sustainability

MDPI

Article

Bioenergy for a Cleaner Future: A Case Study of Sustainable Biogas Supply Chain in the Malaysian Energy Sector

Nur Izzah Hamna A. Aziz [1], Marlia M. Hanafiah [1,2,*], Shabbir H. Gheewala [3,4] and Haikal Ismail [1,5]

- [1] Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia; izzahhamna@ukm.edu.my (N.I.H.A.A.); haikal.b.ismail@gmail.com (H.I.)
- [2] Centre for Tropical Climate Change System, Institute of Climate Change, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
- [3] The Joint Graduate School of Energy and Environment, Centre of Excellence on Energy Technology and Environment, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand; shabbir_g@jgsee.kmutt.ac.th
- [4] Center of Excellence on Energy Technology and Environment, PERDO, Bangkok 10140, Thailand
- [5] School of Technology Management and Logistics, College of Business, Universiti Utara Malaysia, Sintok 06010, Kedah, Malaysia
- * Correspondence: mhmarlia@ukm.edu.my

Received: 18 March 2020; Accepted: 6 April 2020; Published: 16 April 2020

Abstract: A life cycle assessment (LCA)-based environmental sustainability evaluation conceptual framework of biogas production has been proposed to improve the sustainability of biogas supply chains. The conceptual framework developed in this study can be used as a guideline for the related stakeholders and decision makers to improve the quality and enhance the sustainability of biogas production in Malaysia as well as promoting biogas as a clean, reliable and secure energy. A case study on an LCA analysis of a zero waste discharge treatment process has been conducted. In the zero discharge treatment system, biogas can be produced with a maximum water recycle and reuse. It was indicated that the biogas production and zero discharge treatment of a palm oil mill effluent were environmentally sustainable as the system utilized organic waste to produce bioenergy and achieved zero discharge. However, there were other aspects that should be taken into consideration, particularly regarding the sources of electricity and upstream activity, to ensure the sustainability of the system holistically.

Keywords: clean technology; renewable energy; life cycle assessment; zero discharge; waste treatment; sustainability

---

1. Introduction

Energy plays a crucial and challenging role in sustainable development. The Malaysian government has been continuously reviewing its energy policy to ensure the sustainability of energy resources due to the increase of energy demand [1,2]. The emerging of renewable energy production to replace fossil fuels consumption could certainly reduce environmental pollution because it provides a low-carbon energy system [3]. Nonetheless, the production of renewable energy consists of input and output flows and operational processes which may influence its performance. It is essential to obtain renewable energy in sustainable ways in order to achieve sustainable development as well as promoting economic growth in the country. Clean energy, sustainable cities and communities, responsible consumption and production and climate action are included in the 17 Sustainable Development Goals (SDGs). Griggs et al. [4] argued that planetary stability should be integrated in the United Nations' targets, which are to eliminate poverty and protect the earth's life-support system.

Biogas is produced by the indirect conversion of solar energy stored in natural organic matter into a gaseous energy carrier by anaerobic fermentation; therefore, biogas is the end product of microbiological fermentation [5,6]. The main combustible component in biogas is methane (CH_4), and it also contains significant amounts of carbon dioxide (CO_2) and other trace gases [7,8]. Biogas can be used for heating, electricity generation, as a fuel for vehicle or distributed via the natural gas grid [9,10]. Furthermore, the digestate produced by the anaerobic digestion process can be used as a biofertilizer in agriculture, thus reducing the need for chemical fertilizers [11,12]. However, questions about the sustainability of bioenergy pathways have been raised, because the conversion of biomass into energy consists of input and output flows which may affect its environmental performance. Therefore, a holistic and comprehensive environmental tool like Life Cycle Assessment (LCA) can be used to assess and ensure the environmental sustainability of biogas supply chains [13,14].

Life cycle assessment (LCA) is a comprehensive assessment and a holistic approach that can provide relative and accurate information to be applied in environmental management [15–17]. LCA can be used to assess environmental burdens related to a product, process or service by identifying the energy, materials used and emissions released to the environment [18–20]. The LCA approach has long been practiced around the world, and it has significantly improved in recent years. According to Talve [21], LCA was first introduced in 1960 in the United States of America by Harold Smith. He presented his research in the 1963 World Energy Conference on the assessment of the cumulative energy needed to produce chemical products. However, this methodological approach is still new and under development in Malaysia. Hence, this study has taken a further step in the direction of evaluating the environmental impacts of biogas production based on the LCA perspective.

2. Sustainable Biogas Production

Recent years have seen a surge of interest in assessing the environmental impacts of the production of green goods and services. This is true particularly in the renewable energy system, increasingly concerned with sustainable environmental requirements. For example, Malaysia has recently become one of the most important poles of biofuel technology in the world [22]. This is due to its huge palm tree plantations, a source of biofuel production. Moreover, there is an abundant biomass source in Malaysia from agricultural crops and wastewater from industrial activity that can be utilized as feedstock for bioenergy production [23,24]. However, without appropriate wastewater treatment and management, a huge source of renewable energy will be wasted and, at the same time, become a menace to the environment. Hence, biogas production from available biomass waste and wastewater could be one of the suitable solutions to overcome the wastage. Biomass waste utilization has a direct impact on the recovery of energy. There are a number of energy recovery methods which can be used, such as biochemical (e.g., anaerobic digestion, composting and vermicomposting), thermal conversions (e.g., gasification, incineration, fast and slow pyrolysis) and chemical conversions (e.g., transesterification) [25,26].

In Malaysia, LCA studies were mostly conducted by the Malaysian Palm Oil Board (MPOB) and SIRIM Berhad. Various areas have been covered in the LCA study, such as waste management, petroleum, agro-industry and palm oil [27,28]. A study conducted by Aziz et. al [24] revealed the potential of biogas production from six types of substrates in Malaysia. In addition, recent studies on biogas production from the anaerobic digestion of a palm oil mill effluent have been conducted to highlight the feasibility of the LCA approach in biogas production, as well as the opportunity and challenges from the Malaysian perspective [27]. However, there are no strict regulations issued by the government concerning biogas plant installation and utilization, despite the various green policies that have been developed and introduced. Even though biogas generation is still at a nascent stage in Malaysia, it has a high potential in the way forward to achieve sustainable development.

Therefore, it is important to assess the environmental performance of the system to ensure and enhance its sustainability [28,29]. A proper guideline, like a LCA-based conceptual framework, would also assist the government and related stakeholders in making decisions to improve the environmental performance of biogas production. Hence, an LCA-based conceptual framework was developed and proposed in this study (Figure 1). The framework shows the integration of policy drivers, proposed actions, existing green initiatives, green market influences and sustainability evaluation using the LCA approach affecting the sustainability of biogas production supply chains.

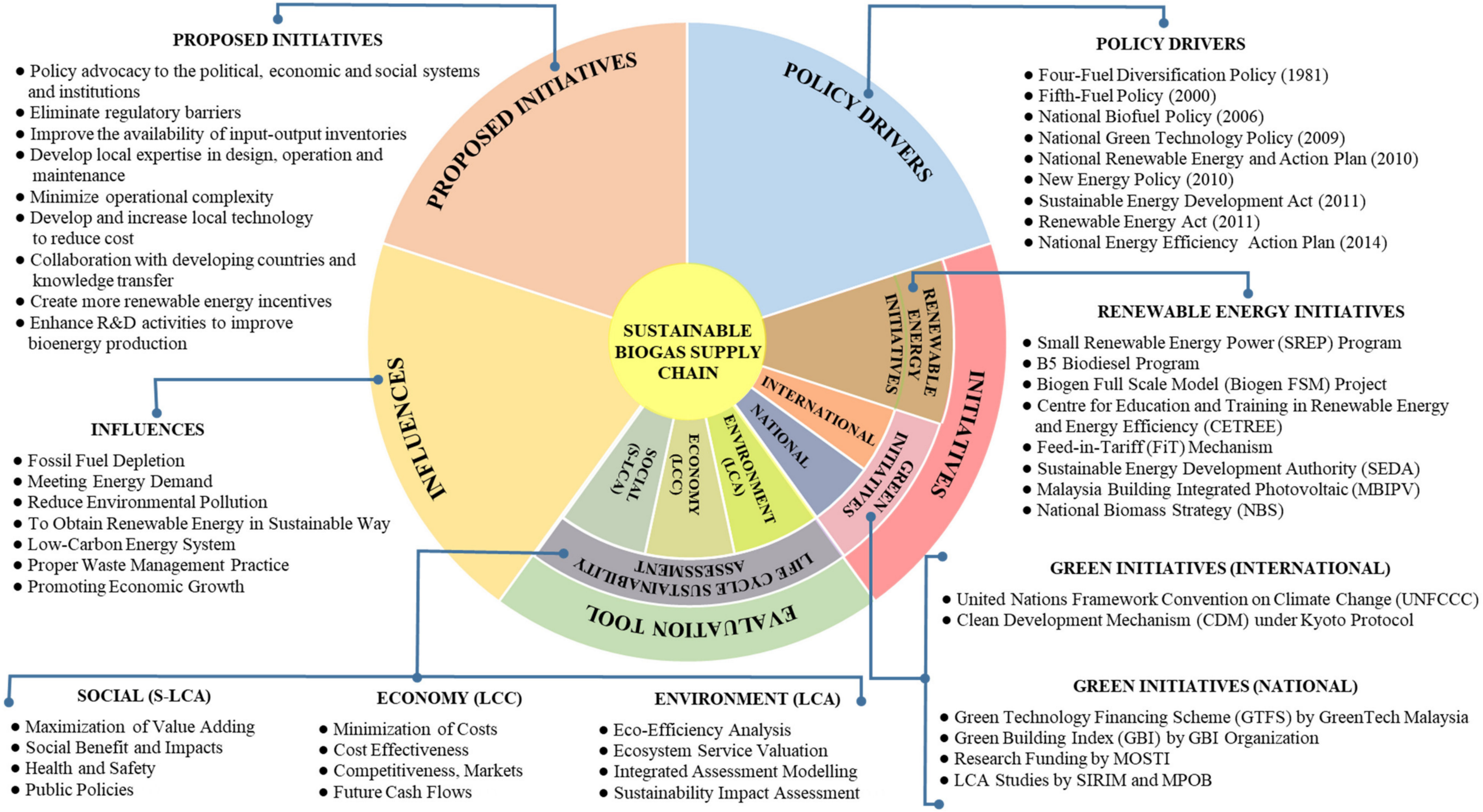

Figure 1. Conceptual framework of a life cycle assessment (LCA)-based environmental sustainability evaluation of biogas production supply chains.

