Life Cycle Assessment of Thermal Storage System

by

Ahmad Hazwan bin Ahmad Hariri

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

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Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
DECEMBER 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own work except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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AHMAD HAZWAN BIN AHMAD HARIRI

ABSTRACT

The main equipments of Thermal Storage System are Steam Absorption Chiller (SAC), Electric Chiller (EC) and Thermal Energy Storage (TES) Tank. Manufacturing and disposal process of these equipments may cause some effects to the environment, either directly or indirectly. Life Cycle Assessment (LCA) was normally done to assess these effects. This study was done by referring to the Thermal Storage System of Universiti Teknologi PETRONAS Gas District Cooling Plant (UTP GDC).

The assessment was conducted based on the technical LCA framework standardized by International Organization for Standardization (ISO). Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) were conducted using openLCA Framework software; an open source software for sustainability assessment. The software was used to calculate the environmental loads emitted by the whole process and then categorized them into specific environmental impacts.

The environmental impact for this assessment was categorized to five categories, namely; Global Warming Potential, Stratospheric Ozone Depletion Potential, Acidification Potential, Human Toxicity Potential and Eutrophication Potential. Each of these impacts has its own characterization factor which consists of specific substances. Manufacturing process of SAC, EC and TES Tank contributed to the emission of 7.148×10^9 kg CO_2 equivalent, 1.827×10^{-3} kg CFC-11 equivalent, 2.024×10^5 kg SO_2 equivalent, 2.036×10^5 kg 1,4-dicholorobenzene equivalent and 7.203×10^3 kg PO_4^{3-} equivalent. Therefore, it is important that the manufacturing and disposal processes of the thermal storage system equipments to be monitored closely in order to reduce the environmental impact.

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LIST OF ABBREVIATIONS

CML	Center of Environmental Science, Leiden University (CML)
EC	Electric Chiller
ELCD	European Reference Life Cycle Data System
GDC	Gas District Cooling
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NREL	National Renewable Energy Laboratory
SAC	Steam Absorption Chiller
SETAC	Society of Environmental Toxicology
TES	Thermal Energy Storage
UTP	Universiti Teknologi PETRONAS

CHAPTER 1

INTRODUCTION

1.1 Project Background

As environmental awareness has grown throughout the world, customers are more willing to pay higher price for “green” products. Companies with improving products will gain advantages of being the leaders in the marketplace. Through early introduction, a product could have a marketplace advantage by gaining earlier customers who will then develop loyalty (Cattanacth et al, 1995).

One of the products that are usually used in industry is thermal storage system. Thermal storage system is merely used to store thermal energy either in form of high temperature or low temperature. In direct cooling system, thermal storage system reduces emissions, increases efficiency, saves energy, and reduces refrigerant inventories. It helps to maintain ices thus reducing the usage of electricity. However, in relation to the environmental issue, there is always one question to be answered: is the system safe to environment? The implementation of thermal storage system requires a lot of processes and energy consumption. Therefore, it is crucial to assess the environmental impacts associated to the system.

The environmental impacts associated to thermal storage system requires an assessment of the emission released and the consumption of materials and energy during its entire life cycle. Life Cycle Assessment (LCA) is an effective tool to evaluate the environmental effect associated with product life cycle by identifying and quantifying energy and materials used and wastes released to the environment (Chai Hoon, 2006). The assessment covers the entire life cycle of the product including the raw material acquisition, manufacturing, transportation, installation, performance, and disposal or re-use. Each cycle may have different level of energy intensiveness and the material’s toxicity. Throughout Life Cycle Assessment, researcher can identify process that can cause environmental impacts and take appropriate action to solve the problem.

1.2 Problem Statement

Over the past 20 years, environmental issues have gained greater public recognition. Production, usage and disposal of all goods virtually present potential value of health and environmental impacts. Development of thermal storage system has given a large impact in improving the efficiency of energy conservation. Thermal Storage System is an important system that distributes chilled water to the buildings in UTP. The system consists of three main equipments which are Steam Absorption Chiller, Electric Chiller, and Thermal Energy Storage Tank. The main materials used for the manufacturing of these equipments are stainless steel, carbon steel, copper and mineral wool. The manufacturing and disposal process of these equipments may have impact to the environment. Therefore, Life Cycle Assessment of Thermal Storage System could provide further information of environmental impacts associated to the manufacturing process of the equipment.

1.3 Objective

To undertake Life Cycle Assessment for the thermal storage system at Universiti Teknologi PETRONAS Gas District Cooling Plant.

1.4 Scope of Study

This study concentrates on three main equipments of Thermal Storage System. They are Steam Absorption Chiller (SAC), Electric Chiller (EC), and Thermal Energy Storage (TES) Tank. Main components for SAC and EC are evaporator, condenser, high temperature generator, low temperature generator and absorber while the main components for TES Tank are storage tank and diffuser. The LCA is conducted from the raw material acquisition, manufacturing and disposal stage.

CHAPTER 2

LITERATURE REVIEW

2.1 Life Cycle Assessment

Life Cycle Assessment is the assessment of product's environmental impacts (Buczynski, 2009). Nowadays, LCA has found official recognition in international standards as it has been introduced to ISO (International Standard Organization) normative. Based on ISO 14040 (1997), LCA is defined as a technique which estimates the environmental aspects and potential long term impacts of the world life cycle of products or services, namely (Vezzoli & Manzini, 2008):

- Compiling and inventorying the implications of the system's input and outputs
- Evaluation of the potential impacts regarding these inputs and outputs
- Interpreting the results of inventory and evaluation phases according to given scope and objectives

Main concern of LCA is the consideration of ecological impacts of the examined system, which is related to the environmental impacts, human health and depletion of natural resources. However, LCA does not concern with economic and social character. Take note that LCA works with models, which means a simplification of the real product and does not pretend to handle environmental interactions in an absolute manner.

2.1.1 Product Life Cycle

According to Society of Environmental Toxicology (SETAC), life cycle of product is defined as consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal. The life cycle stages of product are defined by SETAC (1991) as follows (Giudice et al, 2006):

- *Raw Material Acquisition*
  All necessary processes required to obtain material and energy resources from environment.

- *Processing and Manufacturing*
  All activities and processes needed to convert resources to the desired product.

- *Distribution*
  Activities involved in product distribution to customer. It includes transport and storage.

- *Use, Maintenance, Repair*
  It is related to the entire phase of product usage, including the service operation.

- *Recycle*
  Begins after the product has served its main function. This includes all the recycling options, which are within the same product system (closed loop) and enters a new product system (open loop).

- *Waste Management*
  Concern on the unrecyclable fraction of the product and consist of the final waste disposal.

The life stages and material flows of a product are illustrated in the **Figure 2.1**. Combination of all stages represent the whole cycle which is from cradle to grave. However, partial LCA can be possibly conducted by defining one or more levels. There are three partial LCA variants (Hundal, 2002):

- Cradle to Gate

  Analysis of the portion of life cycle upstream from the gate

- Gate to Grave

  Analysis of the portion of life cycle downstream from the gate

- Gate to Gate

  Analysis of the portion of life cycle between two gates

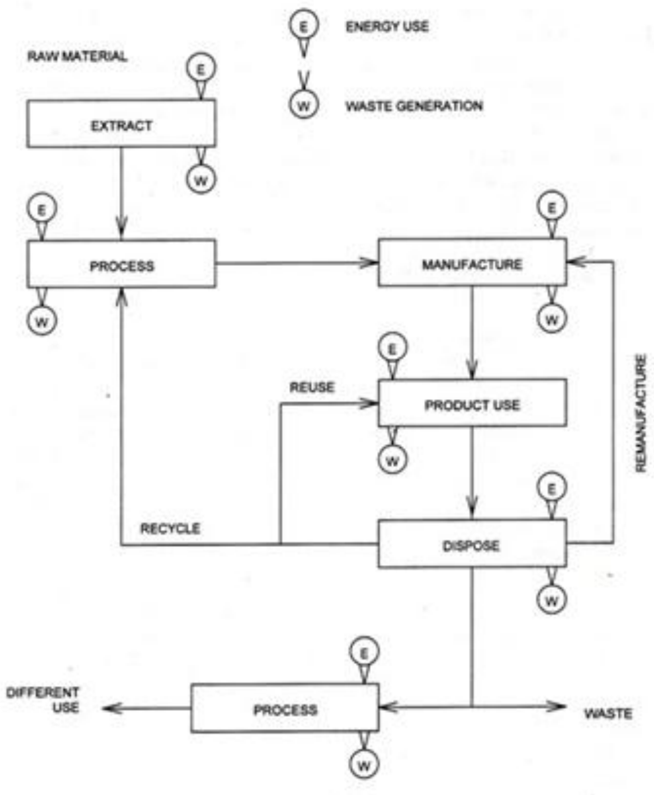

Figure 2.1: Product life stages and material flows (Hundal, 2002)

2.1.2 General LCA Framework

In 1990s, ISO has standardized the technical framework of Life Cycle Assessment methodology. According to ISO 14040 (1997), LCA methodology is divided into these phases (Masruroh et al, 2005). **Figure 2.2** shows phases of LCA:

- *Goal and Scope Definition*

  Obtain objective of the study as well as the required specification for the LCA study. This phase can be conducted by following these procedures:

  i. State the purpose of LCA study, following by the definition of functional unit, which describe the quantity references of the study.
  ii. Identification of the scope of study, which including two main tasks:
     - Definition of the spatial limit among the product system and environment.
     - Drawing system's process flowchart. The flowchart should includes the input and output from the system to environment
  iii. Identification of required data. This includes the specification of necessary data for the inventory analysis and for the subsequent impact assessment phase.

- *Inventory Analysis*

  Obtain all the necessary data of the unit processes within a product system and correlates them to the functional unit. This phase can be conducted by following these steps:

  i. Collect all necessary data including the specification of all input and output flow of the processes within the product system.
  ii. Create normalization of the functional unit. This step requires all the collected data to be quantitatively related to one quantitative output of the product system under study (e.g., choose 1 kg of material).
  iii. Make allocation. The step includes the distribution of emissions within a given process throughout its different products.

iv. Evaluation of data, involving the quality assessment of the data (e.g., sensitivity analysis)

- *Impact Assessment*

  This phase aims to create more understandable and more manageable result of the Inventory Analysis in relation to human health, the availability of the resource and the natural environment. The steps in this phase include:

  i. Definition of impact categories such as global warming, acidification, etc.
  ii. Classification; which involves correlating the results of Inventory Analysis to the relevant impact categories.
  iii. Characterization; which determines the value of environmental indicators relating to various impact categories. This step consists of converting the Inventory Analysis results into common unit and aggregating them in terms of adequate factors of different types of substances within the impact categories.

- *Interpretation*

  This phase focuses on evaluating the results obtained from Inventory Analysis or Impact Assessment. The results are compared to with the goal of the study defined during the first phase. This phase can be achieved by following these steps:

  i. Identification of the foremost result of the Inventory Analysis and Impact Assessment.
  ii. Evaluation of the study outcomes, consisting of completeness check, sensitivity analysis, uncertainty analysis and consistency check.
  iii. Make conclusions, recommendations and reports. This step consists of defining the final outcome, comparing with the original goal of the study, drawing up recommendation, formulate the critical review and do the final reporting of the results.

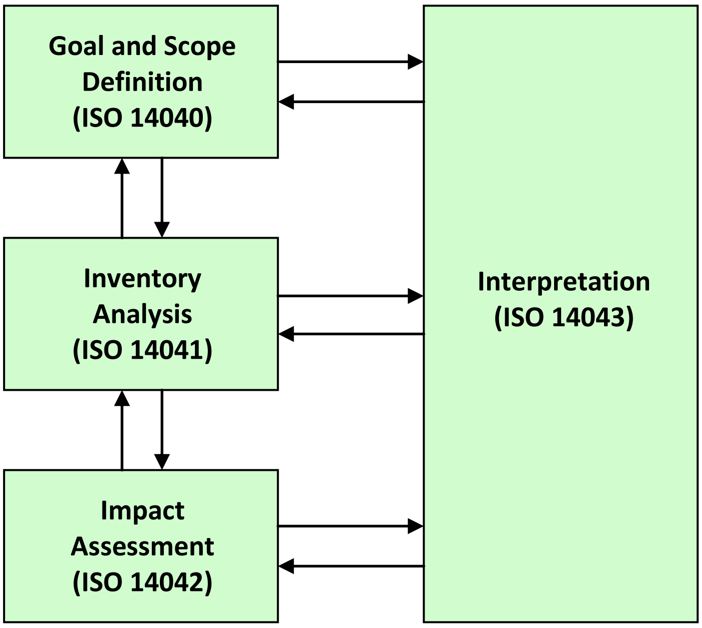

Figure 2.2: Phases of LCA based on ISO 14040 (1997)

The LCA is not necessarily conducted in single sequence. Basically, LCA is an iterative process in which subsequent round can attain increasing level of detail which is from partial LCA to full LCA. It is also possible that the first phase is lead to change prompted by the results of the last phase.

