CLEANER PRODUCTION STRATEGIES IN STEAM METHANE REFORMING PROCESS FOR HYDROGEN PRODUCTION

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ABSTRACT

Hydrogen gas is a clean fuel, when consumed in a fuel cell, produces only water. It makes an attractive fuel option for transportation and electricity generation application. As the world moves towards a more sustainable approach, hydrogen gas has a promising future in the role to play as a clean energy. Among the different technologies, steam methane reforming (SMR) is the most vital and economic process, being used in most of the hydrogen manufacturing industries. SMR comes with advantages such as initial low capital investments, greater scalability and sitting flexibility for locations unable to accommodate more traditional larger reactors. Besides that, SMR also has the potential of enhanced safety and security compared to other technology available. However, the drawback is that SMR emits significant carbon dioxide (CO_2) emissions as a byproduct of hydrogen production. For 1 kg of hydrogen produced, about 4 kg of CO_2 is emitted directly from the process alone, not accounting to the indirect CO_2 emission.

Therefore, in this work, an overall assessment was conducted for the full life cycle of steam methane reforming process to identify possible greening opportunities using cleaner production (CP) strategy. From this initiative, a checklist and general guideline that can be used to green the current operations has been developed in order to reduce the carbon footprint.

Thereafter, a CP audit was carried out in a SMR production site which is located at Melaka. Based on the analysis, carbon footprint can be possibly reduced from 7,430 tons monthly to 4,963 tons monthly for the current hydrogen production monthly with all the CP options proposed. This is equivalent to 66.8 % of reduction from the total of 7,430 tons of CO_2 emitted without implementing any CP strategies. Based on the CP options, those falls under the category of implementation without cost (immediate actions) are given the highest priority followed by implementation with cost, whereby the Rate of Investment (ROI) is lesser than 5 years and future implementation. The three finest CP options were installing steam traps at the steam drum, changing the current technology to electrolysis and installing Carbon Capture and Storage (CCS) to the existing SMR has tremendous potential to reduce carbon footprint, increases the efficiency of the process and improves the quality of the product.

Keywords: hydrogen production, carbon dioxide, carbon footprint, reforming process, energy recovery

STRATEGI PENGELUARAN PEMBERSIH DALAM PROSES REFORMASI STEAM METANA UNTUK PENGELUARAN HIDROGEN

ABSTRAK

Gas hidrogen adalah bahan bakar yang bersih, bila dikonsumsi dalam sel bahan bakar, hanya menghasilkan air. Ini menjadikan pilihan bahan bakar yang menarik untuk aplikasi pengangkutan dan penjanaan elektrik. Ketika dunia bergerak ke arah pendekatan yang lebih lestari, gas hidrogen memiliki masa depan yang menjanjikan dalam peranannya sebagai energi bersih. Di antara teknologi yang berbeza, pembaharuan metana wap (SMR) adalah proses yang paling penting dan ekonomi, digunakan di kebanyakan industri pembuatan hidrogen. SMR hadir dengan kelebihan seperti pelaburan modal rendah awal, skalabiliti yang lebih besar dan fleksibiliti tempat untuk lokasi yang tidak dapat menampung reaktor tradisional yang lebih tradisional. Selain itu, SMR juga berpotensi meningkatkan keselamatan dan keamanan dibandingkan dengan teknologi lain yang ada. Namun, kekurangannya ialah SMR mengeluarkan pelepasan karbon dioksida (CO_2) yang signifikan sebagai produk sampingan pengeluaran hidrogen. Untuk 1 kg hidrogen yang dihasilkan, kira-kira 4 kg CO_2 dipancarkan secara langsung dari proses sahaja, tidak menyumbang kepada pelepasan CO_2 tidak langsung.

Oleh itu, dalam karya ini, penilaian keseluruhan dilakukan untuk kitaran hidup penuh proses pembaharuan metana wap untuk mengenal pasti kemungkinan peluang penghijauan menggunakan strategi pengeluaran bersih (CP). Dari inisiatif ini, senarai semak dan garis panduan umum yang dapat digunakan untuk menghijaukan operasi semasa telah dikembangkan untuk mengurangkan jejak karbon.

Setelah itu, audit CP dilakukan di lokasi pengeluaran SMR yang terletak di Melaka. Berdasarkan analisis, jejak karbon dapat dikurangkan dari 7,430 tan setiap bulan menjadi

4,963 tan bulanan untuk pengeluaran hidrogen semasa setiap bulan dengan semua pilihan CP dicadangkan. Ini setara dengan 66.8% pengurangan dari jumlah 7.430 tan CO_2 yang dikeluarkan tanpa melaksanakan strategi CP. Berdasarkan pilihan CP, yang termasuk dalam kategori pelaksanaan tanpa biaya (tindakan segera) diberi keutamaan tertinggi diikuti dengan pelaksanaan dengan biaya, di mana Tingkat Pelaburan (ROI) kurang dari 5 tahun dan pelaksanaan di masa depan. Tiga pilihan CP terbaik adalah memasang perangkap stim pada drum stim, mengubah teknologi semasa menjadi elektrolisis dan memasang Carbon Capture and Storage (CCS) ke SMR yang ada berpotensi besar untuk mengurangkan jejak karbon, meningkatkan kecekapan proses dan meningkatkan kualiti produk.

Kata kunci: pengeluaran hidrogen, karbon dioksida, jejak karbon, proses pembaharuan, pemulihan tenaga

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LIST OF SYMBOLS AND ABBREVIATIONS

ATR	:	Autothermal Reforming
CO_2	:	Carbon Dioxide
CH_4	:	Methane
CP	:	Cleaner Production
N_2O	:	Nitrous Oxide
PFC	:	Perfluorocarbon
PO	:	Partial Oxidation
PP	:	Payback Period
ROI	:	Rate of Investment
SF6	:	Sulfur Hexafluoride
SMR	:	Steam Methane Reformer
UNEP	:	United Nations Environment Program

CHAPTER 1: INTRODUCTION

1.1 Background

Hydrogen is the lightest and ample element in the universe. As an energy fuel, hydrogen has a broad prospect in the energy transition and can significantly realize the decarbonization of the global energy and transportation industries. Hydrogen produced from various resources using various technologies around the world. Steam methane reforming (SMR) is the common and economic process adopted by most gas manufacturing companies**.** However, SMR emits significant carbon dioxide (CO_2) emissions as a byproduct of hydrogen production. About 2-3 kg of carbon dioxide is released for every kilogram of fossil fuel burned such as diesel, gasoline, LPG and LNG (Wang & Eng). An average of 10kg of carbon dioxide is released for every kilogram of hydrogen gas produced using the conventional steam methane reformer technology. Moreover, steam methane reformer uses natural gas as its raw feedstock. Being said that SMR can be one of the most polluting industrial processes.

Figure 1.1: Picture of a conventional steam reformer plant located in Singapore

To tackle the issue with the current steam methane reformer technology, through this study, we aim to evaluate and study the cleaner production (CP) approaches to combat greenhouse gas emissions. CP is a strategic means by preventative methods to manage the environmental ramifications of business processes and products (Srinivas, 2010)**.** Changes in technology, unit processes, resources, or practises are used by CP to reduce waste, environmental and health risks, reduce environmental damage, efficiently use energy and resources, boost business profitability and competitiveness, and improve the efficiency of specific production processes. All businesses, regardless of size or nature, can benefit from cleaner production.

In this study, we will approach this matter through a structured CP audit. Special attention is given to energy efficiency. Cleaner production audit will take account the CP practices such as good housekeeping, substituting the input materials with a more sustainable ones or the one with less toxicity, better operational procedures, modifying the existing production and process equipment in order to lower waste and emission generation rates, enhancement of the technology, reuse the wasted materials or byproducts for another potential usage within the company, modification of the product and by utilizing the energy efficiently, Some of the key advantages of cleaner production implementation are improving the environmental situation, continuous environmental improvement, gaining competitive advantage, increase in terms of productivity and increase in economic benefits in longer run.

As much as implementation of cleaner production carries a vast array of benefits, there are several barriers that can stand on its way which is lack of expertise and information, low environmental awareness among the company's management, the pressure for short term profits, financial obstacles to adopt the cleaner production solutions, lack of communication in the company and not having enough skilled labor force to implement the solution (Institute of Environmental Engineering (APINI) Kaunas University of Technology, Lithuania, 2012).

Therefore, an overall assessment to identify carbon dioxide emission in the SMR production site is required. Possibility of applying cleaner production strategy will be also explored within the boundary of SMR process in the production site.

1.2 Problem Statement

Steam reforming of hydrocarbons, especially natural gas, is the most prominent and economical process to produce hydrogen in the industrial gas manufacturing companies. The glitch in this process is that, during this process, a huge amount of carbon dioxide is being released to the atmosphere, contributing to the carbon footprint. According to a study conducted by (A et al., 2015), carbon dioxide emissions from the steam methane reformer (SMR) process contribute to 0.44 Nm3 CO_2/ Nm3 hydrogen produced. Besides that, SMR process is energy intensive, requiring high temperature for the reforming process in addition to co-producing a huge amount of CO_2. Although, hydrogen is an emission-free fuel, the feedstock and manufacturing process for hydrogen generally use natural gas, which results in greenhouse gas emissions. The growing acceptance of cleaner production and its incredible benefits piqued interest in investigating cleaner production in hydrogen manufacturing units and exploring the choices discovered through this research. Pollution caused by SMR might not be completely prevented, but it could be significantly reduced if there are cleaner production (CP) approaches. Cleaner production in steam methane reforming sectors is not very common and there is limited research on this topic. Therefore, research will be conducted at steam methane reformer production site in Malaysia to improve the process and the operation of hydrogen production through cleaner production methods.

1.3 Research Questions

I. What are the current issues with steam methane reforming process contributing to carbon footprint?

II. How does CP implementation minimize the CO_2 emission and improves the efficiency of the process?

III. How the effectiveness of CP strategies in steam methane reforming process is measured in the perspective of carbon footprint?

1.4 Aim of the Study

The purpose of this research study is to apply the CP strategies to green the existing SMR and its related process to reduce CO_2 emission.

1.5 Objectives of Study

Since the research study scope is huge, the main objectives are:

1. To identify CO_2 emission sources from steam methane reforming production site.
2. To determine overall carbon footprint for steam methane reforming production site.
3. To evaluate feasibility of using cleaner production options in the steam methane reforming production site.

1.6 Scope of the Study

The scope of study of this project comprises the following:

I. Performing detailed assessment on the steam methane reformer technology for production of hydrogen in a production site located in Melaka, Malaysia.

II. The scope will be focused on the process, from the burning of natural gas to the production of hydrogen. System boundary of liquid and solid waste management are focused within the production site; however the utilities and energy consumption are solely focused on SMR.

III. The referential unit is 1 ton of hydrogen produced at the plant gate. The hydrogen process upgrading, and delivery of hydrogen are not taken into account in this study.

1.7 Thesis Outline

This study consists of 5 chapters as follows:

1. Chapter 1 - Introduction

   This chapter consists of the general statements relating to the overview of this research topic. It also states out the background of steam methane reformer technology in the production of hydrogen gas and the flaws it exhibits currently. This chapter also discusses the problem statement, aim and objectives of the study and scope of the study.

2. Chapter 2 - Literature Review

   This chapter discusses current and previous findings on hydrogen gas production technologies and the impact it has on carbon footprint. Discussions on cleaner production and carbon footprint have also been highlighted here. An in-depth review has been listed in this chapter on the steam methane reformer process flow, the advantages and disadvantages of using steam methane reformer, material balances and science behind the production of hydrogen gas and its uses in the market.

3. Chapter 3 - Research Methodology

   This chapter outlines the steps taken to address the problem statement. It comprises various methods used in gathering the data and information which is relevant to this study. Some of the methods are site visits, interviews with the site production team, cleaner production audit at the site. All the information gathered are analyzed for the possible implementation of cleaner production solutions. Carbon dioxide emissions are calculated based on the mathematical formula with the aid of computer software.

4. Chapter 4 - Results and Discussion

   This chapter involves results obtained by implementing cleaner production strategies in the premises. All the cleaner production options proposed will be further analysis and

   discussed in this chapter. The effectiveness of cleaner production options are measured by carbon footprint quantification. The barriers and challenges on the implementation are also reviewed accordingly.

5. Chapter 5 - Conclusion and Recommendations

This chapter summarizes the overall findings from the cleaner production audit conducted and the approaches suggested to reduce the carbon footprint. Besides that, the initial hypothesis will be assessed whether the results justify the objectives and aim. Suggestions and recommendations for future studies are highlighted in this chapter in the recommendations section.

1.8 Significant of the Study

The results from this study are important for identifying the areas of improvement where can be used to improve SMR process to reduce carbon dioxide emission. The study also evaluates various unit operations that may cause most of the carbon dioxide emitted to the environment. Companies adopting SMR technology to produce hydrogen can use the guidelines in this study as a cleaner production option to eliminate or minimize carbon footprint when reasonably feasible in addition to lower the operating cost and maximize the process efficiency.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Steam Methane Reforming (SMR)

Steam methane reforming (SMR) is a well-developed, commercial technology and chemical process in the hydrogen gas manufacturing industry to produce hydrogen on a big scale. This process involves two chemical reactions that converts water and methane, which is in the form of natural gas normally, into pure hydrogen and carbon dioxide, (CO_2) (Bakey, 2015). After that, the hydrogen gas is purified to the customer's specifications. SMR is the most common and cost-effective method of producing hydrogen gas, which may be used to create power, refine oil, perform numerous chemical processes, and a variety of other industrial purposes.

The SMR process can be further distinguished into five distinct steps (Bakey, 2015):

1. Under high temperature, water enter the furnace to produce steam.
2. Steam reacts with natural gas, producing hydrogen and carbon monoxide.
3. Carbon monoxide and steam reacts together in the water gas shift reactor to form carbon dioxide and hydrogen gas.
4. The hydrogen gas is purified to the customer's specifications, removing contaminants.
5. Purified hydrogen will be supplied to the customer.

These separate steps work together to form a continuous process. A huge plant can produce a steady stream of hydrogen at all hours of the day. Steam reforming reaction is endothermic which is heat must be supplied to the process for the chemical reaction to proceed. Steam reforming can also be used to produce hydrogen from other fuels such as ethanol, propane or gasoline.

2.2 Current Issues of Steam Methane Reforming (SMR)

The use of steam reforming units mitigates the problems of storage and distribution of hydrogen tanks for hydrogen vehicles (Chen, 2010). Furthermore, when compared to other commercially accessible hydrogen production processes such as partial oxidation of heavy oil and coal, as well as coal gasification, SMR has the highest efficiency. Unfortunately, hydrogen synthesis from natural gas steam reforming does not remove greenhouse gas emissions. In reality, it contributes to carbon dioxide emissions, which are greenhouse gases.

2.3 Process Configuration and Description

A conventional SMR plant consists of four-unit systems which are desulfurization, reforming, High-Temperature Shift (HTS) and Pressure Swing Absorption (PSA). These systems purposed to remove sulfur, aid the reforming reaction, aid the water gas shift reaction and to perform hydrogen purification (Rapier, 2020).

