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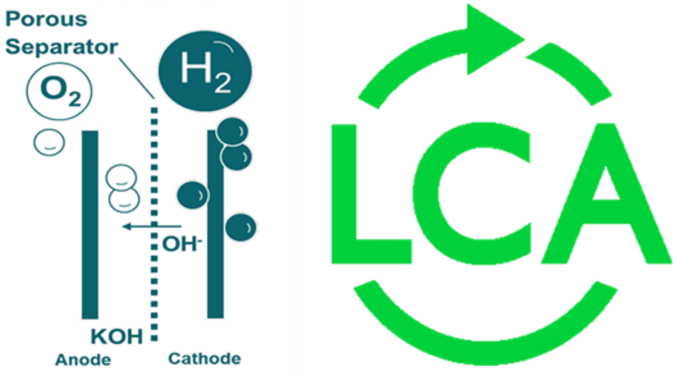
EXCHANGE MASTER PROGRAM

LIFE CYCLE ASSESSMENT OF A DEVELOPED DRY-TYPE OXYHYDROGEN (HHO) GENERATOR KIT APPLICATION FOR THE INTERNAL COMBUSTION ENGINES



[1], [2]

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Summary

This study performs a life cycle assessment (LCA) on a dry-type Oxyhydrogen/hydroxyl gas (HHO) generator kit designed explicitly for internal combustion engines. The upgraded version of the current dry-type HHO cells produces a blend of hydrogen and oxygen gases through water electrolysis. These gases are introduced into the engine's intake manifold to improve combustion efficiency and decrease fuel consumption and emissions.

The study assesses the ecological consequences of the generator kit over its life cycle, starting from the extraction of raw materials to the end of manufacturing (cradle-to-gate). This evaluation is conducted using OpenLCA software and the Ecoinvent 3.8 database. The assessment evaluates the environmental impact of specific industrial categories, such as greenhouse gas emissions, energy consumption, and resource depletion, using the ReCiPe midpoint (H) method.

The results offer valuable insights into environmental performance, explicitly indicating potential advantages, disadvantages, areas of concern, and crucial stages during the life cycle. The current work enhances our understanding of the environmental consequences of adopting the generator kit and emphasizes the importance of a holistic view in sustainability evaluation.

Preface

This thesis showcases the findings of a master's research project between August 2023 and December 2023 under the guidance of internal and external supervisors. The study aims to do a thorough Life Cycle Assessment of an advanced Dry-Type HHO generator kit designed for Internal Combustion Engines. The objective was to assess the environmental effects of the generator kit during its entire life cycle, employing the LCA approach and the ReCiPe midpoint (H) method to evaluate environmental consequences. The project encountered difficulties in the availability and quality of data, but it offered great opportunities for learning in Life Cycle Assessment (LCA) methodology and data analysis. The researcher extends gratitude to the supervisors and anticipates that the thesis will contribute to the understanding and use of LCA (Life Cycle Assessment) in the generation of HHO gas. The thesis aims to provide valuable insights into this process's environmental performance and sustainability.

Porsgrunn, 30/11/2023

MIRINCHIGE BUDDHIKA DASUN KAUSHALYA SIRIWARDENA

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Nomenclature

CF	Characterization Factor
CO_2	Carbon Dioxide
CO	Carbon Monoxide
N_2O	Nitroxide
ECU	Electronic Control Unit
EF	Environmental Footprint
EFI	Electronic Fuel Injection
GHG	Greenhouse Gas
HHO	Hydroxyl/Oxyhydrogen
H_2SO_4	Sulfuric Acid
IAM	Impact Assessment Method
ICE	Internal Combustion Engine
ILCD	International Life Cycle Data
ISO	International Organization for Standardization
KOH	Potassium Hydroxide
LCA	Life Cycle Assessment
LCEP	Life Cycle Environmental Performance
LCI	Life Cycle Inventory
OEF	Organization Environmental Footprint
PEF	Product Environmental Footprint
PEFCR	The Product Environmental Footprint Category Rules
PLCA	Product Life Cycle Assessment
PM	Particulate Matter
SMAA	Stochastic Multi-Attribute Analysis

1 Introduction

The dry-type Oxyhydrogen (HHO) generator, known as a Brown's Gas generator, is precisely engineered to generate a mixture of hydrogen and oxygen gases through water electrolysis without a liquid electrolyte solution[3]. The type of gas, such as brown, green, and blue, depends on the energy source used to generate HHO gas[3]. This technique aims to enhance combustion efficiency and minimize fuel consumption and emissions in internal combustion engines (ICE) by injecting HHO gas into the intake manifold. The environmental consequences of hydrogen-based power generation are contingent upon the technologies and methodologies utilized, even though hydrogen can be obtained from many sources. Nevertheless, the ecological ramifications of producing the HHO generator unit have not been thoroughly investigated. This thesis seeks to fill this void by assessing the manufactured dry-type HHO generator kit's environmental consequences throughout its life cycle, offering valuable perspectives on its sustainability and ecological efficacy.

Life cycle assessment (LCA) is a method to evaluate the environmental impacts of a product or system throughout its life cycle, from raw material extraction to end-of-life disposal or recycling[4]. LCA can help identify the hotspots of environmental burdens, compare different alternatives, and support decision-making for sustainability. Applying the LCA helps assess the environmental performance by reducing carbon emissions from hydrogen-based power generation, which has been considered a potential solution to reduce greenhouse gas emissions from conventional fossil fuels as a hybrid method.

1.1 Aim of the research

The primary aim of this study is to evaluate the environmental impacts associated with the developed dry-type HHO generator kit across its entire life cycle, spanning from raw material extraction to end-of-production (Cradle to Gate). An extensive literature review has been conducted to achieve a comprehensive analysis, examining previous studies on several types of HHO generators utilizing electrolysis technology and applying LCA methodology in assessing environmental impacts.

1.2 Functional unit

The functional unit is defined as producing one HHO generator kit (generator unit and gas separator) with a capacity of 100cc and its coupling with a 100 mL gasoline ICE for 5,000 km of driving. The impact assessment method is ReCiPe midpoint (H), which evaluates the environmental impacts in 18 categories, such as climate change, ozone depletion, human toxicity, and fossil depletion.

The literature review identifies critical parameters and variables to ensure a robust analysis using the openLCA software with the Ecoinvent 3.8 database. Specifically, this research focuses on the developed dry-type HHO generator kit and its manufacturing process up to the end of the gate. The evaluation aims to determine the environmental impact of selected categories based on the chosen impact assessment method, which includes greenhouse gas emissions, energy consumption, and resource depletion. These categories will be assessed using the ReCiPe midpoint (H) method.

The findings of this life cycle assessment will provide valuable insights into the environmental performance of the developed dry-type HHO generator kit, enabling us to ascertain its suitability for coupling with internal combustion engines. The analysis will unveil the potential benefits and drawbacks of using this technology. Furthermore, identifying environmental hotspots and critical life cycle stages will allow for developing targeted improvement strategies.

By quantifying the ecological and environmental impacts, this research will contribute to a better understanding of the environmental implications of adopting the developed dry-type HHO generator kit in internal combustion engines. The outcomes of this study will enable stakeholders to make informed decisions regarding implementing this technology. Additionally, this research emphasizes the significance of considering life cycle perspectives when assessing the sustainability of emerging technologies.

The data sources and assumptions for the inventory analysis are described in the following chapters. The results and discussion of the impact assessment and the sensitivity analysis are presented in the later chapters. The main conclusions are summarized in the final chapter.

1.3 The objective of the research

Therefore, this research aims to conduct a life cycle assessment (LCA) of the developed dry-type HHO generator kit, a final product applicable to internal combustion engines. The dry-type HHO generator kit represents an improved version of existing dry-type HHO cells, capable of producing a mixture of hydrogen and oxygen gas (HHO) through water electrolysis and injecting it into the intake manifold of an internal combustion engine. Using HHO gas can enhance combustion efficiency, reduce fuel consumption, and mitigate engine emissions.

2 Literature Review

The literature review chapter in this research report evaluates the environmental impacts of a developed dry-type HHO generator kit throughout its life cycle. It begins with an extensive review of previous studies on HHO generators and the application of life cycle assessment (LCA) methodology. The aim is to identify critical parameters and variables for a comprehensive analysis using the openLCA with Ecoinvent 3.8 database. The evaluation assesses categories such as greenhouse gas emissions, energy consumption, and resource depletion using the ReCiPe midpoint (H) method. The results provide insights into the environmental performance of the kit, identifying hotspots and critical stages. This research contributes to understanding the ecological implications of implementing the dry-type HHO generator kit in internal combustion engines, allowing stakeholders to make informed decisions. It also emphasizes the importance of considering life cycle perspectives in assessing the sustainability of emerging technologies.

2.1 Introduction

The topic of LCA application to the developed dry-type HHO generator kit is a device that produces HHO gas from water electrolysis and can be used to supplement the fuel of internal combustion engines[3], [5]. The literature review helps to measure the environmental impacts of the developed dry-type HHO generator kit in the manufacturing process before its integration with internal combustion engines, following a selected impact assessment method. It also provides the theoretical and methodological basis for the study, which aims to conduct a life cycle assessment (LCA) of the developed dry-type HHO generator kit and its application.

2.2 Internal Combustion Engines and Hybrid systems

Due to their impressive power output and dependable performance, internal combustion engines (ICEs) have long been relied upon for transportation and power generation. However, the emissions produced by ICEs, such as nitrogen oxides (NOx) and particulate matter (PM), have raised concerns regarding air pollution and its detrimental effects on human health.[6] Researchers and developers have focused on hydrogen as a potential fuel or alternative to traditional fossil fuels in ICEs to address these challenges. Emissions can be significantly reduced by incorporating hydrogen into combustion while enhancing engine efficiency and performance.

One innovative approach that has emerged involves the integration of HHO generators with internal combustion engines. These hybrid systems utilise HHO generators to produce hydrogen on demand, which is then supplied to the engine alongside gasoline fuel. By introducing hydrogen into the combustion mixture, engine efficiency and emissions can be reduced, and overall fuel economy can be increased.[7] As illustrated by Table 2.1, according to the past research data below,

Table 2. 1: Efficiency development cases by applying HHO gas with IC engine [8]

Case	Type of case	Effect	Amount (%)	Catalyst	Concentration (g/L)
1	Thermal efficiency	Increased	10	NaOH	6
	Fuel consumption	Reduced	34	KOH	4
	Concentration of NO_x, CO, HC	Reduced	14		
2	Thermal efficiency	Increased	10.26	NaOH	4
	Fuel consumption	Reduced	6.35		
	Concentration of NO_x, CO, HC	Reduced	4		

Using HHO generators coupled with internal combustion engines represents a promising avenue for research and development. By harnessing the cleaner-burning properties and higher combustion efficiency of hydrogen, these systems have the potential to revolutionise the way we power vehicles and generate electricity. Through ongoing advancements in this field, we can strive towards a greener and more sustainable future, where the harmful impacts of conventional ICEs are mitigated, and air quality is significantly improved.

2.3 Hydroxyl (HHO) gas generation

Hydrogen, the most abundant element globally, is vital in various power generation sources. Notably, the sun serves as the primary power supply for our planet, and through different utilisation methods, energy is derived from these sources. Fossil fuels, formed deep within the Earth's layers due to intense pressure and heat acting on ancient organic matter, have been extensively exploited, resulting in rapid depletion. Consequently, they are classified as non-renewable energy sources. It is a significant energy resource in most countries, including developing countries. As a result of utilisation, the combustion of fossil fuels releases greenhouse gases in substantial amounts, contributing to the pressing issue of global warming. Researchers are actively seeking innovative and sustainable alternatives to reduce emissions to combat this.

In the pursuit of renewable energy solutions, hydrogen has emerged as a prominent contender. It is a renewable energy source that is currently trending and holds great potential. Several technologies are utilised to generate hydrogen, each with benefits and applications. These are illustrated in Table 2.2 below,

Table 2. 2: Types of Technologies Utilizing the Generation of Hydrogen

Technology	Description
Steam-methane reforming (SMR)	• The widely employed method utilizes natural gas and water to produce hydrogen. • It is cost-effective and constitutes the most common source of industrial hydrogen, accounting for 50% of global production.

Partial oxidation	- It is derived from heavier hydrocarbons like oil and coal through partial oxidation. - The process contributes to approximately 30% of the world's hydrogen production.
Coal gasification	- By converting coal into a mixture of gases, including hydrogen, coal gasification represents about 18% of global hydrogen production. - Offers an alternative pathway for utilizing coal reserves while minimizing environmental impact.
Electrolysis	- Utilize electricity to split water into hydrogen and oxygen. - It is more expensive than other methods but is heavily used in applications because of hydrogen purity.

In addition to these main methods, other avenues are being explored for hydrogen production, including biomass gasification, methane pyrolysis, solar-thermal, and photochemical processes. While these methods are less common and experimental, they promise future advancements in hydrogen generation.

The primary focus of the content revolves around the process of water splitting, also known as electrolysis, as it relates to the research topic. It is essential to highlight the distinct types of hydrogen generated through various energy applications during production. This information can be effectively illustrated through Table 2.3, which provides a comprehensive breakdown of these hydrogen types. This categorisation aids in comprehending the different approaches to producing hydrogen and highlights the significance of electrolysis as a renewable and environmentally friendly method.

Table 2. 3: Types of Hydrogen

Type	Description
Green Hydrogen	- The cleanest form of hydrogen (does not release any climate pollutants) - Most are produced by an electrolyser, which uses electricity to split water into hydrogen and oxygen. - Created by using renewable energy (wind, solar, ocean energy)
Blue/Industrial Hydrogen	- It is produced using a process called 'steam methane reforming', which uses steam to separate hydrogen from natural gas. - Derived from fossil fuels, specifically natural gas, and captures some of the carbon emissions. - Produce greenhouse gases, but carbon capture and storage technologies capture and store those emissions.
Brown/Coal Hydrogen	- It is produced by coal gasification. It can also produce hydrogen using electrolysis powered by fossil fuels. - It is produced from coal and has the highest emissions and the gloomiest outlook for global warming. - Produces a lot of greenhouse gases into the atmosphere.

As the global community endeavours to transition towards a more sustainable energy landscape, the versatility and potential of hydrogen as a renewable energy source cannot be underestimated. Through continuous research and development efforts, hydrogen has the potential to play a pivotal role in meeting our energy demands while simultaneously addressing environmental concerns. Its clean and efficient characteristics render it an attractive option for powering diverse sectors, offering a pathway toward a greener and more sustainable future.

2.3.1 Process of Electrolysis

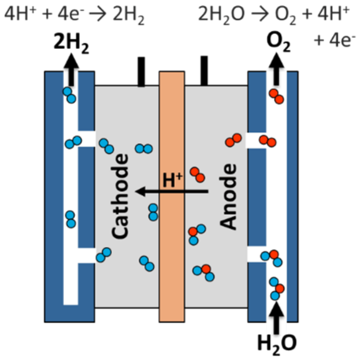


Figure 2. 1: Structure of the Simple Electrolyser [9]

Electrolysers are essential components in the electrolysis process, consisting of an anode, a cathode, and an electrolyte. Their functionality depends on the chosen electrolyte material and its conductive properties. Figure 2.4 can effectively demonstrate the impact of electrolyte selection on electrolyser efficiency. Electrolysis offers a sustainable method for producing carbon-free hydrogen using renewable or nuclear power sources. It involves using electricity to separate water into hydrogen and oxygen. Electrolysers come in different sizes, from small-scale decentralised units to more extensive facilities integrated with non-greenhouse-gas-emitting electricity generation methods.

In electrolysis, the anode and cathode have distinct roles. The anode, typically made of a metal or metal oxide, undergoes oxidation, releasing electrons into the circuit. The cathode, made of a conductive material, undergoes reduction and facilitates the desired chemical reactions by attracting electrons. The electrolyte, positioned between the anode and cathode, allows the movement of ions necessary for electrolysis.

2.3.2 Types of Electrolyser

In the quest for clean and sustainable energy solutions, electrolysis has emerged as a prominent method for hydrogen production. Electrolysers, the devices used in electrolysis, vary in design and operation based on the type of electrolyte material employed and the ionic species it conducts. Understanding each type of electrolyser is crucial in exploring their potential for generating hydrogen efficiently and sustainably. These equations capture the transformative process in which water undergoes decomposition, forming hydrogen and oxygen. Let us now explore these equations, unravelling the intricate chemical reactions driving the fascinating water-splitting phenomenon.

Equation (2.1) is the half-cell reaction of the anode.

$$2H_2O \rightarrow\ O_2 + 4H^+ + 4e^- \qquad (2.1)$$

Equation (2.2) is the half-cell reaction of the cathode.

$$4H^+ + 4e^- \rightarrow\ 2H_2 \qquad (2.2)$$

Equation (2.3) is the overall reaction of the cathode.

$$2H_2O\ +\ 4H^+ \rightarrow\ O_2 +\ 4H^+ +\ 2H_2 \qquad (2.3)$$

Furthermore, various electrolysers and their unique characteristics highlight their advantages, limitations, and potential applications. By examining alkaline, solid oxide, and polymer electrolysers, we can gain insights into the diverse approaches and technologies driving the advancement of hydrogen generation through electrolysis. Let us now explore these electrolyser types in detail, uncovering their inner workings and role in shaping the future of clean energy production. This information can be effectively illustrated through the utilisation of Table 2.5 below,

Table 2. 4: Types of Electrolyser in Hydrogen Generation[3], [10]–[12]

Type of Electrolyzer	**Description**
Polymer Electrolyte Membrane (PEM)	The electrolyte is a solid, speciality plastic material. Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons). Oxygen gas is formed from the anode side, and the hydrogen ions selectively move across the PEM to the cathode (flow of the electrons through an external circuit). Must operate temperature at 70°–90°C. Hydrogen ions combine with electrons at the cathode, forming Hydrogen gas.
Alkaline	Operate via hydroxide ions (OH-) transport through the electrolyte from the cathode to the anode with hydrogen generated. Sodium or Potassium hydroxide is used as a liquid alkaline solution. Must operate temperature at less than 100°C.

	Commercially available for many years but mostly available on a lab scale.
Solid Oxide	Uses a solid ceramic material as the electrolyte that selectively conducts negatively charged oxygen ions. Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. The oxygen ions pass through the solid ceramic membrane, react at the anode to form oxygen gas and generate electrons for the external circuit. Must operate at temperatures high enough to function appropriately at 700°–800°C.

The literature content further delves into an in-depth exploration of the exclusive implementation of alkaline electrolyser technology, with a particular focus on applying the developed dry-type alkaline electrolysers.

2.3.3 Application of Faraday's law

Faraday's law of electrolysis is a fundamental principle that relates the amount of substance produced or consumed during an electrolytic reaction to the amount of electric charge passed through the system[5]. This law applies to alkaline hydrogen electrolysis, which involves the generation of hydroxyl gas through the electrolysis of water in an alkaline electrolyte[5]. Here, an electric current is passed through an electrolytic cell containing an alkaline solution, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH), consisting of cathode and anode electrodes[5]. The cathode is the negative electrode, where hydrogen gas is produced, while the anode is the positive electrode, where oxygen gas is generated[5].

According to Faraday's law, the amount of hydrogen gas produced during alkaline hydrogen electrolysis can be determined by the quantity of electric charge passed through the cell. The law states that the mass of a substance produced or consumed at an electrode is directly proportional to the number of moles of electrons transferred in the redox reaction and the molar group of the essence[13]. Faraday's law can be expressed as,

Equation (2.4) is the Faraday equation, which is used to calculate the mass of the substance.

$$m = \frac{(Q \times M)}{(n \times F)} = \frac{(I \times t)}{(n \times F)} \qquad (2.4)$$

In the given equation, m represents the mass of the substance produced in grams (g), Q represents total electric charge measured in coulomb (C), M represents the molar mass of the substance measured in grams per mole (g/mol), I represent current measured in ampere (A), t represents time measured in seconds (s), n represents no. of electrons, and F represents Faraday's constant.

In the context of alkaline hydrogen electrolysis, considering ampere and time, the substance of interest is hydroxyl gas (H_2), and the number of electrons involved in its production is 2. The Faraday's constant represents the charge of one electron mole and equals 6,485 C/mol [14]. Faraday's law allows us to calculate the amount of hydrogen gas generated by measuring the applied current and the time over which electrolysis occurs. This information is essential for determining the efficiency and rate of hydrogen production in alkaline hydrogen electrolysis systems.

2.3.4 Selection of Desired Electrodes

The selection of electrodes is crucial for the performance and lifespan of an HHO generator. Carbon Nanotube plates are commonly used due to their high oxidation resistance, surface area, and low internal resistance compared with graphite and stainless steel. [15] Metals like titanium and platinum are the most efficient electrodes, but their high cost makes them impractical for lab-scale HHO production. [16] Other affordable options are stainless steel, iron, and aluminium, although they can create toxins during electrolysis. [17] Figure 2.2 shows the Graphite Plates, 304 Stainless Steel, and Carbon Nanotube Plates.

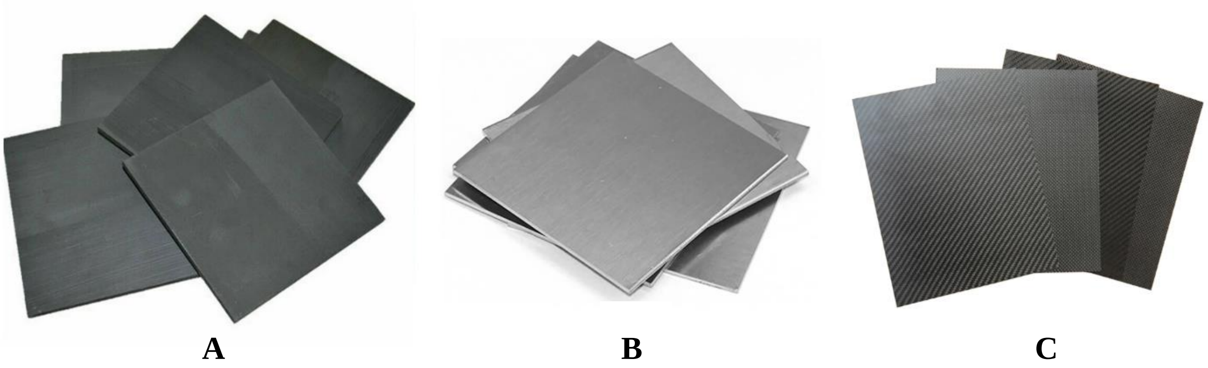


Figure 2. 2: Graphite Plates (A), 304 Stainless Steel (B), Carbon Nanotube Plates (C)

The goal of selecting the best electrode for a project is to conduct experiments and compare the results. In this case, carbon nanotube, graphite plate, and grades 304 stainless steel are being considered [18]. The purity and composition of the electrolyte and the operating conditions of the HHO generator also play a significant role in the quality of the generated gas.[19] Measuring the gas flow rate with a gas flow meter is essential to ensure proper combustion in the internal combustion engine and minimise emissions.

2.3.4.1 Advantages and Disadvantages of Different Electrode Materials

HHO generators use electrolysis to split water into its constituent elements, hydrogen and oxygen. Electrodes are an essential component of the HHO generator, and the choice of electrode material can significantly impact its performance. Some advantages and disadvantages of different electrode materials in HHO generators are presented in Table 2.7.

Table 2. 5: Advantages and Disadvantages of Different Electrode Materials [17]

Material	Advantage	Disadvantage
Stainless steel electrodes	are widely available and relatively inexpensive. Have a long lifespan and are resistant to corrosion.	Require a higher voltage to produce the same amount of HHO gas as other materials. Reduce efficiency due to scaling and contamination.
Carbon nanotube electrodes	Promotes excellent electrical conductivity by faster reaction kinetics. The high surface area provides more active sites for electrochemical reactions. Long-term stability and durability of the electrodes because of the corrosion.	Increase the overall cost of manufacturing because of expensiveness. The controlled synthesis with desired properties occurs in a challenging and complex production. the risk of contamination from impurities or defects during the production
Titanium electrodes	Highly durable and resistant to corrosion. Requires a lower voltage than stainless steel electrodes and is more efficient.	It is more expensive than stainless steel electrodes and not widely available. It needs to be handled carefully due to its brittleness and propensity to cracking.
Graphite electrodes	Highly conductive and efficient. It is resistant to corrosion and has a long lifespan.	Difficult to find due to relatively expensive. Requires a higher voltage than titanium electrodes.
Platinum electrodes	The lowest voltage is required to produce HHO gas due to the highest efficiency of all electrode materials. Highly durable and resistant to corrosion.	It is costly and not practical for most HHO generator applications.

2.3.5 Electrolyte

Different types of electrolysers employ various electrolyte materials, including alkaline, acidic, solid oxide, and polymer electrolytes[13]. Alkaline electrolysers employ a potassium hydroxide (KOH) or sodium hydroxide (NaOH) solution as the electrolyte, while acidic electrolysers employ sulfuric acid (H_2SO_4) or phosphoric acid (H_3PO_4)[13]. Solid oxide electrolysers employ solid ceramic electrolytes, such as yttria-stabilised zirconia (YSZ), while polymer electrolysers use ion-conductive polymers like Nafion[13].

The choice of electrolyte material is influenced by operating temperature, electrolysis efficiency, durability, and cost. Each electrolyte type possesses unique characteristics and performance capabilities, making them suitable for specific applications within electrolysis[20].

2.3.5.1 Selection of Electrolyte

The selection of electrolytes is also critical for the performance of the HHO generator. Potassium hydroxide (KOH) is a commonly used electrolyte in HHO generators due to its high solubility, low cost, and high conductivity with low metal oxidation compared to Sodium hydroxide (NaOH) [21], [22]. It can also operate at various temperatures and produce a high gas volume. Additionally, KOH has a low vapour pressure, reducing gas leakage risk. [23].

Other potential electrolytes for HHO generators include NaOH (sodium hydroxide), LiOH (lithium hydroxide), and NaCl (sodium chloride). NaOH and LiOH have comparable properties to KOH, while NaCl is non-toxic and widely available. [17], [23] Sodium chloride (NaCl) is a commonly available electrolyte with a lower conductivity than other electrolytes, such as sulfuric acid or potassium hydroxide. [23] As a result, it may require a higher voltage to generate the same amount of gas. As well as, during the electrolysis of NaCl, chlorine gas (Cl_2) is produced at the anode. Chlorine gas is highly toxic and corrosive [24]. Therefore, it is not commonly used in HHO generators or other electrolysis applications where the gas must be used for combustion or other purposes [7], [22].

Instead, other safer and more efficient electrolytes, such as potassium hydroxide or sodium hydroxide, are often used. As well as the concentration of the electrolyte can also affect the gas generation rate and the quality of the generating gas. [17] It is important to note that the electrolytes used in HHO generators should be managed with care due to their corrosive and hazardous nature [21].

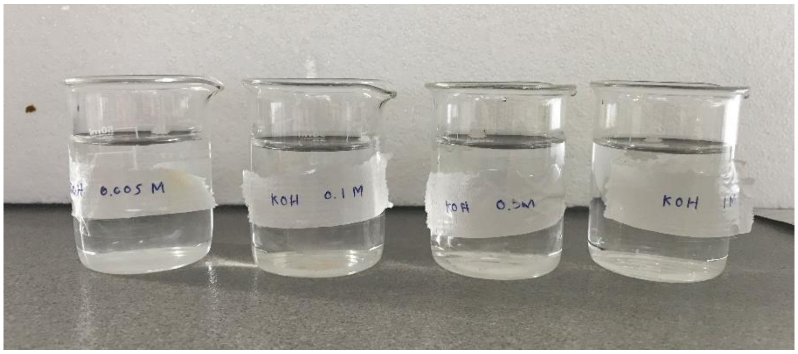


Figure 2. 3: Different Concentrations of KOH Solution

The concentration of the electrolyte solution can significantly impact the performance of HHO generators. Maintaining a critical range of solution concentration is essential to achieve optimum levels of HHO gas generation. As a result, 0.1M is suitable for holding the concentration of KOH electrolyte with distilled water [25], [26]. Figure 2.3 illustrates solutions the different concentrations of KOH solutions. This process involves adjusting the attention of the electrolyte solution and monitoring the output of the HHO generator to identify the concentration range that yields the highest gas generation efficiency. Additionally, it is worth noting that the optimum electrolyte concentration can vary depending on the type of electrolyte used and the specific design of the HHO generator. Therefore, experiments are required to identify the optimal concentration for each system.

2.3.6 Potential Synergy with Renewable Energy Power Generation

Hydrogen production through electrolysis offers a promising opportunity to synergize with dynamic and intermittent power generation, a characteristic of various renewable energy technologies. While the cost of wind power has been declining, the inherent variability of wind poses a challenge to its effective utilization [27]. Similarly, solar power farms also produce high-density electricity, especially in areas near the equator with the highest solar energy potential on Earth [28], [29]. These regions receive more direct sunlight throughout the year, resulting in higher solar irradiation levels [28]. Therefore, integrating hydrogen fuel and electric power generation at wind and solar farms provides the flexibility to adjust production to align with resource availability, operational needs, and market dynamics. Furthermore, during periods of surplus electricity production from wind and solar farms, rather than curtailment, the excess electricity can be utilized for hydrogen production via electrolysis [13].

The potential for constructive collaboration between renewable energy power generation and HHO gas production through electrolysis presents a compelling avenue for enhancing the efficiency and sustainability of energy systems. HHO gas generation via electrolysis can be integrated to address critical challenges and capitalize on opportunities by leveraging dynamic and intermittent power generation from renewable sources such as wind and solar [28]. The current grid electricity, generated using technologies associated with greenhouse gas emissions and high energy consumption, is not the most suitable source for electrolysis. However, leveraging a grid mix incorporating electricity from renewable or nuclear energy technologies can potentially overcome these limitations for hydrogen production through electrolysis. Table 2. 6 illustrates the benefits of applying constructive collaboration to electrolysis.

Table 2. 7: Benefits of Applying Constructive Collaboration to Electrolysis.

Impact	Description
Optimizing Energy Production	HHO gas generation through electrolysis can effectively complement wind and solar energy by allowing flexible adjustment of HHO gas production to align with available resources, contributing to a more balanced and reliable energy supply [30].
Mitigating Surplus Energy	Surplus energy from renewable sources can be channelled into electrolysis for HHO gas generation during excess electricity production, mitigating waste and providing a valuable avenue for energy storage, grid stability, and resilience [31].
Green Hydrogen Production	Renewable energy utilization for electrolysis ensures the production of green hydrogen, aligning with decarbonization and sustainable energy transition objectives [31].

Grid Integration and Demand Response	Integrating HHO gas generation with renewable energy facilitates enhanced grid integration and demand response capabilities, efficiently matching HHO gas production with system operational needs and market dynamics [31].
Technological Advancements and Cost Reduction	Ongoing efforts to reduce the cost of renewable-based electricity production and enhance the efficiency of electrolysis technologies further amplify the potential for constructive collaboration, with advancements in electrolysis technology and renewable energy systems driving down costs and improving overall system performance [5].

2.3.7 HHO Generator performance

The performance of HHO generators is typically evaluated based on several parameters, including input power, gas generation rate, specific energy input, generator efficiency, the temperature of the HHO generator, and quality [32] of generating gas. Those key factors are,

2.3.7.1 Input power

The input power is required to generate a specific amount of HHO gas. The input power depends on various factors, such as the size of the HHO generator, the type of electrodes used, and the electrolyte used.[32], [33] Electric energy is required to produce HHO gas through water splitting. As a result, the magnitude of generator input power should be known. The formula for calculating the total input power of a cell is given below.

Equation (2.5) is used for the power calculation of input and output.

$$P = \mathrm{V} \times \mathrm{I} \tag{2.5}$$

In the given equation, P represents power measured in watts (W), V represents voltage measured in volts (V), and I represents electrical current measured in amperes (A).

2.3.7.2 Gas Generation rate

The gas generation rate in an HHO generator depends on several factors, including the size and design of the generator, the type and concentration of the electrolyte solution, the applied voltage and current, and the temperature and pressure of the reaction environment. [26], [32] Typically, the gas generation rate is proportional to the current applied to the electrolytic cell. According to the Faraday law, the gas generation rate is inverse to the production rate of HHO gas. However, excessive current can cause overheating and damage to the generator cores because of the internal heat generation by internal resistance [26]. As a result, the gas generation rate and quality are lacking because of the electrode's resistance enhancement from the heat [26]. Moreover, the gas generation rate also depends on the type of electrolyte solution used.[34] The amount of gas a generator produces depends on its size and design. Larger generators with more electrodes and larger surface areas can produce more gas than smaller generators [7], [9].