Steps of LCA are distributed along the ISO patterns. ISO 14040 is generally described the general framework of LCA while ISO 14041, ISO 14042 and ISO 14043 provide guidance for Inventory Analysis, Impact Assessment and Interpretation phase. The main heading of these standards and a summary of their specific contents is shown in **Appendix 2-1.**

2.1.3 LCA Examples

2.1.3.1 Life Cycle Analysis of a Solar Thermal System with Thermochemical Storage Process

Though solar energy is considered as environmental friendly as it manages to reduce the greenhouse effect, it also encounters with myriad problems in its process. This resulting in the development of a more economical and proficient solar thermal system called SOLARSTONE with the basic of a pair of salt-water endothermic or exothermic reactions. In order to ensure the system to work efficiently, LCA technique which is based on ISO 14040 (1997) is applied to the SOLARSTONE.

The objective is to discover the environmental significances and raw material consumption associated with the system as well as to test the earlier assumption and hypothesis saying that the system could create less impact to the nature (Masruroh et al, 2005). As the system is made up of two different major units, LCA study can possibly be conducted for both of them separately.

Since the SOLARSTONE system manages to store and release solar thermal energy without consuming any other resources, the use phase of the system is eliminated from LCA as long as it can cover the full energy requirement. However, having a backup boiler which is based on conventional energy production is a must in case the system might probably face insufficient energy to cover the system. To overcome the problem where the system is lack of data, the processes of installation and maintenance were excluded from the LCA technique. After losing the ability to store or release solar thermal energy, SOLARSTONE system should be thrown away while the reactive compounds and equipments should be recycled. **Figure 2.3** shows the raw materials that are used to construct SOLARSTORE system.

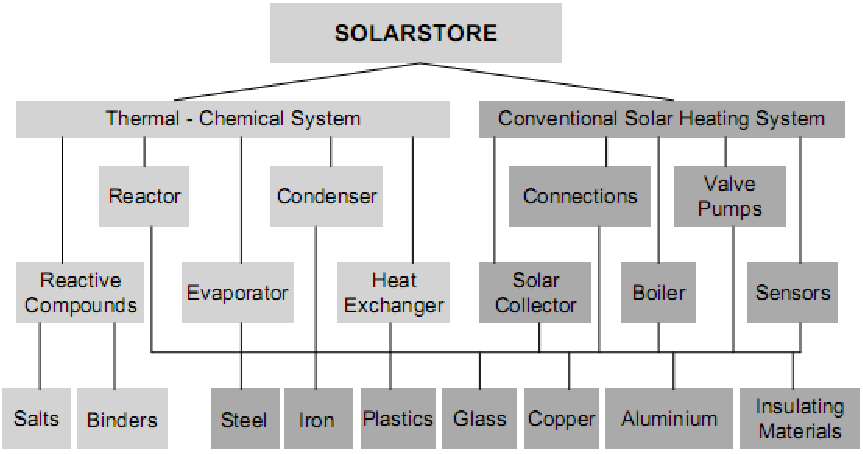

Figure 2.3: SOLARSTORE Raw Material Tracing (Masruroh et al, 2005)

Figure 2.4 shows the system boundary of this LCA study:

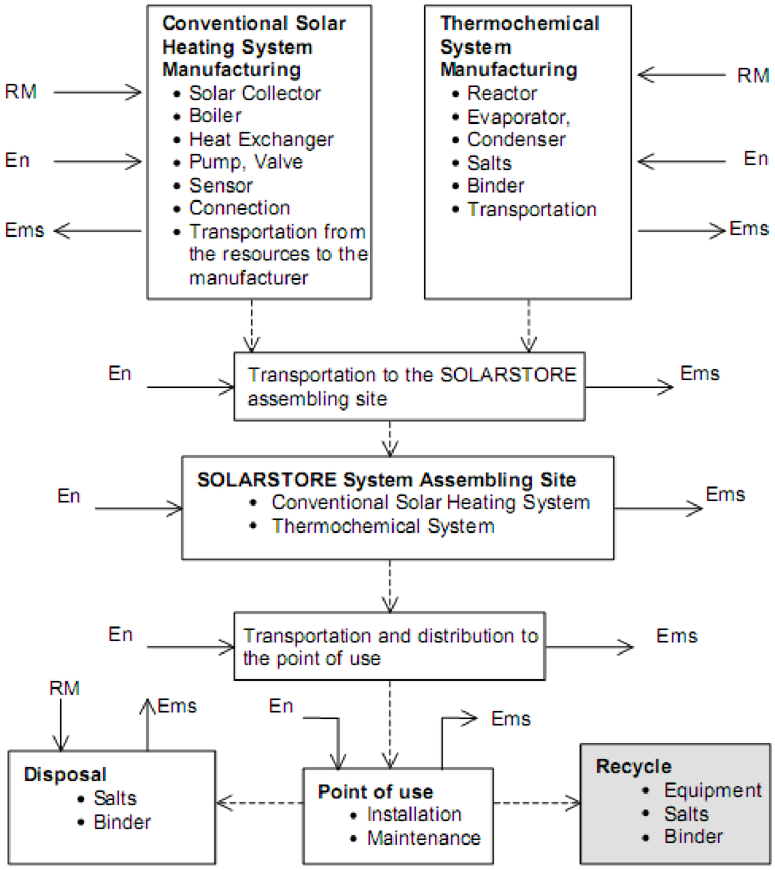

Figure 2.4: SOLARSTORE LCA Boundary (Masruroh et al, 2005)

Based on the technique used to test the system, it was found that the consequences of producing 1 GJ energy through SOLARSTORE are global warming potential of 6.3-10 kg CO_2, acidification potential of 46.6-70 g SO_2, eutrophication of 2.1-3.1 g phosphate and photochemical oxidant of 0.99-2.2 g C_2H_4 (Masruroh et al, 2005). The study reveals that during the whole life cycle, raw material acquisition and component manufacturing phase cover 99% of the emissions. Based on the overall view towards this technique, it can be clearly seen that SOLARSTONE system contributes a greater result in saving our environment compared to the traditional heating systems.

2.1.3.2 Life Cycle Assessment of Natural Gas Power Plants in Thailand

Natural gas plays a significant role in Thailand, as it is the main source of primary energy for electricity, accounting for 73% of the total fuel consumption for power generation (Kamalaporn et al, 2009). To produce a better solution for reduction of negative environmental impacts, the Thailand government currently runs these two major technologies called thermal and combined cycle power plant.

In order to measure the environmental emissions from each process and make comparison between these two, the LCA technique was undertaken. The scope for this technique includes natural gas extraction, natural gas separation, natural gas transmission, and natural gas power production and the one of the vital aims is actually to balance all the these materials and environmental information (Kamalaporn et al, 2009). Global warming, acidification, photochemical ozone formation, and nutrient enrichment potential are among the impact categories considered in this research.

System boundary of this assessment includes the entire life cycle of electricity production from Bang Pakong power plant, including natural gas production, natural gas transmission, Rayong gas separation plant unit and finally power generation at the Bang Pakong combined cycle power plant units 1-4 and thermal units 1-4 **(Figure 2.5)**.

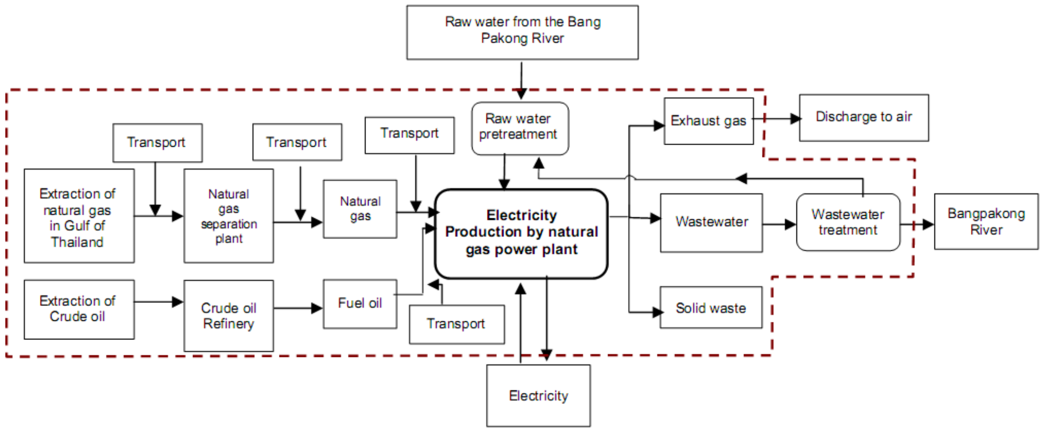

Figure 2.5: Life Cycle Diagram for Electricity Production by Thermal Power Plant at Bang Pakong (Kamalaporn et al, 2009)

Through the result, it can be clearly seen that the combined cycle power plant shows better performance compared to the thermal power plant for global warming potential (GWP), acidification potential (ACP), and photochemical ozone formation potential (POCP), leaving only the nutrient enrichment potential (NEP) where the combined cycle power plant contributes greater emission to it.

Based on the research conducted, it can be concluded that the thermal power plants include 56% of natural gas and 44% of fuel oil, while the combined cycle power plants are generally operated with natural gas (Kamalaporn et al, 2009). The power production for both thermal and combined cycle power plants are found the cause the largest contribution to GWP, ACP and NEP. In addition, the POCP for the thermal power plant is also from the power production, which is slightly different from the combined cycle power plant as it is mainly from transmission of natural gas. Summary of resulting impacts can be seen in **Table 2.1:**

Table 2.1: Impact potential contributions of various processes related to whole life cycle of the combined cycle power plants (Kamalaporn et al, 2009)

Combined cycle power plant					
Potential	Stage				Total
	Natural gas extraction	Natural gas separation	Natural gas transmission	Natural gas power plant	
GWP ($g\ CO_2$-eq/MWh)	28,498	21,713	3,749	485,499	539,459
ACP ($g\ SO_2$-eq/MWh)	–	3.88E-03	–	761.06	761.06
POCP ($g\ C_2H_4$-eq/MWh)	2.22	8.88E-05	1.14	–	3.36
NEP ($g\ NO_3^-$-eq/MWh)	–	7.30E-03	–	1,452.96	1,457.83

In conclusion, reduction of the fuel might probably produce a better outcome in the performance of the thermal power plants. To put it laconically, these results are vital for future power plants and the further research on these technologies.

2.2 Description of the Study Site

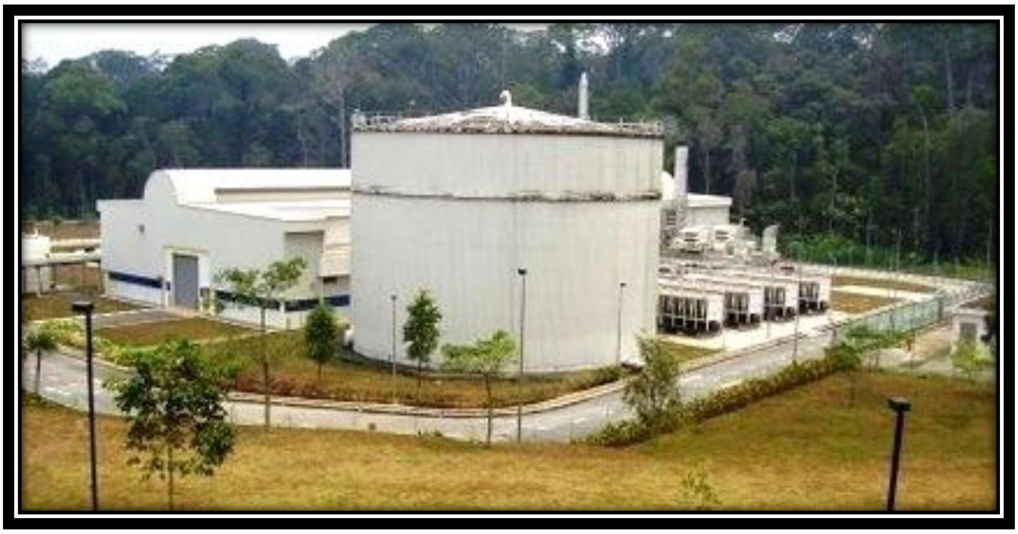

Figure 2.6: UTP GDC Plant (Mohd Raffi, 2010)

The main production of UTP Gas District Cooling Plant is chilled water. It is being used to cool Chancellor Complex, academic building and UTP mosque (Mohd Raffi, 2010). There are three main systems that being used to produce chilled water. They are steam absorption chiller, electric chiller and thermal energy storage.

Type of SAC used in this plant is double effect steam absorption chiller. The double effect SAC use two generators, which are low and high stage generator. The capacity of SAC is 1250 RT. Type of EC used is air cooled screw chiller. The EC has capacity of 325 RT (Mohd Raffi, 2010).

The TES used in this plant has capacity of 10,000 RTH. Function of thermal energy storage tank is to store chilled water in reducing the total chiller work capacity. Electric chillers are use to charge TES tank. They also help to maintain the return and differential pressure of chilled water supply and return.

2.2.1 Thermal Storage System

Thermal storage system can be defined as temporary storage of thermal energy for either high or low temperature (Ercan Ataer, 2006). The thermal storage can help to reduce time between energy supply and energy demand. It is also can help to smoothing supply and increasing reliability of energy systems. High efficiency of thermal storage helps to conserve energy and reduce the operation cost.