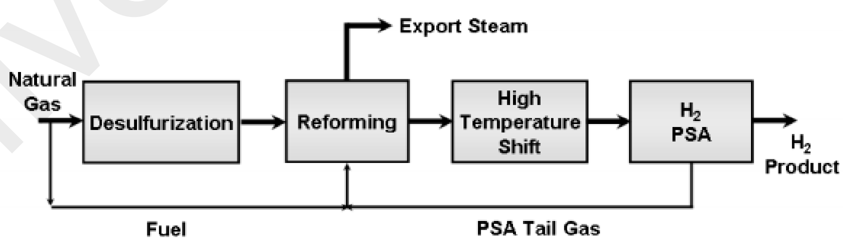

Figure 2.1: Block diagram of the hydrogen production by using steam methane reforming technology

The creation of the furnace steam is the initial phase in the process. For the reaction to occur, water should be in steam form at very high temperatures. Water is then enters the furnace as a liquid and heated to temperatures up to 816 ºC. These high temperatures foster reactions between methane and water to capture as much hydrogen as possible from the process.

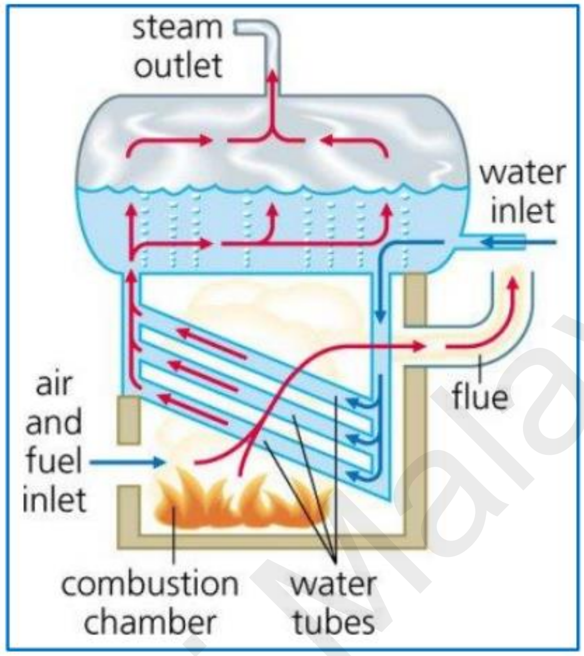

Figure 2.2: Illustration showing the furnace-steam production

Next for the reforming reaction, steam produced from the furnace will react with natural gas containing methane to initiate the reaction. This steam-gas mixture will be the entry to the reformer through the inlet manifold. The reforming tubes are surrounded by burners, keeping the temperature of the mixture above 816 ^{0}C. Methane interacts with steam at these temperatures to produce hydrogen and carbon monoxide. The addition of nickel catalyst speeds up the reactions and allow more hydrogen gas to be retained. The hydrogen-carbon monoxide mixture exits the reformer via the cold outlet manifold. Carbon monoxide is an unwanted item of the reaction and is harmful if it is being released to the environment. One mole of methane reacts with one mole of water to produce three moles of hydrogen gas and one mole of carbon monoxide.

Next step, carbon monoxide will be used and more hydrogen gas will be produced, the carbon monoxide from the reforming reaction then enters the water gas shift reactor for further chemical reactions to happen. This reactor contains water and iron-chrome based catalyst that breaks down steam into oxygen and hydrogen. While hydrogen is collected, carbon monoxide from the reforming reaction is combined with oxygen to make carbon dioxide. Carbon dioxide is less harmful to the environment than carbon monoxide and can be recycled for some useful processes.

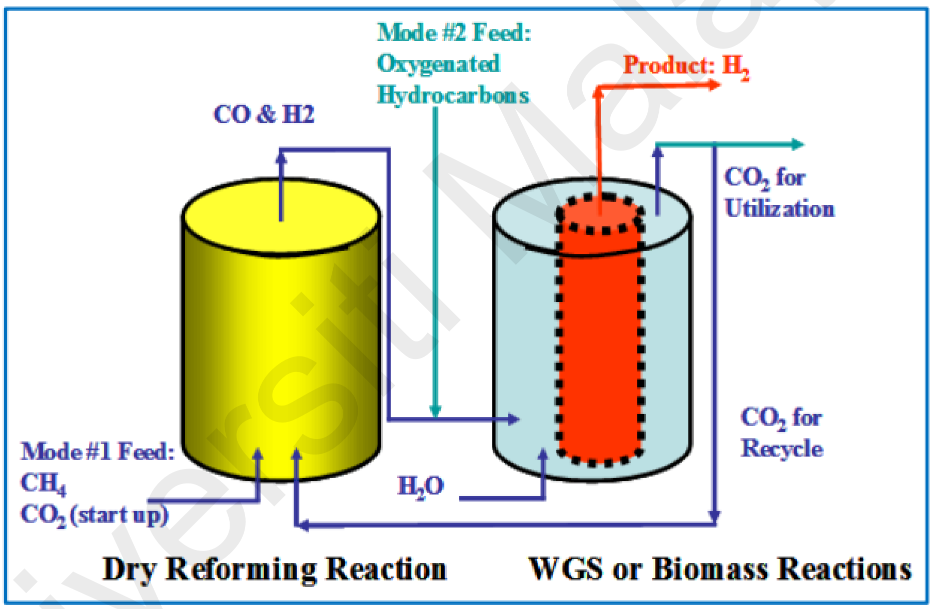

Figure 2.3: A water-gas shift reactor diagram

The gas mixture that exits the water gas shift reactor is not pure hydrogen, thus it must be refined further to fulfil the customer's requirements. Despite the fact that numerous technologies exist for purifying hydrogen, pressure swing adsorption (PSA) is the most often employed in the industry. Contaminants will be captured by the adsorbents inside the PSA under high pressure as the gas mixture enters the PSA. Purified hydrogen is pumped out of the vessel. Finally, the vessel is de-pressurized to release trapped contaminants. Pressure swing adsorption is used for the removal of carbon dioxide, methane, carbon monoxide, and water from hydrogen. Finally, because SMR is only 65-75% effective, some methane remains unreacted at the end of the process. The last of the hydrogen has been delivered to the customer at their desired pressure and purity. efficient, so a percentage of methane remains unreacted after the process is complete.

Table 2.1: Typical operating parameters of the SMR unit operations

	Desulfurization
Function	Remove all sulfur compounds to less than 0.1 ppm.
Typical operating temperature	340 ℃ to 400 ℃
Processing steps	Hydrotreating reactor - Converts sulfur compounds to H_2S and saturates any olefins. - Catalyst: Nickel-Molybdenum or Copper-Molybdenum - Typical catalyst life: 7 years.
	Reforming
Functions	Converts methane and light hydrocarbons to hydrogen and carbon monoxide.
Reactions	- Reforming: Methane reacts with water in the presence of heat to produce hydrogen and carbon monoxide. - Water gas shift: Carbon monoxide reacts with water to produce carbon dioxide, hydrogen and releases some heat.
Characteristics	- Nickel based catalyst poisoned by sulfur and chloride compounds. - Excess steam suppresses carbon formation. - Catalyst life: 5 years.
Typical operating conditions	- Process gas outlet temperature: 760 ℃ - Pressure: 1379 kPa to 3103 kPa.
Equipment	Reformer tubes: 4-inch diameter by 40 ft long. Reformer tube life: 10 years
	High Temperature Shift
Function	Converts carbon monoxide to hydrogen.
Reaction	Water gas shift: $CO + H_2O \rightarrow CO_2 + H_2 + Heat$ This reaction is mildly exothermic, favored by mild temperature and excess steam and converts about 75% of carbon monoxide.
Catalyst	Iron/chrome
Catalyst life	5-7 years
Typical operating temperature	371 ℃

Table 2.1: continued….

Pressure Swing Adsorption (PSA)	
Function	Purify hydrogen gas up to 99.9%.
Adsorbents	Molecular sieve, activated carbon, alumina and silica gel.
Typical operating conditions	- Feed pressure: 1379 kPa to 6205 kPa. - Feed hydrogen composition: 50 to 95%. - Tail gas pressure: 483 kPa. - Hydrogen recovery: 65 to 95%.
Typical operating equipment	- Adsorber vessels. - Surge tank. - Valve skid and controls.

In Table 2.1, the main unit operations and its operating conditions are listed. By looking into the unit operations separately, it could give room to identify the areas of improvement in terms of maximizing the efficiency and reduce the energy consumption which will contributes to overall reduction of the carbon footprint. For instance, catalyst is a key component in the reformer and in the water gas shift reactor, if operating conditions are not well maintained and monitored, it may shorten the lifespan of the catalyst, contributing to unexpected solid waste.

Although the production of hydrogen via steam methane reforming process is well-established some problems remain with the industrial operation. SMR has high emission of carbon dioxide as it produces carbon dioxide as its by-product and is vented out into the atmosphere. Almost 9 kg of CO_2/kg of hydrogen is emitted on average and contributes about 3% of global industrial sector gaseous emissions. Besides, even though the SMR capital investment cost is low, its operating cost is high due to catalyst deactivation and high energy consumption (Ayodele F. , Mustapa, Ayodele, & Mohammad, 2020).

2.4 Existing Technologies for the Production of Hydrogen

2.4.1 Autothermal Reforming (ATR)

The ATR process consists of the natural gas oxidation and shifting, in which the feedstock reacts with oxygen, in a sub-stoichiometric conditions and steam in a single reactor (Rivera & Bouallou, 2010). In ATR, syngas, composed of hydrogen and carbon monoxide is produced by partially oxidizing a hydrocarbon feed with oxygen and steam followed by subsequent catalytic reforming.

The ATR reaction are as follows:

$$\mathrm{CH_4} + \frac{\mathrm{O_2}}{4} + \frac{\mathrm{H_2O}}{2} \rightarrow \mathrm{CO} + 2.5\mathrm{H_2}$$

It is a combination of both partial oxidation and SMR in one reactor operating at 900 to 1100 ℃ with energy lower than that of SMR. Moreover, the feed to SMR is unreacted natural gas and as a result, it has a higher combustible component concentration in its feed than a secondary reformer. Therefore, there would be a higher soot being generated (Rice & P.Mann, 2007).

2.4.2 Water Electrolysis

Water electrolysis technology uses electrodes immersed in water and channeling electrical current to the water so that the water can be converted to hydrogen and oxygen. There is three different methods for water electrolysis which is electrolyte alkaline, proton exchange membrane (PEM), and solid oxide electrolysis (SOE) (El-Shafie et al., 2019). The commercial low temperature electrolyzes were developed and have efficiencies of (56% - 73%) at conditions of (70.1 - 53.4 kWh·kg−1 H2 at 1 atm and 25˚C) (Turner et al., 2007).

When compared to other water electrolysis processes, alkaline electrolysis systems are the most frequent. Solid oxide electrolysis (SOE), which is still in development, is the most electrically efficient approach. SOE technology has considerable issues such as corrosion, sealing, heat cycling, and chrome migration. Alkaline electrolysers are less efficient than proton exchange membrane (PEM) electrolysis devices. Although alkaline electrolyzer units have a low initial investment cost, they are inefficient processes that could consume a lot of electricity if employed on a wide scale for hydrogen production. Lately, there are more demand in using electrolysers to produce hydrogen with high purity by using high-pressure. (Jansenn, Bringmann, Emonts, & Schroeder, 2004). The use of high pressure operation unit eliminates the need for costly hydrogen compressors. The high expense of producing hydrogen on a wide scale using the water electrolysis approach was demonstrated by hydrogen production utilizing water electrolysis equipment. Additionally, the water electrolysis systems utilize the non-renewable power generation source to produce electricity for the water electrolysis systems.

2.4.3 Photonic

Hydrogen is produced from the photonic process through making use of photon energy. It can be segregated into two different methods, the photocatalytic and the photo electrolysis water splitting (photoelectrochemical water splitting). The direct method to produce hydrogen would be by a photocatalytic water splitting process by utilizing normal light instead of sunlight. Photocatalytic method exhibits a low efficient process. The titanium oxide (TiO2) is used in the photolysis reactions. Different researchers are interested in photocatalyst development (R et al., 2015).

In addition to the photocatalytic water splitting process, there is also a photo electrolysis method which uses a similar concept. Photo electrolysis has degraded water directly into hydrogen and oxygen by using the sunlight. Photo electrolysis and photovoltaic systems are similar in that they both utilize semi-conductor materials. P-type and N-type semiconductors materials are employed in photovoltaics. In the photo electrolysis process instead of generating the electric current water is decomposed into hydrogen and oxygen.

2.4.4 Partial Oxidation

Partial oxidation (POX) reforming of hydrogen is also widely available and accepted in today's market to produce hydrogen. The hydrogen is derived from the hydrocarbons. Methane or some other hydrocarbon is oxidized to produce carbon monoxide and hydrogen:

$$CH_4 + \frac{1}{2O_2} \rightarrow 2H_2 + CO$$

Because of the exothermic reaction, there is no requirement for an indirect heat exchange. Because of the high temperature, catalysts are not required. Catalysts, on the other hand, can considerably boost hydrogen yield. A hydrogen plant based on POX consists of a partial oxidation reactor, a shift reactor, and hydrogen purification equipment. A partial oxidation reactor is more compact than a steam reformer because it does not need a heat exchanger. POX has as an efficiency rate of 70 to 80% which is reasonably high. However, due to high temperatures are involved, making POX as an energy intensive process. This accelerates heat losses and the issue of heat recovery. In the plant, heat can be recovered from the flue gas to increase steam for the reaction (Salameh, 2014).

2.4.5 Comparison of the Existing Technologies

There are various technologies available to produce hydrogen. Table 2.2 compares the technology against each other including SMR. There are many factors influences the adoption of a particular technology to produce hydrogen such as the investment cost, scalability of the plant, based on the hydrogen demand, location, purity of the hydrogen produced, social and environmental impact.

Table 4.2: Table showing the comparisons between steam methane reformer, partial oxidation, water electrolysis, photonic and autothermal reforming.

	SMR	**Partial Oxidation**	**Water Electrolysis**	**Photonic**	**Autothermal Reforming**
Limitations	1. Higher hydrogen pressure limits methane conversion. 2. Excess steam production. 3. Low nitrous oxide levels required in stack gas.	1. Limitation in synthetic gas yield from the direct oxidation. 2. Cannot be used in gasifying diesel, methanol and ethanol.	1. Limits the hydrogen production. 2. Have to opt for renewable sources for electricity, otherwise it is energy intensive.	1. Low efficiency. 2. Low hydrogen throughput. 3. Sunlight required.	1. Must use clean and light hydrocarbon feed. 2. Limitation in hydrogen pressure. 3. Limitation in exit temperature. 4. Cost of oxygen.

