develop LCA model for assessment of CO_2 saves by HRSG during operation phase and also to evaluate the CO_2 saves through the operation of HRSG.
- Life cycle inventory – by utilizing the HRSG data obtain from UTP GDC in order to keep track of the HRSG during its operation phase.
- Life cycle impact – evaluating the saving of CO_2 of the HRSG with the developed LCA model.
- Interpretation – provide the results of the evaluation of the CO_2 saves and recommendation of reducing the environmental impact of the HRSG.

3.6 LCA model

For this project, the LCA model was built based on the gas and steam temperature profile of an HRSG. The LCA boundary of the model was set to be only the HRSG so that the only data that will be used is the waste heat taken from gas turbine and the steam generated by the HRSG. The first thing needed in the model was the inlet temperature of the HRSG. This data can only be obtained from the UTP-GDC plant personnel. Then, the gas temperature leaving the evaporator was needed to be calculated. The water temperature leaving the evaporator was also needed to be calculated. Both data was needed to calculate the pinch point (PP) and approach point (AP) of the HRSG. In order to get the amount of steam generated, the enthalpy absorbed by steam in evaporator was also needed to be calculated and then it can be divided by evaporator duty to get the steam generated. This model can also determine the economizer duty and gas temperature drops, hence it can calculate the gas temperature leaving the economizer. The steam generated was converted to electricity generated. Due to the lack of data on way to convert the steam generated into carbon dioxide equivalent, the steam generated was converted to electricity generated (kW) and then it was converted into carbon dioxide equivalent.

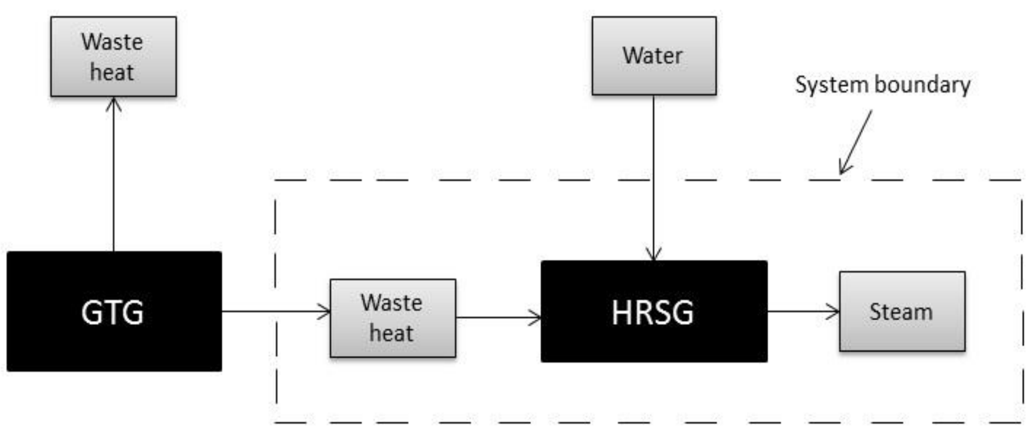

Figure 3.5: LCA boundary of the HRSG

Figure 3.6 shows the LCA model that has been developed using the gas and steam temperature profile of an HRSG. The saturated temperature of the HRSG will be constant. The only variable for this model was the inlet temperature of the HRSG and the temperature of gas coming out from the HRSG. Based on the HRSG formula, the steam generated from the HRSG can be calculated using this model.