Storage time is one of the important characteristics of a thermal storage system. The thermal energy may loss to environment by radiation, convection and conduction (Ercan Ataer, 2006). Good thermal storage system should have a long storage time which energy can be kept stored with minimum losses. Thermal storage system is also characterized by energy kept per unit volume. Good thermal storage system should be able to kept large amount of energy per unit volume.

There are two common types of thermal energy storage (Ercan Ataer, 2006):

1. Sensible heat

   The heating process of liquid or solid occur without changing their phase. The amount of energy stored is depends on the temperature change of the material. Maximum energy is based on the highest possible heat capacity of the phases.

2. Latent heat

   Changing of material phase occur during the heating process of the material. The amount of energy stored is depends on the mass and the latent heat of fusion of the material. This storage operates isothermally at the melting point of the material.

2.2.2 Steam Absorption Chiller

Steam absorption chiller is a cooling system that uses heat instead of compressor to provide cooling capability (Whitman et al, 2009). Operation of this device is similar to that used by conventional air conditioning systems or mechanical chillers except it use thermal compressor instead of mechanical compressor. A thermal compressor consists of an absorber, a generator, a pump, and a throttling device to replace the mechanical vapor compressor (Cogeneration Technologies, 2010).

Efficiency of absorption chiller is lower compared to mechanical chiller. However, absorption chiller can substantially reduce operating costs because they are powered by low-grade waste heat (EERE, 2006). In contrast, mechanical chiller must be motor or engine driven. In single-effect absorption chiller, all condensing heat cools and condenses in the condenser before being released to the cooling water. A double-effect absorption chiller adopts a higher heat efficiency of condensation and divides the generator into a high-temperature and a low-temperature generator.

2.2.3 Electric Chiller

Type of electric chiller used in UTP GDC Plant is air cooled screw chiller. It is the most widely used type in industry and large public buildings. This chiller use vapor-compression method which utilize circulating refrigerant as a medium to remove heat from the desired room or places (Cengel, 2008). Screw compressor chiller has capability to handle large volume refrigerant with few moving parts. This is a positive displacement compressor which is able to handle some liquid refrigerant without compressor damage (Whitman et al, 2009).

2.2.4 Thermal Energy Storage Tank

TES Tank is also known as cool storage. It is a technology that reduces electric costs by shifting chilling activities to off-peak times. Water is chilled or ice is made during off-peak hours to either replace or augment building cooling equipment during the day. TES is good to use in facility that has large cooling load during daytime and little or no cooling load at night, such as a university (Ndlovu & Roy-Aikins, 2004).

TES uses the heat storage properties of a material to store heat in or alternatively cool the material for later usage. The system efficiencies of 95 to 99% are common because of the small amount of energy lost as chilled solutions gain heat during storage and transfer (Chvala, 2001). TES is merely a cost savings technology, not an energy savings technology. The system may use more total energy, but will experience significant energy and demand reductions during critical peak hours. The technology saves cost by allowing facilities to reduce peak demand charges and shift electric consumption to off-peak times (Chvala, 2001).

2.3 Life Cycle Assessment of Thermal Storage System

2.3.1 Goal and Scope Definition

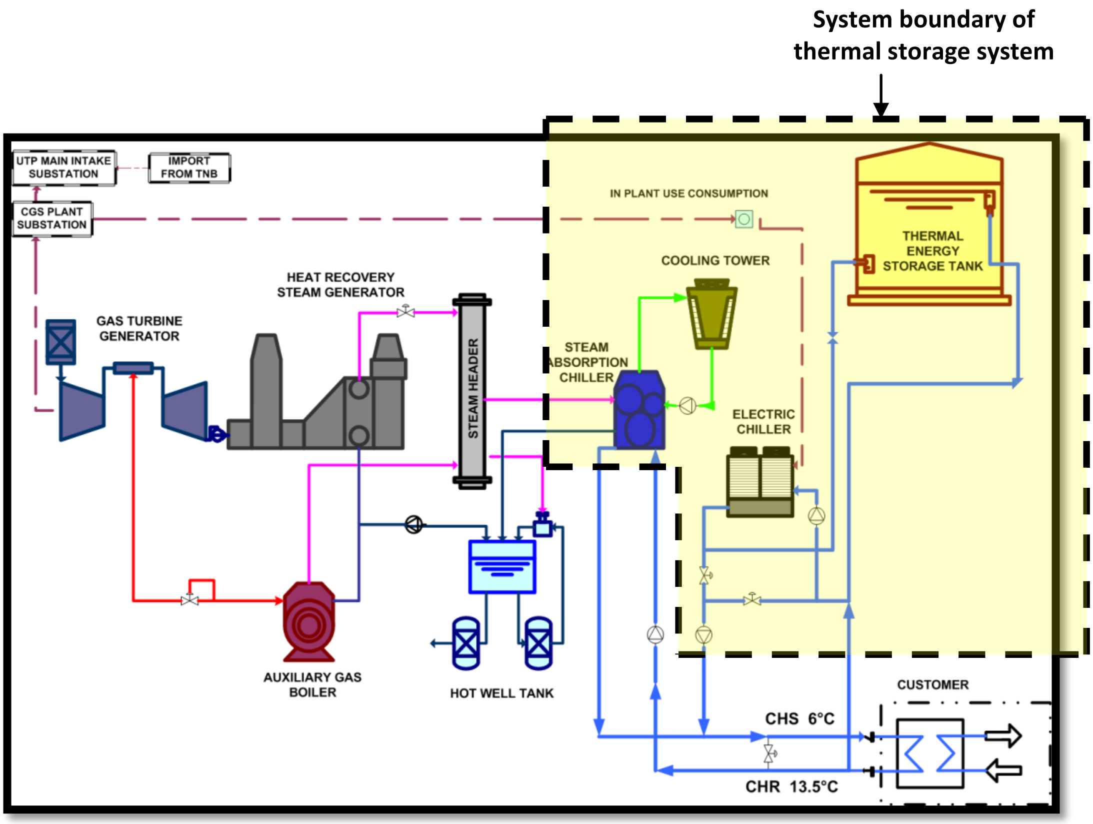

Figure 2.7: UTP GDC Process Flow Diagram (Mohd Raffi, 2010)

The study is mainly focused on the main components of thermal storage which are SAC, EC and TES Tank. Figure 2.8 shows the simplified diagram of the system boundary. The study is more focusing in the manufacturing process of these equipments which is mainly related to their production materials

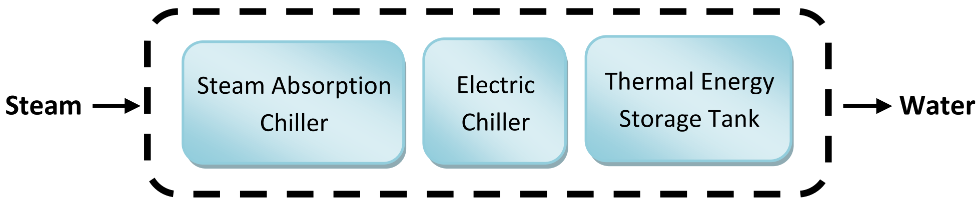

Figure 2.8: Simplified Diagram of the System Boundary

The LCA should consider all the activities involves in the product life cycle which are from raw material acquisition to disposal. However, it is not necessarily to apply the entire life cycle of a product to the LCA. This situation is called as partial LCA (Hundal, 2002). In this case, LCA has been limited from the raw material acquisition to the process and manufacturing stages due to the lack of information.

2.3.2 Life Cycle Inventory (LCI)

In this stage, all the environmental loads or effects generated during a product's life cycle are identified and evaluated. LCI is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emission, solid wastes and other releases for entire life cycle of a product (SAIC, 2006).

Based on USEPA (1993) and USEPA (1995), implementation of LCI involves:

i. *Process flow diagram*

   Flow diagram is required to show the input and output of the system. The flow diagram is related to the definition and scope of study.

ii. *Data collection plan*

   This is the early stage of data collection which is required to ensure accuracy of data.

iii. *Collection of data*

   Data collection can be obtained from direct contact with experts or through commercially available LCA software package.

iv. *Evaluation and documentation of LCI Results*

   Involves calculation of environmental loads and presentation of result in appropriate ways.

2.3.3 Life Cycle Impact Assessment (LCIA)

LCIA involves the evaluation of potential human health and environmental impacts of the environmental release identified during the LCI (SAIC, 2006). Purpose of LCIA is to assess the LCI in order to get better understanding of its environmental significance. By evaluating the life cycle inventory results to impact categories, LCIA provides wide perspective of environmental issues of a product system. The calculated results define the LCIA profile of the product system, which shows the environmental impacts associated with the system.

The framework of LCIA consists of several elements. Based on ISO 14042 (2000), the elements of LCIA are as follow:

- Selection of the impact categories indicators and models
- Classification of environmental loads within the different categories of environmental impact
- Characterization of environmental loads by means of a reference pollutant typical of each environmental impact category.

In this assessment, the LCIA is conducted based on the method developed by Center of Environmental Science, Leiden University (CML). The method is called as CML 2001 (Guinee et al, 2001). It is one of impact assessment methods, which inhibit quantitative modeling to relatively early stages in the cause-effect chain. The method limits the assessment of impact to several categories (e.g. global warming potential, stratospheric ozone depletion potential, etc) (Guinee et al, 2001). The impact categories that being considered in this study are as follows:

i. Global Warming Potential

Global warming can be defined as the rising of the global temperature due to emission of greenhouse gases (Chai Hoon, 2006). The main contributors to global warming are CO_2, N_2O, CH_4 and aerosols.

According to Tao Zhu (2004), for a substance to be regarded as contributing to global warming, it must be a gas at normal atmospheric temperature and:

- should be able to absorb infrared radiation and should last in the atmosphere with a residence time of years to centuries
- should be based on fossil origin and being converted to CO_2 on degradation in atmosphere.

An equivalency factor system has been developed by the Intergovernmental Panel on Climate Change (IPCC) (Gupta et al, 2003; Swart et al, 2003; Siebenhuer, 2003), which can weight various substances according to their efficiencies as greenhouse gases. They describe global warming potential (GWP) as a characterization factor that defines to characterization of potential contribution from a given substance which is in use for a time horizon of 100 years (standard). This method use CO_2 as the reference material. Therefore, all emission that characterized by this method are expressed as kilogram of CO_2 equivalent (Guinee et al, 2001).

ii. Stratospheric Ozone Depletion Potential

Stratospheric ozone can be defined as the thinning of the stratospheric ozone layer as a result of anthropogenic emission (Guinee et al, 2001). This leads to an increase in the amount of UV light reaching the earth's surface. The UV light has potential harmful impacts on human health, animal health and aquatic ecosystems.

The stratospheric ozone depletion can occur as a result of man-made emissions of halocarbons (CFCs, HCFCs), halons and other gases that contain chlorine or bromine. Characteristic of substances that can contribute to stratospheric ozone depletion are as follows (Tao Zhu, 2004):

- A gas at normal atmospheric temperature
- Contain chlorine or bromine
- Have a stable lifetime in the atmosphere for several years to centuries

CFCs, HCFCs, halons, and methyl bromide are the top contributors of stratospheric ozone depletion since these substances contain either chlorine or bromine. However, HFCs are a group of hydrocarbon that is not regarded as contributors to this impact. It is because HFCs contain only fluorine. Stratospheric ozone depletion is expressed in kilogram of CFC-11 equivalents (Guinee et al, 2001).

iii. *Acidification Potential*

Acidification can be referred to atmospheric pollution arising from derived sulphur (S) and nitrogen (N) as NOx or ammonia (Annur Aiman, 2008). The main contributor to the acidification potential is acids and compounds that are convertible to acids. When these substances are emitted to the water and soil, decreasing of pH value will occur, thus cause an increase in acidity.

A substance can be considered as contributor to acidification when it cause release of hydrogen ions in the environment; and the anions which accompany the hydrogen ions must be leached or washed from the system (Tao Zhu, 2004). The addition of hydrogen ions occurs when the substance itself is an acid or converted to an acid, or when hydrogen ions are released as the substance is converted in the environment. Acidification is expressed in kilogram of SO_2 equivalents (Guinee et al, 2001).

iv. *Human Toxicity Potential*

Human toxicity is referred to toxic substance that could cause health problems. The exposure to human toxicity could be taken place through air, water or soil especially when involving food chain.

This impact category is contrast to other impact categories where human toxicity includes many different impact mechanisms such as damage to DNA, induction of allergy or inhibition of specific enzymes (Olsen et al, 2001; Bakhsi, 2002). As it is still in development stage, many substances cannot be described in term of their mechanism of action (Huijbregts et al, 2001). Therefore the different mechanisms which underlie toxicity are treated as if there were one primary impact mechanism. Compared with the other environmental impact categories, the list of substances from the product system classified as contributing to human toxicity is more comprehensive and less uniform.

There are several ways to become exposed to this impact. The direct exposure includes inhalation, ingestion of polluted groundwater, surface water and soil (Vermeire et al, 1999). Indirect exposure could occur through ingestion of primary producers which are exposed to pollution, ingestion of consumers or their products (USEPA, 1997). This impact is expressed in kilogram of 1,4-dichlorobenzene equivalents (Guinee et al, 2001).

v. Eutrophication Potential

Eutrophication is related to the excessive level of nitrogen (N) and phosphorus (P) in environment. Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems (Guinee et al, 2001). It is also can cause water as unacceptable source of drinking water. Increasing concentration of nitrogen and phosphorus may also lead to excessive growth of algae in aquatic ecosystem. This will lead to the depressed oxygen level since the oxygen consumption has increased. The eutrophication potential is expressed in kilogram of PO_4^{3-} equivalent (Guinee et al, 2001).

