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Article

Greenhouse gas inventory mapping: a case study in Malaysia’s solid fuel testing facility

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ABSTRACT

Solid fuels still play an important role as energy sources in Malaysia. The Solid Fuel Testing Facility (SFTF) system is one of the best systems for assessing the performance of various solid fuel types before their adoption in thermal power plants in Peninsular Malaysia. Given the inherent nature of solid fuel combustion, greenhouse gas (GHG) emissions are unavoidable during SFTF operations. By thoroughly examining the GHG emissions associated with the SFTF system, the reporting company can significantly contribute to environmental stewardship in the power generation sector. The study conducted an assessment of the GHG emissions mapping (Scopes 1 to 3) from the SFTF facility during the reporting year. The decarbonization of international shipping and the progress of energy transition in Malaysia hold significant potential to reduce GHG emissions across all scopes effectively. Additionally, utilizing local biomass to reduce dependence on external coal suppliers for SFTF testing is essential for lowering GHG emissions. Investments in technological advancements that minimize or eliminate reliance on Liquefied Petroleum Gas (LPG) in SFTF operations can reduce Scope 1 GHG emissions. Furthermore, procurement policies that prioritize low-GHG-emitting goods are essential for future GHG emissions reduction.

1. Introduction

Solid fuels, particularly coal, remain crucial energy sources for numerous countries, especially China and India, due to their widespread availability and affordability [1, 2]. This is also the case for Malaysia, where coal constitutes roughly 20% of the total energy supply. Over the past few decades, Malaysia's dependence on coal has surged, with its share in the energy mix growing fourfold between 1996 and 2016. The escalating need for cost-effective electricity, which drives Malaysia’s power generation sector, has led to a pronounced reliance on thermal power plants that dominate the energy portfolio. Situated in Southeast Asia, Malaysia spans the South China Sea, comprising Peninsular Malaysia and parts of Borneo. The nation comprises 13 states, including 11 in Peninsular Malaysia, alongside Sabah and Sarawak on Borneo, collectively called East Malaysia [1]. Peninsular Malaysia has been the focal point of significant electrification advancements, supporting the country's economic growth and hosting numerous thermal power plants to drive industrial and social progress.

As of 2023, Peninsular Malaysia's power sector relied on coal-fired thermal plants with a total capacity of 12.2 GW, all operating under Power Purchase Agreements (PPAs) to ensure sufficient generation capacity for meeting electricity needs [3]. Table 1 outlines these generating facilities (GF), which form a key component of the region's energy infrastructure. The JEP power plant, which began operations in 2019, marks the final coal-fired power plant constructed by Tenaga Nasional Berhad (TNB), Malaysia's leading utility company. In alignment with the TNB Sustainability Pathway 2050, the company has declared its commitment to refraining from building additional coal-fired facilities, redirecting its focus toward renewable and environmentally friendly energy sources [16-17]. As noted in Table 1, the Power Purchase Agreement (PPA) for the JEP power plant is set to conclude in 2044, leaving it with approximately 20 years of operation remaining as of 2023. Consequently, for a sustainable future, Peninsular Malaysia's coal-fired power plants must adopt clean coal technologies to mitigate their environmental impact during their remaining operational years.

Table 1. Coal-fired power plants (Peninsular Malaysia) [4-15]

Thermal power plant	Technology	Total MW	Commissioning year	PPA tenure end year
Kapar Energy Ventures (KEV) - GF2, GF3	Sub-critical	1600	1989	2029
Janamanjung - GF1	Sub-critical	2100	2003	2030
Tanjung Bin	Sub-critical	2100	2006	2031
Jimah Energy Ventures (JEV)	Sub-critical	1400	2009	2034
Janamanjung M4 - GF2	Ultra-super critical	1000	2015	2040
Tanjung Bin Energy	Ultra-super critical	1000	2016	2041
Janamanjung M5 - GF3	Ultra-super critical	1000	2017	2042
Jimah East Power (JEP)	Ultra-super critical	2000	2019	2044

2. Pre-qualification of solid fuels for power plants

Solid fuels are heterogeneous in nature, varying in rank, maceral composition, and associated impurities [18]. The combustion of these fuels, particularly coal, poses several ash-related challenges, including erosion, corrosion, slagging, and fouling. These issues often lead to reduced efficiency in coal-fired utility boilers and can result in unexpected shutdowns. While advancements in boiler designs aim to enhance capacity and routine soot-blowing systems are used to mitigate slagging and fouling, unforeseen complications persist in areas where cleaning systems are either ineffective or inaccessible due to strong bonding between deposits and surfaces. Moreover, ash deposition complicates the process of combustion tuning in coal-fired power plants [19]. Tightening environmental regulations and dwindling supplies of high-quality solid fuels further threaten the operational viability of thermal power plants. To address these challenges, various combustion strategies have been introduced to enhance fuel flexibility and lower emissions in coal-fired facilities. Among these, solid fuel blending and co-firing with alternative green fuels, such as hydrogen, ammonia, and biomass, are the most widely adopted [20-22]. However, uncertainties remain regarding the fundamental aspects of these proposed solutions, primarily due to proprietary information and the need to adapt to local design and operational characteristics. Establishing standardized measurement parameters will be crucial to evaluating performance guarantees and contractual obligations. Therefore, any adoption of these combustion solutions must first involve a comprehensive risk assessment of potential impacts on the utility boiler and downstream systems. Additionally, power utilities in Peninsular Malaysia annually receive new coal brands for use in their thermal power plants. Given the wide variety of coal sources and the complexities of the global coal supply chain, acquiring a consistent and desirable coal brand is a significant challenge. To maintain profitability and sustainability, the technical and financial risks associated with new coal brands must be thoroughly evaluated and validated before implementation in coal-fired power plants. The Solid Fuel Testing Facility (SFTF) system has proven to be an effective approach for evaluating the performance of various solid fuel types, including sub-bituminous coal, bituminous coal, biomass-coal blends, and ammonia-coal blends, prior to their adoption in Peninsular Malaysia's thermal power plants. This system serves as a vital pre-qualification tool for assessing solid fuels used in power generation. Malaysian entities such as TNB Research and TNB Fuel, recognized experts in the fields of fuel and combustion, have consistently performed pre-qualification assessments through detailed analytical fuel testing.

