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UNIVERSITI TEKNOLOGI PETRONAS

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By

CHIMA CYRIL HAMPO

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by

CHIMA CYRIL HAMPO

A Thesis

Submitted to the Postgraduate Studies Programme

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MASTER OF SCIENCE

MECHANICAL ENGINEERING

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR,

PERAK

DECLARATION OF THESIS

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hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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DEDICATION.

This research project is dedicated to my loving parents Mr and Mrs Cyril Hampo, my brother Justin Ebuka Hampo, my lover Ms. Kalpani Rasangika Ambagaha Hewage Dona and friend Musa Muhammed, for their words of encouragement and support.

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ABSTRACT

About 50% of the global energy consumption is attributed to heating, ventilation, and air conditioning systems installed in buildings. In addressing the intensity of energy consumed for air conditioning purposes, there has been a global increase in the installation of District Cooling (DC) plants. In traditional DC setup, standalone Vapor Compression Chillers (VCC) function to produce chilled water for air conditioning purpose in remote building network. In achieving better flexibility between energy generation and usage, modern DC plants are now installed with Thermal Energy Storage (TES) tanks. Pairing the functionalities of VCC and TES allows the VCC to operate during off peaks hours, producing chilled water to charge the TES tanks, which would be used during peak times. The operation of the VCC plants is considered as the most energy-intensive component, accounting for about 40% of the entire electricity supplied to the DC plant. In the literature, few studies have considered the sustainability of various types of vapor compression systems, but none is available on the integrated VCC-TES systems, especially as it is now a mandatory requirement by governmental bodies to conduct holistic sustainability assessment of energy intensive systems. In addressing this gap, a Life Cycle Assessment (LCA) and a Life Cycle Cost (LCC) model were developed. The LCA model is used to investigate the environmental impact, while the LCC model is used to assess the economic implications resulting from the life cycle of the VCS respectively. The Life Cycle Impact Assessment (LCIA) results reveal that the carbon footprint per 1RTh of the produced chilled water is estimated at 0.72kg CO_2 eq/ RTh, which indicates a 40% reduction in comparison with the conventional DC setup. While the LCC result per 1RTh of chilled water produced by the VCC is estimated at MYR 1.44/RTh which indicates a 28.6% reduction in comparison with the conventional DC setup. Among other optimized scenarios further considered, incorporating a more stable oilless magnetic compressor and sourcing electricity from a Natural Gas Plant (NGP) in the VCC system presented the most significant environmental savings (78%) and economic improvements (51%), respectively.

ABSTRAK

Kira-kira 50% daripada penggunaan tenaga global dikaitkan dengan pemanasan, pengudaraan, dan sistem penyaman udara yang dipasang di bangunan. Dalam menangani keamatan tenaga yang digunakan untuk tujuan penyaman udara, terdapat peningkatan global dalam pemasangan loji District Cooling (DC). Dalam persediaan DC tradisional, penyejuk mampatan vapor (VCC) yang berfungsi secara berdiri sendiri untuk menghasilkan air sejuk untuk tujuan penyaman udara di rangkaian bangunan jauh. Dalam mencapai fleksibiliti yang lebih baik antara penjanaan tenaga dan penggunaan, loji DC moden kini dipasang dengan tangki Penyimpanan Tenaga Terma (TES). Menggandingkan fungsi VCC dan TES membolehkan VCC beroperasi semasa waktu puncak, menghasilkan air sejuk untuk mengecas tangki TES, yang akan digunakan pada waktu puncak. Operasi loji VCC dianggap sebagai komponen yang paling intensif tenaga, menyumbang kira-kira 40% daripada keseluruhan elektrik yang dibekalkan ke loji DC. Dalam kesusasteraan, beberapa kajian telah mempertimbangkan kelestarian pelbagai jenis sistem mampatan wap, tetapi tidak ada yang terdapat pada sistem VCC-TES bersepadu, terutamanya kerana ia kini menjadi keperluan mandatori oleh badan-badan kerajaan untuk menjalankan penilaian kelestarian holistik sistem intensif tenaga. Dalam menangani jurang ini, model Penilaian Kitaran Hayat (LCA) dan Kos Kitaran Hayat (LCC) telah dibangunkan. Model LCA digunakan untuk menyiasat kesan alam sekitar, manakala model LCC digunakan untuk menilai implikasi ekonomi yang terhasil daripada kitaran hayat VCS masing-masing. Keputusan Penilaian Impak Kitaran Hayat (LCIA) mendedahkan bahawa jejak karbon setiap 1RTh air sejuk yang dihasilkan dianggarkan pada 0.72kg $CO2$ eq / RTh, yang menunjukkan pengurangan 40% berbanding dengan persediaan DC konvensional. Manakala keputusan LCC bagi setiap 1RTh air sejuk yang dihasilkan oleh VCC dianggarkan sebanyak MYR 1.44/RTh yang menunjukkan pengurangan 28.6% berbanding dengan persediaan DC konvensional. Antara senario lain yang dioptimumkan bagi selanjutnya dipertimbangkan, menggabungkan pemampat magnetik tanpa minyak yang lebih stabil dan mendapatkan elektrik dari Loji Gas Asli (NGP) dalam sistem VCC masing-masing membentangkan penjimatan alam sekitar yang paling ketara (78%) dan peningkatan ekonomi (51%).

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LIST OF ABBREVIATIONS

AC	Air Condition
AD	Acidification
AHU	Air Handling Units
ASEAN	Association of Southeast Asian Nations
BMS	Building Management Systems
CC	Chilled Ceiling
CN	China
CF	Carbon Footprint
CL	Cooling Load
COP	Coefficient of Performance
CW	Chilled Water
DC	District Cooling
DCS	District Cooling System
ECC	Electric Centrifugal Chiller
EEV	Electronic Expansion Valve
EL	Environmental Load
EP	Electric Power
EU	Eutrophication
FD	Fossil Depletion
FET	Freshwater Ecotoxicity
FM	Fuel Mix
FU	Functional Unit
GHG	Green House Gas
GLO	Global
GWP	Global Warming Potentials
HVAC	Heat, Ventilation and Air Conditioning
HT	Human Toxicity
IGV	Inlet Guide Vanes

ISO	International Standard Organization
KC	Kalina Cycle
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCEL	Life Cycle Environmental Load
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MET	Marine Ecotoxicity
MY	Malaysia
MYR	Malaysia Ringgit
NEG	National Electricity Grid
NG	Natural Gas
NGP	Natural Gas Plant
OD	Ozone Depletion
POC	Photochemical Oxidant Creation
POF	Photochemical Oxidant Formation
RE	Renewable Energy
RM	Malaysia Ringgit
RoW	Rest of the world
SAC	Suction Absorption Chiller
TES	Thermal Energy Storage
TET	Terrestrial Ecotoxicity
VCC	Vapor Centrifugal Chiller
VCS	Vapor Compression System
VSD	Variable Speed Drives
WD	Water Depletion

CHAPTER 1

INTRODUCTION

1.1 Chapter Overview

This chapter presents an overview of the project background with details of the research ideology associated with the sustainable utilization of a Vapor Compression System installed in the District Cooling Plant.

1.2 Background of study

About 50% of the consumed energy in many regions of the world is attributed to heating, ventilation, and air conditioning (HVAC) systems, especially in hot tropical countries like Singapore, Malaysia, etc. [1]. Conventional cooling systems like split AC units, chillers installed in the basement of buildings are commonly used to satisfy cooling demands globally [2]. On the other hand, a well-managed District Cooling DC Technique to supply air conditioning services to a network of buildings in cities is 50% more efficient than a conventional technique [3]. However, researchers have developed several methods over the past few decades to optimize District Energy operations' performance [3, 4].

In recent times, the integration of storage systems technologies into DC setups has gained worldwide implementation. In various DC facilities, TES systems have been installed to optimize the operation of the DC plant and meet the fluctuating demand for supply of chilled water for air conditioning purposes. Different electricity tariffs during various times of the day benefit the integration of the TES technology. The TES tank assists with load leveling and peak shaving [5]. The peak load shaving is achieved by charging the TES tanks during the off-peak period (at night) with the VCC operating at full capacity when it exhibits maximum performance. The stored chilled water satisfies the district cooling load during the day (on-peak) while the VCC systems are shut down.

This setup allows the cooling technologies in the central cooling station to be sized closer to the average load than the peak load. In addition, the electricity used for pumping water through the district network and operating electricity-based chillers can be shifted to off-peak hours.

Out of the total electricity supplied to the DC plant, VCC accounts for about 40%, making it the most energy-consuming system in the DC plant [6]. Since it is now a national and international requirement to conduct sustainability assessment of energy intensive system (like VCC), it is therefore necessary to evaluate the environmental impact of the chiller system in terms of their material and energy consumed, especially with its integration with the TES tank.

Several qualitative and quantitative methodologies have been developed and adopted to assess the environmental performance of the energy system. These classified quantitative or qualitative techniques commonly used include environmental benchmarking, simplified LCA checklist, Material, Energy, Toxic emissions Matrix, Life Cycle Assessment LCA, etc. Amongst these options, the LCA methodology stands out as the most preferred tool for analyzing the environmental performance of energy-intensive systems [7, 8]. Although the LCA methodology has significantly been used to analyze various energy systems in the literature, only limited research on HVAC systems is presently available, with non on VCC and TES systems used in DC plants.

With the global increase in integrating the functionalities of VCC and TES operations into modern DC plants, it is vital to understand the contributions of these emerging technologies to achieving the global energy and climate change goals and the environmental and economic sustainability of these energy-intensive systems as compared to conventional systems. This is the primary objective of this thesis, as further discussed in the section below. A case study of a DC plant situated in Putrajaya Precinct 1 in Malaysia is analyzed to achieve this study's objectives. The Putrajaya DC plant is the largest in Malaysia, installed with four VCC systems and two large TES tanks. This study model the VCS based on LCA and LCC methodologies, and the results based on their environmental and cost implications are presented and analyzed.

1.3 Problem Statement

Sustainable development is a key instrument for national and international energy roadmaps, influencing the actors involved in decision-making strategies and processes [9]. Investigating the sustainability of energy systems are critical puzzles for humanity, as it accounts for the largest causes of GHG emissions globally [10], as a result, new advanced technologies that can provide improved environmental quality, efficiency, cost management, and energy security are in high demand.

In terms of the global energy consumption, about 50% is attributed to heating, ventilation, and air conditioning systems installed in several households to big shopping and industrial complexes [10]. In addressing the intensity of energy consumed for air conditioning purposes, there has been several installations of DC plants, especially in tropical countries like Malaysia. In traditional DC setup, standalone VCC systems function to produce chilled water used for air conditioning purpose within the building network. In achieving better flexibility between energy generation and usage, in terms of time, temperature, power, etc., modern DC plants are installed with TES tanks [5]. Pairing the functionalities of VCC and TES allows the VCC to operate during off peaks hours, producing chilled water to charge the TES tanks, which would be used during peak times [10]. Although, there have been a few studies in the literature that considered the sustainability of several types of vapor compression systems [11], none have focused on the integrated VCC-TES systems in the DC plant, especially in comparing the ecological and economic gains to traditional setups. Therefore, there is an urgency, especially as it is now a mandatory requirement by governmental bodies (like Malaysia [12]) to conduct holistic sustainability assessment of energy intensive systems.

Since decision making processes involve logical choices from a set of available options, especially in relation to energy systems, the search for a logical and optimal solution is a complex process as it involves many sources of uncertainty, long time frame, capital-intensive investments and a large number of stakeholders with different views and preferences [13]. In this sense, multiple criteria are needed to reflect the complexity of the sustainability assessment for decision-makers. This means taking into account not only technical and environmental criteria but also economic indicators.

This study employs the Life Cycle Assessment and Life Cycle Costing standardized methodologies to holistically assess the environmental and cost implication of the VCS.

1.4 Research Objective

The following are the study's objectives in relation to the above-mentioned problem statement:

1 To evaluate the total environmental impact of the vapor compression system installed with a thermal energy storage in the DC plant by adopting a comprehensive cradle-to-grave life cycle assessment system modelling.

2 To estimate the economic implications of the Vapor Compression System integrated with a thermal energy storage in the DC plant by developing an LCC model.

3 To compare the sustainability of the case study in terms of their environmental and cost contribution with the conventional DC setup, while evaluating them for practical applications and potential operational improvements.

1.5 Scope of Research

The project aims to evaluate the environmental and economic performance of four VCC systems installed in a DC plant throughout its life span of 25 years, using the Putrajaya DC plant as a case study. Firstly, the environmental impact resulting from the Cradle-to-Grave life cycle of the chiller components is assessed. This evaluation is carried out using the LCA methodology, with the system modeled in Umberto LCA+ software installed along with the Eco-Invent database. An economic evaluation of the system is performed using Life Cycle Cost analysis. Electrical Power (EP) used to power these systems are acquired directly from the Malaysia grid electricity supply. Tenaga Nasional Berhad (TNB) tariff C2 is used to estimate the cost of electricity utilized throughout the plant operation phase.

The component materials, design capacities, and operational data of the VCC system are sourced from the plant technicians, literature, and EcoInvent database for this analysis. The VCC systems are installed with constant speed compressors, which drive the system to produce Chilled Water (CW) at maximum load capacity to charge the TES tank during off-peak periods (10 p.m.–8 a.m.). Microsoft Excel spreadsheet software is used to prepare, manage, and analyze the data obtained in raw format.

1.6 Organization of the Thesis

This research work is sectioned into five chapters: introduction, literature review, methodology, results, discussion, and conclusion and recommendation. The first chapter is presented in the above section.

The second chapter presents an overview of District Cooling plants and their mode of operation. This is followed by discussions on Chilled Water Production, types of chiller systems, and the mathematical modeling of a Vapor Compression System. An extensive review of the performance modeling of vapor compression chillers is also conducted. Thermal Energy Storage was also discussed, along with its function and charging and discharging procedures. The presentation included an explanation of LCA and LCC and a comprehensive literature review on the Life Cycle Analysis of HVAC systems. The chapter ended with a summary of the review and a discussion of the research gap.

Chapter 3 presented a flow chart summarizing the methodology for achieving the research objectives. Then the thermodynamics modeling of the VCS to estimate the performance parameters of the system was conducted. Afterward, the LCA and LCC models were developed using the Umberto LCA+ software. This section was concluded by defining other alternative scenarios for potential system optimization.

In chapter 4, the Life Cycle Inventory results were presented. This was followed by Life Cycle Impact Assessment results and the contribution of each life cycle phase to the overall impact assessment. Afterward, the result of the case study is then compared with several optimized models and the literature to estimate the environmental savings. This is then followed by the result of the Life Cycle Cost of the base VCS. The economic implication as a result of operating the VCS under several considered conditions was also presented

The last chapter presented a conclusion of the research work, which summarizes the major findings related to the stated objectives. Research proposals then followed this in the form of recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

This chapter provides relevant information on the background of the intended study. It includes an extensive review of the design configuration and performance evaluation of the VCS and their functionalities in a District Cooling Plant. This is then followed by a comprehensive review of research works on the optimization of the performance parameter of the system. Subsequently, studies on assessing the environmental and economic impacts resulting from life cycle energy and material usage of various HVAC and chiller systems were also extensively reviewed. However, despite the range of modeling options available in the literature, a research gap that forms this research's objective was obtained.

2.2 Overview of District Cooling plants.

District Cooling is a centralized infrastructure for producing and distributing thermal energy in the form of chilled water to a large complex or areas comprising residential, offices, and commercial buildings for air conditioning purposes. A district cooling system consists of the cooling sources, distribution network, and customer installations.

The centralization of chilled water production in DC plants eliminates the need for each building to have its cooling production system, which would involve a very high capital and operational cost. A third party owns, operates, and manages the chilled water and distributes it through a network to respective customers. However, this operation requires installing heat exchangers, i.e., Air Handling Units (AHUs), at buildings.

The review by Lake et al. [14] gave numerous instances where district energy systems produced reduced GHG emissions compared to conventional systems [15]. This reduction is a result of the higher efficiency equipment utilized in the centralized energy production plants.

In a more technical setting, the operation of a DCS is complemented by a TES tank with the chiller system. This allows for an increased operation flexibility, as the chillers are not required to be used to always meet the cooling demands, especially during peak hours. The storage tanks are supplied with chilled water during off-peak periods for future use (especially during peak periods).

In the comprehensive review of several types of TES applications by Alva et al. [16], water-cooled TES tanks are identified as the most common type of TES due to their high thermal capacity and availability. While Rismanchi et al. [17] concluded that cold TES systems have the highest energy efficiencies, ranging from 90%–98%, and lowest exergy efficiencies often below 20%. TES tanks can also be designed to support both daily and seasonal cycles [18]. In terms of using the TES system to satisfy daily demands, thermal energy can be produced during the night when the cost of tariff is usually at the lowest and the system functions more efficiently, and then used during the day when the price of electricity tariff is at its highest and the plant operates less efficiently.

2.3 Chilled Water Production in District Cooling Plants.

Chilled water is the main product of the DC plant. Two chiller types based on their mode of operation and energy source used in DC plants include the Vapor Compression Chillers (VCC) and the Absorption Chillers. This section would focus on the description of the vapor Compression Chiller.

2.3.1 Vapor Compression Chiller

The Vapor Compression Chiller (VCC) system comprises four major components: the expansion valve, condenser, evaporator, and compressor. The refrigerant is circulated around the system and is condensed by the high pressure of the condenser, whereas the evaporator vaporizes the refrigerant as it experiences low vapor pressure. While the compressor and expansion valves aid in the compression and expansion of the refrigerant, the condenser functions by rejecting the heat from the refrigerant vapor. Based on the compressor designs, the various VCC systems like the screw, reciprocating, and centrifugal compressor are categorized [19].

2.3.1.1 Mathematical modeling of a Vapor Compression System

VCC system employs the vapor-compression cycle to chill water and eject the heat into the atmosphere. Figure 2.1 displays the basic components of an ideal vapor-compression cycle.

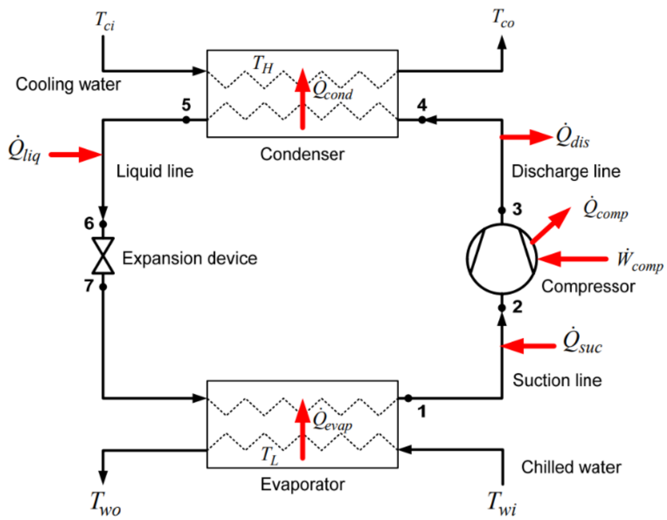


Figure 2.1: **Schematic diagram of a vapor-compression system [20]**.

The compressor raises the refrigerant temperature and pressure above the ambient to aid heat dissipation from the system to the atmosphere. Meanwhile, the refrigerant temperature is reduced by the Electronic Expansion Valve (EEV) to aid the absorption of heat from the water medium. The efficiencies of the heat pumps and vapor compression chillers are strongly linked to the inlet and outlet temperatures of the external sources and control systems. Therefore, to compute the energy consumed by each unit system, it is necessary to know the energy efficiency and heating capacity of the existing system.

In evaluating the performance of a simple refrigeration unit system, a numerical model is developed as described in ref [20]. This model provides a mathematical formula for estimating the cooling load and power consumed. Knowledge of detailed geometric and performance parameters of the system components is not required for this model but only unit details of the compressor and refrigerant circuit.

With the given input parameters of the condenser fan speed, water supply set-points, compressor motor velocity, and the properties of the vapor compression cycle, the model can estimate the chiller cooling capacity, the power consumptions, and the COP value of the systems. The first law of efficiency of a vapor-compression chiller system used in this study's analysis is defined as follows:

$$COP_{act} = \frac{Q_{evap}}{W_{comp}} \tag{2.1}$$

The second law of efficiency is the ratio of the actual COP to the highest feasible COP under given conditions.:

$$\eta_{II} = \frac{COP_{act}}{COP_{rev}} \tag{2.2}$$

where COP_{rev} is defined as:

$$COP_{rev} = \frac{T_L}{(T_H - T_L)} \tag{2.3}$$

2.3.1.2 Performance modeling of vapor compression chillers.

Simulation and statistical evaluations are established techniques for analyzing the performance of chiller systems. A mathematical model is developed, validated by experimental or operating data to identify the theoretical energy performance under an ideal scenario. The result of the model is then compared with the actual performance data to see if any fault or abnormalities causes a decline in the COP value.

Several models were developed in the literature for the first principle and correlation-based case modeling of VCS.

Cecchini and Marshal [21] created a model for simulating refrigeration and air conditioning specified by the first principle. The model assumed a steady-state operation, constant subcooling, and superheating at the condenser and evaporator outlets, respectively. In a related analysis, the model developed by Gordon and Ng [22] relates the COP and cooling load of the chiller using a simple thermodynamic numerical modeling. Internal losses, chilled water leaving temperature, and condenser water entering temperature are all used in the model to calculate condenser and evaporator performance.

For vapor compression chillers, the correlation-based model has been utilized for a variety of reasons. Models for direct and indirect ice storage modeling were developed by Strand et al. [23]. The simulation program was used to model the operation characteristics of the evaporator, compressor, and condenser. By comparing data on condenser supply temperature in water-cooled chillers, Figuera et al. [24] established a model for water-cooled centrifugal chillers.

Jahing et al. [25] developed a semi-empirical model for representing domestic refrigerator/freezer compressor. McIntosh et al. [26] developed two models for vapor compression systems using a simple vapor compression cycle as a framework for compressors and heat exchangers. In the simulation of vapour compression chillers, the model was built for fault diagnosis and detection.

Ng et al. [27] developed a basic thermodynamic model for a centrifugal chiller using regression analysis and experimentally verified the model using data from an air-conditioning facility. Due to the throttling action of the guiding vanes, the model accurately anticipated the operating regimes for the chillers in terms of high and low load and efficiency. Bourdouxhe et al. [28] created a toolbox for calculating the energy consumption of HVAC systems. For the heat exchangers, a realistic technique was used while the pressure decreases were ignored. Some fundamental formulae for different compressors were established to determine the mass flow rate of the refrigerant in the system.