2.3.7.3 Temperature of the generator

Temperature is a crucial factor that significantly affects the performance and efficiency of alkaline HHO generators. However, elevated temperatures can also lead to electrode corrosion and reduced generator lifespan. Therefore, it is essential to maintain an optimal temperature for the HHO generator to balance the gas generation rate and generator lifespan [26]. Here is a valuable introduction explaining the effects of temperature on alkaline HHO generators. It is illustrated by Table 2.7 according to the past research data below,

Table 2. 8: Parameters Change with Temperature

Parameter	Condition of the operation
Optimal Operating Range	Operate within a specific temperature range of between 50 to 80 degrees Celsius, [19]
Electrolyte Conductivity	Temperature is directly influencing the conductivity of the solution by temperature increasing [19] such as, • solution becoming more conductivity • Allowing for better ion mobility • Enhanced electrolysis efficiency
Reaction Rate	Higher temperatures result in faster reaction rates, increasing hydroxyl gas production [27].

	Lower temperatures can slow the reaction by reducing gas output [27].
Energy Efficiency	Higher temperatures can improve energy efficiency by reducing internal resistance and voltage drop across the electrolyte because of better electrical conductivity and reduced energy loss [35].
Safety Considerations	Extreme temperatures can lead to the generation of hazardous gases ($Cl_{2(g)}$) from the electrolyte solution [36]. It is essential to monitor and control temperatures to prevent such safety risks [36].

2.3.7.4 Quality of the generating gas

Several factors come into play to achieve optimal HHO gas quality through an alkaline electrolyser. These factors include the electrolytic cell's design and size and the power supply employed. High-quality electrode and electrolyte materials ensure consistent gas purity and minimise impurities [37]. Thus, the electrode material also dramatically impacts the generation of the HHO gas, mainly because of the conductivity and metal oxidation resistance.

The HHO gas produced should adhere to specific standards appropriate for its intended application. This includes maintaining the correct stoichiometric ratio of hydrogen and oxygen gases. It is equally important to ensure that the gas is free from any impurities or moisture that could potentially compromise combustion and cause damage to the engine [37]. Furthermore, the gas flow meter is commonly employed to measure the generated gas volume[38] accurately. Click or tap here to enter text. Finally, it is possible to develop HHO gas at an optimum level of quality by implementing these measures in conjunction with an alkaline electrolyser.

2.3.8 Reasons for Considering This Pathway

When considering the pathway for hydrogen production, electrolysis emerges as a critical contender in achieving the Hydrogen Energy Earth shot goal. The aim is to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram within a decade [27]. Electrolysis offers the potential for zero greenhouse gas emissions in hydrogen production, with the caveat that the source of the electricity used must be considered[10], [39]. This includes cost, efficiency, and the emissions associated with electricity generation. It's important to note that in many regions, the current power grid may not be optimal for providing the electricity needed for electrolysis due to greenhouse gas emissions and the inefficiency of the electricity generation process [12].

2.4 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a generally accepted approach used to assess the environmental consequences of products, supply chains, production processes, and consumer systems [40], [41]. LCA consists of four phases according to ISO 14040 to 14044 standards, which include the analysis of Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA)[40], [41]. In the interpretation phase, key elements are determined by analyzing the results of the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA)[40]. This analysis includes assessing the data's comprehensiveness, sensitivity, and coherence, drawing conclusions, acknowledging limitations, and providing recommendations. Figure 2.4 graphically shows the process stages of the LCA.

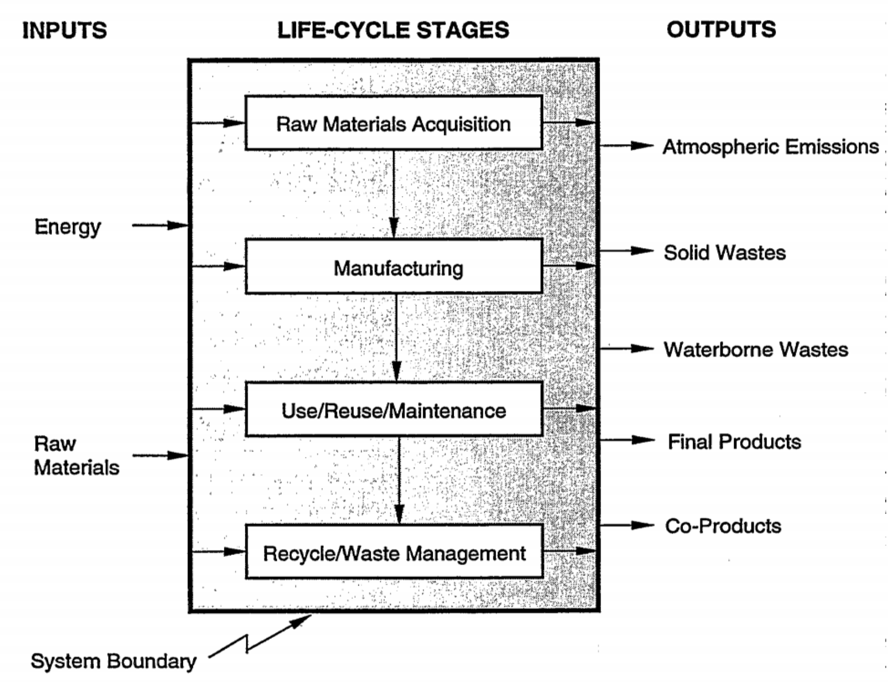


Figure 2. 4: Process stages of an LCA[41]

The European Commission has implemented efforts to establish a standardized method for evaluating environmental effects, referred to as the Environmental Footprint (EF), which includes both Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF)[40], [41]. The interpretation phase of Life Cycle Assessment (LCA) holds growing significance as it directly affects decision-making in policy contexts and possesses the capacity to influence entire sectors or societies[40]. The European Union has recently made efforts, such as implementing the Building the Single Market for Green Products program, to emphasize the need to interpret Cycle Assessment (LCA) data appropriately 40].

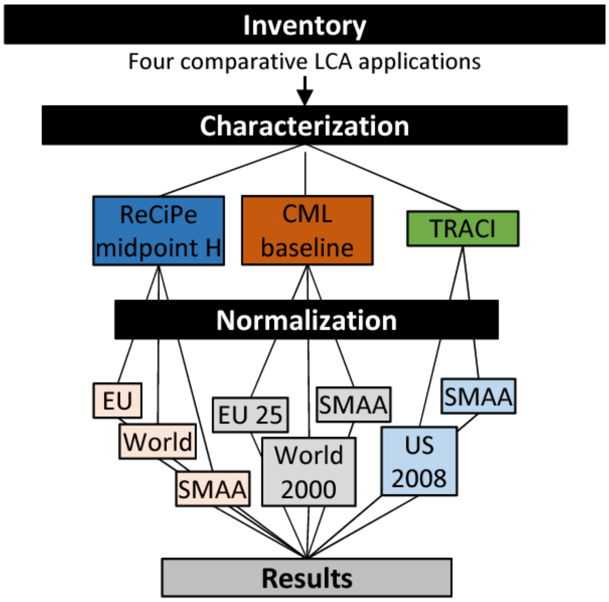


Figure 2. 5: Schematic of the methodology evaluating the effects of normalization approaches in three LCIA methods [42]

Many authors have emphasized the significance of interpretation in LCA research and provided suggestions or recommendations based on the study's objective [40]. While some initially saw interpretation as a less significant subject, others emphasized the need for meticulous interpretation of findings to improve the quality of outcomes and facilitate the development of sustainable decision-making processes [40]. Several authors have suggested innovative methods, such as stochastic multi-attribute analysis (SMAA), presented in Figure 2.5, to assist in interpretation and decision-making [40]. The importance of sensitivity analysis in enhancing the reliability of results and developing sector-specific guidelines has been emphasized. A structured approach that includes the life cycle impact assessment (LCIA) phase has been suggested, focusing on systematically analyzing the sensitivity of impact assessment models [41].

2.4.1 Stages of LCA in its lifespan

LCAs are a fundamental element of various methodologies used to assess sustainability. The methods include risk analysis, exposure assessment, life cycle costing, and techno-economic evaluation. What sets LCA apart from other tools is its comprehensive assessment of the environmental consequences, including the entire technological life cycle of a product or process. The life cycle of a product is determined by many stages throughout its existence. Table 2. 9 illustrates the process stages of the LCA.

Table 2. 10: Process stages of the LCA

Process Stage	Description

Raw Material Extraction	It begins with the extraction of raw materials from the earth's sources, which involves activities such as mining, logging, farming, or harvesting, and it has significant implications for land use, energy consumption, water usage, and biodiversity[43].
Product	The stage that involves manufacturing procedures, energy consumption, emissions, waste creation, and use of chemicals or other resources is known as the processing and manufacturing phase, where the raw materials are transformed into the finished product[43]. Gaining a comprehensive understanding of the ecological consequences of manufacturing is crucial for discovering potential avenues to enhance efficacy and mitigate environmental loads[43].
Distribution & Transportation	Goods are conveyed from production plants to distribution hubs, vendors, and eventually to end-users[43]. The transportation phase encompasses energy consumption, vehicle emissions, packaging materials, and the corresponding environmental consequences, including air pollution, greenhouse gas emissions, and traffic congestion[43].
Use Phase	During the utilization phase, the product is employed for its designated purpose. This stage includes energy use, water utilisation maintenance, durability, and any related effects on human health and the environment[43]. Understanding how items are utilized yields valuable insights for identifying opportunities to enhance efficiency and optimize resources[43].
End-of-Life Management	Once a product reaches the point where it can no longer be used effectively, it enters the end-of-life phase[43]. Mainly involves either disposing of the product, recycling it, or finding a way to reuse it. It encompasses the management of trash, the establishment of recycling facilities, the recovery of materials, and the possible effects on ecosystems and human well-being[43]. Implementing efficient strategies for managing the end-of-life phase can minimize waste and advance the concepts of a circular economy[43].

LCA is a complete method for assessing the environmental consequences of products and systems by thoroughly analyzing all stages of a product's life cycle, from the extraction of raw materials to the management of its disposal at the end of its useful life[43]. This comprehension facilitates well-informed decision-making, environmentally friendly design, and resource-efficient techniques across the life cycle[43].

2.4.1.1 Goal and Scope Definition

During this stage of the LCA, the cooperation between the client and the LCA practitioner is vital in determining the essential inquiries the assessment will tackle and the methodology employed for the study.

- A distinct research goal is defined.
  It includes the intended aim of the project and the intended use of the results. The main objective is to assess a product's or process's ecological efficiency and to compare several alternatives[44]. Nevertheless, the act of comparison necessitates standardization. Every choice is associated with a pre-established functional unit that determines the service offered and establishes a quantitative foundation for the study[44].
- Every option being compared transforms into a reference flow representing the identical functional unit.
  When comparing the impact of plastic and paper bags, it is not appropriate to directly compare them because they have different capacities, such as 5 and 10 litres, respectively. A standardized functional unit is created with 10 litres to speed up comparison. The comparative reference flows could involve, for example, comparing two plastic bags to 1 paper bag.
- Determine the system boundary.
  It specifies the exact inputs, processes, and emissions included in the analysis. The investigation is formulated to follow the research target, guaranteeing that no noteworthy circumstances potentially impacting the results are disregarded[44]. Excluding problematic data components with limited predicted impact is OK if these assumptions are acknowledged[44]. For example, while examining the life cycle of a cup of coffee, the analysis may focus on the transportation of coffee beans while neglecting the emissions linked to the construction of highways, as these roads are utilized by many other vehicles.

2.4.1.2 Life Cycle Inventory (LCI) Analysis

The LCI involves a comprehensive compilation of all resources used and emissions generated during the production of the reference flow for each product alternative, including the data collection process[44]. The LCA practitioner initially gathers primary data from the site in creating the LCI where the item is produced or used, which may include specific details such as the precise number of tissues used in a medical procedure[44]. Foreground data represents the variables directly indicating usage, though it does not encompass the entire life cycle[43]. LCA practitioners establish a connection between the number of tissues and the emissions across the whole supply chain by integrating foreground data on usage with background data from LCI databases[43], [44]. The background data, accumulated through extensive research over several decades, comprehensively document all inputs and emissions throughout various material and product supply chains[45]. Given the time-intensive nature of these investigations, utilizing LCI databases enhances existing knowledge[46]. These databases, such as Ecoinvent, are compiled by governmental and commercial entities and provide a wealth of information from meticulous research.

In complex projects, conservators and engineers collaborate to establish precise reference flows for each conservation item, gathering relevant data from manufacturers and practitioners and integrating it with contextual data from databases like ecoinvent[47]. Subsequently, an algorithm adjusts the magnitudes of the flows in the product system based on the quantities required to achieve the ultimate reference flow[48]. The product system may exhibit a high level of complexity, encompassing emissions occurring at every stage of the supply chain, such as converting wood into pulp, log transportation, truck fuel production, and manufacturing[48], [49]. The life cycle inventory represents a comprehensive and refined compilation of resource inputs and emissions[49].

2.4.1.3 Life Cycle Impact Assessment (LCIA)

This phase evaluates the environmental consequences of each flow in our life cycle inventory[48]. Multiple impact categories are in place to delineate the diverse ways our actions affect the environment and our well-being[46]. Examples of illustrative occurrences include global warming, depletion of the ozone layer, and ecotoxicity[48], and each flow is classified according to its distinct impact. Nitrous oxide (N_2O) serves as an example, being accountable for both the occurrence of global warming and the circumstance of ozone depletion. Afterwards, it is assigned a value or categorized according to its effectiveness for each impact form [48]. The word employed to denote this concept is a characterization factor (CF) expressed concerning an indicator substance. When evaluating the impact of global warming, we measure the carbon footprint compared to carbon dioxide[40]. Consequently, all gases that contribute to the greenhouse effect are measured and expressed in units of carbon dioxide equivalents ($CO_{2(eq)}$).

Characterization entails amalgamating models from various scientific fields, including environmental science, chemistry, physics, ecology, and toxicology[40], [41]. This integration aims to establish a causal relationship between an emission in a particular region and the subsequent worldwide physical changes and damages that ensue. It is crucial to ensure proper management of a treatment chemical discharged into wastewater, its transportation processes in rivers, its transformation or degradation, its interaction with aquatic life, and its potential harm caused by ecotoxicity[40]. The combination of these elements is commonly known as an LCIA technique.

The Recipe Midpoint H impact assessment method is essential to environmental impact assessment[40], [41]. This approach is utilized in the United States and was devised by the Environmental Protection Agency[40]. The comprehensive compilation of impact categories is provided in the case studies. The selection of impact categories for a survey is a decision that is impacted by the research's purpose and is typically determined through collaboration between the LCA practitioner and the client[40], [41]. This tailored strategy ensures that the study aligns with its unique focus and goals, hence enhancing the significance and applicability of the impact assessment's findings.

The outcomes derived from LCA often display variable units due to comparing choices across multiple sustainability indicators. Converting data across impact categories into relative units, such as a proportion of a person's average annual effects, or further assigning weights to the results to create a single score, can enable a more straightforward comparison of different product options[40], [41].

2.4.1.4 Interpreting LCI and LCIA Results

The LCA's interpretation phase examines information gathered from preceding stages, encompassing study objectives, quality assurance protocols, reporting criteria, findings, assumptions, and external participation [40]. The ISO 14040 to 14044 standards provide a framework for analyzing Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) data. These standards focus on identifying essential concerns and conducting thorough evaluations of completeness, sensitivity, and consistency checks.

The initial step of interpretation involves examining and organizing the findings from previous stages to identify essential factors, such as crucial contributors to LCIA results, relevant stages of the life cycle, processes and elementary flows, impact categories, and influential methodological choices, assumptions, and data utilized [47] which shows Figure 2.6. Completeness checks gauge the extent to which the inventory is fully accounted for, whereas sensitivity checks appraise the dependability of the results. Consistency checks guarantee the uniform implementation of assumptions, methodologies, and data throughout the investigation.

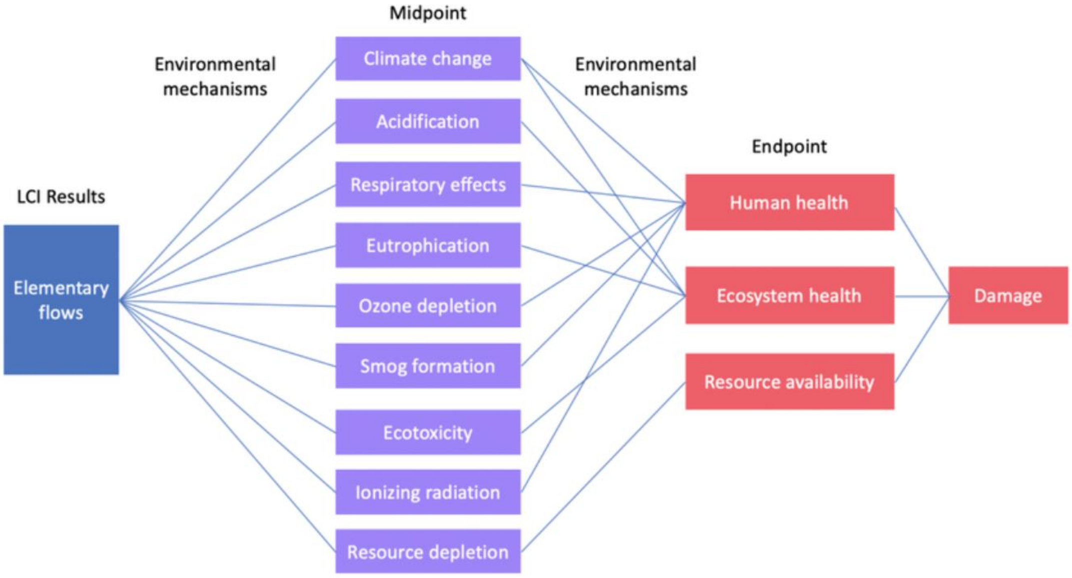


Figure 2. 6: Relationship between LCI results and environmental impact midpoints and endpoints [49]

Then, the final step of the interpretation phase is to combine the results of the previous steps, make conclusions, identify any limits, and create suggestions that align with the study's objectives and intended uses [47]. The practical workflow follows an iterative process to obtain reliable results and suggestions based on the principles outlined in ISO 14040 to 14044 [40]. Considering this as a supplementary implementation of the standards specified in these publications rather than a replacement is essential.

2.4.2 Assessing Environmental Impact from the LCA

The LCA serves as a complete instrument for measuring the resource requirements, particularly for water or energy, and the pollutants, primarily carbon emissions, produced at each stage of a product's life cycle[44, ultimately leading to a full assessment of its environmental impact. For example, while doing an LCA of a solvent, it is essential to examine the emissions that occur during its manufacturing from petrochemical or biological feedstocks and the emissions associated with packing and transportation to distribution sites. In addition, LCA expands its scope to include emissions throughout the storage process, transportation to the place of consumption, potential evaporation during usage, and different end-of-life choices like recycling or disposal[44].

This approach offers a comprehensive analysis of the sources of emissions, providing valuable insights into possible improvements for products and processes at every stage to reduce environmental and social impacts[44]. Instead of exclusively concentrating on the physical product, LCA acknowledges the more comprehensive technological framework in which things function, revealing the frequently neglected indirect factors contributing to environmental damage.

2.4.3 Identifying Key Issues

It is crucial to pinpoint the critical issues in the initial stages of interpreting LCA results, which then allows for a thorough evaluation of the study's robustness through completeness, consistency, and sensitivity checks [49]. Here, it provides an overview of the methodological framework of hotspot analysis, as developed in the United Nations Environment Programme/ (UNEP/SETAC) Life Cycle Initiative - Flagship Project and tested in the EF pilot phase [40], [41]. Hotspot analysis is considered a standalone subject in the UNEP/SETAC LCI. At the same time, the EF pilot phase focuses on interpreting screening study results of an average or representative product in the EU Environmental Footprint [40], [41].

2.4.4 Hotspot Analysis in the UNEP/SETAC Life Cycle Initiative

The benefits of hotspot analysis include ensuring focus on priority issues according to UNEP/SETAC, such as waste, water, and materials of concern, identifying the appropriate life cycle stage of material acquisition, manufacturing, use, end of life, and targeting the right actors of producers, manufacturers, suppliers, retailers, customers to evaluate, influence, and implement solutions [41], [42]. Additionally, hotspot analysis helps understand the implications of trade-offs and effectively allocate resources, such as time and money, to actions [40].

2.4.5 Hotspot Analysis in the Environmental Footprint Pilot Phase

In the Environmental Footprint (EF) pilot phase, the main objectives were to test the process for developing product and sector-specific rules, evaluate different approaches to verification, and assess communication methods for conveying life cycle environmental performance (LCEP) to business partners, consumers, and other company stakeholders [40], [41], [47].

The hotspot analysis in the EF context aims to identify the most relevant impact categories, life cycle stages, processes, and elementary flows to guide and focus attention on improving the environmental performance of a product or an organization [40]. This is crucial for decision-making regarding which life cycle stages, processes, and elementary flows are considered hotspots (> 50% contribution) and which are relevant (> 80% contribution) [40], [41]. Hotspots play a significant role in indicating areas where organizations should concentrate their efforts to enhance the environmental performance of a product or an organization [40].

The materiality principle leads to a different approach in the EF context, where the best quality of data should be provided for processes contributing most to the results regarding environmental impacts or savings. In contrast, data of lower quality can be utilized for less relevant processes [40].

2.4.5.1 Procedure to Identify most relevant Impact Categories, Life Cycle Stages, and Processes

The Technical Secretariat chooses the most essential effect categories for communication reasons [41]. This decision is based on the normalized and weighted results of the PEF screening research. The Product Environmental Footprint Category Rules (PEFCR) provide instructions for evaluating the ecological consequences of a product over its complete life cycle, encompassing processes such as extraction of raw materials, production, distribution, utilization, and disposal [50]. Additionally, it delineates a defined sequence of life cycle stages to guarantee uniformity across various PEFCRs or OEFSRs.

2.4.5.2 Procedure to Identify the Most Relevant Elementary Flows and Hotspots

Those that contribute more than 80% cumulatively to the impact category are considered the most significant concerning the primary factors that have the greatest impact [40]. Additionally, any primary factors contributing more than 5% to the impact category are considered relevant [41]. After identifying the most significant elementary flows, they should be connected to the activities that produce them.

Hotspots can be recognized at several levels of detail, such as effect category, life cycle stage, process, or elementary flow. Within the PEF/OEF pilot phase, a hotspot is defined as either Option A, where life cycle stages, processes, and elementary flows collectively contribute to at least 50% of any impact category before normalization and weighting, or Option B, which necessitates identifying the two most significant life cycle stages, processes, and at least two elementary flows as hotspots [41]. The Technical Secretariats can identify additional hotspots.

It is crucial to consider absolute values (disregarding the negative sign) to accurately determine the percentage contribution of a process or flow when computing percentage contributions [40], [41]. This ensures that any credits are appropriately taken into account.

2.4.5.3 Specific Instructions for Aggregating Elementary Flows

Specifically in categories to assess the impact of toxicity, such as "Human toxicity, cancer effects," "Human toxicity, non-cancer effects," "Freshwater ecotoxicity," and "Particulate matter," it is recommended to combine the fundamental emissions at the level 2 category (emissions to air, water, soil) during the contribution analysis [40]. It is advisable to simplify the analysis by excluding the level 3 category, as it does not contribute any new information when examining at the process level. Modelling foreground data in the level 3 category for particles and dangerous material fluxes is crucial due to the possibility of significant variances in characterisation parameters.

It is advisable to consolidate the flows for each specific metal (silver, copper, and nickel) as indicated in the source files when performing a contribution analysis for metal resource flows [49]. It is recommended to combine the flows of brown coal, crude oil, hard coal, natural gas, and peat when conducting a contribution analysis for fossil fuel-related resource flows [49]. This should be done by considering the distinct calorific values provided in different background databases [50].

2.4.5.4 Life Cycle Inventory (LCI) Phase for Hotspot Analysis

The main objective throughout the life cycle inventory phase is to ensure that data collection and modelling align with the study's specific objectives and scope [40]. The generated LCI is used as input for the succeeding step of LCIA [40]. The primary goals at the LCI level include improving the inventory model, doing sensitivity analysis, refining the LCA model, and drawing suitable conclusions [41]. Performing a sensitivity analysis is crucial to validate the dependability of the findings.

When utilizing primary data, which the performing firm directly gathers, it is reasonably easy to maintain consistency with the study's objective and scope [50]. Nevertheless, it is imperative to meticulously assess the coherence between secondary datasets and the core data, as well as the objectives and extent of the study. Discrepancies in modelling assumptions among datasets that reflect the exact product system can result in different outcomes, which can affect the dependability of the LCA study [42]. The choice of secondary datasets can substantially impact LCA outcomes and pose difficulty in ensuring the accuracy and reliability of LCA [47].

An additional crucial factor in life cycle inventories is the data's quality, which encompasses its accuracy in terms of time, geography, and technology, as well as its precision, adherence to methodology, and documentation [40].

Consistency and completeness are crucial when considering specific features, such as determining the cut-off and deciding which elementary processes to include or exclude, in the context of LCIs [40]. Assessing the completeness of an inventory can be a difficult task, but it is crucial to evaluate it in terms of the study's objective and extent [40]. For instance, if the study exclusively examines the impact of climate change, the inventory's completeness ould be assessed based on the emissions that contribute to climate change within the defined system boundaries [40].

2.4.6 Analysis of data sources

First and first, it is crucial to carefully choose the most suitable data to demonstrate the importance of various data sources in LCA investigations [40]. The information in this paragraph is mainly derived from the selected research, which describes the limits of the system, the fundamental assumptions, the modelling of the primary system, and the influence of the impact assessment. The primary objective is to analyze secondary datasets, and data can be collected using specific databases such as Agribalyse, Agri footprint, Ecoinvent, etc.[40]. The researcher conducting LCA performed three separate analyses.

- Comparison of system boundaries and underlying assumptions Evaluation of how the foreground system is modelled in each dataset, focusing on various aspects such as fertilizers application, plant protection products, heavy metals input, irrigation, agricultural operations, and land occupation.

- Comparison of the life cycle impact assessment results for the foreground system, including the relative contribution of the background.
- Foreground system analysis is the evaluation of the foreground system, which compares the activities modelled in the datasets in each field, such as agricultural operations, fertilizers application and nutrients environmental fate, plant protection products (PPP) application and related environmental fate, heavy metals (HMs) input and related environmental fate, irrigation, and land occupation and transformation.

2.4.6.1 Data quality

Precision of data is crucial in quantitative studies such as LCA. Therefore, it is essential to evaluate the data used in the life cycle inventory phase according to the study's objective and scope during the interpretation phase [41]. This evaluation involves assessing the extent to which the data quality is in line with the purpose of the study, its consistency, and its comprehensiveness. If the data quality is considered inadequate, it may be essential to revisit the LCI phase to improve the data quality [48]. ISO 14040 to 14044 sets forth criteria for data quality, including factors such as temporal coverage, spatial coverage, technological coverage, accuracy, comprehensiveness, representativeness, consistency, repeatability, data sources, and information uncertainty [40], [41], [48], [49]. The main goals of EF methods are to ensure consistency and reproducibility. Data sources must comply with International Life Cycle Data (ILCD) EF standards and should be mentioned if they follow a PEFCR/OEFSR [40]. The EF technique assesses both precision and uncertainty, leading to the identification of six semi-qualitative data quality standards [46] that contrast with the nine requirements specified in ISO14044 [40], [47].

When assessing the applicability and quality of data used to compile the LCI, it is necessary to evaluate it based on requirements. If a dataset is of low quality, searching for an alternate dataset consistent with the study's objective and scope is advisable. It is essential to comprehend the methodological decisions made in constructing the datasets, such as establishing the limits between nature and Technosphere and considering the timeframes of emissions. Assessing the quality of background data should also include examining the modelling concepts of the database providers, as they are crucial sources for evaluation [40].

2.4.6.2 Completeness and consistency checks

In LCA evaluations of mining activities, excluding effect categories such as Resource Depletion, fossils, and minerals may suggest that essential factors associated with exploiting natural resources have been overlooked in the inventory [46], [48]. Hence, it is necessary to appraise the utmost significance and determine if the elements deemed irrelevant can be appropriately classified as such [46]. It is crucial to determine how much the LCI model covers the impact categories the assessor intends to evaluate [40].

According to ISO 14044, the cut-off explicitly determines the quantity of material, flow of energy, or degree of environmental importance that should be deliberately left out of research [46]. An evaluation and explanation of the impact of the chosen cut-off criteria on the study's results should be conducted and documented in the final report. The selection of cut-off criteria can be determined by factors such as mass, energy, or environmental impact. It should be tailored to align with the specific objectives and scope of the study [46], [48]. When conducting studies to make comparisons and comparative statements, it is necessary to perform a sensitivity check utilizing all three criteria [40].

Long-term emissions persist for over 100 years and can extend to thousands of years. Some databases do not consider long-term emissions as part of their system boundaries, and this omission can result in a disproportionate focus on impact categories related to toxicity in LCA conclusions [40], [41]. Verifying whether the datasets utilized incorporate long-term emissions is crucial, as their absolute quantities may be considerably larger than during a 100-year timeframe. Long-term emission estimation models are subject to significant uncertainty, necessitating their consideration in LCA studies to avoid biased results and inaccurate recommendations [41]. It is crucial to evaluate a baseline situation when addressing long-term emissions, conduct a sensitivity analysis incorporating long-term emissions in the Life Cycle Inventory (LCI), and examine the uncertainty related to their inclusion that does not consider long-term emissions [40].

2.4.7 Interpretation of Life Cycle Impact Assessment

The elementary flow inputs and outputs obtained from the inventory are converted into impact indicator results during the LCIA phase of an LCA [46], [48]. This conversion is achieved through mandatory processes of categorization and characterization, as well as optional processes of normalization and weighting.

The LCIA phase encompasses the interpretation of multiple aspects, such as the applicability of diverse characterization models, normalization sets, and weighting sets [48]. It also entails identifying the most susceptible components in determining the outcomes, conclusions, and suggestions while comparing the extent of characterisation features to the recorded elementary flows [51].

The case studies will examine sensitivity analysis utilizing various characterization models for impact categories related to toxicity and resources, and they will also explore the application of different methods for impact assessment, as well as the mapping of the coverage of characterization factors for toxicity-related categories in comparison to the inventoried elementary flows [51].

2.4.8 Life Cycle Assessment (LCA) System Boundaries

LCA entails assessing a product's or system's ecological consequences from its inception to its ultimate disposal. The many system boundaries in LCA provide distinct viewpoints and levels of intricacy when evaluating environmental effects, enabling customized studies according to research objectives and extent. The main types of system boundaries in LCA are shown in Table 2.9.

Table 2. 11: Types of System Boundaries

System Boundary	Definition

Cradle to Grave Cradle to end of life)	Encompasses all stages of a product's life cycle, from raw material extraction to the end of the product's life, including manufacturing, distribution, use, and disposal[43]. Provides a comprehensive view of the environmental impacts associated with the product's life cycle 43].
Cradle-to-Gate	Includes all stages of a product's life cycle up to the point of leaving the factory gate. Excludes impacts associated with the product's use phase and its end-of-life treatment.
Cradle-to-Cradle (Closed Loop)	Covers the entire product life cycle, including the potential for recycling, reusing, or returning materials to the production process[46]. Aims to minimize waste and promote a circular economy by considering the possibility of reusing resources.
Gate-to-Gate	Focuses solely on a specific stage or process within the product's life cycle, such as only the manufacturing phase or transportation phase[46]. Provides a narrower focus compared to cradle-to-gate or cradle-to-grave assessments.

2.4.9 Characterization: Sensitivity Analysis

Using different characterization models to assess an effect category can significantly affect the calculation of results and the identification of critical areas of concern, such as the most significant life cycle phases, processes, and elementary flows [46].

Sensitivity analysis is essential for determining how different models affect the results of LCA. The process entails methodically modifying the parameters and assumptions inside the characterization models to evaluate their influence on the overall outcomes. Practitioners of LCA can acquire vital knowledge on the resilience, dependability, and possible uncertainties linked to the selected characterization models through the implementation of sensitivity analysis [46], [48]. This process improves the clarity and reliability of the LCA findings. It allows for well-informed decision-making based on a thorough understanding of the possible differences in impact assessment conclusions [48].