2.3.4 Life Cycle Interpretation

This is the last phase of LCA which involves the interpretation of data obtained from the preceding phases. The interpretation is related to identification of actions to be undertaken in order to reduce the environmental impact of the system (Giudice et al, 2006). This phase is a step where a correlation is being made between the results of LCI and LCIA to achieve the objective of the study. ISO 14043 (2000) said that the data from the previous phase must be organized in clear and understandable manner in order to provide useful indications for improvement.

2.3.5 OpenLCA Framework Software

OpenLCA Framework software is used to conduct LCIA **(Figure2.9)**. It is modular open source software for sustainability assessment developed by GreenDeltaTC (Ciroth, 2006). Open source software is free to use without any cost and is fully transparent to be modified by anybody. The OpenLCA Framework is licensed and released under the terms of the Mozilla Public License (MPL) 1.1 (OpenLCA, 2010).

The software helps to calculate life cycle assessment of a product through its framework. It covers graphical inventory modeling, impact assessment and interpretation. The LCA databases use in this software is imported online from European Reference Life Cycle Data System (ELCD) (EUROPA JRT, 2010) and United States Life Cycle Inventory Database developed by National Renewable Energy Laboratory (NREL) (NREL, 2010).

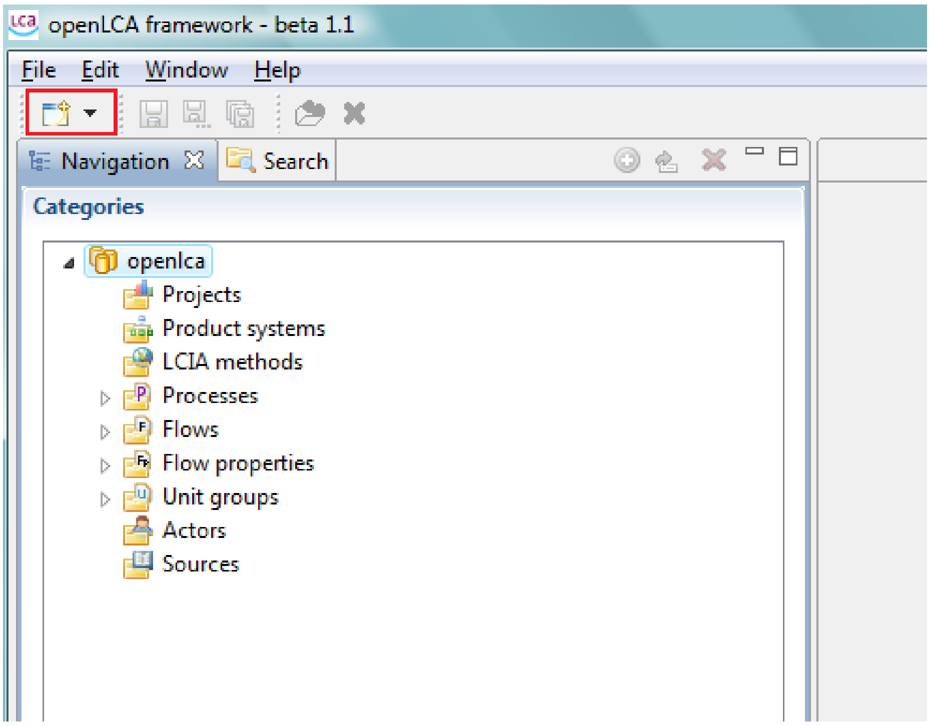

Figure 2.9: OpenLCA Framework Interface (OpenLCA, 2010)

Both inventory and impact assessment is calculated by using this software. The impact assessment is calculated based on CML 2001 method (Guinee et al, 2001). Characterization factors that cause contribution to each impact category are shown in **Appendix 2-2**.

CHAPTER 3

METHODOLOGY

3.1 Basic Project Methodology

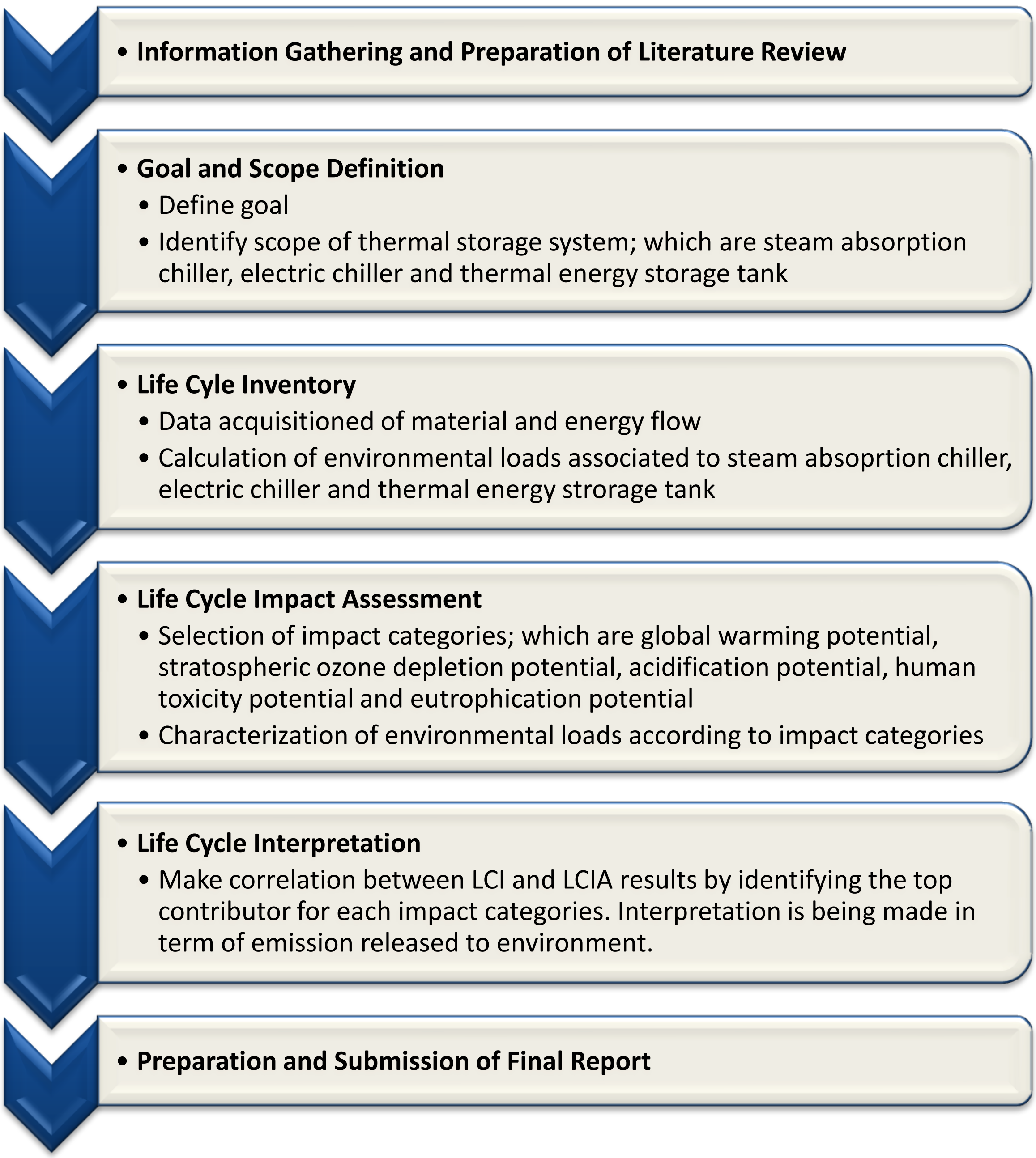

Figure 3.1: Basic Project Methodology

3.2 Detailed Project Methodology

According to ISO 14040 (1997) Life Cycle Assessment phases consist of goal and scope definition, inventory assessment, impact assessment and interpretation. This study is being conducted based on those four phases:

1. Goal and Scope Definition
   a. *Definition of goal*

      The objective of this study is to undertake Life Cycle Assessment for the thermal storage system at Universiti Teknologi PETRONAS Gas District Cooling Plant.

   b. *Scope of study*

      This study concentrates on three main equipments of Thermal Storage System which are SAC, EC, and TES Tank. In this study, LCA has been restricted from the raw material acquisition to the process and manufacturing stages due to the limitation of data obtained.

2. Life Cycle Inventory
   a. *Data acquisition of material and energy flow*

      This phase involves gathering of technical data associated to the manufacturing process of SAC, EC and TES Tank. The data comprised of input and output for the whole process which are related to raw material, energy requirement and emission released:

      i. Main components for SAC and EC are evaporator, condenser, high temperature generator, low temperature generator and absorber while the main components for TES Tank are storage tank and diffuser.
      ii. Main materials of the components are stainless steel, carbon steel, copper and mineral wool.
      iii. Required weight for each material is determined from various sources (Noor Ilyia, 2010; Dunham-Bush, 2009; Heath et al, 2009):

- SAC
    - ➢ Stainless steel (2068 kg)
    - ➢ Copper (66980 kg)
- EC
    - ➢ Stainless steel (253.5 kg)
    - ➢ Copper (8196.5 kg)
- TES Tank
    - ➢ Stainless steel (305.5 kg)
    - ➢ Carbon steel (442500 kg)
    - ➢ Mineral wool (141500 kg)

b. *Calculation of environmental load*

Input and output data obtained from the earlier step are transferred to openLCA Framework software. Total environmental load associated to SAC, EC and TES Tank is calculated and presented in **Table A4.1 (Appendix 4-1)**.

3. Life Cycle Impact Assessment

The emission released from the manufacturing process of SAC, EC and TES Tank are grouped and quantified into several numbers of impact categories namely:

- Global warming potential (kg CO_2 equivalent)
- Stratospheric ozone depletion potential (kg CFC-11 equivalent)
- Acidification potential (kg SO_2 equivalent)
- Human toxicity potential (kg 1,4-dichlorobenzene equivalent)
- Eutrophication potential (kg PO_4^{3-} equivalent)

This process is done using openLCA Framework software where process contributions for each impact categories are shown in graphs.

4. Life Cycle Interpretation

   The result obtained from Life Cycle Inventory and Life Cycle Impact Assessment is analyzed based on their cause and effect. The major contributor to environmental impact is identified and suggestion for future improvement is made.

3.3 Project Gantt Chart

Details of the scheduled project are shown in the **Appendix 3-1**.

CHAPTER 4

RESULTS AND DISCUSSION

In this section, result of Life Cycle Inventory and Life Cycle Impact Assessment were obtained. Generally, this part involved with the usage of openLCA Framework software. The software was needed to calculate environmental loads associated to manufacturing process of SAC, EC and TES Tank. The emissions were then categorized to five impact categories namely; global warming potential, stratospheric ozone depletion potential, acidification potential, human toxicity potential and eutrophication potential.

4.1 Results

4.1.1 Life Cycle Inventory (LCI)

This phase involved with gathering of technical data associated to the manufacturing process of SAC, EC and TES Tank. The data comprised of input and output for the whole process which merely related to raw material, energy requirement and emission released. The material weight was determined by referring to several sources (Noor Ilyia, 2010; Dunham-Bush, 2009; Heath et al, 2009). The input and output data for environmental load were mainly obtained from online database of European Reference Life Cycle Data System (ELCD) (EUROPA JRT, 2010) and United States National Renewable Energy Laboratory (NREL) (NREL, 2010).

4.1.1.1 Steam Absorption Chiller

Table 4.1 shows the general information of Steam Absorption Chiller.

Table 4.1: General Information of Steam Absorption Chiller
(Mohd Raffi, 2010; Whitman et al, 2009; Noor Ilyia, 2010)

Type / Capacity	Type: Double Effect Steam Absorption Chiller Capacity: 1250 RT
Major Components	• Evaporator • Condenser • High temperature generator • Low temperature generator • Absorber
Main Materials	• Stainless steel (2068 kg) • Copper (66980 kg)

4.1.1.2 Electric Chiller

Table 4.2 shows the general information of Electric Chiller.

Table 4.2: General Information of Electric Chiller
(Mohd Raffi, 2010; Whitman et al, 2009; Dunham-Bush, 2009)

Type / Capacity	Type: Air Cooled Screw Chiller (Outdoor) Capacity: 325 RT
Major Components	• Evaporator • Condenser • High temperature generator • Low temperature generator • Absorber
Main Materials	• Stainless steel (253.5 kg) • Copper (8196.5 kg)

4.1.1.3 Thermal Energy Storage Tank

Table 4.3 shows the general information of Thermal Energy Storage Tank

Table 4.3: General Information of Thermal Energy Storage Tank (Mohd Raffi, 2010; Whitman et al, 2009; Heath et al, 2009)

Type / Capacity	Type: Cylindrical Steel Tank Capacity: 10,000 RTH
Major Components	• Storage Tank • Diffuser
Main Materials	• Stainless steel (305.5 kg) • Carbon steel (442500 kg) • Mineral wool (141500 kg)

4.1.1.4 Environmental Load Calculation

Calculation of environmental load began with the determination of material and process tracing. The main materials needed for the manufacturing process of thermal storage system were stainless steel, carbon steel, copper and mineral wool. These materials were linked together in the openLCA Framework software to show the process tracing of Thermal Storage System **(Figure 4.1)**.