For a centrifugal chiller with variable speed control, Braun et al. [29] utilized a mechanistic model to estimate cooling capacity, power requirements, and circumstances when compressor surge occurs. The heat exchanger pressure decreases, and the impact of sensible cooling of the superheated refrigerant on the condensing heat transfer coefficient was not taken into account in the model. The centrifugal, screw, and reciprocating compressors of the chillers whose specifications were not provided were modeled using the DOE2 program by Beyene et al. [30]. The performance of the chiller under full and half load was predicted using parameters such as occupancy and weather data. The research was based on the performance of 39 conventional chillers. The results were significantly different from the manufacturer's expectations. Yik and

Chan [31] developed a model that can estimate the performance requirement of a given air-conditioning design and also provide the optimum design option that would account for a higher performance system rating. The formulation of the model is based on regression analysis which is specifically developed for refrigeration system components.

In summary, some research mainly focused on data mining for improving the energy efficiency of VCS in buildings. However, many studies in the literature rely on software simulations, using software like TRNSYS. Data analytics using accurate building performance parameters can assist in estimating energy savings, which forms the basics for most technical decision-making. Other research focuses on techniques like machine learning to forecast the energy efficiency and rate of consumption in the building and then compare the predicted results with the conventional ones to detect possible defections. The other technique found in the literature is a grey box modeling approach, which merges the qualities and quantity of both the physics-based and data-driven models.

Concerning the measurement of energy efficiency, several indicators (EEI) can be used in the data analysis, ranging from the COP or EER (Energy Efficiency Ratio) to more complex indicators such as IPLV (Integrated Part Load Value), SEER (Seasonal Energy Efficiency Ratio) and SCOP (Seasonal Coefficient of Performance), which consider seasonal chiller operations and capacity modulation. In this study, thermodynamics modelling of the VCC system was performed using the second law of thermodynamics (outline in equation 2.6) to compute the COP value, electricity consumed, and cooling load, using operational plant performance data.

2.3.2 Thermal Energy Storage in District Cooling System

Thermal Energy Storage tank helps store chilled water during periods of less cooling requirements and discharge the cold energy to satisfy cooling loads at a different time, often during peak demands. Integrating the functionalities of a TES tank in a DC setup helps reduce the operational cost, especially in regions that offer different tariff charges for peak and off-peak periods of the day. Therefore, the operation of TES has a positive impact on the electricity grid system, as it can reduce the peak electricity demand and simultaneously lowering the cost of refrigeration as electricity consumption is shifted to the off-peak hours with lower energy prices.

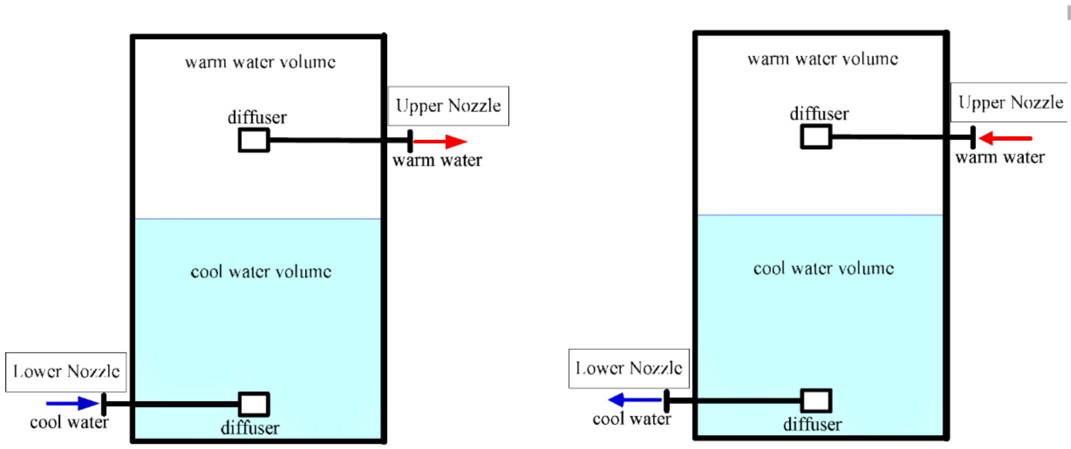
However, if there is no significant difference in the tariff charges during peak and off-peak hours, integrating the TES technology is not the most economical option.

In terms of the choice of the storage medium, water ranks as the most preferred medium among other storage mediums due to its availability, low cost, and high thermal capacity. Also, water as a storage medium makes the connecting networks of the DC system technically less complex. Another popular storage medium is ice storage, which takes advantage of the latent heat of ice, therefore resulting in a smaller storage volume. This type of storage is popular in Paris, France [32]. In conclusion, though ice storage requires less storage space, the production requires low evaporation temperature, resulting in lower plant efficiency in cold energy production. Meanwhile, water-based storage can take advantage of the higher temperature requirement, which provides higher efficiencies, but the volume of the tank required is higher. The water-based storage type is adopted in the case study used in this research.

2.3.2.1 The charging and discharging of the thermal energy storage tank.

The TES tanks are mostly cylindrical vessels installed with two nozzles, one at the top and the other at the bottom area of the tank [5]. The effect of the TES tank stratification, which indicates the quality of the stored chilled water, is preserved by the diffusers provided at the end of the nozzle connections. The diffusers assist in minimizing the disturbance caused by the inlet and outlet water flow in and out of the tank [33]. Charging and discharging of the TES tank are made possible through this system configuration. The tank is often charged during the off-peak period when the cooling demand is lower and discharged during peak periods when the cooling demand is highest [5].

The process of charging involves introducing cool water into the lower nozzle of the TES tank, while warm water is withdrawn from the top nozzle of the TES tank [5]. On the reverse, discharging is done by withdrawing cool water from the lower nozzle of the tank while introducing warm water from the upper nozzle of the tank. Figure 2.2 shows the schematic of the charging and discharging cycle of the stratified TES tank. The temperature of the water entering the TES tank via the lower nozzle from the chiller is considered the charging inlet temperature in a closed charging loop between the chiller and the TES. The outlet temperature represents the temperature of the water exiting the tank from the top nozzle.



(a) (b)

Figure 2.2: **Charging and discharging cycle of the TES tank: (a) Charging: (b) Discharging**

2.4 Life Cycle Assessment

LCA is a systematic analytical tool designed to assess a systems' environmental performance. LCA evaluates a product from the standpoint of the environmental impact on the ecosystem, natural resources, and human health [34]. LCA methodology provides a uniquely defined concept in the form of a functional unit that allows comparison among similar systems and designs. The integrated LCA approach is a unique chain of defined formulas, mass and energy balances that represent the collection and analysis of several system inputs, outputs, and corresponding ecological impact.

LCA has a standardized methodology, as revealed in ISO 14040 [35] and 14044 [36], which researchers and practitioners universally apply. As provided in the ISO 14040 series, the general LCA methodology is characterized by a technically robust framework covering every aspect of the product life cycle, including the system up and downstream. As shown in Figure 2.3, the framework includes four steps: goal and scope, Life Cycle Inventory (LCI phase), Life Cycle Impact Assessment (LCIA), and life cycle interpretation.

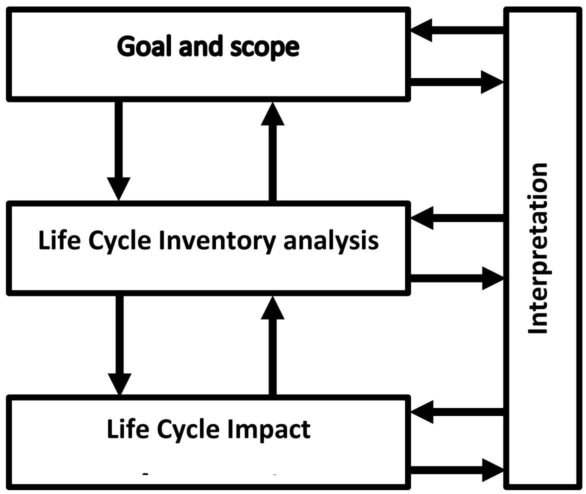


Figure 2.3: **LCA Framework ISO 14040 [35]**

2.4.1 LCA framework

A brief description of the LCA framework is given below.

2.4.1.1 Goal and Scope:

The goal addresses questions on the target audience and objective of conducting the assessment, while the scope defines the depth and breadth of the system boundary, describing the functional unit, data sources, quality of data, and method of impact assessment.

2.4.1.2 Life cycle inventory analysis (LCI):

This phase involves gathering and analyzing system data in order to achieve the study's objectives. LCI produces a quantitative assessment of environmental load. Each unit process of the system is represented by numerous inputs (e.g., material and energy) and their corresponding outputs (e.g., emissions and products) in this evaluation. As a result, the LCI is calculated by combining all of the fractional input and output contributions from each unit process involved in the product's life cycle.

2.4.1.3 Life cycle impact assessment (LCIA):

The environmental impact of the product's weighted ecological load is characterized at this stage [37]. The LCI findings are allocated to the environmental impact classification chosen, and the category indicators are calculated to characterize the result.

2.4.1.4 Life cycle interpretation:

In this last phase, environmental results are evaluated based on sensitivity, completeness, and consistency of the LCA of the product. A report is therefore drawn summarising the various steps, conclusions, and recommendations made.

2.4.2 LCA boundaries

2.4.2.1 Cradle-to-grave:

This phase spans the extraction of raw materials to the usage and disposal of the finished product.

2.4.2.2 Cradle-to-cradle:

This starts with the raw material extraction phase and continues through the product usage and disposal phase to the product recycling phase.

2.4.2.3 Cradle-to-gate:

This begins with the extraction of raw materials and ends at the factory gate.

2.4.2.4 Gate-to-gate:

The investigation begins at a certain point in the product's life cycle and progresses to a predetermined stage.

2.5 Life Cycle Costing

Life cycle costing (LCC) is a technique used to estimate the total accumulated cost of a system over its lifetime [38]. In terms of a complete sustainable analysis, it is often paired with LCA to evaluate the environmental and economic impact of a product. [38, 39]. Several LCC standard techniques applied in the literature can be categories as follows [39]:

1. Cost-Benefit Analysis (CBA)
2. Budget Based Analysis
3. LCA-type LCC.

The capacity to calculate total costs from a consumer perspective and the compatibility of the chosen LCC technique with the LCA methodology are important concerns in this study. The selected LCC model should be able to link measurable cost values to estimated environmental effects. To align the LCA-LCC techniques as suggested by Greening [40], a steady-state modeling is assumed for this study analysis. The LCA-type LCC methodology was chosen for this study since it is the only one of the three techniques described above that uses a steady-state model.

The assumptions established in this study were explained in the next paragraph based on the importance of cost categories, cost bearers, cost models, and cost aggregation to the overall LCC approach [39]. Like all of the methods mentioned above, the LCC approach should select cost categories relevant to the life cycle stages in the associated LCA. The sort of cost bearing that may be considered, on the other hand, differs amongst LCC methods. For example, the technology owner can be designated as the cost bearer in both budget and LCA-type LCC, but the cost bearer in CBA-LCC is a global society [39]. As a result, CBA-LCC is not an appropriate approach for calculating the life cycle cost of a Vapor Compression System technology from the consumer's perspective. In addition, the chosen LCC technique should quantify costs using a model that is comparable to the one used to assess environmental impacts [38].

A steady-state environmental model with no future ecological discount is used in LCA, indicating that in a compatible LCA-LCC method, a steady-state economic model with no future discounting cost should be used [41, 42]. Although the latter is more commonly used, especially in industry, discounting has numerous drawbacks, including the selection of appropriate discounted rates and the fact that it overlooks future generations' costs and benefits [43].

An approach for determining life cycle costs is cost aggregation. This might include summing up all of a product's costs across its life cycle, calculating Payback Time, or determining Net Present Value. In this study, the individual costs involved in each phase of the product's life cycle are tallied without taking inflation or discounting into account to comply with the LCA steady-state model. In an ideal world, discounting expenditures would be done for comparison reasons, but owing to the research restrictions, it is not explored here, with the major objective of using a procedure that runs concurrently with the environmental assessment. On the other hand, discounting expenditures is an area where additional studies may be conducted in the future.

2.6 Literature reviews on Life Cycle Analysis of HVAC systems.

This section examines literature dealing with the Life Cycle Analysis (studies addressing either LCA or LCC or both) of the overall HVAC system. The review structure is divided into two sections, with one section addressing notable research on sustainable life cycle analysis of residential building heating and air conditioning systems, while the other sections address studies on sustainable life cycle analysis of chillers.

2.6.1 Reviews on sustainable life cycle analysis of residential building heating and air conditioning systems.

Several literature reviews address the environmental impact and economic implications of integrating the functionalities of HVAC systems in buildings. A brief overview of these studies is presented in the following paragraphs below.

In terms of assessing heating systems installed in buildings, Prek [45] used the Eco-indicator 95 technique in his research to examine the environmental effect of three single-family heating systems. The investigation focused on the component manufacturing phase of the main system, excluding energy generation for heating. According to the findings, eco-indicator value varies substantially amongst systems with various material components.

In other similar research, L. Gu et al. [44] reported a study on the design of HVAC systems using an integrated index covering the total environment in terms of resource consumption, energy consumption, and emission pollutants through building a life in guiding designs of building energy system. Economic evaluation and Life Cycle Environmental Load (LCEL) of four cooling and heating systems were analyzed and compared with the proposed optimal option. The findings noted that the option with a gas-fired boiler and water-cooled electrical chiller for heating and cooling has the lowest LCEL and best economic performance.

Concerning studies that considered integrating renewable energy sources with HVAC systems in buildings, S. Liu et al. [45] conducted an LCA study to analyze a chilled ceiling system installed in buildings in Singapore. The result of the research indicates that the use phase of the system accounts for most environmental burdens. The accumulated ecological impact of the use-phase recorded a drastic decrease as cleaner energy sources were introduced into the grid electricity mix. Similarly, Shah et al. [46], in their study made a life cycle impact assessment comparison of 3 installed HVAC system in four residential locations in USA. The study analyzed the efficacy of using highly efficient and renewable energy source to their corresponding environmental impact in terms of their regional context. Jing et al. [47] analyzed an HVAC system powered by solar energy and natural gas. Result of the life cycle impact revealed that the material, operation, and fuel stages accounted for the most significant impact than the other considered phases. The integration of cleaner fuels into the system operation also drastically reduced the environmental load of the system. Meanwhile, Martinopoulos et al. [50] mainly focused on the manufacturing phase of solar heating systems. In their research, the influence of various production techniques and material flows in making the solar flat plate collectors used in domestic solar hot water systems is investigated. Result of the study shows that a lower environmental load is recorded using the solar flat plate collector as compared to using electricity to power the domestic hot water systems.

In the study of Finocchiaro et al. [51], the environmental impact of a HVAC system powered with a photovoltaic and a thermal plant is compared to a standard conventional system. Result of the analysis revealed that the production phase accounted for about 95% of the total environmental load of the system, with the other phases sharing the remaining 5%. The solar system made a 200% environmental savings compared to the conventional system.

Some studies also examined the environmental impact resulting from the choice of refrigerant used in air conditioning systems. For example, Kazuta et al. [48] in their study used LCA methodology to quantify and compare the environmental impact of air conditioners using alternative refrigerants. The study involved two air conditioner units for residential use comparatively. The refrigerant used in this study included HCFC22, HFC410A, and HFC32. The result of the study revealed that the effect of global warming is reduced to a certain level by using HFC410A and gets even better with HFC32 refrigerant. Therefore, it is proved that HFC32 is a more environmentally friendly refrigerant than the other refrigerants considered in the study. While Cascini et al. [49] conducted an LCA study on a commercial refrigerator system with alternative refrigerants and different user configurations, Life Cycle Impact Assessment (LCIA) step is performed by evaluating the Carbon Footprint (CF) associated with each life cycle phase of both refrigerator and refrigerant blend. The study reported that energy consumption during the use phase resulted in the highest magnitude of CF in its life cycle, about 76% of the entire CF. In comparison, gas leakage contributed about 20.2% of the CO_2 emissions. The authors, however, noted that the environmental impact of the manufacture and disposal phase of the refrigerator is negligible.

Table 2.1 gives a summary of the literature review on the sustainable life cycle analysis of the HVAC systems including details like the author's reference, study location, aim of study, life cycle phases, life cycle impact method, software and the findings.

Table 2.1: **Summary of the reviews on sustainable life cycle analysis of residential building heating and air conditioning systems (cont. in page 41).**

Authors	**Country**	**System**	**Aim of study**	**Life Cycle phase**	**LCIA**	**Software**	**Findings**
Kazuta et al. [48] (2000)	Japan	Air conditioners	Analyze the environmental effect of HFC and HCFC used as air conditioner refrigerants.	Cradle to Grave	GWP		Global warming is reduced to a certain level by using HFC410A and gets even better with HFC32 refrigerant.
Matjaz Prek [50] (2004)	Slovenia	Heating and air conditioning systems	The environmental impact of three different heating systems was investigated.	Cradle to Gate	Eco-indicator 95		The material flows that make up the system had a significant influence on the Ecological impact.
L. Gu et al. [44] (2007)	China	Building cooling and heating source system	LCA study on the design of HVAC systems using an integrated index covering the total environmental impact	Cradle to Grave	BELES	Designer's Simulation Toolkits	A gas-fired boiler and water-cooled electrical chiller for heating and cooling have the lowest LCEL and best economic performance.
Shah et al. [46] (2008)	USA	Residential heating and cooling systems	Compare and contrast the impacts of three different heating and cooling systems, each system type, energy usage, and geographic location.	Cradle to Gate	Impact 2002+	SimaPro	The most significant influence on the system's environmental performance came from the integrated energy sources.

Table 2.1: **Summary of the reviews on sustainable life cycle analysis of residential building heating and air conditioning systems (cont. in page 42).**

Authors	**Country**	**System**	**Aim of study**	**Life Cycle phase**	**LCIA**	**Software**	**Findings**
Kalogirou [51] (2009)	Cyprus	Thermosiphon solar water heaters	To investigate the thermal performance, economics, and environmental advantages of using heating systems.				The system evaluation yields good financial results with an estimated payback period of three years and life cycle savings of 2240 € with electrical backup. The LCA results reveal that the energy spent on solar system manufacturing and installation is repaid in around 13 months.
Jing et al. [47] (2012)	China	Solar building cooling heating and power	Examine and compare the environmental and energy efficiency of various operation modes.	Cradle to Gate			The findings show that the materials, operation, and fuel phases contribute more than the manufacturing and shipping stages. Furthermore, the operation mode of thermal loads leads to lower emissions.
Martinopoulos et al. [52] (2013)	Greece	Domestic solar hot water system.	To learn how the various materials and processes used in DSHWS manufacturing impact environmental performance.	Cradle to Grave	Eco-Indicator '99	SimaPro	The impact on the environment is influenced by the varied materials used in the manufacturing of solar collectors, mostly due to changes in their technical features and, as a result, their efficiency.

Table 2.1: **Summary of the reviews on sustainable life cycle analysis of residential building heating and air conditioning systems (continued from page 41).**

Authors	**Country**	**System**	**Aim of study**	**Life Cycle phase**	**LCIA**	**Software**	**Findings**
Cascini et al. [49] (2013)	Italy	Commercial refrigeration system	To evaluate the environmental performance of a commercial cooling unit.	Cradle to Grave	GWP and climate change	SimaPro	Energy consumption during the use phase resulted in the highest magnitude of CF in its life cycle, about 76% of the entire CF. In comparison, gas leakage contributed about 20.2% of the CO_2 emissions.
Finocchiaro et al. [53] (2016)	Italy	Desiccant Evaporative Cooling system	Assessment of the system's environmental effect and comparing its performance to that of a conventional air conditioning system.	Cradle to grave	ILCD 2011		The production phase showed a predominant impact compared to other life cycle steps, reaching 95%. Thus, the conventional system has a more dominant impact (about 200%) than the solar system.
S. Liu et al. [45] (2016)	Singapore	Chilled Ceiling (CC) system	To assess the environmental impact of a CC system in tropical climates throughout its whole life cycle	Cradle to Grave	GWP100	eBalance	The use phase accounted for the environmental burdens. The accumulated ecological impact of the use-phase recorded a drastic decrease as cleaner sources of energy was introduced into the grid electricity mix

2.6.2 Reviews on sustainable life cycle analysis on chiller systems.

A few notable reviews are available addressing the environmental impact and economic implications of chiller systems. The available literature reviews of the chiller systems are addressed below.

In the study of Beccali et al. [54], they evaluated the environmental effect of an absorption chiller and a traditional system, both of which were powered by grid-connected and stand-alone photovoltaic (PV) plants. The traditional system with a PV grid-connected plant outperformed the stand-alone PV-assisted systems in virtually every design scenario. This is due to the significant environmental impact of the energy contribution, which accounts for about 90% of the usage phase.

Bukoski et al. [55] used the LCA methodology to assess the environmental impact of installing a solid hybrid cooling system in a 15,000-seat Thai stadium. The baseline research compares a solar-powered absorption chiller system against an electric-powered vapour compression chiller system. The solar system saved around 26–40% in terms of environmental effect compared to the other two systems.

Hang et al. [56] performed an LCC and LCA of the solar cooling system using external compound parabolic concentrator solar collectors and an absorption chiller as a source of solar energy. Two workplaces were compared to conventional and solar energy systems in three California locations. The first version was constructed with a solar collector and absorption chiller to handle the peak cooling load. Configuration 2 improves the capacity of solar collectors and absorption chillers to meet half of the peak cooling demand. Compared to traditional systems, configuration 2 can offer lower present value costs throughout its life cycle than configuration 1. As mentioned above, by using solar energy instead of traditional systems, the solar system's carbon footprint is reduced by 35-70 percent, with configuration 2 achieving an even lower footprint than configuration 1.

Researchers in ref. [57] utilized life cycle assessment to examine the environmental and energy performance of a small solar SHC system with an adsorption chiller in various European regions. In the study, the traditional system outperformed the SHC system throughout the whole life cycle.

Sonia Longo et al. [57] examined the life cycle energy and environmental performance of a small solar Space Heating and Cooling (SHC) system with an adsorption chiller in different European areas using the Life Cycle Assessment (LCA) technique. The new system was also compared to the previous one, which relied on a vapour compression unit. According to the research, the conventional system outperforms the SHC system over its whole life cycle (10 years). Furthermore, while the SHC system's manufacturing phase has the most significant influence on the life cycle phase, the operational phase is the most important.

Nan Xie et al. [58] evaluated the environmental advantages of combining a LiBr/H2O absorption chiller and Kalina Cycle KC with individual KC using the LCA approach. They discovered that energy production during the operation stage is a more environmentally-friendly option. Compared with the individual KC, the combined system displayed a significantly higher number of ecological indexes, increasing by 46.17 %.

To analyze the influence of energy systems on environmental profiles, Catrini et al. [59] presented a combined technique based on thermoeconomics and life cycle assessment. This approach is being used to assess a water-cooled Scroll Compression Chiller built to cool a big office building. The authors used an IMST-ART simulator to model the operation of the chiller system and compare different chiller designs to their associated environmental improvements. According to the authors, the use phase has the most significant influence on the environment. They also claimed that the electricity production mix utilized to power the chiller (the Italian grid energy mix) presented more substantial trade-offs between efficiency and cost.