2.4.9.1 Importance of Sensitivity Analysis in Characterization

Sensitivity analysis is crucial for determining the influence of different models on life cycle assessment (LCA) results. This analytical methodology facilitates the systematic assessment of how various characterization models react to variations in input parameters, thus enabling a comprehensive comprehension of the stability, dependability, and potential uncertainties linked to the selected characterization models [40]. This section will explore the importance of sensitivity analysis in characterisation, emphasizing its ability to detect hotspots, aid in decision-making, and improve the clarity of LCA findings, as shown in Table 2.10.

Table 2. 12: Benefits from Sensitive Analyze to the LCA [41]

Benefit	Behaviour of Effection
Model Robustness	It enables the investigation of how various characterization models react to modifications in input parameters, aiding in determining the chosen model's resilience in accurately representing fluctuations in environmental influences across diverse scenarios [41].
Identification of Hotspots	Professionals may determine the primary factors that influence the results of impact assessment through systematic manipulation of the characterisation parameters, and it allows them to identify crucial areas within the life cycle that require focused efforts to reduce adverse effects [41].
Decision-Making Support	It allows stakeholders to understand better the possible environmental consequences linked to the evaluated product or process, facilitating more knowledgeable and adaptable decision-making [41].

2.4.9.2 Methodological Considerations

It is essential to consider the following methodological aspects when conducting sensitivity analysis in the context of characterization, shown by Table 2.11 below,

Table 2. 13: Methodological Aspects for the Sensitive Analysis

Aspect	Description
Parameter Selection	It is a varied, careful selection of the parameters, ensuring that they encapsulate the key factors driving the environmental impacts within the chosen impact category[41].
Quantification of Uncertainty	Explicitly quantifying the uncertainties associated with the input parameters and characterizing the range of potential variations in impact assessment results [40].
Comparative Evaluation	Conducting comparative assessments of the outcomes obtained from different characterization models under varying scenarios, elucidating the magnitude of differences and their implications [40].

2.4.10 Estimation of uncertainty

The assessment of uncertainty in LCA research is intricately linked to the LCI and LCIA stages. It aims to measure the variability of LCA data to establish the importance of the indicator outcomes [40], [41]. It facilitates a more comprehensive comprehension of the obtained outcomes, the incremental enhancement of an LCA investigation, and aids the intended audience in evaluating the resilience and relevance of the study findings[46], [51].

PEF studies identify two primary sources of uncertainty: stochastic uncertainties of the inventory data (involve statistical measures of variance around a central value) and choice-related uncertainties resulting from methodological decisions (cannot be quantified using statistical descriptions)[46].

Uncertainty analysis seeks to characterize the potential range of probable outcomes given a specific set of inputs[46]. It is distinct from sensitivity analysis, which examines the degree to which the results are influenced by changes in input parameters[48]. Evaluating uncertainty is crucial during the inventory, characterisation, normalization, and weighting stages, as uncertainties impact every step of a quantitative process[40].

2.4.11 Meta-analysis

The significance of meta-analysis in LCA studies has grown due to the escalating amount of research in this domain, and approaches are being employed to merge and reassess findings from individual LCA research [46]. Highlighting the importance of critical aspects in collecting and utilising LCA data by selecting a suitable checklist of crucial variables for carrying out and documenting systematic reviews and meta-analyses in LCA[48]. A significant obstacle in performing a meta-analysis of LCA investigations is the wide range of findings and characteristics seen among the various studies. The variability in LCAs results from the adaptable guidelines provided for conduction, which leads to differences in assumptions and methodological decisions[49]. Moreover, the absence of uniformity in reporting LCA outcomes introduces intricacy to the data collection process. The discrepancies observed in different studies primarily stem from variations in the delineation of system boundaries, the methods used for impact assessment, the definition of functional units, the inclusion of both direct and indirect land use change, the level of technological maturity, and the modelling of multifunctional systems, these factors can have a substantial influence on the results of an LCA study[40], [41]. These findings are consistent with the results of other research in the literature.

Suppose we aim to perform a meta-analysis of LCA for wood energy services. In that case, the study examines the main factors that led to varying results in different LCA studies, including data sources, transportation routes, feedstock qualities, combustion capability, and energy service supplied [50]. In a similar manner, If we consider a meta-analysis on LCA studies of electricity generation with carbon capture and storage, which is focused on the influence of various choices in LCA methodology and parameters, such as data quality, time horizon, spatial representation, life cycle inventory, operational valuation, and weighting methods [40].

Moreover, the diversity in the scope of LCA research, wherein certain studies primarily examine greenhouse gas (GHG) emissions while others encompass additional factors such as acidification, eutrophication, and particulate matter, introduces intricacy to the comparability of outcomes. It is crucial to improve the coordination and clarity in the documentation of LCA data to tackle these difficulties and enhance comprehension and comparability of findings and deductions derived from these investigations.

2.4.12 Application of LCA to Hydrogen Gas Generators by Electrolyzing

Using LCA for hydrogen gas generators via electrolysis involves a comprehensive assessment of the environmental impacts of the entire LC of hydrogen production[50]. This encompasses raw material extraction, generator manufacturing, the electrolysis process, distribution, hydrogen utilization, and potential end-of-life scenarios[50]. LCA provides stakeholders with valuable insights into the environmental implications of hydrogen production, enabling them to pinpoint areas for enhancement and make informed decisions that support sustainable hydrogen generation technologies[50].

3 Methodology

This chapter describes the methods used to conduct an LCA of the developed Dry-Type HHO generator kit for internal combustion engines. The task consists of two main stages: the development phase of the HHO kit and the implementation of LCA to evaluate the created HHO kit. Furthermore, it signifies a progression from prior studies on HHO generator devices that operate with liquid. The study's main goal was to quantitatively assess the environmental effects of the created HHO gas generator kit, which can be used in internal combustion engines.

3.1 Collection of Design data of the HHO kit (Phase 1)

The first step of phase one entailed collecting the requisite data from recently published journal articles, books, and prior study reports. An initial version of the design and measurements for the HHO generator kit was formulated using the data obtained from these sources. The HHO kit comprised three primary components: the gas separator, the HHO generator unit, and the pneumatic fittings. Nevertheless, the pneumatic fittings were pre-existing manufactured components chosen based on the design parameters.

The final design of the Dry-type HHO generator kit was finalized during the data collection phase. Nevertheless, this accomplishment was attained by cooperative oversight with my mentors, as modifications were implemented to the electrode material (shifting from graphite to carbon nanotube) and the dimensions of the generator fixes. The volume of the HHO generator was subsequently established using calculations derived from the applicable internal combustion engine volume. The detailed specs of the completed HHO kit are shown in Table 3.1.

Table 3. 1: HHO generator specifications

Parameter	Unit	Specification
Operating Voltage (DC)	V	1.3 - 2.0
Working Current range	A	1 – 2.5
The volume of the HHO generator	cm^3	53
Reactive area of electrodes	cm^2	16
Solution Molarity	$\frac{\text{moles}}{cm^3}$	0.1
The volume of the gas separator	cm^3	200

Some parameters of the HHO kit, such as volume of the HHO kit, operating voltage, gas separator volume, and applicable sizes of the fittings, were calculated as given below, Equation (3.1) is used to calculate the fuel consumption rate of the IC engine.

$$FCR = \frac{ml}{min} = \frac{l}{h} \times \frac{1000}{60} \tag{3.1}$$

Here, ml is the volume of gasoline, and min is the time in minutes.

Equation (3.2) calculates the gasoline flow rate per minute.

$$\frac{\mathrm{FCR}}{Engine\ Displacement} \tag{3.2}$$

Equation (3.3) calculates the gasoline flow rate per minute from l/km.

$$\frac{1}{\mathrm{FCR}} \times \mathrm{Speed\ in\ km/min} \tag{3.3}$$

The equations 3.1, 3.2, and 3.3 were employed to ascertain the required gasoline flow rates for the designated engine, subsequently enabling the computation of the equivalent HHO gas flow rate. The computation was predicated on the assumption that the bike's velocity is 60 kilometres per hour, equal to 1 kilometre per minute.

$$\text{Gasoline flowrate} = \frac{\frac{1}{60} l\ per\ km}{1 km\ per\ min}$$

$$\frac{1}{60} l\ per \min = \frac{1000}{60}\ l\ per\ min$$

$$\underline{16.67\ mililiter\ per\ min}$$

The gasoline to HHO gas ratio in this instance was 1:8. Hence,

$$\text{HHO gas Flowrate} = \frac{16.67}{8}\ mililiter\ per\ min$$

$$\underline{2.83\ mililiter\ per\ min}$$

3.1.1.1 Material inventory of the Design

Before initiating the building of the design, all drafts were manually sketched by hand before the designing phase. After the hand-drawn drawings were finished, past research data from research papers were followed to reach a final version.

Cyanoacrylate glue was expected to attach gas separator plates of medium and large sizes. This adhesive is specifically formulated for attaching plastic components. Five 8mm holes were deliberately positioned in ideal areas to allow the necessary fittings for optimal performance. Table 3.2 shows the complete material requirement for the HHO generator manufacture below,

Table 3. 2: Material Requirement for the HHO Generator Unit

Item	Dimensions (mm)	Material	Quantity (No.)
Anode and Cathode Electrodes	$50 \times 50 \times 2$	Carbon nanotube	8
Neutral Electrodes	$50 \times 50 \times 2$	Carbon nanotube	6
Electrode terminal plate	$50 \times 50 \times 1$	Copper	4
Side fixing plates	$80 \times 80 \times 8$	Acrylic	2
Rubber gaskets	$40 \times 50 \times 3$	EPDM rubber	11
Frame Fixing Bolts	$6M \times 90$	Stainless steel	8
Frame Fixing Nuts	6M	Stainless steel	24
Frame Fixing Washers	6M	Stainless steel	32
Terminal Fixing Bolts	4M × 85	Stainless steel	2
Terminal Fixing Nuts	4M	Stainless steel	10
Terminal Fixing Washers	4M	Stainless steel	12
Pneumatic fittings	8M	PVC	4

Table 3.3 shows the complete material requirement for the gas separator unit manufacture below,

Table 3. 3: Material Requirement for the Gas Separator Unit

Item	Dimensions (mm)	Material	Quantity (No.)
Plastic Sheet (Large)	$120 \times 80 \times 2$	Acrylic	4
Plastic Sheet (Medium)	$80 \times 45 \times 2$	Acrylic	2
Pneumatic Fittings	6M	PVC	5

In addition, 6M pneumatic plastic fittings were selected for the HHO generator unit and gas separator to sustain a low pressure of around 1 bar. Durable pneumatic hoses, appropriate for the gas separator and HHO generating units, were securely attached to the permanent fittings. The process involved the attachment of carbon nanotube plate electrodes to copper terminal plates using graphite paste. This method successfully guarantees conductivity and prevents any leakage of electrolytes and HHO gas.

3.1.2 Design of the HHO kit using the Solidworks Software

The design proportions were created following ISO standards, which included the integration of fastening bolts, threaded cuts, and extrusions. The design approach used SolidWorks, a specialized 3D modelling software designed primarily for mechanical engineering.

3.1.2.1 Design of the HHO generator unit

The HHO generator unit's design comprised essential subunits, including Electrodes, HHO generator frame, Supply terminal, Frame and terminal fixings, and pneumatic fixings with hoses. Table 3.4 provides an illustrative overview of all subsections.

Table 3. 4: Specification of Subunits in HHO Generator unit

Subunit	Sub Element	Material	Quantity (No.)
Electrode	Neutral	Carbon Nanotube	1
	Anode and Cathode	Carbon Nanotube	2
	Terminal plate	Copper	1
Frame	Side Plates	Acrylic	2
	Bolts	Stainless Steel	8
	Nuts	Stainless Steel	24
	Washers	Stainless Steel	32
Supply Terminal	Bolts	Stainless Steel	2
	Nuts	Stainless Steel	10
	Washers	Stainless Steel	12
Pneumatic Fixings	Fittings	PVC	4
	Hose	HDPE	4

Each subunit was constructed by referring to the design drafts using the SolidWorks software, using Metric units of MMGS (Millimeter, Gram, Second). Afterwards, all these parts were joined together utilizing the mate function within the SolidWorks software. The supplied data showcases the altitudes of the primary subunit in the model.

3.1.2.1.1 ELECTRODE

This component functioned as the primary unit in the HHO generator, playing a vital part in producing HHO gas via electrolysis. The structure comprised two discrete regions: carbon nanotube and copper termination plates. The carbon nanotube plates were arranged in a sandwich-like configuration, with each plate securely attached to a copper terminal using graphite paste. Figures 3.1 and 3.2 illustrate the completed fabrication of the electrode assembly.

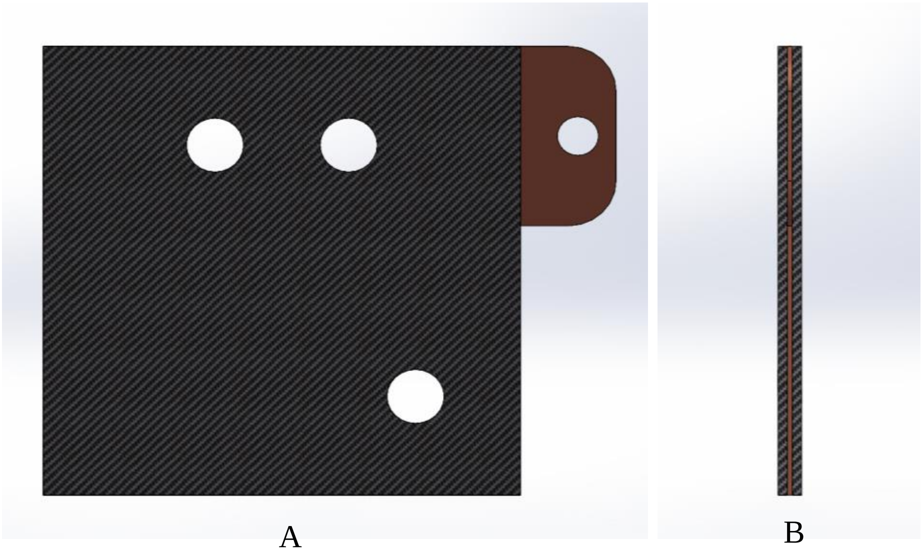


Figure 3. 1: Front Elevation (A), End Elevation (B) of the Electrode Assembly

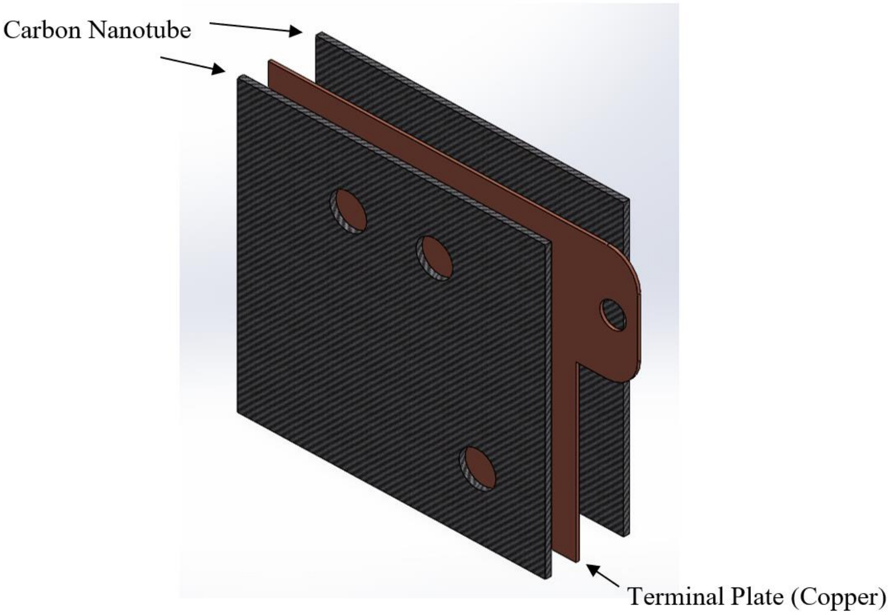


Figure 3. 2: Exploded view of the Electrode Assembly

3.1.2.1.2 Gasket

The gasket for the HHO generator was developed as an individual component during the design process using the option of part in software like other parts. The gasket material used was EPDM rubber, also known as high-temperature rubber, with a thickness of 3mm. Figure 3.3 illustrates the completed design component.

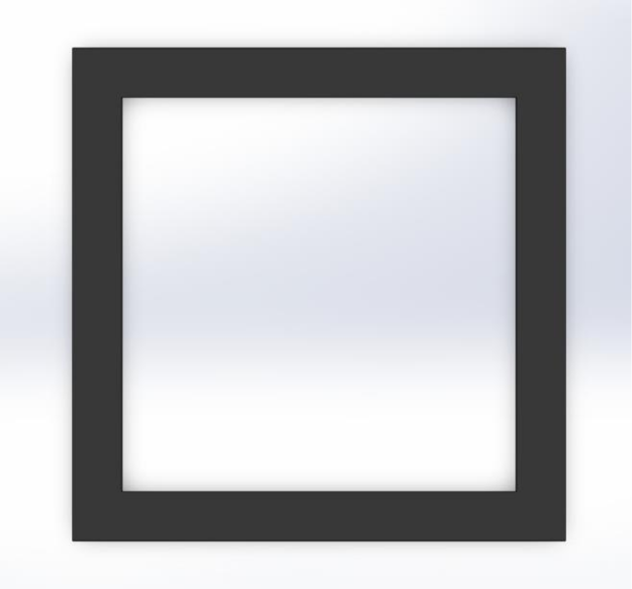


Figure 3. 3: Gasket of the HHO Generator Unit

3.1.2.1.3 Frame

The side frame plates for the HHO generator were developed as an individual component during the design process using the Solidworks software using the option of part design, and the used material was a transparent acrylic sheet, also known as high-temperature plastic, with a thickness of 8mm. Figure 3.4 illustrates the completed design component in each elevation.

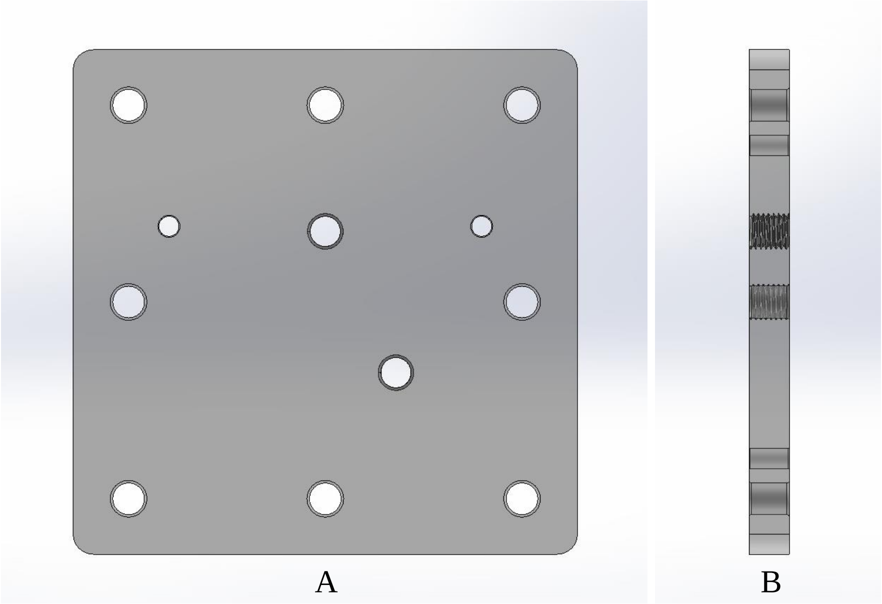


Figure 3. 4: Front Elevation (A), End Elevation of the Side Plate

3.1.2.1.4 Fittings

The pneumatic plastic fittings for the HHO generator were designed as a standalone component using the option of part in software, with PVC being the chosen material as an external company produced it. That product was used as a finished item, excluding the production process involving other components of the HHO kit. Figures 3.5 and 3.6 depict the fully finished design element in elevations.

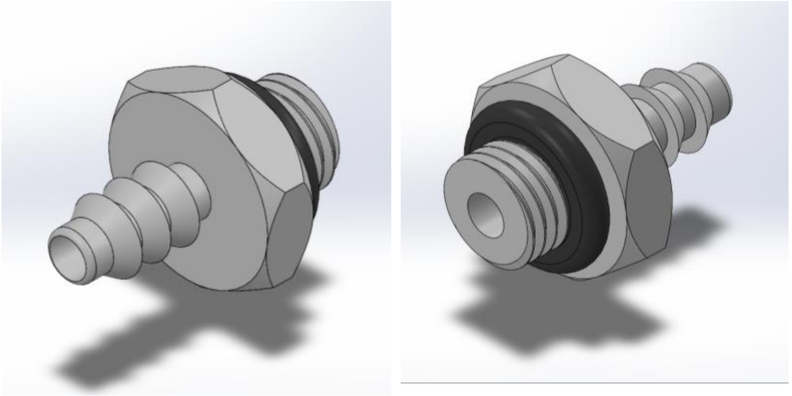


Figure 3. 5: Isometric view of the Pneumatic Fitting

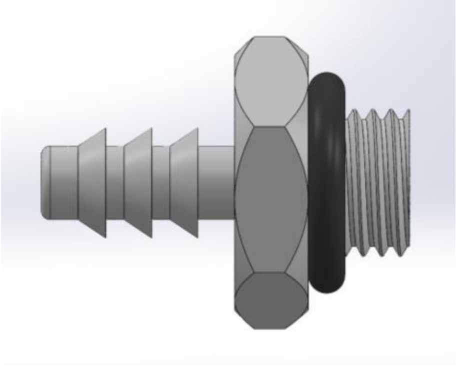


Figure 3. 6: Front Elevation of the Pneumatic Fitting

3.1.2.2 Design of the Gas Separator unit

The gas separator unit's design comprises two essential subunits: fixing plates and pneumatic fixings. Table 3.5 provides an illustrative overview of all subsections.

Table 3. 5: Specification of Subunits in Gas Separator unit

Subunit	Part	Material	Quantity (No.)
Fixing plates	Large plate	Acrylic	4
	Medium plate	Acrylic	2
Pneumatic Fixings	Fittings	PVC	5
	Hose	HDPE	1

The Gas separator unit for the HHO kit was designed as a standalone component using the option of part in software, with acrylic thermos plastic being the chosen material. The same pneumatic fittings and hose were applied to that unit as well. Figure 3.7 depicts the fully finished design element in elevations.

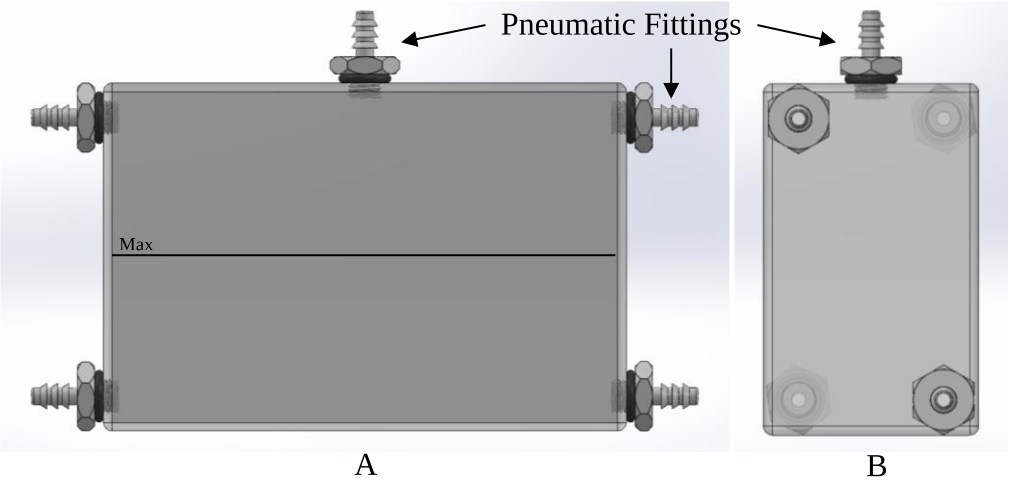


Figure 3. 7: Front Elevation (A), End Elevation (B) of the Gas Separator Unit

3.1.2.3 Assembly of the HHO Generator unit

The HHO generating unit for the HHO kit was assembled by combining individual components such as electrodes, supply terminals, gaskets, side frame plates, and pneumatic fittings using the SolidWorks assembly software's mating function. Therefore, the selection was based on the combination of different material types. That unit also utilized identical pneumatic fittings and hoses. Figures 3.8 and 3.9 illustrate the completed design feature from different angles.

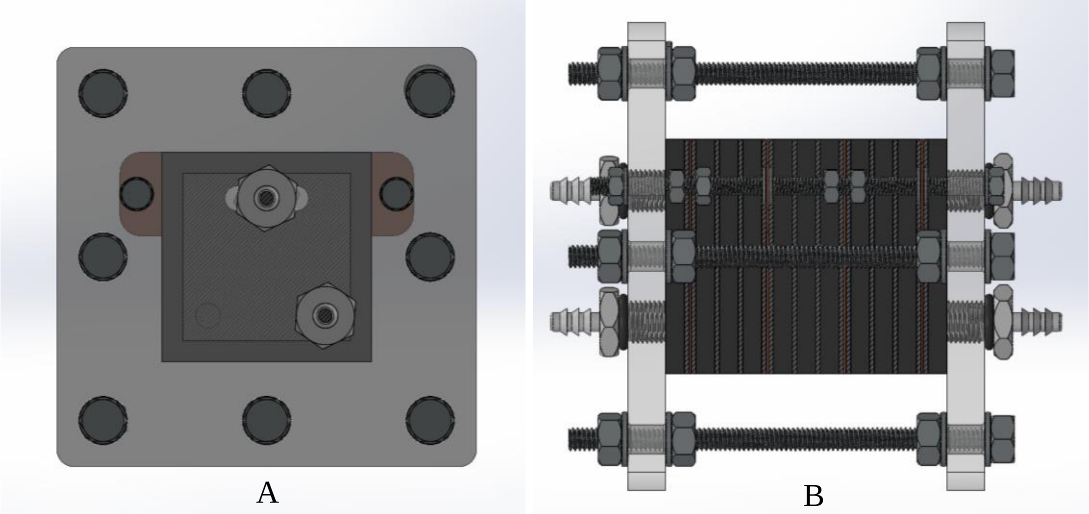


Figure 3. 8: Front Elevation (A), end Elevation (B) of the Assembly of the HHO Generator Unit

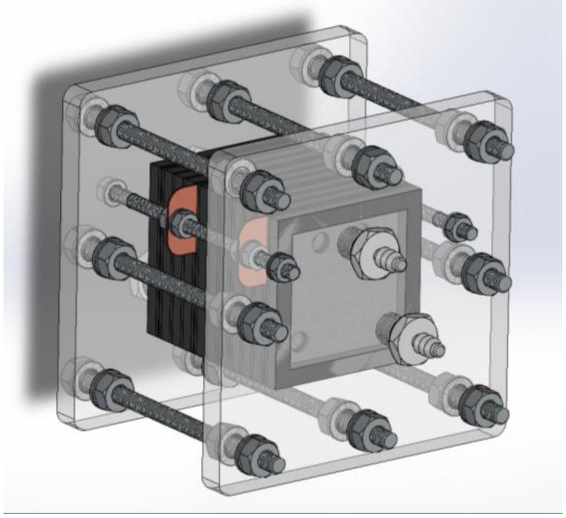


Figure 3. 9: Isometric Elevation of the assembly of the HHO Generator unit

3.1.2.4 Final Assembly of HHO kit

That was the final step of the designing process of the HHO kit, which was assembled by combining individual components and unit assembles such as the Gas separator unit, HHO gas generator unit, and pneumatic hose using the SolidWorks assembly software's mating function, same as last. That unit also utilized identical pneumatic fittings and hoses. Figure 3.10 illustrates the completed design feature as seen from isometric elevation.

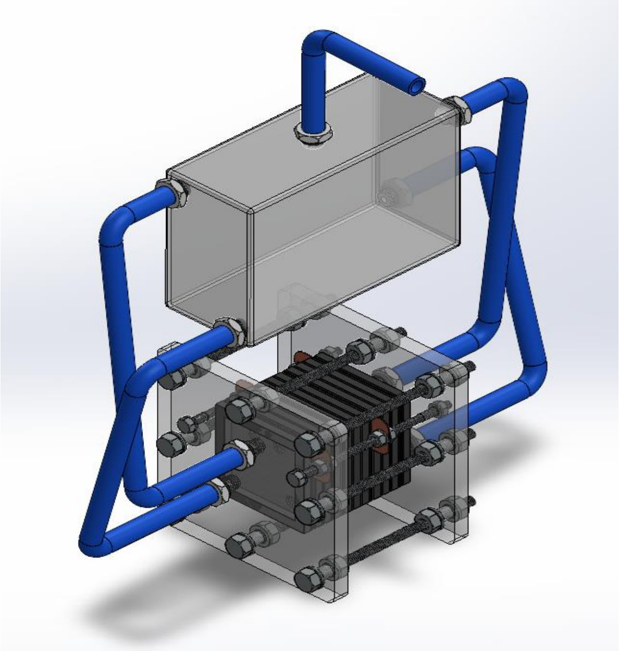


Figure 3. 10: Isometric Elevation of the Final Assembly of the HHO kit

3.2 LCA of the developed HHO kit (Phase 2)

This stage sought to comprehend the environmental efficiency of the HHO kit in practical situations, expanding on the previous development phase. The main goal was to measure the environmental impacts linked to the production of the HHO gas generator kit in a projected facility in Sri Lanka, focusing on improving performance and reducing emissions in gasoline-powered selected vehicle IC engines.

The LCA application phase aimed to examine the environmental performance of the HHO gas generator kit during its manufacture. That was achieved by following a defined process and collecting reliable data. The results obtained from that analysis could offer significant insights for decision-making.

3.2.1 Goal and Scope Definition

The scope of the Life Cycle Assessment (LCA) for the production phase of the Dry-Type HHO generator kit was included,

3.2.1.1 Goal of the LCA

The objective of the LCA for manufacturing the HHO generator kit was to evaluate the ecological consequences linked to the complete production procedure, encompassing the extraction and refinement of raw materials up to the assembly of the product, particularly material processing, electricity, and transportation.

3.2.1.2 Scope of the LCA

3.2.1.2.1 System Boundary

The assessment covered the complete manufacturing process of the HHO generator kit, starting from the extraction of raw materials to the final packing. It included material processing, component production, assembly, and packaging. It was the cradle-to-gate system boundary, which is illustrated in Figure 3.11.

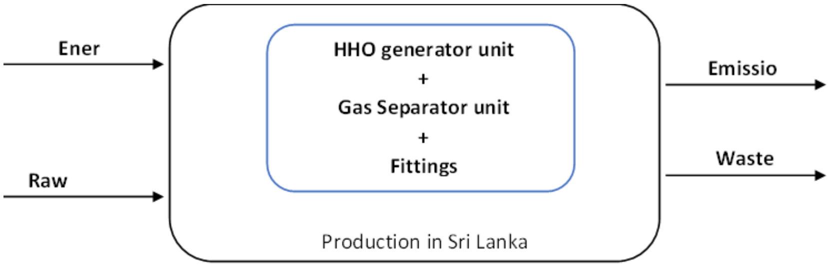


Figure 3. 11: System boundary of the HHO kit Manufacturing

3.2.1.2.2 Functional Unit

The LCA defines the functional unit as a specific quantity of the HHO generator kit, providing a standardized basis for comparison across different materials and processes. Here, there were four central functional units,

- HHO generator unit
- Gas separator unit
- Pneumatic fittings
- Electrolyte

3.2.1.2.3 Impact Categories

The scope includes an assessment of impact categories such as Agricultural land occupation (m^2a), Climate change (kg CO_2-Eq), Fossil depletion (kg oil-Eq), Human toxicity (kg 1,4-DCB-Eq), Ozone depletion (kg CFC-11-Eq), Water depletion (m^3) throughout the manufacturing process.

3.2.1.2.4 Materials Considered

Assessing the environmental impacts associated with the production phase of the developed HHO kit, focusing on materials such as carbon nanotubes, copper, acrylic, stainless steel, EPDM rubber, Graphite paste, synthetic rubber, Polyvinyl Chloride (PVC), and High-Density Polyethylene (HDPE) plastics, as well as packaging materials including cardboard, polyethene, and aluminium.