The development of the SFTF system was driven by the need to enhance the pre-qualification process for a diverse range of solid fuels intended for use in thermal power plants.

3. Greenhouse gas emissions mapping for the SFTF

In recent years, there has been a significant increase in attention devoted to reducing GHG emissions, attracting the participation of scientists, academics, policymakers, and industry stakeholders [23-26]. Crucially, a company's capability to measure, monitor, and assess GHG emissions resulting from its operations and systems enables it to actively contribute to a global low-carbon future [24, 27]. Therefore, a comprehensive and reliable GHG emissions mapping for the SFTF must be developed. GHG emissions take two forms: direct and indirect [28]. According to the GHG Protocol, direct emissions are those emitted from sources owned/controlled by the reporting entity, whereas indirect emissions are those emitted from sources owned/controlled by another entity because of the reporting entity's activities [24, 29]. GHG emissions are categorized into three scopes: Scope 1, Scope 2, and Scope 3. Scope 1 covers direct GHG emissions, Scope 2 accounts for indirect emissions from purchased energy (such as heat, steam, or electricity), and Scope 3 encompasses all other indirect emissions throughout the value chain.

The latest report from the International Energy Agency's Greenhouse Gas Research and Development (IEA-GHG R&D) program emphasizes the significance of two distinct approaches to GHG emissions accounting: ex ante-assessment and ex post-assessment [24, 30-31]. Ex ante-assessment entails estimating the entire range of GHG emissions associated with a product or activity, including extraction, manufacturing, transportation, construction, and end-of-life [24, 32]. Ex-post-assessment, on the other hand, is the real-time estimation of GHG emissions over a specific period (e.g., annually) [33-34]. This latter approach is particularly useful for developing carbon abatement policies and facilitating international reporting. The ex-post-assessment method, also known as the absolute emission approach, is widely used by governments, environmental organizations, and international bodies such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) [24]. This approach has a significant impact on national GHG inventories, policymaking, and regulatory initiatives aimed at reducing GHG emissions. Academic literature is also replete with studies that use the absolute emissions approach [35-37]. Kachoee et al. [35] found that incorporating renewable generation into Iranian electricity systems could result in a significant reduction of 294.6 million tons of GHG emissions. The European Commission (EC) conducted a study that revealed that achieving a 55% reduction in GHG emissions by 2030 would require an increase in photovoltaic (PV) capacity in the European Union (EU) and the United Kingdom, ranging from 455 to 605 GW [38]. Similarly, a study in the United States focused on methane emissions from the electricity system, finding that increasing the renewable share to 10% would only result in a 0.26% reduction in methane emissions [39]. The British electricity sector saw a remarkable 46% reduction in absolute emissions between 2013 and 2016, owing to a significant increase in renewable share, among other factors [40]. Li et al. [29] conducted a study to create a GHG emission inventory for several drinking water plants in China. Their findings revealed that these water treatment facilities accounted for approximately 0.15% of total GHG emissions in China. The absolute emissions approach has also been used to assess the potential for carbon capture and storage (CCS) technologies to reduce GHG emissions [41]. The integration of CCS with the ethanol production plant is expected to achieve GHG reduction potentials of 104% to 138% compared to the fossil comparator [42]. In Mexico, Castrejon et al. [36] investigated various carbon abatement scenarios in the energy sector and discovered that deploying CCS technologies held promise for lowering GHG emissions in the electricity sector. In conclusion, the absolute emissions assessment approach has proven useful in numerous studies, providing a valuable tool for comprehensively understanding emissions dynamics, scenario comparisons, and evaluating GHG emissions abatement strategies. Hence, the absolute emission approach is used in the current assessment for the SFTF.

The existing literature demonstrates the widespread GHG emissions reporting in a variety of applications. This methodology provides a comprehensive understanding of emissions dynamics in a variety of contexts, revealing valuable insights that can be applied to the SFTF system. The SFTF system is critical for evaluating solid fuels before they are used in power plants throughout Peninsular Malaysia. Given the inherent nature of solid fuel combustion, GHG emissions are unavoidable during SFTF operations. Recognizing this, there is a need to characterize the entire carbon footprint of the SFTF system, from manufacturing to the end of the cycle (waste, etc.). This characterization is especially important in aligning with TNB's sustainability commitments, emphasizing the company's dedication to a sustainable pathway.

4. Materials and methods

4.1 GHG emission inventory: Scopes 1, 2, and 3

Scope 1 emissions are direct GHG emissions produced by an organization's controlled or owned sources. Scope 2 emissions are indirect GHG emissions caused by the purchase of power, steam, heating, or cooling. Scope 3 emissions are caused by actions involving assets that are not owned or managed by the reporting organization but have an indirect impact on the organization's value chain. Scope 3 emissions refer to any sources that do not fall inside an organization's scope 1 and 2 restrictions. One organization's scope 3 emissions are equivalent to another's scope 1 and 2. Scope 3 emissions, also known as value chain emissions, typically account for the majority of a company's total GHG emissions [43], as illustrated in Figure 1.