In a separate research, K. Almutairi et al. [60] reported on an LCA and economic analysis of a VCC placed in residential structures in Saudi Arabia. According to the findings, the usage phase has the most significant environmental effect. The quantity of the effects assessed was impacted by the type of main fuel utilized to power the facility. According to an economic study, clients in apartments and conventional houses are not interested in using a more efficient air conditioner.

According to the government, installing and using more energy-efficient air conditioner systems is always advantageous from an economic and environmental standpoint.

In the study of Emillo et al. [11], LCA methodology is used to evaluate the global warming potentials of two 500-ton capacity water chiller systems, focusing on the manufacturing stage, one with an oil-lubricated bearing system and the other with a magnetic bearing system. These are typical chillers installed in commercial buildings for air conditioning purposes. The study found that over 90% of the emissions from the water chiller system's operating stage are due to power consumption, with the most significant emissions coming from material extraction and production. As a result, magnetic bearing systems reduce life cycle greenhouse gas emissions more than oil-lubricated bearings. However, according to the sensitivity and uncertainty analyzes, both electrical energy generation factor and chiller efficiency NPLV can strongly affect GHG emissions, though the more significant reduction in emissions can occur when the power supply for chillers is mixed with clean energy resources.

Saidur et al. [61] analyzed the consumption of energy and the emissions related to the running of the chiller and other chiller plant components installed in the building of a university powered by fossil fuel-generated electricity. The authors, in their research, estimated the emissions and energy savings from incorporating the chillers and motors with Variable Speed Drives (VSDs). They also reported that integration of VSDs in chiller systems resulted in a 60 % speed reduction and a total of 2,426,769 kg of carbon emission savings.

Relating to studies on LCC, Chillvento [10] reported a study on life cycle costing analysis of generic water-cooled chiller models from cities representing hot, warm, cool, and cold climates worldwide. Results are normalized to 500-ton peak load with two 288-ton chillers. Oil-free designs reduce yearly maintenance and do not require frequent bearing inspections. Its designs help maintain energy efficiency for a more extended period [62].

F.W. Yu and K.T. Chan [62] examine the life cycle electricity cost of chillers with enhanced condenser features such as evaporative pre-coolers (EC), variable speed-condenser fans (VSF), and condensing temperature control using an LCC analysis. Simulators were also run on an air-cooled chiller with constant-speed screw compressors to see how enhanced COP behaved in the steady-state at various operational settings. According to the authors, the electricity cost savings for a chiller plant serving an office building for 15 years range from HK$ 2,099,742 with EC to HK$ 6,399,564 with all three features.

Table 2.2 gives a summary of the literature review on the sustainable life cycle analysis of the chiller systems including details like the author's reference, study location, aim of study, Functional Unit, life cycle phases, life cycle impact method, software and the findings.

Table 2.2: Summary of the reviews on sustainable life cycle analysis chiller systems (cont. in page 48)**.**

Authors (Year)	**Country**	**System**	**Aim of study**	**Functional Unit**	**Life Cycle phase**	**LCIA**	**Software**	**Findings**
Beccali et al. (2012)	Italy	Absorption chiller	Examine the environmental impact of a solar absorption chiller fueled by a solar plant throughout its complete life cycle.	kWh of cooling and heating energy generated by the plant.	Cradle to Grave	US EPA 2001	SimaPro	The use phase accounts for 70–90% of the energy and environmental consequences of the plant life cycle. The traditional system fared better when compared to stand-alone PV aided systems.
Bukoski et al. (2014)	Thailand	Absorption chiller /conventional Vapor compression chiller	To assess the environmental impact of a standard electric-powered VC chiller system compared with a solar-assisted AC system.	The production of chilled water at a rate of 9,575 RFT-hr per week for 30 years in the HVAC system.	cradle-to-grave	CML 2 baseline 2000		The conventional VC chiller cooling system provides effect potentials of more than 200 percent across all impact categories compared to the solar-assisted AC system.
Hang et al. (2014)	USA	solar absorption cooling system	To compare the cost and environmental effect of a solar cooling system with an absorption chiller.	The amount of cooling energy produced for cooling the building.	Cradle to grave	IPCC 2007	SimaPro	Configuration 2 provides higher life cycle economic and environmental performance with an identical setup than configuration 1 with solar collectors, absorption chiller, and natural gas as a backup.

Table 2.2: **Summary of the reviews on sustainable life cycle analysis chiller systems (cont. in page 49).**

Authors (Year)	**Country**	**System**	**Aim of study**	**Functional Unit**	**Life Cycle phase**	**LCIA**	**Software**	**Findings**
Sonia Longo et al. (2017)	Italy	Adsorption chillers	In terms of energy and environmental performance, an SHC system implemented in various locations is compared to a traditional system.	A cooling and heating system for the reference building with a 10-year useful life.	Cradle to Grave			The most important life cycle phase is system operation, whereas SHC system manufacture has substantial influence. Throughout its entire life cycle, the conventional system outperforms the SHC system.
Nan Xie et al. (2020)	China	Absorption chiller and Kalina cycle	Evaluate an integrated LiBr/H2O absorption chiller/Kalina cycle system.	Potentially disappear a fraction of species (PDF) from a specific area (m2) over a period (1 year) as PDF·m2 ·year.	Cradle to Grave	CML 2001, Eco-indicator 99	GaBi	Findings reveal that the integration of absorption chiller and Kalina cycle system leads to an estimated 44% overall environmental index improvement.
FW Yul and K.T. Chan (2006)	China	air-cooled chillers	To examine the LCC of electricity usage of the chiller systems with the improved condenser features, evaporative pre-coolers, and variable speed condenser fans.				TRNSYS	The LCC savings for a chiller plant servicing an office building for 15 years are estimated to vary from HK$ 2,099,742 with EC to HK$ 6,399,564 with all three features.

Table 2.2: **Summary of the reviews on sustainable life cycle analysis chiller systems (continued from page 48).**

Authors (Year)	**Country**	**System**	**Aim of study**	**Functional Unit**	**Life Cycle phase**	**LCIA**	**Software**	**Findings**
Catrini et al. (2018)	Italy	water-cooled chiller	Examine the chiller's energy and environmental consequences throughout its life.	Cooling a large office building for 20 years (with a peak demand of 315 kW)	Cradle to Gate	ILCD 2011	IMST-ART	The electricity mix accounted for the most significant energoenvironmental impacts. Poor maintenance resulted in the system's high cost.
Emillo et al. (2021)	USA	water-cooled chillers	To determine the GWP of oil-lubricated bearing chillers and magnetic bearing water chillers during their whole life cycle.	The working unit is a 500-ton chiller that can cool a 150,000-square-foot office building.	cradle-to-cradle			The use phase accounted for about 90% of the emissions are caused by energy use. Magnetic bearing systems also outperformed oil-lubricated bearing systems in terms of environmental savings.

2.7 Chapter summary and research gap.

This chapter comprehensively highlights the system design configuration and performance optimization of various HVAC systems in most research and projects analyzed in the literature, spanning from a range of building heating and cooling appliances. In most studies, simulation and statistical analysis are used to assist the design, optimization, and parametric evaluation of the energy systems to determine the effect of the operation conditions and fuel choice on the overall performance indicator.

The review of the life cycle analysis of the studies conducted in this project includes assessing the environmental and economic impacts resulting from life cycle energy and material usage of various HVAC and chiller systems. However, despite the range of modeling options available in the literature, a gap exists.

From the general overview of the literature, three research gaps can be drawn, especially related to vapor compression systems. Firstly, the VCS analyzed in the literature considered small capacity chillers (standalone) and HVAC systems installed in various building to satisfy the cooling demands. However, no available research addresses the environmental and economic benefits from integrating the functionalities of a large thermal energy storage tank and the vapor compression chiller in a district cooling plant, especially in comparison to the conventional setup.

Secondly, only a few studies were found to evaluate or optimize the VCS at a combined three aspects, addressing the energy, economy, and environment. Therefore, a methodology that assesses the life cycle energy, economic, and environmental performance of the VCS systems is highly desirable.

Hourly sensor measurements are used to create the electrical and thermal energy employed in this study. Hourly energy, rather than yearly energy, gives a better understanding of daily energy demand variations, such as peak and non-peak hours. An LCA and LCC approach is utilized to model the energy systems, including all upstream and downstream activities related to generating and utilizing energy. This method will aid in the analysis of energy system performance by taking into account the various product life stages as well as their environmental and economic effect. Global effects, such as greenhouse gases, regional effects, acid rain, and local effects, such as smog production, are all possible. Considering all these characteristics rather than assuming a single parameter, such as carbon dioxide emissions, can result in a more complete environmental impact evaluation. Furthermore, the findings may be utilized to forecast the performance of DC systems in various optimization applications by utilizing an LCA and LCC technique to simulate the VCS under actual operating circumstances.

CHAPTER 3

METHODOLOGY

3.1 Chapter Overview

The approach adopted for this research has been illustrated in Figure 3.1. The project started with an in-depth perusal of the published literature related to the life cycle analysis, mainly about vapor compression systems. A thermodynamic model of the system is developed to estimate the energy consumption of the various components. Then the Vapor Compression System comprising the electric chillers and the TES is modeled on Umberto LCA+ software to estimate the environmental and cost implications.

3.2 Literature Reviews on LCA and LCC studies

The initial stage in this study approach is theoretical reading from previous research articles and textbook materials. Academic resources, including research journals and textbooks, are obtained from the library, the internet, and websites and are especially relevant to the chiller, TES, and DC system research concerns. Some of the factors utilized in this study's comparative analysis were also taken from earlier research.

3.3 Thermodynamics modeling of Vapor Compression System

The actual cycle of a Vapor Compression System consists of major components, including the condenser, compressor, throttle/expansion valve, coupling pipes, and the evaporator, as seen in Figure 3.2. The irreversibility associated with the system is the principal factor that differentiates it from the ideal vapor-compression refrigeration cycle. However, excluding the compressor, the aforementioned main components are assigned a zero work value to simplify the energy balance. In addition, the gas throttling through the valves is also assumed to be adiabatic, while the compressor, on the other hand, is assumed to do real work (compression).

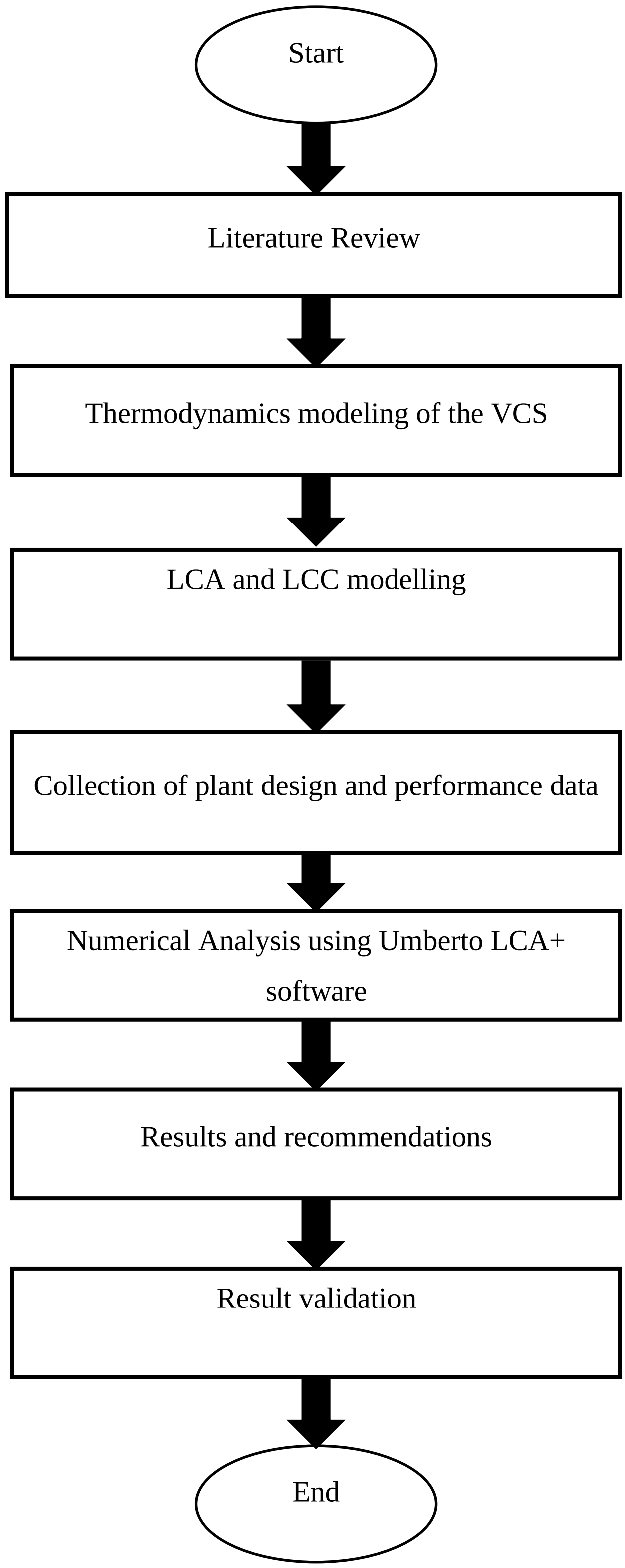


Figure 3.1: **Flowchart of the project methodology**

Furthermore, all the components are attributed to insignificant changes in both potential and kinetic energy. A thermodynamics performance model to estimate the cooling load and energy consumption of the system throughout its daily operation is given in the equation below.

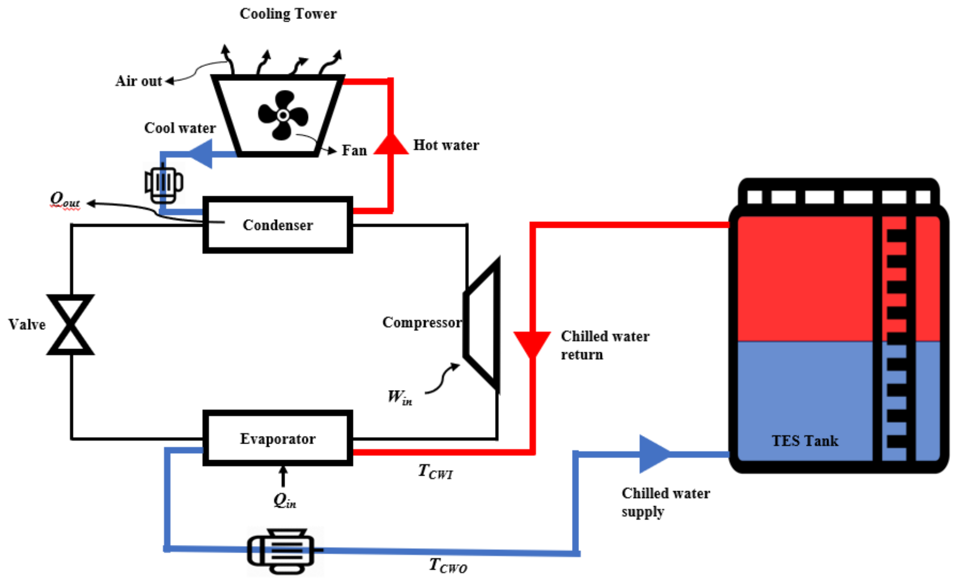


Figure 3.2: **Schematic diagram of a Vapor-Compression System.**

The mathematical formulation to estimate the Cooling Load satisfied per hour by the chillers is given by equation (3.1). The real time values of the plant performance parameters used in this study were retrieved from the technicians.

$$Q_{in} = m_w C_p \left(T_{CW_o} - T_{CW_i}\right) \tag{3.1}$$

where,

Q_{in} = Cooling Load(RTh)

m_w = mass flowrate(m^3/h)

C_p = specific capacity of water (J/(kgK)

T_{CW_o} = Chilled Water supply Temperature (^{0}C)

T_{CW_i} = Chilled Water return Temperature (^0C)

3.3.1 First- and Second Law of Efficiency of Chillers

The first-law efficiency of a vapor-compression chiller unit is frequently referred to as the COP and is defined as follows:

$$COP = Q_{in}/W_{in} \quad (3.2)$$

where,

COP = Coefficient of Performance,

W_{in} = Electric Power used by the compressor

3.4 LCA model development in Umberto LCA+ software.

In fulfilling the objectives of this study, an LCA model is developed using the Umberto LCA+ software. The flowchart for the modeling process is outlined in Figure 3.3 and explained below.

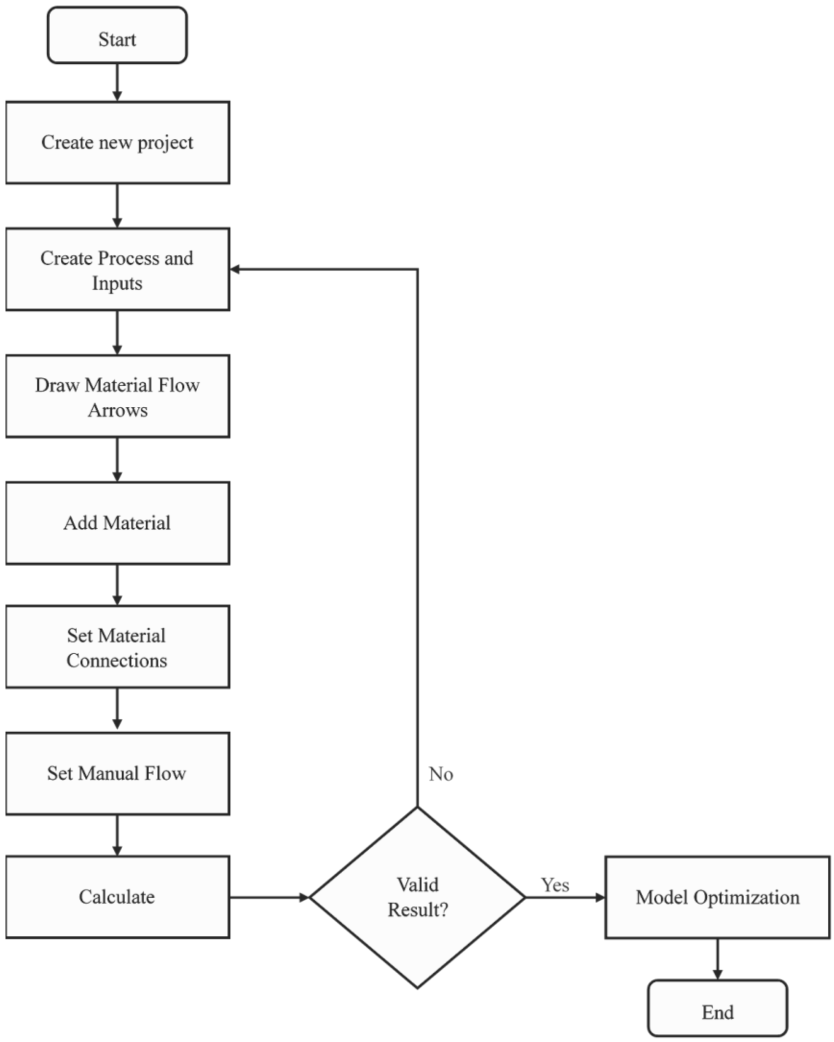


Figure 3.3: **LCA modeling flowchart in Umberto LCA+ software.**

3.4.1 Create a new project.

A new project file must be opened before a model can be created using the Umberto LCA+ software. Go to File in the top-left corner of the screen and select "New" to begin a new project. This may also be done by clicking the 'New Project' File button in the top-left corner of the main toolbar and specifying a file name. The workspace is displayed in Figure 3.4 after opening a new project file in Umberto's graphical user interface. On the monitor, there are four windows. 'Net Editor' is the name of the biggest window. For constructing a graphical model, the net editor is utilized. The 'Project Explorer' is the windowpane on the upper left. It shows all of the Umberto project's system models and resources. The 'Property Editor' is located at the bottom left of the window panel. At the top of the window panel, the type, format, and name of the chosen element appear first. The additional characteristics of this element are also shown and may be modified from this page. Underneath the net editor is the 'Specification Editor,' used to specify the model elements. The computation results are displayed in this window as well.

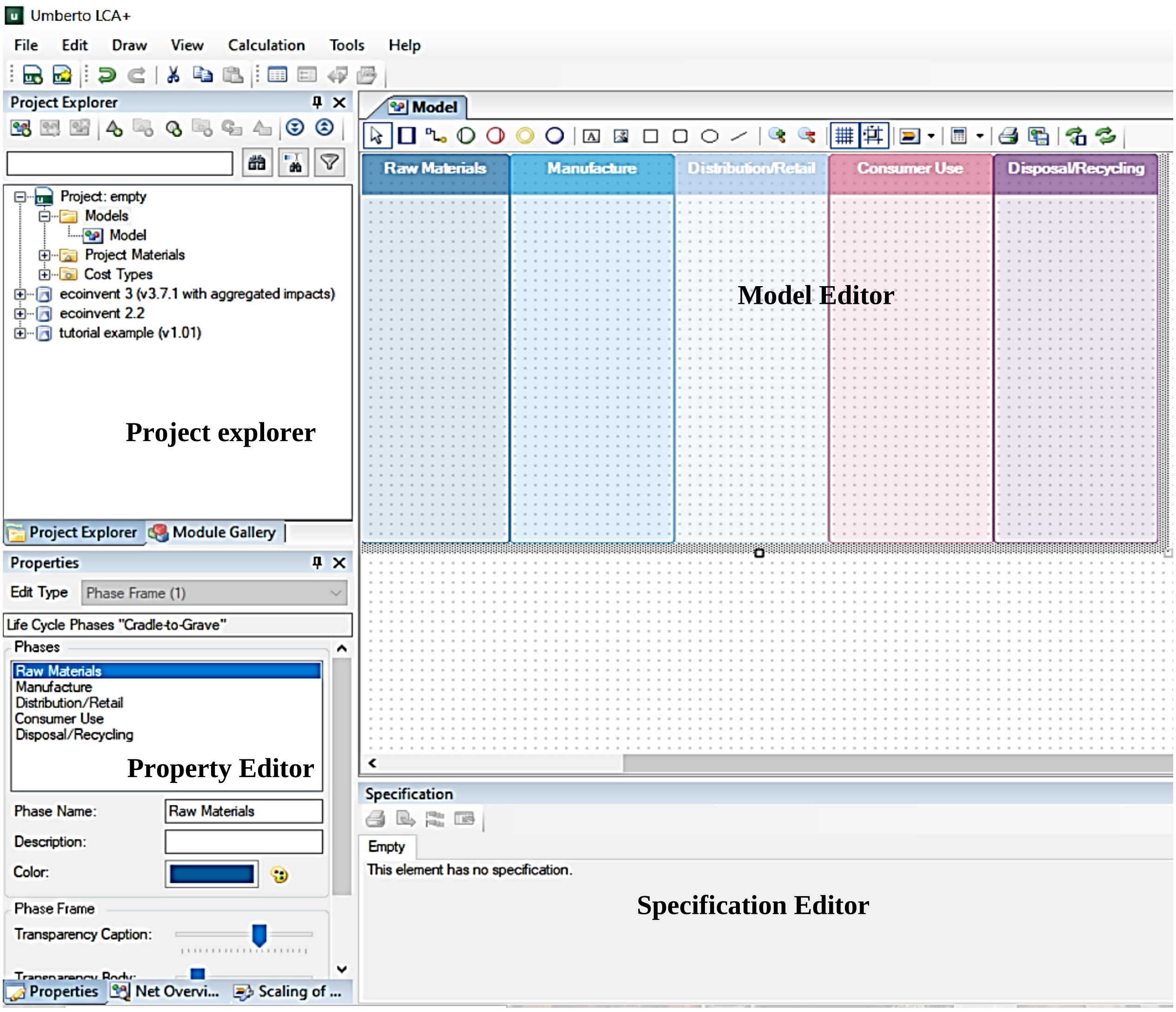


Figure 3.4: **Modeling Software interface of Umberto LCA+.**

3.4.2 Create Process and Inputs.

An Umberto LCA model is a graphical representation of a product's life cycle that includes several components such as process, location, and arrow. A model is made up of at least one net (the 'Main Net'). Umberto LCA+ uses a range of modeling components to set up the needed procedures. Figure 3.5 depicts the numerous elements accessible in the software interface, such as input, output, and connection elements, as colored circles (For example, yellow, green, and red). The modeling area must be developed first, based on each process's numerous unit operations.