3.2.2 Data Collection

Various subcategories of actions were undertaken during the data collection procedure.

3.2.2.1 Identify Key Manufacturing Processes

Regarding the production of the HHO gas generator kit at the facility in Sri Lanka, the following essential manufacturing processes and activities are included, covering the extraction of raw materials, assembly, and packaging shown in Table 3.6.

Table 3. 6: Key manufacturing Processes

Key Process	Description
Raw Material Extraction	Sourcing acrylic sheets, carbon nanotubes, copper plates, EPDM rubber sheets, graphite paste, and stainless-steel fasteners (nuts, bolts, washers) from their respective suppliers.
Material Processing	The raw materials were processed and refined to make them suitable for the succeeding production stages, such as cutting, bonding, shaping, and drilling. Additionally, finishing techniques were applied to manufacture the required components for the HHO gas generator kit.
Component Fabrication	The HHO gas generator kit was manufactured by fabricating its components using various procedures, including cutting, bonding, shaping, drilling, and finishing, all carried out within the factory environment to make the required parts.

Assembling	The process involved integrating several parts and sub-assemblies to assemble the HHO gas generator kit.
Packaging	Materials such as cardboard boxes, plastic, and aluminium were employed to complete HHO gas generator kits, guaranteeing adequate safeguarding and logistical preparedness for distribution.
Factory Construction	The Life Cycle Assessment (LCA) encompasses evaluating the factory's structure, considering factors such as the building materials used, energy usage, and the environmental consequences linked with the establishment of the manufacturing facility.

The purpose of the LCA was to thoroughly assess the environmental effects of each stage of the HHO gas generator kit production, encompassing the extraction of raw materials, the manufacturing process, and the establishment and operation of the factory in Sri Lanka.

3.2.2.2 Raw Material Inputs

It mentioned the collected information on raw materials for the HHO kit in the manufacturing stage. Table 3.7 provides information on the material inputs required for component fabrication, assembly, and packaging of the HHO generator and gas separator at the factory in Sri Lanka.

Table 3. 7: Raw Material Inputs

Unit	Product	Material	Amount (g)
HHO Generator Manufacturing	Anode and Cathode Electrodes, Neutral Electrodes	Carbon nanotube	38.78
	Electrode terminal plate	Copper	45.52
	Side fixing plates	Acrylic	185.64
	Rubber gaskets	EPDM rubber	42.50
	Frame fixings and terminal fixings (nuts, bolts, washers)	Stainless steel	279.26
	Graphite paste	Graphite	100.00
	Electrolyte	KOH	5.61
Gas Separator Manufacturing	Medium and Large Plates	Acrylic	86.53
	Bonding glue	Super Glue	10.00
	Fittings	PVC	10.17

Pneumatic Fittings	Hose	HDPE	15.52
Packaging	Rapping	Cardboard	0.48
	Frame	Aluminium	0.38
	Filling	Synthetic rubber	0.12
	Frame Supportive	Plastic	0.16

3.2.2.3 Energy Inputs

Here, the collected information on energy sources and consumption associated with each manufacturing stage was mentioned. Table 3.8 provides information on the energy inputs required for material processing, component fabrication, assembly, and packaging of the HHO generator and gas separator at the factory in Sri Lanka. The table specifies the energy utilization of average voltage per unit for the HHO generator and gas separator.

Table 3. 8: Energy inputs of each process

Unit	Product	Energy Type	Units (kWh)
HHO Generator Manufacturing	Laser 500W CNC	Electricity	0.10
	Metal working	Electricity	
	Lighting	Electricity	
Gas Separator Manufacturing	Laser 60W CNC	Electricity	0.01
	Metal working	Electricity	
Packaging	Lighting	Electricity	0.01
	Packing equipment	Electricity	
	Metal working	Electricity	

3.2.2.4 Transportation

Table 3.9 displays the input data for delivering raw materials to the manufacturing location inside the boundaries of the cradle-to-gate system.

Table 3. 9: Transportation Inputs

Unit	Method	Direction	Distance (t*km)

HHO Generator Materials	Train	China Factory to Harbour	360
	Cargo	China Harbour to Sri Lanka Harbour	8056
	Lorry	Sri Lanka Harbour to Factory	27
Gas Separator Materials	Train	China Factory to Harbour	360
	Cargo	China Harbour to Sri Lanka Harbour	8056
	Lorry	Sri Lanka Harbour to Factory	27
Packaging Materials	Train	China Factory to Harbour	360
	Cargo	China Harbour to Sri Lanka Harbour	8056
	Lorry	Sri Lanka Harbour to Factory	27

3.2.3 Impact Assessment

The evaluation of potential environmental consequences was revealed in the inventory that took place during the impact assessment phase. The effects encompassed:

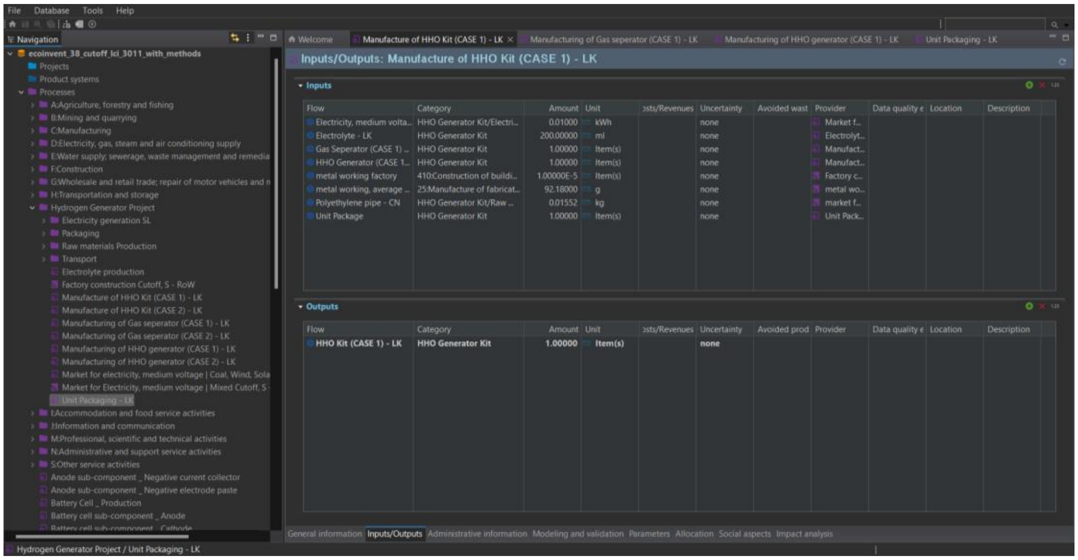
- Agricultural land occupation
- Climate change
- Fossil depletion
- Human toxicity
- Ozone depletion
- Water depletion

The assessment of environmental consequences was explicitly linked to the production stage of the HHO generator kit, which includes the HHO generator unit, Gas separator unit, pneumatic fixings for both units and packaging. In addition, it considered the transit options between China and Sri Lanka, including cargo, rail, and lorry. Various factors were considered, including energy usage, emissions reduction, and potential collateral consequences. The impact assessment used modelling approaches in the dry-type HHO generating kit. This entailed utilizing recipe midpoint H's chosen effect assessment methodology after detecting the environmental emissions linked to the procedure.

3.2.4 Inventory Analysis

The research method involved analyzing the acquired raw materials, energy, and transportation data for both the HHO generator and Gas Separator units using the OpenLCA program shown in Figure 3.12. The investigation utilized the Ecoinvent 3.8 database, explicitly employing the Recipe Midpoint H impact assessment approach.

The analysis entailed the development of distinct workflows utilizing procedures from various directories for the HHO generator unit, Gas Separator, installation of fittings for both units, packaging procedures involving material extraction, and other factors such as transportation, energy consumption, and factory construction.



Inputs/Outputs: Manufacture of HHO Kit (CASE 1) - LK

Inputs

Flow	Category	Amount	Unit	osts/Revenues	Uncertainty	Avoided wast	Provider	Data quality e	Location	Description
Electricity, medium volta...	HHO Generator Kit/Electri...	0.01000	kWh		none		Market f...			
Electrolyte - LK	HHO Generator Kit	200.00000	ml		none		Electrolyt...			
Gas Seperator (CASE 1) ...	HHO Generator Kit	1.00000	Item(s)		none		Manufact...			
HHO Generator (CASE 1...	HHO Generator Kit	1.00000	Item(s)		none		Manufact...			
metal working factory	410:Construction of buildi...	1.00000E-5	Item(s)		none		Factory c...			
metal working, average ...	25:Manufacture of fabricat...	92.18000	g		none		metal wo...			
Polyethylene pipe - CN	HHO Generator Kit/Raw ...	0.01552	kg		none		market f...			
Unit Package	HHO Generator Kit	1.00000	Item(s)		none		Unit Pack...			

Outputs

Flow	Category	Amount	Unit	osts/Revenues	Uncertainty	Avoided prod	Provider	Data quality e	Location	Description
HHO Kit (CASE 1) - LK	**HHO Generator Kit**	**1.00000**	**Item(s)**		**none**					

Figure 3. 12: Preview of Utilization of the OpenLCA software with Ecoinvent 3.8 database

The primary geological regions examined for the extraction of raw materials were China and Sri Lanka, with due consideration given to various modes of transportation. Pre-existing flows were incorporated for many factors, such as transportation, energy consumption, machine waste, and trash generation when pre-existing data were used. When it was calculated, 100,000 units of HHO kits annually were considered, and a thorough evaluation was conducted to analyze the effects of this quantity.

4 Results

4.1 System description and flowcharts

Figure 4.1 presents the system flow defined by the production of the HHO generator kit. The components of the HHO generator kit have been grouped into four main features: HHO generator unit, Gas separator unit, Fittings, and packaging. Flowcharts of the various main components and their sub-components are presented in this section. Transportation and infrastructure are not included in the flowcharts. See Inventory for details.

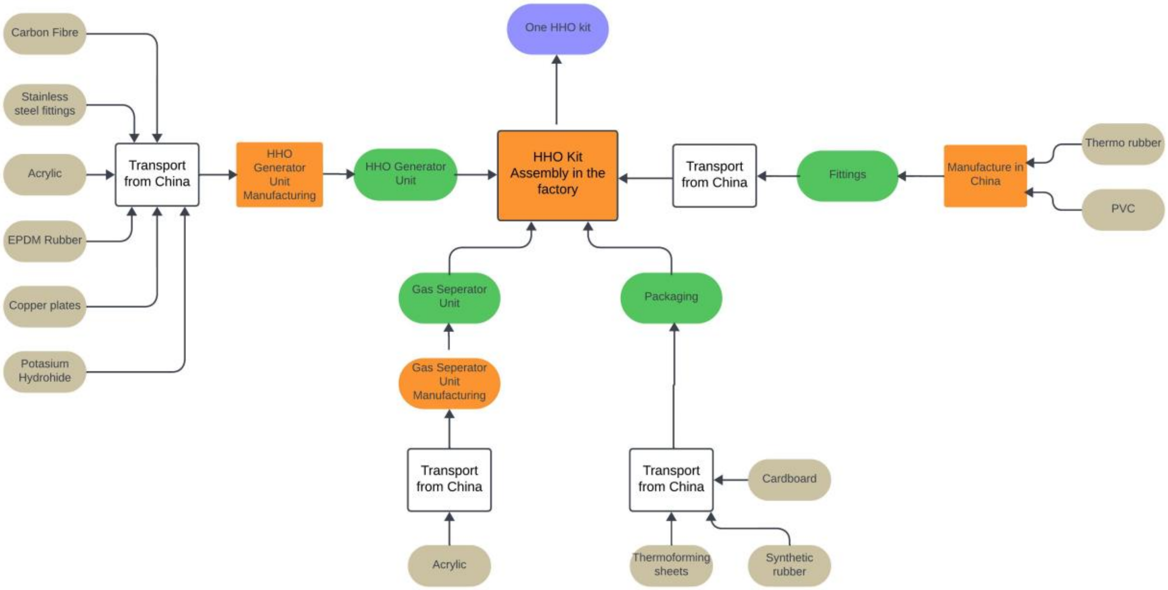


Figure 4. 1: System Flow for the HHO kit

Circles represent products or materials, while squares represent processes. Orange represents the manufacturer's assembly process, the ash represents the raw materials used, blue represents the final product, and white represents transportation.

4.1.1 HHO Generator Unit

The HHO generator unit comprises five main components: Electrode, gaskets, Frame, and electrolyte.

4.1.1.1 Electrode

The flow diagram of the electrode in the HHO generator unit is shown in Figure 4.2.

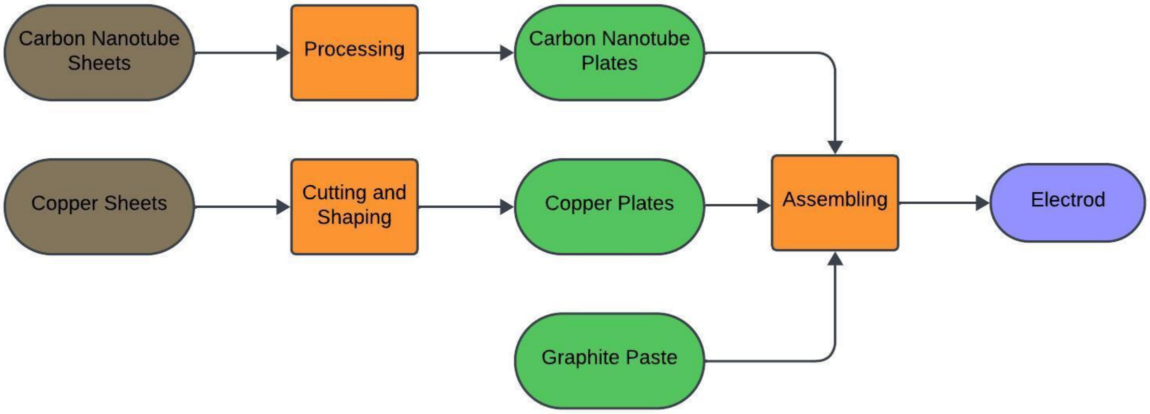


Figure 4. 2: Flow of Electrode Processing

4.1.1.2 Gasket

The flow diagram of the gasket in the HHO generator unit is shown in Figure 4.3.

Figure 4. 3: Flow of Gasket Processing

4.1.1.3 Frame

The flow diagram of the frame in the HHO generator unit is shown in Figure 4.4.

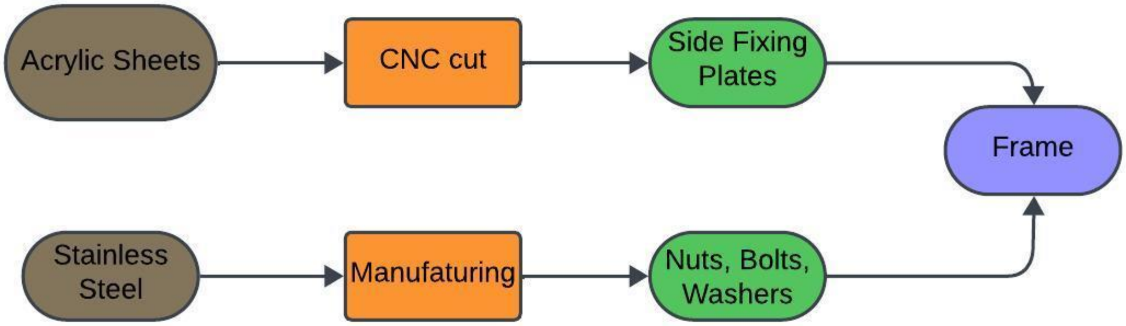


Figure 4. 4: Flow of Frame Processing

4.1.1.4 Electrolyte

The flow diagram of the electrolyte in the HHO generator unit is shown in Figure 4.4.

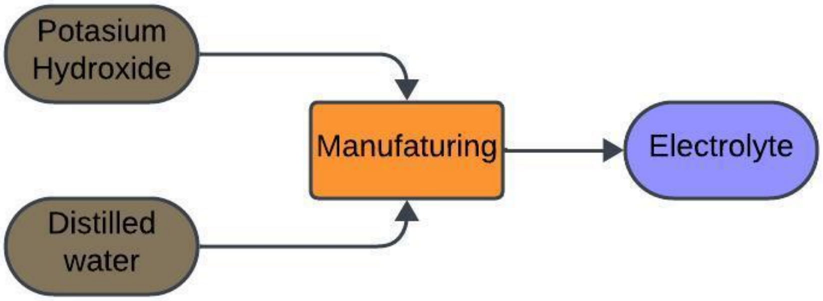


Figure 4. 5: Flow of Electrolyte Processing

4.1.2 Gas separator Unit

The flow diagram of the gas separator in the HHO generator kit is shown in Figure 4.6.

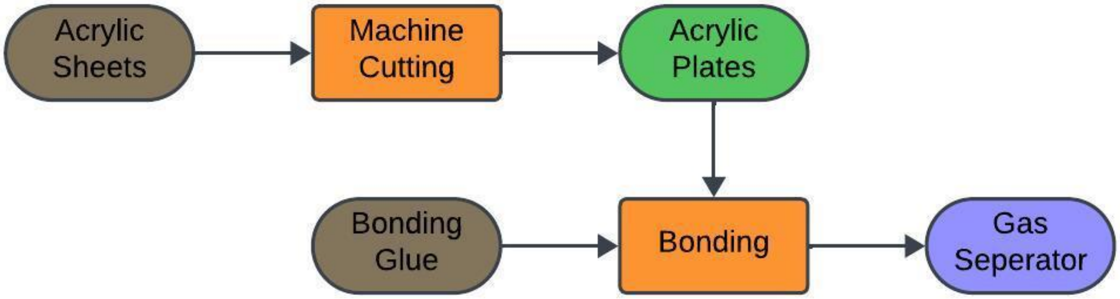


Figure 4. 6: Flow of Gas Separator Processing

4.1.3 Fittings

The flow diagram of the fittings in both the HHO generator unit and gas separator is shown in Figure 4.7.

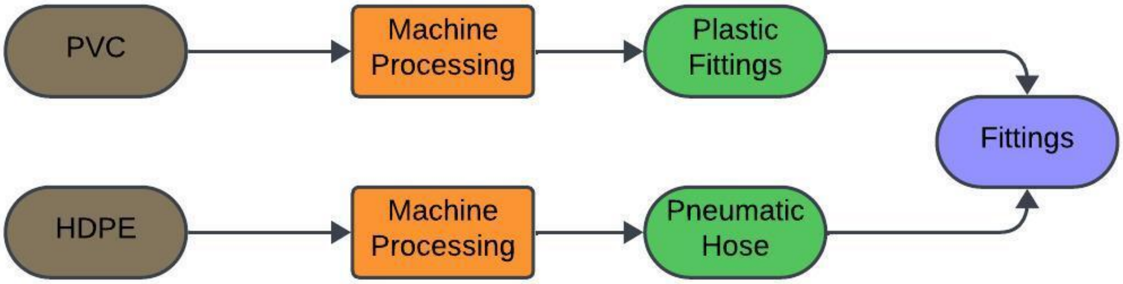


Figure 4. 7: Flow of Fittings Processing

4.1.4 Packaging

The flow diagram of the packaging to the HHO kit to finalize as a final product is shown in Figure 4.2.

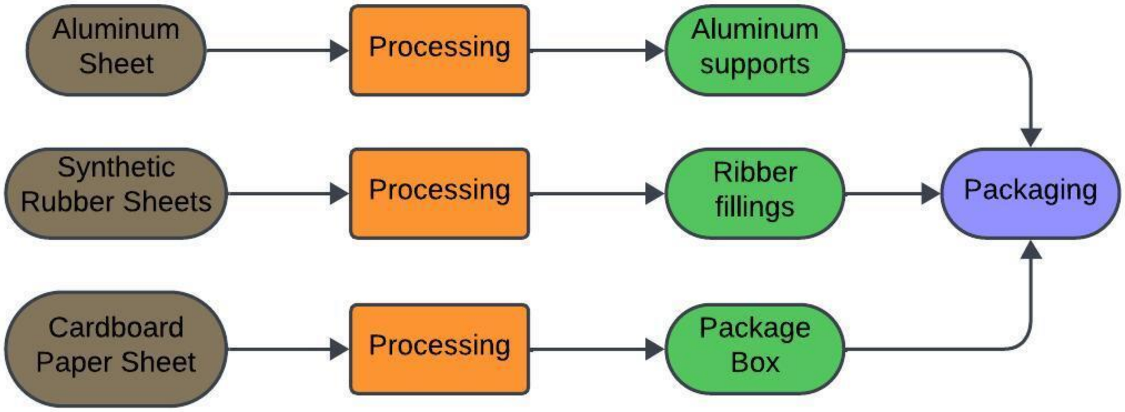


Figure 4. 8: Flow of Package Processing

4.2 Inventory results

Here, the analysis of the inventory results for the dry-type HHO cell, which graphically shows all of the inputs in Figure 4.9 by pie chart and the used data table is attached in Appendix B.

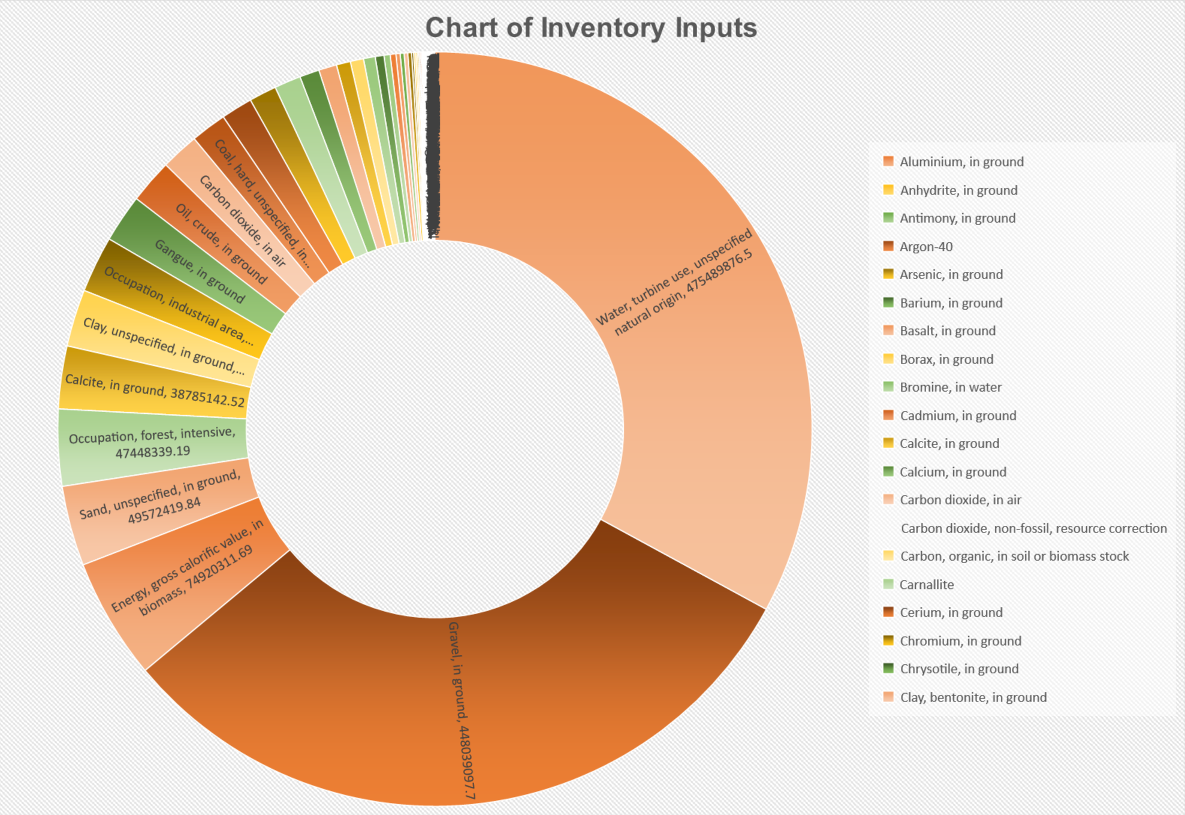


Figure 4. 9: Graph of Input Inventory Results

Furthermore, the analysis of the inventory results for the dry-type HHO kit, which graphically shows all the inputs in Figure 4.10 by pie chart and the used data table is attached in Appendix C.

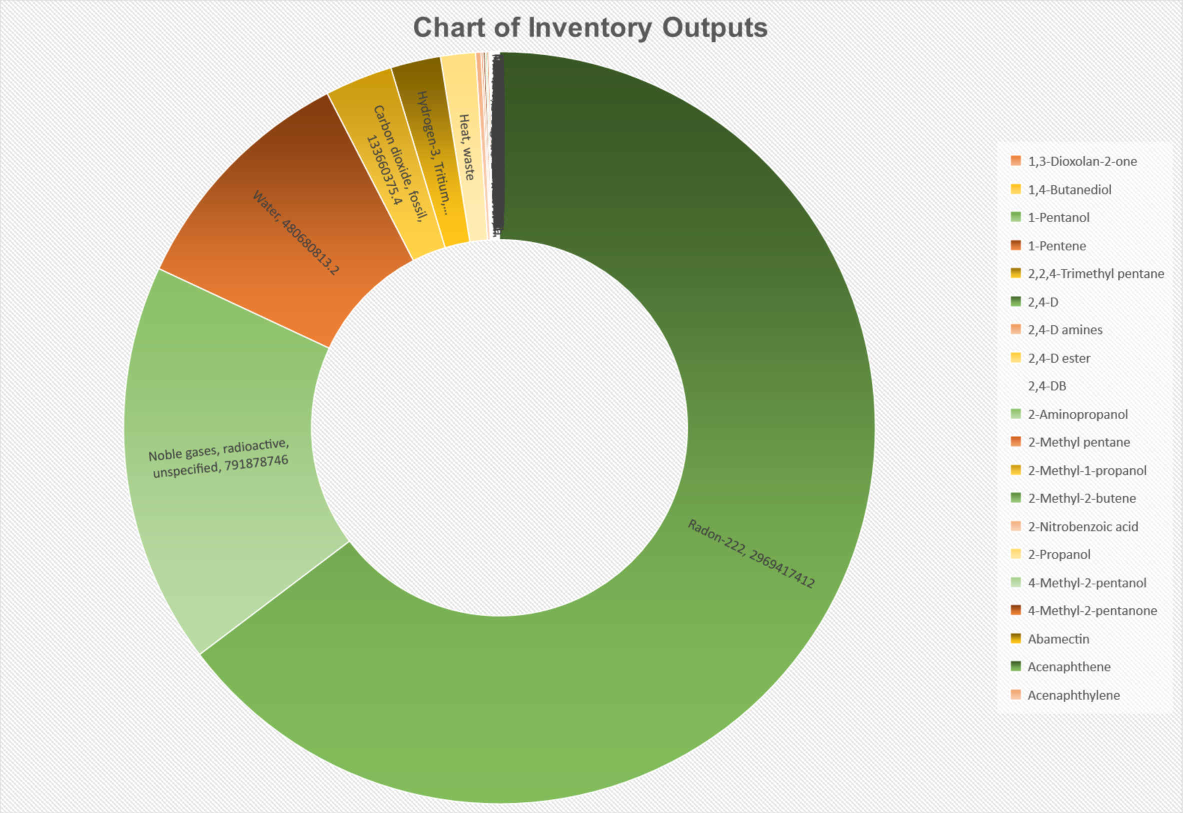


Figure 4. 10: Chart of Inventory Output Result

4.3 Impact assessment results

The impact assessment results for the dry-type HHO kit, which show the environmental impacts in selected categories of Agricultural land occupation, Climate change, Fossil depletion, Human toxicity, Ozone depletion, and Water depletion, from 18 impacts in recipe midpoint H impact assessment method. Table 4.3 illustrates the values in each impact category and according to utilizing table values, it could be constructed in Figure 4.11, which is below,

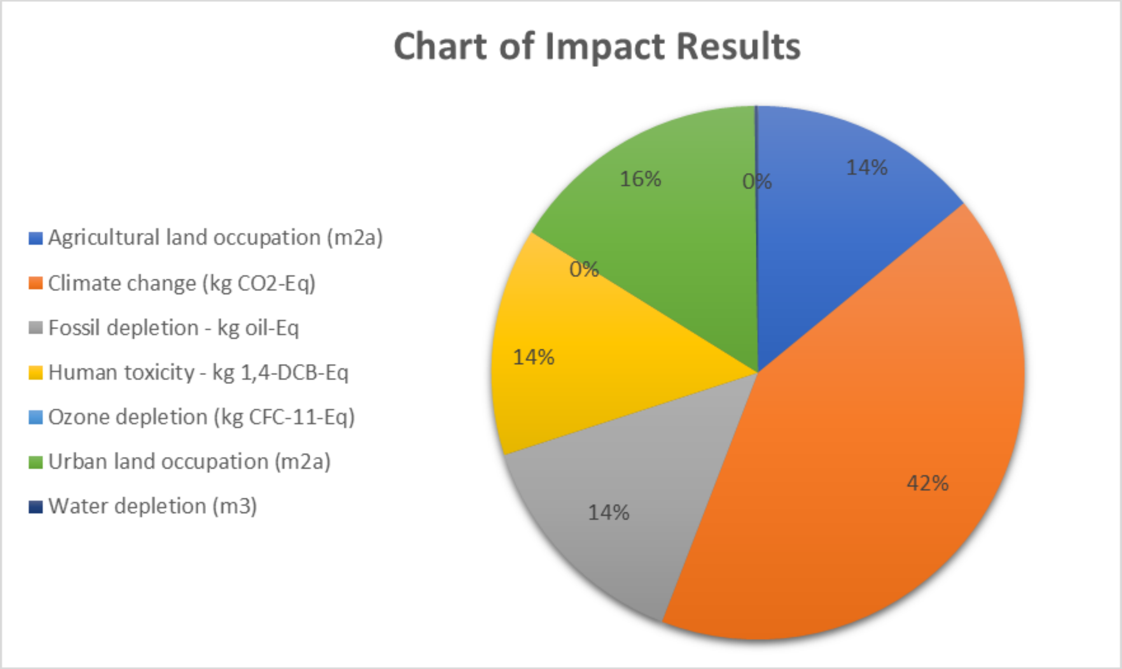


Figure 4. 11: Chart of Impact Results

Table 4. 1: Impact Assessment Results in Selected Categories

Impact category	Reference unit	Overall Impact Results
Agricultural land occupation	m^2a	4.81E+07
Climate change	kg CO_2-Eq	1.43E+08
Fossil depletion	kg oil-Eq	4.85E+07
Human toxicity	kg 1,4-DCB-Eq	4.74E+07
Ozone depletion	kg CFC-11-Eq	1.78E+01
Urban land occupation	m^2a	5.47E+07
Water depletion	m^3	7.20E+05

4.4 Sensitivity analysis results

The following part explores the outcomes of the sensitivity analysis for the dry-type HHO kit. The results are affected by distinct effect categories arising from different phases in the kit production process. Through the analysis of the sensitivity of these findings, the main objective is to reveal the complex interaction between these categories concerning the total environmental impact of the HHO kit. By conducting a meticulous analysis of the data utilizing visual representations such as charts and tables, the aim is to offer a thorough comprehension of how various manufacturing divisions impact the ecological impact of the kit.

4.4.1 HHO Generator Unit

During the production of HHO generators, a range of impacts were created and classified into specific categories, beginning from the 18th impact. As a result, the chart of Figure 4.12 illustrates that as well as the data used from Table 4.4.