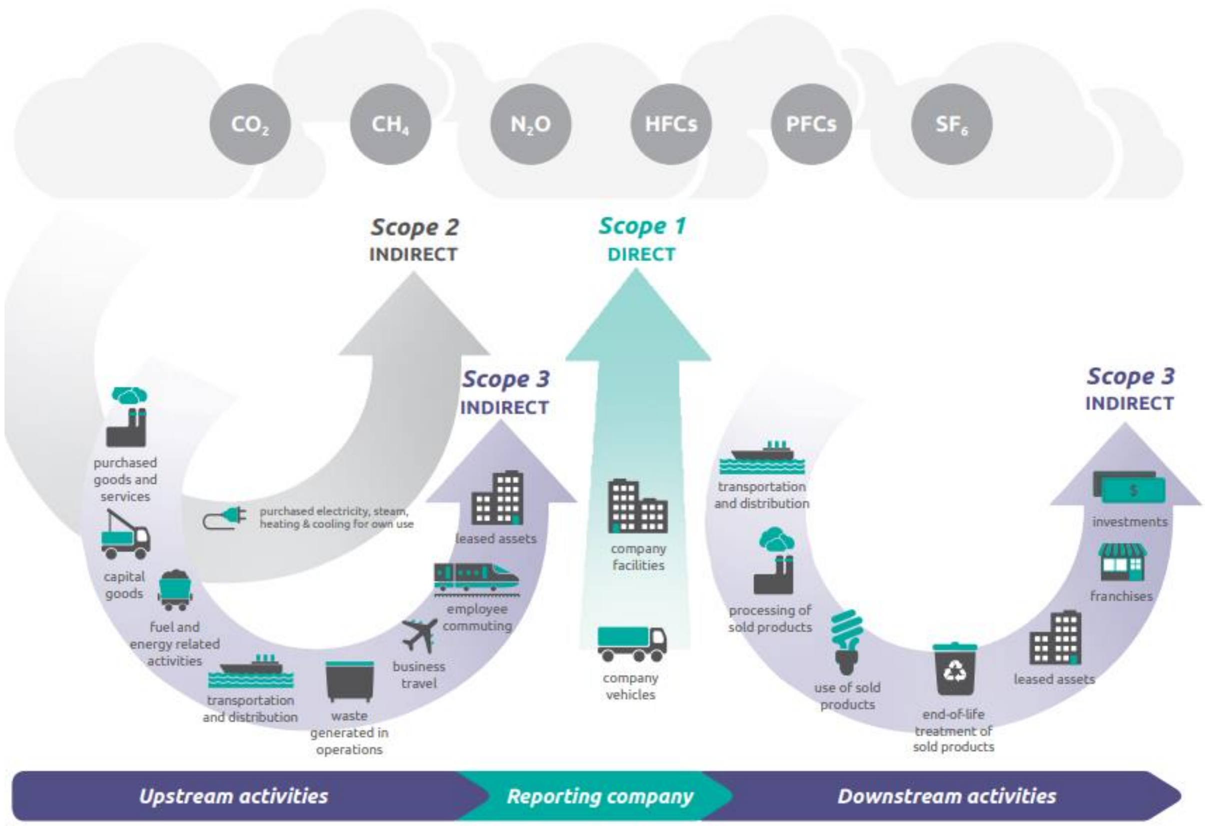

Figure 1. Overview of GHG Protocol scopes and emissions across the value chain [43]

4.1.1 Scope 1

The Scope 1 GHG inventory for the SFTF facility is calculated using a method that includes identifying and quantifying direct GHG emissions from combustion sources owned and controlled by the facility's management organization. The Scope 1 assessment consists of all equipment in the SFTF facility where fuel combustion occurs, ensuring a thorough evaluation of direct GHG emissions. The SFTF was internally operated and is the sole source of stationary combustion within the entire SFTF system. The main body of the SFTF is designed in a horizontal L-shape with a cylindrical cross-section made of stainless steel. Each section of the SFTF has viewing windows made of quartz glass that can withstand working temperatures of up to 1500°C. The SFTF's exterior is insulated with a steel encasement, and the internal walls of the pre-heating and main combustion sections are reinforced with refractory material. A water jacket layer is added to the downstream sections, particularly the slagging-fouling and exhaust segments. A thermal imaging camera is strategically placed in the main combustion section to capture the flame's dynamics while in operation, allowing for real-time monitoring and visualization. Another thermal imaging camera is installed in the slagging and fouling section to record the ash buildup process. To facilitate data collection, ash deposition probes are installed in both the slagging and fouling sections, as well as the exhaust section, allowing for slagging and fouling material sampling. In the main combustion section, a Type B thermocouple is installed.

Additionally, Type K thermocouples and pressure transducers are strategically placed throughout the SFTF to capture temperature and pressure profiles. Figure 2 depicts the SFTF system, which consists of four major interconnected systems: solid fuel feeding, Liquefied Petroleum Gas (LPG) feeding, cooling, and exhaust.

Over the course of one year, the SFTF has been estimated to test a wide range of solid fuel types, including coal and biomass. Throughout each combustion test, LPG was used to raise the flame temperature, simulating the conditions in an actual power plant's boiler. To simplify the categorization of the tested coals, each coal, regardless of brand name, has been labeled Coal A, Coal B, Coal C, and Coal D. These coals have varying carbon content values. Over one year, these four coal types were tested in various scenarios, including single coal type firing, blending of multiple coal types, and blending with biomass. The biomass variants tested during this period are referred to as Biomass A, Biomass B, and Biomass C, with each presenting a different carbon content. Table 2 shows the approximate fuel usage for the year. There are multiple methods available to calculate GHG emissions for Scope 1, which depend on the data available from suppliers and other literature sources. Essential data comprises fuel characteristics such as carbon content, higher heating value (HHV), and emission factors. The carbon content and HHV of each type of coal can be determined using the certificate of sampling and analysis (COSA) provided by suppliers, as indicated in Table 3.