The LCA-based environmental evaluation is an integrated approach which can assess the environmental performance of biogas production. LCA is a cradle-to-grave approach for assessing the impacts of a product throughout its life cycle, from raw materials extraction, through production, manufacture, transportation and use, to the management of the discarded product, either by recycling or final disposal [30]. The information from the conceptual framework of an LCA-based environmental evaluation of biogas production could assist the consumer in making choices towards green goods and services. Moreover, an LCA approach will act as a continuous measure and help both policy and decision makers to identify the opportunities for environmental improvements.

2.1. Policy Drivers

Many initiatives have been proposed and implemented by the government to promote sustainable development. As shown in Figure 1, a total of nine policy drivers have been identified concerning renewable energy evolution: Four Fuel Diversification Policy (1981), Fifth Fuel Policy (2000), National Biofuel Policy (2006), National Green Technology Policy (2009), National Renewable Energy and Action Plan (2010), New Energy Policy (2010), Sustainable Energy Development Act (2011), Renewable Energy Act (2011) and National Energy Efficiency Action Plan (2014). The energy-related policies were introduced to ensure future energy security and stability [31,32].

In 1981, the Four Fuel Diversification Policy was proposed to prevent over-reliance on oil as the main energy source, with a diversification of the energy mix to include gas, hydropower and coal. The National Biofuel Policy promoted the use of biofuels through incentives and making available 5% diesel and 5% palm olein biodiesel blends. The National Green Technology Policy targeted the development of renewable energy for energy security and considered renewable energy as an important factor for economic growth. The utilization of indigenous renewable resources was introduced through the National Renewable Energy and Action Plan to achieve electrical supply security and sustainable socioeconomic development. Under the Renewable Energy Act, a tariff system to promote renewable energy generation was established. The transition of attention towards renewable energy generation can be seen through the continuous development and realignment of energy policies.

Many countries' governments around the world have committed to decreasing greenhouse gas (GHG) emissions by promoting renewable energy. Both developed and developing countries have set a renewable energy target and promulgated legislation and regulations to encourage renewable energy development. Table 1 shows the regulations and measures related to renewable energy in several countries. The policies and measures were designed to reduce fossil fuel dependency, to promote the development and utilization of renewable energy, diversifying energy supplies, ensuring energy security, protecting the environment and considering economic and social sustainability [33,34]. According to Yaping Hua et al. [34], by the year 2013, at least 144 countries had set different renewable energy targets and policies at the national level. In addition, there was a total investment of 244 billion USD in renewable energy development globally.

Table 1. Renewable energy related policies and measures in several countries (adapted from [35]).

Country	**Legislation and Regulation**
	Developed Countries
Germany	2017 Amendment of the Renewable Energy Sources Act (EEG 2017) Subsidy for solar PV with storage installations Ground-Mounted PV Auction Ordinance (2015) 2014 Amendment of the Renewable Energy Sources Act (EEG 2014) CHP Agreements with Industry KfW Program Offshore Wind Energy Law on Energy and Climate Fund "Energy of the Future" monitoring process Sixth Energy Research Program

Table 1. *Cont.*

Country	Legislation and Regulation
	Developed Countries
Germany	Biofuels Quota Act (2010) Energy Concept National Energy Action Plan (NREAP) (2010) KfW Renewable Energies Program KfW Program Energy-Efficient Rehabilitation Renewable Energies Heat Act (2009) Climate Legislation Package Enacted under the Integrated Climate Change and Energy Program (2008) Integrated Climate Change and Energy Program Funding for Solar Power Development Center Energy Industry Act (2005) (amended 2012) Law to Amend the Mineral Oil Tax Law and Renewable Energy Law (2002) Combined Heat and Power Law (2002) Eco-Tax Reform (1999) Market Incentive Program Preferential Loan Program offered by the Reconstruction Loan Corporation (KfW) Federal Building Codes for Renewable Energy Production Green Power Ordinance on the Fee Schedule for Architects and Engineers (1995) Federal States Support for Renewable Energy (1985)
Australia	Renewable Energy (Electricity) Act 2000 Renewable Energy (Electricity) (Small-Scale Technology Shortfall Charge) Act 2010 Renewable Energy (Electricity) (Large-Scale Generation Shortfall Charge) Act 2000 Renewable Energy (Electricity) Regulation 2001, Renewable Energy Certificates (RECs)
Japan	Law Concerning the Promotion of the Development and Introduction of Alternative Energy Long-Term Energy Supply and Demand Outlook (2015) Strategic Energy Plan (2014) Feed-in Tariff for Renewable Electricity and Solar PV Auction (2012) Global Methane Initiative (2010) Cool Earth-Energy Innovative Technology Plan (2008) Seaway Signals Converted to Use Renewable Energy (2000) Promotion of New and Renewable Energy (1997) Special Measures Law for Promoting the Use of New Energy (1997) Projects for Development and Deployment of New and Renewable Energy by NEDO and by NEPC (1980) Law on Establishment of NEDO (1980)
	Developing Countries
China	Renewable Energy Law Regulation on Administration of Power Generation from Renewable Energy Measures on Supervision and Administration of Grid Enterprises in the Purchase of Renewable Energy Power Trial Management Measures for Renewable Power Pricing and Cost Share Trial Management Measure for Allocation of Renewable Energy Tariff Surplus Revenue Notice of Strengthening the Construction and Management of Biofuel Ethanol and Promoting Sound Industrial Development Trial Management Measures for the Special Development Fund Implementation Guidelines on Promoting Wind Power Industry Guides to Renewable Energy Development
Thailand	Thailand Alternative Energy Development Plan (AEDP 2015-2036) Feed-in Tariff for Very Small Power Producers (VSPP) (excluding solar PV) Feed-in tariff for distributed solar systems Biodiesel blending mandate Renewable Energy Development Plan (REDP) 2008-2022 Small and Very Small Power Purchase Agreements Energy Conservation Program (ENCON)

Table 1. *Cont.*

Country	Legislation and Regulation
	Developed Countries
Vietnam	National Power Development Plan 7 (PDPD7 – revised) (2016) Vietnam Renewable Energy Development Strategy 2016-2030 with outlook until 2050 (REDS) Decision on support mechanisms for the development of biomass power project in Vietnam (biomass feed-in tariff) Decision on support mechanisms for the development of waste-to-energy power projects in Vietnam (feed-in tariff) Accelerated depreciation tax relief for renewable energy projects Electricity Law (2005) Decree No. 45/2001/ND-CP on electric power operation and use (2001)

2.2. The Green Initiatives in Malaysia

The government has provided a great effort and commitment through many renewable energy and green initiatives at both the national and international levels to promote green and sustainable development (Figure 1). Renewable energy initiatives like the Small Renewable Energy Power (SREP) program, Biogen Full Scale Model (Biogen FSM) project, Feed-in-Tariff (FiT) mechanism, Malaysia Building Integrated Photovoltaic (MBIPV), B5 biodiesel program, Centre for Education and Training in Renewable Energy and Energy Efficiency (CETREE), Sustainable Energy Development Authority (SEDA) and National Biomass Strategy (NBS) have been introduced [36,37]. In addition, the Green Technology Financing Scheme (GTFS) by GreenTech Malaysia, Green Building Index (GBI) by GBI organization, research funding by MOSTI and LCA studies by SIRIM and MPOB are the examples of green initiatives conducted at the national level.

Malaysia also took part at the international level (i.e., United Nations Framework Convention on Climate Change (UNFCCC) and Clean Development Mechanism (CDM) under the Kyoto Protocol), which shows the commitment of the government to shifting towards cleaner and sustainable development. More innovative initiatives and strategies would help to identify multiple pathways towards sustainable energy. Due to this commitment, the environmental evaluation of a biogas production system using LCA tools can be integrated into Malaysia's policies and action plans to take further steps towards sustainable development in the future.

2.3. Life Cycle Sustainability Assessment

Sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [38]. In order to develop a life cycle sustainability assessment (LCSA), integrated environment, economy and social perspectives need to be considered by looking at three different dimensions of the same system [39–41] (Figure 1). The LCA produces numerical data and indicators to evaluate the used resources and environmental impacts; life cycle costing (LCC) produces cost indicators to evaluate the cost-effectiveness; and the social life cycle (S-LCA) introduces social indicators to evaluate the corporate policy and human rights of a product or system. Therefore, if the study could extend into economic and social dimensions in the future, a thorough understanding on the sustainability of the system could be achieved. According to Coyle and Rebow [42] and Jürgensen et al. [43], sustainability in energy systems is usually associated with energy efficiency and energy with lower emissions. An evaluation tool like the LCA can be used to assess the environmental performance and determine the hotspots along the supply chains, thus providing a comprehensive assessment of the sustainability of the renewable energy system. The evaluation tool is one of the important factors that should be integrated into sustainable energy, in addition to public awareness, sustainability education and training and the promotion of renewable energy resources.