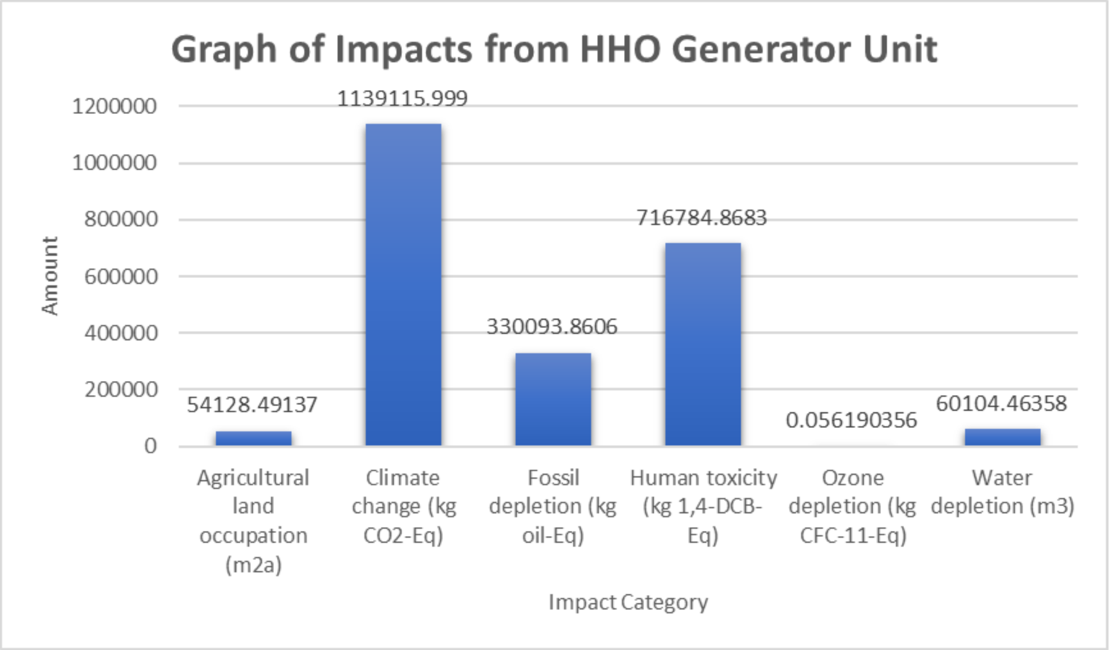


Figure 4. 12: Graph of Impacts from HHO generator Unit Manufacturing

Table 4. 2: Impacts from HHO generator Unit in each Category

Impact category	**Agricultural land occupation (m2a)**	**Climate change (kg CO2-Eq)**	**Fossil depletion (kg oil-Eq)**	**Human toxicity (kg 1,4-DCB-Eq)**	**Ozone depletion (kg CFC-11-Eq)**	**Water depletion (m3)**
Acrylic sheets	114.6138333	3206.754431	528.2387911	1165.575744	0.000147357	37.85795531
Copper sheet	182.3000836	2106.92746	621.2238739	24620.56605	0.00011864	31.30696603
EPDM rubber production	175.0501168	7395.982943	7313.484256	2187.23768	0.001883249	14.52328263
Graphite paste	691.386203	19229.6384	11883.96636	11890.77326	0.002068673	108.1532213
The market for carbon fibre	21991.144	317993.7542	88758.71967	107055.526	0.007014646	849.2625259
Market for Stainless Steel	16744.83999	276532.7306	78455.21635	247771.6251	0.017079197	1275.514918
Laser machining, metal, 500W power	12188.41377	471089.2812	132613.048	295675.7995	0.025530723	56480.1745
Steel turning, roughing, cnc	2040.743364	41560.92997	9919.963325	26417.76488	0.002347871	1307.670213
Total	54128.49137	1139115.999	330093.8606	716784.8683	0.056190356	60104.46358

4.4.2 Gas Separator Unit.

During the production of the Gas Separator, a range of impacts were created and classified into specific categories, beginning from the 18th impact. As a result, the chart of Figure 4.13 illustrates that as well as the data used from Table 4.5.

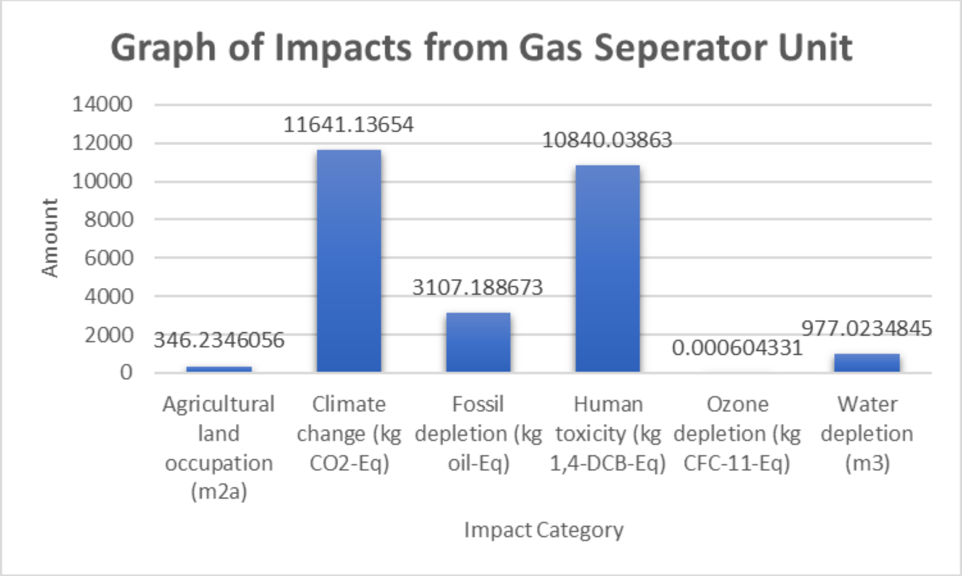


Figure 4. 13: Graph of Impacts from Gas Separator Unit Manufacturing

Table 4. 3: Impacts from Gas Separator Unit in each Category

Impact category	**Acrylic sheets**	**laser machining 60W**	**Total**
Agricultural land occupation (m2a)	53.42439342	292.8102122	346.2346056
Climate change (kg CO2-Eq)	1494.748979	10146.38756	11641.13654
Fossil depletion (kg oil-Eq)	246.2254004	2860.963272	3107.188673
Human toxicity (kg 1,4-DCB-Eq)	543.3042007	10296.73442	10840.03863
Ozone depletion (kg CFC-11-Eq)	6.8687E-05	0.000535644	0.000604331
Water depletion (m3)	17.64654615	959.3769383	977.0234845

4.4.3 Fittings

Various impacts were created and classified into specific categories during the production of fittings, beginning from the 18th impact. As a result, the chart of Figure 4.14 illustrates that as well as the data used from Table 4.6.

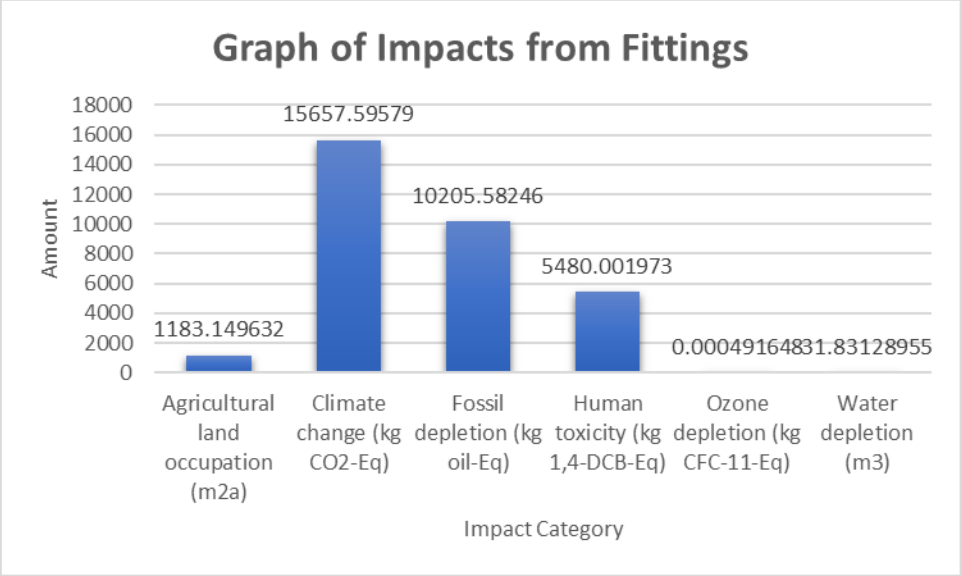


Figure 4. 14: Graph of Impacts from Fittings Manufacturing

Table 4. 4: Impacts from Fittings in each Category

Impact category	The market for extrusion plastic fittings	Market for polyethylene pipe	Market for sulfur hexafluoride	Total
Agricultural land occupation (m2a)	14.0593367	1169.089461	0.000834491	1183.149632
Climate change (kg CO2-Eq)	523.5114958	15133.85436	0.229934655	15657.59579
Fossil depletion (kg oil-Eq)	141.2975636	10064.28131	0.003586151	10205.58246
Human toxicity (kg 1,4-DCB-Eq)	200.6397263	5279.353742	0.00850505	5480.001973
Ozone depletion (kg CFC-11-Eq)	3.07994E-05	0.000460848	5.91145E-10	0.000491648
Water depletion (m3)	2.175333691	29.65589432	6.15367E-05	31.83128955

4.4.4 Packaging

During the production of Packaging, a range of impacts were created and classified into specific categories, beginning from the 18th impact. As a result, the chart of Figure 4.15 illustrates that as well as the data used from Table 4.7.

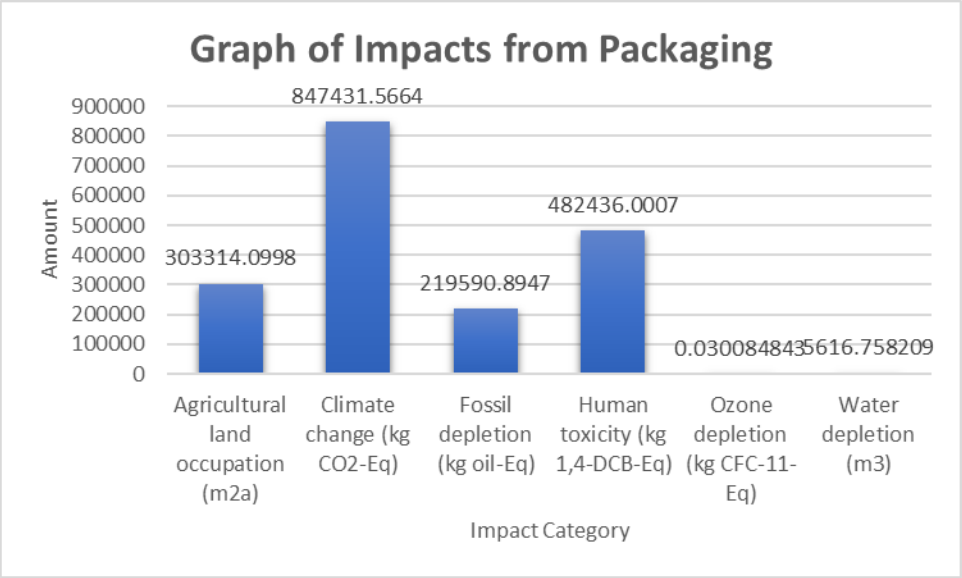


Figure 4. 15: Graph of Impacts from Packaging Manufacturing

Table 4. 5: Impacts from Packaging in each Category

Impact category	**Aluminium production**	**The market for solid board cartons**	**Market for thermoforming of plastic sheets**	**Synthetic rubber production**	**Total**
Agricultural land occupation (m2a)	7863.17326	290459.9305	222.208023	4768.788007	303314.0998
Climate change (kg CO2-Eq)	748611.7558	63301.03015	9068.676097	26450.10437	847431.5664
Fossil depletion (kg oil-Eq)	175793.1587	19840.78689	2416.484695	21540.46434	219590.8947

Human toxicity (kg 1,4-DCB-Eq)	441857.7661	25959.66669	3442.041819	11176.52611	482436.0007
Ozone depletion (kg CFC-11-Eq)	0.018983557	0.004084698	0.0002645	0.006752087	0.030084843
Water depletion (m3)	2382.963061	3134.542088	35.44343419	63.80962544	5616.758209

4.4.5 Transportation

During the transportation for raw material extraction, various impacts were classified into specific categories, beginning from the 18th impact. As a result, the chart of Figure 4.16 illustrates that as well as the data used from Table 4.8.

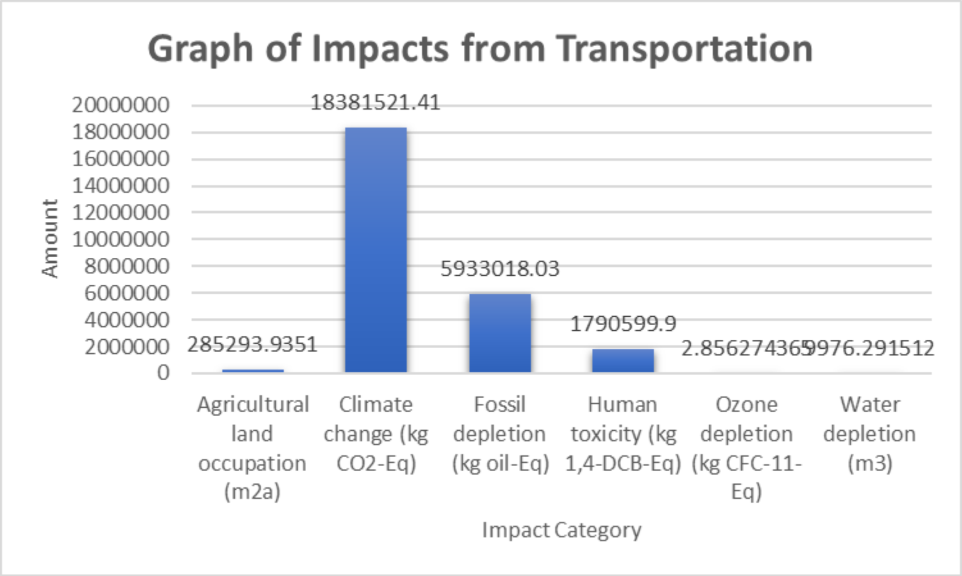


Figure 4. 16: Graph of Impacts from Transportation for Raw Material Extraction

Table 4. 6: Impacts of Transporting in each Category

Impact category	Transport, freight train, electricity	Transport, freight, sea, container ship	Market group for transport, freight, lorry	Total
Agricultural land occupation (m2a)	198528.1844	73572.33109	13193.41959	285293.9351
Climate change (kg CO2-Eq)	1023635.287	16566056.9	791829.2265	18381521.41
Fossil depletion (kg oil-Eq)	271167.5766	5363278.308	298572.1451	5933018.03
Human toxicity (kg 1,4-DCB-Eq)	530981.9888	1022462.861	237155.0503	1790599.9
Ozone depletion (kg CFC-11-Eq)	0.080670914	2.64192442	0.133679031	2.856274365
Water depletion (m3)	4708.274923	4505.029849	762.9867401	9976.291512

4.4.6 Energy (Electricity)

During the electricity utilization in manufacturing of the HHO kit, a range of impacts were created and classified into specific categories, beginning from the 18th impact. It was a passive emission because another party generated the electricity, and this was only utilization. As a result, the chart of Figure 4.17 illustrates that and the data used from Table 4.9.

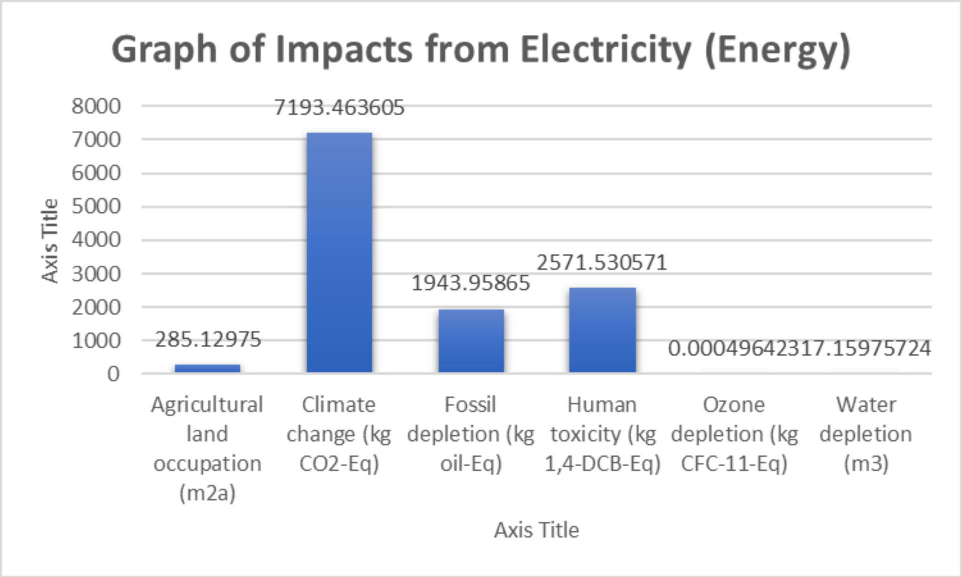


Figure 4. 17: Graph of Impacts from Electricity Utilization to the Production

Table 4. 7: Impacts from Electricity Utilization in each Category

Impact category	The market for electricity high voltage	The market for electricity, medium voltage	Transmission network construction, electricity, medium voltage	Total
Agricultural land occupation (m2a)	283.8332141	0	1.296535881	285.12975
Climate change (kg CO2-Eq)	7142.809777	43.776	6.877828305	7193.463605
Fossil depletion (kg oil-Eq)	1942.26165	0	1.697000292	1943.95865

Human toxicity (kg 1,4-DCB-Eq)	2507.29498	0	64.23559086	2571.530571
Ozone depletion (kg CFC-11-Eq)	0.000496069	0	3.54346E-07	0.000496423
Water depletion (m3)	17.07490721	0	0.084850031	17.15975724

4.4.7 Factory Construction

During the fabrication of HHO kits in the factory, several impacts were generated and categorized into various groups, beginning with the 18th impact. The factory utilization and construction duration ratio to the annual production quantity of HHO kits was calculated. Figure 4.18 illustrates the chart derived from the data collected from Table 4.10.

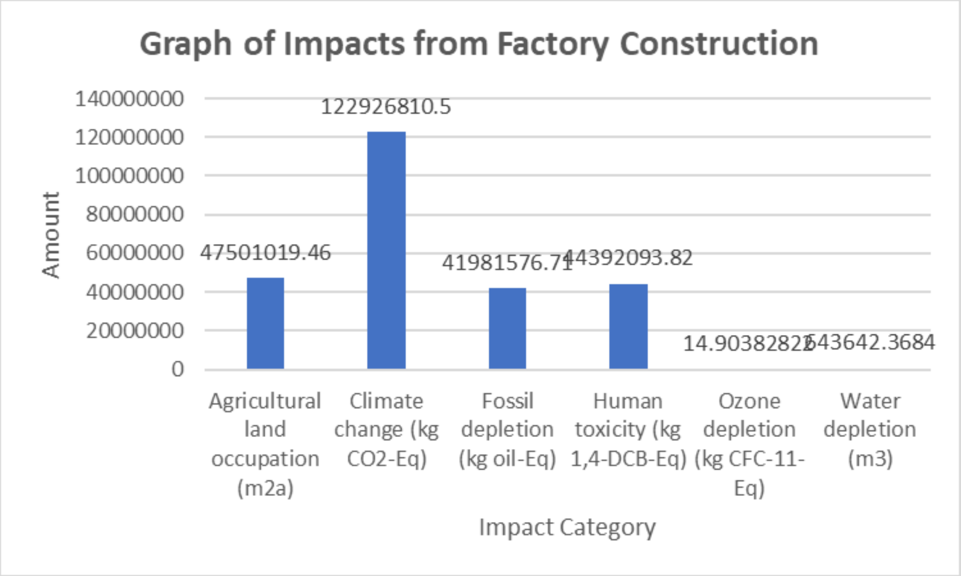


Figure 4. 18: Graph of Impacts from Factory Construction and Utilization

Table 4. 8: Impacts from Factory Construction in each Category

Impact category	Factory construction	Total
Agricultural land occupation (m2a)	47501019.46	47501019.46
Climate change (kg CO2-Eq)	122926810.5	122926810.5
Fossil depletion (kg oil-Eq)	41981576.71	41981576.71
Human toxicity (kg 1,4-DCB-Eq)	44392093.82	44392093.82
Ozone depletion (kg CFC-11-Eq)	14.90382822	14.90382822
Water depletion (m3)	643642.3684	643642.3684

5 Discussion

The following section thoroughly analyses the results and approaches utilized in the LCA of the developed Dry-Type HHO generator kit built explicitly for internal combustion engines. This undertaking consists of two main stages: creating the HHO kit and using LCA to evaluate its environmental consequences. Furthermore, it diverges from prior studies on liquid-operated HHO generation devices. The primary objective of this study is to quantitatively assess the ecological impacts linked to the recently developed HHO gas generator kit's manufacturing phase, specially designed for mobile small-scale engines like motorbikes and three-wheelers.

5.1 Design of the HHO Kit

It was the beginning of the research, and relevant data was collected from valuable resources as methodology descriptions to make a sustainable design with suitable measurements for the expected layout of the HHO generator kit. It was accomplished through collaborative endeavours with mentors, encompassing alterations to the electrode material (shifting from graphite to carbon nanotube) and refinements to the generator fixes.

In the designing phase, the design approach used SolidWorks, a specialized 3D modelling software designed primarily for mechanical engineering modelling, designing, and drawing. The design proportions were created following ISO standards, which included the integration of fastening bolts, threaded cuts, and extrusions with Metric units of MMGS (Millimeter, Gram, Second). Here, the software is limited to generating only the initial portion before proceeding with the assembly procedure. Therefore, the design was partitioned into various pieces.

5.1.1 HHO Generator Unit

There are main sub-elements to construct an HHO generator by assembling all of them.

5.1.1.1 Electrodes

The improved electrodes of anode, cathode and neutral were developed by employing carbon nanotubes, a form of carbon fibre, as a substitute for graphite. The procedure entailed affixing carbon nanotube plate electrodes to copper terminal plates employing graphite paste. The leaves were made of copper, renowned for its exceptional conductivity. The plates were connected using conductive graphite, which ensured no electrolyte or HHO gas leakage. Furthermore, this technique decreased the gap between the plates, facilitating effective electron transmission because of the interconnected surface areas of both plates.

Consequently, any worries regarding internal resistance were eliminated. The neutral electrodes serve the dual purpose of operating as both anodes and cathodes, effectively isolating the reaction and minimizing heat generation. The electrode possesses a reaction area with dimensions of 40x40mm. The electrode has two distinct types of apertures: gas transfer apertures, two of which are situated on the upper surface of the electrode within the reaction zone, and an electrolyte transfer aperture located at the bottom of the electrode within the reaction zone. Each hole has a dimension of 6M.

5.1.1.2 Frame

Acrylic plates were used as side plates to link the electrodes and gaskets, forming a frame. The electrodes and gaskets were affixed to the side plates using stainless-steel fasteners. The selection of acrylic was predicated upon its robust material strength and exceptional transparency, facilitating the visual monitoring of HHO gas production. The fastenings were made of stainless steel, which was selected for its superior resistance to corrosion compared to ferrous materials. This choice was made because the unit was expected to be exposed to moist circumstances, as it was designed for outdoor use.

5.1.1.3 Gasket

It is one of the main sub-elements in the HHO generator unit because it prevents the leakages of electrolytes and HHO gas from going outside. Also, it controls the short circuit by interconnecting the anode and cathode electrodes and reserving the volume for both anode, cathode, and neutral electrodes. The gasket has a uniform thickness of 3mm and is the same size as the electrode. It includes a 40x40mm inner cut to create a reserved electrode reaction area. The EPDM rubber material is resistant to reactions in acidic and basic conditions. The reason for utilization was because of the application of base electrolyte. Its soft nature allows it to fit perfectly against the surfaces of the electrodes.

5.1.2 Gas Separator Unit

The fully acrylic base chamber was designed using two different plate sizes: four plates measuring 120x80x2mm and two plates measuring 80x45x2mm. Cyanoacrylate glue was intended to attach these plates, as this adhesive is specially made for bonding plastic components. Five 8mm holes were intentionally placed strategically to allow for the required fittings to ensure optimal performance. The chamber is designed to withstand internal gas pressure of up to 1 bar, using 2mm thick acrylic sheets.

5.1.3 Pneumatic fittings

Precise design criteria, encompassing pressure, weight constraints, and cost, dictated the selection of pneumatic fittings. 6M pneumatic plastic fittings were selected for both the HHO generating unit and gas separator unit to comply with the specifications of the HHO kit, as it can withstand a low pressure of around 1 bar. Durable pneumatic hoses, appropriate for the gas separator and HHO generating units, were firmly attached to the permanent fittings. During the installation of the fittings, a thread seal is applied to the threaded surface to ensure a secure fixation. The fittings were prefabricated components procured from China.

Afterwards, all design components generated separately were merged utilizing the match function in the software's assembly area. Subsequently, a procedure was enacted to assess the weight of each element using SolidWorks sustainability individually. This was performed to determine the significance of individual members and sections in conducting an LCA during the phase of material extraction.

5.2 The Requirement of HHO Gas flowrate

The flow rate of gasoline is a crucial parameter for determining the volume of the HHO generator and separator unit during the design phase, considering the appropriate size of fittings. Based on equation usage, the flow rates of HHO gas and gasoline were determined during the design phase of the approach. Crucially, a ratio may be applied to hybrid systems combining HHO gas and internal combustion engines. The optimal balance for achieving peak performance in the internal combustion engine is one-part HHO gas to eight parts gasoline. The measured flow rate of HHO gas was determined to be 2.83 millilitres per minute, and the unit was specifically constructed to accommodate this flow rate.

5.3 Electrolyte

The design adheres to the alkaline electrolyzer approach, so KOH was selected based on its superior electrolyte properties compared to other choices. Combining KOH with distilled water according to the predicted molar mass is advised to get optimal concentrations of high-quality electrolytes. Using pure KOH with a purity level of around 98% is recommended. Thus, a concentration level of 0.1M was upheld to minimize oxidation and electron transfer obstacles while bubbling, enhancing the reactive surface area.

5.4 Application of the LCA

It is aimed to evaluate the environmental impact of the HHO gas generator kit manufacturing in Sri Lanka, focusing on improving performance and reducing emissions in gasoline-powered selected range of vehicle types such as motorcycles and three-wheelers. The process involved defining the objective, assessing effects, and interpreting outcomes through data collection and analysis. The goal was to produce practical conclusions and suggestions for future production choices. The LCA application phase comprehensively evaluated the environmental consequences of the production process, including material extraction, electricity, and transportation.

The assessment covered the complete manufacturing process of the HHO generator kit, starting from the extraction of raw materials to the packing process to finalize as a product. It included material processing, component production, assembly, and packaging. Hence, a system boundary was selected, called the cradle-to-gate system boundary. The detailed system boundary is illustrated in Figure 5.1.

Four main functional components were involved in this case: the HHO generation unit, Gas separator unit, Pneumatic fittings, and electrolyte. The impact assessment scope encompassed diverse categories, contingent upon the chosen impact assessment methodology. In this case, the ReCiPe Midpoint H technique was selected to quantitatively assess impacts in six categories: Agricultural land occupation, Climate change, Fossil depletion, Human toxicity, Ozone depletion, and Water depletion. A total of eighteen impact categories were considered. This method was considered the most appropriate for evaluating the anticipated impact categories within the defined boundaries of the system. The inventory primarily consisted of various materials such as carbon nanotubes, copper, acrylic, stainless steel, EPDM rubber, graphite paste, synthetic rubber, PVC, and HDPE plastics. Packaging materials such as cardboard, polyethene, and aluminium were also included.

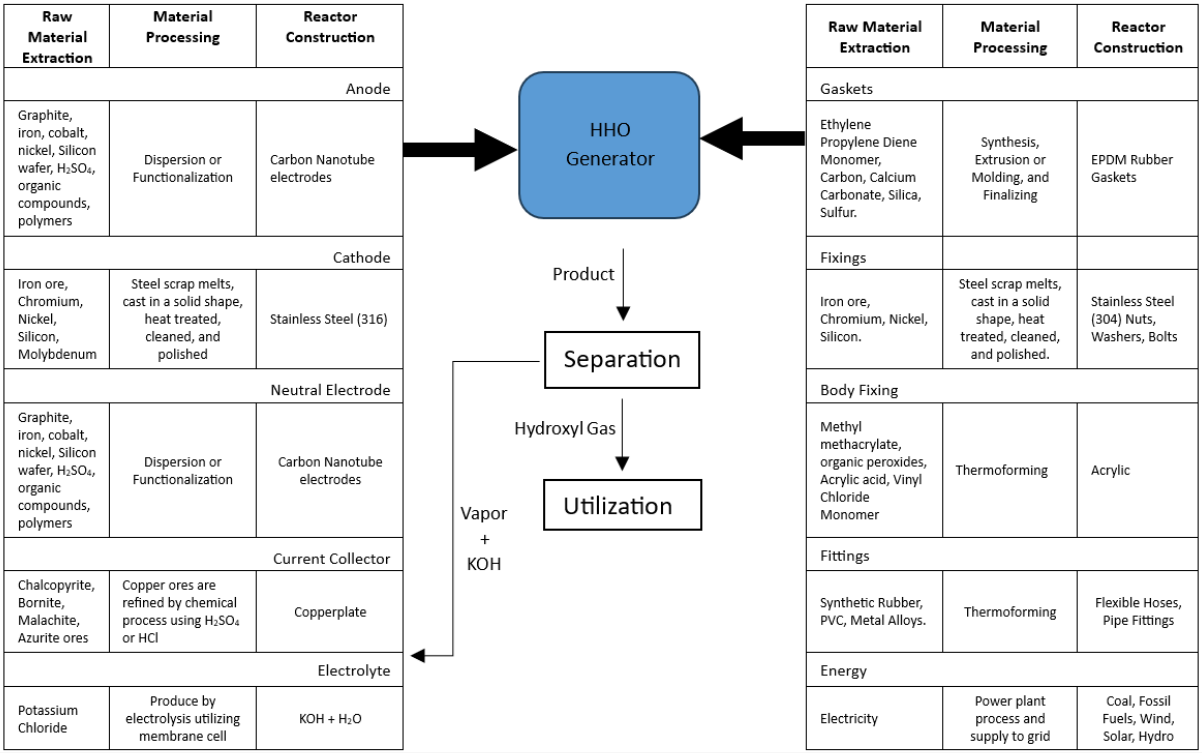


Figure 5. 1: Detailed System Boundary of the HHO kit Manufacturing

The application of LCA to the HHO kit involves several crucial production stages, namely Raw Material Extraction, Material Processing, Component Fabrication, Assembling, and Packaging. The figures for these procedures were meticulously derived from the Solidworks sustainability software, which offers the precise mass of each component following the design building.

In addition, the product's construction and operation were evaluated to assess the impact of the factory. This assessment covered aspects such as the materials used for construction, energy consumption, and the environmental repercussions of establishing the manufacturing facility. The allocation of factory construction was calculated by dividing the overall construction expenditure by the annual production volume of manufactured goods. The methodology visually depicted the material inputs, energy inputs, and transportation amounts.

The OpenLCA software, noted for its precision, was utilized for inventory analysis. It uses the very accurate Ecoinvent 3.8 database under ISO 14040 to 14044 standards to provide a framework for analyzing LCI with cut-off data sets. The process function incorporated all subunits that utilize raw materials into the software. The geographic factors played a vital role, as the data connection is unique to each region, and specific components of the HHO kit (fittings) were produced in

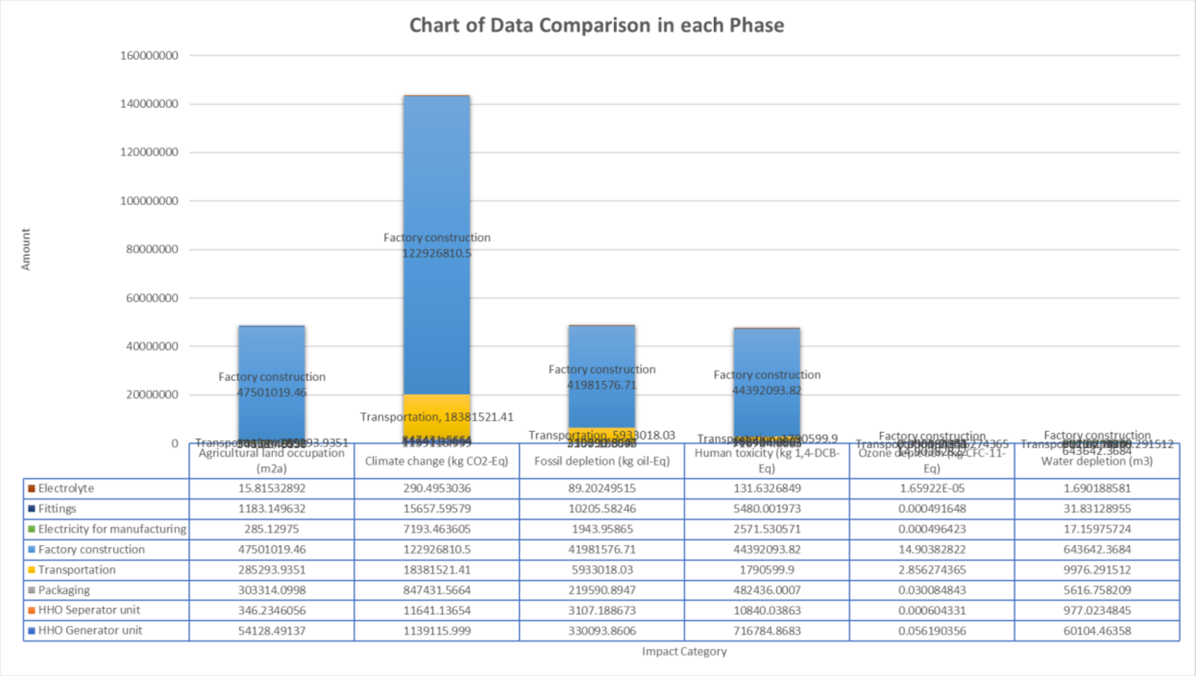
China. At the same time, the manufacturing was situated in Sri Lanka. Furthermore, certain elements were previously present in the database, enabling the retrieval of data that corresponds to the appropriate geographical location.