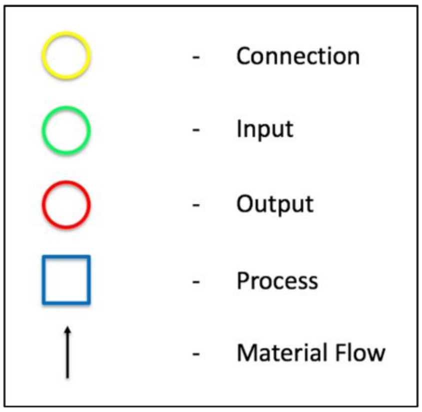


Figure 3.5: **Elements in Umberto LCA+ software.**

The processes are then built using the drag-and-drop function of the software, based on the Input-Process-Output paradigm for each process. Each process includes a processing element (blue square) that depicts the actual process, as well as many inputs (green circles) and outputs flows (red circles). Connecting components (yellow circles) are used to link several operations.

3.4.3 Draw Material Flow Arrows.

The black arrows represent material flows (as seen in Figure 3.5). One comes from each input flow to the process, while the other comes from the process to the output flow. The arrow button is located on the model toolbar.

3.4.4 Add Material.

The model must then be fed the essential materials that make up the system. In order to feed the essential materials into the model, the database installed alongside the Umberto LCA+ software is used, known as EcoInvent 3 (updated version 3.7.1 with aggregated impacts). To find a material or activity in the installed database (e.g., EcoInvent or GaBi), add the search phrase in the 'project explorer,' for example, "stainless steel," in the project explorer's search field and click the filter button, as seen in the picture below (Figure 3.6).

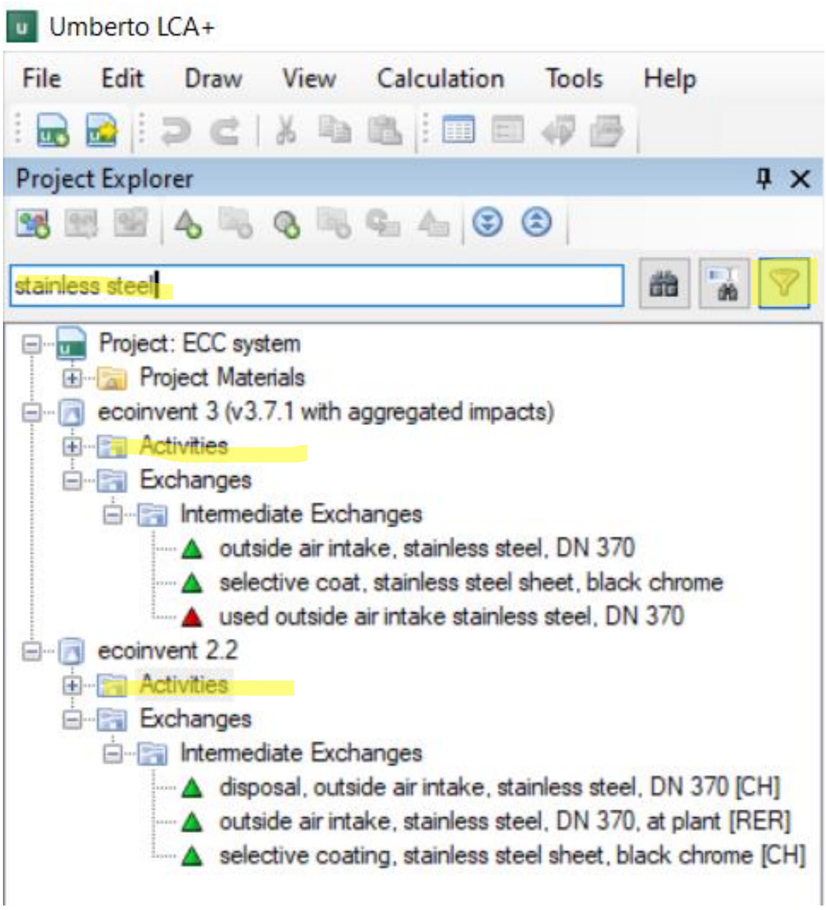


Figure 3.6: **Material addition on the project explorer's search panel.**

Clicking on the process place allows two columns (input and output) to appear at the bottom window, known as the 'Specification window.' The drag and drop function move each material from the project explorer window into the input (left) and output (right) columns, as shown in Figure 3.7.

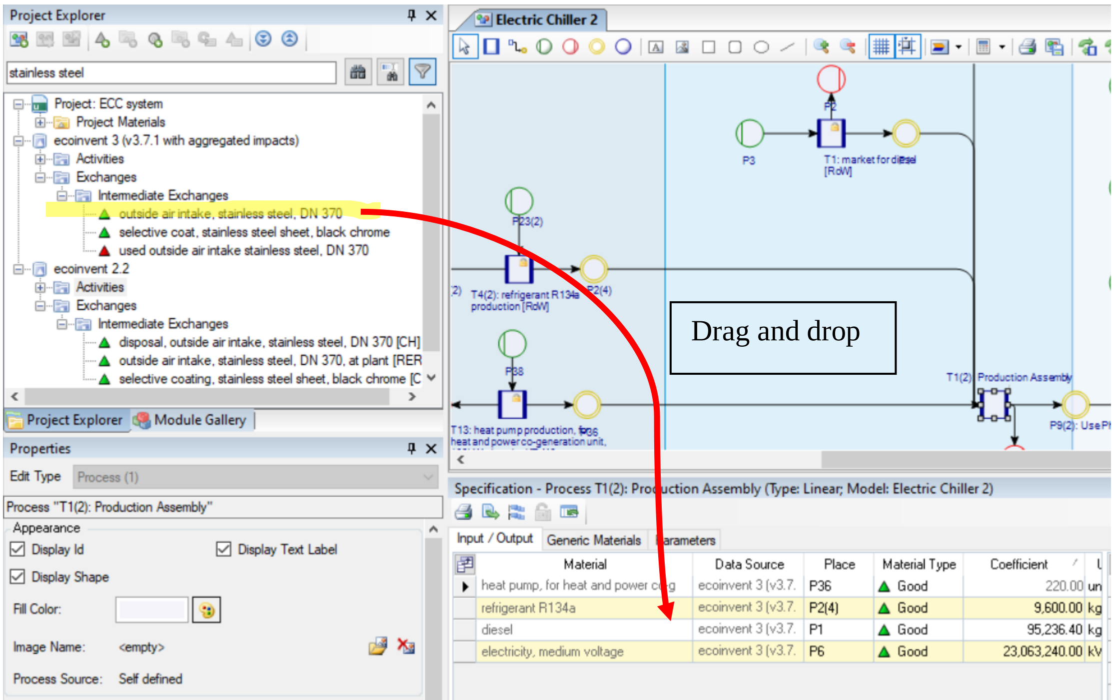


Figure 3.7: **Adding material to the input/output column of the specification window.**

3.4.5 Set Material Connections.

In this section, the materials added to the lists are specified in terms of where they come from, where they go, their quantities, and the proportions they are transformed. To set the material connections, the place of the materials flow is defined by clicking on the respective origin and their corresponding destination for each material in the process.

3.4.6 Set Manual Flow.

In setting the manual flow, we are basically instructing Umberto on the quantity we would like to see in the results. This is regarded as the functional unit of the LCA, e.g., one Ton of refrigeration used in this study. The specified material flow is the ' manual flow based on the defined FU symbolized by a purple arrow.'

3.4.7 Calculate.

The model is now ready to be computed after specifying the manual flow. The model is calculated in a few moments after the calculation symbol in the model toolbar is activated, and the result is shown. The algorithm calculates all material and energy flows from the trigger flow and evaluates the process requirements in the first section of the result. The initial computation must be successful before the product-related flows and LCIA result values can be calculated in the second portion. If the first computation fails, the second calculation will not begin and instead display the log file. The LCIA values and flows per product are calculated in the second computation. The allocation factors developed for multi-product operations are used to calculate product flows. When the second phase of the computation, where the overall flows are assigned to the products (reference flows) defined in the system, is completed successfully, two new tabs, 'Inventories' and 'Results,' appear in the Specification Editor area.

3.4.8 Model Optimization.

The process is concluded by optimizing the system environmental performance variables by selecting desired scenarios for potential system improvement.

3.5 LCA modeling of the Vapor Compression System

This paper applies the LCA methodology, consistent with the ISO 14040 [35] series, to present an eco-econ-balance of the VCS under different working scenarios. The methodology of LCA is applied to examine the environmental impacts arising from the VCS installed with a TES tank in a DC plant.

3.5.1 Goal and scope definition

The first step of the LCA framework is the goal and scope definition phase. This study aims to quantify the environmental impact incurred from the entire life cycle of the vapor compression system, including the thermal energy storage tank. A cradle-to-grave approach is adopted for this purpose. Conclusions in this study are intended to aid policymakers and plant designers in making an informed decision to ensure environmental sustainability. In weighing the environmental benefits, results derived from the base LCA analysis are compared with the following potential scenarios,

1. With the latest compressor system (Scenario A).
2. Sourcing electrical energy from the Natural Gas Plant to power the plant (Scenario B).

3.5.2 System Description

Putrajaya Cogen plant serves various buildings, including government complexes in Precinct 1, Putrajaya, Malaysia. The total length of the chilled water reticulation loop is about 8 km, with pipe diameters ranging from 550 mm to 1200 mm, with a water holding capacity of 21,000 m^3. Figure 3.8 shows the coverage of the district network at Putrajaya Precinct 1.

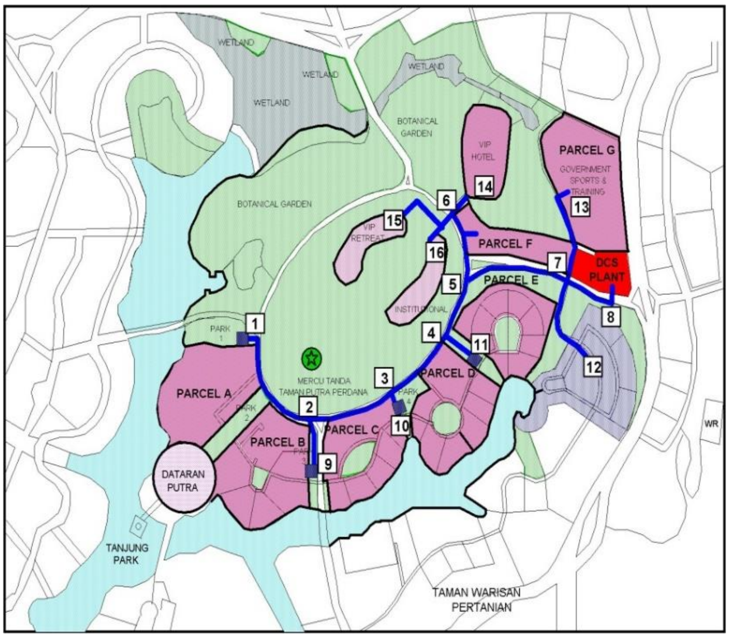


Figure 3.8: **Overview of the precinct 1 Putrajaya Cogeneration Plant network coverage.**

The DC plant is installed with four VCC systems with a rated Coefficient of Performance COP 5.5 and two TES tanks with a total holding capacity of 50,000RTh with a dimension of 24.5m in diameter and 27.8m in height. The VCC system uses the R134a refrigerant and supplies chilled water to the Air handling Unit at 5℃ and receives at 11℃, while it supplies cooling water at 33℃ and receives at 28℃ to and from the Cooling Tower. An overview of the system configuration and the type of energy used to fuel the plant is presented in Figure 3.9.

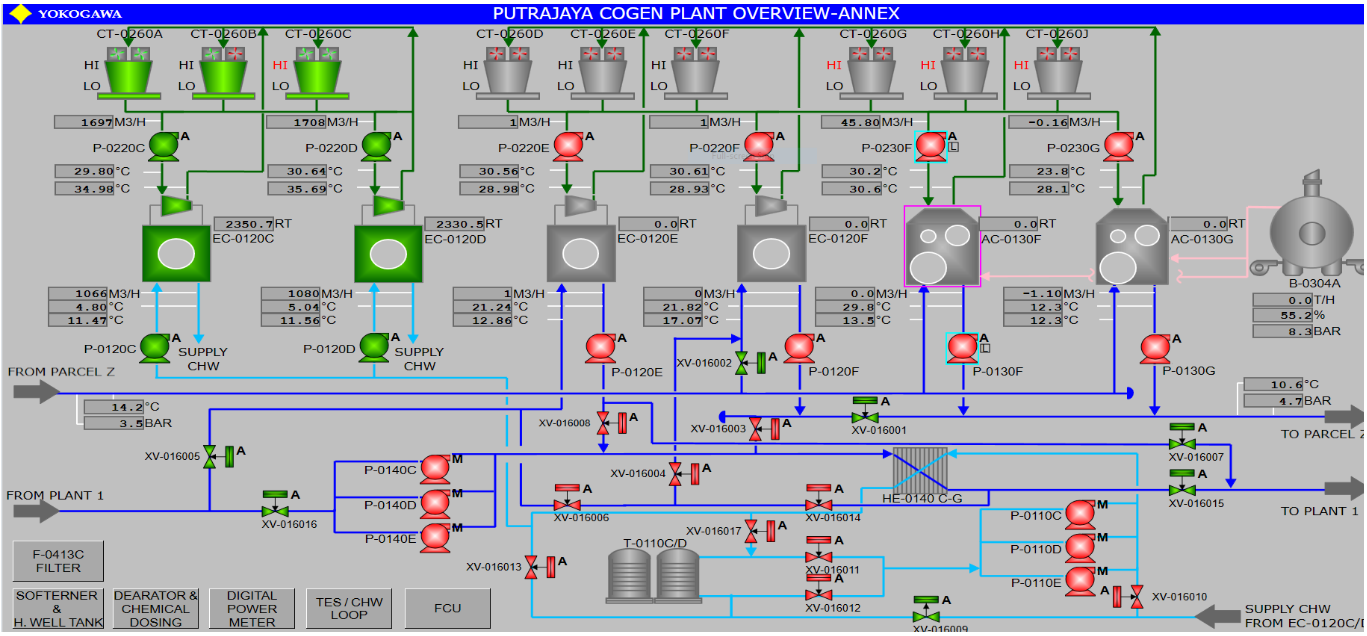


Figure 3.9: **Overview of the Putrajaya Cogen Plant.**

The chiller system is designed to function on a full operating strategy where the two VCC systems operate at full capacity during the off-peak period (10 pm-8 am) to charge the TES tanks. The other two VCC systems are used as standby chillers to support the cooling load during breakdown or scheduled maintenance of the plant and in scenarios of high chilled water demand. A sample data illustrating a week's operation of the four VCC systems is reported in Figure 3.10 [5].

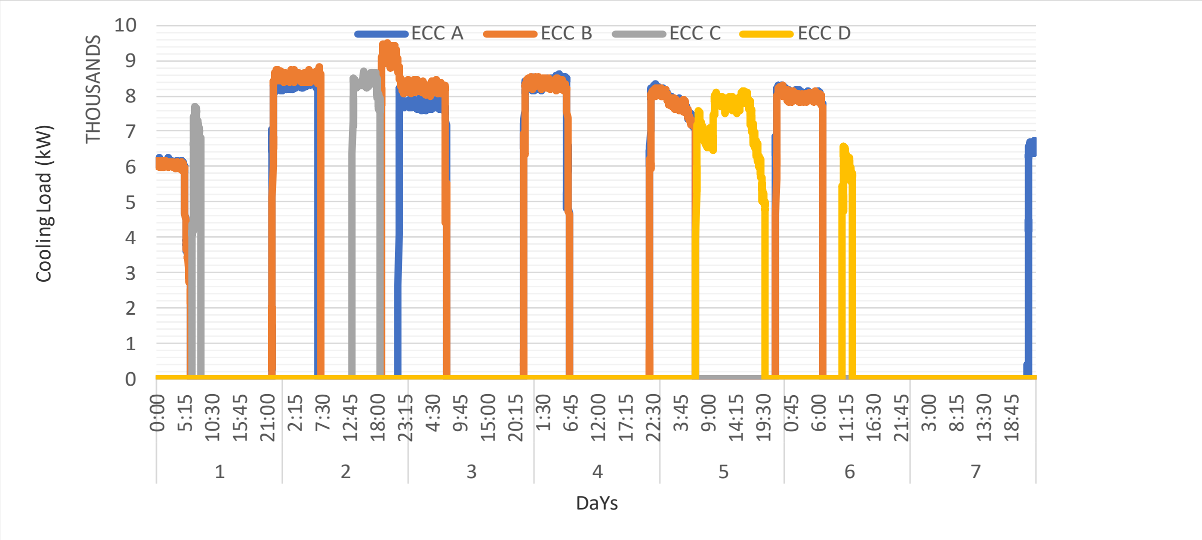


Figure 3.10: **A week operation of the four VCC systems.**

3.5.2.1 Functional Unit (FU).

The idea of FU helps provide the basis for comparison of these systems with other design alternatives in other to highlight possible and meaningful benefits. The FU chosen in this study are the VCC systems used to charge the TES tank in a DC plant. This represents 1RTh of chilled water produced for air-conditioning purposes. The base study result allows for comparison with other plant design scenarios.

3.5.2.2 System boundaries and limitations.

The system boundary considered in this study covers the upstream and downstream of the life cycle of the VCS. The chiller plants and the TES tanks are estimated to have a 25year use-life. In this study, the rule for setting the system boundary consists of three decision criteria for each candidate component: unit process, mass, and energy contributions to the entire plant. In detail, a selected unit process must have a significant contribution, for example, higher than 5% of the entire product, to at least one decision criterion. Once the main unit processes are selected, the major materials involved in each unit process are chosen based on the “cut-off” result. The EcoInvent database and literature are primarily used to gather information for the upstream and downstream

Life Cycle impact assessments. On a global scale, system boundaries are established at the RoW (Rest of the World) level. The system model "Cut-Off" was chosen for all EcoInvent data. Generic datasets of firms from EcoInvent are utilized for particular procedures. The EcoInvent database categorized the datasets as "global average." [63]

Figure 3.11 shows the system boundary of the VCS under investigation. Steel, copper, aluminium, and other minor metals and polymers are utilized as raw materials in the electronics and control panels of a traditional water-cooled chiller. After the steel sheets have been delivered to the plant and cut into forms, shot blasting, which uses small steel beads to blast into a surface, enhances the surface profile [64]. Following that, the steel sheets are rolled into cylinders. Finally, the seams between the evaporator and condenser cylinders are welded [64]. Steel sheets are also cut into shape for the endplates of the chiller cylinders. Along with the cut steel sheet, holes will be drilled in specific positions on the endplates so that the entire chiller's steel chassis may be drilled together to keep its shape. After that, the chiller system is welded together to ensure that no air leaks exist. [63]. Copper tubing is then attached to the evaporator and condensers. The outer cylindrical chassis is next checked for leaks by pouring water through it and verifying no excessive water leakage [63].

The condenser and evaporator must then be connected. In the evaporator, copper tubes are enclosed by a shell. Water is utilized to eliminate any unwanted flow within the copper tubes, as the refrigerant is on the outside. To protect the seal within the shell from leaking out, it is welded and drilled together. The condenser is welded and drilled together with a steel shell and copper tubing to ensure that the seal inside the shell does not leak [63]

Interworking elements such as impellers, rods, rings, and cylinder walls are added to the compressor. If the compressor is oiled-bearing, lubricating oil is added to the interworking components in order for the moving parts to function correctly. The compressor is then placed in the condenser and evaporator shell stack of the chiller [63]. The compressor, condenser, and evaporator are the internal components of the chiller, and they must all be connected for the chiller system to work correctly. The last step is to install intermediate pipework, sensors, and valves for the compressor, condenser, and evaporator and connect the wires that connect all of these distinct elements within the chiller shell. After the individual parts of the chiller system have been connected, insulation is applied to the chiller system to isolate it and mitigate any unwanted encroachment of thermal energy from the mechanical space in which the chiller is installed. This improves efficiency and ensures that the chiller maintains a consistent temperature. The chiller is then sealed and painted on the outside when all of that has been completed.[63].

To link the chiller plant and the TES tanks, supply and return piping networks are employed. The materials used to construct the layered TES tanks are varied. These materials have desirable thermophysical characteristics such as a favorable melting point for the specific thermal application, high latent heat, high specific heat, high thermal conductivity, and so on. Carbon steel, stainless steel, concrete, and other water-tight materials are used to construct stratified water TES tanks [65].

The power-sizing technique suggested by Sullivan et al. [66] is used to estimate the material size used in this study compared with other plant capacities found in the literature, database, and manufacturer’s log list. The power-sizing technique is given by equation 3.3.

$$\frac{Material\ mass_1}{Material\ mass_2} = \left(\frac{Capacity_1}{Capacity_2}\right)^X \tag{3.3}$$

Where X denotes the ratio of cost to capacity, which is 1, assuming a linear relationship.

However, owing to a lack of quantitative data, the installation, and transportation stages of the life cycle are not addressed in this system boundary. Figure 3.11 depicts the life cycle phases from the cradle-to-grave, including raw material acquisition, manufacturing, operation, and recycling. Auxiliary equipment such as fans, pumps, and pipes were not included in this study's scope due to a lack of data. Both the inventory study and the effect assessment are done using the modeling software Umberto LCA+. The different stages of the VCS's life cycle processes are linked to all the data sources used.