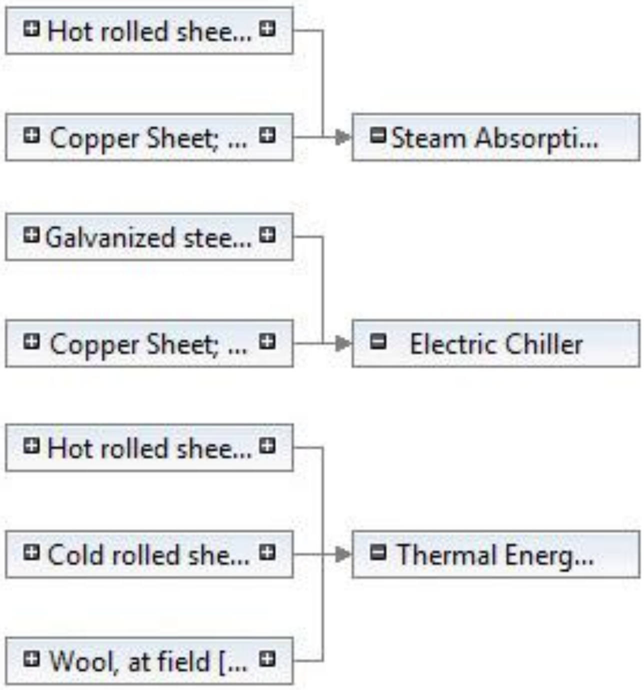

Figure 4.1: Thermal Storage System Manufacturing Process Tracing

Each process had their own input and output which contributed to various environmental loads. The data for each process were imported to openLCA Framework software from online database of European Reference Life Cycle Data System (ELCD) (EUROPA JRT, 2010) and United States National Renewable Energy Laboratory (NREL) (NREL, 2010). Detailed results were presented in **Table A4.1 (Appendix 4-1)**.

4.1.2 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment calculation was derived from the results of Life Cycle Inventory. Environmental loads emitted by the manufacturing process of SAC, EC and TES Tank were selected and characterized according to five impact categories namely; global warming potential, stratospheric ozone depletion potential, acidification potential, human toxicity potential and eutrophication potential. The results for LCIA were expressed as kg equivalent based on specific characterization factor. The characterization factor for each impact categories can be referred in **Appendix 2-2.**

Table 4.4 summarized the LCIA for SAC, EC, and TES Tank based on five different impact categories.

Table 4.4: Life Cycle Impact Assessment Results

Impact Categories	SAC	EC	TES Tank
Global Warming Potential (kg CO_2 eq.)	2.014×10^5	2.804×10^4	7.147×10^9
Stratospheric Ozone Depletion Potential (kg CFC-11 eq.)	1.627×10^{-3}	1.995×10^{-4}	-
Acidification Potential (kg SO_2 eq.)	3.403×10^{-3}	6.6×10^1	2.02×10^5
Human Toxicity Potential (kg 1,4-dichlorobenzene eq.)	3.146×10^2	4.975×10^1	2.033×10^5
Eutrophication Potential (kg PO_4^{3-} eq.)	2.198×10^2	3.061×10^1	6.953×10^3

The results showed that the manufacturing process of TES tank has the highest emission value for most of the impact categories. However, it did not contribute to stratospheric ozone depletion since copper did not occupy as the main materials of TES tank. The NREL (2010) database showed that processing of steel and mineral wool did not produce any substance with CFC-11 equivalent.

4.1.2.1 Global Warming Potential

The overall manufacturing processes of SAC, EC and TES Tank contributed to the emission of 7.148 x 10^9 kg CO_2 equivalent. **Table 4.5** and **Figure 4.2** show the top 5 processes that contributed to global warming potential.

Table 4.5: Top Process Contributions for Global Warming Potential

Process	Global Warming Potential Impact (kg CO_2 eq.)
Mineral wool production	7.140 x 10^9
Quicklime processing	2.879 x 10^6
Bituminous coal combustion	1.709 x 10^6
Hot rolled steel sheet production	1.181 x 10^6
Steel production	3.125 x 10^5
Others	1.091 x 10^6

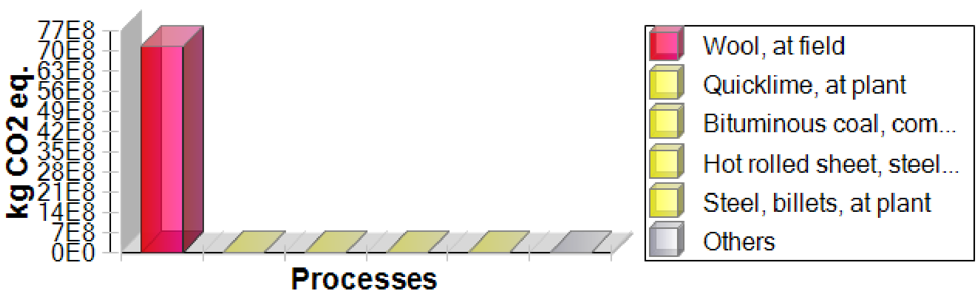

Figure 4.2: Top 5 Process Contributions for Global Warming Potential

The graph showed that most of the emitted CO_2 gases came from the processing of mineral wool. Most of CO_2 emission occurred during the melting process of wool which is mainly occupied in TES Tank. CO_2 gases were emitted from fuel combustion and decomposition of carbonates in the batch materials. The total emission is high because large quantity of mineral wool was required as the thermal insulator for TES tank.

4.1.2.2 Strathospheric Ozone Depletion

The overall manufacturing processes of SAC, EC and TES Tank contributed to the emission of 1.827×10^{-3} kg CFC-11 equivalent. **Table 4.6** show the process contributor of strathospheric ozone depletion potential.

Table 4.6: Process contribution of Strathospheric Ozone Depletion Potential

Process	Stratospheric Ozone Depletion Potential (kg CFC-11 eq.)
Copper sheet production	1.827×10^{-3}

The table showed that the emitted CFC gases come from the processing of copper sheet. The emission of CFC usually occurred from the erosion of unused copper scrap. In this study, copper was the only materials that contributes to the emission of CFC-11 equivalents.

4.1.2.3 Acidification Potential

The overall manufacturing processes of SAC, EC and TES Tank contributed to the emission of 2.024×10^{5} kg SO_2 equivalent. **Table 4.7** and **Figure 4.3** show the top 5 process that contributed to acidification potential.

Table 4.7: Top Process Contributions for Acidification Potential

Process	Acidification Potential (kg SO_2 eq.)
Mineral wool production	1.722×10^{5}
Bituminous coal combustion (Wool)	1.477×10^{4}
Natural gas processing	8.340×10^{3}
Electricity (Bituminous coal)	1.791×10^{3}
Hot rolled steel sheet production	1.777×10^{3}
Others	3.504×10^{3}

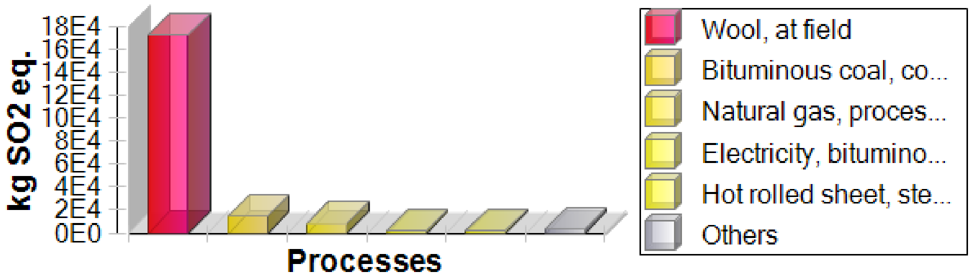

Figure 4.3: Top 5 Process Contributions for Acidification Potential

The graph showed that production of mineral wool had the highest contribution to the SO_2 emission. The emission was mainly produced during the combustion of coke. Reaction between sulfur and oxygen in the furnace caused the formation of SO_2 gases.

4.1.2.4 Human Toxicity Potential

The overall manufacturing processes of SAC, EC and TES Tank contributed to the emission of 2.036 x 10^5 kg 1,4-dicholorobenzene equivalent. **Table 4.8** and **Figure 4.4** show the top 5 process that contributed to human toxicity potential.

Table 4.8: **Top Process Contributions for Human Toxicity Potential**

Process	Human Toxicity Potential (kg 1,4-dichlorobenzene eq.)
Mineral wool production	1.893 x 10^5
Bituminous coal combustion (Wool)	5.508 x 10^3
Transportation (Train)	1.899 x 10^3
Hot rolled steel sheet production	1.810 x 10^3
Transportation (Truck)	1.194 x 10^3
Others	3.912 x 10^3

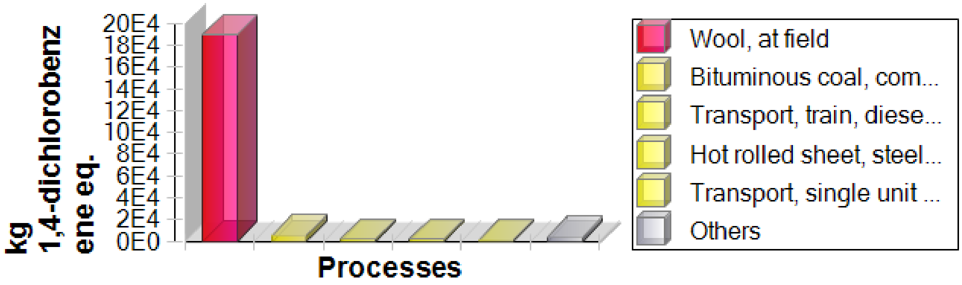

Figure 4.4: Top 10 Process Contribution for Human Toxicity Potential

The graph showed that production of mineral wool had the highest contribution to human toxicity potential. The impacts could be happening due to emission of organic and inorganic substances. Human toxicity potential did not specifically appointed to certain substances. Therefore the different mechanisms which underlie toxicity were treated as if there were one primary impact mechanism.

4.1.2.5 Eutrophication Potential

The overall manufacturing processes of SAC, EC and TES Tank contributed to the emission of 7.203 x 10^3 kg PO_4^{3-} equivalent. **Table 4.9** and **Figure 4.6** showed the top 5 process that contributed to eutrophication potential.

Table 4.9: Top Process Contributions for Euthrophication Potential

Process	Eutrophication Potential ($kg\ PO_4^{3-}$ eq.)
Mineral wool production	6.172 x 10^3
Hot rolled steel sheet production	7.093 x 10^2
Steel production	1.699 x 10^2
Copper sheet production	1.174 x 10^2
Galvanized steel sheet production	1.507 x 10^1
Others	1.929 x 10^1

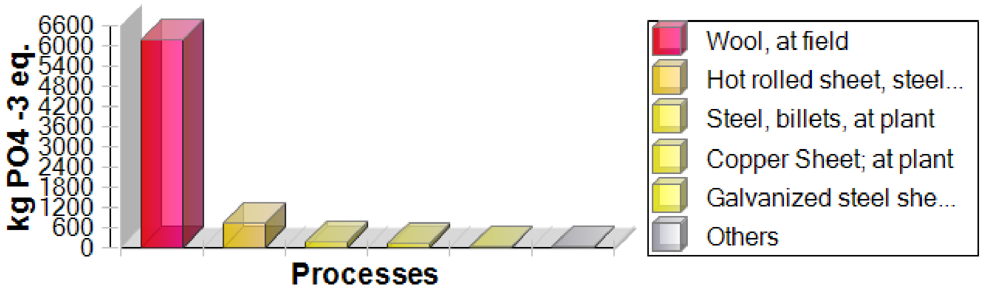

Figure 4.5: Top 5 Process Contributions for Euthrophication Potential

The graph showed that production of mineral wool had the highest contribution to eutrophication potential. This was due to the emission of substances such as ammonia, nitrate, nitric acid, phosphate, etc. Production of mineral wool involved with the usage of various organic and inorganic substances. Therefore, emission of these substances to environment could lead to euthrophication potential.

4.2 Life Cycle Interpretation / Discussion

The manufacturing processes of SAC, EC and TES Tank had contributed to the emission of various substances. Some of the substances may cause bad effects to the environment as well as human health. The emission of substances had been categorized to different types of impacts. They are global warming potential, stratospheric ozone depletion potential, acidification potential, human toxicity potential and eutrophication potential.

Based on the result, CO_2 has the highest amount of contribution to the environmental impacts. The result indicated that the manufacturing processes of SAC, EC and TES Tank could cause various environmental impacts to the green environment. The emission of CO_2 contributed to global warming as well as green house effect. These impacts caused the increasing of earth's temperature thus leading to the melting of icebergs.