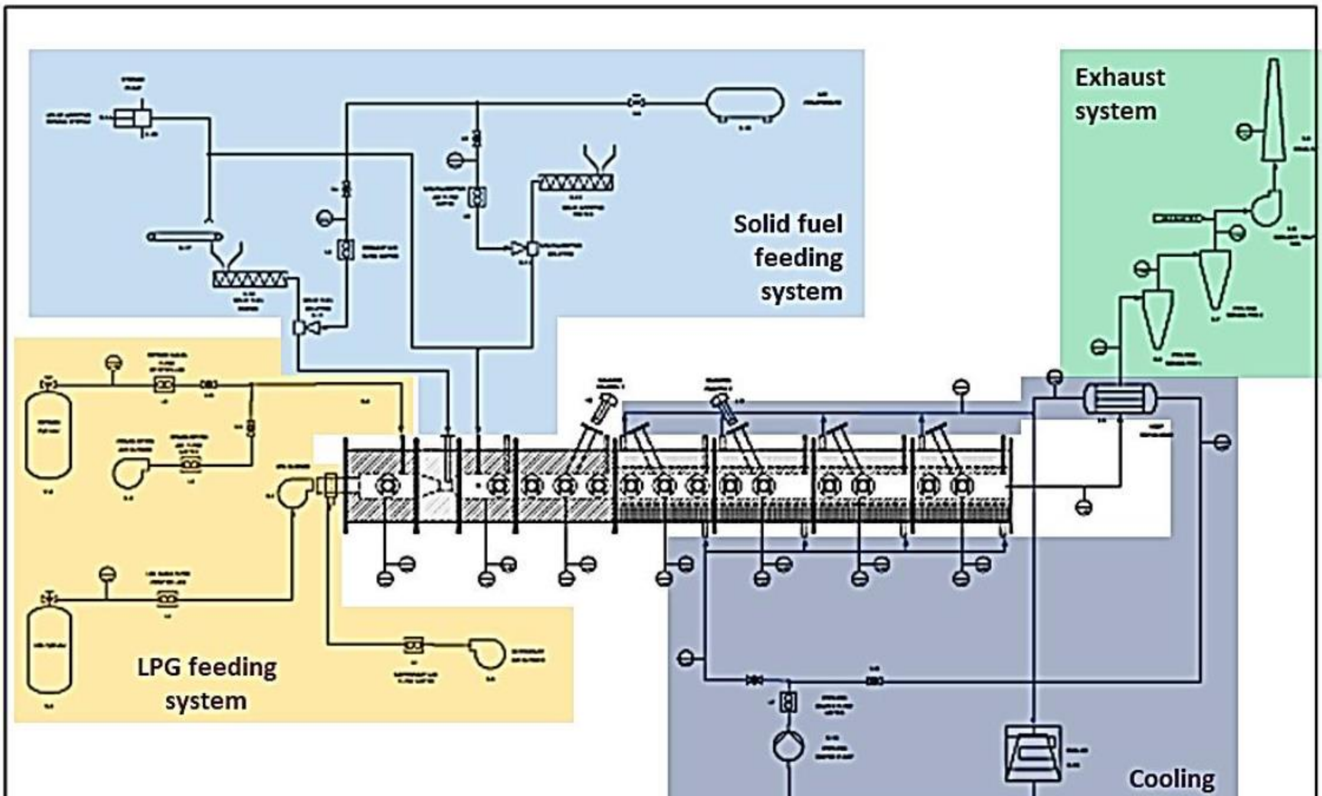

Figure 2. SFTF system

Table 2. Fuel usage (ton)

Months	Coal A	Coal B	Coal C	Coal D	Biomass A	Biomass B	Biomass C	LPG
Total	0.170	0.192	0.206	0.139	0.007	0.003	0.008	0.349

Table 3. Fuel properties

Fuel	Coal A	Coal B	Coal C	Coal D	Biomass A	Biomass B	Biomass C	LPG
Carbon content	0.618	0.658	0.608	0.752	0.441	0.491	0.455	0.825
HHV (kcal/kg)	5732.57	5932.49	5422.60	5822.56	5067.00	4852.00	4876.00	11840

This data enables the implementation of the fuel analysis method outlined in the GHG Inventory Guidance of the U.S. Environmental Protection Agency (EPA) Center for Corporate Climate Leadership [44]. Equations 1 and 2 from the GHG Inventory Guidance can be utilized to estimate the GHG emissions, as the carbon content and HHV for each fuel type are already known.

$$Emissions = Fuel \times HHV \times EF_2 \quad (1)$$

$$Emissions = Fuel \times CC \times (44/12) \quad (2)$$

where,
Fuel: Mass or volume of fuel combusted,
HHV: Fuel heat content (higher heating value), in units of energy per mass or volume of fuel,
EF_2: CO_2, CH_4, or N_2O emission factor per energy unit,
CC: Fuel carbon content, in units of mass of carbon per mass or volume of fuel,
Emissions (Equation 2): Mass of CO_2, CH_4, or N_2O emitted,
Emissions (Equation 3): Mass of CO_2 emitted.

Equation 2 is suggested for computing carbon dioxide (CO_2) emissions when the actual carbon content of the fuel is known. The carbon content is commonly quantified as a mass percentage, necessitating the use of fuel consumption data in units of mass. The equation is commonly used for CO_2 calculations due to the direct correlation between CO_2 emissions and the carbon content of the fuel. Since Equation 2 is specifically designed for CO_2 emissions, Equation 1 should be utilized in combination to compute methane (CH_4) and nitrous oxide (N_2O) emissions. To calculate CO_2 equivalent emissions, it is necessary to multiply the emissions of CH_4 and N_2O by their respective global warming potential (GWP). The most recent version of the EPA's GHG Emission Factors Hub is used as a point of reference for GWP values [45]. The total CO_2 equivalent (CO_2eq) emissions are obtained by adding the emissions of CO_2, CH_4, and N_2O. The emissions resulting from the combustion of fuels in reporting organization's vehicles (mobile combustion sources) are also considered in Scope 1 of GHG mapping. The methodology for determining CO_2eq emissions from mobile combustion sources differs from the methodology used to calculate stationary combustion emissions. CO_2 emissions can be determined by using Equations 1 or 2, which consider the amount of fuel consumed. However, the emissions of CH_4 and N_2O are primarily influenced by the emissions control equipment, such as the type of catalytic converter and the distance traveled by the vehicle (for on-road vehicles) [46]. The emissions of these gases also differ depending on the efficiency and age of the combustion technology, as well as the maintenance and operational practices.