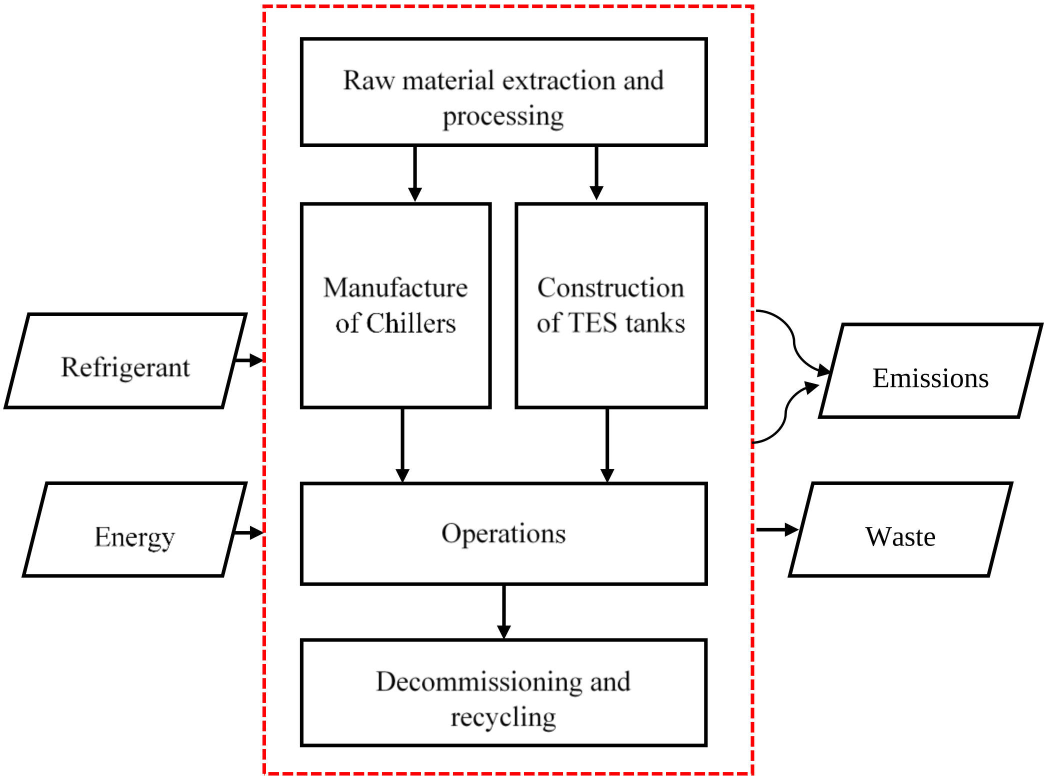


Figure 3.11: **System boundary of the LCA study**

3.5.3 Life cycle inventory.

3.5.3.1 Raw material phase.

The environmental impact from this phase comes from the mining and processing of raw materials and the energy requirements to produce the VCS components. Samples of the raw materials used are outlined in Table 3.1 and 3.2 for the chiller and TES systems, respectively. There are different varieties of material required for both chiller designs and TES systems. The EcoInvent database installed alongside the Umberto LCA+ software serves as the source of the materials presented [67].

Table 3.1: **Input raw material flow of the Vapor Compression chiller [11, 59, 65, 67].**

Material	% Composition
Steel	75.15%
Cast Iron	19.21%
Aluminium	4.27%
Copper	1.38%

Table 3.2: **Input raw material flow of TES tanks. [11, 59, 65, 67].**

Material	% Composition
Sand	61.93%
Molten Salt	26.57%
Calcium Silicate	0.09%
Stainless Steel	0.01%
Carbon Steel	2.04%
Mineral Wool	0.55%
Concrete	7.16%
Foam Glass	0.15%
Refractory Brick	1.49%

3.5.3.2 Manufacturing and construction phase

The main environmental impact in this phase comes from the unit, parts energy, and consumables requirements for processing and assembly of various components of the entire VCS, including the chillers and the TES tanks. As a result of limited credible data, some units like insulation glue, acetylene, cleaning agents, etc., involved in this phase were ignored. However, these units are in small quantity, and their impacts are generally considered negligible. The research data for the analysis in this phase are obtained from the literature and the EcoInvent database [67]. Details of the inventory data of the manufacturing and assembly phase are presented in Table 3.3. The electricity utilized in the manufacturing phase is described as a "market group for electricity, medium voltage [CN]." This EcoInvent dataset describes the electricity available on a medium voltage level in China, where the VCC is assumed to be manufactured and assembled.

Table 3.3: **Input raw material flow for the manufacturing phase [11, 59, 65, 67].**

Material	**Amount**	**Unit**
Refrigerant R134a	9,600.00	kg
Diesel	95,236.40	kg
Electricity, Medium Voltage (CN)	23,063,240.00	kWh

3.5.3.3 Operation phase

The material flows considered in the use phase include unit electricity consumption, usage, and refrigerant discharge. The plant operation and design data were obtained from the plant technicians, technical datasheets of the unit components, and literature. The data included minute sensor readings of the four VCC systems in an entire year (January-December 2019). The data revealed parameters like the chilled water temperatures and mass flowrates, chilled water suction and discharge pressure, Coefficient of Performance COP, and Tons of Refrigeration RT of chilled water generated per unit time. Analyzing the raw data, it is observed that the COP value of the VCC systems throughout its operation showed slight variation, with an average value of 5.5. This is as a result of the stable ambient temperature as experienced in the region. Also, the VCC systems are installed with constant speed compressors, which are used to drive the system to produce CW at full load capacity to charge the TES tank during off-peak periods (10 pm - 8 am). Since the base study is in Malaysia, the eco-profile considered for the electricity used in running these VCC systems is the Malaysia power generation mix (Tenaga Nasional Berhad) [68]. According to the Malaysia energy statistics handbook [69], the present fuel mix used in generating electricity in Malaysia contains 43.4% Coal, 39% Gas, 15.6% Hydro and 1.92% of others. Climatic data provided by the Malaysian Meteorological Department [70, 71] is used to compare the monthly chilled water demand trend based on the average monthly temperature.

The lifespan of the chiller system is 25years. Excel spreadsheet software is used to prepare, manage, and analyze the data obtained in raw format from the plant technicians. The design specification sheet of the VCC system under study is given in Figure 3.12. Details of the inventory data of the input material flow of the operation phase are presented in Table 3.4.

Mathematical formulation to estimate the amount of Electrical Power EP used per hour by the chillers is given equation 3.4. The Electric Power W_{in} used to drive these systems is acquired directly from the grid electricity supply for this case study.

$$Win = \sum_{m=1}^{m=j} \left\{ \sum_{n=1}^{n=60} \frac{Qevap}{COP} . 3.51685 \right\} \qquad (3.4)$$

W_{in} = Electrical Power demand (kWh),

m = number of Chiller,

n = number of minutes,

j = number of considered working chillers,

Converting RT to kW: 1 refrigeration ton equals 3.5168525 kilowatts.

SPECIFICATION SHEET

Model	HC-F2500GXG-SAT	Quantity	2 set
Made NO.	D17092001、D17092002	SERIAL NO.	UD20001249、UD20001250

○Specifications		
Cooling Capacity		2500 USRT 8791 kW
Capacity control range		100% - Approx. 20%
Installation Condition		Indoor, non-explosion-proof
Standard		GB/T18430. 1-2007
Chilled Water	Inlet Temp.	12 ℃
	Outlet Temp.	5 ℃
	Flow Rate	1080 m^3/h
	Number of passes	2
	Pipe Diameter	DN450
	Pressure Drop	66 kPa
	Max. working Press.	1. 0 MPa(G)
	Fouling Factor	0. 086 m^2℃/kW
Cooling Water	Inlet Temp.	32 ℃
	Outlet Temp.	37. 5 ℃
	Flow Rate	1623 m^3/h
	Number of passes	2
	Pipe Diameter	DN500
	Pressure Drop	89 kPa
	Max. working Press.	1. 0 MPa(G)
	Fouling Factor	0. 086 m^2℃/kW
Motor	Estimated Input	1510 kW
	Motor Output	1420 kW
	Power Source	11000V 50Hz 3Φ3W
Starter	Power Source	11000V 50Hz
		CT Ratio 100/5 A
	Starting Method	Auto-transformer
	2E	Operating current: — Current scale value: — Operating time: —
		Reverse-phase: — Open-phase: — Overcurrent: —
Method of operation		Fully automatic operation
Auxiliary electrical power source		400V 50Hz 3Φ3W
Other	Ref. Amount (Initial charge)	HFC-134a 2400 kg ⚠1
	Lubrication Oil	108 L
	Shipping Method	One complete unit shipping
	Shipping Weight	35500 kg
	Operating Weight	40700 kg
Coating Color	Chiller main unit	Gray (Anti-corrosive primer coating)
	Control Panel(inside/outside	Munsell 5Y 8/1 gloss(Finish coat)
	Starter(inside/outside)	—
	Transformer(inside/outside)	Munsell 5Y 8/1 gloss(Finish coat)

RE-REGD										Johnson Controls-Hitachi Wanbao Air Conditioning(Guangzhou)Co., Ltd.
	⚠1	1		L17-100001	CH. YANG	WCH. LI	L. CHEN	XJ. ZHENG	12. 19. 2017	江森自控日立万宝空调(广州)有限公司
REGD	SYM.	No.	Subarea	ECN No.	Design	Revised	Checked	Approved	Date	Title
Design	CH. YANG	11. 14. 2017	Class		Quality		Scale			DELIVERY SPECIFICATION
Revised	CH. ZHENG	11. 14. 2017					NTS			DWG No.
Checked	L. CHEN	11. 14. 2017			SH. 2/4					L17-100
Approved	XJ. ZHENG	11. 14. 2017								

Figure 3.12: **Design specification sheet of the Vapor Compression Chiller under study.**

Table 3.4: **Details of the estimated electricity consumption throughout the operation phase**

Material	Amount	Unit
Electricity, high voltage (MY)	17,412,439,194	kWh

3.5.3.4 Decommissioning, Waste, and Recycling Phase

Considering the material component of the chiller and TES systems, an almost full recovery can be achieved during the recycling process. The systems are composed mainly of copper, steel, aluminium, iron, granite, etc., which are recovered and reused as scraps. Data for the environmental impact for the recycling process is sourced from the EcoInvent database as provided in the Umberto LCA+ software. This phase also takes into account the list of all considered input materials and the waste refrigerant. The refrigerants it is generally destroyed and rarely reused. Details of the recycling phase in terms of the input and output flows for both the chiller and cooling tower units are presented in Table 3.5. The complete system modeling in Umberto LCA+ software is shown in Figure 3.13.

Table 3.5: **Output material flow for the recycling/waste phase [11, 59, 67].**

Material	**Amount**	**Unit**
scrap aluminium	31.24	kg
scrap copper	28,150.93	kg
scrap steel	6,899,486.53	kg
scrap steel	71,540.03	kg
used refrigerant R134a	9,600.00	kg
waste brick	3,038,615.74	kg
waste concrete	23,633,678.00	kg
waste foundry sand	62,952,802.98	kg
waste mineral wool	1,111,345.57	kg

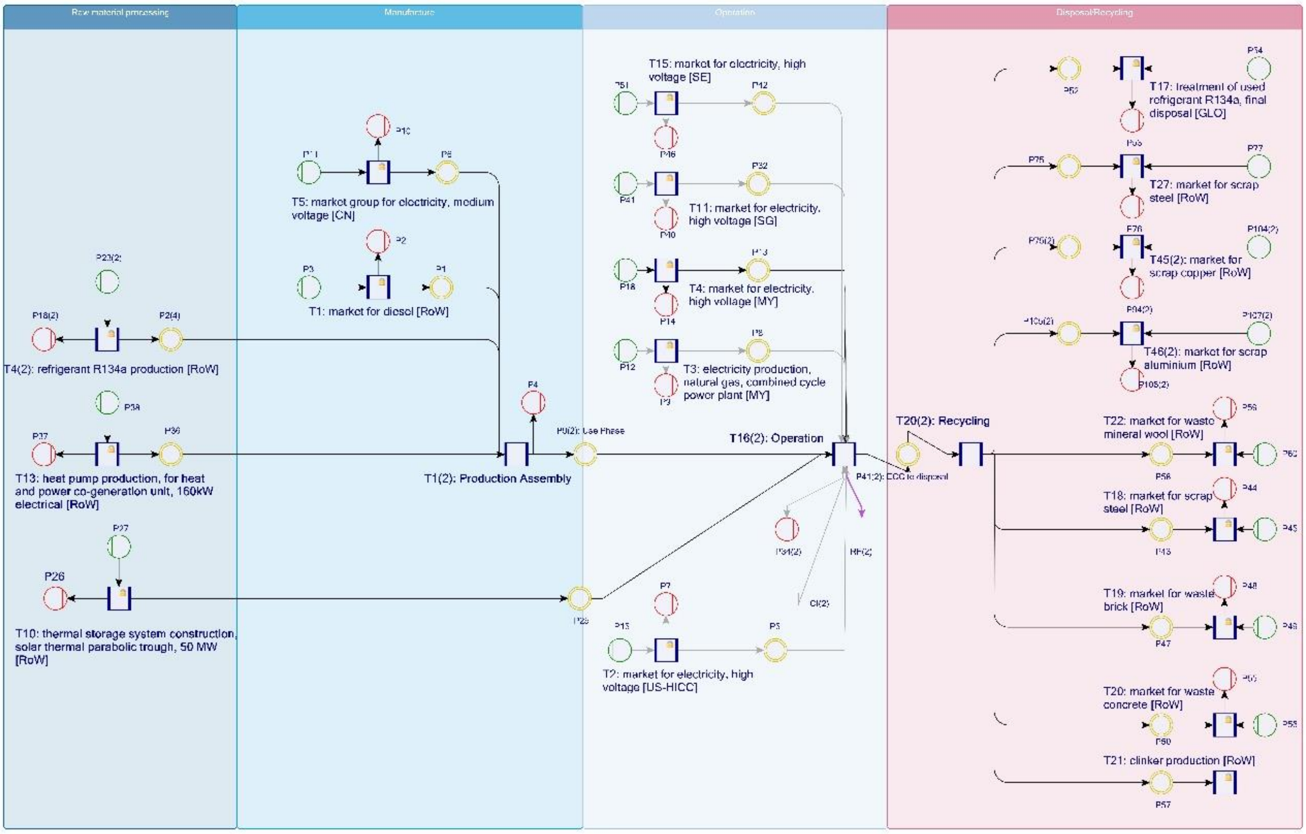


Figure 3.13: **The complete system modeling in Umberto LCA+ software.**

3.5.4 Life Cycle Impact Assessment

The impact category indicator is calculated by multiplying the LCI result by the characterization factor. The Cumulative Energy Demand method [67] is used to estimate the consumption of renewable (biomass, wind, solar, geothermal, and water) and non-renewable (fossil, nuclear) energy sources in the Primary energy calculations. The Umberto LCA+ software and the chosen ReCiPe Midpoint impact assessment approach are used to compute the environmental characterization variables [72, 73].

The impact categories listed in Table 3.6 were utilized to calculate the FU's environmental performance over the system life cycle stages.

Table 3.6: **Selected Impact Categories**

ReCiPe Midpoint	Unit
1. Climate Change, GWP	kg CO2-Eq
2. Fossil Depletion, FDP	kg oil-Eq
3. Freshwater Ecotoxicity, FET	kg 1,4-DCB-Eq
4. Human Toxicity, HT	kg 1,4-DCB-Eq
5. Marine Ecotoxicity, MET	kg 1,4-DCB-Eq
6. Ozone Depletion, OD	kg CFC-11-Eq
7. Photochemical Oxidant Formation, POF	kg NMVOC
8. Terrestrial Ecotoxicity, TET	kg 1,4-DCB-Eq
9. Water Depletion, WD	m^3

3.6 Life Cycle Cost Analysis

Due to the lack of credible data, the scope of this LCC analysis of the considered systems only covers the capital (acquisition), operation, and maintenance cost. Auxiliary equipment, such as the pumps and pipes, were not included in the study. The costs of installation and decommission were also not considered in this study. The following sections reveal details on how these costs have been accumulated and calculated.

3.6.1 Capital Cost

This entails the cost of acquiring the four VCC systems and constructing the TES tanks. Details of the cost of system acquisition were among the information retrieved from the technicians. Equations 3.5 and 3.6 show the formula for determining the total capital cost of the systems. The details of the capital cost of the systems under study are presented in Table 3.7.

$$C_{TC} = \sum_{i=1}^{n} C_{VCC} + \sum_{j=1}^{m} C_{TES} \tag{3.5}$$

$$C_{TC} = \left(C_{VCC_A} + C_{VCC_B} + C_{VCC_C} + C_{VCC_D}\right) + \left(C_{TES_A} + C_{TES_B}\right) \tag{3.6}$$

where,

C_{TC} – Total capital cost (MYR)

C_{VCC} – Capital cost of chillers (MYR)

C_{TES} – Capital cost of the TES tank (MYR)

A, B, C, D – Individual system

n – Total number of chillers

m – Total number of TES tanks

Table 3.7: **Capital cost of the VCS.**

System	Unit Initial Investment (MYR)	Total cost (MYR)
TES	4,500,000	9,000,000
EC	2,000,000	8,000,000
Total sum		**17,000,000**

3.6.2 Operation and Maintenance Cost

The operation cost can be calculated by evaluating the product of the energy consumed (W_{in}) by the VCS and the electricity tariff cost throughout the operation phase. Since the energy consumed by the accessories of the TES tank during its lifespan is considered to be minimal [74], it is not included in this analysis. The energy consumed by the VCS is estimated by conducting a thermodynamics performance analysis using the hourly, daily, monthly, and annual operation data. The cost of electricity used in the calculation is based on the TNB tariff plan [68, 69], and the details of the plan are outlined in Table 3.8. In this study, the TNB tariff used is tariff C2. It should be noted that the tariff costs used are assumed to be constant throughout the lifespan.

Table 3.8: **Electricity Tariff Category. Source: TNB [68].**

CATEGORY OF TARIFF	RATES (1 JAN 2014 - 2021)
TARIFF B – LOW VOLTAGE (COMMERCIAL TARIFF)	
1. For the first 200kwh (1-200kwh) per month	43.5 sen/kWh
2. For the next kWh (201 kWh onwards) per month	50.9 sen/kWh
3. The minimum monthly charge is RM7.20	-
TARIFF C1 – MEDIUM VOLTAGE GENERAL (COMMERCIAL TARIFF)	
1. For each kilowatt of maximum demand per month	30.3 RM/kW
2. For all kWh	36.5 sen/kWh
3. The minimum monthly charge is RM600	-
TARIFF C2 – MEDIUM VOLTAGE PEAK/OFF-PEAK (COMMERCIAL TARIFF)	
1. For each kilowatt of maximum demand per month during the peak load	45.1 RM/kW
2. For all kWh during the peak period	36.5 sen/kWh
3. For all kWh during the off-peak period	22.4 sen/kWh
4. The minimum monthly charge is RM600	-

Since Malaysia happens to be among the first 30 countries in the world with the most Natural Gas (NG) reserves, the price of NG is comparatively lower than electricity in the country. Therefore, comparing with the cost of other sources of electricity with the base case, the current tariff of NG per kWh is presented in Table 3.9.

Table 3.9: **Natural gas prices per kWh [75]**

Prices of natural gas per kWh	Date	Ringgit (MYR)	Dollar (USD)
1. Residential/Households	1st of Dec, 2020	0.086	0.021
2. Commercial/Business	1st of Sept, 2020	0.109	0.026

The average annual maintenance cost as contained in the datasheet retrieved from the plant technicians is used in this analysis. The preventive maintenance cost (overhauling cost) is also considered in the study for electric chillers every five years and breakdown maintenance cost every ten years as 324,000 MYR/overhaul and 54,000 MYR/breakdown, respectively. The Total Cost of Maintenance (C_{TM}) for the four VCC systems is given by equation 3.7.

$$C_{TM} = \sum_{i=1}^{n} C_{M_{VCC}} + \sum_{j=1}^{m} C_{M_{TES}} \tag{3.7}$$

where,

C_{TM} – Total cost of maintenance (MYR)

C_M – Cost of maintenance (MYR)

The Cost of Refrigeration (C_R) is the product of the Tariff Cost (C_T) and the energy consumed (W_{in}) by the VCC system, as presented in equation 3.8. Likewise, the Total Cost of Refrigeration (C_{TR}) expended in the operation of the four VCC systems to produce chilled water is given by equations 3.9 and 3.10.

$$C_R = C_T \times W_{in} \tag{3.8}$$

$$C_{TR} = \sum_{i=1}^{n} C_R = C_{R_A} + C_{R_B} + C_{R_C} + C_{R_D} \tag{3.9}$$

$$C_{TR} = \sum_{i=1}^{n} (C_T \times W_{in}) \tag{3.10}$$

$$= (C_T \times W_{in})_A + (C_T \times W_{in})_B + (C_T \times W_{in})_C + (C_T \times W_{in})_D$$

where,

C_R – Cost of refrigeration (MYR)

C_T – Tariff cost per kWh (MYR/kWh)

C_{TR} – Total cost of refrigeration (MYR)

The Total Cost of operation (C_{TO}) is the summation of the Total cost of refrigeration (C_{TR}) and the Total Cost of Maintenance (C_{TM}) as given by equation 3.11.

$$C_{TO} = C_{TM} + C_{TR} = \sum_{i=1}^{n} (C_M + C_R) \tag{3.11}$$

where,

C_{TO} – Total Cost of Operation (MYR)

3.6.3 Life Cycle Cost

Of the three approaches previously discussed in section 2.5, LCA-type LCC is the only approach that employs a steady-state model. Therefore, in pairing the result of both life cycle analyses, the life cycle cost is the total cost incurred over the entire lifetime of the VCC system normalized per functional unit of 1Rth of refrigeration supplied, excluding the incentives and discounting rates. Further details on the LCC technique chosen for this analysis is as previously explained in section 2.5. Equation 3.12 represents the formula to calculate the LCC.

$$\text{LCC} = \frac{C_{TC} + C_{TO}}{Q_{in}} \quad (3.12)$$

where,

LCC – Life cycle cost of the technology (MYR/RTh)

3.7 Defining other alternative scenarios.

To achieve a reduced environmental impact and enhanced economic benefits in terms of the life cycle of the VCS, especially in the operation phase, some adjustments are needed to be made. In this study, the environmental and economic performance of the base system is compared to other scenarios to point out the potential improvement that can be effected to achieve a more efficient and sustainable system. These alternative scenarios are classified below,

1. **Scenario A:** This scenario incorporates modern Oil-Free magnetic bearing Centrifugal Compressors into the electric chiller system.

2. **Scenario B:** This scenario involves sourcing electrical energy from the Natural Gas Plant to power the DC plant.

These scenarios are explained in further detail below;

1. **Scenario A:** Oilless, magnetic bearing compressor technology removes the need for complicated oil lubrication management systems, resulting in a chiller design that is more reliable and requires less maintenance. Magnetic bearings combined with an integrated variable speed drive provide industry-leading efficiency with no performance degradation during the compressor's lifetime. The permanent magnetic synchronous motor is small and efficient. The two-stage compression design can benefit both water and air-cooled chiller systems.