Apart from CO_2, emission of the other substance also contributed to the affection of environment and human health. The emission of CFC gases contributed to ozone depletion and lead to excessive amount of ultraviolet light entering atmosphere. Exposure to ultraviolet light may cause generation of skin cancer. Emission of PO_4^{3-} ions into water contributed to excessive growth of algae in aquatic ecosystem. Large quantities of algae caused reduction in oxygen level and made water as unacceptable source of drinking water (Guinee et al, 2001).

However, the impacts can be reduced by controlling the emission in proper way. Filtration of dangerous gases to atmosphere could be magnificent in encountering this problem. It will reduce the percentage of the impacts from further happening.

Result of the Life Cycle Impact Assessment showed that the processing of mineral wool had the highest contribution to the emission of CO_2 gases. In this study, mineral wool is mainly used as the thermal insulator for TES Tank. However, there are several materials that can be also used as thermal insulator. They are Polypropylene, Polyol Ether and Polyethylene Terephthalate. These materials are processed into foam in order to be used as thermal insulator. **Table 4.10** shows the environmental impact value of TES Tank by using these materials as thermal insulator:

Table 4.10: Environmental Impact Value for Different Types of TES Tank Thermal Insulator

Impact Categories	Mineral Wool	Polypropylene	Polyol Ether	Polyethylene Terephthalate
Global Warming Potential (kg CO_2 eq.)	7.147×10^9	1.387×10^6	1.666×10^6	1.589×10^6
Acidification Potential (kg SO_2 eq.)	2.02×10^5	5.309×10^3	6.795×10^3	4.703×10^3
Human Toxicity Potential (kg 1,4-dichlorobenzene eq.)	2.033×10^5	2.348×10^3	3.075×10^3	2.830×10^3
Eutrophication Potential (kg PO_4^{3-} eq.)	6.953×10^3	7.671×10^2	7.790×10^2	7.787×10^2

Based on the table above, Polypropylene, Polyol Ether and Polyethylene Terephthalate had lower value of environmental impact compared to mineral wool. Among all the materials, Polypropylene had the lowest value of emission for most of the impact categories. In order to have a greener product, Polypropylene could be used to substitute mineral wool as the thermal insulator of TES Tank. However, further study should be done to determine whether this material could provide performance that is comparable to mineral wool.

CONCLUSION AND RECOMMENDTION

Main components for thermal storage system are Steam Absorption Chiller, Thermal Energy Storage Tank and Electric Chiller. The main materials used for these equipments are stainless steel, carbon steel, copper and mineral wool.

Various substances have been released trough the manufacturing process of thermal storage equipment. Some of these substances could be harmful to the environment where they can lead to certain environmental impacts. They are global warming potential, Stratospheric Ozone Depletion Potential, Acidification Potential, Human Toxicity Potential and Eutrophication Potential. Manufacturing process of SAC, EC and TES Tank contributed to the emission of 7.148×10^9 kg CO_2 equivalent, 1.827×10^{-3} kg CFC-11 equivalent, 2.024×10^5 kg SO_2 equivalent, 2.036×10^5 kg 1,4-dicholorobenzene equivalent and 7.203×10^3 kg PO_4^{3-} equivalent.

Production of Thermal Energy Storage Tank has the highest contributions to the environmental impacts. This is mainly due to its size; which involves more materials and processes. The highest emission to environment is CO_2 gases. The reason for this is because CO_2 is the common product of any combustion.

All the impact would be worsen if improper method of disposal is applied to the system. Therefore, disposal of potential contributor to environmental pollution should be monitored seriously. This is a good practice towards safe environment and also can reduce environmental pollution.

In conclusion, manufacturing and disposal processes of SAC, EC and TES Tank could cause severe effect to the environment if it is not conducted properly. Therefore, it is important that the manufacturing and disposal processes of the thermal storage system equipments to be monitored closely in order to reduce the environmental impact.

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APPENDICES

APPENDIX 2-1

Table A2.1: ISO International Standards and Technical Reports for LCA (Giudice et al, 2006)

DESIGNATION DOCUMENT TYPE YEAR	TITLE	CONTENTS
ISO 14040:1997 International Standard 1997	Environmental management: Life Cycle Assessment – Principles and framework	• General framework, principles, and requirements for conducting and reporting LCA studies
ISO 14041:1998 International Standard 1998	Environmental management: Life Cycle Assessment – Goal and scope definition and inventory analysis	• Requirements and procedures necessary for the compilation and preparation of the definition of goal and scope for LCA, and for performing, interpreting, and reporting a Life Cycle Inventory Analysis (LCI)
ISO 14042:2000 International Standard 2000	Environmental management: Life Cycle Assessment – Life cycle impact assessment	• General framework for the Life Cycle Impact Assessment (LCIA) phase of LCA • Key features and inherent limitations of LCIA • Requirements for conducting the LCIA phase • Relationship to the other LCA phases
ISO 14043:2000 International Standard 2000	Environmental management: Life Cycle Assessment – Life cycle interpretation	• Requirements and recommendations for conducting Life Cycle Interpretation phase in LCA or LCI studies
ISO / TR 14047:2003 Technical Report 2003	Environmental management: Life Cycle Assessment – Examples of application of ISO 14042	• Examples to illustrate practice in carrying out LCIA according to ISO 14042
ISO / TS 14048: 2002 Technical Specification 2002	Environmental management: Life Cycle Assessment – Data documentation format	• Requirements and a structure for a data documentation format, to be used for transparent and unambiguous documentation and exchange of LCA and LCI data
ISO / TR 14049:2000 Technical Report 2000	Environmental management: Life Cycle Assessment – Examples of application of ISO 14041 to goal and scope definition and inventory analysis	• Examples of practices in carrying out a LCI as a means of satisfying certain provisions of ISO 14041

APPENDIX 2-2

Table A2.2: GWP_{100} Characterisation Factor (Guinee et al, 2001)

Substance	GWP_{100} (kg CO_2 equivalent)
1,1,1-trichloroethane	110
Carbon dioxide	1
CFC-11	4000
CFC-113	5000
CFC-114	9300
CFC-115	9300
CFC-12	8500
CFC-13	11700
Dicholoromethane	9
Dinitrogen oxide	310
HALON-1301	5600
HCFC-123	93
HCFC-124	480
HCFC-141b	630
HCFC-142b	2000
HCFC-22	1700
HCFC-225ca	170
HCFC-225cb	530
HFC-125	2800
HFC-134	1000
HFC-134a	1300
HFC-143	300
HFC-143a	3800
HFC-152a	140
HFC-227ea	2900
HFC-23	11700
HFC-236fa	6300
HFC-245ca	560
HFC-32	650
HFC-41	150
HFC-43-10mee	1300
Methane	21
Perfluorobutane	7000
Perfluorocyclobutane	8700
Perfluoroethane	9200
Perfluorohexane	7400
Perfluoromethane	6500
Perfluoropentane	7500
Perfluoropropane	7000
Sulphur hexafluoride	23900
Tetrachloromethane	1400
Trichloromethane	4

Table A2.3: Stratospheric Ozone Depletion Characterisation Factor (Guinee et al, 2001)

Substance	Stratospheric Ozone Depletion (kg CFC-11 equivalent)
1,1,1-trichloroethane	0.11
CFC-11	1.0
CFC-113	0.90
CFC-114	0.85
CFC-115	0.40
CFC-12	0.82
HBFC-2401	0.25
HBFC-1201	1.4
HBFC-2311	0.14
HALON-1202	1.25
HALON-1211	5.1
HALON-1301	12
HALON-2402	7
HCFC-123	0.012
HCFC-124	0.026
HCFC-141b	0.086
HCFC-142b	0.043
HCFC-225ca	0.034
HCFC-225cb	0.017
Methyl Bromide	0.37
Methyl Chloride	0.02
Tetrachloromethane	1.2

Table A2.4: Acidification Characterisation Factor (Guinee et al, 2001)

Substance	Acidification (kg SO_2 equivalent)
Ammonia	1.6
Nitrogen oxides (as NO_2)	0.5
Sulphur dioxide	1.2

Table A2.5: Eutrophication Characterisation Factor (Guinee et al, 2001)

Substance	Eutrophication (kg PO_4^{3-} equivalent)
Ammonia	0.35
Ammonium	0.33
Nitrate	0.1
Nitric Acid	0.1
Nitrogen	0.42
Nitrogen dioxide	0.13
Nitrogen monoxide	0.2
Nitrogen oxides	0.13
Phosphate	1
Phosphorus acid (H_3PO_4)	0.97
Phosphorus (P)	3.06
Phosphorus (V) oxide (P_2O_5)	1.34
Chemical oxygen demand (COD)	0.022

APPENDIX 3-1

Table A3.1: Project Milestone

No	Detail/Week	FYP 1														FYP 2													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of project topic																												
2	Preliminary research work																												
3	Further research																												
4	**Project work**																												
5	**Goal and Scope Definition**																												
6	Definition of goal																												
7	Scope of study																												
8	Research																												
9	Software learning																												
10	**Life Cycle Inventory**																												
11	Data acquisition																												
12	Calculation of environmental load																												
13	**Life Cycle Impact Assessment**																												
14	Selection of impact categories																												
15	Characterization of environmental Loads																												
16	**Life Cycle Interpretation**																												
17	Interpretation of LCI and LCIA results																												
18	Preparation and submission of final report																												

APENDIX 4-1

Table A4: LCI Results for Thermal Storage System

Input

Flow	Category	Flow property	Unit	Amount	Flow type
Anthracite coal, at mine	Flows	Mass	kg	731.7886211	Product flow
bentonite, at processing	construction materials/additives	Mass	kg	0.07605234	Product flow
Calcium carbonate	water/unspecified	Mass	kg	200.1830843	Elementary flow
Carbon dioxide, in air	resource/in air	Mass	kg	21313.21634	Elementary flow
Chromium	air/high population density	Mass	kg	1.2006798	Elementary flow
Coal, 26.4 MJ per kg, in ground	resource/in ground	Mass	kg	79349.9846	Elementary flow
Coal, bituminous, 24.8 MJ per kg, in ground	resource/in ground	Mass	kg	1330584.503	Elementary flow
Copper	air/high population density	Mass	kg	106.1487303	Elementary flow
Energy, from hydro power	resource/in water	Energy	MJ	112691.4204	Elementary flow
Gas, natural, 46.8 MJ per kg, in ground	resource/in ground	Mass	kg	44885.52765	Elementary flow
Gas, natural, in ground	resource/in ground	Volume	m^3	398649.7007	Elementary flow
Iron ore, in ground	resource/in ground	Mass	kg	843579.3564	Elementary flow
Limestone, in ground	resource/in ground	Mass	kg	7434352.346	Elementary flow
Manganese	air/high population density	Mass	kg	0.04944795	Elementary flow
Occupation, arable, reduced tillage	resource/land	Area*time	m^2*a	3205.975547	Elementary flow
Occupation, pasture and meadow	resource/land	Area*time	m^2*a	16895100	Elementary flow
Oil, crude, 42 MJ per kg, in ground	resource/in ground	Mass	kg	43708.81063	Elementary flow
Oil, crude, in ground	resource/in ground	Mass	kg	1057.83723	Elementary flow
Oxygen, in air	resource/in air	Mass	kg	60306.95862	Elementary flow
Sand, unspecified, in ground	resource/in ground	Mass	kg	7.200338399	Elementary flow
Sodium chloride, at plant	Flows	Mass	kg	159329.0002	Product flow
Sodium chloride, in ground	resource/in ground	Mass	kg	71.7589579	Elementary flow

Sulfur	soil/agricultural	Mass	kg	0.00023215	Elementary flow
Uranium oxide (U3O8), 332 GJ per kg, in ore	resource/in ground	Mass	kg	2.477574219	Elementary flow
Uranium, 2291 GJ per kg, in ground	resource/in ground	Mass	kg	0.313229402	Elementary flow
Water, river	resource/in water	Length	m	53770000	Elementary flow
Water, well, in ground	resource/in water	Length	m	31299800	Elementary flow
Wood and wood waste, 9.5 MJ per kg	resource/biotic	Mass	kg	90.9552903	Elementary flow

Output

Flow	Category	Flow property	Unit	Amount	Flow type
1-Methyl-2-pyrrolidinone	air/unspecified	Mass	kg	0.000701539	Elementary flow
2,4-D	air/low population density	Mass	kg	94.345125	Elementary flow
2,4-D	water/unspecified	Mass	kg	4.044086386	Elementary flow
2-Chloroacetophenone	air/unspecified	Mass	kg	0.002269343	Elementary flow
2-Hexanone	water/unspecified	Mass	kg	0.008271021	Elementary flow
2-Propanol	air/unspecified	Mass	kg	0.00102042	Elementary flow
Acenaphthene	air/unspecified	Mass	kg	0.000188861	Elementary flow
Acenaphthylene	air/unspecified	Mass	kg	9.25793E-05	Elementary flow
Acetaldehyde	air/unspecified	Mass	kg	0.200121095	Elementary flow
Acetochlor	water/unspecified	Mass	kg	0.010031158	Elementary flow
Acetone	water/unspecified	Mass	kg	0.012667224	Elementary flow
Acetophenone	air/unspecified	Mass	kg	0.004862878	Elementary flow
Acidity, unspecified	water/unspecified	Mass	kg	4.76724E-05	Elementary flow
Acids, unspecified	water/unspecified	Mass	kg	7.4421E-05	Elementary flow
Acrolein	air/unspecified	Mass	kg	0.071730466	Elementary flow
Adipate, bis(2-ethylhexyl)-	air/unspecified	Mass	kg	0.001403077	Elementary flow
Alachlor	air/low population density	Mass	kg	0.02304665	Elementary flow
Aldehydes	air/unspecified	Mass	kg	0.000483229	Elementary flow
Aldehydes, unspecified	air/unspecified	Mass	kg	3.250848281	Elementary flow
Aluminum	water/unspecified	Mass	kg	24.63391716	Elementary flow