The calculation of CH_4 and N_2O emissions from mobile combustion sources is subject to a higher level of uncertainty compared to the calculation of CO_2 emissions, due to the complexity involved. The most recent emission factors obtained from the EPA's Emission Factors Hub offer CH_4 and N_2O emission factors categorized by fuel type, vehicle type, and model year [45]. Therefore, it is utilized in conjunction with Equation 3 to compute CH_4 and N_2O emissions [46]. Emission factors are determined by the fuel characteristics and the emission control technologies utilized in a particular vehicle model year. Table 4 lists the specifications of the reporting company's own vehicles used in the SFTF facility, as well as the estimated distance traveled during the reporting year. The estimated distance traveled includes key activities such as transporting waste from fuel combustion in the SFTF, data collection at power plants, and transportation associated with the purchase of SFTF-related goods and services, among others.

$$Emissions = Distance \times EF_4 \quad (3)$$

where
Distance: Vehicle distance traveled
EF_4: CO_2 or CH_4 or N_2O emission factor per distance unit

Table 4. Vehicle details

Vehicle type	Model year (assumed)	Fuel type	Distance traveled (km)
Pickup truck	2017	Gasoline	678

Fugitive emissions, a key category of Scope 1 direct GHG emissions, arise from the unintentional release of GHG into the atmosphere through equipment and processes [47]. In the case of SFTF systems, fugitive emissions primarily stem from refrigeration and air conditioning systems, as emissions from fire suppression systems and industrial gases are considered negligible. Historically, air conditioning and refrigeration equipment relied heavily on ozone-depleting substances (ODSs) such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). However, these substances are being phased out in compliance with the Clean Air Act Amendments of 1990 (Title VI) and the Montreal Protocol. Hydrofluorocarbons (HFCs) and, to a lesser extent, perfluorocarbons (PFCs) have replaced ODSs as refrigerants alongside non-halogenated alternatives like ammonia, CO_2, propane, and isobutane in specific systems. Emissions from refrigeration and air conditioning occur during manufacturing, leakage throughout operational use, and disposal at the end of the equipment's lifespan. These refrigerants often have a GWP exceeding 1,000 times that of CO_2, making their impact on climate change substantial [47]. Consequently, reducing emissions of these gases can yield significant environmental benefits. Within the SFTF, there are several air conditioning units, and a cooling system integrated directly into its structure, featuring key components such as a water-cooled chiller. As specific information about the refrigerant used in the chiller was unavailable, it was assumed to utilize R407C based on a review of the supplier's water-cooled chiller information available online. The operational days for the air conditioning and chiller systems were estimated based on the total hours of fuel testing conducted annually, under the assumption that these systems are active only during testing periods. The guideline table for the annual leak rate of refrigeration and air conditioning fugitive emissions is provided in Table 5, based on the IPCC's Guidelines for National Greenhouse Gas Inventories [48].

Table 5. Fugitive emissions leak rate guideline

Equipment type	Capacity (kg)	Annual leak rate (% of capacity)
Domestic Refrigeration	0.05 – 0.5	0.5
Stand-alone Commercial Applications	0.2 – 6	15
Medium and Large Commercial Refrigeration	50 – 2000	35
Transport Refrigeration	3 – 8	50
Industrial Refrigeration (including food processing and cold storage	10 – 10000	25
Chillers	10 – 2000	15
Residential and Commercial Air Conditioning Systems (including heat pumps)	0.5 – 100	10
Mobile Air Conditioning	0.5 – 1.5	20

Of the various air conditioning systems, only one is estimated to be used frequently due to its location in a small office primarily utilized by personnel during testing for tasks such as data analysis and monitoring. Consequently, the fugitive emissions included in this assessment are restricted to this particular air conditioning unit and the chiller integrated into the SFTF system's main body. Table 6 outlines the assumed specifications of these systems, including their refrigerant types and capacities, used to calculate the fugitive emissions. The formula to calculate the fugitive emissions is shown in Equation 4 [48]. The most recent version of the EPA's GHG Emission Factors Hub is used as a point of reference for GWP values of the blended refrigerants [45].

$$Fugitive\ emissions = Capacity\ \times GWP \times\ Leak \qquad (4)$$

Where Leak is the annual leak rate.

4.1.2 Biogenic CO_2 emissions

Biomass refers to organic material derived from plants and animals, encompassing a wide variety of sources such as wood, agricultural crops, and plant or animal waste. When utilized as a fuel, biomass can be converted into bioenergy through processes like combustion, gasification, or anaerobic digestion [22]. During combustion, biomass releases CO_2 that was previously absorbed by plants during their growth. This CO_2 is classified as biogenic, as it is part of the natural carbon cycle. According to the GHG Protocol, biogenic CO_2 emissions from biomass combustion are reported separately from fossil fuel emissions. While they are not included under Scope 1 emissions, they are tracked as a distinct category called biogenic CO_2 emissions. This separation highlights the renewable nature of biomass, as the carbon it releases is part of a short-term cycle, in contrast to fossil fuels, which emit carbon that has been stored for millions of years. Reporting biogenic emissions separately emphasizes biomass's role in the carbon cycle and its potential as a renewable energy source. Therefore, in this assessment, CO_2 emissions from the combustion of biomass tested in the SFTF were categorized under biogenic CO_2 emissions, outside of Scope 1. However, CH_4 and N_2O emissions resulting from biomass combustion were included in Scope 1 emissions [46].

4.1.3 Scope 2

The assessment utilized the electricity emission factor based on location. The electricity grids in Peninsular Malaysia supply electricity. Therefore, the location-based method considers the average emission factors of the electricity grids that supply electricity. The regional emission factor was computed for the electricity purchased and delivered through the grid. The method involved obtaining data on the CO_2eq emissions from electricity generation in Malaysia for the reporting year, as well as the electricity generation capacity in Malaysia for that year [49]. By utilizing this information, one can compute the regional emission factor and then multiply it by the electricity consumption of the SFTF facility during the reporting year to determine the CO_2eq generated from the facility. Table 7 shows the SFTF facility's electricity consumption for the reporting year.