After incorporating the necessary ingredients, a production system was established for manufacturing 1000 units per year, utilizing the primary manufacturing process of the HHO kit. Afterwards, the ultimate computation was executed, opting for the effect evaluation of ReCiPe Midpoint H. This extensive inquiry yielded a complete comprehension of the environmental ramifications linked to the production stage of the products.

5.5 Comparison of the Impact Data Analysis

The main consequences of industrial development can be classified into specific categories, including Agricultural land occupation, Climate change, Fossil depletion, and Human toxicity within this framework. Climate change is afforded the highest importance among these categories compared to the others. Furthermore, transportation is of higher importance in contrast to the other elements, except for industrial building and use. Nevertheless, the production phase of the HHO Kit exhibited a somewhat lower influence on emissions compared to other factors.

Thus, it can be inferred that the factory can effectively reduce its emissions by increasing the annual production of HHO kits and minimizing transportation frequencies through effective management of raw material extraction and utilization. This reduction is achieved by lowering the emission factor compared to the analysis time value. Figure 5.2 illustrates the chart of comparison.



	Agricultural land occupation (m2a)	Climate change (kg CO2-Eq)	Fossil depletion (kg oil-Eq)	Human toxicity (kg 1,4-DCB-Eq)	Ozone depletion (kg CFC-11-Eq)	Water depletion (m3)
■ Electrolyte	15.81532892	290.4953036	89.20249515	131.6326849	1.65922E-05	1.690188581
■ Fittings	1183.149632	15657.59579	10205.58246	5480.001973	0.000491648	31.83128955
■ Electricity for manufacturing	285.12975	7193.463605	1943.95865	2571.530571	0.000496423	17.15975724
■ Factory construction	47501019.46	122926810.5	41981576.71	44392093.82	14.90382822	643642.3684
■ Transportation	285293.9351	18381521.41	5933018.03	1790599.9	2.856274365	9976.291512
■ Packaging	303314.0998	847431.5664	219590.8947	482436.0007	0.030084843	5616.758209
■ HHO Seperator unit	346.2346056	11641.13654	3107.188673	10840.03863	0.000604331	977.0234845
■ HHO Generator unit	54128.49137	1139115.999	330093.8606	716784.8683	0.056190356	60104.46358

Figure 5. 2: Graph of Data Comparison in each Phase

5.6 Possibility Impacts

During the consumption phase of this fully developed commercial product, it can have both sound and adverse effects.

Using chosen IC engines principally reduces carbon and NOx emissions due to the enhanced combustion process within the combustion chamber. This is comparable to the influence of Electronic Fuel Injection (EFI) technology on the calibre of combustion gas emissions in internal combustion engines. The detection of water vapour at the silencer's exit is readily apparent because of the interaction between hydrogen and gasoline, causing the dissociation of carbon from the process. When installed on the selected IC engine, this unit will operate as an EFI engine, increasing engine braking power while decreasing greenhouse gas emissions (GHG). As a result, this will have a beneficial effect on the environment.

The application of electrolytes when utilizing phase can happen in several ways, including improper disposal or leakage of KOH, which can lead to chemical discharge into water bodies and soil quality by changing the pH levels and potentially disrupting aquatic ecosystems. Hence, handling, utilising, and disposing of KOH to minimise its environmental impact is essential, as well as following proper guidelines and regulations for handling hazardous chemicals and waste disposal. It's the same as wet type battery acid handle, utilize, and dispose of.

In addition, carbon nanotube, copper, stainless steel, EPDM rubber, and synthetic rubber can be recycled as disposable materials, except for acrylic, PVA, and HDPE. Adhering to appropriate standards and laws is crucial when contemplating the use and disposal of products that comprise carbon nanotubes, copper, stainless steel, EPDM rubber, and synthetic rubber. It is essential to adhere to rules when dealing with waste containing carbon nanotubes and to consider specific ways for recycling or disposing of these nanomaterials. Copper and stainless-steel materials are highly recyclable, and it is essential to recycle items made from these materials through proper routes to minimize the necessity for fresh resource extraction. EPDM rubber can be recycled and transformed into other products or integrated into alternative materials using appropriate recycling processes. Synthetic rubber, such as EPDM rubber, can be recycled through proper channels. It is essential to follow responsible disposal techniques to reduce its environmental impact. Therefore, it also contributes to the circular economy by increasing the likelihood of recycling and upcycling.

6 Conclusion

The main goal of this study was to evaluate the environmental impact of manufacturing the HHO Kit in Sri Lanka, specifically concerning its effects on performance and emissions in gasoline-powered vehicles. The focus was on assessing the ecological implications during the LCA phase of the kit's production. This study focuses on creating a specialized Dry-Type HHO generator kit for internal combustion engines, developed explicitly for small-scale mobile machines like motorcycles and three-wheelers. The kit consists of two primary phases: its development and the application of LCA to assess its environmental impacts.

The design procedure involved altering the electrode materials and improving the generator fittings. SolidWorks was used to create the various components. The notable elements of the HHO generator unit consist of improved electrodes made from carbon nanotubes, an acrylic plate frame, and EPDM rubber gaskets. Meanwhile, the gas separator unit includes a base chamber made entirely of acrylic, which contains plates of varying diameters. The pace at which HHO gas flows and the management of KOH concentration are crucial elements that impact the volume and lifespan use of the HHO kit.

LCA involves interconnected activities, from defining the objective and proceeding to conducting a thorough examination of the environmental impacts and interpreting the results. The conclusive inventory analysis findings reveal that the manufacturing process has a minor effect compared to other operations. This positions the HHO Kit as an environmentally friendly product with favourable environmental consequences

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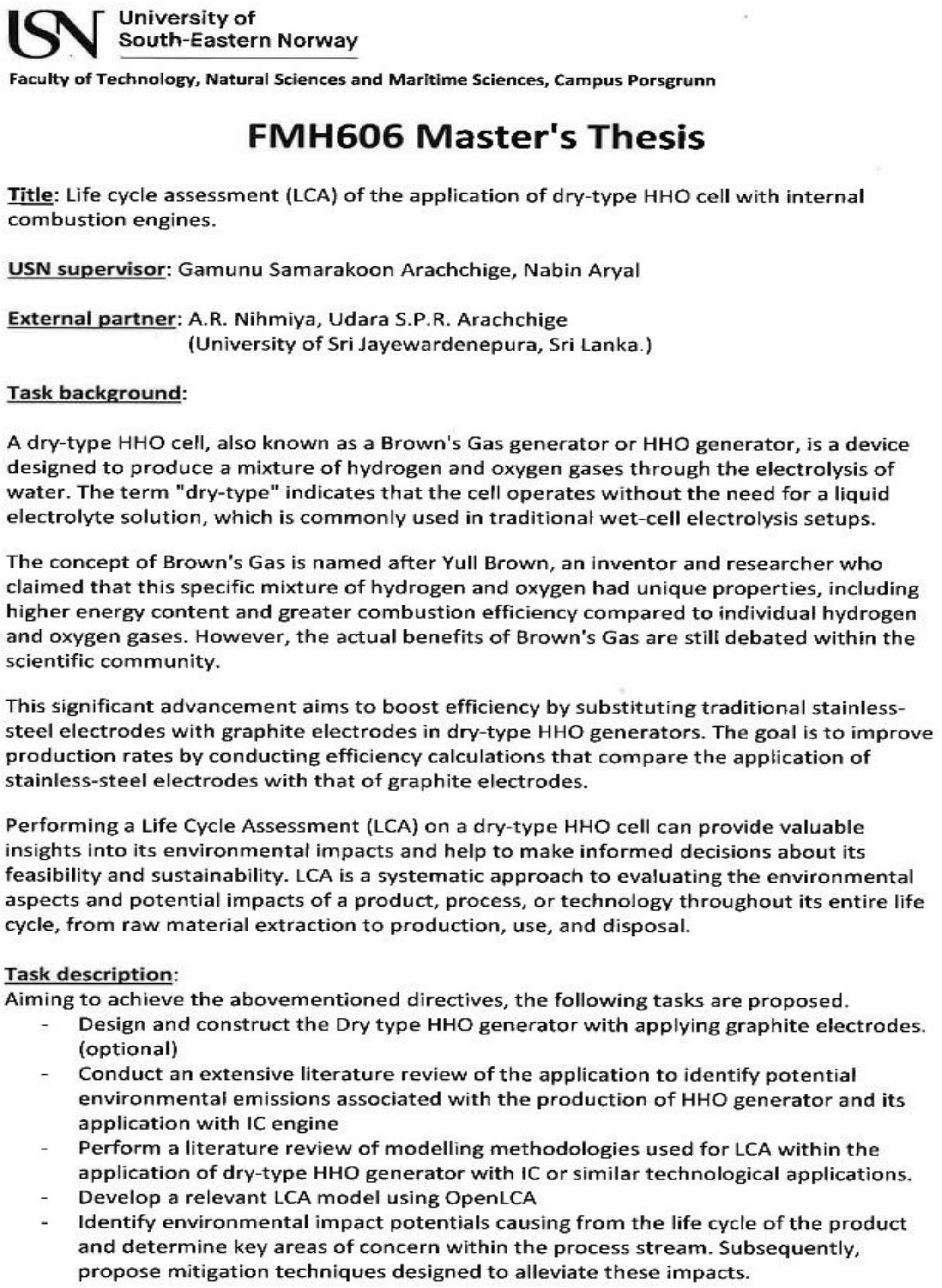
Appendixes

Appendix A Research Proposal



University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Life cycle assessment (LCA) of the application of dry-type HHO cell with internal combustion engines.

USN supervisor: Gamunu Samarakoon Arachchige, Nabin Aryal

External partner: A.R. Nihmiya, Udara S.P.R. Arachchige
(University of Sri Jayewardenepura, Sri Lanka.)

Task background:

A dry-type HHO cell, also known as a Brown's Gas generator or HHO generator, is a device designed to produce a mixture of hydrogen and oxygen gases through the electrolysis of water. The term "dry-type" indicates that the cell operates without the need for a liquid electrolyte solution, which is commonly used in traditional wet-cell electrolysis setups.

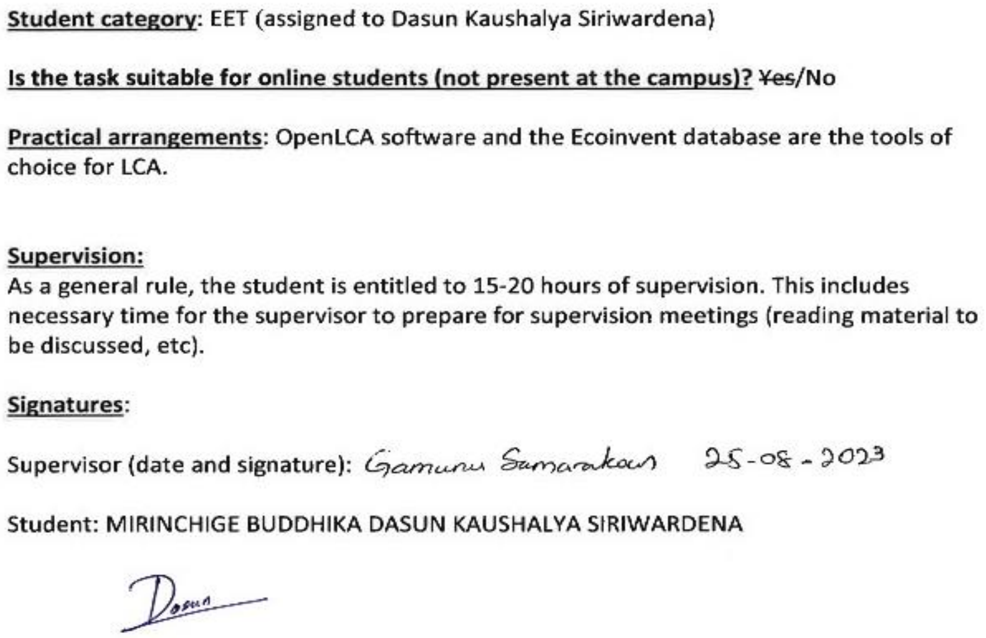
The concept of Brown's Gas is named after Yull Brown, an inventor and researcher who claimed that this specific mixture of hydrogen and oxygen had unique properties, including higher energy content and greater combustion efficiency compared to individual hydrogen and oxygen gases. However, the actual benefits of Brown's Gas are still debated within the scientific community.

This significant advancement aims to boost efficiency by substituting traditional stainless-steel electrodes with graphite electrodes in dry-type HHO generators. The goal is to improve production rates by conducting efficiency calculations that compare the application of stainless-steel electrodes with that of graphite electrodes.

Performing a Life Cycle Assessment (LCA) on a dry-type HHO cell can provide valuable insights into its environmental impacts and help to make informed decisions about its feasibility and sustainability. LCA is a systematic approach to evaluating the environmental aspects and potential impacts of a product, process, or technology throughout its entire life cycle, from raw material extraction to production, use, and disposal.

Task description:
Aiming to achieve the abovementioned directives, the following tasks are proposed.

- Design and construct the Dry type HHO generator with applying graphite electrodes. (optional)
- Conduct an extensive literature review of the application to identify potential environmental emissions associated with the production of HHO generator and its application with IC engine
- Perform a literature review of modelling methodologies used for LCA within the application of dry-type HHO generator with IC or similar technological applications.
- Develop a relevant LCA model using OpenLCA
- Identify environmental impact potentials causing from the life cycle of the product and determine key areas of concern within the process stream. Subsequently, propose mitigation techniques designed to alleviate these impacts.



Student category: EET (assigned to Dasun Kaushalya Siriwardena)

Is the task suitable for online students (not present at the campus)? ~~Yes~~/No

Practical arrangements: OpenLCA software and the Ecoinvent database are the tools of choice for LCA.

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature): Gamunu Samarakoon 25-08-2023

Student: MIRINCHIGE BUDDHIKA DASUN KAUSHALYA SIRIWARDENA

Dasun

Appendix B: Table of Inventory Inputs Results

Inputs

Flow	Result	Unit
Aluminium, in ground	823582.9	kg
Anhydrite, in ground	14.81524	kg
Antimony, in ground	4.264405	kg
Argon-40	42016.81	kg
Arsenic, in ground	2.640468	kg
Barium, in ground	100506.4	kg
Basalt, in ground	2566878	kg
Borax, in ground	303.4534	kg
Bromine, in water	6.459581	kg
Cadmium, in ground	70.04372	kg
Calcite, in ground	38785143	kg
Calcium, in ground	74184.64	kg
Carbon dioxide, in air	23503468	kg
Carbon dioxide, non-fossil, resource correction	-5800265	kg
Carbon, organic, in soil or biomass stock	22466.22	kg
Carnallite	316.0471	kg
Cerium, in ground	813.22	kg
Chromium, in ground	10118.36	kg

Chrysotile, in ground	1893.609	kg
Clay, bentonite, in ground	143655.5	kg
Clay, unspecified, in ground	35350349	kg
Coal, brown, in ground	3809190	kg
Coal, hard, unspecified, in ground	22199719	kg
Cobalt, in ground	127.2161	kg
Colemanite, in ground	371.7168	kg
Copper, in ground	57236.2	kg
Diatomite, in ground	0.003802	kg
Dolomite, in ground	428555	kg
Dysprosium, in ground	0.790388	kg
Energy, geothermal, converted	280631.6	kWh
Energy, gross calorific value, in biomass	74920312	kWh
Energy, gross calorific value, in biomass, primary forest	150469.8	kWh
Energy, kinetic (in wind), converted	2422861	kWh
Energy, potential (in hydropower reservoir), converted	19448235	kWh
Energy, solar, converted	49048.02	kWh
Europium, in ground	3.501905	kg
Feldspar, in ground	1.063323	kg
Fish, demersal, in ocean	1.3E-21	kg
Fish, pelagic, in ocean	1.41E-11	kg

Fluorine, in ground	590.7244	kg
Fluorspar, in ground	6847.247	kg
Gadolinium, in ground	11.09743	kg
Gallium, in ground	254.586	kg
Gangue, bauxite, in ground	8711147	kg
Gangue, in ground	29670155	kg
Gas, mine, off-gas, process, coal mining	184151	m3
Gas, natural, in ground	8209712	m3
Gold, in ground	1.983065	kg
Granite, in ground	16415775	kg
Gravel, in ground	4.48E+08	kg
Gypsum, in ground	1290356	kg
Hafnium, in ground	79.51062	kg
Iodine, in water	1.424793	kg
Iron, in ground	11139426	kg
Kaolinite, in ground	1485.972	kg
Kieserite, in ground	0.000805	kg
Krypton, in air	5.64E-09	kg
Lanthanum, in ground	434.9142	kg
Laterite, in ground	194534.8	kg
Lead, in ground	129196.4	kg

Lithium, in ground	0.050437	kg
Magnesite, in ground	50004.1	kg
Magnesium, in ground	59685.28	kg
Manganese, in ground	145801.5	kg
Mercury, in ground	0.110246	kg
Metamorphous rock, graphite containing, in ground	11751.62	kg
Molybdenum, in ground	1022.226	kg
Neodymium, in ground	286.2247	kg
Nickel, in ground	68202.25	kg
Niobium, in ground	68.39243	kg
Nitrogen	2265906	kg
Occupation, annual crop	13991.2	m2*a
Occupation, annual crop, irrigated	2017.448	m2*a
Occupation, annual crop, irrigated, intensive	2.770962	m2*a
Occupation, annual crop, non-irrigated	74.6762	m2*a
Occupation, annual crop, non-irrigated, extensive	37.1973	m2*a
Occupation, annual crop, non-irrigated, intensive	102877	m2*a
Occupation, arable land, unspecified use	1.531829	m2*a
Occupation, construction site	14680.44	m2*a
Occupation, dump site	540600.9	m2*a
Occupation, forest, extensive	493178.8	m2*a

Occupation, forest, intensive	47448339	m2*a
Occupation, grassland, natural (non-use)	11077.23	m2*a
Occupation, grassland, natural, for livestock grazing	9.13E-05	m2*a
Occupation, industrial area	34904834	m2*a
Occupation, inland waterbody, unspecified	76.72471	m2*a
Occupation, lake, artificial	420702.8	m2*a
Occupation, mineral extraction site	1208282	m2*a
Occupation, pasture, man made	0.000166	m2*a
Occupation, pasture, man made, extensive	0.000192	m2*a
Occupation, pasture, man made, intensive	9.204525	m2*a
Occupation, permanent crop	2727.517	m2*a
Occupation, permanent crop, irrigated	448.4324	m2*a
Occupation, permanent crop, irrigated, intensive	3.300203	m2*a
Occupation, permanent crop, non-irrigated	13971.94	m2*a
Occupation, river, artificial	82791.86	m2*a
Occupation, seabed, drilling and mining	3830.746	m2*a
Occupation, seabed, infrastructure	36.286	m2*a
Occupation, shrub land, sclerophyllous	29958.01	m2*a
Occupation, traffic area, rail network	120850.7	m2*a
Occupation, traffic area, rail/road embankment	842170.8	m2*a
Occupation, traffic area, road network	17001625	m2*a

Occupation, unspecified	34914.77	m2*a
Occupation, unspecified, natural (non-use)	12906.53	m2*a
Occupation, urban, discontinuously built	60.35471	m2*a
Occupation, urban/industrial fallow (non-use)	6.152363	m2*a
Oil, crude, in ground	27315034	kg
Olivine, in ground	5.368044	kg
Oxygen	12207602	kg
Palladium, in ground	0.162312	kg
Peat, in ground	27316.02	kg
Perlite, in ground	5.423665	kg
Phosphorus, in ground	3603.306	kg
Platinum, in ground	0.15613	kg
Potassium, in ground	3344.477	kg
Praseodymium, in ground	95.09611	kg
residual wood, dry	0.001322	m3
Rhenium, in ground	0.0951	kg
Rhodium, in ground	0.020386	kg
Samarium, in ground	15.64109	kg
Sand, unspecified, in ground	49572420	kg
Scandium, in ground	1.057588	kg
Selenium, in ground	70.27864	kg

Shale, in ground	7235117	kg
Silicon, in ground	7870.541	kg
Silver, in ground	315.4715	kg
Sodium chloride, in ground	5408916	kg
Sodium nitrate, in ground	46.35073	kg
Sodium sulphate, various forms, in ground	566.1865	kg
Sodium, in ground	81.44615	kg
Spodumene, in ground	7.858892	kg
Strontium, in ground	237.8429	kg
Sulfur, in ground	26591.79	kg
Sylvite, in ground	4012.942	kg
Talc, in ground	233.2033	kg
Tantalum, in ground	2.629952	kg
Tellurium, in ground	13.09184	kg
Terbium, in ground	0.474233	kg
Tin, in ground	340.0558	kg
Titanium, in ground	23742.96	kg
Transformation, from annual crop	12745.35	m2
Transformation, from annual crop, irrigated	1738.905	m2
Transformation, from annual crop, irrigated, intensive	0.819901	m2
Transformation, from annual crop, non-irrigated	117302.3	m2

Transformation, from annual crop, non-irrigated, extensive	33.35246	m2
Transformation, from annual crop, non-irrigated, intensive	448.9524	m2
Transformation, from arable land, unspecified use	6762.758	m2
Transformation, from cropland fallow (non-use)	164.3237	m2
Transformation, from dump site, inert material landfill	5049.718	m2
Transformation, from dump site, residual material landfill	539.0897	m2
Transformation, from dump site, sanitary landfill	328.1285	m2
Transformation, from dump site, slag compartment	73.80285	m2
Transformation, from forest, extensive	110294.2	m2
Transformation, from forest, intensive	503101.9	m2
Transformation, from forest, primary (non-use)	1632.784	m2
Transformation, from forest, secondary (non-use)	137.443	m2
Transformation, from forest, unspecified	39008.45	m2
Transformation, from grassland, natural (non-use)	650.0906	m2
Transformation, from grassland, natural, for livestock grazing	164.7308	m2
Transformation, from heterogeneous, agricultural	1.746342	m2
Transformation, from industrial area	290.651	m2
Transformation, from mineral extraction site	10456.32	m2
Transformation, from pasture, man made	11027.43	m2
Transformation, from pasture, man made, extensive	3.85E-06	m2
Transformation, from pasture, man made, intensive	26.36823	m2

Transformation, from permanent crop	202.2653	m2
Transformation, from permanent crop, irrigated	16.24571	m2
Transformation, from permanent crop, irrigated, intensive	0.141579	m2
Transformation, from permanent crop, non-irrigated	698.5972	m2
Transformation, from river, natural (non-use)	2626.121	m2
Transformation, from seabed, infrastructure	0.084496	m2
Transformation, from seabed, unspecified	3832.847	m2
Transformation, from shrub land, sclerophyllous	6283.125	m2
Transformation, from traffic area, rail/road embankment	2289.891	m2
Transformation, from traffic area, road network	3.27E-14	m2
Transformation, from unspecified	889401.2	m2
Transformation, from unspecified, natural (non-use)	6.243286	m2
Transformation, from wetland, inland (non-use)	2975.858	m2
Transformation, to annual crop	2597.261	m2
Transformation, to annual crop, irrigated	1738.905	m2
Transformation, to annual crop, irrigated, intensive	2.868586	m2
Transformation, to annual crop, non-irrigated	117283	m2
Transformation, to annual crop, non-irrigated, extensive	45.42091	m2
Transformation, to annual crop, non-irrigated, intensive	11754.79	m2
Transformation, to arable land, unspecified use	9684.878	m2
Transformation, to cropland fallow (non-use)	320.2762	m2

Transformation, to dump site	3438.942	m2
Transformation, to dump site, inert material landfill	5049.718	m2
Transformation, to dump site, residual material landfill	539.116	m2
Transformation, to dump site, sanitary landfill	328.1285	m2
Transformation, to dump site, slag compartment	73.80285	m2
Transformation, to forest, extensive	3793.754	m2
Transformation, to forest, intensive	604243.3	m2
Transformation, to forest, secondary (non-use)	3.85E-14	m2
Transformation, to forest, unspecified	12871.29	m2
Transformation, to grassland, natural (non-use)	147.6964	m2
Transformation, to grassland, natural, for livestock grazing	3.02E-06	m2
Transformation, to heterogeneous, agricultural	755.6874	m2
Transformation, to industrial area	697593.2	m2
Transformation, to inland waterbody, unspecified	0.767247	m2
Transformation, to lake, artificial	5380.917	m2
Transformation, to mineral extraction site	61478.7	m2
Transformation, to pasture, man made	29.29345	m2
Transformation, to pasture, man made, extensive	3.85E-06	m2
Transformation, to pasture, man made, intensive	0.462266	m2
Transformation, to permanent crop	631.6544	m2
Transformation, to permanent crop, irrigated	16.24571	m2

Transformation, to permanent crop, irrigated, intensive	0.141579	m2
Transformation, to permanent crop, non-irrigated	698.5972	m2
Transformation, to river, artificial	880.7747	m2
Transformation, to seabed, drilling and mining	3830.746	m2
Transformation, to seabed, infrastructure	2.101478	m2
Transformation, to seabed, unspecified	0.084496	m2
Transformation, to shrub land, sclerophyllous	5990.739	m2
Transformation, to traffic area, rail network	279.5329	m2
Transformation, to traffic area, rail/road embankment	8214.203	m2
Transformation, to traffic area, road network	167366.4	m2
Transformation, to unspecified	2942.154	m2
Transformation, to unspecified, natural (non-use)	314.7934	m2
Transformation, to urban, discontinuously built	1.209183	m2
Transformation, to urban/industrial fallow (non-use)	0.082032	m2
Transformation, to wetland, inland (non-use)	1.22E-13	m2
Ulexite, in ground	10.14464	kg
Uranium, in ground	161.483	kg
Vanadium, in ground	2.72437	kg
venting of argon, crude, liquid	3.907561	kg
venting of nitrogen, liquid	-72.4323	kg
Volume occupied, final repository for low-active radioactive waste	3.704637	m3

Volume occupied, final repository for radioactive waste	0.068791	m3
Volume occupied, reservoir	2298932	m3*a
Volume occupied, underground deposit	8.81101	m3
Water LK	20	m3
Water, cooling, unspecified natural origin	3543446	m3
Water, in air	395.0291	m3
Water, lake	18389.82	m3
Water, river	250738.8	m3
Water, salt, ocean	34415.91	m3
Water, salt, sole	16252.59	m3
Water, turbine use, unspecified natural origin	4.75E+08	m3
Water, unspecified natural origin	1021259	m3
Water, unspecified natural origin	44141.08	m3
Water, well, in ground	449822.7	m3
Wood, hard, standing	1939.239	m3
Wood, soft, standing	25096.68	m3
Wood, unspecified, standing	0.132515	m3
Xenon, in air	6.61E-10	kg
Yttrium, in ground	2.898089	kg
Zinc, in ground	599592.5	kg
Zirconium, in ground	4380.452	kg

Appendix C: Table of Inventory Output Results

Outputs

Flow	Result	Unit
1,3-Dioxolan-2-one	38.73499	kg
1,4-Butanediol	0.002243	kg
1,4-Butanediol	0.005159	kg
1-Pentanol	0.000693	kg
1-Pentanol	0.000289	kg
1-Pentene	0.000524	kg
1-Pentene	0.017487	kg
2,2,4-Trimethyl pentane	2.77E-05	kg
2,4-D	0.013681	kg
2,4-D	3.079167	kg
2,4-D amines	4.16E-12	kg
2,4-D amines	1.71E-14	kg
2,4-D amines	7.93E-13	kg
2,4-D amines	1.34E-10	kg
2,4-D ester	3.85E-12	kg
2,4-D ester	1.58E-14	kg
2,4-D ester	9.5E-13	kg
2,4-D ester	1.24E-10	kg
2,4-DB	-6.6E-09	kg

2,4-DB	-2.7E-11	kg
2,4-DB	-9.3E-10	kg
2,4-DB	-2.1E-07	kg
2-Aminopropanol	0.000652	kg
2-Aminopropanol	0.000271	kg
2-Methyl pentane	1.392167	kg
2-Methyl-1-propanol	0.000862	kg
2-Methyl-1-propanol	0.002068	kg
2-Methyl-2-butene	3.95E-07	kg
2-Methyl-2-butene	1.65E-07	kg
2-Nitrobenzoic acid	0.000649	kg
2-Propanol	0.009825	kg
2-Propanol	0.85765	kg
2-Propanol	3.483849	kg
2-Propanol	0.00048	kg
2-Propanol	50.68375	kg
4-Methyl-2-pentanol	0.001959	kg
4-Methyl-2-pentanone	0.379762	kg
4-Methyl-2-pentanone	0.01675	kg
4-Methyl-2-pentanone	1.05E-05	kg
4-Methyl-2-pentanone	0.055356	kg

Abamectin	0.00051	kg
Acenaphthene	0.000905	kg
Acenaphthene	0.001114	kg
Acenaphthene	0.000343	kg
Acenaphthene	0.008415	kg
Acenaphthylene	0.005873	kg
Acenaphthylene	2.15E-05	kg
Acenaphthylene	0.000473	kg
Acephate	0.001454	kg
Acephate	3.506729	kg
Acetaldehyde	33.948	kg
Acetaldehyde	463.717	kg
Acetaldehyde	124.4695	kg
Acetaldehyde	36.82762	kg
Acetamide	0.000358	kg
Acetamide	0.000178	kg
Acetamiprid	0.002889	kg
Acetic acid	73.72714	kg
Acetic acid	196.8682	kg
Acetic acid	38.75877	kg
Acetic acid	458.2609	kg

Acetochlor	0.037326	kg
Acetone	2.130126	kg
Acetone	0.039924	kg
Acetone	91.07418	kg
Acetone	156.3932	kg
Acetone	8.8596	kg
Acetonitrile	0.000231	kg
Acetonitrile	1.95325	kg
Acetyl chloride	0.000544	kg
Acidity, unspecified	12.79526	kg
Acidity, unspecified	0.84004	kg
Acifluorfen	0.0002	kg
Acifluorfen	8.56E-06	kg
Aclonifen	8.33E-07	kg
Acrinathrin	4.81E-16	kg
Acrolein	20.81696	kg
Acrolein	0.783666	kg
Acrolein	0.215154	kg
Acrylate, ion	0.069725	kg
Acrylic acid	0.02946	kg
Actinides, radioactive, unspecified	133.7039	kBq

Actinides, radioactive, unspecified	3308.73	kBq
Aerosols, radioactive, unspecified	21.7157	kBq
Alachlor	0.001413	kg
Alachlor	0.000807	kg
Aldehydes, unspecified	0.343252	kg
Aldehydes, unspecified	1.588237	kg
Aldehydes, unspecified	0.228189	kg
Aldicarb	0.015324	kg
Aldrin	0.004554	kg
Allyl chloride	0.006586	kg
Alpha-cypermethrin	0.000833	kg
Aluminium	78.84311	kg
Aluminium	81.92441	kg
Aluminium	6441.515	kg
Aluminium	452.0331	kg
Aluminium	6.268661	kg
Aluminium	86.87617	kg
Aluminium	1650.364	kg
Aluminium	916.9073	kg
Aluminium	224.426	kg
Aluminium	412254.9	kg