Ammonia	air/unspecified	Mass	kg	122.9442098	Elementary flow
Ammonia	water/unspecified	Mass	kg	21.52946782	Elementary flow
Ammonia	air/low population density	Mass	kg	58326.3	Elementary flow
Ammonia, as N	water/unspecified	Mass	kg	3.7375E-05	Elementary flow
Ammonium chloride	air/unspecified	Mass	kg	0.131500266	Elementary flow
Ammonium, ion	water/unspecified	Mass	kg	8155.624987	Elementary flow
Ammonium, ion	water/ground-	Mass	kg	1.8543E-07	Elementary flow
Anthracene	air/unspecified	Mass	kg	7.77666E-05	Elementary flow
Antimony	water/unspecified	Mass	kg	0.014405409	Elementary flow
Antimony	air/unspecified	Mass	kg	0.008098855	Elementary flow
Arsenic	air/unspecified	Mass	kg	0.134301158	Elementary flow
Arsenic, ion	water/unspecified	Mass	kg	0.28109628	Elementary flow
Atrazine	water/unspecified	Mass	kg	0.019553345	Elementary flow
Barium	water/unspecified	Mass	kg	364.1385285	Elementary flow
Bentazone	water/unspecified	Mass	kg	7.97696E-05	Elementary flow
Benzene	air/unspecified	Mass	kg	30.9991559	Elementary flow
Benzene	water/unspecified	Mass	kg	36.82443858	Elementary flow
Benzene, 1,2,4-trimethyl-	air/unspecified	Mass	kg	0.000829091	Elementary flow
Benzene, 1-methyl-4-(1-methylethyl)-	water/unspecified	Mass	kg	0.000126584	Elementary flow
Benzene, chloro-	air/unspecified	Mass	kg	0.007132221	Elementary flow
Benzene, chloro-	water/unspecified	Mass	kg	0.000829091	Elementary flow
Benzene, ethyl-	air/unspecified	Mass	kg	0.030474036	Elementary flow
Benzene, ethyl-	water/unspecified	Mass	kg	0.119539153	Elementary flow
Benzene, pentamethyl-	water/unspecified	Mass	kg	9.49372E-05	Elementary flow
Benzenes, alkylated, unspecified	water/unspecified	Mass	kg	0.012600781	Elementary flow
Benzo(a)anthracene	air/unspecified	Mass	kg	2.96253E-05	Elementary flow
Benzo(a)pyrene	air/unspecified	Mass	kg	1.40721E-05	Elementary flow
Benzo(a)pyrene	water/unspecified	Mass	kg	3.705809013	Elementary flow
Benzo(b,j,k)fluoranthene	air/unspecified	Mass	kg	4.07349E-05	Elementary flow
Benzo(ghi)perylene	air/unspecified	Mass	kg	9.99857E-06	Elementary flow
Benzoic acid	water/unspecified	Mass	kg	1.285034834	Elementary flow
Benzyl chloride	air/unspecified	Mass	kg	0.226934307	Elementary flow
Beryllium	air/unspecified	Mass	kg	0.008048971	Elementary flow
Beryllium	water/unspecified	Mass	kg	0.012710299	Elementary flow
Biphenyl	air/unspecified	Mass	kg	0.009777051	Elementary flow

Biphenyl	water/unspecified	Mass	kg	0.000815884	Elementary flow
BOD5, Biological Oxygen Demand	water/unspecified	Mass	kg	238.7657713	Elementary flow
Boron	water/unspecified	Mass	kg	11.36053313	Elementary flow
Bromide	water/unspecified	Mass	kg	271.4768044	Elementary flow
Bromoform	air/unspecified	Mass	kg	0.012643483	Elementary flow
Bromoxynil	air/low population density	Mass	kg	0.00408014	Elementary flow
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	air/unspecified	Mass	kg	98.21208779	Elementary flow
Butadiene	air/unspecified	Mass	kg	0.000723366	Elementary flow
Cadmium	air/unspecified	Mass	kg	0.037278342	Elementary flow
Cadmium, ion	water/unspecified	Mass	kg	0.149686271	Elementary flow
Calcium, ion	water/unspecified	Mass	kg	4071.606324	Elementary flow
Carbofuran	air/low population density	Mass	kg	0.003488054	Elementary flow
Carbofuran	water/unspecified	Mass	kg	0.000149485	Elementary flow
Carbon dioxide	air/unspecified	Mass	kg	3029104.226	Elementary flow
Carbon dioxide, biogenic	air/unspecified	Mass	kg	4891.481975	Elementary flow
Carbon dioxide, fossil	air/unspecified	Mass	kg	2495449.388	Elementary flow
Carbon disulfide	air/unspecified	Mass	kg	0.042144943	Elementary flow
Carbon disulfide	water/unspecified	Mass	kg	0.000829091	Elementary flow
Carbon monoxide	air/unspecified	Mass	kg	11.11638992	Elementary flow
Carbon monoxide, fossil	air/unspecified	Mass	kg	7727.973757	Elementary flow
CFCs and HCFCs, unspecified	air/unspecified	Mass	kg	2.84129E-11	Elementary flow
Chloride	water/unspecified	Mass	kg	50303.72139	Elementary flow
Chloride	air/unspecified	Mass	kg	3.54298E-06	Elementary flow
Chloride	soil/agricultural	Mass	kg	46.9843742	Elementary flow
Chlorine	air/unspecified	Mass	kg	0.009976921	Elementary flow
Chloroform	air/unspecified	Mass	kg	0.01912732	Elementary flow
Chlorpyrifos	air/low population density	Mass	kg	0.026841583	Elementary flow
Chromate	water/unspecified	Mass	kg	0.002378438	Elementary flow
Chromium	air/unspecified	Mass	kg	0.106913555	Elementary flow
Chromium	water/unspecified	Mass	kg	1.019413221	Elementary flow
Chromium compounds	air/unspecified	Mass	kg	0.00714294	Elementary flow
Chromium VI	air/unspecified	Mass	kg	0.029254983	Elementary flow
Chromium VI	water/unspecified	Mass	kg	0.01422414	Elementary flow
Chromium, ion	water/unspecified	Mass	kg	0.641011177	Elementary flow
Chrysene	air/unspecified	Mass	kg	3.70317E-05	Elementary flow

Chrysene, 5-methyl-	air/unspecified	Mass	kg	8.14697E-06	Elementary flow
CO2 / CO2 equ.	Flows	Mass	kg	1502746.615	Elementary flow
Cobalt	water/unspecified	Mass	kg	0.028064531	Elementary flow
Cobalt	air/unspecified	Mass	kg	0.050022447	Elementary flow
COD	water/unspecified	Mass	kg	1346.559833	Elementary flow
COD, Chemical Oxygen Demand	water/unspecified	Mass	kg	450.8539295	Elementary flow
Copper	air/unspecified	Mass	kg	0.001474436	Elementary flow
Copper compounds	air/unspecified	Mass	kg	0.003635246	Elementary flow
Copper, ion	water/unspecified	Mass	kg	0.206337104	Elementary flow
Creosol	water/unspecified	Mass	kg	0.000829091	Elementary flow
Cresol	water/unspecified	Mass	kg	0.000829091	Elementary flow
Cumene	air/unspecified	Mass	kg	0.001718217	Elementary flow
Cyanazine	air/low population density	Mass	kg	0.004023054	Elementary flow
Cyanide	air/unspecified	Mass	kg	0.810479669	Elementary flow
Cyanide	water/unspecified	Mass	kg	423.8359503	Elementary flow
Cyanide, amenable	water/unspecified	Mass	kg	6.37762E-05	Elementary flow
Decane	water/unspecified	Mass	kg	0.036924514	Elementary flow
Detergents, oil	water/unspecified	Mass	kg	1.26194757	Elementary flow
Dibenzofuran	water/unspecified	Mass	kg	0.000240866	Elementary flow
Dibenzothiophene	water/unspecified	Mass	kg	0.00019767	Elementary flow
Dicamba	air/low population density	Mass	kg	0.023705764	Elementary flow
Diisocyanates	air/unspecified	Mass	kg	0.000548476	Elementary flow
Dimethenamid	water/unspecified	Mass	kg	0.002399399	Elementary flow
Dinitrogen monoxide	air/unspecified	Mass	kg	1120.93151	Elementary flow
Dinitrogen monoxide	air/low population density	Mass	kg	16187.81662	Elementary flow
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	air/unspecified	Mass	kg	2.40128E-06	Elementary flow
Dissolved organic matter	water/unspecified	Mass	kg	2.28521E-07	Elementary flow
Dissolved solids	water/unspecified	Mass	kg	58854.79012	Elementary flow
Disulfoton	water/unspecified	Mass	kg	5.91985E-05	Elementary flow
Docosane	water/unspecified	Mass	kg	0.001355526	Elementary flow
Dodecane	water/unspecified	Mass	kg	0.070059371	Elementary flow
Dust, unspecified	air/unspecified	Mass	kg	74.5075325	Elementary flow
Eicosane	water/unspecified	Mass	kg	0.019289317	Elementary flow
Ethane, 1,1,1-trichloro-, HCFC-140	air/unspecified	Mass	kg	0.006483918	Elementary flow
Ethane, 1,1,1-trichloro-, HCFC-140	water/unspecified	Mass	kg	0.000829091	Elementary flow

Ethane, 1,2-dibromo-	air/unspecified	Mass	kg	0.00038903	Elementary flow
Ethane, 1,2-dichloro-	air/unspecified	Mass	kg	0.012967675	Elementary flow
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	air/low population density	Mass	kg	0.000150898	Elementary flow
Ethane, chloro-	air/unspecified	Mass	kg	0.013616058	Elementary flow
Ethene, tetrachloro-	air/unspecified	Mass	kg	0.0187445	Elementary flow
Ethene, trichloro-	air/unspecified	Mass	kg	0.002563438	Elementary flow
Ethylene glycol	air/unspecified	Mass	kg	0.000567609	Elementary flow
Fluoranthene	air/unspecified	Mass	kg	0.000262925	Elementary flow
Fluorene	air/unspecified	Mass	kg	0.000336988	Elementary flow
Fluorene, 1-methyl-	water/unspecified	Mass	kg	0.000144165	Elementary flow
Fluorenes, alkylated, unspecified	water/unspecified	Mass	kg	0.000730274	Elementary flow
Fluoride	air/unspecified	Mass	kg	14.45993925	Elementary flow
Fluoride	water/unspecified	Mass	kg	126.181006	Elementary flow
Fluorine	water/unspecified	Mass	kg	0.000446419	Elementary flow
Formaldehyde	air/unspecified	Mass	kg	3.746174879	Elementary flow
Furan	air/unspecified	Mass	kg	2.07742E-07	Elementary flow
Glyphosate	water/unspecified	Mass	kg	0.002156867	Elementary flow
Glyphosate	air/low population density	Mass	kg	0.050328387	Elementary flow
Hexadecane	water/unspecified	Mass	kg	0.076468757	Elementary flow
Hexane	air/unspecified	Mass	kg	0.021720855	Elementary flow
Hexanoic acid	water/unspecified	Mass	kg	0.266115256	Elementary flow
Hydrazine, methyl	air/unspecified	Mass	kg	0.055112618	Elementary flow
Hydrocarbons, unspecified	water/unspecified	Mass	kg	2.85935E-07	Elementary flow
Hydrocarbons, unspecified	air/unspecified	Mass	kg	0.758970394	Elementary flow
Hydrogen chloride	air/unspecified	Mass	kg	270.0957059	Elementary flow
Hydrogen fluoride	air/unspecified	Mass	kg	42.75390414	Elementary flow
Hydrogen sulfide	air/unspecified	Mass	kg	1.14521E-07	Elementary flow
Indeno(1,2,3-cd)pyrene	air/unspecified	Mass	kg	2.25894E-05	Elementary flow
Iron	water/unspecified	Mass	kg	242.5558035	Elementary flow
Isobutanol	water/unspecified	Mass	kg	0.000829091	Elementary flow
Isocyanic acid	air/unspecified	Mass	kg	0.00255105	Elementary flow
Isophorone	air/unspecified	Mass	kg	0.188031283	Elementary flow
Isoprene	air/unspecified	Mass	kg	116.1273172	Elementary flow
Kerosene	air/unspecified	Mass	kg	0.132119462	Elementary flow
Lead	air/unspecified	Mass	kg	1.196151361	Elementary flow