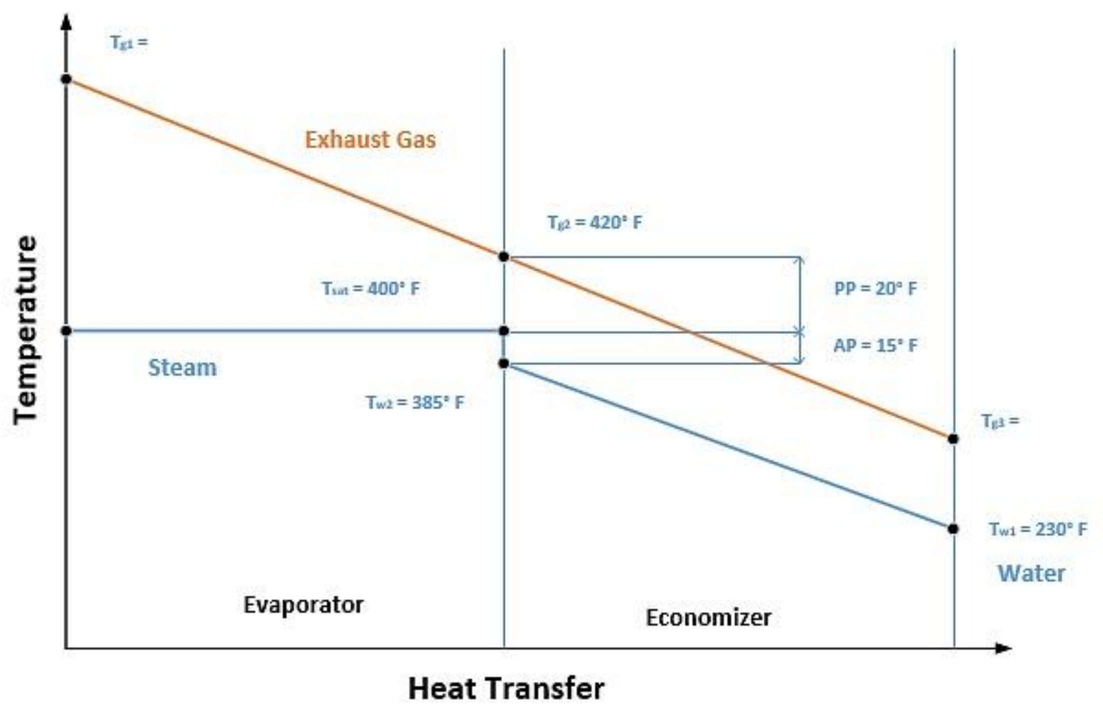

Figure 3.6: LCA model of the HRSG

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Energy Usage

The first step taken was by preparing a material inventory for the life cycle of the HRSG and also established a material balanced. Next step was to assume the main energy that was being used for extraction of raw materials and production of the HRSG in the material inventory by following the requirements of the energy. Followed by, estimating the energy used for disposal and recycle of the materials. Life cycle energy used was estimated by using the total energy of the full life cycle of the HRSG. Next, calculate the energy used per functional unit from the total steam generation and energy used during operational phase of the HRSG.

Table 4.1: Material use in the HRSG [18, 19, 20]

Materials inflow	**Quantity (in ton)**
Construction phase	
Steel [19]	1,250
Iron [18]	15.5
Aluminium [18]	10.5
Concrete [19]	3,750
Water [20]	7,500
Operational phase	
Exhaust gas	950°F (~30%-60%)
Saturated steam	103,335 lbs/month

Because of the difficulties in obtaining primary data, most of the data was done by estimation. Based on the past studies, a material inventory during construction phase was established. Raw materials in bulk usage were being considered for example like steel, iron and concrete. Even though there are some materials for example like glass was being used in the construction phase, there was hardly any data found from this such material due to lack of access to the industry. However, from earlier sensitivity analysis studies, it was found that the energy use and emission was hardly comes from the construction phase of the HRSG compared to the emissions and energy use during the operational phase. During operational phase, the accumulated steam generation for the whole 25 years of the HRSG life time was projected based on the net efficiency of the equipment. During the disposal and recycle phase, there would only be material out flow. Since, the material will be recovered through recycling.

Table 4.2: Life cycle energy use in the HRSG

Life cycle phases	**Energy use (MJ_t/kW_e)**	**Percentage (%)**
Construction phase	0.015	0.13
Operational phase	11.676	99.67
Disposal & recycle phase	-0.001	-0.01

The energy used in every life cycle was estimated by using the empirical relations X.1, X.2 and X.3 (in Appendix 1). To estimate the energy used in extraction and exploration, the specific energy consumption of the equipment was used [20]. It was assumed that 30% of the energy used for material extraction was the energy requirement to manufacture and assemble plant equipment [23]. The energy used for construction of the equipment was estimated to be 10% of the energy used for manufacturing and material production.

Operational phase is known as the material and energy extensive phase [12]. The energy used during operational phase was estimated using Eq. X.2 (see Appendix 1).

Based on Table 4.2, it is clear that the energy used in other phases can be ignored except operational phase. It is because the other phases do not use much energy and therefore, the carbon dioxide emission is not significant.

4.2 Theoretical Carbon Dioxide Emission

Based on the data obtained from UTP GDC plant, the saturated temperature of the heat recovery steam generator was $400°F$. The pinch point, PP and approach point, AP was assumed based on Table 4.1 given below based on the type of evaporator.