The environmental life cycle assessment of biogas production supply chains helps to define the up- and down-streams of the whole system and identify possible problems at each stage of the evaluation process [44,45]. The contribution of the process to the selected impact categories can be determined. Several actions and improvement strategies can be proposed for enhancing the environmental sustainability of biogas production. Other tools that can be used to support the decision making and to evaluate the impacts of renewable energy systems are the ecological footprint, energy analysis, net energy balance, carbon footprint, GHG life cycle analysis, material flow analysis, sustainability indicators, fuel cycle analysis and life cycle risk assessment [46]. However, it has been found that the LCA is preferable as a research-based approach and able to holistically assess the environmental sustainability of renewable energy systems [46]. As reported by Sala et al. [47] and Takeda et al. [48], the LCA approach could identify deficiencies for further improvements and help to avoid problem and burden shifting from one part of the system to the others.

Bioenergy production from organic waste does not automatically imply that its production, conversion and utilization are sustainable [49]. Based on the findings of LCA studies for renewable energy by Milazzo et al. [50] and Turconi et al. [51], the sustainability of bioenergy is more than just GHG savings. It is also associated with specific resource use and the potential environmental consequences. The sustainability of these components is important because any deficiencies could lead to market distortion and consequently impede the efforts to increase renewable energy shares in Malaysia’s energy capacity.

2.4. *Influences and Proposed Actions*

Figure 1 shows some issues that influence the growing interest towards sustainable renewable energy production. Fossil fuels depletion, increasing energy demand and environmental pollution problems have been a major influence in the transition of attention towards renewable and sustainable energy [52,53]. The current plan also aims to obtain renewable energy in sustainable ways, to have a low-carbon energy system and to have a proper waste management practice, as well as promoting economic growth. However, it is crucial to have an appropriate action plan to overcome the obstacles and barriers which limit the feasibility of sustainable biogas production supply chains in Malaysia.

According to Figure 1, a few strategies and initiatives that could be proposed to help improve the sustainability of the system are the research and development (R&D) activities, which should be enhanced to improve bioenergy production, more renewable energy incentives, collaborations with developing countries and knowledge transfer, developing and increasing local technology to reduce cost, minimizing operational complexity, developing local expertise in design, operation and maintenance, improving the availability of input-output inventories, eliminating regulatory barriers and also conducting policy advocacy to the political, economic and social systems and institutions.

3. Promoting Biogas Production from a Palm Oil Mill Effluent as a Renewable Energy Source in Malaysia

The palm oil industry in Malaysia has boosted the country’s economy, as it was one of the largest palm oil exporters and producers in the world. The palm oil industry has supported a variety of food products like margarine, cooking oils and animal feeds, and non-food products like soaps, detergents, cosmetics, pharmaceuticals and biofuels [54–58]. The by-products generated during the palm oil milling process can be recycled and recovered into reusable materials or products (e.g., shells and fibers used as fuel for boilers, empty fruit bunches used as soil conditioner and palm oil mill effluent (POME) utilized as a source of energy generation) [59,60]. Figure 2 shows the overview of the flow process and products of the palm oil industry. According to Basri et al. [61] and Oswal et al. [62], POME has been applied as feedstock in most palm oil mills to generate biogas. Due to its high organic content, POME can be a good source to generate methane gas for energy production. The exploitation of POME for renewable energy production would enhance the sustainability of palm oil industries. As a consequence, bioenergy generation from POME can be an added value to the palm oil industry in Malaysia.

Issues on energy security and environmental concerns lead to the utilization of renewable energy sources. Upgrading biogas to biomethane and injecting it into the natural gas grid could be an efficient way of integrating the biogas into the energy sector [60]. Accordingly, biomethane can substitute the use of natural gas and can also be used as transportation fuel. However, the unattractive connection price to the grid, the irregular supply of biomass, the low efficiency of combustion technology and poor supporting systems like interconnection infrastructure have caused a shortfall in national renewable energy capacity in Malaysia. In 2017, the total electricity demand in Malaysia was approximately 12 607 ktoe [27]. The estimated energy potential generated from 50k tonnes of POME produced in a year is about 3.2 million MWh of electricity, contributing to 2.19% of the total electricity demand. Though the utilization of biogas as renewable energy is still unregulated in Malaysia, it is crucial because it could improve long-term energy security and environment protection.

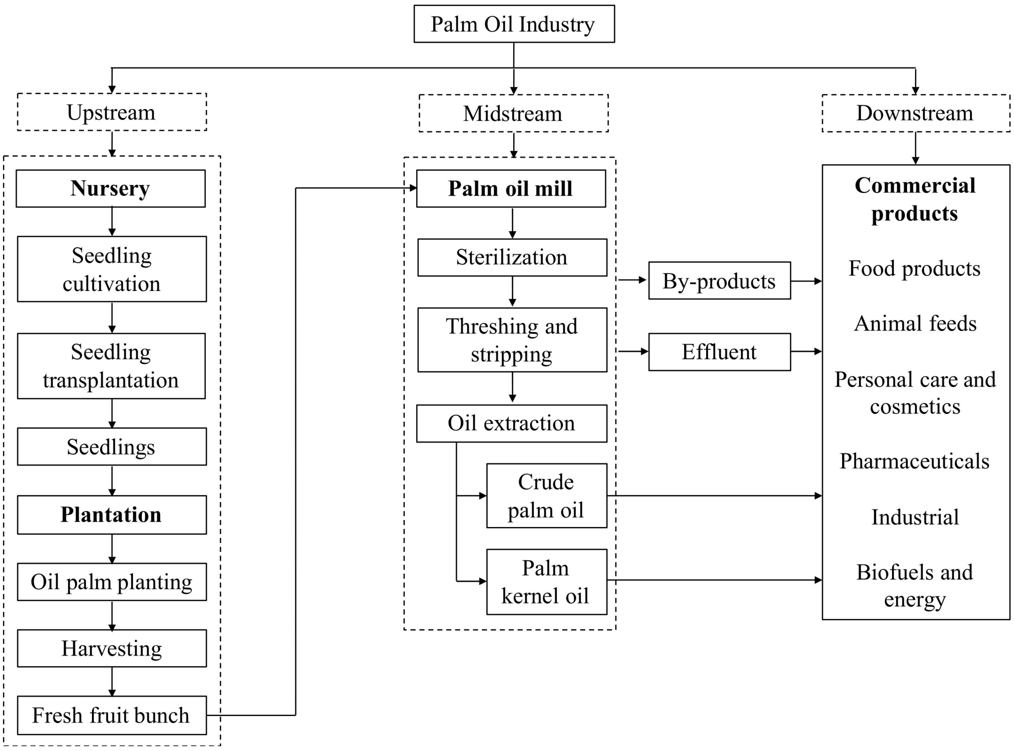

Figure 2. Overview of the flow process and products of the palm oil industry in Malaysia.

Current developments in the local and global economies are closely connected to sustainable energy resources. The feed-in-tariff (FiT) mechanism administered by the Sustainable Energy Development Authority (SEDA) was designed to correspond to the National Renewable Energy and Action Plan (2010), that suggested the requirement of legislative solutions to increase the renewable energy share in Malaysia's energy mix [63,64]. The type of resources included in the FiT mechanism are biogas, biomass, hydropower and solar photovoltaic power. At 40 MW, the oil palm biomass contributed the highest grid-connected capacity among renewable technologies in the Ninth Malaysia Plan (2006–2010) [65–67]. In addition, oil palm biomass emerged as a major contributor towards achieving the capacity target set under the FiT of 800 MW of grid-connected capacity by the year 2020 [63,68].

However, the survey carried out by Umar et al. (2014) [67] showed that some of the palm oil millers were less interested in embarking on a renewable energy venture. This is due to the fact that most of the mill operators' financial capability is too low to participate in a high cost project, and renewable energy was not a profitable business. Therefore, an innovative incentives scheme should be proposed to reduce the financial pressure on energy providers. In addition, the cost could be reduced by developing and increasing local technology, as well as local expertise in design, operation and maintenance. The operational complexity should also be minimized, so that the system can be conducted and managed easily and the palm oil millers would not overlook the efficiency and effectiveness of the system. Other strategies that could be executed to enhance and promote the sustainability of biogas production in the country are the improvement of research and development (R&D) activities and the establishment of collaborative research with other developed and developing countries, along with a concurrent transfer of knowledge.

Conducting an LCA for a product or system requires a transparent inventory, so that an excellent overview of areas in which inputs could be substituted by less polluting materials can be acquired for the good of the environment. Hence, it is important for industries to record and make available their input and output inventories for research purposes. The conceptual framework of the LCA-based environmental evaluation developed in the present study can be used as a guideline for related stakeholders and decision makers to improve the quality and enhance the environmental sustainability of biogas production from POME in Malaysia, as well as promoting biogas as a cleaner, reliable and secure energy. The stakeholders include the government, oil palm producers, financial institutions and oil palm associations. Government intervention is crucial to drive the industry forward to achieve cleaner technology and towards sustainable development. Accordingly, the market community also shares an equal responsibility and influence, in order to increase the use of renewable energy sources and meet the sustainable development goals. A policy advocacy of sustainable renewable energy resources should be conducted at the political, economic, social and institutional levels, to raise awareness to the fact that environmental-friendly products and systems are starting to get local and global attention. According to Aziz et al. [69], various studies on the implementation of the LCA approach to evaluate the environmental performance of biogas production show that the LCA could help improve the environmental profile of the biogas system. There were many initiatives by the Malaysian government towards sustainable development, which can be a potential driving force to apply the LCA to the environmental evaluation of a clean technology.