There is no requirement for oil in the system because of the magnetic bearing compressor. The effectiveness of heat exchange surfaces is also improved by removing oil. The presence of oil in the chiller may impair performance considerably. Oil recovery systems, which are common in older refrigeration systems, can be removed as well. In the compressor, a permanent magnet motor is utilized instead of an induction motor. In comparison, older induction motors have a 92 percent efficiency while modern induction motors have a 95 percent efficiency.

The Turbocor coefficient of performance (COP) in water-cooled applications has been recorded at over 5.6 at full load, equal to 0.62 kilowatts per tonne (kW/ton), and 9.4 (0.375 kW/ton) at part load [76, 77]. Figure 3.14 depicts the compressor as an open component design.

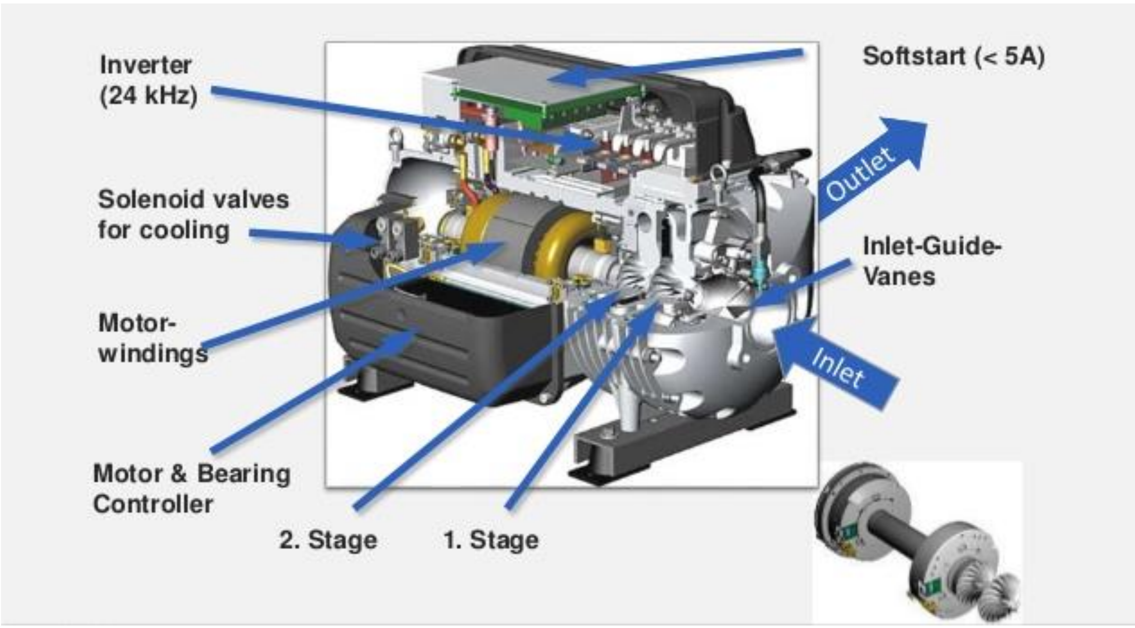


Figure 3.14: **Parts of the Danfoss Turbocor centrifugal chiller [77]**

The oil-free compressors are estimated to exhibit little to no performance deterioration during their useful life. This, along with the contact-free system operation offered by magnetic bearings, ensures that the compressor's performance stays stable over time. Chillers using the oil-free compressor technology have fewer mechanical parts and a simpler system design recorded considerably minimal degradation throughout their lifespan, since all the components associated with the oil management system are eliminated. According to case study research reported in Tsinghua University, China, which was published in the Danfoss engineering (a world class chiller manufacturer) technical report [78], a loss of 10 percent efficiency after five years, 20 percent efficiency loss after 10 years is recorded in oil-lubricated chillers [78, 79]. Therefore, the magnetic VCC system's total energy used throughout its lifetime is estimated to be 3,576,420,329 kWh and 17,412,439,194 kWh for the Oil VCC system.

2. **Scenarios B:** This scenario involves sourcing electricity from Natural Gas Plant (NGP). Malaysia has an abundant reserve of natural gas, which poses as a cleaner form of energy compared to coal and other fossil forms of energy. Natural Gas is fired in gas fired power stations at a very high efficiency rating, converting a large proportion of the energy in natural gas into electrical energy [80]. These NGPs connected with gas pipes are installed in strategic locations across Malaysia where electricity is distributed and sourced.

3.8 Chapter Summary

This chapter discussed the methodology used to achieve the objectives of the research. In analyzing the environmental and economic sustainability of the Vapor Compression System combined with a DC plant, the technique uses a life cycle analysis approach. The steps involved formulating a thermodynamic model to estimate the cooling load and electric power demands, using the performance parameters of the operating plants. The LCA and LCC models are then developed using the Umberto LCA+ program to analyze the system's environmental and economic sustainability. Potential optimized design scenarios were also stated for comparison with the base result. The findings of the numerical analysis are presented and discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Chapter Overview

In fulfilling the objectives of this project, the results of the environmental and economic sustainability assessments of the VCS are presented and discussed. This includes identifying the most environmental and economic pathway in terms of the influence of the material flow, electricity mix, and system configuration.

4.2 Life Cycle Inventory result

The result of the monthly contribution of the individual ECC in the production of chilled water supplied to the DC networks is reported in Figure 4.1. The result as analyzed indicates April and June as the months with the highest and lowest cooling demands, respectively. The average monthly temperature trend on the chart also proves the influence of climatic weather conditions on refrigeration demands. This clearly shows that as the earth keeps warming up, the demand for air conditioning will keep increasing. The percentage contribution made by individual ECC systems in satisfying the monthly and yearly cooling demands are revealed in Figures 4.1 and 4.2, respectively. As represented, the result shows that ECC A and B satisfied 79% of the yearly cooling load, while ECC C and D covered the rest 21%. This indicates that ECC A and B consumed more electricity than ECC C and D in their overall operation. The total estimate of energy used by the VCS system is estimated to be 17,412,439,194 kWh.

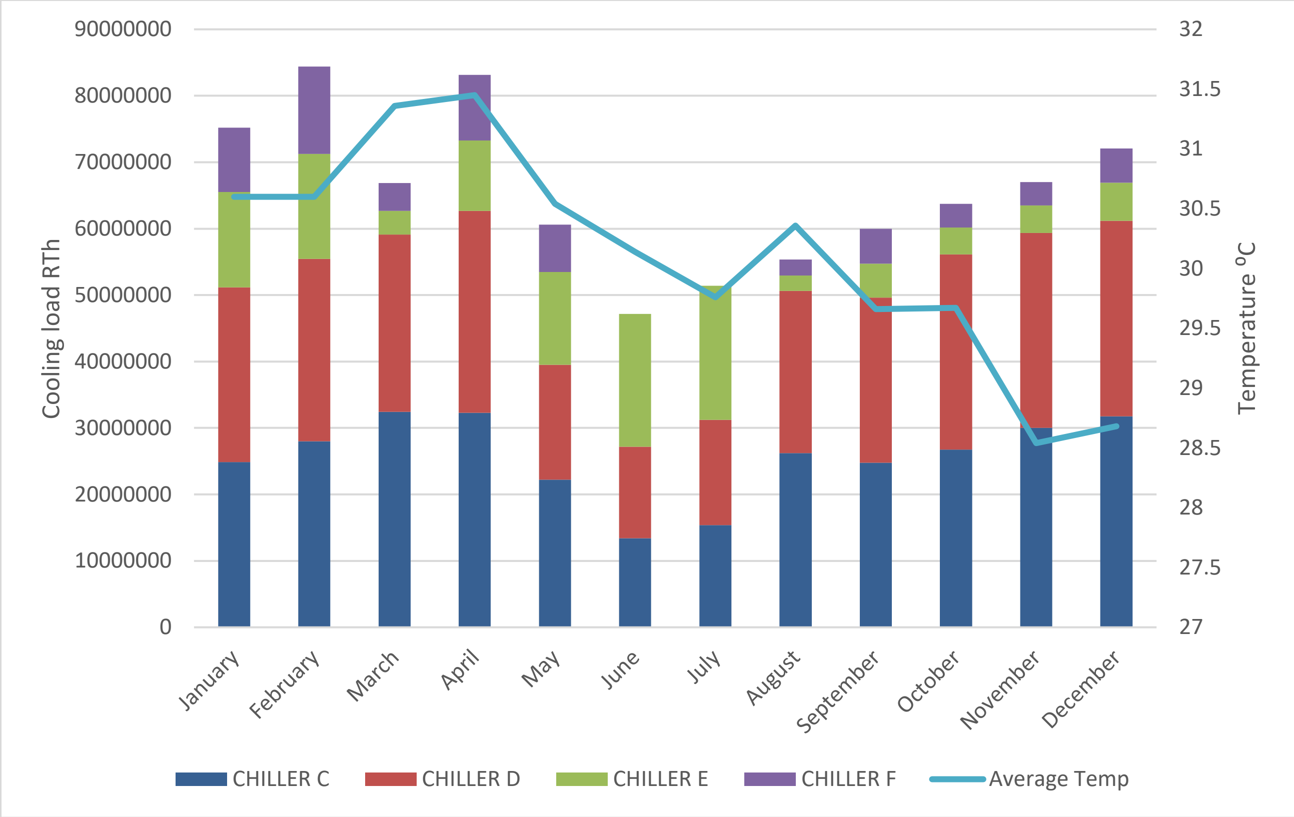


Figure 4.1: **Average climate temperature, monthly cooling load, and ECC cooling contribution.**

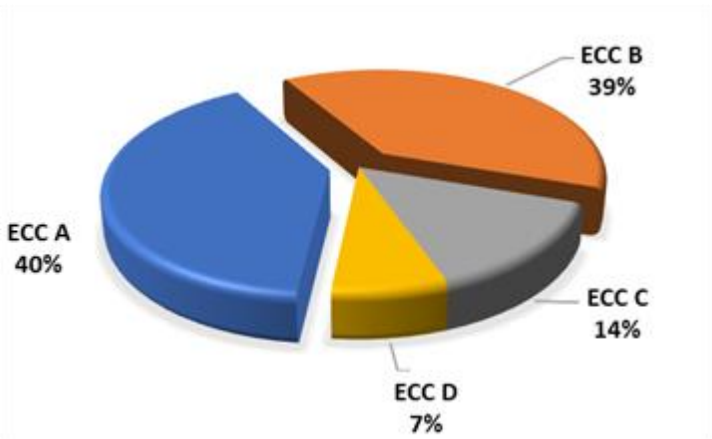


Figure 4.2: **The individual ECC system percentage contribution for the study year [6].**

The result presented in Figure 4.3 shows the estimated monthly EP usage by the VCC systems in producing chilled water for the DC networks. As expected, the month of April and June consumed the highest and lowest amount of electrical energy respectively in the study year, which is proportional to the rate of their usage with time.

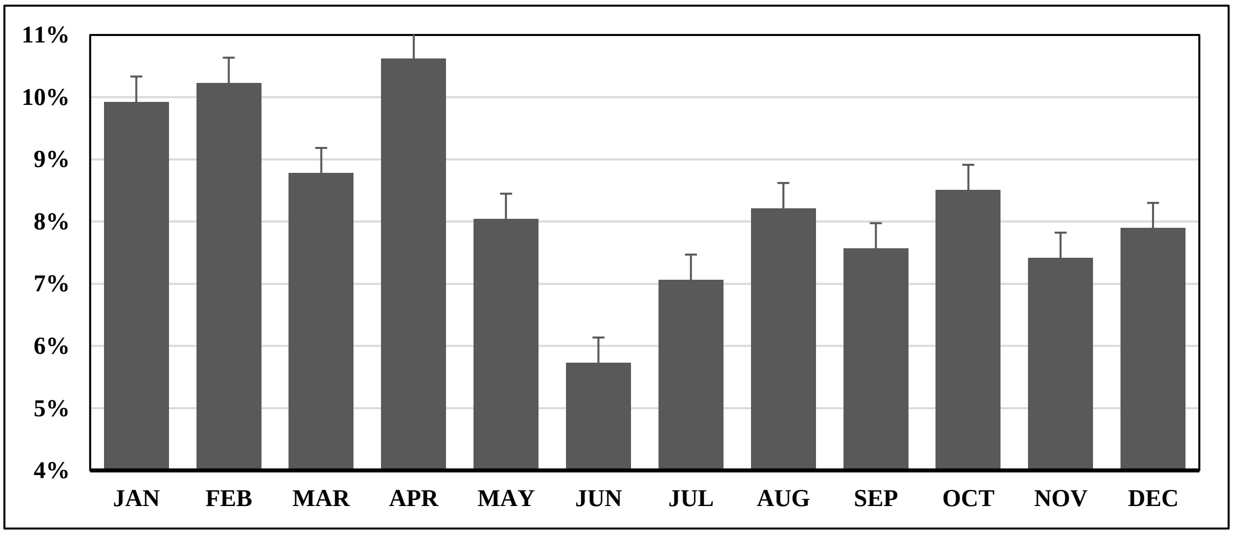


Figure 4.3: **Result of Electrical Power consumption by VCC systems throughout the year.**

Due to the performance degradation experienced by the four installed ECC systems over time, the COP of the oiled centrifugal chiller tends to reduce with time. According to the study of Ref. [78, 79], conventional oiled compressors like in VCC systems are prone to significant performance degradation resulting from excessive bearing wear, oil impurities, rotor tip contact, poor system maintenance, and other factors. Ref [76] suggested a 10% loss in efficiency of the VCS system after every five years. This assumption was applied to the case study to determine the performance degradation to energy consumption over a lifetime period of 25years. The result of this analysis is presented in Figure 4.4.

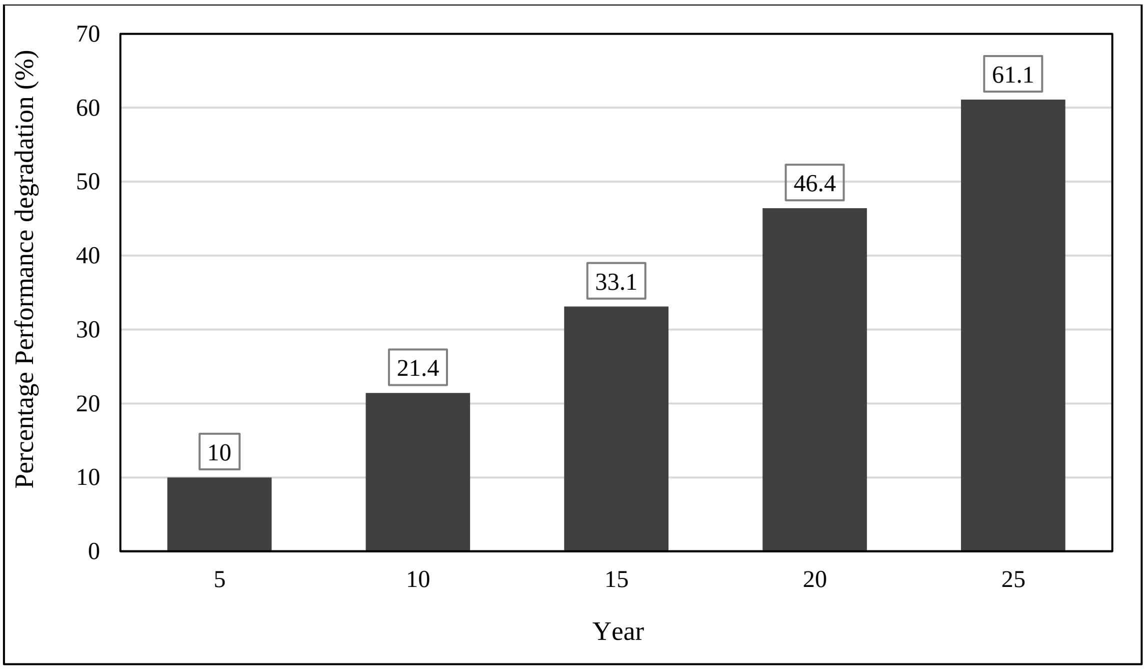


Figure 4.4: **Percentage performance degradation of the VCC system throughout its lifetime.**

As shown in Figure 4.4, after an operation period of 10 years, the percentage increase in performance degradation would amount to about 21.4%. However, this percentage would increase progressively from 33.1% through 46.4% to 61.1% after an operation of 15, 20, and 25years, respectively. By implication, the subsequent performance degradation is observed to increase progressively to 11.4%, 11.7%, 13.3%, and 14.7% after 10, 15, 20, and 25years, respectively. This also implies that after a period of 25years of usage, the performance efficiency of the system would have decreased to about 40% of the initial efficiency value. However, such degradation is minimal in magnetic non-oiled centrifugal chillers, and the efficiency is almost constant throughout their lifetime usage [11].

4.3 Life Cycle Impact Assessment results

In understanding the dynamic trend of the life cycle environmental impact of the VCS, the result of the Carbon Footprint per Functional Unit of 1 Ton of Refrigeration is given as 0.72kg $CO_{2\ eq}$/RTh. The result of the contribution of each process to the overall carbon footprint of the LCA analysis is presented in Table 4.1. From the result, about 98% of the overall carbon footprint per FU is caused by the indirect emission from commercial electricity usage to drive the VCS during its 25years of operation.

Table 4.1: **Contribution of the Processes to the overall Carbon Footprint per Functional Unit.**

Material/Product [Location]	**kg CO2 eq/FU**	**% Contribution**
Market For Scrap Aluminium [Row]	4.66542E-10	0.0000%
Market For Scrap Steel [Row]	3.02899E-08	0.0000%
Market For Waste Mineral Wool [Row]	4.59914E-07	0.0001%
Market For Scrap Copper [Row]	9.68952E-07	0.0001%
Market For Waste Brick [Row]	1.67555E-06	0.0002%
Treatment Of Used Refrigerant R134a, Final Disposal [GLO]	1.90174E-06	0.0003%
Market For Diesel [Row]	2.30996E-06	0.0003%
Market For Scrap Steel [Row]	2.92123E-06	0.0004%
Production Assembly	4.13515E-06	0.0006%
Refrigerant R134a Production [Row]	9.18885E-06	0.0013%
Market For Waste Concrete [Row]	9.96476E-06	0.0014%
Heat Pump Production, 8791kw Electrical [Row]	2.25347E-05	0.0031%
Market Group for Electricity, Medium Voltage [CN]	0.001174443	0.1634%
Thermal Storage System Construction, 50 MW [Row]	0.011567746	1.6099%
Market For Electricity, High Voltage [MY]	0.705737789	98.2188%
Grand Total	**0.71853607**	

In Table 4.2, the proportion of the indirect GHG emissions to the overall environmental footprint is presented. From the result, about 90% of the recorded GHG emission is occupied by Carbon dioxide gases. This is mainly due to the high proportion of fossil fuels (non-renewable energy) present in the country's (Malaysia) commercial electricity mix. This is closely followed by Methane Gas (recording about 3%), primarily due to fossil and non-fossil fuel usage.

Table 4.2: **Ratio of the indirect GHG contribution to the overall Environmental Footprint for the base scenario.**

GHG indirect Emission	**kg CO2 eq/FU**	**% Contribution**
Sulfur hexafluoride [air/unspecified]	3.81154E-05	0.01%
Ethane, 1,1-difluoro-, HFC-152a [air/urban air close to ground]	6.68245E-05	0.01%
Methane, fossil [air/urban air close to ground]	8.02556E-05	0.01%
Dinitrogen monoxide [air/urban air close to ground]	0.000292317	0.04%
Dinitrogen monoxide [air/unspecified]	0.001469811	0.20%
Dinitrogen monoxide [air/non-urban air or from high stacks]	0.003029678	0.42%
Carbon dioxide, from soil or biomass stock [air/non-urban air]	0.004633247	0.64%
Methane, non-fossil [air/non-urban air or from high stacks]	0.005042148	0.70%
Methane, fossil [air/unspecified]	0.006708099	0.93%
Carbon dioxide, fossil [air/unspecified]	0.008189787	1.14%
Carbon dioxide, fossil [air/urban air close to ground]	0.015108881	2.10%
Methane, fossil [air/non-urban air or from high stacks]	0.015202434	2.12%
Carbon dioxide, fossil [air/non-urban air or from high stacks]	0.658608535	91.66%
Grand Total	**0.71853607**	

The LCIA result per FU of the selected impact categories is presented in Figure 4.5. From the result, GWP recorded the highest impact of about 60% of the overall result. This is followed by Human Toxicity (HT) and Fossil Depletion (FD), with 19% and 18% impact contributions. The result of other selected impact categories had little or no significance to the overall result.

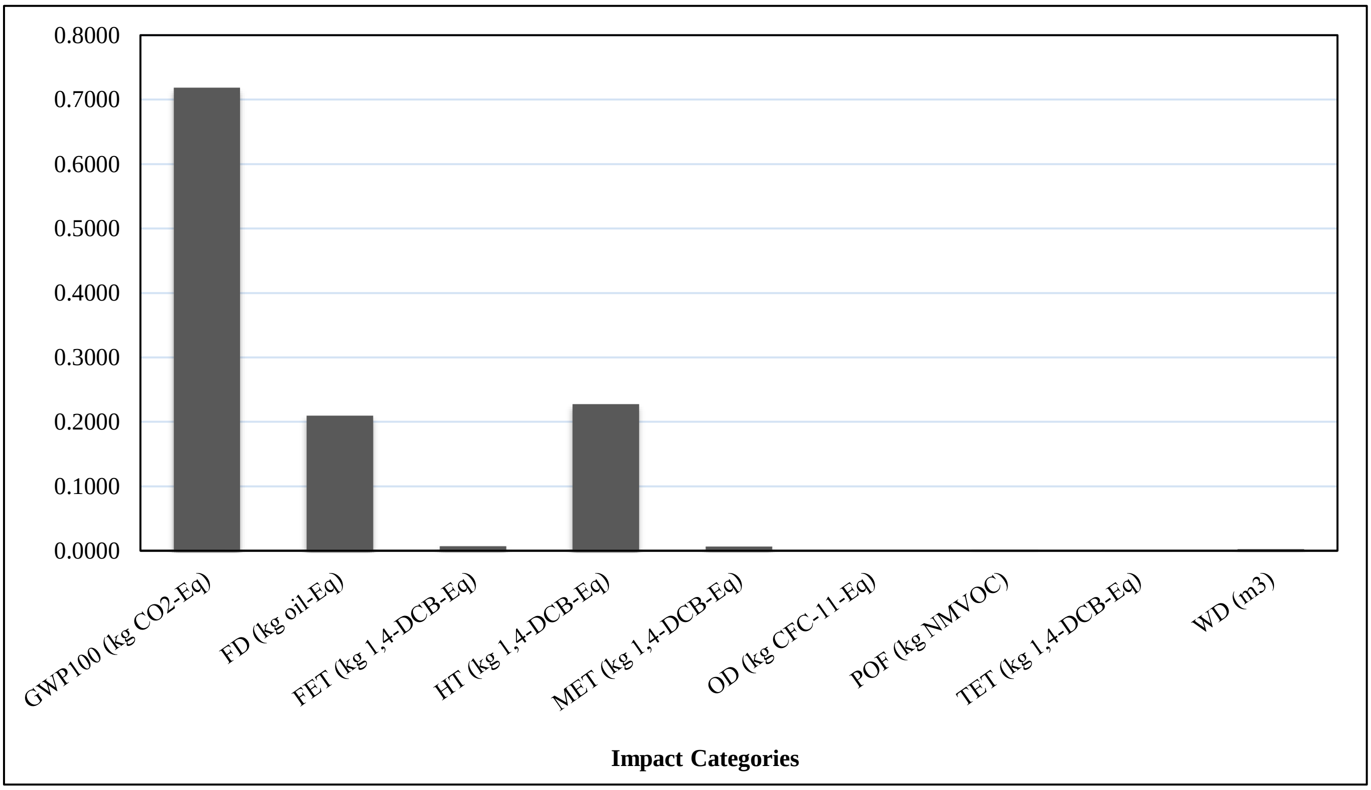


Figure 4.5: **LCAI result of the selected impact categories.**

Figure 4.6 indicates the contribution of different life cycle stages to the selected impact categories. The major contributor is the operation phase, contributing an overall average of 95% in all categories, with Human Toxicity (HT) and Freshwater Ecotoxicity (FET) recording the highest (98.6%) and lowest (91.6%) readings, respectively. The strong influence of the operation phase on the LCAI result is primarily linked to the high energy consumption and the high ratio of fossil fuel in the grid commercial mix used to drive the plants. On the other hand, the Manufacture phase contributes an average of 0.15%, with the highest and lowest contribution of 0.26% and 0.05% to the Photochemical Oxidant Formation (POF) and Ozone Depletion (OD), respectively. The Raw Material phase contributes an average of 4%, with the highest and lowest contribution of 8.12% and 1.26% to the Ozone Depletion (OD) and Human Toxicity (HT), respectively. The Disposal/Recycling phase contributes an average of 0.38%, with the highest and lowest contribution of 1.7% and 0.0013% to the Freshwater Ecotoxicity (FET) and Water Depletion (WT).