4.1.4 Scope 3

The total CO_2eq was calculated based on the 15 categories of Scope 3 accounting, as seen in Table 8 [43]. However, there are several categories that are not relevant in the assessment, including upstream leased assets, downstream transportation and distribution, processing of sold products, use of sold products, end-of-life treatment of sold products, downstream leased assets, franchises, and investments. In the category of upstream leased assets, the reporting company did not lease any assets during the reporting year. In the category of downstream transportation and distribution, the reporting company's SFTF facility does not sell any products. Therefore, the assessment does not consider the transportation and distribution of products between the reporting company's operations and the end consumer. This also applies to the processing, use, and end-of-life management of sold product categories. In the reporting year, the reporting company did not operate any assets owned by them and leased to other entities in the downstream leased assets category.

Table 6. Refrigeration and chiller details for the SFTF

Equipment	Assumed equipment type	Assumed capacity (kg)	Assumed refrigerant type	GWP	Leak rate (% of capacity)
Air conditioning 1	Residential and Commercial Air Conditioning System	5	R407C	1774	0.5
Water-cooled chiller	Chillers	200	R401A	16	15

Table 7. Electricity consumption

Month	Electricity usage (kWh)
Jan	950
Feb	1173
Mar	770
Apr	1250
May	930
Jun	720
Jul	740
Aug	1180
Sep	1350
Oct	910
Nov	760
Dec	980
Total	**11713**

Table 8. Scope 3 categories

Category number	Categories	Applicable (Y/N)
1	Purchased goods and services	Y
2	Capital goods	N
3	Fuel- and energy-related activities	Y
4	Upstream transportation and distribution	Y
5	Waste generated in operations	Y
6	Business travel	Y
7	Employee commuting	Y
8	Upstream leased assets	N
9	Downstream transportation and distribution	N
10	Processing of sold products	N
11	Use of sold products	N

Since there are no franchises of the SFTF facility, the franchises category is not relevant. There were no investment activities during the reporting year. Table 9 displays the estimated amount of goods and services (category 1) that were acquired for the SFTF facility during the reporting year. The emission factor was obtained from existing literature and internet sources. A cradle-to-gate emission factor was utilized to calculate or estimate the emissions associated with each product. However, the transportation-related emissions are not included in Cradle-to-gate emission factors units since it was included in the different Scope 3 categories.

Fuel- and energy-related activities (category 3) refer to the emissions generated from the production, purchase, and use of fuels and energy by the reporting company. These emissions are not included in Scope 1 or Scope 2 calculations. Considering the extraction and production of solid fuels is necessary due to the primary purpose of the SFTF facility being the testing of such fuels. To determine the emissions produced before the fuels were purchased, a cradle-to-gate life cycle analysis (LCA) approach was employed. This approach allowed for the estimation of emissions starting from the extraction of raw materials up until the fuels were received by the SFTF facility. Coal maritime transportation is classified as upstream transportation and distribution (category 4), rather than fuel or energy-related, because the coal transportation from supplier sites to Malaysia's seaport was handled by a separate company specializing in maritime transportation. It has been assumed here that the SFTF facility sourced its coal from Indonesia, a major supplier of coal in Peninsular Malaysia, to meet its electricity needs. Adaro, the supplier, has published its most recent sustainability report for the reporting year, which includes the emission factor for its coal production and its associated power consumption [56]. Therefore, the emission factor data was obtained from the document. The purchased biomass originated from a primary supplier located in Peninsular Malaysia. The biomass used was in the form of empty fruit brunches (EFB) pellets. Because there was not enough data available on the emission factor for producing this biomass from the supplier, existing literature [57] was relied upon as the primary source to estimate the emission factor for EFB pellet production. Upstream transportation and distribution (Category 4) in the current assessment primarily addresses the transport of coal and biomass (EFB) to the SFTF facility. Other purchased goods and services were delivered using the reporting company's own vehicles, and are therefore accounted for under Scope 1. Table 10 provides a summary of the transportation details for these fuels. For the transportation of EFB, the vehicle specifications are assumed to align with the information in Table 3, with the exception of the transportation distance, which is 240 km in this case. Regarding waste generated during SFTF facility operations (category 5), several factors must be considered when managing waste within the facility.

Table 9. Estimated emission factors for purchased goods and services

Purchased goods and services	Unit	Cradle-to-gate emission factors per kg (kg CO_2eq /kg)	Weight per unit (kg)	Cradle-to-gate emission factors unit (kg CO_2eq /unit)	References
Helmet (hard hat)	10	-	-	1.2	[50]
Goggles	10	-	-	1.69	[51]
Gloves	50	-	-	0.026	[52]
Office chair	15	-	-	72	[53]
Wooden filing cabinet	3	-	-	48	[53]
Rectangular office desk	2	-	-	35	[53]
Six-person bench desk	1	-	-	228	[53]
Laptops	3	-	-	361	[54]
Additional compressors	2	1.27	24	-	[55]
Spare parts	5	1.27	2	-	[55]
Mini pulveriser (grinder)	1	1.27	16	-	[55]

Table 10. Transportation details

Fuel	Transportation type	Distance traveled (km)	Emission factor (g CO_2eq /ton-km)	References
Coal	Maritime (Panamax)	2073	4.7	[56, 58]

The categories of waste to address are:

- Residual coal waste: This term refers to coal remnants that remain unconsumed following combustion. Proper handling and disposal methods are critical to reducing environmental impact. Most of the residual coal waste was returned to the nearest power plant.
- Ash wastes: Ash residues, which are produced by the combustion of solid fuels such as coal, present unique challenges due to their potentially hazardous nature. Ash may contain heavy metals and other pollutants, necessitating specialized disposal methods. All ash waste was transported back to the nearest power plant for disposal.
- Employee-generated waste: Aside from operational waste streams, waste generated by facility personnel is an important aspect of waste management, and the reporting company has hired a specific vendor to dispose of the waste.