4. Life Cycle Assessment of Zero Discharge Treatment

POME is a remarkably contaminating effluent because of its high content of organic matter (expressed as chemical oxygen demand (COD) and biochemical oxygen demand (BOD)), which can have harmful effects on the environment, particularly on the water resources to which POME is discharged. In recent years, POME has been recognized as a prospective source of renewable energy. Accordingly, the production of bioenergy will be more sustainable and cleaner when operating simultaneously with wastewater treatment. There are various existing processes for POME treatment and the conversion of POME into bioenergy, such as aerobic and anaerobic digestion, physico-chemical treatment and membrane separation [70–73]. Nevertheless, in the integrated biological treatment of the POME system, which includes membrane treatment, higher quality effluents can be produced. This system is also called zero discharge treatment system. In the zero waste discharge treatment system, all wastewater is purified and recycled. Therefore, the plant discharges zero effluents into the water, which in effect reduces environmental pollution. The anaerobic digestion of POME can produce biogas and a final discharge which meets the proposed regulatory standard of the Department of Environment (DOE), Malaysia. However, in the zero discharge treatment system, biogas can be produced with a maximum water recycle and reuse.

Zero waste discharge treatment has been implemented in several countries around the world (i.e., Italy, United States, Canada, Malaysia, China and India). For instance, this technology has been used for reusing the wastewater produced by car manufacturing and secondary sewage [74], heavy oil recovery [75], wastewater reclamation and reuse in marine ports [76], the treatment of chromium-containing leather waste [77] and treating POME [78]. However, the environmental sustainability of this treatment process in terms of the LCA approach is still under development. One study has been carried out in India by Rajakumari and Kanmani [79] on zero liquid discharge treatment technologies for textile industries, using pretreatment, reverse osmosis (RO) and evaporator treatment units. The results of the study show that the energy consumption in the treatment plant had contributed to the global warming potential (GWP) by

5.56 kg CO_2-eq per functional unit of 1 m^3 of textile wastewater. It was reported that CO_2 was a leading pollutant, which can be reduced by using biomass gasification.

Wastewater recovery and recycling has become a growing trend because it not only minimizes the environmental impact of discharged water, but can also be an additional water resource which promotes water sustainability [80]. On that account, palm oil mills in Malaysia, particularly, should explore and adopt the zero discharge technology to achieve zero discharge concepts. According to Madaki and Seng [81], POME is a very difficult and expensive waste to manage. Hence, there is a need to shift from the conventional system to the current advanced POME treatment technology. Although the zero discharge treatment system is a promising sustainable technology, its application requires a high amount of energy consumption, which will result in some environmental impacts [82]. Therefore, an LCA of the zero waste discharge treatment process is important, as it will provide additional insights into the environmental sustainability of the technology.

4.1. Material and Methods

4.1.1. Goal and Scope, Unit Process, Functional Unit and System Boundaries

In this study, the zero discharge treatment of POME has been used as a case study. The LCA includes four phases: goal definition and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation. A gate-to-gate approach was used, focused on the process of zero discharge treatment. The goal of using the LCA method was to determine the environmental impacts of the zero discharge treatment system and to derive measures to reduce them. The energy and material requirements, as well as the emissions to the environment, were taken into account. The functional unit for impact assessment was a metric tonne of POME. Figure 3 shows the system boundary for the LCA of the zero discharge treatment of POME. Three main processing units (i.e., pretreatment, biological treatment (anaerobic and aerobic treatment) and post-treatment (ultrafiltration and reverse osmosis)) were included in the environmental assessment.

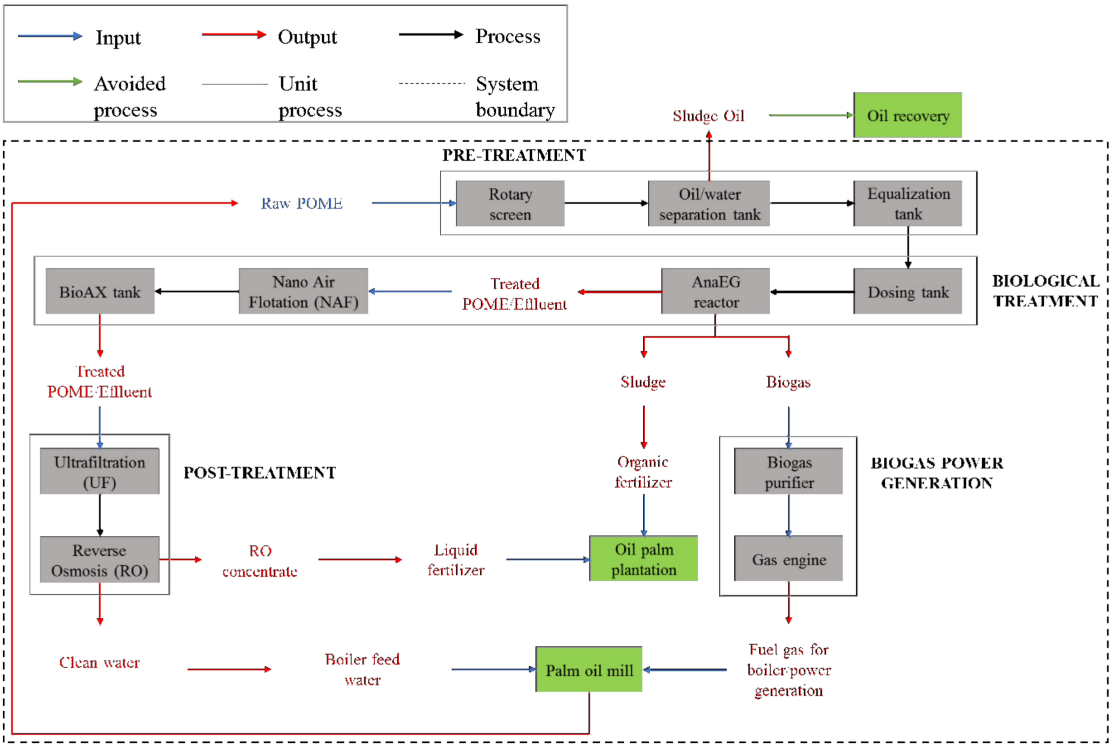

Figure 3. Life cycle flow chart of a zero discharge treatment system of POME.

4.1.2. Database and Analysis Methods

SimaPro 8.5.2 software was used to gather and analyze the inventory data. SimaPro 8.5.2 is an LCA software that can be used to monitor the performance of the sustainability of a product or service. This software can analyze a complex life cycle systematically and can evaluate the environmental impact of a product or service at each stage of the life cycle. Ecoinvent 3.4 [83], Agri-footprint 4.0 [84] and USLCI [85] were chosen as background data sources. Ecoinvent 3.4 database was used for this study because it contains LCI data from various sectors, such as energy production, transportation, chemicals production and also fruits and vegetables. Agri-footprint 4.0 database was chosen due to its comprehensive LCI database focusing on the agriculture and food sectors, which covers data on agricultural products (i.e., food, feed and biomass). Besides, Agri-footprint 4.0 covers materials and inputs from agriculture, while USLCI database contains data modules that quantify the material and energy flows into and out of the environment. Using Ecoinvent 3.4, Agri-footprint 4.0 and USLCI data as proxies, the background databases were already incorporated in SimaPro, while foreground databases were newly included in the software for analysis, obtained from survey and existing regional datasets.

Life cycle impact category indicators were calculated using ReCiPe 2016, developed by Huijbregts et al. [86]. ReCiPe 2016 evaluates 18 different impact categories at the midpoint level, namely global warming (GWP), stratospheric ozone depletion (ODP), ionizing radiation (IRP), ozone formation (human health) (HOFP), fine particulate matter formation (PMFP), ozone formation (terrestrial ecosystems) (EOFP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), human carcinogenic toxicity (HTPc), human non-carcinogenic toxicity (HTPnc), land use change (LUC), mineral resource scarcity (SOP), fossil resource scarcity (FFP) and water consumption (WCP). The impact categories were then divided into three damage assessment categories at the endpoint level, namely damage to human health (HH), damage to ecosystem quality (ED) and damage to resource availability (RA).

4.1.3. Life Cycle Inventory

The life cycle inventory includes inventory data from the inputs and outputs in the process of zero discharge treatment. Inventory data consist of the amount of energy and materials consumed and the quantities of emissions released to the environment. All data were obtained from a set of questionnaires, on-site data, literature reviews and databases in SimaPro 8.5.2. The raw data information was obtained directly from the owner of the mill chosen in the present study. For compatibility, the questionnaires were developed based on the guideline provided by ISO 14044 [87], consisting of the generic information (i.e., annual reports and company brochures), process description and the input and output flows of the analyzed product. An interview with the mill owners and officers was conducted to obtain and validate information regarding the production process, technology used, mill operation and operational issues.