Table 4.3: Suggested pinch and approach point

Suggested pinch and approach point:			
	Pinch Point, $°F$		Approach Point, $°F$
Inlet Gas Temperature, $°F$	Evaporator type		
	Bare	Finned	
1200-1800	130-150	30-60	40-70
700-1200	80-130	10-30	10-40

i) Determine the pinch point (PP) and approach point (AP),

Given that $PP = 20°F$ and $AP = 15°F$ (obtained from manual selection where ranges of PP and AP are 15°F-30°F) therefore,

- Gas temperature leaving evaporator, T_{g2}

$$T_{g2} = T_{sat} + PP = 400°F + 20°F = 420°F$$

- Water temperature leaving evaporator, T_{w2}

$$T_{w2} = T_{sat} - AP = 400°F - 15°F = 38°F$$

ii) Determine the evaporator duty,

$$Evaporator\ Duty = 151{,}400 \frac{lbs}{hr} \times (1 - 0.01) \times 0.270 \times (950°F - 420°F)$$

$$= 21.45M \frac{Btu}{hr}$$

iii) Determine enthalpy absorbed by steam in evaporator,

$$entalphy\ absorbed\ by\ steam\ in\ evaporator$$

$$= h_s - h_{w@Tw2(fluid)} + bl \times \left(h_{w@Tw2(vapour)} - h_{w@Tw2(fluid)}\right) \ldots (1)$$

where:

h_s = *enthalpy of steam at* T_{sat}*

$h_{w@Tw2\,(fluid)}$ = *enthalpy of saturated water entering evaporator,* $h_f@T_{w2}$*

$h_{w@Tw2\,(vapour)}$ = *enthalpy of saturated water in vapour state,* $h_f@T_{sat}$*

bl = *blowdown factor*

**(Values can be obtained from Table A-4E Saturated Water – Temperature Table)*

$$entalphy\ absorbed\ by\ steam\ in\ evaporator$$
$$= 1201.4\frac{Btu}{lbs} - 353.53\frac{Btu}{lbs} + 0.05 \times \left(375.04\frac{Btu}{lbs} - 353.53\frac{Btu}{lbs}\right)$$
$$= 848.95\ Btu/lb$$

iv) Determine the steam generated per hour, $\dot{m}_{steam}$,

$$steam\ generated = \frac{evaporator\ duty}{entalphy\ absorbed\ by\ steam\ in\ evaporator} \ldots (2)$$

$$steam\ generated = \frac{21.45M\ \frac{Btu}{hr}}{848.95\ \frac{Btu}{lbs}} = 25{,}267\ \frac{lbs}{hr}$$

v) Determine the steam generated daily,

The steam generated is then being calculated for daily generation;

$$steam\ generated\ (24hours) = 25{,}267\frac{lbs}{hr} \times 24hr = 606{,}408\frac{lbs}{day}$$

vi) Determine the steam generated for a month;

The steam generated is then being calculated for production in a month;

$$steam\ generated\ (24hours) = 25{,}267\ \frac{lbs}{hr} \times 24\ hr = 606{,}408\ \frac{lbs}{day}$$

$$steam\ generated\ (30days) = 606{,}408\ \frac{lbs}{day} \times 30\ days = 18{,}194{,}240\ \frac{lbs}{mth}$$

vii) Determine the steam generated in a year;

The steam generated for a year;

$$steam\ generated\ (12months) = 18{,}194{,}240\ \frac{lbs}{mth} \times 12\ mths = 218{,}330{,}880\frac{lbs}{yr}$$

viii) Determine the steam generated for 10 years;

The amount of steam generated for 10 years;

$$steam\ generated\ (10years) = 218{,}330{,}880\ \frac{lb}{yr} \times 10\ yrs = 2{,}183{,}308{,}800\ lbs$$

ix) Determine the steam generated for 25 years;

The amount of steam generated in 25 years;

$$steam\ generated\ (25years) = 218{,}330{,}880\ \frac{lb}{yr} \times 25\ yrs$$
$$= 5{,}458{,}272{,}000\ lbs\ (2475830532.58\ \ kg)$$

x) Convert the steam generated to kWh;

The amount of steam generated in hour converted to kWh;

$$electric\ power\ produced\ per\ hour = 5{,}458{,}272{,}000\ lbs \times 0.305$$
$$= 166{,}477{,}296\ kW$$

xi) Convert the electricity generated to carbon dioxide emission;

The amount of carbon dioxide emission;

$$carbon\ dioxide\ emission = 166{,}477{,}296\ kW \times 0.41205$$
$$= 68{,}596{,}969.82\ kg\ CO_2e$$

Based on the calculation, if the HRSG consumed the maximum exhaust gas temperature which was 950ºF from the gas turbine, it will save up to 68,596,969.82 kg of CO_2e. If this amount of carbon dioxide was saved from release to the surroundings, it will reduce the effect of global warming.