The residual coal waste that was transported to the closest power plant was presumed to be combusted in the coal-fired facility to produce electricity, which was subsequently supplied to the main grid network. Therefore, this activity can be classified as a form of waste-to-energy (WTE). Nevertheless, because the residual coal waste generated by the SFTF facility operation was negligible, it was assumed to be zero for the Scope 3 calculations. It was assumed that the power plant would dispose of the ash waste at the nearest landfill. Due to the variety of waste treatment technologies, ash waste was assumed to be disposed of in sanitary landfills equipped with gas recovery systems, with the specific emission factor for this type of waste treatment set at 0.11 t $CO2eq$/ton of waste. The value was obtained from the study of Malakahmad et al. [59], which investigated the carbon footprint emissions of solid waste treatment and disposal techniques in Malaysia. Employee-generated waste was also calculated with this specific emission factor because it is assumed to be disposed of using the same landfill technology.

The SFTF facility has been assumed to produce approximately 0.02442 tons of ash and employee-generated waste during the year. For business travel (category 6), the category includes emissions from the transportation of employees for business-related activities in vehicles owned or operated by third parties. The SFTF facility's test results were presented at several conferences, and air travel and automobile travel (via e-hailing) were required to meet the travel requirements. Assuming the distance-based method, information about the distance traveled by the vehicle type is required to calculate the CO_2eq. The specific emission factor for each business travel type in Table 11 is based on the most recent emission factors available from the EPA's Emission Factors Hub, which includes CO_2, CH_4, and N_2O emission factors [45].

Table 11. Business travel details

Business travel type	Vehicle type	Distance traveled (km)	Emission factor (g CO_2eq /km)
Air travel	Air Travel - Medium Haul	2073	4.7
Automobile travel	Passenger car	240	102.1

In category 7, employee commuting, there were multiple employees working at the SFTF site with different working modes. The majority of technicians were primarily working on-site, whilst most executives were predominantly working in hybrid modes. Technicians are primarily responsible for carrying out operations on the SFTF, particularly during testing. On the other hand, executives are mostly responsible for analyzing data. This difference in roles leads to distinct work schedules for technicians and executives. The disparity in their commuting experience is also evident in Table 12, where it is shown that the executives traveled a shorter distance during their commute as a result of their work arrangements. All employees drove their own cars, hence the emission factor for passenger cars shown in Table 11 was used.

Table 12. Employee commuting details

Employee	Estimated number of times on-site per month	Estimated distance traveled per month (km)
Senior executive	10	636
Executive 1	10	444
Executive 2	10	432
Executive 3	10	506
Executive 4	10	236
Executive 5	10	66
Technician 1	20	472
Technician 2	20	472
Technician 3	20	472
Technician 4	20	472
Technician 5	15	660

5. Results and Discussion

Figure 3 displays the overall findings of the GHG emissions mapping for the SFTF facility throughout the reporting year. These results provide valuable information about the GHG “hot spots” within the SFTF facility. This information can be used to determine the most important areas to focus on when reducing GHG emissions throughout the entire value chain. According to the overall findings, Scope 3 is the primary source of GHG emissions among all scopes, accounting for 60% of total GHG emissions within the reporting year. Scope 3's primary source of GHG emissions is category 4, specifically upstream transportation and distribution. This category contributes 14.35 tCO_2eq/year, accounting for 83% of Scope 3's total GHG emissions. The primary source of emissions in Category 4 is the maritime transportation of coal used for the fuel test at the SFTF facility, which accounts for approximately 99.5% of total GHG emissions in Category 4. As previously stated, the tested coal's maritime transportation is classified as category 4, rather than fuel or energy-related (Category 3), since the coal was transported from supplier sites to Malaysia's seaport by a separate company specializing in maritime transportation. This highlights the crucial need for maritime decarbonization on a global scale. Even for a small facility like the SFTF, maritime transportation significantly impacts its GHG emissions mapping due to its integral role in the global economy. Liquid marine fuels derived from crude oil are extensively used, with various types, such as marine gas oil (MGO), marine diesel oil (MDO), and heavy fuel oils (HFO), being produced through oil refinement processes [60]. Due to the reliance on these carbon-intensive fuels, international shipping is responsible for approximately 2% of global energy-related CO_2 emissions in 2022 [61].

Another significant GHG "hot spot" is found in Scope 2 emissions. Malaysia, with its abundant oil and natural gas reserves, heavily relies on fossil fuel-based power plants, which constitute a significant portion of the country's electricity mix [1]. As of 2020, renewable-based power plants accounted for only 23% of Malaysia's installed capacity, as shown in Figure 4. Consequently, the grid emission factor in Malaysia remains relatively high, largely due to the predominance of non-renewable power plants, which affects Scope 2 GHG emissions. However, Malaysia's renewable energy (RE) generation is expected to grow significantly in the future, driven by favorable government policies and incentives. In 2021, the Malaysian government raised its RE targets, aiming for 31% RE capacity by 2025 and 40% by 2035, a substantial increase from the previous goal of 20% by 2025. The Malaysia Renewable Energy Roadmap, developed by the Sustainable Energy Development Authority (SEDA) Malaysia, outlines this transition plan. Various RE programs and initiatives, such as the Feed-in Tariff scheme (FiT), Large Scale Solar auction (LSS), Net Energy Metering (NEM), and Self-Consumption (SELCO), reflect the commitment of government agencies like SEDA Malaysia and the Energy Commission (EC), both under the Ministry of Natural Resources, Environment, and Climate Change (NRECC). Additionally, the recently announced National Energy Transition Roadmap (NETR) serves as a comprehensive guide to achieving a 70% RE capacity by 2050 [62].