The case study was based on POME-based biogas production from a palm oil mill with biogas and zero discharge treatment facilities in Malaysia, and the data were collected for a period of three years. Data on the inputs and outputs of the production process, including the amount of energy, materials consumed and transportation, were available from 2012 to 2016. However, the quantity and quality of the data were not consistent from year to year. Therefore, this study was conducted based on the average of three years (2013 until 2015) data. The data chosen were the most complete and with best quantity and quality. The validation of data was performed by on-site visits, comparison with other data sources and recalculation. The results from the LCI were subsequently used to assess the environmental performance of the zero discharge treatment process.

The zero discharge treatment system of POME consists of three main processing units, as shown in Figure 3: pretreatment, biological treatment and post-treatment. The core technologies in the POME zero discharge system in this study were AnaEG and BioAX. AnaEG is an advanced anaerobic expanded granular sludge bed reactor, while BioAX is an advanced biocontact aerobic process with internal circulation. In the AnaEG bioreactor, the wastewater flows upwards in a plug flow pattern consisting of a two-phase anaerobic process in one reactor. The BioAX tank contains biofilm that provides a suitable environment for the growth of microbes to further enhance the degradation of organic matter. In BioAX, returned sludge was not required. Table 2 shows the inventory data for the treatment of a metric tonne of POME. The treatment plant was installed in the palm oil mill, and hence no vehicle was needed for the transportation of feedstock. In this study, only a small amount of water is required for the treatment process, approximately 0.2 L per tonne of POME. Rainwater harvesting has been practiced in the treatment plant to collect and store rainwater for on-site reuse. Though Malaysia has sufficient water resources, some regions in the country are facing water scarcity, and the water demand is also increasing nowadays. Hence, rainwater harvesting as an alternative water resource was proposed by the government as part of the solutions to mitigate water scarcity problems [88]. 50% of the total electricity consumption was taken from the national grid and another 50% from the biogas engine. The utilization of biogas for electricity generation could reduce the cost as well as the dependency on non-renewable energy sources.

Table 2. LCI for the zero discharge treatment system of POME (per tonne of POME).

Input/Output	Unit	Amount	Data Source	Link Process/Substance in SimaPro 8.5.0
Input from technosphere				
Materials and fuels				
Palm oil mill effluent (POME)	t	1	On-site data	Palm oil mill effluent
Energy				
Electricity from grid	kWh	0.385	On-site data	Electricity mix, AC, consumption mix, at consumer, < 1 kV/MY Mass
Electricity from biogas	kWh	0.321	On-site data	Biogas, zero discharge treatment plant/MY
Output to technosphere				
Products and co-products				
Clean water	t	0.75	On-site data	Clean water
Biogas	m^3	28	On-site data	Biogas, zero discharge treatment plant/MY
Sludge oil	kg	4.70	On-site data	Sludge oil
Organic solid sludge	kg	28.98	On-site data	Organic solid sludge
RO concentrate (K_2O & MgO)	kg	3.41	On-site data	RO concentrate (K_2O & MgO)
Input from environment				
Resource				
Water	m^3	0.0002	On-site data	Water, rain

During the pretreatment of POME, suspended matter such as oil and solids was removed to ensure the effective anaerobic treatment of POME. The sludge oil produced was recovered and sold out as by-product. The biological treatment process produced an average of 28 m^3 biogas per tonne of POME and generated a final discharge with a BOD of less than 20 mg/L. The biogas composition was 65-70% CH_4, 25-36% CO_2 and 800-1500 ppm H_2S. The biogas produced was burned in a gas engine to generate power for internal use as electricity and was also utilized as fuel for the boiler to generate steam in the palm oil mill. The treated sludge (digestate) was recovered from the anaerobic digester and sent to the plantation as an organic fertilizer. According to Loh et al. [89], the application of the treated sludge as organic fertilizer could enhance soil fertility due to its high content of nutrients. In this treatment system, no water back flow process is needed in the anaerobic reactor and no returned sludge is required in the aerobic treatment process. The effluent generated from the biological treatment contains a low level of organic and suspended solids. Finally, the post-treatment process' final discharge was clean water that can be reused as boiler feed water in the mill. An RO concentrate amounting to 40% of rejected water was recovered and collected as liquid fertilizer with s high content of potassium and magnesium.

The ultimate goals of this treatment system are to produce biogas as a source of renewable energy, zero emissions of GHG, a final discharge with less than 20 mg/L of BOD and clean water which can be used as boiler feed water. Table 3 shows the characteristics of POME after each treatment in the zero discharge treatment system according to Tabassum et al. [90]. In the presented results, the average removal of COD and BOD after the biological treatment were 98.5% and 99.9%, respectively. After the membrane treatment UF/RO process, the value of COD and BOD were almost undetectable. The quality of water from each treatment stage shows an improvement in terms of color, odor and turbidity and obtained > 90% removal of chemical oxygen demand (COD), biochemical oxygen demand (BOD) and suspended solid (SS). At the final stage, the RO permeate was odor-free, clear and with a pH of 9.48. The zero discharge treatment system was able to reclaim water as boiler feed water, since the water quality complied with the boiler feed water standard set by the American Boiler Manufactures Association (ABMA), which is pH 7.5 until 10 [78]. It is the ideal pH for boiler feed water to prevent corrosion. After the entire treatment processes, higher percentages of water could be recovered and used as boiler feed water, and the recovered biogas could be utilized to produce heat and electricity for self-consumption. Therefore, the products and effluents produced can be considered environmentally sustainable.

Table 3. The characteristics of POME after each treatment (adapted from [80]).

Parameter	**Unit**	**Raw POME**	**EQ**	**AnaEG Effluent**	**Nano Clarifier**	**BioAX Effluent**	**UF/RO Permeate**
pH		4.30	4.00	7.00	7.50	8.00	9.48
COD	mg/L	75000	65000	4500	2000	1100	ND
BOD_5	mg/L	27000	NM	NM	820	<20	ND
TS	mg/L	100000	48600	22600	8200	5650	NM
SS	mg/L	50000	22778	13840	350	191	ND
TVS	mg/L	80000	40200	14300	3000	1600	NM
Dissolved solids	mg/L	50000	25882	8760	7850	5459	NM
VFA	mg/L	2184	NM	413	NM	NM	NM
Total Alkalinity	mg/L	536	NM	4100	NM	NM	NM
Turbidity	NTU	NM	NM	NM	700	110.0	0.4

ND: not detected; NM: not measured.

4.2. Results and Discussion

Life Cycle Impact Assessment

The potential impacts were determined using the results from the inventory analysis (LCI). There are four steps in the life cycle impact assessment (LCIA): classification, characterization, normalization and weighting. According to ISO 14044 [87], classification and characterization are mandatory steps for the LCIA, while normalization and weighting are optional steps depending on the goal and scope of the study. In the present study, the classification and characterization steps were included.

The assessment has been carried out on a zero discharge treatment system based on the functional unit of 1 tonne of POME. The impact results at the midpoint level are presented as characterization values in Table 4. The characterization factors indicate the environmental impact per unit of stressor. As presented in Table 4, the most significant contribution to all impact categories originated from the electricity consumption from the national grid. Hence, electricity production from the national grid is an important contributor to all impact categories. This is because the Malaysian grid energy profile is largely composed of non-renewable energy sources, with 45% from natural gas, 41% from coal, 6% from hydroelectric power and 8% from oil [91].

Table 4. The characterization values at the midpoint level per 1 t of POME.

Impact Category	Unit	Total
GWP	kg CO_2-eq	4.42×10^2
ODP	kg CFC11-eq	7.75×10^{-9}
IRP	kBq Co-60-eq	4.80×10^{-7}
HOFP	kg NO_x-eq	2.15×10^{-4}
PMFP	kg $PM_{2.5}$-eq	1.49×10^{-3}
EOFP	kg NO_x-eq	2.17×10^{-4}
TAP	kg SO_2-eq	1.00×10^{-2}
FEP	kg P-eq	6.65×10^{-12}
MEP	kg N-eq	2.42×10^{-7}
TETP	kg 1,4-DCB	3.08×10^{-2}
FETP	kg 1,4-DCB	1.82×10^{-4}
METP	kg 1,4-DCB	2.49×10^{-4}
HTPc	kg 1,4-DCB	7.93×10^{-5}
HTPnc	kg 1,4-DCB	8.50×10^{-3}
SOP	kg Cu-eq	1.32×10^{-7}
FFP	kg oil-eq	4.06×10^{-2}
WCP	m^3	2.02×10^{-4}

In 2015, the total electricity generation in Malaysia was approximately 144,565 GWh, and 89.3% of the electricity mix was generated by using fossil fuels [92]. The energy demand in Malaysia had increased from 40,845 ktoe in 2009 to 51,807 ktoe in 2015 [93]. It was reported that the use of energy for electricity generation is the largest source of emissions of GHG when compared to other human activities. From 2000 to 2015, the emissions from electricity generation had increased by 45% [91]. CO_2 emissions resulting from the oxidation of carbon in fuels during combustion account for the largest share of global anthropogenic GHG emissions. The cumulative effect of other GHG emissions like CH_4 and N_2O towards global climate were estimated to be at least one order of magnitude lower than that of CO_2 [94,95]. However, fossil fuels are still being utilized extensively by developing countries in order to meet the energy demand and to support development and economic growth.