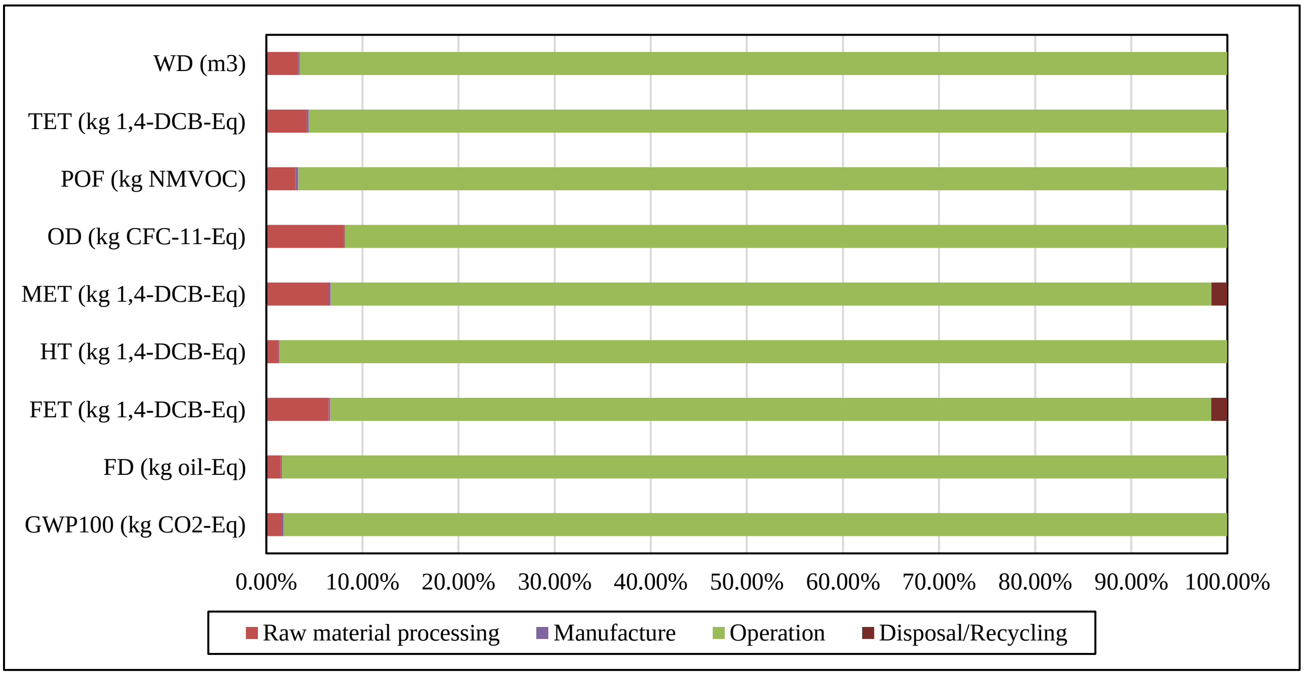


Figure 4.6: **Contribution of different life cycle stages of the VCS to the life cycle impacts categories.**

4.4 Comparison of the base study with a Conventional District Cooling setup.

A few studies on the LCA of VCC systems have been carried out in the literature [11, 59]. However, owing to numerous assumptions, such as plant capacity, use time, refrigeration outputs, load factors, longevity, and geographic locations where VCC systems are built, a direct comparison of the various outcomes is problematic. Various background data, such as national commercial electricity blends expected for VCS operation, result in different outcomes.

In this section, a comparison of the study conducted by Byrd et al. [11] with the case study is conducted to analyze the environmental gains resulting from integrating TES tanks in the operation of a DC system.

A VCC system placed directly in commercial buildings in the United States is examined in the study by Byrd et al., [11]. The study's functional unit is a 500-ton chiller that can cool a 150,000-square-foot office building. The cradle-to-cradle LCA, which encompasses raw material extraction, production, consumption, and end-of-life phases, is covered by the system boundary of their study. The amount of electrical energy consumed by the chiller system is estimated at 31,478,174 kWh throughout its lifetime. The calculated emissions of the chiller system (considering the USA electricity mix) throughout its lifecycle are estimated at 16,654,097.46 kgCO_2eq. This implies that for every 1kW of energy used to drive the VCC system, 1.9kg of CO_2 is emitted.

For the base study with TES tanks installed, the total amount of energy used by the VCS is estimated at 17,412,439,194 kWh throughout its lifetime. For the sake of comparison, the US electricity mix is assumed for this analysis. The calculated emissions of the chiller system throughout its lifecycle are estimated at 15,518,780,377 kgCO_2eq. This result implies that for every 1kW of energy used to drive the VCS, 1.1kg of CO_2 is emitted. The result of this analysis is presented in Figure 4.7, and it shows that about 40% of the CO_2 emission is avoided by TES tanks, thereby making their incorporation in a DC setup a more sustainable option.

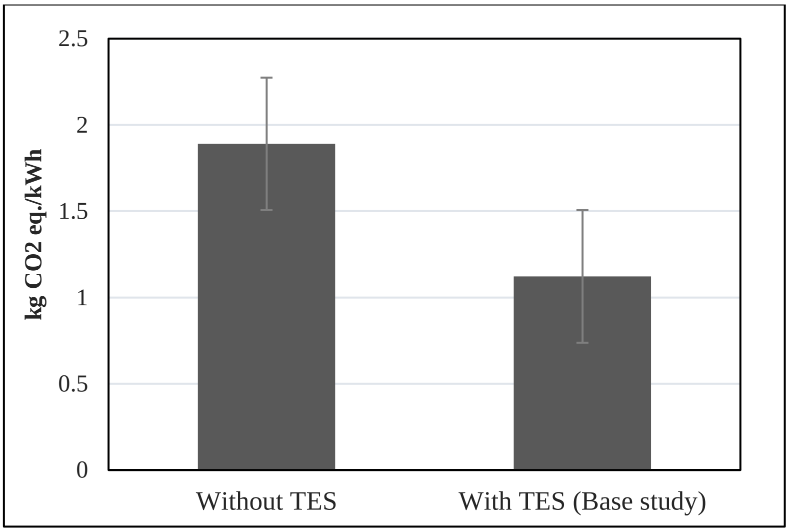


Figure 4.7: **The carbon footprint of a VCC system installed with and without a TES tank.**

4.5 Model Optimization: Comparison of Scenarios (Scenarios A, B, and the base case).

Since the use phase has shown to make the most significant contribution to the system's environmental impacts, measures targeted at lowering energy consumption and utilizing cleaner fuels during VCS operation may improve the whole system's environmental profile.

Figure 4.8 presents the environmental implications from considering the different scenarios in comparison with the base study. The result of the Carbon Footprint per refrigeration from sourcing electricity from NGP is given as 0.47kg CO_2eq/RTh, which represents about 65% of the Carbon contribution of the base case and a 35% decrease in the environmental footprint. In assuming the base scenario while improving the design of the electric chiller component by incorporating a more efficient compressor (Oilless magnetic compressor), a 0.16kg CO_2eq/RTh of the Carbon Footprint per refrigeration is recorded. This accounts for about 22% of the Carbon contribution of the base case and a 78% decrease in the environmental footprint to the base scenario.

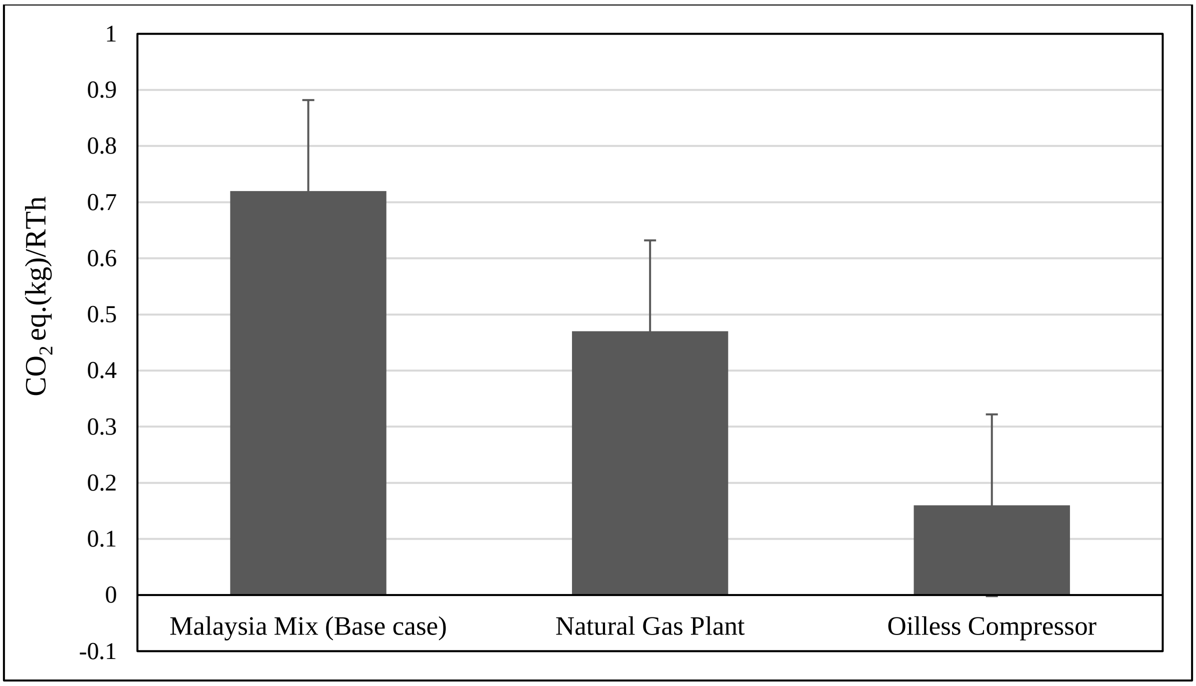


Figure 4.8: **Carbon Footprint of the considered Scenarios.**

The result presented in Table 4.3 shows the contribution of the indirect GHG emissions to the overall environmental footprint for integrating Natural Gas to generate electricity in the NGP supplied to the DC. From the result, about 60% of the recorded GHG emission is occupied by Carbon dioxide gases, representing about a 30% reduction from the result of the base scenario.

Table 4.3: **The ratio of GHG contribution to the overall Environmental Footprint for the Natural Gas scenario.**

GHG indirect emission	**kg CO2 eq/RTh**	**% Contribution**
Copper, ion [water/ground-, long-term]	0.001206042	0.18%
Bromine [water/unspecified]	0.001515455	0.22%
Water, river [natural resource/in water]	0.001592639	0.23%
Oil, crude, in ground [natural resource/in ground]	0.001861116	0.27%
Coal, hard, unspecified, in ground [natural resource]	0.001940703	0.28%
Dinitrogen monoxide [air/non-urban air]	0.002246956	0.33%
Manganese [water/ground-, long-term]	0.002801371	0.41%
Carbon dioxide, fossil [air/unspecified]	0.003259315	0.48%
Methane, fossil [air/non-urban air or from high stacks]	0.00801974	1.17%
Carbon dioxide, fossil [air/urban air close to ground]	0.01216082	1.77%
Methane, fossil [air/unspecified]	0.014536219	2.12%
Barium [water/unspecified]	0.021302053	3.11%
Gas, natural, in ground [natural resource/in ground]	0.185830757	27.11%
Carbon dioxide, fossil [air/non-urban air or from high stacks]	0.420296407	61.32%
Grand Total	**0.685397774**	**100.00%**

The result presented in Table 4.4 shows the contribution of the indirect GHG emissions to the overall environmental footprint for installing the Oilless magnetic compressor to the Electric Chiller compartment. From the result, about 60% of the recorded GHG emission is occupied by Carbon dioxide gases, representing about a 26% reduction from the result of the base scenario. This phenomenon is due to the reduction of energy consumed by the chiller system as a result of integrating a more stable and efficient non-lubricating compressor system.

Table 4.4: **The ratio of GHG contribution to the overall Environmental Footprint for the Oilless compressor case scenario**

GHG indirect emission	**kg CO2 eq/RTh**	**% Contribution**
Copper, ion [water/ground-, long-term]	0.001212376	0.47%
Methane, fossil [air/unspecified]	0.001435643	0.56%
Barium [water/unspecified]	0.002055066	0.80%
Oil, crude, in ground [natural resource/in ground]	0.002132234	0.83%
Selenium [water/ground-, long-term]	0.002322189	0.90%
Arsenic, ion [water/surface water]	0.003046367	1.18%
Carbon dioxide, fossil [air/unspecified]	0.003195881	1.24%
Arsenic, ion [water/ground-, long-term]	0.003557839	1.38%
Methane, fossil [air/non-urban air or from high stacks]	0.003618032	1.41%
Carbon dioxide, fossil [air/urban air close to ground]	0.007130019	2.77%
Gas, natural, in ground [natural resource/in ground]	0.018730213	7.28%
Coal, hard, in ground [natural resource/in ground]	0.02411289	9.37%
Manganese [water/ground-, long-term]	0.031914842	12.40%
Carbon dioxide, fossil [air/non-urban air]	0.139172415	54%
Grand Total	**0.257327424**	**100.00%**

The LCIA result per refrigeration based on the selected impact categories of all the considered scenarios is presented in Table 4.5. The total of their environmental impacts per refrigeration for the base case, Natural Gas Plant, and the oilless chiller options are given by 1.17, 0.68, and 0.26, respectively. The Natural Gas and Oilless chiller options all had GWP as the highest impact category, with an average of 60 % impact contribution. This is followed by Fossil Depletion (FD) and Human Toxicity (HT), with an average contribution of 16%. The result of other selected impact categories had little or no influence on the overall result. However, the Oilless chiller options recorded a lower FD contribution of 18% and a higher HT contribution of 19%.

Table 4.5: **LCIA result of all considered Scenarios.**

Impact Category (Unit)	**NGS**	**Oilless Compressor**
GWP100 (kg CO2-Eq)	0.4609	0.1578
FD (kg oil-Eq)	0.1898	0.0458
FET (kg 1,4-DCB-Eq)	0.0025	0.0019
HT (kg 1,4-DCB-Eq)	0.0287	0.0492
MET (kg 1,4-DCB-Eq)	0.0013	0.0017
OD (kg CFC-11-Eq)	0.0000	0.0000
POF (kg NMVOC)	0.0005	0.0003
TET (kg 1,4-DCB-Eq)	0.0000	0.0000
WD (m3)	0.0017	0.0006

The percentage change of all considered scenarios to the base case study is presented in Table 4.6. In analyzing the results, the case of the Oilless magnetic compressor design scenario provided the most sustainable option with an average of

76% environmental savings across all selected impact categories, having its highest (78.38%) and lowest (72.84%) impact savings on HT and FET, respectively. This is followed by the NGP case scenarios, with an average of 32% environmental savings. The Natural Gas Plant case scenario recorded its highest environmental savings of 87% on HT and made an extra 69% to the base case on the OD impact category.

Table 4.6: **Percentage of environmental savings of all considered scenarios to the base case.**

Impact Category (Unit)	Natural Gas Plant	Oilless Chiller
GWP100 (kg CO2-Eq)	36%	78%
FD (kg oil-Eq)	9%	78%
FET (kg 1,4-DCB-Eq)	65%	73%
HT (kg 1,4-DCB-Eq)	87%	78%
MET (kg 1,4-DCB-Eq)	80%	73%
OD (kg CFC-11-Eq)	-69%	73%
POF (kg NMVOC)	63%	77%
TET (kg 1,4-DCB-Eq)	-18%	76%
WD (m^3)	35%	77%
Average	**32%**	**76%**

4.6 Result of Life Cycle Cost

From the base study result evaluation, the overall life cycle cost per refrigeration ton of the VCS system is estimated to be MYR 1.44/RTh. However, as shown in Figure 4.9, switching the energy source from the National Electricity Grid (NEG) to Natural Gas Plant (NGP) resulted in a 50.6% cost savings per refrigeration. The result also indicates that TES inclusion in a conventional DC setup resulted to about 28.6% cost savings.

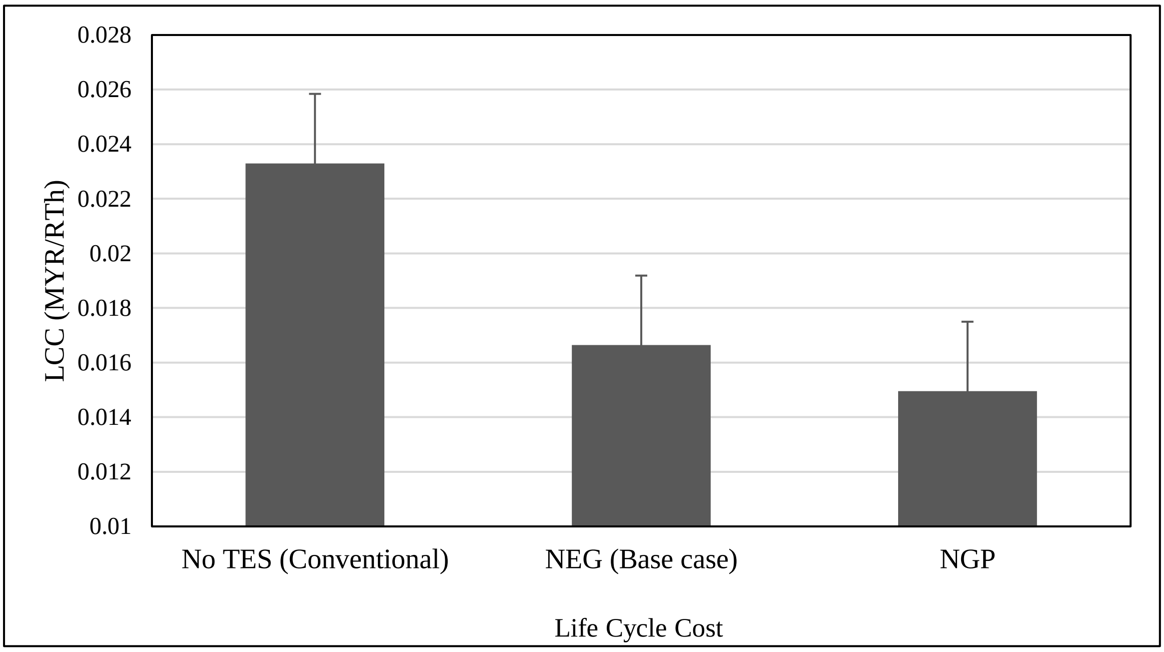


Figure 4.9: **LCC per refrigeration of the VCS systems using electricity and natural gas as energy sources.**

In considering operating an electric chiller with an integrated Oilless magnetic compressor, the result of the LCC is given as MYR 1.045/RTh and MYR 0.52/RTh while using commercial grid electricity and natural gas energy sources, respectively. The result presented in Figure 4.11 reveals that about a 28% increment in the LCC value is attributed to system degradation over the plant lifetime. The result also implies that operating the existing VCC system with natural gas offered a more preferred economic option than using an Oilless VCC system powered by commercial grid electricity. This is due to the 31% cost savings recorded from the comparative analysis of both scenarios, as shown in Figure 4.10.