Table 4.2: Continued ………

	SMR	Partial Oxidation	Water Electrolysis	Photonic	Autothermal Reforming
Challenges	1. Reduce steam to carbon ration. 2. Materials limitations in alloys used for tube. 3. Carbon dioxide generated in huge amount.	1. Along with hydrogen production, it produces heavy oils and petroleum coke. 2. Difficulty in controlling the reaction selectivity towards total combustion. 3. Production of carbon monoxide.	1. Storage and transportation problem. 2. High capital costs.	1. Lesser amount of hydrogen produced with low quality. 2. Necessity of huge volume of reactor.	1. Reduce steam to carbon ratio. 2. Carbon free burner operation. 3. Increase in vessel size needed. 4. Formation of soot.
Advantages	Well-developed technology and able to cater for high hydrogen yield.	Faster transient response and external heating is not required.	Zero greenhouse gas emissions and oxygen are produced as by-product which can be sold to customers (resale value).	Zero greenhouse gas emissions and oxygen is produced as byproduct.	Well-established technology and low investment.
CO_2 emission	Yes	Yes	No	No	Yes
Capital Investment	Low	Low	High	High	Low
Product Yield	High	Low	Low	Low	High

2.5 Greening Strategies at the Production Site

Green strategy is the finest method to reduce emission of carbon dioxide at any production site. If green practices are implemented at the production site, it brings many great benefits to the process and to the overall production site. In Malaysia, most of the organizations emphasized on quality initiatives of green technology to be applied not only in premises but also in their businesses. The environmental performance can be improved by using a green supply chain management strategy and a green balanced scorecard plan. There are 3 types of green strategies as discussed below:

1. Green practices.

   It is a practice to reduce negative impacts of operations on the environment. Green practices can be introduced to the site through green purchase, creating awareness on customers of green purchasing, eco-design and investment recovery. Green practice helps the site to gain extra profit and has an advantage of increased competition. Implementing green practises in a facility saves money, improves efficiency, shortens the time it takes for customers to respond, and reduces energy consumption, trash generation, and the use of hazardous materials.

2. Green innovation.

   Green Innovation of a site comprises saving of energy, pollution prevention, recycling waste and designing green products and processes. Green innovation at site can be achieved with the cooperation of environmental commitment, environmental benchmark and strength of research and development. Besides that, through this innovation, the site can benefit from cost saving, good product quality and increased efficiency and productivity. At the same time, it improves performance while lowering environmental impact.

3. Green performance.

   The focal point is to improve the environmental management system. The combination of both green practice and green innovation at a site alleviates greenery performance by implementing relevant strategies, initiatives and opportunity. The environmental performance enhances the air emission to be reduced, minimizing the discharge of solid and liquid waste from the consumption of hazardous materials.

CO_2 emissions can be decreased indirectly through energy conservation and efficiency measures. Thus, the Malaysian government has outlined policies and legislations to enhance energy efficiency and to promote renewable energy in manufacturing industries. Table 2.2 below shows the policies and legislation that was established by Malaysian government to reduce emission of CO2 (Lee et al., 2013).

Table 2.3: Policy, Acts and Regulations in Malaysia

Policy/Act/Regulations	Aim and Objectives
National Energy Policy	● Providing adequate, effectiveness of costing, safe and multiple sources of energy supplies. ● Promoting effective energy use and consumption, as well as environmental protection in energy production and consumption.
Five-Fuel Policy 2002	● Reduce dependency on oil as an energy source by enhancing the fuel mixing with oil, gas, hydro-electric and coal and renewable energy.
Efficient Management of Electrical Energy Regulation 2008	● Implementing systematic electrical energy management.
National Green Technology Policy 2009	● Initiating activities of green technology to the route of sustainable rise in the consumption of energy, environmental, economy, and society.
Malaysia National Renewable Energy Policy and Action Plan 2010	● Utilizing original renewable energy sources as a contribution to the route of national electricity supply security and sustainable development of socio-economy
Renewable Energy Act 2011	● Establishing and implementing special system to generate renewable energy

Malaysia is dedicated to the growth of a clean and efficient economy, also known as “green economy” (Abdullah, Abu Bakar, Mohd Jali, & Ibrahim , 2017). By adopting the growth of green firms and green products, it will result in the creation of “green jobs”. There is a driven momentum to move towards cleaner production as several policies was established as listed in the Table 2.3. As Malaysia strives to raise environmental consciousness, it is critical to set national benchmarks against which progress toward a greener economy may be measured.

2.6 Cleaner Production

Cleaner production is a comprehensive word that includes waste minimization, waste avoidance, pollution control, and other related ideas. It comprises measures like improved management and housekeeping, toxic and hazardous material substitutes, process and product adaptations, and internal waste product reuse. It is “the continual application of industrial processes, products, and services to prevent pollution and decrease wastes at their source,” as its definition says. Cleaner production, according to the OECD, is defined as technologies that extract and use natural resources as efficiently as possible throughout their lives, resulting in products with fewer or no potentially harmful components, minimizing releases to air, water, and soil during product fabrication and use, and producing durable products that can be recovered or recycled as much as possible. Cleaner products is known as any materials or equipment that must be manufactured by respecting the environmental legislation. But, there are obstacles in calculating the investment level by industry in cleaner product and process manufacture. The only main issue is allocating a relevant baseline date for calculating environmental improvement and hence capital expenditure for environmental. It could also be argued that statutory requirements for cleaner products simply alter the basic market condition for all producers and hence the resulting investments and operational costs incurred might be regarded as for commercial, rather than environmental, purposes.

Properly implemented cleaner production possibly increases profitability, lowers manufacturing costs, boosts productivity, gives a quick return on any investment, boosts product yields, and results in more efficient use of energy and raw resources. (Institute of Environmental Engineering (APINI) Kaunas University of Technology, Lithuania, n.d.).

There are a number of issues that must be addressed in order to obtain a reliable assessment of the amount of investment and employment created as a result of the implementation of clean production in most industries, including:

- The three parts of clean production are difficult to define: technology, housekeeping, and changing inputs. Changing inputs and housekeeping are difficult to analyse.
- Cleaner production is a dynamic concept and as its uptake in a particular industrial sector becomes the norm, its definition will have to evolve accordingly.
- Cleaner production investments must not be included as a part of new processes investment in which the environmental aspect is not the main concern.
- Cleaner production investment analysis must include the additional investment of replacing a certain component was already part of the plan.
- Certain industrial areas, especially chemicals and food, lend themselves to the application of clean manufacturing, however investment within sectors might vary dramatically over time. In other sectors, the scope for applying such innovations may be less.
- Unlike end-of-pipe technologies, which are often standard equipment, cleaner technologies are sometimes process-specific or even proprietary, necessitating an in-depth understanding of processes that only the investing businesses may possess.

In conclusion, cleaner production brings vast number of benefits to SMR through various strategies. For instance, through technological change as a substitute to SMR to avoid carbon dioxide emission. Even though, there are several challenges and limitations to the approach, it does not seem as a huge blocking point for the CP adoption in SMR industries.

2.7 Principles of Cleaner Production

CP strategy can be generated based on these components for SMR:

2.7.1 Waste Elimination and Reduction

As in the instance of pollution prevention, the term waste refers to all various types of waste including both hazardous and solid waste, liquid and gaseous wastes and waste heat. The goal of CP is to achieve zero waste discharge. For example, having an inventory file to keep track of the liquid chemicals stock to avoid liquid waste and wastages at the SMR production site.

2.7.2 Non-Polluting Production

The concept of CP takes place a closed loop boundary with no contaminant released. That is the ideal production processes. As SMR itself is a polluting process, options can be considered to change the technology to a lesser or non-polluting such as electrolysis or installing a carbon capture in the existing SMR process. By doing so, the current process can be greener.

2.7.3 Production Energy Efficiency

The highest standards of energy efficiency and conservation are required by CP. The highest ration of energy usage to product production determines energy efficiency. Energy conservation, on the other hand, refers to the reduction of energy usage. The excess steam generated can be recycled back to a steam turbine to generate electricity. This electricity can be used for the process as well as for the overall production site. This would reduce the amount of energy used.

2.7.4 Safe and Healthy Work Environments

CP tries to reduce worker risks in order to create a cleaner, safer, and healthier work environment. For instance, at the SMR production site, safety audit can be conducted on weekly basis to rule out any safety risks which poses serious hazard threats.

2.7.5 Environmentally Sound Products and Packaging's

All marketable by-products and the end product should be as environmentally appropriate as possible. Health and environmental concerns must be addressed early in the product and process design process, and they must be taken into account throughout the product life cycle, from manufacture through use and disposal. Wherever feasible, product packaging should be kept to a minimum. When packaging is required to protect the product, promote it, or make it easier to consume, it should be as environmentally friendly as feasible. As most of the hydrogen product is supplied as gas to the customer through a pipeline, it is important to ensure the pipeline is well-insulated to avoid product loss.

There are many tools and standards for CP , for example, eco-labelling, life cycle analysis (LCA), eco-efficiency, industrial ecology, environmental audits, occupational health and safety systems, public environmental reporting and environmental indicators (Universiti Teknologi Malaysia, Skudai, Johor, n.d.)

2.8 Carbon Footprint in Steam Methane Reforming

According to Kyoto Protocol, the six main greenhouse gases causing climate change are identified as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF6), hydrofluorocarbonization (HFC) and perflurocarbon (PFC). Therefore, the carbon footprintcan be defined as the total greenhouse gas emissions of a product or service throughout its lifecycle and its environmental impact. In the context of a SMR production site, CO_2 is the main culprit in contributing to the carbon footprint as CO_2 is a greenhouse gas.

Two components can be considered to the carbon footprint calculation of SMR hydrogen production unit. Firstly, by the SMR and water-gas shift reactor,100% of the carbon from the methane is fully transformed to CO_2. When one molecule of CO_2 is created, four molecules of hydrogen are produced as well, with the surplus of hydrogen coming from steam. Thus, for 1 million of standard cubic feet (SCF) of hydrogen produced from methane, 250 000 SCF of CO_2 will be produced (Rapier, 2020). There are 19,253 SCF of CO_2 in one metric ton, so 1 million SCF will create 13 metric huge loads of CO_2.

The carbon footprint linked with the different process units is the second portion. Steam must be produced, and the reactor must be heated. When the SMR exhaust gas is cooled, however, steam is produced, which helps to offset the carbon burden. The carbon footprint associated with the separate process steps has been broken down based on a PraxAir study (Rapier, 2020):

1) Combustion for reforming energy: 8.7 kg of CO_2/kg of hydrogen.

2) Combustion for steam: 5.9 kg of CO_2/kg of hydrogen.

3) Power for separation and compression: 0.24 kg of CO_2/kg of hydrogen.

Adding the carbon dioxide produced by the natural gas reaction, the total CO_2 produced per kg hydrogen is 14.8 kg. However, based on the study conducted to estimate the CO_2 emission, it mentioned that this theoretical value is minimum (Bonaquist, 2010). Due to heat losses and inefficiencies, the actual number in practice in a large hydrogen plant can be more significant. The carbon footprint is generally reported in the form of energy. For example, power plants often report their carbon footprint in kilo-watts hour (kWh). 1 kg of hydrogen contains 79.1 kW hours of energy.

This is only the carbon footprint from SMR process alone without taking into account the compression, transportation and overall electricity of the production site. The fuel cell itself must also be built and these construction process will generate carbon emissions. Moreover, the construction of SMR production unit also contributes to carbon emission.

2.9 Methodologies for Implementing Cleaner Production

Cleaner manufacturing is a strategic resource that is primarily used to reduce emissions. Furthermore, it is used to reduce effluents and waste by continuously improving production processes and products. As a result, for environmental and economic reasons, cleaner production can be seen from top level to end-of-pipe technology. A total of five general principles needed to implement CP in steam methane reformer site which includes:

a. Substitution with greener materials/processes.

It is possible to substitute raw materials that are less dangerous and have a longer lifespan. The catalyst used in the reformer is toxic to the environment and humans. It can be replaced with a more environmentally friendly material.

b. Adaptation of new technologies.

By boosting operational efficiency, new technology adoption can reduce resource consumption and waste generation. This strategy necessitates a significant financial investment, but the return period can be extended. For example, outdated equipment or machinery can be upgraded and modified to meet current specifications to increase efficiency.

c. Incorporating new product design.

By limiting the use of hazardous materials and facilitating trash disposal, product design can contribute to the product's life cycle. Furthermore, this innovative design product will cut energy consumption and improve production efficiency. An entire steam methane reformer, for example, might be redesigned into a more environmentally friendly product that requires less energy and resources in its manufacture.

d. Good housekeeping practises.

Good housekeeping can improve the efficiency of production output. To ensure a smooth production process the next day, process equipment should be maintained well. Workers should be well-trained in maintaining a clean and safe work environment.

e. Inhouse recycling method.

To limit the amount of waste in the disposal area, materials can be recycled. For example, during the production process, water from the air compressor can be recycled as makeup water for the cooling water tower.

As a result, a more thorough production audit will be done, and greening techniques will be applied in the production site of steam methane reforming. The implementation of CP will be based on the analysis and data gathered from the CP audit, employee's interviews, and general observation. The data collected will be analyzed and CP options will be proposed. Before implementing, the proposed CP options will be evaluated based on its technical feasibility, economic and environmental feasibility. CP options for implementation will be ranked according to the feasibility as CP practices enables the controlling process and reduces the operational cost. Overall, it can be said that CP helps to achieve sustainable development in manufacturing industries (Paul et al., 2014).

2.10 Summary of Literature Review

Steam methane reforming process is widely established and adopted by most industries to produce hydrogen. SMR comes with strong advantages such as lower capital investment, higher hydrogen yield, easy plant configuration and flexible for scale-up. SMR process distinguishes the need of storage tanks for hydrogen. As much as SMR comes with many advantages, this technology is old and need to be revamped as it suffers a big drawback. The drawback being said, SMR emits significant amount of carbon dioxide from the process alone without taking into account the overall production site and the transportation of hydrogen via cylinders. The carbon dioxide emission can lead to serious environment impact. Carbon dioxide is recognized as a greenhouse gas (GHG) which contributes to ozone layer depletion and affects climate change. Options of applying greener strategies must be explored more to enhance the concept of cleaner production in SMR process and its production site.

Climate change has always been a major concern in today's world. More and more policies and guidelines are being developed globally to raise awareness amongst the industries especially those which contributes higher amount of GHG such as SMR industries, however this is still at infant stage. Applying cleaner production strategies could further minimize direct and indirect emission of carbon dioxide, hence understanding the overall process and practices at the production site could be beneficial. The effective use of materials and the on-site recycling of liquids, fluids and waste should be further studied from the perspective of cleaner production. Although the end-of-the pipe treatment may be the least popular choice, the feasibility of selling the carbon dioxide to potential customers or capturing it must be explored. Identifying carbon footprint of the process could be beneficial to locate the area need to be focused for cleaner production implementation.

In summary, SMR production site operations have actively carried out a number of works to reduce carbon dioxide emission. However, there are still improvements and lack of transparency, especially in certain unit operations and its waste generation. Therefore, a study is required to analyze possible inefficiency in the SMR process and its production site and how implementing cleaner production strategies could further green the operations at the site.

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Introduction

The research study is conducted based on the workflow prepared as per Figure 3.1. Firstly, the CP audit documentations are prepared. This is including checklists, informal interview questions and pre-obtained data for study purposes before visiting the production site. It is important to plan and prepare the CP documentations ahead before visiting the site to ensure the timeline is adhered to and there is a clear vision on what to do. Next, after obtaining the travel authorization letter from the management and police office, site visit is planned. Once at the site, a thorough CP audit is conducted including informal interviews with the site team. Site walk is also conducted to observe any process inefficiencies, safety, health and environmental risks as well as to observe if there is any practices that can be improved in general. After the audit is performed, results are gathered and analyzed. From the results, CP options are generated. Carbon footprint is evaluated based on the audit findings and CP options proposed. Finally, the options are presented upon the site management for further future implementation plan.