In this study, the treatment plant consumed approximately 0.38 kWh of electricity from the national grid, which affected 17 impact categories. The impacts on GWP, ODP, HOFP, PMFP, EOFP, TAP, MEP, TETP, FETP, METP, HTPc, HTPnc and FFP were caused by the production of natural gas, anthracite coal, lignite coal, bituminous coal, diesel and residual fuel oil. The electricity production from hydroelectric power contributed to IRP, FEP, SOP and WCP. As reported before, the electricity generation in Malaysia includes production processes from several fossil fuel resources. The burning of fossil fuels has huge consequences for the environment. Figure 4 shows the proportion of electricity production resources which contributed to 13 impact categories. The data for the electricity production process were adopted from the USLCI and ELCD databases. In the presented results, natural gas was the largest proportion contributing to the GWP, ODP, MEP, FETP, METP, HTPnc and FFP impact categories, at 37% (4.39×10^{-2} kg CO_2-eq), 91% (7.03×10^{-2} kg CFC11-eq), 76% (1.83×10^{-7} kg N-eq), 66% (1.20×10^{-4} kg 1,4-DCB-eq), 60% (1.51×10^{-4} kg 1,4-DCB-eq), 43% (3.64 × 10–3 kg 1,4-DCB-eq) and 40% (1.62×10^{-2} kg oil-eq), respectively. Anthracite coal was the largest contributor towards PMFP, TAP, TETP and HTPc, at 51% (2.30×10^{-4} kg $PM_{2.5}$-eq), 51% (7.87×10^{-4} kg SO_2-eq), 68% (2.09×10^{-2} kg1,4-DCB-eq) and 47% (3.71×10^{-5} kg 1,4-DCB-eq), respectively. For HOFP and EOFP, the largest contributor was lignite coal, with an impact of 31% (6.61×10^{-5} kg NO_x-eq) for both categories. For electricity production from hydropower, which is a non-fossil energy, the assumption is made that there is no environmental impact.

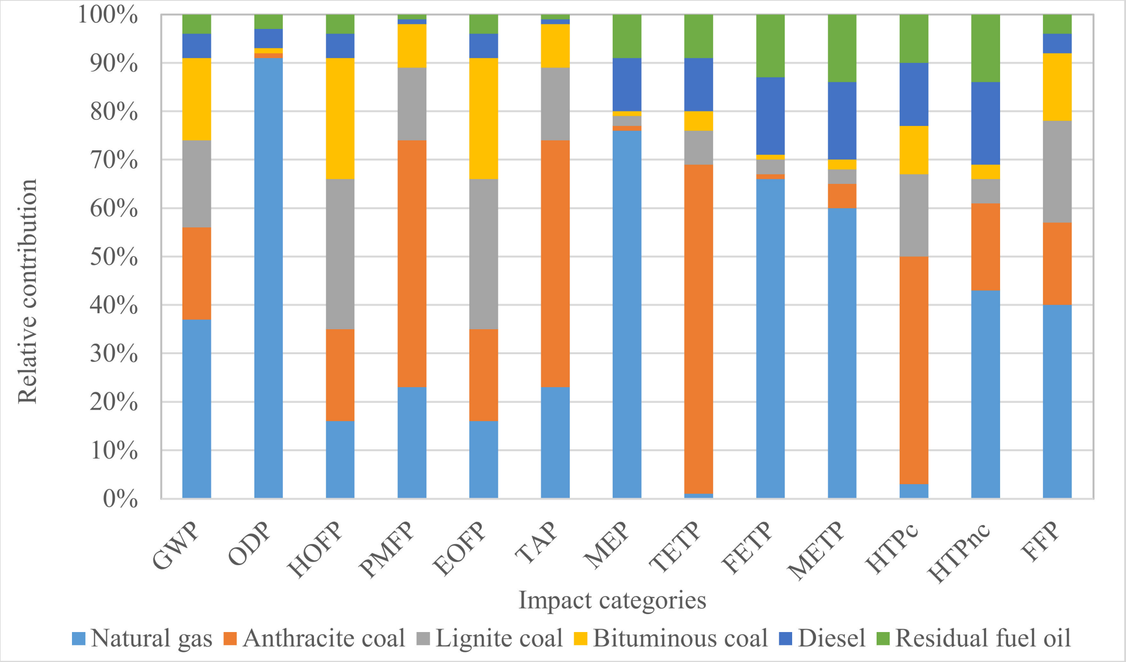

Figure 4. Relative contribution from electricity sources to each impact category.

Based on the study conducted by Lijó et al. [96] on the LCA of electricity production from anaerobic co-digestion of pig slurry and energy crops in Italy, the electricity consumption from the grid contributed to the abiotic depletion potential (ADP), ozone layer depletion potential (ODP) and nuclear energy demand (CED). This is due to the fact that the Italian grid was also composed of non-renewable energy. According to Wang et al. [97], in the study on the LCA of biogas production from straw in China, the electricity consumption from the grid had a harmful effect on human health. The electricity was mostly produced from coal-fired power plants which release gaseous pollutants. Those findings were consistent with those of Roux et al. [98], which show that the impact of electricity consumption on GWP and ADP were due to the higher share of coal and gas power plants in the French electricity mix.

Table 5 shows the results of the damage assessment at the endpoint level. The zero discharge treatment system impacted HH, ED and RA at 4.13×10^{-4} DALY, 1.24×10^{-6} species·year and 0.009 USD, respectively, due to electricity consumption. As reported by Loh et al. [89], Tabassum et al. [90] and Wang et al. [99], there were no GHG emissions into the atmosphere from the zero discharge treatment system, as the system produces zero discharge. Nevertheless, this study shows, on the other hand, the pollution emissions in the system were caused by the electricity consumption. Although the treatment system could treat all the incoming effluent and leave nothing behind, there are other aspects that should be taken into consideration (i.e., energy sources, water sources, etc.) to ensure the environmental sustainability of the system holistically.

Table 5. The results of damage impact at the endpoint level.

Area of protection	Unit	Total
Human Health		
GWP, Human health	DALY	4.12×10^{-4}
ODP	DALY	4.11×10^{-12}
HOFP	DALY	1.96×10^{-10}
PMFP	DALY	9.38×10^{-7}
HTPc	DALY	2.63×10^{-10}

Table 5. *Cont.*

Area of protection	Unit	Total
Human Health		
HTPnc	DALY	1.94×10^{-9}
Total	**DALY**	$\mathbf{4.13 \times 10^{-4}}$
Ecosystem Damage		
GWP, Terrestrial ecosystems	species.yr	1.24×10^{-6}
GWP, Freshwater ecosystems	species.yr	3.39×10^{-11}
EOFP	species.yr	2.80×10^{-11}
TAP	species.yr	2.13×10^{-9}
MEP	species.yr	4.12×10^{-16}
TETP	species.yr	3.51×10^{-13}
FETP	species.yr	1.26×10^{-13}
METP	species.yr	2.62×10^{-14}
Total	**species.yr**	$\mathbf{1.24 \times 10^{-6}}$
Resource Availability		
FFP	USD	9.00×10^{-3}
Total	**USD**	$\mathbf{9.00 \times 10^{-3}}$

Figure 5 shows the relative contribution from electricity production resources to each damage impact category. Anthracite coal had the largest impact to both HH and ED categories, at 42.1% (1.66×10^{-7} DALY) and 34.4% (2.35×10^{-10} species.yr), respectively. According to Oh et al. [93], about 70% of coal demand is for energy production. The coal reserves in Malaysia were estimated to be approximately 1.9 billion metric tonnes [92]. The country consumed more than 20 million metric tonnes annually, and therefore 90% of coal supplies were imported mainly from Indonesia and Australia [100,101]. However, the combustion of coal poses major challenges like GHG emissions and air pollutants such as sulphur dioxide (SO_2) and CO_2. In contrast with gas, coal emitted a higher amount of CO_2 emissions due to its heavy carbon content per unit of energy released [102]. The emission of GHG will lead to an increase in the global mean temperature, which will consequently result in damages to human health and ecosystems. Therefore, at the endpoint level, damages to human health, terrestrial ecosystems and freshwater ecosystems can be estimated.

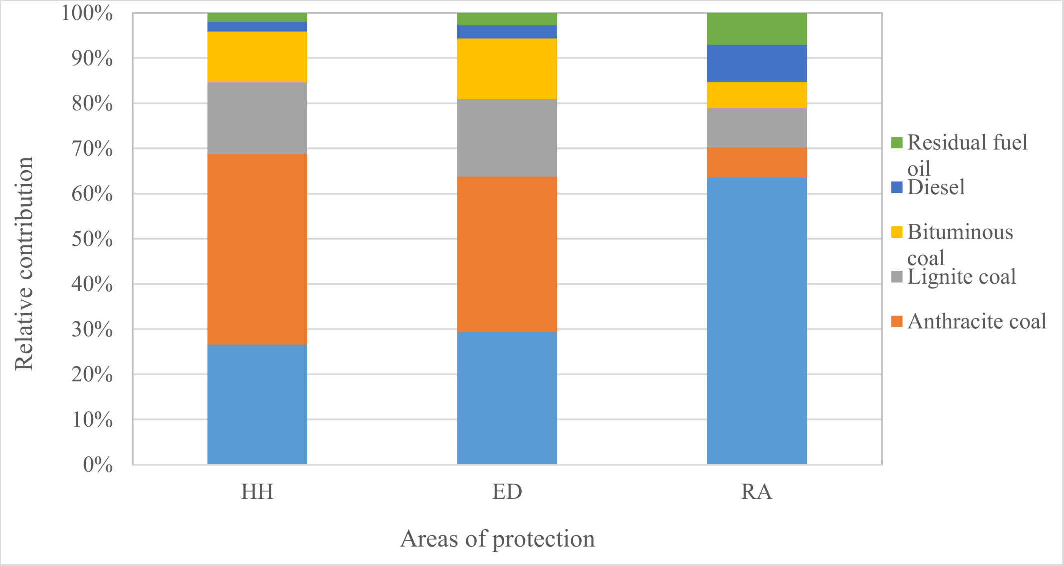

Figure 5. Relative contribution from electricity production resources to each damage impact.