4.3 UTP GDC Plant Data Analysis

Assumptions for absorption system (HRSG and SAC system) are listed as below:

- Temperature of the steam coming out from the HRSG was constant at 400°F.
- The total steam generated by HRSG was taken as energy input to SAC.

Table 4.4: Operating parameters of UTP-GDC plant GTG

Components	Operating Parameters	Value
Gas Turbine Generator (GTG)	$\dot{m}_{fuel}$	0.26 kg/s
	LHV	41000 kJ/kg.K
	Capacity	8.4 MW (4.2 MW each)
	Isentropic Efficiencies	0.89-0.91
	Compression Ratio	11.7
	$T_{exhaust\ gas}$	950°F

Figure 4.1 shows the data of inlet temperature obtained from UTP-GDC plant. Based on the graph below, there was some inconsistency on the trend of the data collected. Generally, the inlet temperature taken to calculate the steam generated using the LCA model is ranging from 420°F to 570°F. This is because when the inlet temperature was below 420°F the resultant steam generated will be negative, and it can be assumed that the HRSG was not supplying the steam because the steam header was already full.

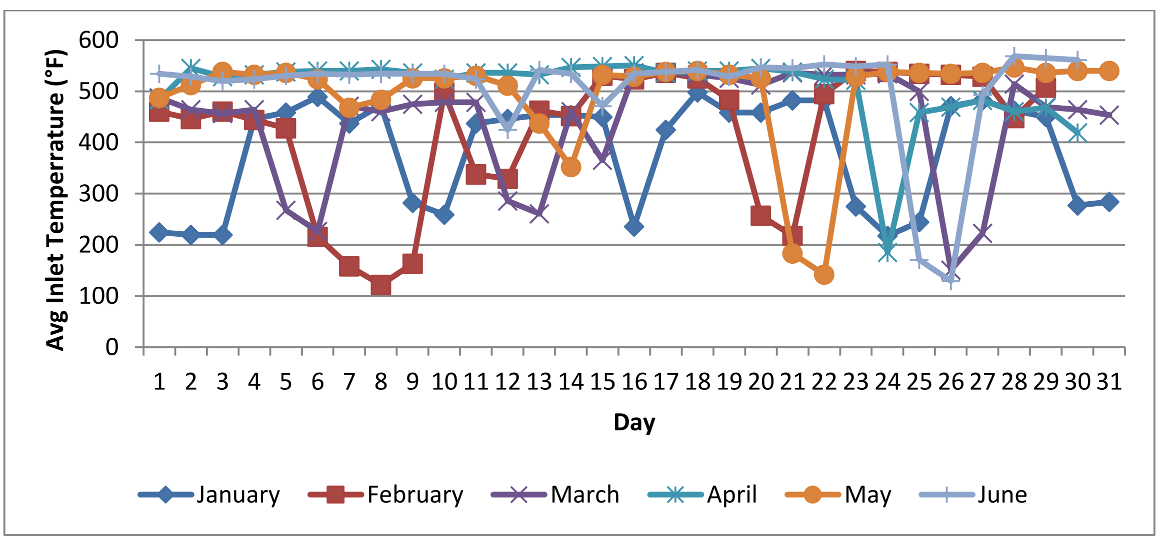

Figure 4.1: Average inlet temperature of the HRSG

4.3.1 Steam generated

Based on the inlet temperature data, the steam generated of the HRSG can be calculated using the HRSG formula based on the gas and steam temperature profile. As shown in Table 4.5 and Figure 4.2, the steam generated by the HRSG was varying from January to June 2016. This is because the demand for steam from SAC is different from month to month.