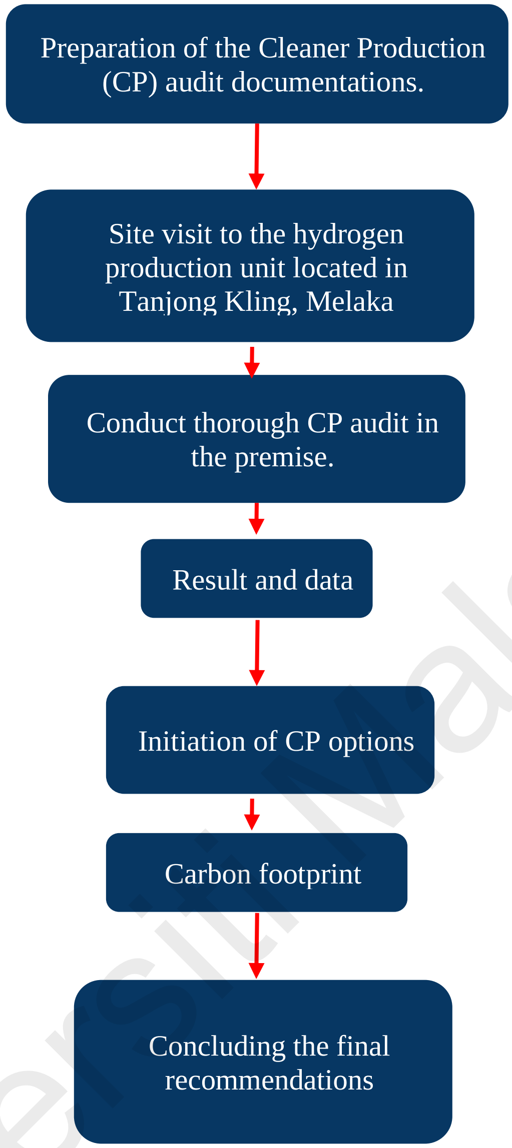

Figure 3.1: Diagram showing on the research study methodology workflow

3.2 Site Visit to the Production Site

During this pandemic period, it would be quite a challenge to travel to the production plant which is located in a different state. For this, a valid work travel authorization must be obtained first from the authority. Upon arrival at the production plant, safety orientations conducted by the safety officer will take place to familiarize the visitors with the emergency exits and feed them with information on what to do in the case of an emergency, for instance, fire and explosion which happens to be a common risk in hydrogen production units. The most crucial aspect in the site visit is touring around the site with observing to assess the information needed for deeper understanding of the site current practices. During this site walk, informal interviews among the plant technicians and engineers were conducted to build the knowledge on the process and what could be their pain points. It has to be made clear with all the parties involved in the site including the management that the cleaner production audit is an improvement strategy and not a policing tool which is bound to be enforced. By being transparent to the site workers, a strong camaraderie can be established which eases the cleaner production evaluation.

3.3 Cleaner Production Audit

It is critical to undertake a cleaner production audit in order to put cleaner production procedures in place. Cleaner production audit is a development procedure which consists of a cleaner production plan of technical, economy and environment feasible, and find out the reason for high energy consumption, high material consumption, and pollution. It is important to prepare the right audit plan and to use it to develop audit protocols in advance to utilize the time given effectively. As a result, a cleaner production audit is an essential component of an ongoing program aimed at maximizing resource optimization and process performance (DEPARTMENT OF ENVIRONMENT Ministry of Natural Resources and Environment, Malaysia, 2007).

Cleaner production audit is a structured checklist which comprises the following aspects compiled in Table 3.1:

Table 3.1: Some key examples of items to be included in the CP audit checklist

Description
Raw materials used:
Type of waste generated:
Source of the waste:
Quantity of waste:
Main products:
Byproducts:
Unit operations:
Water usage:
Energy usage:
Current safety and risks practices:
Identify process efficiency and areas of process control:
Transportation of product:
Identify areas of poor housekeeping:
Evaluation of existing end-of-pipe treatment:
List of other facilities at site

Interviews were also conducted to aid in the cleaner production auditing process. Targeted interviewees are the production team such as site technicians, team leaders, engineers and the facility manager. Besides that, the supply chain team were also interviewed which was helpful to get vital understanding on the packaging, sourcing of the raw materials, transportation of end products and the inventory list. At this point of time, it was explained clearly to these candidates that the interview was meant solely for cleaner production auditing purposes and the confidentiality of the personal details and the datas obtained through them are respected.

There are various audit methodologies suggested by different organizations. A systematic approach to conduct a CP audit may be described in terms of the following distinct phases:

1. Objectives and scope are well defined.
2. A CP audit team is formed. It could involve various key stakeholders.
3. Pre-assessment; listing of unit operations and constructing process flow diagram.
4. Material balances are listed, the process inputs and outputs.
5. Synthesis and identification of CP options.
6. Evaluation and implementation of the CP options generated..

3.4 General Safety During Site Visit

Safety is the topmost priority that has to be well-informed and adhered to strictly in the production plant. During site visit, each time entering and exiting the premises, a logbook must be filled to catch the entering time and exit time for safety purposes. The plant log-in sheet is located in the front office. Personal protective equipment (PPE) must be worn at all times. For this production plant, the minimum required PPEs are steel toe boots, fire retardant clothes, safety glasses, hearing protection and safety helmets. Moreover, safety data sheets are available readily so that a better understanding of the hazards are understood. Smoking is prohibited within the plant area. No cameras are allowed in the plant unless special permission is obtained from the Facility Manager. Cell phones in the hydrogen production section are prohibited as this area is prone to fire and explosion. As there are many trucks moving in and out of the site, it is important to obey the traffic rules. The location of all fire extinguishers and firefighting equipment can be found on maps located in the plant's office and operator's room.

3.5 Carbon Footprint Calculation

Industrial energy is the main cause of greenhouse gas production. Therefore, the carbon footprint calculation is used to calculate the total amount of greenhouse gas emitted during the hydrogen product life-cycled produced via steam methane reformer. This calculation used as an estimation tool in managing and reducing the emission of carbon dioxide. Intergovernmental Panel on Climate Change (IPCC) reported that GHG is increased from activities of all nations, and this has noteworthy negative impact on climate change. Therefore, it can be proved that of all greenhouse gases, CO_2 contributes the most.

Malaysia's emission factors were used to calculate the entity emission factor. This joint calculation involves the emission factors in the Intergovernmental Panel of Climate Change (IPCC) National Greenhouse Gas Inventory Guide. The total CO_2 emissions can be calculated by adding the individual CO_2 in the entity emission factor (Rahim & Abdul Rahman, 2017). The equation used are as below to calculate the quantity of CO_2 released:

$$CO_2 \text{ emission (kg } CO_2\text{) in total} = \sum(\text{Unit of data x Unit of emission factor})$$

Table 3.2 shows the emission factor of carbon:

Table 3.2: Emission factor of carbon

Source and Waste	**Emission Factor**	**Unit**	**Reference**
Electricity	0.67	kg CO_2/kW	(Rahim & Abdul Rahman, 2017)
Fuel-Diesel	2.69	kg CO_2/litre	
Waste from Solid (Scheduled)	3.0	kg CO_2/kg	
Waste from Solid (Non-Scheduled)	2.8	kg CO_2/kg	
Waste from Liquid	2.0	kg CO_2//kg	
Raw Material	1.5	kg CO_2//kg	

3.6 Cleaner Production Options Generation

Cleaner manufacturing solutions will be offered to be used in this site for ongoing improvement and development based on the entire data gathering and analysis. Cleaner production reduces all pollutants generated at the production site in a premise to the lowest level possible. It also leads to increased profits as a result of increased productivity and environmental performance’s options can be categorized as listed below:

1. Material Substitution

   The most common use of material substitution is to launch CP options. Cleaning agents, catalyst, natural gas and light gas are used in the process and at site generally. By examining the qualities of each material utilized in the premise, material replacement can be accomplished. Through this way, we can help to identify which material gives negative impact to the environment and that particular material can be replaced to an environmental-friendly material. It is also important to ensure the material substituted must not affect the quality of the product.

2. Modification of Process Control.

   Analyzing the equipment instructions and the online procedure can be used to control the process. Typically, process control modifications are carried out on the advice of a supplier or vendor, or on the advice of knowledgeable employees. As a result, any process control that is carried out must not have an impact on the overall process or the completed goods' efficiency. Process of record keeping must be diligent to enable the processes carried out in a more efficient way and at a lower rate of waste and emission generation.

3. Design Change/Modification.

   Modifying current industrial machinery or equipment to run the process more efficiently and with less waste is referred to as design change. If parts of machinery are out of specification or are too old, they must be replaced. This has the potential to make a huge difference at the site and in the process.

4. Housekeeping.

   During any operation procedure, housekeeping is an appropriate managerial and operational step to prevent any leaks or spills. Good housekeeping can also provide a safe and clean working environment for all employees, resulting in increased daily production.

5. Change in Technology

   Changes in technology can be done by replacing old machinery with new machinery that is more efficient in terms of waste creation. Many machineries are available on the market that have the potential to reduce material and energy usage.

6. Recycle and Reuse.

   Recycling and reuse are the most cost-effective and environmentally friendly choices, according to the environmental management hierarchy. In this scenario, the remaining elements from the premix can be recycled and reused in the mixing process. This installation may eliminate the need for waste management choices. However, during recycling and reuse, the person in charge must make sure the properties of mixing material to be within required specification.

7. Training and Awareness of the Employees.

   Workers must be instructed on how to use a cleaner manufacturing method for the duration of their employment. Employees with a lack of CP knowledge may contribute to significant waste generation by limiting productivity.

3.7 Payback Period Calculation

The payback period (PP) specifies the amount of time it will take for the site to return its initial investment in the CP option and calculate the predicted savings. The most preferred CP option in this project is the low payback period because the time required for the investment cost capability is very short. Equation below shows the equation used to calculate payback period:

$$\text{Payback period} = \frac{\text{Total Investment Cost}}{\text{Annual Savings}}$$

The investment is represented by the cost of the following items:

1. Process Equipment
2. Material and location of preparation
3. Utility connection iv) Construction and installation
4. Engineering and consulting services
5. Start-up which includes training to operators and maintenance personnel
6. Subsidies

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Case Study in SMR Production Site

A thorough audit was conducted in the steam methane reforming production site based on the scope specified. This site is located at Tanjong Kling, Melaka. At the production site, there are a total number of 30 headcounts including production team, electrical team, mechanical team, safety team, admin staff and security officers. Besides production technicians, the rest of the staff works 8 hours per day and 5 days per week. For the production technician, they work in 12 hours of rotational shift, 3 technicians per shift. There is day shift which starts from 7am to 7pm and night shift which starts from 7pm till the next day 7am. This production site has the capacity to produce almost 4,500 tons of hydrogen gas per month. CO_2 is produced as a byproduct and it is vented out the atmosphere. The site operates 24 hours, and the process is a continuous process rather than a batch process. According to the company standard regulated by the headquarters, every three years, a shutdown maintenance is planned to repair problems identified during previous major shutdowns and to inspect parts of the plant that are not accessible during operations. Consumption of material energy and waste generation were recognized and analyzed based on the collected data. Several cleaner production ideas were stipulated based on the audit results and feasibility studies.

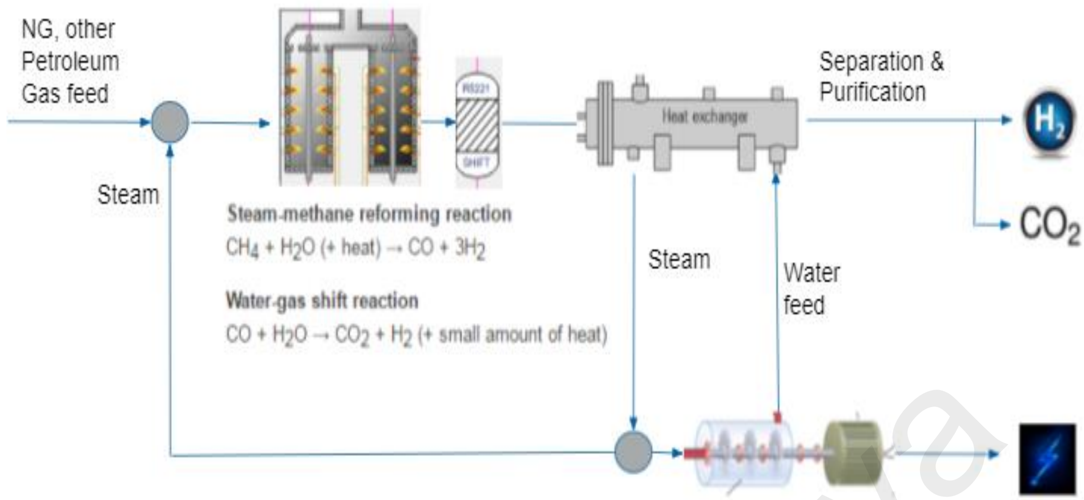

Figure 4.1: Simplified process flow diagram of the Steam Methane Reformer process

4.2 Conduction of Audit in the SMR Production Site

4.2.1 Main Product

The main product from the plant is hydrogen gas with a purity of 99.6%. Based on the customer demand, the production varies. The plant capacity is 4,500 tons per month. The data is taken based on the average one month of production. The gas is supplied at 2,210 kPa to the customer through a stainless-steel pipeline. Besides that, some of the hydrogen gas is also compressed and supplied to customers who purchase hydrogen cylinders. An average of 40 tons per month of compressed hydrogen gas are supplied to customers at 20,000 kPa. The production rate for both hydrogen gas and compressed hydrogen gas heavily depends on the customer demand. When the demand is low, the plant will be offloaded. When the customer demand is high, the plant will be ramped up.

Table 4.1: List of main products

Main Product				
Item	**Product**	**Quantity Produced**	**Supply Pressure**	**Type of packaging**
1.	Hydrogen gas	4,248 tons/month	2,210 kPa	Through the pipeline. (Material: Stainless Steel)
2.	Compressed hydrogen gas	40 tons/month	20,000 kPa	Cylinders

4.2.2 Electricity Consumption

The electricity consumption is calculated based on the electricity bill obtained from Tenaga Nasional Sdn Bhd (TNB). The cost per unit is RM 440.7/MWh based on the referential price obtained from TNB. The electricity consumption price for the production unit alone is RM 2, 860, 000 monthly. The electricity price for a hydrogen filling station is RM 70,071 monthly and the electricity price for compressors is RM 1,014 monthly. Consumption of electricity per month is listed below in Table 4.2.

Table 4.2: Electricity consumption in the premise during the process

Electricity Consumption			
Item	**Type of usage**	**Consumption rate (hours/month)**	**MW.Hr (monthly)**
1.	Power for hydrogen filling station	720	159 MWh
2.	Total power consumption of steam methane reforming process	720	6,500 MWh
3.	Product compressor power	720	2.3MWh

The total power consumption for the process alone is 6,661.3 MWh monthly. This accounts to 0.0016 MWh/kg of product or 1.6 MWh/ton of product.