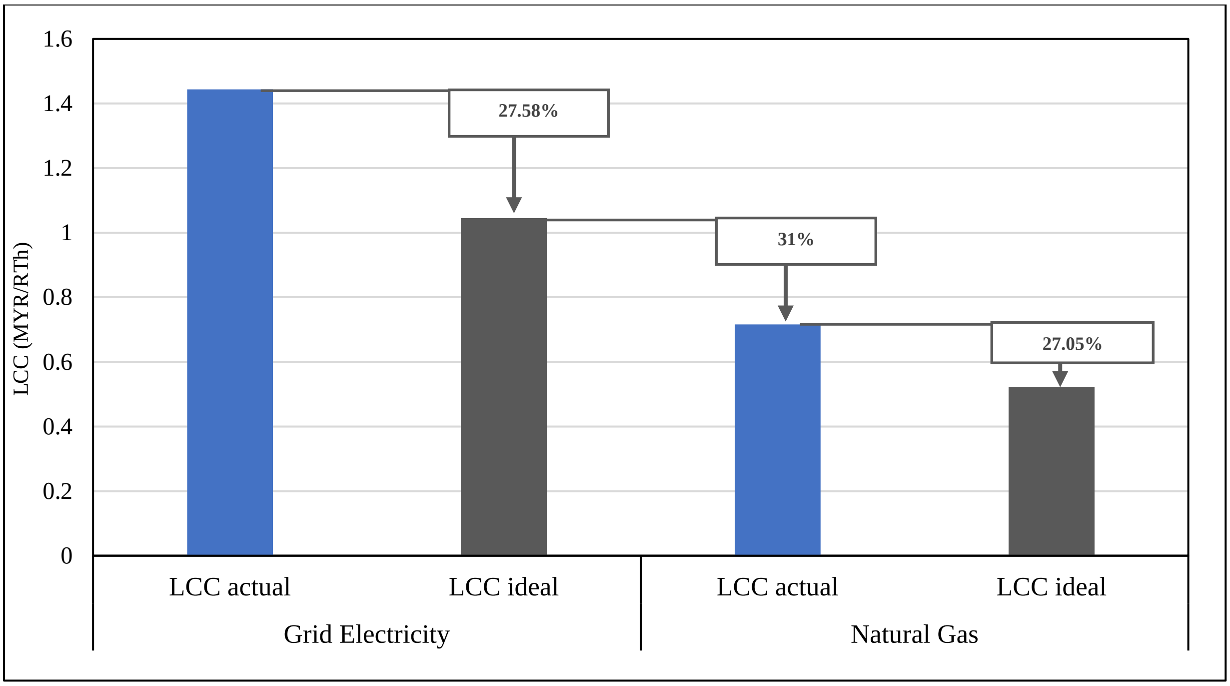


Figure 4.10: **LCC/RTh results of the VCC systems under the considered scenarios.**

The contribution of the life cycle stages in using commercial electricity and natural gas is presented in Figures 4.12 and 4.13, respectively. As expected, the operation phase accounted for most of the cost incurred throughout the life cycle of the chiller system in both scenarios having a value of about 98% and 96% of the total life cycle cost when the VCS system is operated on electricity and natural gas, respectively. This is due to the continuous purchase of energy which accounted for about 99% of the operation cost, while the cost of maintenance occupied the rest. Comparing the results presented in Figures 4.11 and 4.12, a 2% reduction is recorded in the cost attributed to the operation phase as the energy source is changed to natural gas. The lower operating cost of the latter relative to the former is due to the low tariff cost per kWh of the latter, as presented in Tables 3.8 and 3.9. The abundant commercial quantity of natural gas in Malaysia is another contributing factor.

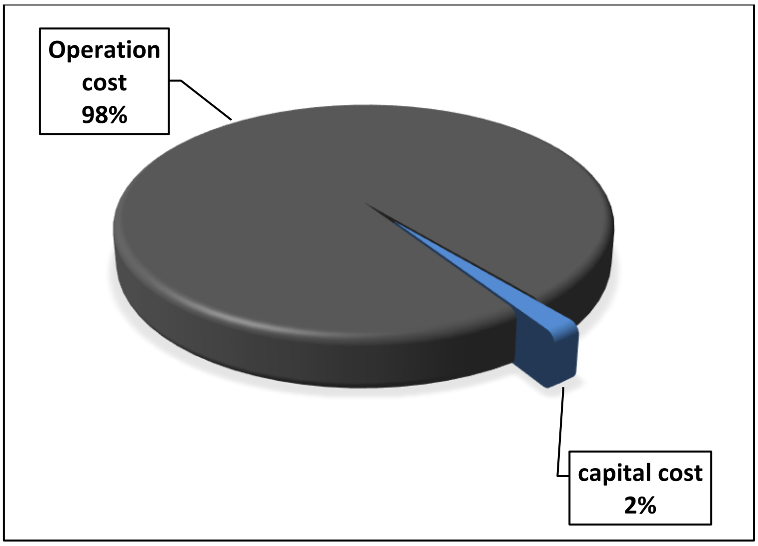


Figure 4.11: **Life cycle phase contribution of the VCS system operating with commercial electricity.**

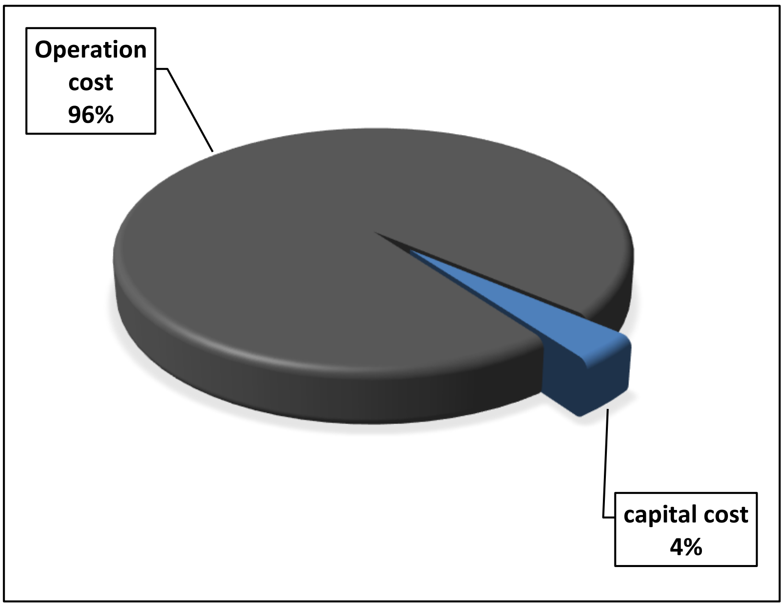


Figure 4.12: **Life cycle phase contribution of the VCS system operating with natural gas.**

Results in Figure 4.13 present the estimated cost per refrigeration rate as the performance efficiency of the chiller system degrades through its life span, showing the result of cost per refrigeration after every 5years of plant usage. From the Figure, as the COP value decreases from 5.5 to 2.75 over the 25years lifespan, the LCC/RTh is observed to increase from 0.239 to 1.443 MYR/RTh with a grid electricity energy source. In comparison, the LCC/RTh result increases from 0.130 to 0.715 MYR/RTh with Natural Gas as the energy source. The result shows that cost per refrigeration has a negative correlation with the system performance degradation. Furthermore, the result reveals that a unit decrease in COP value leads to a corresponding 18.2 % increase in the cost per unit refrigeration of the VCS.

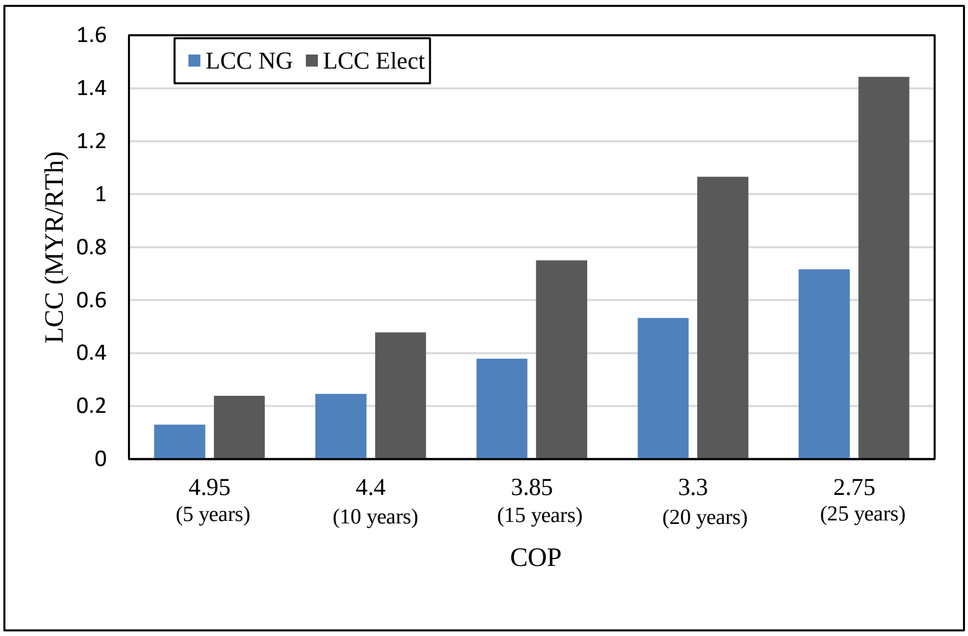


Figure 4.13: **Cost per refrigeration result of the VCS system through its lifespan for both scenarios.**

The further analysis estimates the cumulative percentage increase to the initial LCC value, and the corresponding percentage increase recorded every five years. Considering commercial grid electricity as an energy source, the analysis results are presented in Figure 4.14. From the Figure, the percentage increase for the first five years was found to be 6%. However, the value increases progressively to 8%, 10%, 12%, and 15%, respectively, after 10, 15, and 25 years. Furthermore, a 1.3% increase in the annual cost per unit refrigeration of the VCS system is recorded throughout the lifespan.

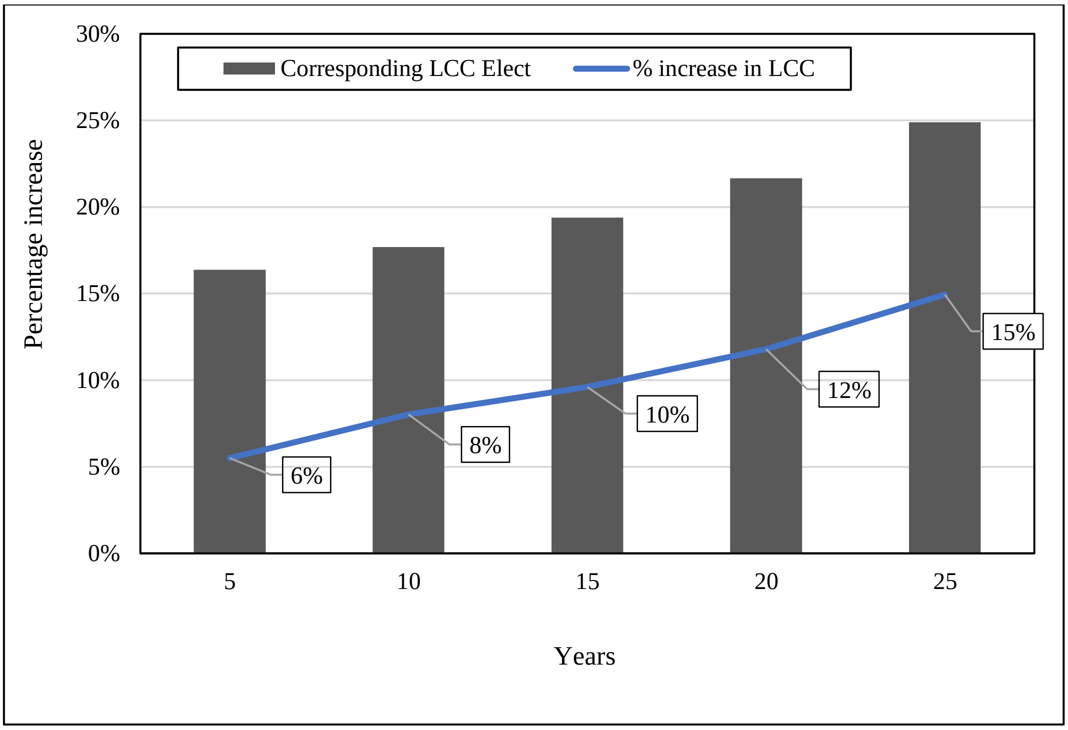


Figure 4.14: **Percentage increase in LCC using commercial grid electricity as an energy source.**

However, when natural gas is considered the energy source, a significant difference was observed in both the cumulative and corresponding percentage increase throughout the lifespan, as presented in Figure 4.15. From the Figure, the percentage increase for the first five years was found to be 4%. However, the value increases to 6%, 7%, 9% and 12% after 10, 15, 20 and 25 years, respectively. Furthermore, a 0.9% increase in the annual cost per unit refrigeration of the VCS system is recorded throughout the lifespan.

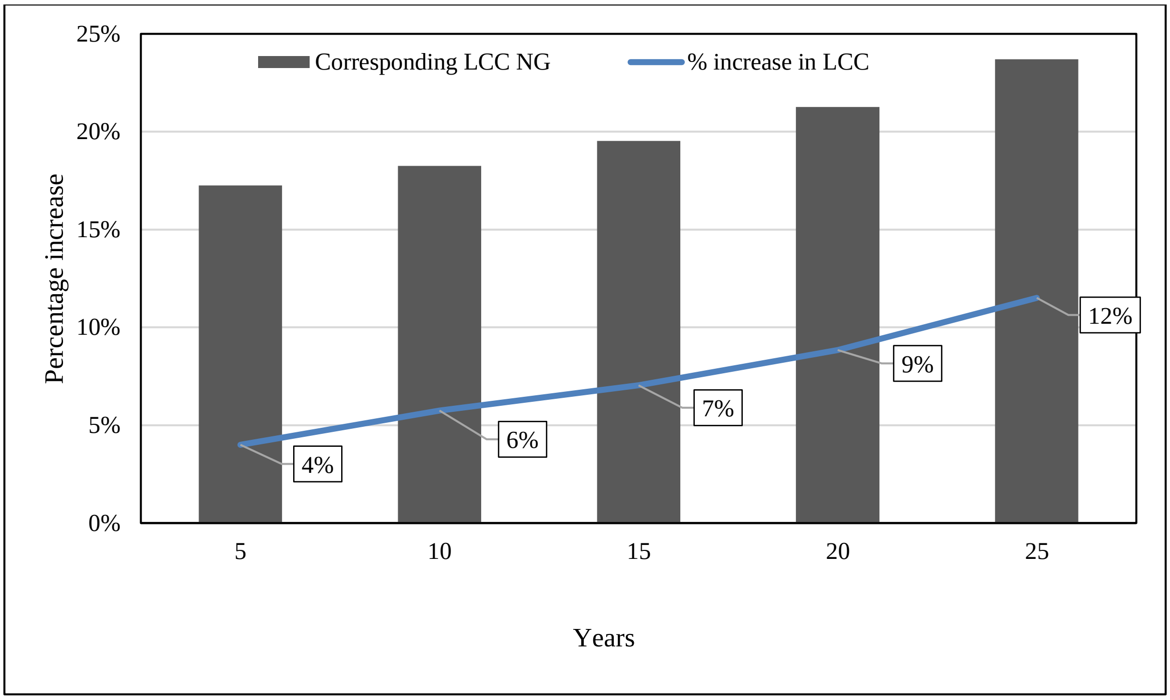


Figure 4.15: **Percentage increase in LCC using natural gas as an energy source.**

4.7 Sensitivity Analysis

The practice of conducting sensitivity analysis is necessary due to the inherent uncertainties in estimating the long-term cost, especially regarding energy functions, regulations and macroeconomic changes such as technological advancement [81]. With this technique, the input variable with the most influential contribution to the output variable is determined [82].

In this study, the operation cost accounts for more than 90% of the entire LCC in both considered scenarios of energy source. Therefore, it is critical to understand the impact of the performance parameters and cost of tariffs on the chiller life cycle cost. The sensitivity analysis is used to model the degree of uncertainty by adopting a 10 % change in value as recommended by the National Institute of Standards and Technology (NIST) [83]. As reported in Tables 4.10 and 4.11, the sensitivity results reveal that the change of tariff cost and COP value significantly impact the LCC of the chiller equipment. In practice, the operation parameters of ECC vary mainly due to geographic locations and times of the year, with different weather and energy tariffs. So, it is essential to study the sensitivity of COP of chillers on the life cycle cost.

From the result in Table 4.10 and 4.11, change in the COP value has a more significant effect on the LCC result compared to change in the tariff cost, as a 10%, 20%, and 30% decrease led to an 11%, 25%, and 45% increase in the LCC respectively, for the baseline condition. While for tariff cost, a 10%, 20% and 30% decrease led to a 10%, 20% and 30% decrease in the LCC result, respectively, for the baseline condition. The result also reveals that the chiller system accounts for its highest life cycle cost as the COP value drops with a corresponding increase in tariff cost. In monitoring the trend in Tables 4.7 and 4.7 as the result move towards the southwest region of the table, the system experiences its highest LCC. The opposite happens when the result moves towards the northeast region of Tables 4.10 and 4.11. The sensitivity analysis result implies that using more efficient ECC systems and cheaper energy sources is a significant criterion in reducing the entire life cycle cost, as a change in their value can significantly affect the LCC. This conclusion is in line with J. Morrissey and R.E. Horne's research [84]. Their study stated that the most cost-effective design is the system with the highest thermal performance.

Table 4.7: **Sensitivity analysis of the ECC system to test the effect of change in COP value and electricity tariff from NEG on the operation cost.**

10% Change of Elect. Tariff (NEG)	**10% Change of COP**						
0	**3.85**	**4.4**	**4.95**	**Baseline 5.5**	**6.05**	**6.6**	**7.15**
0.1568	0%	-13%	-22%	-30%	-36%	-42%	-46%
0.1792	14%	0%	-11%	-20%	-27%	-33%	-38%
0.2016	29%	13%	0%	-10%	-18%	-25%	-31%
Baseline (0.224)	43%	25%	11%	0%	-9%	-17%	-23%
0.2464	57%	38%	22%	10%	0%	-8%	-15%
0.2688	71%	50%	33%	20%	9%	0%	-8%
0.2912	86%	63%	44%	30%	18%	8%	0%

Table 4.8: **Sensitivity analysis of the ECC system to test the effect of change in COP value and electricity tariff from NGP on the operation cost.**

10% Change of Elect. Tariff (NGP)	**10% Change of COP**						
0	**3.85**	**4.4**	**4.95**	**Baseline 5.5**	**6.05**	**6.6**	**7.15**
0.0763	0%	-13%	-22%	-30%	-36%	-42%	-46%
0.0872	14%	0%	-11%	-20%	-27%	-33%	-38%
0.0981	29%	13%	0%	-10%	-18%	-25%	-31%
Baseline (0.109)	43%	25%	11%	0%	-9%	-17%	-23%
0.1199	57%	38%	22%	10%	0%	-8%	-15%
0.1308	71%	50%	33%	20%	9%	0%	-8%
0.1417	86%	63%	44%	30%	18%	8%	0%

4.8 Chapter Summary

The findings of the life cycle environmental and economic assessment of the VCS can be summarised as follows:

1. The result of the cradle to grave life cycle analysis of the VCS is given as 0.72kg $CO_{2\ eq}$/RTh, and about 98% is as a result of indirect emission from commercial electricity usage to drive the system throughout its use life.

2. In the LCIA result of the case study, GWP recorded the highest impact contribution of about 60% of the overall selection. This is followed by Human Toxicity (HT) and Fossil Depletion (FD), with 19% and 18% impact contributions.

3. In comparing the contributions of the life cycle phases to the overall LCAI result, the operation phase made an average of 95% contribution in all selected impact categories, with HT and FET recording the highest (98.6%) and lowest (91.6%) readings, respectively. This is due to the high ratio of fossil fuel in the electricity grid mix used to drive the plants.

4. In analyzing the LCIA result of all the considered scenarios, GWP accounted for the highest impact category, with an average of 60% impact contribution. This is followed by FD and HT, with an average contribution of 21% and 16%, respectively. However, the Oilless chiller options recorded a lower FD of 18% and a higher HT of 19%.

5. In analyzing the LCIA result, incorporating the more stable oilless magnetic compressors option resulted in an average of 76% environmental savings across all selected impact categories. This is followed by sourcing electricity from the Natural gas plant case, with an average of 32% savings across all selected impact categories.

6. Incorporating a more stable oilless magnetic compressors in the VCC system presented the most significant environmental savings, with an estimated 78%

reduction in the environmental footprint to the base case. Meanwhile, sourcing of electricity from NGP recorded about 35% environmental savings.

7. In estimating the environmental gains resulting from the integration of TES tanks in the VCS operation, the base study result is compared with the literature. In analyzing the result, a 40% environmental saving is recorded with TES integration.

8. The result of the Life cycle cost per refrigeration ton of the VCS system is estimated to be MYR 1.44/RTh, accounting for about 28.6% reduction in cost saving compared to the conventional DC setup. Also, switching the energy source from grid electricity to natural gas resulted in about 50% cost reduction. Also, the Natural Gas option offers a better economic option than the oilless chiller powered with the Malaysia grid electricity, with a 31% cost savings.

9. The sensitivity analysis result reveals that a change in the COP value had a more significant effect on the LCC result than a change in the tariff cost. The result implies that using more efficient ECC systems and cheaper energy sources is a significant criterion in reducing the entire life cycle cost, as a change in their value can significantly affect the LCC.

10. In both considered scenarios, the operation phase accounted for most of the cost incurred throughout the life cycle of the chiller system, having a value of about 98% and 96% of the total life cycle cost when the VCS system is operated on the Malaysia grid electricity and natural gas, respectively. The high economic implication resulting from the use phase is also tied to the intensity of energy consumed and the tariff cost.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Chapter Overview

This chapter concludes the research work and also provides recommendations for further studies. The chapter was concluded with the major findings regarding the objectives slated out in the opening chapter. The proposed direction for further studies is a culmination of the findings of this research work which would serve as a substantial contribution to literature.

5.2 Conclusions

Following the results obtained from the numerical analysis in the preceding section, the following conclusions were made.

1. The result of the cradle to grave life cycle analysis of the VCS is given as 0.72kg $CO_{2\ eq}$/RTh. The indirect GHG emission (occupied by 90% CO_2 gases) from the commercial electricity had the most significant influence on the operation phase. GWP recorded the highest impact contribution of about 60% of the overall LCIA result. This is followed by Human Toxicity (HT) and Fossil Depletion (FD), with 19% and 18% impact contributions. The high impact result is proportional to the ratio of fossil fuel in the grid electricity mix and the intensity of energy consumed.

2. The result of the Life cycle cost per refrigeration ton of the VCS system is estimated to be MYR 1.44/RTh. The strong influence of the operation phase on the overall economic impact is linked mainly to the cost of the system maintenance and tariff charge for 1kWh of energy supplied from the commercial grid electricity to power the system throughout its use life. The high economic implication resulting from the use phase is also tied to the intensity of energy consumed. The sensitivity analysis result reveals that a change in the

COP value had a more significant effect on the LCC result than a change in the tariff cost.

3. From the result, it can be concluded that integrating TES in DC systems provides a more sustainable option compared to the conventional DC setups without TES, as a 40% and 28.6% environmental and cost savings were recorded, respectively. In proposing other options with better sustainability index, the result of the case study is compared with other optimized system setups. From the analysis, incorporating a more stable oilless magnetic compressors in the VCC system presented the most significant environmental savings, with an estimated 78% reduction in the environmental footprint to the base case. Meanwhile, sourcing of electricity from NGP recorded about 35% environmental savings. In terms of the economic implications, switching electricity source to the NGP recorded about 51% cost savings. Sensitivity analysis of the result also reveals that a change in the system efficiency had greater influence on the LCC result than a change in the tariff cost, as a more efficient system powered by cheaper and cleaner energy sources would provide the most sustainable option for the VCS design and operations.

5.3 Recommendations

Based on the findings and result analysis carried out in this research project, it is recommended that future research should focus on:

1. Along with the environmental and economic analyzes conducted in this study, the holistic approach to sustainability evaluation should incorporate the life cycle social consequences.

2. Sensitivity and uncertainty evaluations are needed steps to be performed to improve the quality of the data and the research results.

3. Data refinement for the VCS technologies by acquiring additional primary data to decrease the reliance on secondary data from databases.

4. The transportation, installation, and decommissioning phases should also be considered in the VCS life cycle analysis of future studies.

5. The use of realistic escalation and nominal discount rates should be considered in future LCC studies on VSC.

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