Table 4.5: Total steam generated per month by HRSG

Month	Total steam generated per month(lbs)	Electricity generated per month(kW)
January	106,834.33	32,584.47
February	110,766.26	33,783.71
March	109,583.41	33,422.94
April	110,544.02	33,715.92
May	107,121.93	32,672.19
June	108,350.74	33,046.96

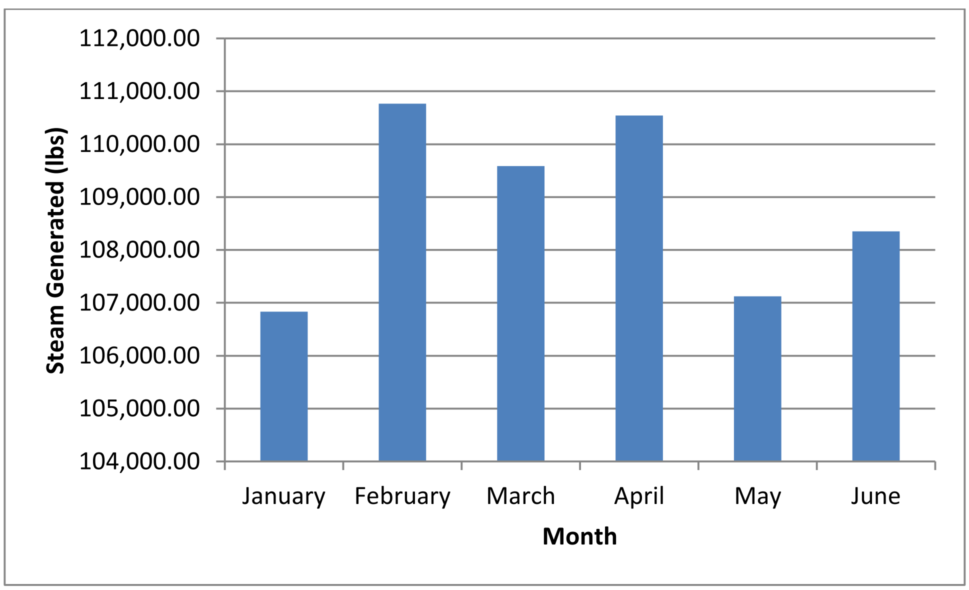

Figure 4.2: Steam generated by HRSG monthly

Since the steam generated by the HRSG cannot be used to calculate the carbon dioxide saved by the HRSG, a different approach needed to be done in order to get the amount of carbon dioxide saved by the HRSG. The steam generated by the HRSG was converted to electricity generated (kWh). This is because electricity generated can be converted into carbon dioxide. Assume that the steam generated was being used to produce electricity just like gas turbine produce electricity. The total steam generated per month was then converted to total electricity generated per month. The conversion was equivalent to 1 steam lbs/hr = 0.305kW [24].

4.3.2 Carbon dioxide emission

The result from electricity generation can be used to measure the carbon dioxide saved by the HRSG. The conversion data was equivalent to 1 kWh = 0.41205 kg CO_2e [24]. Table 4.7 shows the amount of carbon dioxide saved by the HRSG. The actual amount of carbon dioxide saved by the HRSG was far less compared to the theoretical amount of carbon dioxide saves by the HRSG. However, the actual amount of carbon dioxide saved by HRSG was still significant because even though it only takes up to 60% of the waste heat from gas turbine, it still helped to reduce the carbon dioxide emission by the gas turbine to the surroundings.

Table 4.6: Total carbon dioxide emission by HRSG per month

Month	**Electricity generated per month(kW)**	**Total carbon dioxide emission per month (kg CO_2e)**
January	32,584.47	13,426.43
February	33,783.71	13,920.57
March	33,422.94	13,771.92
April	33,715.92	13,892.65
May	32,672.19	13,462.56
June	33,046.96	13,616.99