4.2.3 Byproducts

Steam is produced as a byproduct from the steam methane reforming process. An average of 61,900 tons of steam is produced from where, 34,600 tons of steam is recycled back to the steam turbine to generate electricity. Excess steam is utilized to generate electricity using back pressure steam turbines and condensing steam turbines. The details of the steam turbines are tabulated in Table 4.4 below.

Table 4.3: List of the byproducts produced in the process

Byproducts				
Item	**Product**	**Quantity produced in a month**	**Potential Usage**	**Type of packaging**
1.	Steam	61,900 tons	Used at the reformer to aid chemical reaction.	Pipeline
2.	Steam recycled	34,600 tons	To generate electricity.	

Table 4.4 Overview of steam turbine

Equipment Tag	**Inlet steam pressure (kPa)**	**Inlet steam temperature (deg C)**	**Rated speed (rpm)**	**Rated power (kw)**
ST5001	5000	358	7700	4700
ST5002	1100	205	5710	9781

ST5001 is a back pressure steam turbine while ST5002 is a single casing condensing steam turbine. To startup ST5001, it would require at least 30 t/h and 51 barg of steam from the SMR. To startup ST5002, it would require at least 13 t/h and 43 barg of steam from the steam methane reformer.

4.2.4 Fuel Consumption

The site uses natural gas as a source of fuel for their burners in the reformer. During normal operation, the fuel pressure is maintained above 0.8 kPa which is the minimum supply pressure of the fuel. Through the audit findings, a total of 289 tons of natural gas is used monthly. Pricing of the natural gas is based on three different contracts. The natural gas composition is flowing through the same pipeline from the vendor, but each contract comes with different pricing, maximum quantities that can be nominated by contract and amount that the site is committed to procure every year (Take or Pay). The details of the pricing are illustrated in Table 4.6 below.

Table 4.5: Fuel consumption

Fuel Consumption			
Item	**Type of fuel**	**Used for**	**Average consumption monthly**
1.	Natural gas	For burners	289 tons

The fuel consumption per ton of product is 0.068 ton fuel/ton product.

Table 4.6: Natural gas pricing

Fuel Pricing		
Contract	**Constraint**	**Pricing**
EUA1	Limited to 5.75 bbtud	9.73 USD/mmBtu
EUA2	Limited to 4.6 bbtud	3.11 USD/mmBtu
OTA1	No limitation, but only to be used when EUA1 and EUA2 is maximised	13.62 USD/mmBtu

4.2.5 Raw Materials

The main raw material for steam methane reforming is natural gas and light gas. Natural gas and light gas differ only in the composition. Natural gas has a higher methane content meanwhile light gas has a higher hydrogen content. The light gas is purchased from a customer whose byproduct is light gas.

Table 4.7: List of raw materials used

Raw Material		
Item	**Raw Material**	**Quantities consumed per month**
1.	Natural gas	Average of 279 tons
2.	Light gas	Average of 270 tons

4.2.6 Waste Generation

Waste is categorised as scheduled waste and non-scheduled waste. Any waste that is hazardous and harmful is considered as a scheduled waste. Otherwise, the waste falls under the non-scheduled category. The waste is also further broken down into its physical state, solely solid waste and liquid waste. The total solid non-scheduled waste for a month is 25kg. Meanwhile, the total liquid non-scheduled waste for a month is 2,487 litres. Table 4.8 lists down the non-scheduled waste. For scheduled waste, there is only solid waste. Two types of spent catalyst, nickel catalyst and iron-chrome based catalyst. These catalysts have a long shelf-life as the operating parameters are monitored diligently. Thus, upon interviewing the facility manager and from waste documentations, the catalyst has an average shelf life of 3-4 years.

Table 4.8: List of non-scheduled waste

Item	Physical state	Storage material	Quantity stored in the premise.	Usage	Amount per ton product basis
Hydrochloric Acid	Liquid	Fiberglass tank	120 litres	Cleaning scale from water-cooled condensers and cooling water tower	0.028 litres
Caustic soda	Liquid	Fiberglass tank	80 litres	For water disinfectant	0.019 litres
Sulphuric acid	Liquid	Stainless steel tank	15 litres	To maintain standard pH levels in the cooling water tower.	0.004 litres
Diesel	Liquid	Steel tank	57 litres	For the backup generator	0.01 litres
Potassium hydroxide	Liquid	Stainless steel tank	100 litres	Used for the cooling water tower cleaning	0.024 litres
Boric acid	Solid	Plastic bottle	25 kg	Inhibit the growth of fungi in the water system	$5.89\ x\ 10^{-6}$ tons

Table 4.9: List of scheduled solid waste

Scheduled Solid Waste				
Item	**Description**	**Location**	**Source**	**Quantity per ton product**
1	Spent catalyst	Reformer	Nickel	55 ton
2	Spent catalyst	Shift reactor	Iron-chrome based	35 ton

4.2.7 Utilities Consumption

The main utilities in the side besides water is nitrogen. The nitrogen used can be further divided into its physical state, solid and gaseous form. A total of 213 tons of liquid nitrogen is used for the hydrogen filling station. Some of the usage of the liquid nitrogen consists of providing an inert atmosphere around the filling station area, for blanketing and padding storage tanks in order to prevent explosion and fire and to purge the lines and systems. For instrument air, gaseous nitrogen is used with a total amount of 1,014 tons monthly. The nitrogen supply is obtained from the air separation unit which is located 2 km away from this site. The liquid nitrogen is transported by tankers. The gaseous nitrogen is supplied directly through a pipeline. There is no cost involved as the supply comes from the same company.

Table 4.10: Utilities consumption in the production site during the process

Utilities Consumption		
Item	**Utility**	**Consumption per month**
1.	Liquid nitrogen	113 tons
2.	Gaseous nitrogen for instrument air	814 tons

The total liquid nitrogen, monthly needed per ton of product is 113 tons and for gaseous nitrogen is 814 tons.

4.2.8 Water Consumption

The total amount of water used during steam methane reforming for potable water is 37,000 litres whilst for non-potable water is 79,749,000 litres. The water is sourced from Syarikat Air Melaka Berhad (SAMB). The cost of the water is illustrated clearly in Table 4.12 including the water bill for this site for the past one month based on the plant load.

Table 4.11: Amount of water consumed in a month

Water Consumption			
Item	**Type of Usage**	**Quantities used per month**	**Quantities used per ton of product**
1.	Water	7.98×10^7 litres	1.88×10^5 litres

Table 4.12: Water pricing

Water Consumption		
Item	**Volume**	**Price**
1.	0 - 20 m3	RM 0.60/m3
2.	21 - 35 m3	RM 0.95/m3
3.	Over 35 m3	RM 1.45/m3
Amount paid by site in a month for water consumption		RM 115, 690

4.2.9 Unit Operations

There are several prominent unit operations involved in the steam methane reforming process to be able to produce a high-quality hydrogen gas without interruption. Those unit operations and its purpose are tabulated in Table 4.13 below. Other operations at the site besides the main process are listed in Table 4.14.

Table 4.13: List of unit operations involved

Description	**Used for**	**Potential Optimization Ideas**
Reformer	Converting methane into CO_2,CO and H_2	- Increasing the air fraction in the burner for more efficient process. - Increase the thickness of the insulation shield to prevent energy loss through heat.
Deaerator	Removing O_2	- Automated software to calculate the optimal pressure and temperature at each extraction of O_2 so that the purity of hydrogen is enhanced.
Shift reactor	Converting CO to H_2	- Maintaining optimum temperature and optimum pressure to extend the shelf-life of catalyst. - Improve the insulation to avoid energy loss through heat.
Natural gas compressor	To compress the natural gas.	- Optimization of the recycle-valve to avoid raw material loss in the case of plant upset/tripped.
Steam drum	To separate the saturated steam from the steam-water mixture.	- Insulate steam drum valves to avoid heat loss. - Install steam traps to recover the steam.

Table 4.13: Continued….

Description	Used for	Potential Optimization Ideas
Pressure swing adsorbers (x2 unit)	Purifying H_2	- Tight monitoring of the moisture content in the system by installing alarm triggers to avoid product contamination.
Nitrogen compressor	Compress nitrogen gas upto 4 barg to be supplied as instrument air to some valves.	- Improve the recycle valve process control to avoid product loss in case of customer demand dropped, plant trip or plant upset.
Steam turbine	Generating electricity from steam.	- Losses of recoverable energy from the mechanical design or physical condition of the steam turbine. For improve the design of turbine blades and steam seals, which can increase both efficiency and output, for example steam turbine dense pack technology
Air and water coolers	To cool the process gas down to ambient temperature.	- Install steam traps to recover the excess steam. - Automated system to calculate and monitor the approach temperature to avoid fouling of the coolers.

Table 4.14: List of other non-critical unit operations at the site

Other Activities/Operations		
Item	**Description**	**Used for**
1.	Hydrogen filling station	To compress hydrogen gas in cylinders to be distributed to customers.
2.	Cooling water system	Proper circulation of cooling water supply to the main process units.

4.2.10 Other Facilities at the Site

Through this audit, other areas are covered to obtain a clearer overview on the safety risks and housekeeping practises. Most of the area is also a common area that every typical manufacturing site has. There are no unnecessary rooms and most of the workspace has been occupied and fully functioning. There is no smoking room within the site due to the fact that smoking is highly prohibited at the site.

Table 4.15: List of other facilities at production site

Description	Used for
Control room	To monitor and change parameters of the unit operations via a Distributed Control System (DCS) and SCADA.
Main office	Work area of the safety team, finance team, admin team and facility manager.
Spare part warehouse	The place where all the mechanical spare parts are kept.
Chemical warehouse	Storage place for chemicals such as cleaning agents.
Pantry	Where beverages and food are stored. The site workers often use the pantry area to consume meals, refill water and make beverages.
Maintenance office	Office area of maintenance and electrical team.
Generator room	2 units of generator (genset) are stored here to serve as backup when electricity is down. Monthly test runs of the genset are done to ensure it is in good condition.
Guardhouse	To check on the visitors and external contractors.
Meeting rooms	Rooms used for meetings, in-house trainings and other miscellaneous purposes.
Changing room	There is a dedicated room for technicians or any site staff to change their clothing.

4.2.11 Gaseous Emission

Carbon dioxide is released into the atmosphere resulting from the purification step to increase hydrogen production. For a month, 1,080 tons of carbon dioxide is released based on maximum plant capacity. About 0.25 kg of carbon dioxide is released for every kg of hydrogen produced. From the audit conducted, currently there is no plan to capture the carbon dioxide for other usage or to reduce the quantity of carbon dioxide released.

Table 4.16: List of gaseous emission from the process

Gaseous Emission			
Item	**Type of emission**	**Quantities released in a month**	**Quantities released per ton of product**
1.	Carbon dioxide	1,080 tons	0.25 tons

4.2.12 Safety, Health and Environment Issues

Another aspect during the audit process covered is the safety, health and environmental risks at the site. Several risks were identified, and the level of the risks identified were assessed and prioritized. The risk evaluation is done based on the severity and probability risk matrix as per tabulated in Table 4.17. This method was helpful to construct immediate control steps or actions to be taken if any incidents happen at the site.

Table 4.17: Risk matrix

Risk Probability	Risk Severity				
	Catastrophic A	**Hazardous B**	**Major C**	**Minor D**	**Negligible E**
Frequent (5)	5A	5B	5C	5D	5E
Occasional (4)	4A	4B	4C	4D	4E
Remote (3)	3A	3B	3C	3D	3E
Improbable (2)	2A	2B	2C	2D	2E
Extremely Improbable (1)	1A	1B	1C	1D	1E

Thus, the risk level is identified by multiplying the probability with the severity to find the overall index. The criteria for severity are listed below:

1. Catastrophic (A) – If there is a risk take place, it would cause many deaths or destruction to the process equipment and resources.
2. Hazardous (B) - If the risk occurred it would cause a large reduction in safety margins, physical distress or a workload such that the technicians cannot be relied upon to perform their accuracy or causing serious injury or causing major damage of the process equipment.
3. Major (C) - If the risk occurred, it would reduce the technicians' ability to cope with challenging operational conditions. as a result of an increase in workload or causing serious incidents at the site.

4. Minor (D) - If the risk occurred it would cause nuisance, operating limitation, use of emergency procedures or minor incident events.
5. Negligible (E) - If the risk occurred, there are few consequences which do not affect the technicians or the process equipments and does not hinder any operating conditions of the site.

Table 4.18 shows the risk assessment listed in safety, health and environmental observation was identified at the steam methane reformer site.

Table 4.18: Safety and health risk assessment

Observation of any risk(s)	Risk description	Probability	Severity	Risk Level
Poor housekeeping	Materials are stored improperly.	5	B	5B
	Boxes are left lying around the desk.	5	B	5B
	Chemical bottle found on the instrument valve rack.	4	C	4C
	Oil spillage on the floor.	5	C	5C
	No proper signage at the forklift area.	4	B	4B
Lack of standard operating procedure (SOP) on transmitter calibration.	Can contribute to malfunctioning of the transmitter if proper timely calibration is not performed. Technicians do not have a detailed SOP indicating the full steps to be followed during the transmitter calibration job.	5	C	5C
First aid box is incomplete	There is no proper routine checking on the first aid box. Gauze wool and band-aid were replenished, and it was not restocked.	2	D	2D

Five observations show the risk is high, one observation shows the risk is medium and one observation show the risk is low according to the risk assessment. Mitigation actions should be taken immediately for those of high risks, followed by for the medium risk and the low risk.

4.2.13 Housekeeping Practices

Effective housekeeping and can help reduce or eliminate hazards in the site. It includes keeping work areas clean and orderly, maintaining site and office floors free of slip and trip hazards and removing other fire hazards from the work area. Several poor housekeeping practices are documented in Table 4.19.

Table 4.19: Details on the housekeeping practices

Improvement in Housekeeping Practices			
Item	**Housekeeping problems**	**Location**	**Impact to the quality of the product/productivity/safety**
1.	One section of the desk has boxes and toolboxes lying under the desk.	Maintenance room	Can pose serious safety hazards, for instance, trip and fall.
2.	Pressure regulator left lying down on the floor.	Near the turbine area.	Trip and fall.
3.	Chemical bottle was found on the instrument air valve rack.	Near the turbine area.	Can cause chemical spillage.
4.	No proper signage.	At the forklift area.	Pose safety threats.
5.	Improper storage of materials.	Warehouse.	Difficult to access the materials during the need of it. Can pose safety hazards such as trip and fall.