Aluminium	266.0056	kg
Aluminium	162.9947	kg
Aluminium hydroxide	0.002417	kg
Ametryn	0.000475	kg
Amidosulfuron	8.48E-07	kg
Ammonia	170624.2	kg
Ammonia	4253.838	kg
Ammonia	869.144	kg
Ammonia	1.979178	kg
Ammonia	0.542724	kg
Ammonium carbonate	6.972516	kg
Ammonium sulfate	0.000702	kg
Ammonium, ion	1372.958	kg
Ammonium, ion	4.133828	kg
Ammonium, ion	86.3601	kg
Ammonium, ion	9963.341	kg
Ammonium, ion	375.9604	kg
Aniline	0.006808	kg
Aniline	14.56056	kg
Aniline	0.002834	kg
Anthracene	0.000189	kg

Anthracene	1.13E-08	kg
Anthranilic acid	0.000505	kg
Anthraquinone	-7.4E-06	kg
Antimony	0.045295	kg
Antimony	230.3888	kg
Antimony	0.478318	kg
Antimony	3.174791	kg
Antimony	0.016813	kg
Antimony	0.094244	kg
Antimony	1.740815	kg
Antimony	7.07E-05	kg
Antimony	272.406	kg
Antimony	124.329	kg
Antimony	1.782284	kg
Antimony-122	2.858111	kBq
Antimony-124	11094.38	kBq
Antimony-124	0.004272	kBq
Antimony-125	147.0181	kBq
Antimony-125	0.073982	kBq
AOX, Adsorbable Organic Halogen as Cl	14.60857	kg
AOX, Adsorbable Organic Halogen as Cl	0.002276	kg

AOX, Adsorbable Organic Halogen as Cl	3.87816	kg
Argon-40	21.77355	kg
Argon-41	7158.946	kBq
Arsenic	4.608017	kg
Arsenic	1.370938	kg
Arsenic	29.19513	kg
Arsenic	0.427254	kg
Arsenic	0.277333	kg
Arsenic	0.998061	kg
Arsenic	0.059273	kg
Arsenic, ion	195.3917	kg
Arsenic, ion	236.5642	kg
Arsenic, ion	0.193667	kg
Arsenic, ion	20.90231	kg
Arsenic, ion	1.692984	kg
Arsine	3.43E-07	kg
Asulam	4.92E-10	kg
Atrazine	2.42E-09	kg
Atrazine	6.27E-07	kg
Atrazine	0.001117	kg
Atrazine	0.311153	kg

Azadirachtin	0.03002	kg
Azinphos-methyl	0.001199	kg
Azoxystrobin	0.000661	kg
Azoxystrobin	0.610168	kg
Barite	597.6591	kg
Barite	2386.849	kg
Barium	88.83535	kg
Barium	7.553337	kg
Barium	12.26043	kg
Barium	0.85843	kg
Barium	9.149229	kg
Barium	340.2763	kg
Barium	0.012	kg
Barium	3934.052	kg
Barium	1055.178	kg
Barium	5.705917	kg
Barium	48.02679	kg
Barium	556.3962	kg
Barium-140	6.2072	kBq
Barium-140	2.386414	kBq
Benomyl	0.000254	kg

Bensulfuron methyl ester	2.37E-06	kg
Bentazone	5.57E-09	kg
Bentazone	8.99E-06	kg
Bentazone	0.000612	kg
Bentazone	0.000301	kg
Benz(a)anthracene	7.12E-07	kg
Benz(a)anthracene	0.000113	kg
Benzal chloride	0.04411	kg
Benzal chloride	0.01838	kg
Benzal chloride	2.92E-06	kg
Benzaldehyde	16.09464	kg
Benzaldehyde	0.064165	kg
Benzaldehyde	1.435038	kg
Benzene	1265.582	kg
Benzene	332.4955	kg
Benzene	3892.303	kg
Benzene	12.23532	kg
Benzene	388.1715	kg
Benzene	6.710902	kg
Benzene, chloro-	18.27695	kg
Benzene, dichloro	0.002184	kg

Benzene, ethyl-	0.37657	kg
Benzene, ethyl-	356.1842	kg
Benzene, ethyl-	17.67835	kg
Benzene, ethyl-	6.058686	kg
Benzene, ethyl-	1.324869	kg
Benzene, ethyl-	29.05162	kg
Benzene, hexachloro-	6.94E-07	kg
Benzene, hexachloro-	0.000525	kg
Benzene, hexachloro-	5.04E-11	kg
Benzene, hexachloro-	0.009112	kg
Benzene, pentachloro-	1.14E-06	kg
Benzene, pentachloro-	0.001326	kg
Benzo(a)pyrene	8.65E-08	kg
Benzo(a)pyrene	0.020501	kg
Benzo(a)pyrene	1.318121	kg
Benzo(a)pyrene	27.45702	kg
Benzo(b)fluoranthene	8.44E-08	kg
Benzo(b)fluoranthene	0.000134	kg
Benzo(ghi)perylene	1.19E-08	kg
Benzo(ghi)perylene	8.26E-06	kg
Benzo(k)fluoranthene	3.97E-08	kg

Benzo(k)fluoranthene	9.7E-05	kg
Benzyl alcohol	0.001926	kg
Beryllium	0.04036	kg
Beryllium	0.045233	kg
Beryllium	0.010792	kg
Beryllium	0.112021	kg
Beryllium	0.053986	kg
Beryllium	0.098071	kg
Beryllium	0.034421	kg
Beryllium	118.0472	kg
Beryllium	0.050308	kg
Beryllium	0.147296	kg
Beta-cyfluthrin	3.48E-05	kg
Beta-cyfluthrin	0.036561	kg
Bifenox	-1.2E-06	kg
Bifenthrin	0.022962	kg
Bitertanol	-9.6E-07	kg
BOD5, Biological Oxygen Demand	904283.7	kg
BOD5, Biological Oxygen Demand	222934.7	kg
BOD5, Biological Oxygen Demand	434.9119	kg
BOD5, Biological Oxygen Demand	29027.81	kg

BOD5, Biological Oxygen Demand	4561.85	kg
Borate	0.089092	kg
Borate	0.176264	kg
Boric acid	1.3E-10	kg
Boron	16.83823	kg
Boron	6.44691	kg
Boron	135.785	kg
Boron	0.22051	kg
Boron	25.18973	kg
Boron	0.444455	kg
Boron	9.864434	kg
Boron	3.48353	kg
Boron	0.003001	kg
Boron	633.8894	kg
Boron	20.86506	kg
Boron	5.444371	kg
Boron trifluoride	8.78E-07	kg
Boscalid	1.37E-14	kg
Bromate	45.09854	kg
Bromide	5.735027	kg
Bromine	856.4123	kg

Bromine	0.943438	kg
Bromine	11.05235	kg
Bromine	58.00385	kg
Bromine	0.13518	kg
Bromine	0.263727	kg
Bromine	2.941064	kg
Bromine	993.9979	kg
Bromine	9959.048	kg
Bromine	3.22591	kg
Bromine	38.64202	kg
Bromoxynil	-1.1E-13	kg
Bromoxynil	-6.9E-10	kg
Bromoxynil	-2.5E-09	kg
Bromoxynil	0.003487	kg
Bromuconazole	7.56E-08	kg
Buprofezin	1.25E-07	kg
Butadiene	0.000165	kg
Butadiene	7.17E-05	kg
Butane	149.0771	kg
Butane	291.2319	kg
Butane	1.790435	kg

Butanol	9.157637	kg
Butanol	0.002044	kg
Butene	0.150931	kg
Butene	0.485759	kg
Butyl acetate	11.89864	kg
Butyrolactone	0.000963	kg
Cadmium	0.175399	kg
Cadmium	6.010536	kg
Cadmium	8.50392	kg
Cadmium	0.180128	kg
Cadmium	3.95E-07	kg
Cadmium	0.132393	kg
Cadmium	0.070188	kg
Cadmium	4.581611	kg
Cadmium	0.004813	kg
Cadmium, ion	0.53637	kg
Cadmium, ion	2.81583	kg
Cadmium, ion	2.676656	kg
Cadmium, ion	151.9348	kg
Cadmium, ion	0.149735	kg
Calcium	62.04249	kg

Calcium	218.8158	kg
Calcium	39.06621	kg
Calcium	8.481005	kg
Calcium	312.4561	kg
Calcium	3013.662	kg
Calcium	2077.806	kg
Calcium, ion	13286.4	kg
Calcium, ion	62945.55	kg
Calcium, ion	2064742	kg
Calcium, ion	7685.121	kg
Calcium, ion	2585.614	kg
Captan	6E-07	kg
Carbaryl	9.08E-13	kg
Carbaryl	7.29E-11	kg
Carbaryl	0.000167	kg
Carbaryl	0.000195	kg
Carbendazim	3.155681	kg
Carbetamide	0.002449	kg
Carbofuran	0.141294	kg
Carbon	192461.7	kg
Carbon	167.9779	kg

Carbon	1212.254	kg
Carbon dioxide, fossil	50683299	kg
Carbon dioxide, fossil	65350069	kg
Carbon dioxide, fossil	17619442	kg
Carbon dioxide, fossil	122.8476	kg
Carbon dioxide, fossil	7442.534	kg
Carbon dioxide, from soil or biomass stock	183994.6	kg
Carbon dioxide, from soil or biomass stock	1701.976	kg
Carbon dioxide, non-fossil	8892490	kg
Carbon dioxide, non-fossil	1430040	kg
Carbon dioxide, non-fossil	331683.5	kg
Carbon dioxide, to soil or biomass stock	4428.197	kg
Carbon dioxide, to soil or biomass stock	48.53917	kg
Carbon disulfide	0.003983	kg
Carbon disulfide	0.01059	kg
Carbon disulfide	439.1809	kg
Carbon disulfide	5.42E-07	kg
Carbon monoxide, fossil	378856.1	kg
Carbon monoxide, fossil	29517.5	kg
Carbon monoxide, fossil	99677.38	kg
Carbon monoxide, fossil	0.081336	kg

Carbon monoxide, fossil	2372.732	kg
Carbon monoxide, from soil or biomass stock	1128.544	kg
Carbon monoxide, non-fossil	45336.29	kg
Carbon monoxide, non-fossil	3381.704	kg
Carbon monoxide, non-fossil	4053.978	kg
Carbon-14	1221.864	kBq
Carbon-14	686574.6	kBq
Carbonate	196.2886	kg
Carbonate	333.4076	kg
Carbonate	1.70254	kg
Carbonyl sulfide	28.25423	kg
Carbosulfan	8.91E-06	kg
Carboxylic acids, unspecified	0.000322	kg
Carboxylic acids, unspecified	970.6596	kg
Carboxylic acids, unspecified	4454.577	kg
Carfentrazone-ethyl	1.83E-05	kg
Carfentrazone-ethyl	0.000639	kg
Cerium-141	2.762311	kBq
Cerium-141	0.578398	kBq
Cerium-144	1.523904	kBq
Cesium	0.055203	kg

Cesium	1.210483	kg
Cesium-134	94.35854	kBq
Cesium-134	0.027702	kBq
Cesium-136	0.888417	kBq
Cesium-137	969.4239	kBq
Cesium-137	15321.24	kBq
Cesium-137	0.502664	kBq
Chloramine	0.019606	kg
Chloramine	0.002196	kg
Chlorate	350.835	kg
Chloridazon	6.74E-06	kg
Chloride	156484.2	kg
Chloride	3367.744	kg
Chloride	2851522	kg
Chloride	19.7441	kg
Chloride	707998.3	kg
Chloride	74547.32	kg
Chloride	222774	kg
Chloride	57842.49	kg
Chloride, ion	219.0073	kg
Chlorides, unspecified	1940.996	kg

Chlorimuron-ethyl	0.000333	kg
Chlorimuron-ethyl	0.070298	kg
Chlorinated solvents, unspecified	6.978371	kg
Chlorinated solvents, unspecified	0.016839	kg
Chlorine	75.84694	kg
Chlorine	3.410146	kg
Chlorine	572.8674	kg
Chlorine	20.6933	kg
Chlorine	0.025099	kg
Chlorine	0.953562	kg
Chlorine	6.863484	kg
Chlorine	6.863484	kg
Chlormequat	0.000563	kg
Chloroacetic acid	0.228632	kg
Chloroacetic acid	0.053153	kg
Chloroacetyl chloride	0.00087	kg
Chloroform	0.004871	kg
Chloroform	8.93E-05	kg
Chloroform	0.35684	kg
Chloroform	0.156391	kg
Chloroform	0.016102	kg

Chloropicrin	5.13E-12	kg
Chlorosilane, trimethyl-	2.102585	kg
Chlorosulfonic acid	0.000842	kg
Chlorosulfonic acid	0.000338	kg
Chlorosulfonic acid	9.59E-06	kg
Chlorothalonil	0.334011	kg
Chlorpyrifos	0.006651	kg
Chlorpyrifos	0.081042	kg
Chlorpyrifos methyl	0.206198	kg
Chlorsulfuron	1.04E-07	kg
Chlortoluron	1.34E-05	kg
Choline chloride	1.44E-05	kg
Chromium	50.27867	kg
Chromium	5.460943	kg
Chromium	48.17423	kg
Chromium	1.97E-06	kg
Chromium	0.0012	kg
Chromium	1.794095	kg
Chromium	1.415187	kg
Chromium	8.08378	kg
Chromium	0.055043	kg

Chromium IV	2.31E-06	kg
Chromium VI	1.336732	kg
Chromium VI	0.124091	kg
Chromium VI	0.04867	kg
Chromium VI	1.401007	kg
Chromium VI	0.057018	kg
Chromium VI	5.596353	kg
Chromium VI	860.1747	kg
Chromium VI	2534.836	kg
Chromium VI	3.233238	kg
Chromium, ion	0.330701	kg
Chromium, ion	0.731516	kg
Chromium, ion	14.67505	kg
Chromium, ion	0.056848	kg
Chromium-51	471.0077	kBq
Chromium-51	0.037064	kBq
Chrysene	4.59E-07	kg
Chrysene	1.31E-05	kg
Cinidon-ethyl	1.03E-06	kg
Clethodim	0.000986	kg
Clethodim	0.001605	kg

Clodinafop-propargyl	1.59E-06	kg
Clomazone	8.37E-05	kg
Clopyralid	1.93E-06	kg
Cloquintocet-mexyl	3.72E-07	kg
Cloransulam-methyl	0.000174	kg
Cloransulam-methyl	0.00047	kg
Clothianidin	9.24E-05	kg
Cobalt	0.005723	kg
Cobalt	2.601938	kg
Cobalt	0.896482	kg
Cobalt	5.305134	kg
Cobalt	0.160472	kg
Cobalt	0.545529	kg
Cobalt	1.7258	kg
Cobalt	0.185215	kg
Cobalt	4.411473	kg
Cobalt	1107.89	kg
Cobalt	2.984183	kg
Cobalt	0.099391	kg
Cobalt-57	28.20171	kBq
Cobalt-58	3801.336	kBq

Cobalt-58	0.077757	kBq
Cobalt-60	2527.482	kBq
Cobalt-60	0.576627	kBq
COD, Chemical Oxygen Demand	3770015	kg
COD, Chemical Oxygen Demand	232044.2	kg
COD, Chemical Oxygen Demand	1831.84	kg
COD, Chemical Oxygen Demand	29058.7	kg
COD, Chemical Oxygen Demand	6292.492	kg
Copper	198.9167	kg
Copper	4.0205	kg
Copper	83.66281	kg
Copper	2.551041	kg
Copper	6.64E-05	kg
Copper	2.73525	kg
Copper	6.881013	kg
Copper	31.12015	kg
Copper	-0.07476	kg
Copper, ion	7.164239	kg
Copper, ion	15.57566	kg
Copper, ion	36.53366	kg
Copper, ion	16243.46	kg

Copper, ion	1.39133	kg
Cu-HDO	6.71E-07	kg
Cumene	104.2241	kg
Cumene	214.9081	kg
Cumene	0.00869	kg
Cumene	2.21E-08	kg
Cumene	89.43379	kg
Cyanide	7.839178	kg
Cyanide	21.20291	kg
Cyanide	1.411893	kg
Cyanide	0.002377	kg
Cyanide	52.88192	kg
Cyanide	33.45677	kg
Cyanoacetic acid	0.000276	kg
Cyclohexane	4.6E-09	kg
Cyclohexane (for all cycloalkanes)	0.084294	kg
Cyhalothrin, gamma-	0.000399	kg
Cyhalothrin, gamma-	1.71E-05	kg
Cymoxanil	0.000553	kg
Cypermethrin	0.069651	kg
Cyproconazole	0.365568	kg

Cyprodinil	0.000208	kg
Deltamethrin	2.08E-06	kg
Desmedipham	6.45E-05	kg
Diafenthiuron	2.16E-05	kg
Diazinon	0.004546	kg
Dibenz(a,h)anthracene	8.31E-09	kg
Dibenz(a,h)anthracene	6.62E-05	kg
Dibutyltin	9.02E-23	kg
Dicamba	2.66E-10	kg
Dicamba	6.64E-08	kg
Dicamba	0.000112	kg
Dicamba	0.000873	kg
Dichlorprop	3.86E-12	kg
Dichlorprop	1.58E-14	kg
Dichlorprop	7.71E-13	kg
Dichlorprop	1.24E-10	kg
Dichlorprop-P	0.30687	kg
Dichlorvos	4.58E-07	kg
Dichromate	0.118434	kg
Dichromate	0.166471	kg
Diclofop	-1.2E-05	kg

Diclofop-methyl	-1.2E-05	kg
Diethanolamine	0.000237	kg
Diethyl ether	1.08E-08	kg
Diethylamine	0.003161	kg
Diethylamine	0.001317	kg
Diethylene glycol	9.19E-09	kg
Difenoconazole	0.007466	kg
Diflubenzuron	1.83E-05	kg
Diflubenzuron	0.268111	kg
Diflufenican	2.86E-05	kg
Diflufenzopyr-sodium	3.22E-05	kg
Diisobutyl ketone	0.126896	kg
Dimethachlor	0.000117	kg
Dimethenamid	8.02E-11	kg
Dimethenamid	6.42E-09	kg
Dimethenamid	1.82E-08	kg
Dimethenamid	0.000845	kg
Dimethoate	0.003231	kg
Dimethomorph	0.000119	kg
Dimethyl carbonate	3.76406	kg
Dimethyl ether	0.793841	kg

Dimethyl malonate	0.000347	kg
Dimethylamine	0.009924	kg
Dimethylamine	0.000131	kg
Dinitrogen monoxide	1407.433	kg
Dinitrogen monoxide	701.815	kg
Dinitrogen monoxide	0.365677	kg
Dinitrogen monoxide	1469.505	kg
Dinitrogen tetroxide	0.014085	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2.48E-10	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	4.34E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.5E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.84E-06	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.08E-09	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.1E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	8.89E-08	kg
Diphenyltin	5.71E-21	kg
Dipropylamine	0.001648	kg
Dipropylamine	0.000687	kg
Diquat	0.056667	kg
Discarded fish, demersal, to ocean	1.62E-22	kg
Discarded fish, pelagic, to ocean	5.31E-13	kg

Dissolved solids	44176.95	kg
Dissolved solids	2491.941	kg
Dissolved solids	177579.6	kg
Dithianon	8.48E-06	kg
Diuron	0.380581	kg
DOC, Dissolved Organic Carbon	1500.284	kg
DOC, Dissolved Organic Carbon	3392071	kg
DOC, Dissolved Organic Carbon	70434.4	kg
DOC, Dissolved Organic Carbon	1686.965	kg
DOC, Dissolved Organic Carbon	8310.478	kg
Elemental carbon	1.315561	kg
Elemental carbon	4.501764	kg
Elemental carbon	4.501764	kg
Endosulfan	0.086466	kg
Endothall	3.91E-05	kg
Epoxiconazole	0.132701	kg
EPTC	0.049137	kg
Esfenvalerate	0.000208	kg
Esfenvalerate	0.000681	kg
Ethalfluralin	3.89E-05	kg
Ethane	2349.645	kg

Ethane	0.414997	kg
Ethane	93.94579	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	0.036026	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	0.011079	kg
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	0.064723	kg
Ethane, 1,1,1-trichloro-, HCFC-140	2.17E-12	kg
Ethane, 1,1,1-trichloro-, HCFC-140	0.031933	kg
Ethane, 1,1,1-trichloro-, HCFC-140	4.56E-07	kg
Ethane, 1,1,1-trifluoro-, HFC-143a	2.06E-28	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	0.004006	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	0.014815	kg
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	0.001398	kg
Ethane, 1,1-difluoro-, HFC-152a	0.476418	kg
Ethane, 1,1-difluoro-, HFC-152a	0.030365	kg
Ethane, 1,2-dichloro-	0.13434	kg
Ethane, 1,2-dichloro-	0.000745	kg
Ethane, 1,2-dichloro-	0.116485	kg
Ethane, 1,2-dichloro-	0.509623	kg
Ethane, 1,2-dichloro-	0.063687	kg
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	0.004006	kg
Ethane, hexafluoro-, HFC-116	0.097679	kg

Ethane, hexafluoro-, HFC-116	2.88491	kg
Ethane, pentafluoro-, HFC-125	2.67E-27	kg
Ethanol	21.47306	kg
Ethanol	6.68E-05	kg
Ethanol	11.00541	kg
Ethanol	7.411479	kg
Ethanol	0.000164	kg
Ethene	250.1079	kg
Ethene	269.0533	kg
Ethene	60.53972	kg
Ethene	52.70715	kg
Ethene, chloro-	0.057058	kg
Ethene, chloro-	0.001192	kg
Ethene, chloro-	0.031291	kg
Ethene, chloro-	0.349401	kg
Ethene, tetrachloro-	0.068523	kg
Ethene, tetrachloro-	1.530916	kg
Ethene, tetrachloro-	0.000361	kg
Ethene, trichloro-	0.005345	kg
Ethephon	1.74E-16	kg
Ethephon	2.87E-14	kg

Ethephon	4.36E-13	kg
Ethephon	0.00038	kg
Ethofumesate	0.000342	kg
Ethoprop	0.011385	kg
Ethyl acetate	0.015909	kg
Ethyl acetate	16.39742	kg
Ethyl cellulose	0.032733	kg
Ethylamine	0.003222	kg
Ethylamine	0.001343	kg
Ethylene	0.037089	kg
Ethylene diamine	0.002562	kg
Ethylene diamine	0.001063	kg
Ethylene oxide	0.360551	kg
Ethylene oxide	2.603036	kg
Ethylene oxide	0.224335	kg
Ethyne	22.86346	kg
Ethyne	0.519308	kg
Ethyne	195.7387	kg
Fenbuconazole	2.22E-06	kg
Fenoxaprop	0.000272	kg
Fenoxaprop	0.000936	kg

Fenoxaprop ethyl ester	-1E-06	kg
Fenoxaprop-P ethyl ester	2.09E-05	kg
Fenpiclonil	0.007757	kg
Fenpropidin	0.00014	kg
Fenpropimorph	0.000178	kg
Fentin hydroxide	0.00197	kg
Fipronil	0.398254	kg
Florasulam	-2.4E-07	kg
Fluazifop-p-butyl	0.000391	kg
Fluazifop-P-butyl	0.000354	kg
Flucarbazone sodium salt	6.51E-09	kg
Fludioxonil	2.15E-05	kg
Flufenacet	0.000147	kg
Flufenacet	-2.9E-06	kg
Flumetsulam	3.43E-05	kg
Flumetsulam	5.79E-05	kg
Flumiclorac-pentyl	5.87E-05	kg
Flumiclorac-pentyl	2.51E-06	kg
Flumioxazin	0.000594	kg
Flumioxazin	0.004559	kg
Fluoranthene	0.003737	kg

Fluoranthene	0.001086	kg
Fluorene	0.001377	kg
Fluorene	0.000989	kg
Fluoride	117.9126	kg
Fluoride	63.92956	kg
Fluoride	3.801614	kg
Fluoride	24.77375	kg
Fluoride	693.4109	kg
Fluoride	14276.66	kg
Fluoride	83.93942	kg
Fluorine	1.328468	kg
Fluorine	4.598875	kg
Fluorine	3.366067	kg
Fluorine	2.96891	kg
Fluorochloridone	9.91E-27	kg
Fluosilicic acid	33.8257	kg
Fluosilicic acid	1.310772	kg
Fluosilicic acid	18.79205	kg
Flupyrsulfuron-methyl	1.01E-08	kg
Fluquinconazole	1.93E-06	kg
Fluroxypyr	6.53E-06	kg

Flurtamone	1.29E-05	kg
Flusilazole	6.62E-06	kg
Flutolanil	0.00224	kg
Fomesafen	0.002207	kg
Fomesafen	0.003635	kg
Foramsulfuron	6.04E-06	kg
Formaldehyde	1.19898	kg
Formaldehyde	40.92241	kg
Formaldehyde	847.447	kg
Formaldehyde	801.182	kg
Formaldehyde	545.6439	kg
Formamide	0.001267	kg
Formamide	0.000528	kg
Formate	0.168296	kg
Formic acid	0.000368	kg
Formic acid	0.020528	kg
Formic acid	11.93653	kg
Fungicides, unspecified	0.031998	kg
Fungicides, unspecified	9.67E-06	kg
Furan	52.08667	kg
Furan	3.55E-08	kg

Glufosinate	0.001672	kg
Glutaraldehyde	0.294673	kg
Glyphosate	0.000219	kg
Glyphosate	1.42E-06	kg
Glyphosate	0.000166	kg
Glyphosate	0.442637	kg
Glyphosate	32.94401	kg
Glyphosate	7.356129	kg
Halosulfuron-methyl	6.74E-07	kg
Haloxyfop- (R) Methylester	0.158001	kg
Heat, waste	37879579	kWh
Heat, waste	12384.65	kWh
Heat, waste	19680827	kWh
Heat, waste	5652039	kWh
Heat, waste	49.00924	kWh
Heat, waste	433891.5	kWh
Heat, waste	4702994	kWh
Heat, waste	505496.4	kWh
Helium	0.443442	kg
Helium	42.78712	kg
Heptane	3.524379	kg

Heptane	6.634574	kg
Herbicides, unspecified	0.000657	kg
Hexane	104.5319	kg
Hexane	97.89128	kg
Hexane	6.15E-05	kg
Hydrocarbons, aliphatic, alkanes, cyclic	21.02798	kg
Hydrocarbons, aliphatic, alkanes, cyclic	0.923358	kg
Hydrocarbons, aliphatic, alkanes, unspecified	166.833	kg
Hydrocarbons, aliphatic, alkanes, unspecified	44.00656	kg
Hydrocarbons, aliphatic, alkanes, unspecified	242.5116	kg
Hydrocarbons, aliphatic, alkanes, unspecified	0.000151	kg
Hydrocarbons, aliphatic, alkanes, unspecified	7.176375	kg
Hydrocarbons, aliphatic, alkanes, unspecified	157.3628	kg
Hydrocarbons, aliphatic, unsaturated	1.72E-10	kg
Hydrocarbons, aliphatic, unsaturated	101.6666	kg
Hydrocarbons, aliphatic, unsaturated	31.7638	kg
Hydrocarbons, aliphatic, unsaturated	21.60843	kg
Hydrocarbons, aliphatic, unsaturated	0.662435	kg
Hydrocarbons, aliphatic, unsaturated	14.52735	kg
Hydrocarbons, aromatic	5.208237	kg
Hydrocarbons, aromatic	61.03269	kg

Hydrocarbons, aromatic	232.7578	kg
Hydrocarbons, aromatic	32.10897	kg
Hydrocarbons, aromatic	630.3827	kg
Hydrocarbons, chlorinated	7.052296	kg
Hydrocarbons, chlorinated	179.7255	kg
Hydrocarbons, chlorinated	0.32331	kg
Hydrocarbons, unspecified	130.45	kg
Hydrocarbons, unspecified	34.11937	kg
Hydrocarbons, unspecified	361.283	kg
Hydrocarbons, unspecified	237.0284	kg
Hydrocarbons, unspecified	400.9303	kg
Hydrochloric acid	189.0753	kg
Hydrochloric acid	0.000339	kg
Hydrogen	382.6017	kg
Hydrogen	755.5399	kg
Hydrogen carbonate	204.6223	kg
Hydrogen chloride	78567.32	kg
Hydrogen chloride	2811.707	kg
Hydrogen chloride	5441.586	kg
Hydrogen chloride	67.41456	kg
Hydrogen fluoride	79.87854	kg

Hydrogen fluoride	704.1064	kg
Hydrogen fluoride	640.5285	kg
Hydrogen fluoride	1.082794	kg
Hydrogen peroxide	2.505829	kg
Hydrogen peroxide	0.010739	kg
Hydrogen sulfide	10.38193	kg
Hydrogen sulfide	136.5066	kg
Hydrogen sulfide	504.1362	kg
Hydrogen sulfide	17.9634	kg
Hydrogen sulfide	6.082765	kg
Hydrogen sulfide	5049.568	kg
Hydrogen sulfide	9510.22	kg
Hydrogen-3, Tritium	65323734	kBq
Hydrogen-3, Tritium	31832007	kBq
Hydrogen-3, Tritium	1511537	kBq
Hydroxide	1.299056	kg
Hydroxide	0.430498	kg
Hypochlorite	3.952275	kg
Hypochlorite	4.017744	kg
Imazamox	8.78E-05	kg
Imazamox	0.003256	kg

Imazapyr	8.06E-07	kg
Imazaquin	0.00028	kg
Imazaquin	1.2E-05	kg
Imazethapyr	0.000579	kg
Imazethapyr	0.001184	kg
Imidacloprid	0.450339	kg
Indeno(1,2,3-cd)pyrene	1.3E-07	kg
Indeno(1,2,3-cd)pyrene	2.6E-05	kg
Indoxacarb	0.000183	kg
Insecticides, unspecified	9.85E-10	kg
Iodide	0.293699	kg
Iodide	6.16E-05	kg
Iodide	0.249102	kg
Iodide	129.202	kg
Iodide	5.520288	kg
Iodine	2.250054	kg
Iodine	29.89372	kg
Iodine	0.178893	kg
Iodine	9.91E-07	kg
Iodine-129	82.31595	kBq
Iodine-131	2166.303	kBq

Iodine-131	1623.057	kBq
Iodine-133	4.55991	kBq
Iodine-133	5.754161	kBq
Iodosulfuron	1.29E-07	kg
Iodosulfuron-methyl-sodium	6.31E-09	kg
Ioxynil	5.01E-05	kg
Iprodion	0.004346	kg
Iron	1106.168	kg
Iron	193.6519	kg
Iron	5.756432	kg
Iron	98.31197	kg
Iron	18926.27	kg
Iron	1715.1	kg
Iron	1007.236	kg
Iron	22.6054	kg
Iron, ion	616.2186	kg
Iron, ion	295958	kg
Iron, ion	6327.712	kg
Iron, ion	3.1266	kg
Iron, ion	603.7017	kg
Iron-59	9966.274	kBq

Isocyanic acid	77.35541	kg
Isoprene	0.173622	kg
Isoprene	4.74E-07	kg
Isopropylamine	0.001712	kg
Isopropylamine	0.000713	kg
Isoproturon	0.000396	kg
Isoxaflutole	0.001665	kg
Kresoxim-methyl	5.65E-05	kg
Krypton-85	23815.74	kBq
Krypton-85m	50285.65	kBq
Krypton-87	7774.62	kBq
Krypton-88	10222.84	kBq
Krypton-89	4308.472	kBq
Lactic acid	0.001291	kg
Lactic acid	0.000538	kg
Lactofen	0.000282	kg
Lactofen	1.21E-05	kg
Lambda-cyhalothrin	1.75E-20	kg
Lambda-cyhalothrin	6.96E-18	kg
Lambda-cyhalothrin	1.38E-14	kg
Lambda-cyhalothrin	0.358606	kg

Lanthanum-140	7.400286	kBq
Lanthanum-140	0.203914	kBq
Lauric acid	0.000528	kg
Lead	94.59945	kg
Lead	6.278497	kg
Lead	113.2026	kg
Lead	3.106263	kg
Lead	0.000788	kg
Lead	1.130406	kg
Lead	3.05269	kg
Lead	70.17106	kg
Lead	0.004167	kg
Lead	8.124854	kg
Lead	3.30199	kg
Lead	10.62103	kg
Lead	9197.282	kg
Lead	1.226796	kg
Lead-210	1484.179	kBq
Lead-210	1156.157	kBq
Lead-210	3.8904	kBq
Lead-210	68.37213	kBq