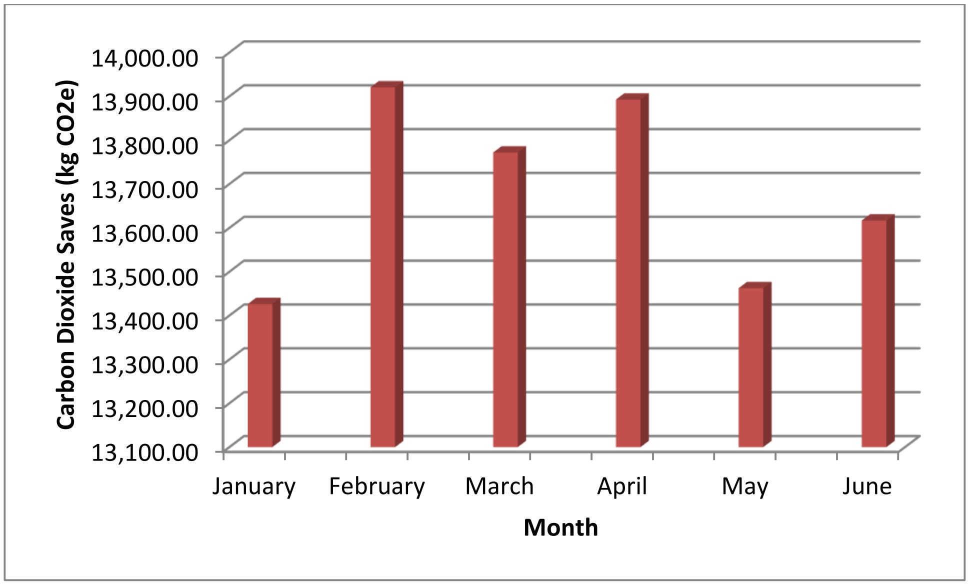

Figure 4.3: Carbon dioxide emission by HRSG monthly

The amount of carbon dioxide saved by the HRSG based on the data from UTP GDC plant can be projected to the amount of carbon dioxide saves by the HRSG for 25 years. This data then can be compared with the theoretical amount of carbon dioxide saves by the HRSG and the different can be seen.

The amount of carbon dioxide saved by the HRSG for January to June 2016 was total up to 82,091.13 kg of CO_2e. Hence the amount of carbon dioxide saved by the HRSG for one year was around 164,182.24 kg CO_2e. The expected number of carbon dioxide saved for 25 years is estimated to be 4,104,556 kg CO_2e.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As the conclusion of the project, life cycle assessment of heat recovery steam generator project met the objectives namely to develop the life cycle assessment model of the HRSG and also to evaluate the saving of carbon dioxide emission by the HRSG. Life cycle assessment procedure is adopted by defining the goal and scope of the project clearly, utilizing the correct life cycle inventory, assessing the life cycle impact and also interpreting the project results in the first half. The life cycle model was evaluated from extraction of raw materials, producing the HRSG, operational of the HRSG and the disposal and recycle of the material. Unfortunately, much of the information regarding the extraction and producing the HRSG was not available. Even though the information was not available, it is still acceptable to continue on the project since the most important result was from the operational phase of the HRSG which uses the energy by 99.67% during its life cycle, whereas the other life cycle which is construction and decommission phase only made up 0.13% and -0.01% respectively.

The theoretical amount of carbon dioxide saved by the HRSG was 68,596,969.82 kg of CO2e, while the actual amount of carbon dioxide saved by the HRSG is 4,104,556 kg CO2e. Even though the comparison was different but the amount of carbon dioxide saved by the HRSG with the actual data is still significant in reducing the amount of CO_2emission to the surroundings. This shows that the usage of HRSG in the plant not only increase the overall plant efficiency but it also helps to reduce the CO_2 emission by the gas turbine to the surroundings.

As for the recommendation, it is highly recommended that the project to be continued by using life cycle cost analysis tool which can estimate the cost of steam generation by the HRSG. Cost is an important factor to be considered in making the decision [11]. Besides that, the project should be continued by quantifying the emission of other GHG such as CH_4 and N_2O. The project should be done for the whole UTP-GDC plant so that all the equipment involved in the plant can be analyzed and GHG emission of the whole plant can be quantified.

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APPENDIX

Appendix A. The formula of life cycle energy use

(X.1)

$$Energy_{construction} = Energy\ (C) + \sum_{i=1}^{n} Energy\ (E - E) + \sum_{i=1}^{n} Energy\ (P - M)$$

(X.2)

$$Energy_{operation} = Energy\ (O) + \sum_{i=1}^{n} Energy\ (E - E) + \sum_{i=1}^{n} Energy\ (P - M) + \sum_{i=1}^{n} Eenrgy\ (F)$$

(X.3)

$$Energy_{decommisioning} = Energy\ (D - D) + \sum_{i=1}^{n} Energy\ (R_{cycle}) - \sum_{i=1}^{n} Energy\ (R_{use})$$

Energy (C) = Energy use during construction phase

Energy (D-D) = Energy using during decommissioning-disposal phase

Energy (E-E) = Energy use during exploration and extraction of the *i*th material

Energy (F) = Fuel energy of embedded energy in the *i*th material

Energy (O) = Energy use during operational phase

Energy (P-M) = Energy use for processing and manufacturing of the *i*th material

Energy (R_{cycle}) = Energy use during recycling of the *i*th materials

Energy (R_{use}) = Energy store to be reused of the *i*th material

Energy (T) = Energy consumed during transportation

Appendix B. Example of HRSG data from UTP-GDC plant (JUNE 2016)

UNIVERSITI TEKNOLOGI PETRONAS DCS/COGEN PLANT

MONTHLY B-0303A /GTG A REPORT

GAS DISTRICT COOLING (UTP)