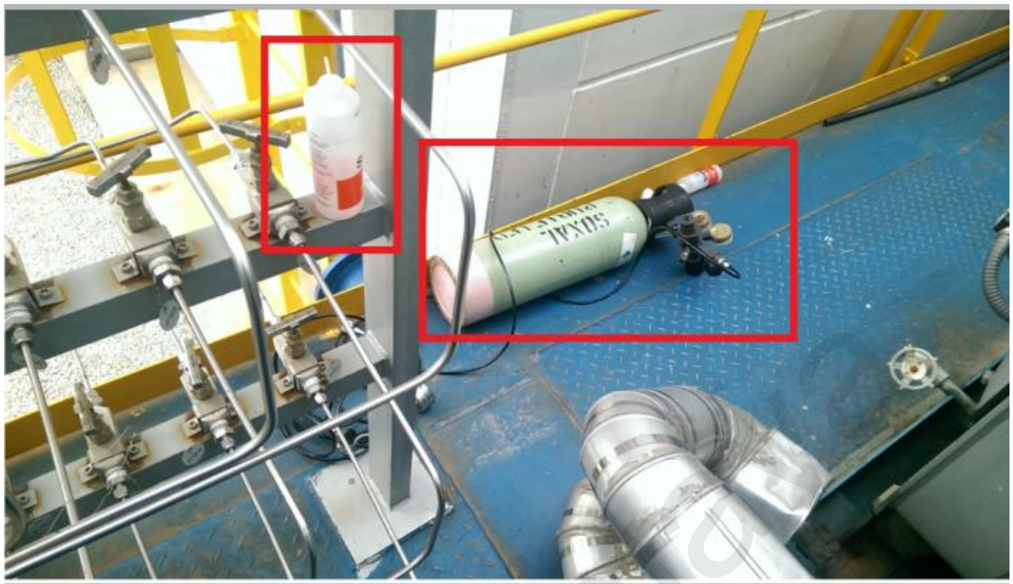

Figure 4.2: Chemical bottle found on the valve rack. Pressure regulator cylinder is found lying down on the floor without being kept upright.

Figure 4.3: Picture showing unorganised office desk at the maintenance room.

Figure 4.4: Slipper was found lying down at the hydrogen filling station.

Figure 4.5: Water hose found lying down on the floor.

4.2.13 Other Observations

During the audit performed, several observations have been listed in Table 4.20 which can be improved for maximizing productivity and efficiency.

Table 4.20: Details on other observations at the site and during the process

Other Observation			
Item	**Description**	**Location**	**Impact to the quality of the product/productivity/safety**
1.	In the case of a customer plant tripped, the compressors take 5-10 minutes to unload causing some amount of hydrogen gas to be vented.	Before the customer supply pipeline. Vent valve is in position.	Loss of product.
2.	The shift technician performs field inspection and collects the parameter's data for manual field transmitters in a paper checklist. This is done in every shift; that is once every 12 hours.	For manual instruments which are not captured in the Distributed Control System (DCS).	Loss of data. Unable to process and visualise the data in a real-time monitoring system.

4.3 Carbon Footprint Calculation

Carbon footprint is the amount of carbon dioxide emissions associated with all the activities within a process. A carbon footprint calculation is a standard method for calculating and reporting the environmental impact of a process. The quantity is measured in metric tons. This equation (Loyarte-López, Barral, & Carlos Morla, 2020) is used to calculate the other remaining consumptions and waste in relation with producing 1 ton of hydrogen:

Carbon dioxide emission in total (kg CO_2) = Data of total entity x Emission factor

Monthly production of hydrogen gas produced is calculated as 4,248 tons. Thus, consumption of electricity, fuel, solid waste, liquid waste, raw material quantity needed and utilities were further derived for 1 ton of product and the CO_2 emission was tabulated in Table 4.21.

4.3.1 Monthly and Annual Production of Hydrogen

Production per day: 141.6 tons

Monthly production: 4,248 tons

Annual production: 50,976 tons

4.3.2 Consumption per 1 ton of Hydrogen

Electricity Consumption for Hydrogen Production and Product Compressors Involved.

Monthly consumption: 6,661.3 MWh/4,248 tons of hydrogen.

Consumption for 1 ton of hydrogen: 1.57 MW/ton of hydrogen.

Fuel Consumption.

Monthly consumption: 298.5 tons/4,48 tons of hydrogen

Consumption for 1 ton of hydrogen: 0.07 tons of fuel/ton of hydrogen.

Non-Scheduled Solid Waste at the Production Site.

Monthly waste: 0.025 tons/4,248 tons of hydrogen.

Waste for 1 ton of hydrogen: $5.9\ x\ 10^{-6}$ tons of solid waste/ ton of hydrogen.

Scheduled Solid Waste at the Production Site.

Monthly waste: 90 tons of waste/4,248 tons of hydrogen.

Waste for 1 ton of hydrogen: 0.021 ton of scheduled solid waste/ ton of hydrogen.

<u>Non-Scheduled Liquid Waste at the Production Site.</u>

Monthly waste: 372 litres /4,248 tons of hydrogen.

Waste for 1 ton of hydrogen: 0.585 litres/ton of hydrogen.

<u>Utilities Consumption at the Production Site.</u>

Monthly consumption: 927 tons /4,248 tons of hydrogen.

Consumption for 1 ton of hydrogen: 0.218 tons/ton of hydrogen.

<u>Raw Material Consumption</u>

Monthly consumption: 546.9 tons of raw material /4,248 tons of hydrogen.

Consumption for 1 ton of hydrogen: 0.129 ton of raw material /ton of hydrogen.

Table 4.21: Overall carbon dioxide emission from steam methane reforming process to produce hydrogen

Source (Monthly Consumption)	For 1 ton of hydrogen	Emission factor	Emission of CO_2 (ton CO_2/ton product)	Emission of carbon dioxide (tons monthly)
6,661.3 MWh for the overall SMR process including the product compressors.	1.57 MWh	0.67 tons CO_2/MWh	1.052	4,460
298.5 tons of fuel consumption	0.07 tons	0.74 tons CO_2/ton fuel	0.052	220
0.025 tons of non-scheduled solid waste	$5.9 \, x \, 10^{-6}$ tons	2.8 tons CO_2/ton of waste	$1.65 \, x \, 10^{-5}$	0.07
372 litres of liquid waste.	0.175 litres	2 tons CO_2/litre of waste	0.35	1,487
927 tons of utilities were used.	0.218 tons	1.0 tons of CO_2/ ton of utilities	0.218	926
546.9 tons of raw material consumed.	0.129 tons	1.5 tons CO_2/ton of raw material	0.194	822
90 tons of scheduled solid waste	0.021 tons	3 tons CO_2/ton of waste	0.063	268
1,080 tons of direct CO_2 emitted from the process	0.254 tons	-	0.254	1,080
Total			**2.18**	**9,263 tons**

Based on Table 4.21, 9,263 tons of carbon dioxide is emitted monthly with 2.18 tons of carbon dioxide is emitted per ton of hydrogen produced.

4.4 Cleaner Production Options for Steam Methane Reforming Site

Based on the result in Table 4.21, the electricity consumption shows the highest amount of carbon dioxide emission which accounted for 4,460 tons monthly followed by liquid waste which contributes 1,487 tons of CO_2 emitted. Next highest is the CO_2 emitted from the process alone, which is the direct emission of CO_2 accounting to 1,080 tons. Contribution of carbon dioxide emission from electricity is high as the process equipment heavily depends on electricity because it is the only energy source to run production. Besides that, the product compressors used to compress the hydrogen gas to a high pressure to meet the customer requirements are also a heavy electricity consumer.

4.4.1 Alternative approach to steam methane reforming process by substituting it with Electrolysis process

Electrolysis is a process that breaks down hydrogen from water using an electric current (US Energy Information Administration, 2021). The process is known as power-to-gas on a big scale, where power is electricity and hydrogen is gas. Other than hydrogen and oxygen, electrolysis produces no wastes or emissions. Electrolysis can be powered by a variety of renewable energy sources, including hydro, solar, and wind. Hydroelectricity can be used as the energy source for water electrolysis in nations having a lot of waterfalls. Photoelectrolysis by where the photovoltaic cells act as electrodes that decompose the water to hydrogen and oxygen gas could also be a good alternative (Zoulias, Varkaraki, Lymberopoulos, Christodolou, & Karagiorgis, 2004).

If the power for electrolysis is generated from the combustion of fossil fuels (coal, natural gas, and petroleum) or biomass, the environmental effects and carbon dioxide emissions are indirectly linked to electrolysis. Since electrolysis can work along with renewable sources, the chances of reducing the carbon dioxide emissions with the current steam methane reforming technology is high. According to a study conducted by A.Konieczny, K.Mondal, T.Wiltowski and P.Dydo, approximately only 4% of hydrogen worldwide is produced by this process. The prominent disadvantages of this process is that this process has low efficiency that being said, the yield of hydrogen production is low (Kalamaras & M.Efstathiou, 2013, pg.9).

At elevated temperatures of 800 - 900 deg C, the electricity power consumption for this process is approximately 1 kWh/Nm3 of hydrogen (Zoulias, Varkaraki, Lymberopoulos, Christodolou, & Karagiorgis, 2004). There is a limitation for this process as being told earlier than the yield of hydrogen gas would be lower thus a thorough economic feasibility studies to be conducted to maximise the usage of the electrolysis process. It could be 50% of the hydrogen gas produced through the steam methane reforming process and another 50% can be produced through the electrolysis process.

4.4.2 Installing Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) is a new technology that will attempt to prevent large quantities of carbon dioxide from being released into the atmosphere. As we noticed from the cleaner production audit results, a huge amount of carbon dioxide is being released to the atmosphere as a byproduct. This amount accounted for 1,080 tons monthly for the production of 4,248 tons of hydrogen produced. That is about a ratio of 1:4 for carbon dioxide emission to hydrogen production. Thus, CCS is often regarded as a means of mitigating the contribution of fossil fuel emissions to global warming. Most widely used processes for carbon capture are chemical absorption by solvents, membrane separation and cryogenic separation (Ayodele F. , Mustapa, Ayodele, & Mohammad, 2020). Based on the process, it can deduce that carbon dioxide can be captured from three possible locations that is:

1. Syngas from the shift-reformer (Option 1).
2. Tail gas from pressure swing adsorption (Option 2)
3. Flue gas from the main reformer (Option 3).

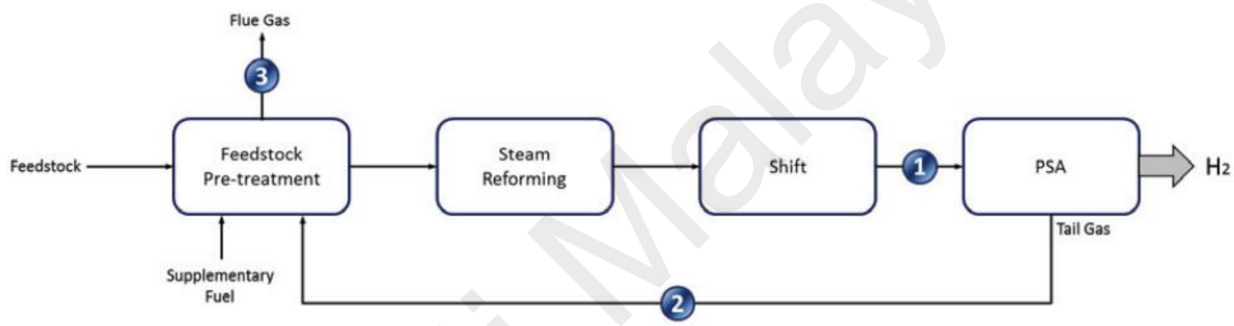

Figure 4.6. Simplified block diagram showing the locations where we can capture the carbon dioxide.

For carbon capture, chemical adsorption is widely used technology and has been in the market for several years now. A techno-economic evaluation study was conducted by Amec Foster Wheeler in collaboration with IEA Greenhouse Gas Research and Development in 2016 to simulate and compare the steam methane reformer without CCS and steam methane reformer with CCS. From this study, it was concluded that a steam methane reformer with a CCS plant managed to reduce the electricity consumption by 38.3% (Collodi, Azzaro, Ferrari, & Santos, 2017). The electricity consumption for steam methane reformer without CCS plant was 21,420 kW meanwhile for steam methane reformer with CCS was 8,200 kW. Besides that, the specific carbon dioxide emissions for the steam methane reformer with CCS plant was lower by 43.3% than that of carbon dioxide emission from a standalone steam methane reformer.

4.4.3 Minimizing Expired Liquid Chemical Products

Through the audit results, it was noticed that some of the chemical liquid products such as hydrochloric acid, caustic soda and sulphuric acid were discarded as a waste due to the products being expired. This can be avoided if there is a properly maintained inventory list for each and every chemical product used in the site. A simple Google Sheets or Excel file can be maintained to keep track of the expiration dates. Besides that, in the inventory list, it should also include the amount to be purchased according to its usage and need. In that way, over buying of chemical products can be avoided, waste management cost can be reduced, and purchase cost can be reduced. The safety department should maintain all disposal records as per regulations.

Below are some guidelines in order to minimize waste especially chemical waste:

1. Before discarding a reagent/chemical, be sure it isn't needed by anyone else to avoid overbuying.
2. Buy modest quantities of chemicals. Small containers' contents are more likely to be used rather than contaminated or degraded.
3. Avoid purchasing chemicals in large quantity. Stock piling entails the acquisition of or accumulation of chemicals in large quantities for use longer than needed.
4. When receiving chemicals, date and store them in such a way that the older compounds are used first. This will create a rotational system, allowing chemicals to be used before their shelf life runs out.

5. Replace any broken or malfunctioning caps and lids. This will protect against the impacts of pollution from the air and moisture.
6. Inventory the chemicals in the site every six months. During the site inspection damaged labels must be discarded and replace it with new, clear labels.

4.4.4 Implementation of Digital Tools for Field Parameters

Technicians spend almost 1-2 hours going down to the field to record down the process equipment parameters which are not connected to the Distributed Control System. Every shift once, they will need to fill a checklist listing down the values of the parameters. There are many digital tools in the market that can automate such readings and avoid the loss of data instead of writing it down in a piece of paper and filing it. One such example is eRound, whereby it is used to support technicians during operational site rounds. It is a combination of web platforms to configure the template of the checklist, manage the users and follow up the reports. Meanwhile in the mobile version which can be downloaded into tablet or smartphone, the checklists can be executed. This tool has many benefits such as easy operational task follow-up, better detection of the anomalies, easy management of history consultation and being able to retrieve the datas for analysis purposes. By implementing eRound, technicians can concentrate on more value-added tasks. Loss of recorded checklists by papers can be avoided and filling these records can be hassle-free.

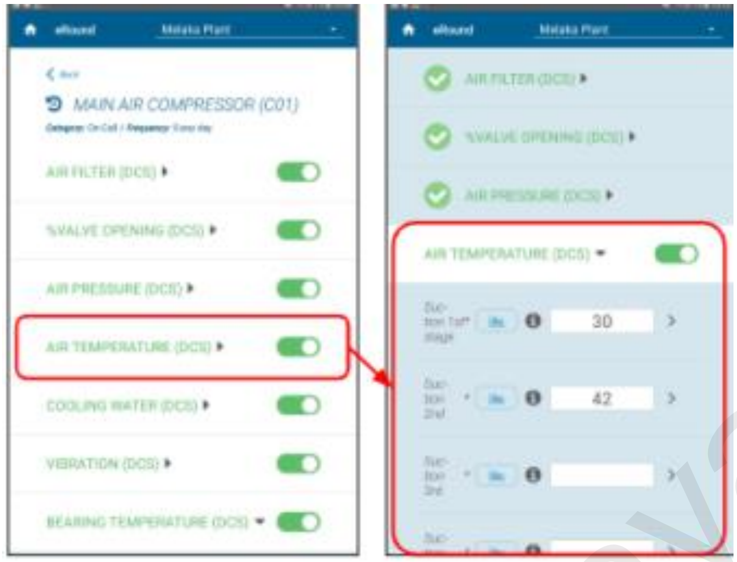

Figure 4.7. Sample checklist interface of digitized checklist using eRound

There is no capital expenditure in procuring the software. There is only operating cost for this software which is RM 3,250 annually. By investing into this digital tool,technicians will be able to perform higher value added tasks in the site, enhance a robust preventive maintenance, foster the adoption of digital tools aligned with Industry 4.0, datas are conserved and able to use the datas for analysis studies.