Lead-210	2695.772	kBq
Lead-210	12617.02	kBq
Lead-210	74.37494	kBq
Lenacil	3.5E-05	kg
Linuron	0.003645	kg
Lithium	0.000225	kg
Lithium	0.017199	kg
Lithium	0.017199	kg
Lithium, ion	0.037869	kg
Lithium, ion	4294.656	kg
m-Xylene	0.001283	kg
m-Xylene	0.121031	kg
m-Xylene	12.34507	kg
m-Xylene	3.447064	kg
m-Xylene	0.001	kg
Magnesium	2506.265	kg
Magnesium	21.31305	kg
Magnesium	21.13775	kg
Magnesium	170.4961	kg
Magnesium	2.592071	kg
Magnesium	885.7677	kg

Magnesium	77.72707	kg
Magnesium	234.5397	kg
Magnesium	7332.955	kg
Magnesium	273590.9	kg
Magnesium	3239.27	kg
Magnesium	2304.206	kg
Malathion	0.004873	kg
Maleic hydrazide	0.012452	kg
Mancozeb	0.444306	kg
Mandipropamid	2.69E-05	kg
Maneb	0.00029	kg
Manganese	14.48468	kg
Manganese	37.02081	kg
Manganese	6.218087	kg
Manganese	17.01721	kg
Manganese	4.502505	kg
Manganese	4.805067	kg
Manganese	111.5337	kg
Manganese	125.1193	kg
Manganese	88.14907	kg
Manganese	23755.94	kg

Manganese	186.6382	kg
Manganese	2.220934	kg
Manganese-54	140.3967	kBq
Manganese-54	0.018981	kBq
MCPA	-7.4E-09	kg
MCPA	-2.9E-11	kg
MCPA	-2.5E-09	kg
MCPA	2.43E-05	kg
MCPB	2.19E-14	kg
MCPB	4.73E-12	kg
MCPB	2.23E-12	kg
MCPB	3.81E-08	kg
Mecoprop	5.95E-06	kg
Mecoprop-P	2.92E-05	kg
Mefenpyr	-1.6E-06	kg
Mefenpyr-diethyl	-1.3E-06	kg
Mepiquat chloride	4.49E-06	kg
Mercury	0.436808	kg
Mercury	0.472354	kg
Mercury	1.127743	kg
Mercury	0.023017	kg

Mercury	2.031534	kg
Mercury	2.75E-09	kg
Mercury	0.009657	kg
Mercury	0.306532	kg
Mercury	0.003548	kg
Mercury	0.241355	kg
Mercury	0.025829	kg
Mercury	19.56543	kg
Mercury	0.012999	kg
Mesosulfuron-methyl (prop)	3.48E-08	kg
Mesotrione	0.00199	kg
Metalaxil	0.016183	kg
Metaldehyde	0.001334	kg
Metam-sodium	2.029227	kg
Metamitron	0.001817	kg
Metazachlor	0.000275	kg
Metconazole	1.48E-05	kg
Methane	6.987623	kg
Methane, bromo-, Halon 1001	0.002019	kg
Methane, bromo-, Halon 1001	6.77E-17	kg
Methane, bromochlorodifluoro-, Halon 1211	0.11859	kg

Methane, bromotrifluoro-, Halon 1301	1.81E-07	kg
Methane, bromotrifluoro-, Halon 1301	1.245748	kg
Methane, chlorodifluoro-, HCFC-22	1.604266	kg
Methane, chlorodifluoro-, HCFC-22	11.86724	kg
Methane, chlorodifluoro-, HCFC-22	3.27E-16	kg
Methane, dichloro-, HCC-30	16.37301	kg
Methane, dichloro-, HCC-30	0.016418	kg
Methane, dichloro-, HCC-30	1.191853	kg
Methane, dichloro-, HCC-30	0.462625	kg
Methane, dichlorodifluoro-, CFC-12	0.01962	kg
Methane, dichlorodifluoro-, CFC-12	4.44E-07	kg
Methane, dichlorodifluoro-, CFC-12	0.000161	kg
Methane, dichlorofluoro-, HCFC-21	0.000207	kg
Methane, fossil	16894.92	kg
Methane, fossil	49150.07	kg
Methane, fossil	201999.3	kg
Methane, fossil	0.044799	kg
Methane, from soil or biomass stock	73.78943	kg
Methane, monochloro-, R-40	0.84574	kg
Methane, non-fossil	42995.6	kg
Methane, non-fossil	6266.995	kg

Methane, non-fossil	40.70397	kg
Methane, tetrachloro-, R-10	5.47E-05	kg
Methane, tetrachloro-, R-10	0.008752	kg
Methane, tetrachloro-, R-10	0.404246	kg
Methane, tetrafluoro-, R-14	0.002741	kg
Methane, tetrafluoro-, R-14	50.45256	kg
Methane, trichlorofluoro-, CFC-11	0.000229	kg
Methane, trifluoro-, HFC-23	0.06592	kg
Methanesulfonic acid	0.000279	kg
Methanol	15.6015	kg
Methanol	0.724541	kg
Methanol	12.62998	kg
Methanol	275.7289	kg
Methanol	17.44103	kg
Methanol	266.0174	kg
Methomyl	2.58E-16	kg
Methomyl	2.3E-14	kg
Methomyl	1.49E-12	kg
Methomyl	4.7E-12	kg
Methyl acetate	0.000361	kg
Methyl acetate	0.00015	kg

Methyl acetate	0.001081	kg
Methyl acrylate	0.653028	kg
Methyl acrylate	0.033428	kg
Methyl amine	0.000648	kg
Methyl amine	0.00027	kg
Methyl borate	0.006398	kg
Methyl ethyl ketone	0.000126	kg
Methyl ethyl ketone	16.42911	kg
Methyl formate	0.001396	kg
Methyl formate	0.003498	kg
Methyl formate	8.41E-06	kg
Methyl lactate	0.000591	kg
Methyl parathion	0.000226	kg
Methyl parathion	9.67E-06	kg
Methyl pentane	0.023452	kg
Methylamine	0.000695	kg
Metiram	0.00846	kg
Metolachlor	1.32E-06	kg
Metolachlor	1.78E-08	kg
Metolachlor	0.004615	kg
Metolachlor	0.110852	kg

Metosulam	1.99E-08	kg
Metribuzin	0.001828	kg
Metribuzin	0.038777	kg
Metsulfuron-methyl	0.002667	kg
Mineral oil	9.478348	kg
Molinate	0.000202	kg
Molybdenum	25.32512	kg
Molybdenum	0.392073	kg
Molybdenum	0.149604	kg
Molybdenum	0.286182	kg
Molybdenum	0.148754	kg
Molybdenum	1.042443	kg
Molybdenum	0.110026	kg
Molybdenum	189.5352	kg
Molybdenum	96.25382	kg
Molybdenum	9.917229	kg
Molybdenum	0.19917	kg
Molybdenum-99	2.288958	kBq
Monobutyltin	1.55E-20	kg
Monochloroethane	0.013447	kg
Monocrotophos	0.028873	kg

Monoethanolamine	76.29966	kg
Monoethanolamine	0.002415	kg
Monophenyltin	1.7E-23	kg
Myclobutanil	5.76E-05	kg
Naphtalene	0.000276	kg
Naphtalene	0.000691	kg
Naphthalene	1.21E-05	kg
Napropamide	0.001744	kg
Nickel	51.53325	kg
Nickel	14.50204	kg
Nickel	162.6393	kg
Nickel	1.167521	kg
Nickel	2.75E-06	kg
Nickel	0.62103	kg
Nickel	1.06913	kg
Nickel	3.13883	kg
Nickel	0.032933	kg
Nickel, ion	9.080255	kg
Nickel, ion	8.032299	kg
Nickel, ion	18.99023	kg
Nickel, ion	4441.11	kg

Nickel, ion	0.252851	kg
Nicosulfuron	0.000794	kg
Niobium-95	13.04756	kBq
Niobium-95	12218.64	kBq
Nitrate	10.50698	kg
Nitrate	10.10043	kg
Nitrate	0.018062	kg
Nitrate	24.253	kg
Nitrate	696.4991	kg
Nitrate	19.8205	kg
Nitrate	3042.599	kg
Nitrate	5507.666	kg
Nitrate	25857.41	kg
Nitrate	188.3768	kg
Nitric acid	0.043899	kg
Nitric oxide	0.275642	kg
Nitrite	0.671878	kg
Nitrite	19.21453	kg
Nitrite	541.543	kg
Nitrite	0.207455	kg
Nitrite	60.27128	kg

Nitrobenzene	62.33632	kg
Nitrobenzene	3.47E-05	kg
Nitrobenzene	15.55495	kg
Nitrogen	13.05611	kg
Nitrogen	15010.55	kg
Nitrogen	1495.055	kg
Nitrogen	5.241986	kg
Nitrogen	464.5606	kg
Nitrogen	81.73723	kg
Nitrogen dioxide	0.02914	kg
Nitrogen fluoride	2.54E-09	kg
Nitrogen oxides	454092.1	kg
Nitrogen oxides	33809.1	kg
Nitrogen oxides	18.50935	kg
Nitrogen oxides	356938.9	kg
Nitrogen oxides	46.10792	kg
Nitrogen, organic bound	73.26489	kg
Nitrogen, organic bound	0.423357	kg
Nitrogen, organic bound	577.0079	kg
Nitrogen, organic bound	16261.73	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	16388.42	kg

NMVOC, non-methane volatile organic compounds, unspecified origin	78426.27	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	158547.2	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	0.006825	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	2.166327	kg
Noble gases, radioactive, unspecified	7.92E+08	kBq
Novaluron	7.74E-05	kg
o-Dichlorobenzene	8.91731	kg
o-Nitrotoluene	0.000561	kg
o-Xylene	0.08816	kg
o-Xylene	4.699659	kg
o-Xylene	0.154775	kg
Oils, non-fossil	4.52E-14	kg
Oils, non-fossil	0.852076	kg
Oils, non-fossil	241.4957	kg
Oils, non-fossil	0.002201	kg
Oils, non-fossil	79.13093	kg
Oils, unspecified	2671.548	kg
Oils, unspecified	147.3277	kg
Oils, unspecified	505.6633	kg

Oils, unspecified	84013.83	kg
Oils, unspecified	9302.642	kg
Oils, unspecified	68071.17	kg
Orbencarb	0.044848	kg
Organic carbon	3.272014	kg
Organic carbon	10.64703	kg
Organic carbon	10.64703	kg
Oxamyl	0.011188	kg
Oxydemeton-methyl	8.99E-06	kg
Oxyfluorfen	0.000359	kg
Oxygen	0.033353	kg
Ozone	1.778694	kg
Ozone	260.3733	kg
PAH, polycyclic aromatic hydrocarbons	365.2971	kg
PAH, polycyclic aromatic hydrocarbons	46.08649	kg
PAH, polycyclic aromatic hydrocarbons	39.10559	kg
PAH, polycyclic aromatic hydrocarbons	0.051599	kg
PAH, polycyclic aromatic hydrocarbons	0.051599	kg
PAH, polycyclic aromatic hydrocarbons	1.439363	kg
PAH, polycyclic aromatic hydrocarbons	12.28779	kg
PAH, polycyclic aromatic hydrocarbons	0.29814	kg

Palladium	0.007058	kg
Paraffins	0.020794	kg
Paraquat	0.001176	kg
Paraquat	1.068946	kg
Parathion	3.3E-05	kg
Particulates, < 2.5 um	13788.08	kg
Particulates, < 2.5 um	56344.97	kg
Particulates, < 2.5 um	29047.15	kg
Particulates, < 2.5 um	8659.95	kg
Particulates, < 2.5 um	0.006234	kg
Particulates, > 10 um	23324.32	kg
Particulates, > 10 um	37546.71	kg
Particulates, > 10 um	133159.4	kg
Particulates, > 10 um	21681.36	kg
Particulates, > 2.5 um, and < 10um	18319.9	kg
Particulates, > 2.5 um, and < 10um	56019.49	kg
Particulates, > 2.5 um, and < 10um	35336.16	kg
Particulates, > 2.5 um, and < 10um	13242.91	kg
Pendimethalin	1.48E-11	kg
Pendimethalin	8.83E-09	kg
Pendimethalin	0.01239	kg

Pendimethalin	0.051943	kg
Pentane	17822.4	kg
Pentane	0.823128	kg
Pentane	1871.586	kg
Permethrin	0.000184	kg
Permethrin	0.000421	kg
Pesticides, unspecified	0.846944	kg
Phenanthrene	0.0031	kg
Phenanthrene	0.015192	kg
Phenmedipham	0.000217	kg
Phenol	6.692762	kg
Phenol	23.84386	kg
Phenol	384.5883	kg
Phenol	3.501215	kg
Phenol	21.34545	kg
Phenol	109.0541	kg
Phenol, 2,4-dichloro	0.000834	kg
Phenol, 2,4-dichloro	4.69E-05	kg
Phenol, pentachloro-	0.0003	kg
Phenol, pentachloro-	12.09143	kg
Phenol, pentachloro-	0.004175	kg

Phenol, pentachloro-	0.000137	kg
Phorate	0.020582	kg
Phosgene	3.093086	kg
Phosmet	0.002266	kg
Phosphate	0.010692	kg
Phosphate	12.81661	kg
Phosphate	9364.248	kg
Phosphate	476.0799	kg
Phosphate	86161.02	kg
Phosphine	3.14E-05	kg
Phosphoric acid	4.6E-09	kg
Phosphoric acid	3.95E-06	kg
Phosphorus	0.09809	kg
Phosphorus	0.003978	kg
Phosphorus	11.79167	kg
Phosphorus	0.506014	kg
Phosphorus	0.277207	kg
Phosphorus	2.078707	kg
Phosphorus	153.8827	kg
Phosphorus	13.10448	kg
Phosphorus	60.4663	kg

Phosphorus	139.834	kg
Phosphorus	12.02419	kg
Phosphorus oxychloride	0.000594	kg
Phosphorus trichloride	0.001046	kg
Picloram	1.3E-08	kg
Picoxystrobin	0.387414	kg
Piperonyl butoxide	6.75E-05	kg
Pirimicarb	0.000166	kg
Platinum	0.007056	kg
Platinum	3.09E-05	kg
Platinum	1.06E-05	kg
Platinum	3.34E-09	kg
Plutonium-238	1.12E-05	kBq
Plutonium-alpha	2.57E-05	kBq
Polonium-210	1484.179	kBq
Polonium-210	5.919721	kBq
Polonium-210	1159.362	kBq
Polonium-210	4932.765	kBq
Polonium-210	22268.33	kBq
Polonium-210	135.8993	kBq
Polychlorinated biphenyls	3.57E-05	kg

Polychlorinated biphenyls	0.11864	kg
Polychlorinated biphenyls	0.013815	kg
Polychlorinated biphenyls	0.0059	kg
Potassium	164.5275	kg
Potassium	605.844	kg
Potassium	16.85363	kg
Potassium	3.081333	kg
Potassium	126.5256	kg
Potassium	357.2035	kg
Potassium	336.2667	kg
Potassium	4.788449	kg
Potassium, ion	4.06E-05	kg
Potassium, ion	166492.1	kg
Potassium, ion	13014.71	kg
Potassium, ion	860.6919	kg
Potassium, ion	828.0141	kg
Potassium-40	1863.118	kBq
Potassium-40	91.84212	kBq
Potassium-40	0.470213	kBq
Potassium-40	750.8969	kBq
Potassium-40	4246.622	kBq

Potassium-40	18.29643	kBq
Primisulfuron	2.01E-05	kg
Prochloraz	2.14E-05	kg
Procymidone	1.86E-05	kg
Profenofos	0.049446	kg
Prohexadione-calcium	7.84E-09	kg
Propamocarb HCl	9.88E-05	kg
Propanal	0.000945	kg
Propanal	0.386306	kg
Propanal	0.012272	kg
Propanal	0.000456	kg
Propane	156.7174	kg
Propane	606.8626	kg
Propane	1.215265	kg
Propanil	0.000523	kg
Propanol	0.001155	kg
Propanol	3.03E-08	kg
Propanol	0.004325	kg
Propargite	0.006602	kg
Propene	208.0726	kg
Propene	105.0493	kg

Propene	8.462035	kg
Propene	1.126104	kg
Propiconazole	-3.4E-10	kg
Propiconazole	0.000216	kg
Propiconazole	1.24E-05	kg
Propiconazole	-3.2E-14	kg
Propionic acid	0.007258	kg
Propionic acid	0.388863	kg
Propionic acid	1.850293	kg
Propionic acid	0.000473	kg
Propoxycarbazone-sodium (prop)	4.35E-08	kg
Propylamine	0.000356	kg
Propylamine	0.000148	kg
Propylene oxide	1.841095	kg
Propylene oxide	1.122989	kg
Prosulfuron	3.64E-06	kg
Protactinium-234	639.4112	kBq
Protactinium-234	233.9472	kBq
Prothioconazol	6.12E-17	kg
Prothioconazol	3.91E-15	kg
Prothioconazol	3.8E-14	kg

Prothioconazol	0.462621	kg
Pymetrozine	0.000632	kg
Pyraclostrobin	2.07E-12	kg
Pyraclostrobin	1.31E-10	kg
Pyraclostrobin	0.000509	kg
Pyraclostrobin (prop)	0.392027	kg
Pyraflufen-ethyl	0.044518	kg
Pyrene	0.002815	kg
Pyrene	0.000793	kg
Quinclorac	8.73E-06	kg
Quinmerac	4.98E-28	kg
Quinoxyfen	3.8E-07	kg
Quintozene	0.01236	kg
Quizalofop ethyl ester	5.31E-06	kg
Quizalofop-ethyl	6.83E-05	kg
Quizalofop-P	2.68E-06	kg
Quizalofop-p-ethyl	8.31E-29	kg
Radioactive species, alpha emitters	21.42711	kBq
Radioactive species, Nuclides, unspecified	575.2853	kBq
Radioactive species, Nuclides, unspecified	79936.88	kBq
Radioactive species, other beta emitters	0.472689	kBq

Radioactive species, other beta emitters	6097.498	kBq
Radioactive species, other beta emitters	4.54E-07	kBq
Radium-224	2760.144	kBq
Radium-224	60524.14	kBq
Radium-226	5298.789	kBq
Radium-226	4.363691	kBq
Radium-226	696.7363	kBq
Radium-226	4259.549	kBq
Radium-226	19.1953	kBq
Radium-226	238.5394	kBq
Radium-226	308836.1	kBq
Radium-226	5271.673	kBq
Radium-228	7443.23	kBq
Radium-228	2793.891	kBq
Radium-228	1099.992	kBq
Radium-228	5.737471	kBq
Radium-228	5520.288	kBq
Radium-228	121048.3	kBq
Radon-220	3972.235	kBq
Radon-220	97420.98	kBq
Radon-220	398.5906	kBq

Radon-222	2.89E+09	kBq
Radon-222	81250818	kBq
Radon-222	2255.249	kBq
Radon-222	223.8686	kBq
Rhodium	0.007056	kg
Rimsulfuron	0.000323	kg
Rubidium	0.552029	kg
Rubidium	12.10483	kg
Ruthenium-103	0.935306	kBq
Ruthenium-103	0.000495	kBq
Scandium	0.001015	kg
Scandium	0.270158	kg
Scandium	0.053119	kg
Scandium	1.78E-06	kg
Scandium	0.276015	kg
Scandium	234.8895	kg
Scandium	5.968958	kg
Scandium	0.797878	kg
Selenium	1.554107	kg
Selenium	0.625818	kg
Selenium	0.039261	kg

Selenium	7.684829	kg
Selenium	3.95E-07	kg
Selenium	0.49549	kg
Selenium	0.09639	kg
Selenium	101.6886	kg
Selenium	15.30396	kg
Selenium	1.342475	kg
Selenium	0.44754	kg
Sethoxydim	0.000147	kg
Sethoxydim	0.000282	kg
Silicon	0.129872	kg
Silicon	163.4185	kg
Silicon	685.3132	kg
Silicon	82.89845	kg
Silicon	17.35731	kg
Silicon	2609.044	kg
Silicon	661.5259	kg
Silicon	701.2764	kg
Silicon	2057.222	kg
Silicon	1118115	kg
Silicon	815.4856	kg

Silicon tetrafluoride	0.012176	kg
Silthiofam	5.84E-07	kg
Silver	0.000484	kg
Silver	0.009977	kg
Silver	0.011827	kg
Silver	0.000889	kg
Silver	0.041117	kg
Silver	0.007972	kg
Silver	1.21E-10	kg
Silver, ion	8.375268	kg
Silver, ion	0.735515	kg
Silver, ion	219.11	kg
Silver, ion	0.08968	kg
Silver, ion	0.033122	kg
Silver-110	1731.261	kBq
Silver-110	0.009896	kBq
Simazine	0.000407	kg
Sodium	0.325967	kg
Sodium	30.26832	kg
Sodium	87.63853	kg
Sodium	9.584939	kg

Sodium	4.391211	kg
Sodium	1895657	kg
Sodium	1487.274	kg
Sodium	8.517904	kg
Sodium chlorate	0.142014	kg
Sodium dichromate	0.034911	kg
Sodium formate	0.024465	kg
Sodium formate	0.010184	kg
Sodium hydroxide	0.032497	kg
Sodium hydroxide	-5.2E-10	kg
Sodium tetrahydridoborate	1.69E-06	kg
Sodium, ion	438740.5	kg
Sodium, ion	345717.5	kg
Sodium, ion	2415.91	kg
Sodium, ion	33357.93	kg
Sodium, ion	53114	kg
Sodium-24	33.15614	kBq
Solids, inorganic	564.1764	kg
Solids, inorganic	16439.06	kg
Solids, inorganic	14038.23	kg
Solids, inorganic	1.31E-15	kg

Spinosad	1.32E-05	kg
Spiroxamine	8.66E-05	kg
Strontium	217.8814	kg
Strontium	1.320603	kg
Strontium	8.58854	kg
Strontium	0.464214	kg
Strontium	11.39255	kg
Strontium	10.2703	kg
Strontium	11.65872	kg
Strontium	0.037766	kg
Strontium	2218.039	kg
Strontium	9837.186	kg
Strontium	156.8882	kg
Strontium	119.7915	kg
Strontium-89	44.26233	kBq
Strontium-90	41724.75	kBq
Strontium-90	1703.417	kBq
Styrene	6.579653	kg
Styrene	620.0449	kg
Styrene	28.00961	kg
Sulfate	8240.714	kg

Sulfate	4825.889	kg
Sulfate	676.6731	kg
Sulfate	87.36106	kg
Sulfate	91.34213	kg
Sulfate	2.057624	kg
Sulfate	33.10279	kg
Sulfate	61856.64	kg
Sulfate	1965305	kg
Sulfate	114133.6	kg
Sulfate, ion	0.365461	kg
Sulfate, ion	33.08876	kg
Sulfentrazone	0.001407	kg
Sulfentrazone	0.755507	kg
Sulfide	4.300844	kg
Sulfide	0.017272	kg
Sulfide	6.552458	kg
Sulfite	0.00018	kg
Sulfite	23.41353	kg
Sulfosate	0.022879	kg
Sulfosulfuron	1.64E-07	kg
Sulfur	28.18865	kg

Sulfur	0.588567	kg
Sulfur	156.8679	kg
Sulfur	555.1232	kg
Sulfur	14242.84	kg
Sulfur	250.9358	kg
Sulfur	28.99384	kg
Sulfur dioxide	47874.46	kg
Sulfur dioxide	375146.4	kg
Sulfur dioxide	67915.02	kg
Sulfur dioxide	0.033127	kg
Sulfur dioxide	65.69883	kg
Sulfur hexafluoride	7.458944	kg
Sulfur hexafluoride	1.02E-08	kg
Sulfur oxides	1613.167	kg
Sulfur trioxide	17.13108	kg
Sulfur trioxide	34.15381	kg
Sulfuric acid	3.990972	kg
Sulfuric acid	0.00933	kg
Sulfuric acid	1.57E-05	kg
Sulfuric acid	27.25522	kg
Sulfuric acid	2.362707	kg

Sulfuric acid	851.4307	kg
Suspended solids, unspecified	8591.41	kg
Suspended solids, unspecified	6752.978	kg
Suspended solids, unspecified	10687.9	kg
t-Butyl methyl ether	0.000764	kg
t-Butyl methyl ether	2.013557	kg
t-Butyl methyl ether	0.214715	kg
t-Butylamine	0.00131	kg
t-Butylamine	0.000546	kg
tau-Fluvalinate	7.95E-30	kg
TCMTB	0.191907	kg
Tebuconazole	3.13E-14	kg
Tebuconazole	1.01E-13	kg
Tebuconazole	0.012478	kg
Tebuconazole	7.53E-17	kg
Tebupirimphos	0.000169	kg
Tebutam	0.006824	kg
Technetium-99m	56.8537	kBq
Teflubenzuron	0.198144	kg
Tefluthrin	3.8E-16	kg
Tefluthrin	2.28E-14	kg

Tefluthrin	4.66E-09	kg
Tefluthrin	0.000133	kg
Tellurium	0.011694	kg
Tellurium-123m	6.973471	kBq
Tellurium-132	0.266209	kBq
Terbufos	0.000451	kg
Terbuthylazin	0.025104	kg
Terpenes	1.627708	kg
Tetramethyl ammonium hydroxide	6.1E-05	kg
Thallium	0.009496	kg
Thallium	0.023702	kg
Thallium	0.54507	kg
Thallium	0.067279	kg
Thallium	0.00548	kg
Thallium	0.00129	kg
Thallium	0.01698	kg
Thallium	0.035783	kg
Thallium	107.8134	kg
Thallium	0.053378	kg
Thallium	0.02124	kg
Thiamethoxam	0.941237	kg

Thifensulfuron	2E-05	kg
Thifensulfuron-methyl	1.16E-06	kg
Thiobencarb	0.000112	kg
Thiocyanate, ion	0.005333	kg
Thiodicarb	7.15E-05	kg
Thiodicarb	0.115999	kg
Thiophanate-methyl	0.305114	kg
Thiram	0.003166	kg
Thorium	0.079236	kg
Thorium	0.000273	kg
Thorium	0.031615	kg
Thorium	5.5E-06	kg
Thorium-228	0.047696	kBq
Thorium-228	262.5646	kBq
Thorium-228	614.3993	kBq
Thorium-228	3.071696	kBq
Thorium-228	11041.42	kBq
Thorium-228	242096.6	kBq
Thorium-230	319.5205	kBq
Thorium-230	54135.98	kBq
Thorium-232	52.84298	kBq

Thorium-232	347.3609	kBq
Thorium-232	195.3585	kBq
Thorium-232	898.0725	kBq
Thorium-232	4.813654	kBq
Thorium-232	1207.01	kBq
Thorium-234	639.8209	kBq
Thorium-234	233.9856	kBq
Tin	30.20116	kg
Tin	0.06597	kg
Tin	5.334821	kg
Tin	0.090639	kg
Tin	0.194149	kg
Tin	2.238955	kg
Tin	0.128727	kg
Tin, ion	0.546899	kg
Tin, ion	400.0351	kg
Tin, ion	0.276	kg
Tin, ion	3.91E-20	kg
Tin, ion	0.322965	kg
Titanium	9.936381	kg
Titanium	17.98345	kg

Titanium	6.93087	kg
Titanium	1.063693	kg
Titanium	97.46708	kg
Titanium	52.92888	kg
Titanium	8.514644	kg
Titanium, ion	20.91391	kg
Titanium, ion	0.021362	kg
Titanium, ion	38.83116	kg
Titanium, ion	26699.82	kg
Titanium, ion	5.842628	kg
TOC, Total Organic Carbon	70453.51	kg
TOC, Total Organic Carbon	3392071	kg
TOC, Total Organic Carbon	1686.965	kg
TOC, Total Organic Carbon	8310.478	kg
TOC, Total Organic Carbon	1500.51	kg
Toluene	429.4949	kg
Toluene	260.999	kg
Toluene	154.7794	kg
Toluene	14.88506	kg
Toluene	130.9327	kg
Toluene	6.34644	kg

Toluene, 2-chloro	0.010485	kg
Toluene, 2-chloro	0.004953	kg
Tralkoxydim	-2.3E-05	kg
Triadimenol	4.75E-06	kg
Triallate	3.52E-07	kg
Triasulfuron	1.04E-07	kg
Tribenuron	4.85E-07	kg
Tribenuron-methyl	7.48E-08	kg
Tributyltin compounds	0.048808	kg
Trichlorfon	0.037094	kg
Trichloroethylene	0.013484	kg
Triclopyr	0.031234	kg
Triethylene glycol	0.807552	kg
Triethylene glycol	0.017093	kg
Triethylene glycol	0.014731	kg
Trifloxystrobin	1.88E-17	kg
Trifloxystrobin	1.16E-15	kg
Trifloxystrobin	1.28E-05	kg
Trifloxystrobin	0.402546	kg
Trifluralin	0.020261	kg
Trifluralin	0.101162	kg

Trimethylamine	0.000756	kg
Trimethylamine	0.000315	kg
Trinexapac-ethyl	2.11E-05	kg
Trioctyltin	4.01E-21	kg
Triphenyltin	1.7E-21	kg
Tungsten	6.68E-05	kg
Tungsten	0.030522	kg
Tungsten	214.7339	kg
Tungsten	102.0653	kg
Tungsten	0.872549	kg
Uranium	0.105338	kg
Uranium	0.000174	kg
Uranium	0.000316	kg
Uranium	8.71E-06	kg
Uranium alpha	24947.58	kBq
Uranium alpha	1504.865	kBq
Uranium-234	699.6546	kBq
Uranium-234	740.0588	kBq
Uranium-235	13.21121	kBq
Uranium-235	825.7394	kBq
Uranium-238	19.50969	kBq

Uranium-238	389.8292	kBq
Uranium-238	1.995933	kBq
Uranium-238	580.2175	kBq
Uranium-238	3176.686	kBq
Uranium-238	15.99617	kBq
Uranium-238	3.196428	kBq
Uranium-238	2217.027	kBq
Urea	0.000158	kg
Urea	0.001421	kg
Vanadium	70.60631	kg
Vanadium	31.96398	kg
Vanadium	0.66283	kg
Vanadium	6.349277	kg
Vanadium	2.128249	kg
Vanadium	11.55699	kg
Vanadium	0.243716	kg
Vanadium, ion	16.97082	kg
Vanadium, ion	5161.216	kg
Vanadium, ion	0.55284	kg
Vanadium, ion	0.323278	kg
Vinclozolin	6.21E-06	kg

VOC, volatile organic compounds, unspecified origin	0.022993	kg
VOC, volatile organic compounds, unspecified origin	235.481	kg
VOC, volatile organic compounds, unspecified origin	19.32101	kg
VOC, volatile organic compounds, unspecified origin	425.04	kg
Water	940854	m3
Water	19845.7	m3
Water	10511.12	m3
Water	0.000302	m3
Water	309.3291	m3
Water	4.79E+08	m3
Water	117474.2	m3
Water	75800.37	m3
Water	40117.99	m3
Xenon-131m	40923.81	kBq
Xenon-133	2456827	kBq
Xenon-133m	1553.524	kBq
Xenon-135	859878.2	kBq
Xenon-135m	374712.4	kBq
Xenon-137	11787.21	kBq
Xenon-138	88012.4	kBq
Xylene	3.209687	kg

Xylene	249.8416	kg
Xylene	20.63814	kg
Xylene	135.8773	kg
Xylene	14.11222	kg
Xylene	113.801	kg
Zeta-cypermethrin	8.45E-05	kg
Zeta-cypermethrin	3.62E-06	kg
Zinc	205.1399	kg
Zinc	43.28336	kg
Zinc	73.13783	kg
Zinc	2.83608	kg
Zinc	0.000395	kg
Zinc	14.9271	kg
Zinc	99.31348	kg
Zinc	85.18646	kg
Zinc	-0.24814	kg
Zinc, ion	149.3493	kg
Zinc, ion	534.5181	kg
Zinc, ion	27.98088	kg
Zinc, ion	15017.8	kg
Zinc, ion	133.0219	kg

Zinc-65	1017.072	kBq
Zinc-65	0.094775	kBq
Zirconium	0.031783	kg
Zirconium-95	4986.815	kBq
Zirconium-95	0.184781	kBq