DATE:	Jun-16	TEMP.	31.4	DEGC	MAX	MIN
					38.3	26.6
		HUMD.	*****	RH%	*****	*****

EFF = STEAM (KG) X (0.2189 - 0.0297) X 100 / [GAS (NM3) X 2.9853] + [OIL (KG) X 3.3594 X 0.8438]

DAY	PI-0303A2		TI-0303A3	FQI-0303A2	GTGA-GFUELFLO	GTGA-LFUELFLO	GTGA-POWERKW	FQI-0303A1	FQI-0303A1		EFFICIENCY		
	PV		PV	SUM	SUM	SUM	SUM	PV	SUM				
	HRSG DRUM PRESS		GTE GAS TEMP. HRSG INLET	FEEDWATER FLOW	GAS FUEL FLOW	LIQUID FUEL FLOW	POWER INKW TOTAL	MAIN STEAM FLOW	MAIN STEAM FLOW		GEN ELECT.	HEAT RECOVERY	TOTAL
	BAR		DEGC	T	NM3	KG	x	T/H	T		%	%	%
1	8.86		279	106.08	28276	0	84357	3.96	95.24		99.9329	21.3457	121.2786
2	7.74		276	98.17	28230	0	83632	3.73	89.48		99.2356	20.0882	119.3239
3	7.47		271	85.38	26471	0	72338	3.15	75.61		91.5413	18.1025	109.6438
4	7.09		273	87.74	27300	0	76883	3.33	79.92		94.3365	18.5527	112.8893
5	7.12		277	123.52	27784	0	79353	5.16	123.84		95.6705	28.2477	123.9181
6	7.61		279	96.01	28491	0	82665	3.60	86.35		97.1895	19.2084	116.3979
7	7.68		278	92.73	28681	0	84254	3.53	84.70		98.4036	18.7160	117.1195
8	7.71		279	91.63	28487	0	84366	3.42	82.13		99.2043	18.2725	117.4768
9	7.73		279	97.64	28273	0	83258	3.70	88.86		98.6421	19.9180	118.5600
10	7.70		279	101.06	28303	0	83105	3.77	90.48		98.3579	20.2601	118.6181
11	7.48		273	91.59	27689	0	79872	3.48	83.50		96.6273	19.1124	115.7397
12	5.37		218	38.42	26253	0	72283	1.39	33.49		92.2278	8.0848	100.3125

13	7.82		283	96.22	28252	0	82905	3.64	87.39		98.2967	19.6030	117.8997
14	7.84		279	94.64	28738	0	85366	3.58	85.96		99.5038	18.9571	118.4609
15	7.00		244	68.18	25802	0	75545	2.64	60.67		98.0774	14.9027	112.9801
16	7.38		279	90.63	29041	0	87101	3.36	80.59		100.4677	17.5883	118.0560
17	7.76		281	86.49	27395	0	80507	3.23	77.70		98.4403	17.9753	116.4155
18	7.27		283	117.46	28089	0	82256	4.73	113.51		98.0950	25.6105	123.7056
19	7.33		276	116.33	27838	0	81019	4.53	108.77		97.4889	24.7633	122.2522
20	7.24		286	107.81	27159	0	77965	4.15	99.65		96.1613	23.2533	119.4146
21	7.73		285	80.27	27309	0	78590	3.09	74.10		96.3996	17.1975	113.5971
22	7.66		289	100.43	28055	0	83422	3.87	92.96		99.6049	20.9997	120.6046
23	7.78		287	91.10	27712	0	80963	3.39	81.43		97.8641	18.6236	116.4878
24	8.20		289	95.91	27455	0	79194	3.54	85.03		96.6237	19.6284	116.2520
25	1.22		77	1.97	356	0	444	-0.01	0.00		41.7737	N.A.	41.7737
26	0.43		54	0.03	469	0	0	-0.01	0.00		N.A.	N.A.	0.0000
27	6.39		256	108.39	21076	0	61640	4.09	98.15		97.9667	29.5126	127.4793
28	8.31		298	114.22	28293	0	83305	4.36	104.41		98.6296	23.3881	122.0178
29	8.36		296	101.45	28751	0	83641	3.76	90.33		97.4475	19.9111	117.3586
30	8.34		294	87.00	25829	0	75598	3.60	78.51		98.0440	19.2635	117.3075
31											N.A.	N.A.	0.0000
AVG	7.12		263	88.95	25729	0	74861	3.39	81.09		95.6	20.0	115.6
TOT				2668.51	771859	0	2245826		2432.73				
MAX	8.86		298	123.52	29041	0	87101	5.16	123.84		100.47	29.51	129.98
MIN	0.43		54	0.03	356	0	0	-0.01	0.00		41.77	8.08	49.86