On the other hand, the largest process contribution to the resource availability impact category was from natural gas, corresponding to 63.5% (5.78×10^{-3} USD). Natural gas, also known as liquefied natural gas (LNG), was the main contributor in Malaysia's energy mix [103]. At the endpoint level, the scarcity of fossil resources is expressed in economic terms [104]. The increase in fossil fuel extraction will cause an increase in costs. Hence, it will lead to a surplus cost potential (SCP), and the damage to natural resource scarcity can be estimated. In 2016, Malaysia became the world's third largest exporter of natural gas, after Qatar and Australia, with an estimated total natural gas reserve of 100.7 tscf [105]. Natural gas production has increased from 54.8 Mtoe in 2010 to 61.4 Mtoe in 2015 to fulfill the growing domestic demand and export contracts [93,106]. The rising of development and exploration activities has subsequently put pressure on the natural gas supply, and more investment is needed for reservoir development.

Electricity was required to run the plant mainly in loading operations, in the digester and in the chiller. More treatment units were used in the zero discharge treatment plant (i.e., AnaEG reactor, BioAX reactor, Nano Air Flotation system and membrane filtration), which may have caused higher electricity consumption. With regard to the impact of electricity consumption, the environmental sustainability of the system can be improved by increasing or enhancing the energy produced from biogas. In the zero discharge treatment plant, the engine generator, also known as gen-set, was used to generate electricity. The generated electricity was utilized for self-consumption and not exported to the grid. Anyhow, most of the biogas plants in Malaysia were running with combustion engines, combined heat and power (CHP) systems or a combination of both technologies [107]. Decentralized power generation with CHP units is the common biogas utilization pathway. Normally, in the typical electricity generation technology (i.e., conventional electricity generation, on-site boiler), the energy produced is wasted in the form of heat discharge to the atmosphere [98,99]. Conventional energy systems include power plants using fossil fuels. By using the CHP generation system, the transmission losses and carbon emissions could be reduced [108–112].

As reported in the study by [67], 86% of the market community were utilizing their biomass resources for on-site consumption, while only a few exported their excess electricity to the grid. This is because the energy produced for on-site electricity generation was sufficient, but it was not sufficient for exporting to the grid. Also, there is a lack of grid transmission lines connecting mills to the existing network systems due to distance constraints [60]. During the Ninth Malaysia Plan (2006–2010), the capacity share of renewable energy in the country's energy mix was 350 MW, or 1.8%. However, due to the slow renewable energy projects, the capacity share ended up at 65 MW, or 0.4%, by the end of the 9th Plan, and biogas contributes 4.95 MW of the grid-connected capacity [67]. Until 2015, the share of fossil fuels within the world energy supply was relatively unchanged, despite the increase of renewable energy in electricity generation to 34% of the global figure [91]. Most of the electricity mix in Malaysia was generated from fossil fuels, although the country has various renewable energy sources.

Apparently, biogas can be one of the best alternatives energy sources to deal with high energy demands and various environmental loads, including fossil fuel depletion and global warming. In addition, biogas adoption can solve waste management issues by utilizing POME for biogas generation. Thus, the environmental sustainability evaluation of biogas production from a broad range of feedstock (e.g., sludge, food waste, dairy manure, municipal wastewater and solid waste, crop residues, energy crops, etc.) is essential in providing a promising renewable energy source. The environmental assessment of biogas would certainly be useful for environmental profile enhancement and a great opportunity to achieve sustainable development. With regard to existing green policy and initiatives, the LCA of biogas production should also be integrated into the sustainable development plan, as this approach could assist in decision-making process.

5. Conclusions

A case study concerning the LCA of the zero waste discharge treatment of POME has been conducted in order to examine the key advances in waste-to-energy technologies that have been adopted for biogas production and waste treatment towards sustainable development. The zero waste discharge treatment system is said to be a promising sustainable technology because it can produce biogas with maximum water recycle and reuse.

In promoting biogas as a green product, Malaysia could gain competitive advantages towards renewable energy production, as well as towards better waste management practices. Therefore, a comprehensive framework enforcement is needed to encourage the embracement of renewable energy and stimulate an energy efficiency culture. A conceptual framework for an LCA-based environmental sustainability evaluation of biogas production has been proposed to improve the sustainability of biogas supply chains. The conceptual framework developed in the present study can be used as a guideline for the related stakeholders and decision makers to improve the quality and enhance the sustainability of biogas supply chains in Malaysia, as well as to promote biogas as a clean, reliable and secure energy.

To conclude, this study indicated that the biogas production and zero discharge treatment of POME have potential as clean technologies to be applied in the Malaysian context, as the system utilized organic waste to produce bioenergy and achieved zero discharge. However, there were other aspects that should be taken into consideration, particularly regarding the sources of electricity and upstream activity, to ensure the environmental sustainability of the system holistically.

Author Contributions: Conceptualization, N.I.H.A.A. and M.M.H.; methodology, N.I.H.A.A.; validation, N.I.H.A.A., M.M.H. and S.H.G.; formal analysis, N.I.H.A.A.; writing—original draft preparation, N.I.H.A.A.; writing—review and editing, M.M.H. and S.H.G.; visualization, H.I.; supervision, M.M.H.; project administration, M.M.H.; funding acquisition, M.M.H. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by the Universiti Kebangsaan Malaysia research grants DIP-2019-001 and MI-2020-005.

Acknowledgments: Marlia M. Hanafiah was supported by the Universiti Kebangsaan Malaysia research grants DIP-2019-001, KRA-2018-054 and MI-2020-005, and by the Ministry of Education of Malaysia (FRGS/1/2018/WAB05/UKM/02/2).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

GWP	global warming
ODP	stratospheric ozone depletion
IRP	ionizing radiation
HOFP	ozone formation (human health)
PMFP	fine particulate matter formation
EOFP	ozone formation (terrestrial ecosystems)
TAP	terrestrial acidification
FEP	freshwater eutrophication
MEP	marine eutrophication
TETP	terrestrial ecotoxicity
FETP	freshwater ecotoxicity
METP	marine ecotoxicity
HTPc	human carcinogenic toxicity
HTPnc	human non-carcinogenic toxicity
SOP	mineral resource scarcity
FFP	fossil resource scarcity
WCP	water consumption

References

1. Hezri, A.A.; Hasan, M.N. Towards sustainable development? The evolution of environmental policy in Malaysia. *Nat. Resour. Forum* **2006**, *30*, 37–50. [CrossRef]
2. Mohamed, A.R.; Lee, K.T. Energy for sustainable development in Malaysia: Energy policy and alternative energy. *Energy Policy* **2006**, *34*, 2388–2397. [CrossRef]
3. Seman, S.Z.A.; Idris, I.; Abdullah, A.; Samsudin, I.K.; Othman, M.R. Optimizing purity and recovery of biogas methane enrichment process in a closed landfill. *Renew. Energy* **2019**, *131*, 1117–1127. [CrossRef]
4. Griggs, D.; Stafford-Smith, M.; Gaffney, O.; Rockström, J.; Öhman, M.C.; Shyamsundar, P.; Steffen, W.; Glaser, G.; Kanie, N.; Noble, I. Policy: Sustainable development goals for people and planet. *Nature* **2013**, *495*, 305–307. [CrossRef]
5. Hanafiah, M.M.; Mohamed Ali, M.Y.; Abdul Aziz, N.I.H.; Ashraf, M.A.; Halim, A.A.; Lee, K.E.; Idris, M. Biogas production from goat and chicken manure in Malaysia. *Appl. Ecol. Environ. Res.* **2017**, *15*, 529–535. [CrossRef]
6. Nagy, V.; Szabó, E. Biogas from organic wastes. *Studia Univ. Vasile Goldis Arad Ser. Stiintele Vietii Life Sci. Ser.* **2011**, *21*, 887–891.
7. Aziz, N.I.H.A.; Hanafiah, M.M. Anaerobic digestion of palm oil mill effluent (POME) using bio-methane potential (BMP) test. *AIP Conf. Proc.* **2018**, *1940*, 020026.
8. Horváth, I.S.; Tabatabaei, M.; Karimi, K.; Kumar, R. Recent updates on biogas production—A review. *Biofuel Res. J.* **2016**, *3*, 394–402. [CrossRef]
9. Aziz, N.I.H.A.; Hanafiah, M.M. The potential of palm oil mill effluent (POME) as a renewable energy source. *J. Green Energy* **2017**, *1*, 323–346. [CrossRef]
10. Bujang, A.; Bern, C.; Brumm, T. Summary of energy demand and renewable energy policies in Malaysia. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1459–1467. [CrossRef]
11. Roubík, H.; Mazancová, J. Small-scale biogas plants in central Vietnam and biogas appliances with a focus on a flue gas analysis of biogas cook stove. *Renew. Energy* **2019**, *131*, 1138–1145. [CrossRef]
12. Scarlat, N.; Dallemand, J.-F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew. Energy* **2018**, *129*, 457–472. [CrossRef]
13. Eriksson, O.; Bisaillon, M.; Haraldsson, M.; Sundberg, J. Enhancement of biogas production from food waste and sewage sludge–environmental and economic life cycle performance. *J. Environ. Manag.* **2016**, *175*, 33–39. [CrossRef]
14. Yasar, A.; Rasheed, R.; Tabinda, A.B.; Tahir, A.; Sarwar, F. Life cycle assessment of a medium commercial scale biogas plant and nutritional assessment of effluent slurry. *Renew. Sustain. Energy Rev.* **2017**, *67*, 364–371. [CrossRef]
15. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]
16. Hanafiah, M.M. Quantifying Effects of Physical, Chemical and Biological Stressors in Life Cycle Assessment. Ph.D Thesis, Radboud University, Nijmegen, The Netherlands, 2013.
17. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.P.; Suh, S.; Weidema, B.P.; Pennington, D.W. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis and applications. *Environ. Int.* **2004**, *30*, 701–720. [CrossRef]
18. Curran, M.A. *Life Cycle Assessment: Principles and Practice*; United States Environmental Protection Agency: Washington, DC, USA, 2006.
19. Heijungs, R.; Goedkoop, M.; Struijs, J.; Effting, S.; Sevenster, M.; Huppes, G. Towards a Life Cycle Impact Assessment Method Which Comprises Category Indicators at the Midpoint and the Endpoint Level. Report of the First Project Phase: Design of the New Method VROM Report. 2003. Available online: http://www.leidenuniv.nl/cml/ssp/publications/recipe_phase1.pdf (accessed on 1 March 2019).
20. Huijbregts, M. A critical view on scientific consensus building in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2014**, *19*, 477–479. [CrossRef]
21. Talve, S. The life cycle assessment management tool for technologies in Eastern Europe: Why and how. *Int. J. Life Cycle Assess.* **2001**, *6*, 181–183. [CrossRef]
22. Hosseini, S.E.; Wahid, M.A. Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia. *Renew. Sustain. Energy Rev.* **2013**, *19*, 454–462. [CrossRef]