Lead	water/unspecified	Mass	kg	90.67631674	Elementary flow
Lead	air/high population density	Mass	kg	9.01136655	Elementary flow
Lead compounds	air/unspecified	Mass	kg	0.001403077	Elementary flow
Lead-210/kg	water/unspecified	Mass	kg	1.31618E-10	Elementary flow
Lithium, ion	water/unspecified	Mass	kg	1355.811669	Elementary flow
m-Xylene	water/unspecified	Mass	kg	0.038380712	Elementary flow
Magnesium	water/unspecified	Mass	kg	795.9932342	Elementary flow
Magnesium	air/unspecified	Mass	kg	4.073485594	Elementary flow
Manganese	water/unspecified	Mass	kg	12.02837943	Elementary flow
Manganese	air/unspecified	Mass	kg	0.179363516	Elementary flow
Manganese compounds, unspecified	air/unspecified	Mass	kg	0.041454561	Elementary flow
MCPA	water/unspecified	Mass	kg	1.3504E-05	Elementary flow
Mercaptans, unspecified	air/unspecified	Mass	kg	70.34928846	Elementary flow
Mercury	air/unspecified	Mass	kg	0.434663447	Elementary flow
Mercury	water/unspecified	Mass	kg	0.000296709	Elementary flow
Mercury compounds, unspecified	air/unspecified	Mass	kg	4.0179E-08	Elementary flow
Metallic ions, unspecified	water/unspecified	Mass	kg	1.014826016	Elementary flow
Metals, unspecified	air/unspecified	Mass	kg	0.105953467	Elementary flow
Methacrylic acid, methyl ester	air/unspecified	Mass	kg	0.006483837	Elementary flow
Methane	air/unspecified	Mass	kg	7215.516688	Elementary flow
Methane	air/low population density	Mass	kg	340024500	Elementary flow
Methane, bromo-, Halon 1001	air/unspecified	Mass	kg	0.051870699	Elementary flow
Methane, chlorotrifluoro-, CFC-13	air/unspecified	Mass	kg	1.9872E-05	Elementary flow
Methane, dichloro-, HCC-30	water/unspecified	Mass	kg	0.000829091	Elementary flow
Methane, dichloro-, HCC-30	air/unspecified	Mass	kg	0.134249533	Elementary flow
Methane, dichlorodifluoro-, CFC-12	air/unspecified	Mass	kg	4.50717E-05	Elementary flow
Methane, dichlorodifluoro-, CFC-12	air/low population density	Mass	kg	3.15724E-05	Elementary flow
Methane, fossil	air/unspecified	Mass	kg	638.6547928	Elementary flow
Methane, monochloro-, R-40	water/unspecified	Mass	kg	5.09872E-05	Elementary flow
Methane, monochloro-, R-40	air/unspecified	Mass	kg	0.17182169	Elementary flow
Methane, tetrachloro-, CFC-10	air/unspecified	Mass	kg	0.004374122	Elementary flow
Methane, tetrachloro-, CFC-10	water/unspecified	Mass	kg	3.18881E-05	Elementary flow
Methane, trichlorofluoro-, CFC-11	air/high population density	Mass	kg	0.000147183	Elementary flow
Methanol	air/unspecified	Mass	kg	0.002232169	Elementary flow
Methyl ethyl ketone	air/unspecified	Mass	kg	0.126434828	Elementary flow

Methyl ethyl ketone	water/unspecified	Mass	kg	0.008137778	Elementary flow
Metolachlor	air/low population density	Mass	kg	0.184987627	Elementary flow
Molybdenum	water/unspecified	Mass	kg	0.029119701	Elementary flow
n-Hexacosane	water/unspecified	Mass	kg	0.000845654	Elementary flow
N-Nitrodimethylamine	air/unspecified	Mass	kg	0.000572629	Elementary flow
Naphthalene	water/unspecified	Mass	kg	28.36984931	Elementary flow
Naphthalene	air/unspecified	Mass	kg	0.056377481	Elementary flow
Naphthalene, 2-methyl-	water/unspecified	Mass	kg	0.020064601	Elementary flow
Naphthalenes, alkylated, unspecified	water/unspecified	Mass	kg	0.000206488	Elementary flow
Nickel	air/unspecified	Mass	kg	0.30754272	Elementary flow
Nickel	water/unspecified	Mass	kg	0.222391899	Elementary flow
Nickel	air/high population density	Mass	kg	0.10609255	Elementary flow
Nickel compounds, unspecified	air/unspecified	Mass	kg	0.000140308	Elementary flow
Nickel, ion	water/unspecified	Mass	kg	0.984817679	Elementary flow
Nitrate	air/high population density	Mass	kg	0.1086462	Elementary flow
Nitrate	water/unspecified	Mass	kg	0.005366394	Elementary flow
Nitrate compounds	water/unspecified	Mass	kg	1.00858E-06	Elementary flow
Nitric acid	water/unspecified	Mass	kg	0.002262292	Elementary flow
Nitrobenzene	water/unspecified	Mass	kg	0.000829091	Elementary flow
Nitrogen	water/ocean	Mass	kg	272.4598296	Elementary flow
Nitrogen	water/unspecified	Mass	kg	0.210846935	Elementary flow
Nitrogen oxides	air/low population density	Mass	kg	157805.6568	Elementary flow
Nitrogen oxides	air/unspecified	Mass	kg	8434.152635	Elementary flow
Nitrogen, total	water/unspecified	Mass	kg	91982.82337	Elementary flow
Nitrogen, total	air/unspecified	Mass	kg	33.73926	Elementary flow
NMVOC, non-methane volatile organic compounds, unspecified	air/unspecified	Mass	kg	58.59921973	Elementary flow
NMVOC, non-methane volatile organic compounds, unspecified origin	air/unspecified	Mass	kg	690.7416934	Elementary flow
NOx (as NO2)	Flows	Mass	kg	1814.487371	Elementary flow
o-Cresol	water/unspecified	Mass	kg	0.036441108	Elementary flow
Octadecane	water/unspecified	Mass	kg	0.01889188	Elementary flow
Oils, unspecified	water/unspecified	Mass	kg	11977.59498	Elementary flow
Organic acids	air/unspecified	Mass	kg	0.000483229	Elementary flow
Organic substances, unspecified	water/unspecified	Mass	kg	8.2241191	Elementary flow
Organic substances, unspecified	air/unspecified	Mass	kg	5.133151652	Elementary flow
p-Cresol	water/unspecified	Mass	kg	0.039318328	Elementary flow

PAH, polycyclic aromatic hydrocarbons	air/unspecified	Mass	kg	0.003108135	Elementary flow
Paraquat	air/low population density	Mass	kg	0.00374455	Elementary flow
Particulates, < 2.5 um	air/unspecified	Mass	kg	3.66936E-09	Elementary flow
Particulates, > 2.5 um, and < 10um	air/unspecified	Mass	kg	1456.106324	Elementary flow
Particulates, unspecified	air/unspecified	Mass	kg	2028.751967	Elementary flow
Pendimethalin	water/unspecified	Mass	kg	0.000824697	Elementary flow
Pendimethalin	air/low population density	Mass	kg	0.01924278	Elementary flow
Pentanone, methyl-	water/unspecified	Mass	kg	0.005323425	Elementary flow
Permethrin	air/low population density	Mass	kg	0.001729337	Elementary flow
Permethrin	water/unspecified	Mass	kg	7.41157E-05	Elementary flow
Phenanthrene	air/unspecified	Mass	kg	0.003487926	Elementary flow
Phenanthrene	water/unspecified	Mass	kg	0.000162885	Elementary flow
Phenanthrenes, alkylated, unspecified	water/unspecified	Mass	kg	8.56181E-05	Elementary flow
Phenol	air/unspecified	Mass	kg	0.014589598	Elementary flow
Phenol	water/unspecified	Mass	kg	0.004970568	Elementary flow
Phenol, 2,4-dimethyl-	water/unspecified	Mass	kg	0.035482301	Elementary flow
Phenols, unspecified	air/unspecified	Mass	kg	0.017258535	Elementary flow
Phenols, unspecified	water/unspecified	Mass	kg	5.022952422	Elementary flow
Phenylisocyanate	air/unspecified	Mass	kg	0.002933707	Elementary flow
Phorate	water/unspecified	Mass	kg	2.2926E-05	Elementary flow
Phosphate	water/ground-	Mass	kg	0.0013929	Elementary flow
Phosphate	water/unspecified	Mass	kg	4.80684865	Elementary flow
Phosphoric acid	air/unspecified	Mass	kg	0.000127552	Elementary flow
Phosphorus	water/unspecified	Mass	kg	9.327440392	Elementary flow
Phosphorus compounds, unspecified	water/unspecified	Mass	kg	2017.507383	Elementary flow
Phthalate, dioctyl-	air/unspecified	Mass	kg	0.023666006	Elementary flow
Propanal	air/unspecified	Mass	kg	0.12319291	Elementary flow
Propene	air/unspecified	Mass	kg	0.047731186	Elementary flow
Pyrene	air/unspecified	Mass	kg	0.000122205	Elementary flow
Radioactive species, Nuclides, unspecified	water/unspecified	Radioactivity	kBq	4083.788543	Elementary flow
Radioactive species, unspecified	air/unspecified	Radioactivity	kBq	11005604.95	Elementary flow
Radionuclides (Including Radon)	air/unspecified	Mass	kg	3.521841039	Elementary flow
Radium-226/kg	water/unspecified	Mass	kg	4.57893E-08	Elementary flow
Radium-228/kg	water/unspecified	Mass	kg	2.34232E-10	Elementary flow
Selenium	air/unspecified	Mass	kg	0.506046674	Elementary flow

Selenium	water/unspecified	Mass	kg	0.012687252	Elementary flow
Silver	water/unspecified	Mass	kg	2.654335226	Elementary flow
Simazine	air/low population density	Mass	kg	0.012150042	Elementary flow
SO2	Flows	Mass	kg	1026.556419	Elementary flow
Sodium, ion	water/unspecified	Mass	kg	12906.49729	Elementary flow
Solids, inorganic	water/unspecified	Mass	kg	5.75181E-06	Elementary flow
Spent chlorofluorocarbon solvents, unspecified	water/unspecified	Mass	kg	0.000829091	Elementary flow
Strontium	water/unspecified	Mass	kg	69.05578809	Elementary flow
Styrene	air/unspecified	Mass	kg	0.008104797	Elementary flow
Sulfate	water/unspecified	Mass	kg	269.5111891	Elementary flow
Sulfate	air/high population density	Mass	kg	7.54854297	Elementary flow
Sulfide	water/unspecified	Mass	kg	1247.294755	Elementary flow
Sulfide	water/ocean	Mass	kg	1.65523E-06	Elementary flow
Sulfite	water/river	Mass	kg	0.000152058	Elementary flow
Sulfur	water/unspecified	Mass	kg	3.356148569	Elementary flow
Sulfur dioxide	air/high population density	Mass	kg	4.5584974	Elementary flow
Sulfur dioxide	air/unspecified	Mass	kg	19643.42901	Elementary flow
Sulfur oxides	air/unspecified	Mass	kg	3920.80162	Elementary flow
Sulfuric acid	air/unspecified	Mass	kg	0.002678602	Elementary flow
Sulfuric acid	water/unspecified	Mass	kg	1.842204284	Elementary flow
Sulfuric acid, dimethyl ester	air/unspecified	Mass	kg	0.01556121	Elementary flow
Suspended solids, unspecified	water/unspecified	Mass	kg	33531862.48	Elementary flow
t-Butyl methyl ether	air/unspecified	Mass	kg	0.011346715	Elementary flow
Tar	air/unspecified	Mass	kg	3.98488E-06	Elementary flow
Tar	water/unspecified	Mass	kg	5.70028E-08	Elementary flow
Terbufos	air/low population density	Mass	kg	0.030248867	Elementary flow
Tetradecane	water/unspecified	Mass	kg	0.030704253	Elementary flow
Thallium	water/unspecified	Mass	kg	0.003045429	Elementary flow
Thermal Storage System	Flows	Mass	kg	1	Product flow
Tin	water/unspecified	Mass	kg	0.139902433	Elementary flow
Titanium, ion	water/unspecified	Mass	kg	0.22154405	Elementary flow
TOC, Total Organic Carbon	air/unspecified	Mass	kg	0.005628985	Elementary flow
Toluene	water/unspecified	Mass	kg	2.008528688	Elementary flow
Toluene	air/unspecified	Mass	kg	0.086010471	Elementary flow
Toluene, 2,4-dinitro-	air/unspecified	Mass	kg	9.07737E-05	Elementary flow

Triethyl amine	air/unspecified	Mass	kg	0.001849511	Elementary flow
Vanadium	water/unspecified	Mass	kg	0.034397944	Elementary flow
Vinyl acetate	air/unspecified	Mass	kg	0.002463858	Elementary flow
VOC, volatile organic compounds	air/unspecified	Mass	kg	604.4175392	Elementary flow
Xylene	water/unspecified	Mass	kg	1.041676387	Elementary flow
Xylene	air/unspecified	Mass	kg	0.017765168	Elementary flow
Yttrium	water/unspecified	Mass	kg	0.008536513	Elementary flow
Zinc	water/unspecified	Mass	kg	0.674887501	Elementary flow
Zinc	air/high population density	Mass	kg	3.17279405	Elementary flow
Zinc	air/unspecified	Mass	kg	0.141934647	Elementary flow
Zinc compounds	air/unspecified	Mass	kg	0.006313849	Elementary flow
Zinc, ion	water/unspecified	Mass	kg	43.12125701	Elementary flow