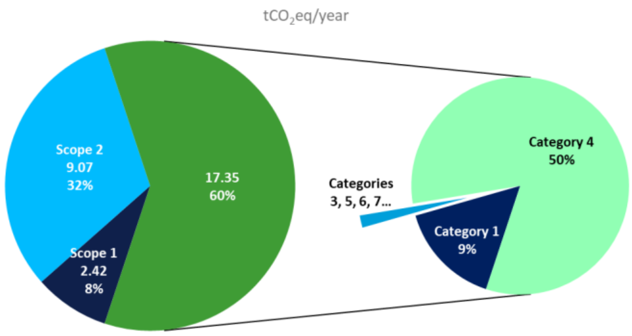

Figure 3. GHG emissions mapping for the SFTF facility

With Malaysia's ambitious energy transition targets, a reduction in Scope 2 GHG emissions for the SFTF facility is anticipated. Additionally, this transition will implicitly lower the facility's Scope 1 GHG emissions. The SFTF facility serves as a testing ground for solid fuels before they are adopted in Malaysia's thermal power plants. Given the Malaysian government's favorable policies towards RE, it is expected that thermal power plants will increasingly adopt renewable fuels to benefit from government green energy incentives. Consequently, carbon neutral solid fuels, such as biomass, will be used more frequently in power plants, either in conjunction with coal or in place of coal entirely. As demand for biomass grows, the SFTF is expected to test more biomass than coal, resulting in a decrease in reported Scope 1 emissions due to its biogenic nature, as discussed previously. Furthermore, Malaysia's robust agricultural economy has significant potential for producing biomass locally [22]. This local production will reduce reliance on external suppliers, lowering maritime transportation needs and, consequently, Scope 3 GHG emissions, particularly in Category 4. While the progress of energy transition on local and international scales governs all the above prospects, the reporting organization of the SFTF facility can take several measures to reduce their GHG emissions. For instance, Scope 1 GHG emissions can be decreased by allocating capital expenditure to enhance SFTF technology, such as increasing its flame temperature without relying on LPG throughout its operation. As shown in Table 3, LPG has a relatively higher carbon content compared to coal and biomass. Therefore, reducing the use of carbon-intensive fuels like LPG in SFTF operations will help lower Scope 1 GHG emissions. A proper procedure for SFTF operations must be established in order to shorten the facility's maintenance intervals. Frequent purchases of spare parts and additional maintenance work contribute to higher Scope 3 GHG emissions, particularly in category 1. It is critical to replace high-GHG-emitting goods with low-GHG-emitting ones while also implementing low-GHG procurement policies. The reporting company can encourage tier 1 suppliers to engage their own suppliers (tier 2 suppliers) and disclose Scope 3 emissions in order to spread GHG reporting throughout the supply chain. The procurement departments of the reporting company play a critical role in reducing GHG emissions from the SFTF facility. They have a significant influence on the upstream portion of the supply chain. Since many businesses are just starting their energy transition activities, the entire supply chain must mobilize on a large scale to reduce its carbon footprint.

Procurement departments can begin by promoting CO_2 emissions reduction efforts via communication tools with suppliers and customers. This can be accomplished through codes of conduct, contractual clauses, or awards presented to partners who excel in the related area.

6. Conclusions

The study conducted an assessment of the GHG inventory from the SFTF facility during the reporting year. The assessment included the mapping of GHG emissions from Scopes 1 to 3. The study also examined the possibilities of decreasing GHG emissions from the facility, emphasizing important policies and proposing additional methods for achieving further reduction. The advancement of energy transition, both at the local and international levels, has a substantial influence on the potential for reducing GHG emissions from the SFTF system. The decarbonization of international shipping and the progress of energy transition in Malaysia have significant potential to effectively reduce GHG emissions in all scopes. In addition, it is crucial to improve the availability of local biomass to reduce the need for external coal suppliers for SFTF testing, which is essential for reducing GHG emissions. Technological progress is crucial for achieving a reduction in GHG emissions. It is advisable to prioritize investments in technological advancements that can minimize or eliminate the reliance on LPG in SFTF operations, consequently leading to a reduction in Scope 1 GHG emissions. In addition, it is essential to have procurement policies that prioritize goods with low GHG emissions. Efforts to reduce CO2 emissions can be promoted by utilizing communication tools with suppliers and customers, such as codes of conduct, contractual clauses, or awards for exceptional partners in the related field.

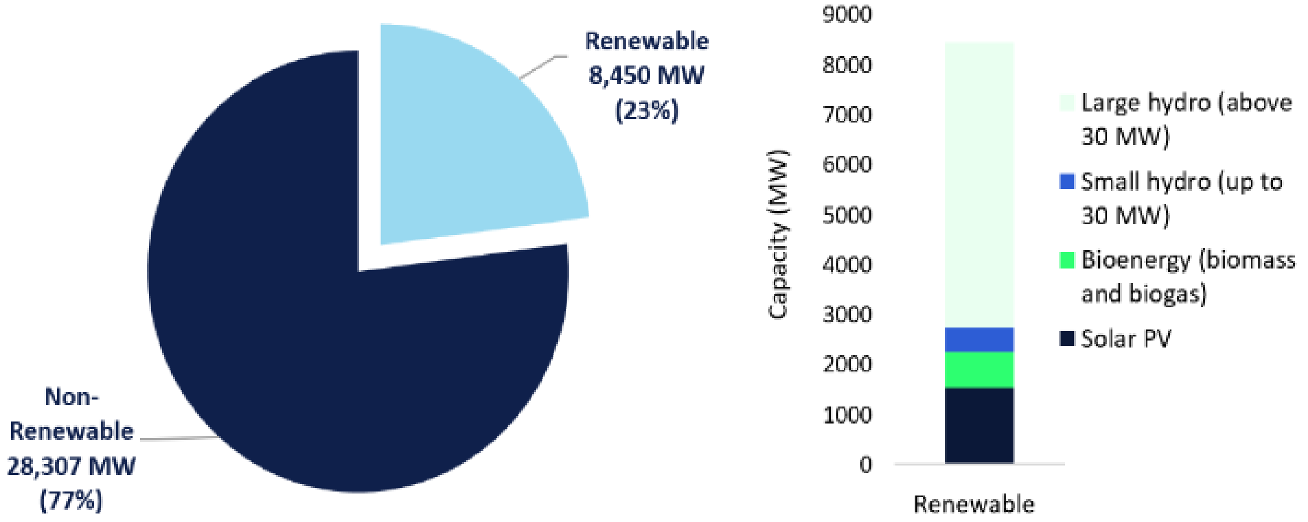

Figure 4. RE installed capacity as of 2020, adapted from [63-64]

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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