4.4.5 Usage of Predictive Data Analysis

Industry 4.0 and the Industrial Internet of Things (IIoT) are accelerating data and software-driven digitalization across a wide range of industries, particularly in industrial automation and manufacturing systems. One of the many advantages provided by current technology is the infrastructure for exploitation of big data, machine learning (ML), analytical tools, and cloud computing software tools, for example in constructing advanced data analytics platforms (Clabungo, LiisaJämsä-Jounela, Schiemann, & Binder, 2020). In predictive data analytics in the process industry, soft sensors are important tools for providing key information of the operating parameters into the state of process operations especially in situation where the direct measurement of key process variables is difficult, nearly impossible or even not realiable. For example, in steam methane reforming plants, understanding the heating value of solid fuel is critical for smooth plant operations, which often results in less changes in the power generated and plant equipment with a longer lifespan (Clabungo et al., 2020) However, real-time assessment of the heating value of solid fuel is problematic due to the heterogeneous character frequently associated with solid fuel source materials, most notably composition.

Hence, soft sensors can be created by the use of mathematical process models, for example, it could be based on mass and energy balances. Soft sensors are a cost-effective alternative to physical measuring devices for real-time process variable prediction, and they can be used in conjunction with or integrated with measuring equipment. These predictive technologies are capable of exploiting large data, particularly on important process equipment characteristics, resulting in improved variable prediction. Industrial automation suppliers and computer services external companies currently offer a variety of hardware and software facilities for handling process data analytics. These tools are increasingly being used to develop data analytics platforms for different process and manufacturing industries (Ruhanen, Kosonen, Kauvosaari, & Enriksson, 2018).

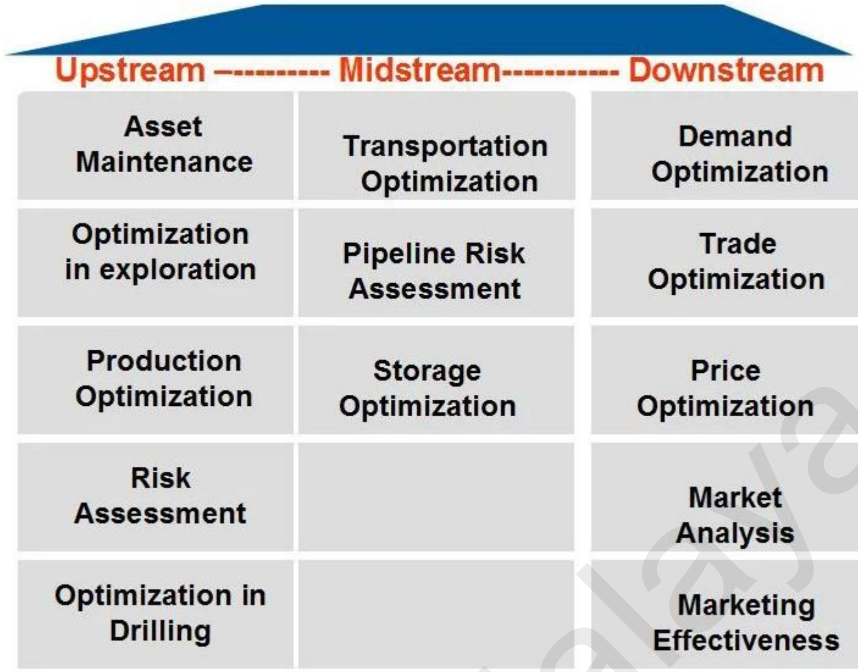

Figure 4.8: Example of predictive analysis tools used in manufacturing industry

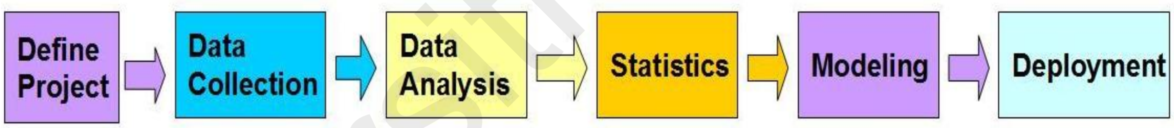

Figure 4.9: The workflow of configuring a predictive analysis.

By implementing predictive analysis in the process, the solid waste can be reduced as catalyst shelf-life is extended, loss of raw material and loss of products can be avoided. There is potential reduction of carbon dioxide emitted monthly from 6,428 tons to 3,214 tons which is a reduction of 50%. There would be significant reduction in the electricity consumption, raw materials consumption, utilities consumption and the fuel consumption with better enhance monitoring.

4.4.6 Implementation of 3R Initiatives for Liquid Waste Generation

3R stands for reduce, recycle and recover. This is an impactful and effective initiative to minimize the generated liquid waste from the site. 3R is a multi-faceted approach that helps in balancing both economic and environmental concerns by reducing, reusing and recycling methods. The waste hierarchy refers to the "3Rs" for instance, reduce, reuse and recycle, which classify waste management strategies according to their desirability. The 3Rs are meant to be a hierarchy, in order of importance. The waste hierarchy has taken many forms over the past decade, but the basic concept has remained the cornerstone of most waste minimization strategies. The aim of the waste hierarchy is to extract the maximum practical benefits from products and to generate the minimum amount of waste (Department of Environment Ministry of Environment and Forests Government of the People's Republic of Bangladesh, 2009).

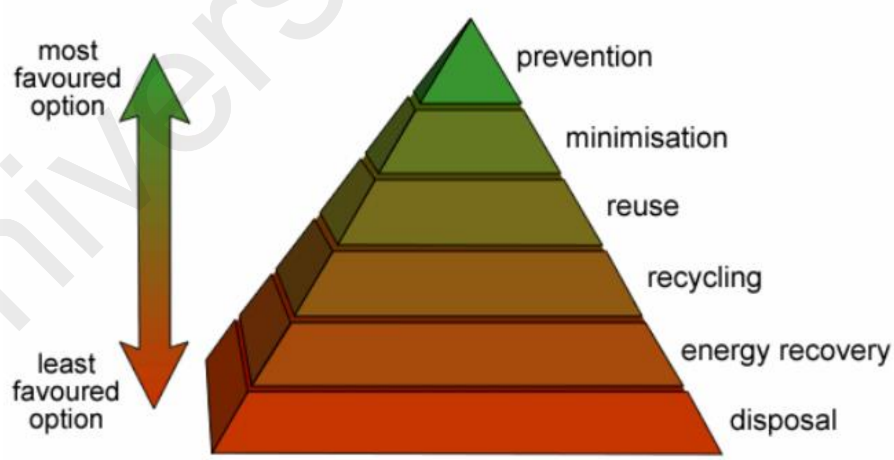

Figure 4.10: Waste hierarchy

As far as the site is concerned, this method can be adapted by raising awareness to the site workers firstly. By having a systemised training module, site workers would have the capability to identify areas of improvement based on the 3R approach to reduce the liquid waste. For example, the purchase of liquid chemical solutions can be reduced based on the need and inventory data to avoid overstocking which may lead to expired chemical solutions. Moreover, condensate can be recovered from the compressors and channeled back to the cooling water tower as makeup water. By doing so, the usage of make-up water from a third-party source can be reduced leading to lower utility cost.

4.4.7 Implementation of Effective Alarm Management for Critical Process Equipment

Alarm flooding, operator error, and time, money, and energy losses can all result from a faulty alarming system. Organizations have a tendency to set up an excessive number of alerts and lose sight of their original goal. After a while, there are so many false or unneeded alerts that personnel tend to disregard them. The irony is that a barrage of alarms can make it more difficult to find the source of the problem. If a significant problem goes unnoticed, it can cost you time, resources, money, and, in the worst-case scenario, your life. During the audit, it was noticed that there were hundreds of alarms flooding on the DCS screen. Some of the alarms are not valid and some are not of critical indication such as tanker offloading alarm. There will be needless or meaningless alarms in every system, which are frequently referred to as "nuisance alarms" (Mehta & Reddy, 2015).

When there are too many alerts, alarm flooding occurs, and the alarms are not prioritized properly, a shift technician may receive more than ten alarms in ten minutes. Operators may develop a habit of disregarding alarms in groups by clicking "Acknowledge All" or completely ignoring alarms. Alarm problems can also arise because of poor work habits such as enabling all alarms by default, having weak management of alarm practices between departments in the same company and frequently using alarms to perform status checks rather than to pay attention to abnormal or anomaly situations. Thus, proper alarm management must be in place to avoid this issue. To start of, a good way would by document the high priority alarm and configuring it into the system with labels as described in Table 4.22 below:

Table 4.22: Recommended five priority labels to be used in alarm management

Rating	**Type/Severity of Alarm**
0	Diagnostic
1	Low
2	Medium
3	High
4	CRITICAL

Of those, only priority levels 1 through 3 should be used on a regular basis while priority level 4 should only be used rarely, for true emergencies. Priority levels are meant to help the operator differentiate the importance of alarms.

Secondly, is to analyze these alarms in the sense of how many alarms shift technicians can manage per day. An operator must detect, recognize, verify, acknowledge, and analyze an alert, take corrective action, and then monitor it for at least a few minutes. Alarm rates of more over 300 per day are simply too high. At that rate, technicians will be forced to dismiss far too many alerts. The basic limit of what an operator can actually accomplish is two alerts in ten minutes (Mehta & Reddy, 2015). Finally, is to incorporate the alarms based on its status, that is either state-based alarming, shelving alarms and scheduling alarms.

4.4.8 Implement 5S Method for Housekeeping

5S is a method for organising a workplace, keeping it clean, and maintaining efficient and consistent working conditions. It instils the discipline required to enable each individual to achieve and maintain a world-class environment.5S stands for five Japanese words which are Seiri, Seiton, Seiso, Seiketsu and Shitsuke. They symbolized the five steps for systematic method for good housekeeping. The English translations of those Japanese words are Sort, Set in order, Shine, Standardize and Sustain, respectively. The workplace becomes cleaner, safer, well-organized, and more pleasant as a result of implementing 5S, floor space utilization improves, workflow becomes more efficient and precise, non-value-added activities are reduced, time spent searching for tools, materials and machine breakdowns are reduced because clean and well-maintained equipment breaks down less frequently. The five steps are compiled in order in Table 4.23.

Table 4.23: 5S Compilation

Rating	Description	Examples
Seiri - Sort	Refers to the act of throwing away all unwanted and unrelated materials in the workplace.	1. Throw away the items which were not used for the past 1 year. 2. Items used once in 6 months may be stored at a distance from the workstation.
Seiton -Set in order	Having things in the appropriate places or put up in such a way that they are easily accessible and eliminate the need to seek.	1. Store materials and equipment at a place allocated to them with proper label or signalization. 2. Use standard colour coding for pipelines for steam, water, gas and drainage.
Seiso - Shine	This can include anything like cleaning the workspace, maintaining its pleasant appearance and using preventive steps to keep the workspace tidy and clean.	1. Display cleaning schedule. 2. Set aside room for the storage of cleaning supplies and consumables.
Seiketsu - Standardize	The visual management, an important aspect to maintain standardized conditions to enable the individuals to always act quickly.	1. Jot down the procedures and guidelines for sorting, set in order and shine. 2. Create a checklist for each section and train site employees in using them
Shitsuke - Sustain	This is about maintaining the improvements done in the previous steps.	1. Raise awareness of the system and make it widely known. Develop 5S News, 5S Posters, 5S Slogans, and 5S Day, for example. 2. Develop audit/evaluation procedures for 5S implementation.

4.4.9 Incorporate Training Modules for Site Technicians in Automated Software Learning System Such as Cornerstone Learning Management System

Technicians must be trained periodically on the overall process especially on performing troubleshooting when there is a problem in the process equipment or in the machines used. This will eliminate the need of heavy reliance on the maintenance team during off-peak periods, for instance, at night. One way to keep track of technicians and shift leaders is by incorporating a learning management system. Training modules will be created in the learning management system and these modules can be assigned individually to each technician with a deadline specified. The technician can complete the modules assigned to them within the given specific time and they would obtain a digital certificate upon completion. Cornerstone is a well-established learning management software which is widely deployed in various corporations to digitalize and streamline training for technicians or employees in general. Cornerstone provides audio, video, digital documents, and instructor-led training in a number of media and virtual reality so employees can learn most effectively and in an engaging manner. This sort of software are extremely useful especially during the pandemic period, where travel is a big concern.

4.4.10 Eliminating Safety, Health and Environmental Risks

There were some observations compiled during the audit which leads to safety, health and environmental concerns. Action must be taken immediately to ensure safety is not compromised at the site. List of action items are compiled in Table 4.24 below:

Table 4.24: Preventive actions to be taken immediately

Safety Issue	Risk Level	Action
Boxes and toolboxes left lying under the employee desk in the maintenance department room. .	High.	● To remove unwanted boxes from the desk. ● To keep items in an organized manner and at any cost, avoiding keeping it in a pathway that can cause trips and slips. ● Toolboxes must be stored in the maintenance or warehouse room.
Improper wiring system. Some wire bundles are found lying down on the walkway.	Medium	● Safety officer/manager must inform the maintenance representative to ensure the proper wiring system is in place. ● Maintenance team should ensure good housekeeping after and before maintenance tasks are carried out.
Pressure regulator left lying down on the floor.	Medium	● To keep the pressure regulator in the warehouse. ● If it is a used pressure regulator which was dismounted, it should be immediately installed back to the maintenance team.
Incomplete first aid box in the control room.	Low	● Safety team should form a team whereby it consists of certified first-aiders and ensure they are fully responsible to ensure the items in the first aid box does not run out.

Table 4.24: Continued….

Safety Issue	Risk Level	Action
Chemical bottles were found at the production site near the instrument air valve.	High	• Chemical products must be kept in a chemical storage area at all times. • Shift team to do a routine housekeeping round every day and at every shift.
Chemical storage area with no secondary containment in place.	Medium	• Secondary containment must be built in the chemical storage area to prevent the spread of any spillage. If the chemical drum is used in production, make sure the drums are on secondary containment pallets as per requirement from the Department of Occupational Safety & Health (DOSH).
No proper signage at the forklift area.	High	• To place safety signs at the forklift area on the hazards around the area and on the preventive & protective measures to be taken while assessing the forklift area.

4.4.11 Reduce Pressure Swing Adsorption Off Gas for Better Recovery

High pressure drop across pressure swing adsorption (PSA) beds were limiting the hydrogen recovery. Current hydrogen recovery in the site is only 85.5%. PSA adsorbent must be removed and a layer of inner ceramic balls must be placed at the bottom of the bed to form a support structure and an easier path for the gasses. The inert ceramic balls help establish uniform flow (Towler & Sinnott, 2014). Once the ceramic balls are placed, the adsorbent can be reloaded. This will improve the hydrogen recovery drastically. Improved PSA recovery reduces the amount of natural gas used to produce hydrogen. The capital investment for this ceramic balls installation is estimated to be RM 50,000. No operating cost is involved. The ceramic balls life expectancy is 3 years or more, provided the operating conditions are optimal.