Appendix C. Example of HRSG model data fo January 2016

January Data									
Day	Avg Inlet Temp, Tg1 (°F	Gas temp leaving evaporator, Tg2 (	Water temperature leaving evaporator, Tw2 (°	Evaporator Duty (Btu/hr	Enthalphy absorbed by steam in evaporator (Btu/lb	Steam generated (lbs/hr	Economizer duty (Btu/hr	Gas temperature drop (°F	Gas temperature leaving economizer, Tg3 (°F)
1-Jan	224.6	420	385	-7907685.588	849.074	-9313.30554	-1517305.112	-35.05486791	455.0548679
2-Jan	219.2	420	385	-8126219.376	849.074	-9570.684506	-1559236.778	-36.0236309	456.0236309
3-Jan	219.2	420	385	-8126219.376	849.074	-9570.684506	-1559236.778	-36.0236309	456.0236309
4-Jan	446	420	385	1052199.72	849.074	1239.232058	201893.2083	4.664414359	415.3355856
5-Jan	458.6	420	385	1562111.892	849.074	1839.782978	299733.7632	6.924861318	413.0751387
6-Jan	489.2	420	385	2800470.024	849.074	3298.263784	537346.5391	12.41451822	407.5854818
7-Jan	437	420	385	687976.74	849.074	810.2671145	132007.0978	3.049809389	416.9501906
8-Jan	473	420	385	2144868.66	849.074	2526.126886	411551.5401	9.50822927	410.4917707
9-Jan	282.2	420	385	-5576658.516	849.074	-6567.929905	-1070034.004	-24.7213961	444.7213961
10-Jan	258.8	420	385	-6523638.264	849.074	-7683.238757	-1251737.892	-28.91936903	448.919369
11-Jan	437	420	385	687976.74	849.074	810.2671145	132007.0978	3.049809389	416.9501906
12-Jan	446	420	385	1052199.72	849.074	1239.232058	201893.2083	4.664414359	415.3355856
13-Jan	453.2	420	385	1343578.104	849.074	1582.404012	257802.0968	5.956098335	414.0439017
14-Jan	453.2	420	385	1343578.104	849.074	1582.404012	257802.0968	5.956098335	414.0439017
15-Jan	449.6	420	385	1197888.912	849.074	1410.818035	229847.6526	5.310256347	414.6897437
16-Jan	235.4	420	385	-7470618.012	849.074	-8798.547608	-1433441.779	-33.11734195	453.1173419
17-Jan	424.4	420	385	178064.568	849.074	209.7161943	34166.54295	0.78936243	419.2106376
18-Jan	498.2	420	385	3164693.004	849.074	3727.228727	607232.6497	14.02912319	405.9708768
19-Jan	458.6	420	385	1562111.892	849.074	1839.782978	299733.7632	6.924861318	413.0751387
20-Jan	458.6	420	385	1562111.892	849.074	1839.782978	299733.7632	6.924861318	413.0751387
21-Jan	482	420	385	2509091.64	849.074	2955.091829	481437.6507	11.12283424	408.8771658
22-Jan	482	420	385	2509091.64	849.074	2955.091829	481437.6507	11.12283424	408.8771658
23-Jan	275	420	385	-5868036.9	849.074	-6911.101859	-1125942.893	-26.01308008	446.0130801
24-Jan	217.4	420	385	-8199063.972	849.074	-9656.477494	-1573214	-36.34655189	456.3465519
25-Jan	244.4	420	385	-7106395.032	849.074	-8369.582665	-1363555.669	-31.50273698	451.502737
26-Jan	471.2	420	385	2072024.064	849.074	2440.333898	397574.318	9.185308276	410.8146917
27-Jan	482	420	385	2509091.64	849.074	2955.091829	481437.6507	11.12283424	408.8771658
28-Jan	462.2	420	385	1707801.084	849.074	2011.368955	327688.2074	7.570703306	412.4292967
29-Jan	449.6	420	385	1197888.912	849.074	1410.818035	229847.6526	5.310256347	414.6897437
30-Jan	276.8	420	385	-5795192.304	849.074	-6825.308871	-1111965.671	-25.69015909	445.6901591
31-Jan	284	420	385	-5503813.92	849.074	-6482.136916	-1056056.782	-24.39847511	444.3984751