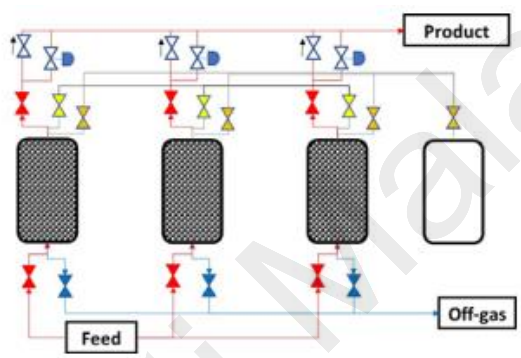

Figure 4.10: Ceramic balls are placed in the PSA for better hydrogen recovery

The payback period will be:

$$\text{Payback period} = \frac{50,000}{104,554}$$

$$= 0.5 \text{ years, approx 6 months.}$$

4.4.12 Install Steam Traps at the Steam Drum to Recover Excess Steam

Steam trap is crucial to get condensate, air and CO_2 out of the system as quickly as they accumulate to prevent loss of steam which is valuable and can be reused in the process to generate electricity. The trap provides minimal steam loss and eliminate dirt problem in the process line, condensate traps dirt and scale in the pipeline and solids may carry over from the boiler. Even particles going through strainer screens are corrosive, so the steam trap must be able to function even when dirt is present.

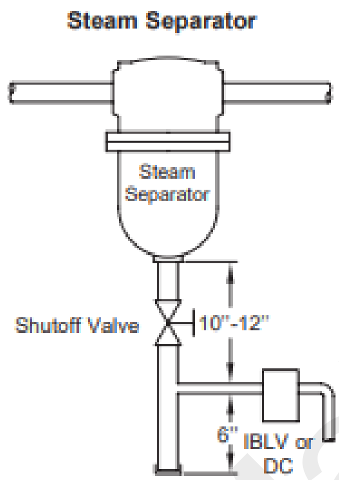

Figure 4.11: Drain downstream side of a steam drum

By installing a steam trap, the excess steam captured will be increased, thus reducing the overall electricity needed for the process. Currently, to produce 1 ton of hydrogen, 1.57 MW is needed. With the installation of the steam trap, the electricity from outsources needed to produce 1 ton would be 1.34 MW.

The installation cost of a standard steam trap per unit is RM 1,247 with the replacement cost of RM 333. The steam trap has life expectancy upto 8 years. Two units are needed for the steam drum. Thus, the payback period will be:

$$\text{Payback period} = \frac{2{,}494}{250{,}861}$$

$$= \text{Quick win}$$

4.5 Cleaner Production Options Evaluations

Evaluation and feasibility study phase is crucial to evaluate the recommended cleaner production opportunities and to select whichever that are suitable for implementation. The opportunities chosen all during the assessment process should be evaluated on their technical, economic, and environmental advantages (Mavengere et al., 2012). The quickest and easiest method of evaluating the different options is to form a group, consisting of the project team and management personnel, and discuss the possible solutions one by one. This process should give a good indication of which projects are feasible and what further information is required. In addition to that, technical evaluation is also critical to implement cleaner production options. A technical evaluation will determine whether the proposed solutions are doable, needed extra manpower, need additional training and the necessary process changes required.

Economical evaluation also must be taken into account to determine the cost effectiveness of the cleaner production opportunities. Economic feasibility is frequently the deciding factor in whether or not a business idea will be pursued. When doing an economic analysis, the expenses of the modification are balanced against the potential savings. Costs are divided into two categories: capital investments and operating costs. Payback period, net present value (NPV), and internal rate of return are common metrics used to assess a project's economic viability (IRR). Finally, is the environmental evaluation. This evaluation is crucial to identify the suggested solutions' positive and negative environmental implications have. In many cases the environmental advantages are obvious which is a reduction in toxicity level or in the number of wastes and emissions. In other scenarios, it may be necessary to determine if, for example, an increase in electricity consumption would outweigh the environmental advantages of reducing the consumption of materials.

Under the basis of technical, economical and environmental evaluations, the proposed cleaner production options with the weighted average score are compiled in Table 4.25. The weighted sum of the scores provides an index for each option and this can be used as a basis to rank alternatives in terms of their level of importance (Mavengere et al., 2012). The options can be grouped into categories such as ‘top’, ‘medium’ and ‘low’ priority. Prioritizing options in this way provides a basis for preparation of the implementation plan

Table 4.25: Evaluation of cleaner production options

Item	Option	Technical Feasibility	Environmental Impact	Economic Feasibility	Total	Rank
	Weight	**20%**	**30%**	**50%**	**10**	
1	Alternative approach to steam methane reforming process by substituting it with Electrolysis process.	6	9	3	6.6	**(11)**
2.	Installing Carbon Capture and Storage (CCS)	8	7	7	7.7	**(7)**
3.	Minimizing Expired Liquid Chemical Products	8	8	8	8.3	**(5)**
4.	Implementation of Digital Tools for Field Parameters	9	4	7	7.2	**(9)**
5.	Usage of Predictive Data Analysis	7	7	9	7.6	**(8)**
6.	Implementation of 3R Initiatives For Liquid Waste Generation	8	8	6	7.9	**(6)**
7.	Implementation of Effective Alarm Management For Critical Process Equipment	9	7	8	8.4	**(4)**

Table 4.25: Continued….

Item	Option	Technical Feasibility	Environmental Impact	Economic Feasibility	Total	Rank
	Weight	**20%**	**30%**	**50%**	**10**	
8.	Implement 5S Method for Housekeeping	9	8	7	8.6	**(3)**
9.	Incorporate Training Modules for Site Technicians in Automated Software Learning System	7	7	7	7.2	**(10)**
10.	Eliminating Safety, Health and Environmental Risks	9	9	9	9.3	**(2)**
11.	Reduce Pressure Swing Adsorption Off Gas For Better Recovery	8	6	5	7.0	**(11)**
12.	Installing steam trap for the steam drum	9	6	9	8.3	**(1)**

From the results of Table 4.25, the options can be implemented according to their rankings, that placing more priority on the option that is ranked first.

4.6 Recommended Cleaner Production Options to Be Implemented at the Site

Based on the findings for cleaner production options and estimation of carbon footprint, electricity and the waste emitted contributes as the major source of carbon dioxide emission in the steam methane reformer site. Recommended cleaner production options for electricity consumption can reduce emission of carbon dioxide and can potentially green the process. This recommendation of cleaner production is selected according to the priority measures which was tabulated in Table 4.25. Options 1 to 6 can be implemented this year as it falls under implementation without cost and implementation with cost but less than 5 years of payback period meanwhile option 7 onwards can be implemented next year as it requires more effort and budget has to be secured beforehand.

This implementation can be successfully adopted by following these guidelines:

- Preparation of implementation plan.

  To ensure implementation of the selected options, an action plan should be developed such as detailing the activities to be carried out, the way in which the activities are to carried out, resource requirements from financial and manpower point as well, persons responsible for undertaking those activities and on the time frame for completion with intermediate milestones.

- Top management's approval.

  The plan which was prepared needs to be submitted to the higher authority at the site for review and approval before implementing cleaner production options.

- Drafting Implementation Schedule.

  A gantt chart must be prepared and briefed to all relevant parties who are involved to ensure the implementation goes on smoothly without major interference to the customer supply. The implementation should be carried on at a time which does not coincide with shutdown maintenance, planned maintenance activities and on high customer demand peak period.

- Training.

  As for other investment projects, the implementation of cleaner production options involves modifications to operating procedures and processes and may require new equipment. The company should, therefore, follow the same procedures as it uses for implementation of any other company projects. However, special attention should be paid to the need for training staff. The project could be a failure if not backed up by adequately trained employees. Training needs should have been identified during the technical evaluation.

- Monitoring the Performance.

  It is very important to evaluate the effectiveness of the implemented cleaner production options. Typical indicators for improved performance are reductions in wastes and emissions per unit of production, reductions in resource consumption (including energy) per unit of production and improved profitability. There should be periodic monitoring to determine whether positive changes are occurring and whether the company is progressing toward its targets.

Table 4.26: Selected cleaner production options

Item	Option	Before: Carbon dioxide emission (kg)(monthly)	After: Estimated carbon dioxide emission (kg)(monthly)
1	Alternative approach to steam methane reforming process by substituting it with Electrolysis process.	7,508	0
2.	Installing Carbon Capture and Storage (CCS)		6,428
3.	Minimizing Expired Liquid Chemical Products	1,487	0
4.	Implementation of 3R Initiatives For Liquid Waste Generation		
5.	Implementation of Digital Tools for Field Parameters	9,263	4,632
6.	Usage of Predictive Data Analysis		
7.	Implementation of Effective Alarm Management For Critical Process Equipment		
8.	Implement 5S Method for Housekeeping	1,487	0
9.	Incorporate Training Modules for Site Technicians in Automated Software Learning System Such As Cornerstone Learning Management System	9,263	3,540
10.	Eliminating Safety, Health and Environmental Risks		0
11.	Reduce Pressure Swing Adsorption Off Gas For Better Recovery	4,460	2.230
12.	Installing steam trap		3,814

Based on Table 4.26, the two best solutions to green the steam methane reforming process is by changing the technology used, that is either by opting for an electrolyser or by installing carbon capture and storage which reduces the carbon dioxide emission by 100% and 14.4%, respectively. The estimated payback period for both options are:

1. Opt in for an electrolyzer.

   Total cost of investment = RM 15,689,770

   Total annual saving of the site = RM 1,158,577

   Payback period = Cost of investment / annual savings

   = 13 years

2. Installing carbon capture and storage.

   Total cost of investment = RM 413,916,667

   Total annual saving of the site = RM 158,336,600 + Cost from resales of carbon dioxide, RM 4,296,115

   Payback period = Cost of investment / annual savings

   = 2.5 years.

Once the recommended cleaner production options are implemented at the production site, the working area in the site will be organized with standard operations. Cleaner production strategies play a vital role in minimizing the loss of electricity, fuel, chemicals and packaging materials. At the same time, it helps to improve the productivity of the employees. For example, employees will be more committed towards work and will produce more output if their working environment is safe and convenient for them. This will increase the production site's reputation and remain competitive in today's world market.

4.7 Summary

Based on the options generated, it can be deduced that by implementing CP options, the CO_2 can be reduced from 33,468 tons per month to 20,644 tons per month. This is equivalent to a reduction of 38.3%. The most prominent option is to change the technology, however as it requires higher capital cost, it may be kept as future implementation. This study has provided an opportunity to explore the how Malaysia is moving towards CP.

Malaysia pledged to reduce CO2 emissions per unit of GDP by 45 percent by 2030 from 2005 levels at the United Nations Climate Change Conference, also known as the 2015 Paris Climate Conference and Conference of Parties (COP) 21, held in Paris, France (Koo, 2019). In support of the pledge, the Malaysian government has been putting in a lot of effort through the Malaysian Green Technology Corporation to promote a framework dubbed the Low Carbon Cities Framework (LCCF). LCCF is a national framework assessment system to guide and assess the development of cities and to support holistic sustainable development in Malaysia.

The Ministry of Energy, Science, Technology, Environment, and Climate Change is in charge of GreenTech Malaysia (MESTECC). Its mission, as stated in the Green Technology Master Plan 2017-2030, is to lead the development and promotion of green technology as a strategic engine of socioeconomic progress (Koo, 2019). The framework includes five key elements: reducing carbon dioxide emissions from building and common area energy use and water consumption, gasoline and diesel consumption by two and four-wheel private vehicles, municipal solid waste ending up in landfills, and increasing carbon sequestration by protecting and adding green spaces.

Implementation of cleaner production strategy is one amongst options for various sectors to reduce pollution through their operational activities. The government must be supportive to emphasize the importance of cleaner production and the impact it has on greening the industries (Sector Policies and Programs Division Office of Air Quality Planning and Standards U.S. Environmental Protection Agency, 2010).. A small change in the working process can help to reduce carbon emission and increase productivity. This greening study for the steam methane reformer process can be set as an example for similar industries in Malaysia to reduce carbon dioxide or even any other greenhouse gases emissions in Malaysia. The audit findings from this production site are believed to be informative and could use as a reference for similar manufacturing sectors in implementing their studies on cleaner production strategy.

CHAPTER 5: CONCLUSION

5.1 Conclusion

Hydrogen is a clean fuel that is in the rise in today's market for sustainable fuel. However, the production of hydrogen through steam methane reforming process is emitting heavy amount of carbon dioxide. An audit was conducted in a SMR site located at Tanjong Kling, Melaka to evaluate the carbon footprint of the process. Based on the audit results, several cleaner production options are generated. These CP options are evaluated based on the technical, economic and environmental feasibility and ranked accordingly. It can be stated from this research that implementing cleaner production procedures can help to green the steam methane reformer production site by lowering CO_2 emissions. It aids in the reduction of waste generation and the efficient utilisation of resources. It also increases the efficiency of the process. CO_2 is estimated to reduce from 33,468 tons per month to 20,644 tons per month which accounts to 38.3% of reduction. Based on the analysis, electricity consumption is the major contribution of CO_2 emission with a total of 4,460 tons of CO_2 per month and 53,520 tons of CO_2 per year. With cleaner production options implementation, the electricity consumption itself can be halved.

A total of 12 options are identified. This comprises improvements to the production process, material usage optimization, electricity and diesel consumption optimization, housekeeping, and the generation of as little solid waste and liquid waste as possible. The options are ranked based on weighted scale from technical, environmental and economical point of view. Total investment of RM 15,689,770 is required for this recommended implementation with 13 years of payback period and the second option is to install CCS whereby the investment needed is RM 413,916,667 with a payback period of 2.5 years which seems reasonable and more economical.

5.2 Recommendations for Further Study

In the future, the manufacturing of hydrogen could be improved by adopting a more sustainable method of producing hydrogen such as through electrolyzer or by changing the raw material, using biomethane as a raw material instead of natural gas. Biomethane is from renewable sources. Thus, it will have less impact in terms of carbon footprint when compared to using natural or light gas as the raw material.

Furthermore, because steam methane reformer procedures suffer from inefficiency, novel and updated catalytic processes are sought for more effective utilisation of precious natural resources. One such technology which is still under study is catalytic decomposition of methane (CDM) whereby methane can be directly thermally or thermo catalytically decomposed to carbon and hydrogen without emission of CO_2. CDM has advantage from its higher total energy output and CO_2-free reaction way.

Moreover, carbon dioxide produced can be sold to customers who may need carbon dioxide as their raw material. This also contributes to the greening of the production site. Not only, this reduce the emission but it also contributes to the revenue that the company generates. There are many demands for carbon dioxide in the market especially in food and beverages industry whereby carbon dioxide is used as dry ice to flash-freeze food or laboratory biological samples, carbonate beverages, make ice cream, solidify oil spills and stop ice sculptures and ice walls from melting.

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