23. Ali, M.Y.M.; Hanafiah, M.M.; Wen, Y.H.; Idris, M.; Aziz, N.I.H.A.; Halim, A.A.; Lee, K.E. Biogas production from different substrates under anaerobic conditions. In Proceedings of the 3rd International Conference on Agricultural and Medical Sciences (CAMS-2015), Singapore, 10–11 December 2015; pp. 54–56.
24. Aziz, N.I.H.A.; Hanafiah, M.M.; Ali, M.Y.M. Sustainable biogas production from agrowaste and effluents–a promising step for small-scale industry income. *Renew. Energy* **2019**, *132*, 363–369. [CrossRef]
25. Choo, Y.M.; Muhamad, H.; Hashim, Z.; Subramaniam, V.; Puah, C.W.; Tan, Y. Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. *Int. J. Life Cycle Assess.* **2011**, *16*, 669–681. [CrossRef]
26. SIRIM. LCA Projects. 2016. Available online: http://lcamalaysia.sirim.my/index.php/project (accessed on 5 March 2019).
27. Aziz, N.I.H.A.; Hanafiah, M.M. Life cycle analysis of biogas production from anaerobic digestion of palm oil mill effluent. *Renew. Energy* **2020**, *145*, 847–857. [CrossRef]
28. Lamnatou, C.; Nicolai, R.; Chemisana, D.; Cristofari, C.; Cancelleiri, D. Biogas production means of an anaerobic-digestion plant in France: LCA of greenhouse-gas emissions and other environmental indicators. *Sci. Total Environ.* **2019**, *670*, 1226–1239. [CrossRef]
29. Lauer, M.; Dotzauer, M.; Hennig, C.; Lehmann, M.; Nebel, E.; Postel, J.; Szarka, N.; Thrän, D. Flexible power generation scenarios for biogas plants operated in Germany: Impacts on economic viability and GHG emissions. *Int. J. Energy Res.* **2017**, *41*, 63–80. [CrossRef]
30. Guinée, J.B. Handbook on life cycle assessment operational guide to the ISO standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [CrossRef]
31. Hussein, M.E.; Alam, R.Z.; Siwar, C.; Ludin, N.A. Green economy models and energy policies towards sustainable development in Malaysia: A review. *Int. J. Green Econ.* **2016**, *10*, 89–106. [CrossRef]
32. Yatim, P.; Mamat, M.N.; Mohamad Zailani, S.H.; Ramlee, S. Energy policy shifts towards sustainable energy future for Malaysia. Clean Technol. *Environ. Policy* **2016**, *18*, 1685–1695.
33. Chen, W.M.; Kim, H.; Yamaguchi, H. Renewable energy in eastern Asia: Renewable energy policy review and comparative SWOT analysis for promoting renewable energy in Japan, South Korea and Taiwan. *Energy Policy* **2014**, *74*, 319–329. [CrossRef]
34. Hua, Y.; Oliphant, M.; Hu, E.J. Development of renewable energy in Australia and China: A comparison of policies and status. *Renew. Energy* **2016**, *85*, 1044–1051. [CrossRef]
35. International Energy Agency (IEA). Policy and Measures, Renewable Energy. 2019. Available online: www.iea.org (accessed on 17 March 2019).
36. Alam, S.S.; Nor, N.F.M.; Ahmad, M.; Hashim, N.H.N. A survey on renewable energy development in Malaysia: Current status, problems and prospects. *Environ. Climate Technol.* **2016**, *17*, 5–17. [CrossRef]
37. Fang, T.P.; Daud, W.R.W.; Halim, L.; Masdar, M.S. How ready is renewable energy? A review on renewable energy and fuel cell teaching in schools. In Proceedings of the 7th World Engineering Education Forum (WEEF), Kuala Lumpur, Malaysia, 13–16 November 2017; pp. 236–244.
38. Brundtland, G. *Our Common Future*; Brundtland Report; United Nations World Commission on Environment and Development: Geneva, Switzerland, 1987.
39. Heijungs, R.; Huppes, G.; Guinée, J.B. Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. *Polym. Degrad. Stab.* **2010**, *95*, 422–428. [CrossRef]
40. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89. [CrossRef]
41. Mälkki, H.; Alanne, K. An overview of life cycle assessment (LCA) and researched-based teaching in renewable and sustainable energy education. *Renew. Sustain. Energy Rev.* **2017**, *69*, 218–231. [CrossRef]
42. Coyle, E.; Rebow, M. Sustainable Design: A Case Study in Energy Systems. In *Engineering in Context*; Dublin Institute of Technology: Dublin, Ireland, 2009; pp. 1–17.
43. Jürgensen, L.; Ehimen, E.A.; Born, J.; Holm-Nielsen, J.B. A combination anaerobic digestion scheme for biogas production from dairy effluent—CSTR and ABR, and biogas upgrading. *Biomass Bioenergy* **2018**, *111*, 241–247. [CrossRef]
44. Ertem, F.C.; Martínez-Blanco, J.; Finkbeiner, M.; Neubauer, P.; Junne, S. Life cycle assessment of flexibly fed biogas processes for an improved demand-oriented biogas supply. *Bioresour. Technol.* **2016**, *219*, 536–544. [CrossRef]

45. Styles, D.; Dominguez, E.M.; Chadwick, D. Environmental balance of the of the UK biogas sector: An evaluation by consequential life cycle assessment. *Sci. Total Environ.* **2016**, *560*, 241–253. [CrossRef]
46. Curran, M. *A Review of Life-Cycle Based Tools Used to Assess the Environmental Sustainability of Biofuels in the United States*; Life Cycle Assessment Research Center; US Environmental Protection Agency: Cincinnati, OH, USA, 2013; Volume 1, p. 61.
47. Sala, S.; Farioli, F.; Zamagni, A. Progress in sustainability science: Lessons learnt from current methodologies for sustainability assessment: Part 1. *Int. J. Life Cycle Assess.* **2013**, *18*, 1653–1672. [CrossRef]
48. Takeda, S.; Keeley, A.R.; Sakurai, S.; Managi, S.; Norris, C.B. Are renewables as friendly to humans as to the environment? A social life cycle assessment of renewable electricity. *Sustainability* **2019**, *11*, 1370. [CrossRef]
49. Markevičius, A.; Katinas, V.; Perednis, E.; Tamašauskienė, M. Trends and sustainability criteria of the production and use of liquid biofuels. *Renew. Sustain. Energy Rev.* **2010**, *14*, 3226–3231. [CrossRef]
50. Milazzo, M.; Spina, F.; Cavallaro, S.; Bart, J. Sustainable soy biodiesel. *Renew. Sustain. Energy Rev.* **2013**, *27*, 806–852. [CrossRef]
51. Turconi, R.; Boldrin, A.; Astrup, T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renew. Sustain. Energy Rev.* **2013**, *28*, 555–565. [CrossRef]
52. Bößner, S.; Devisscher, T.; Suljada, T.; Ismail, C.J.; Sari, A.; Mondamina, N.W. Barriers and opportunities to bioenergy transitions: An integrated, multi-level perspective analysis of biogas uptake in Bali. *Biomass Bioenergy* **2019**, *122*, 457–465. [CrossRef]
53. Meyer, A.K.P.; Ehimen, E.A.; Holm-Nielsen, J.B. Future European biogas: Animal manure, straw and grass potentials for a sustainable European biogas production. *Biomass Bioenergy* **2018**, *111*, 154–164. [CrossRef]
54. Basiron, Y. Palm oil production through sustainable plantations. *Eur. J. Lipid Sci. Technol.* **2007**, *109*, 289–295. [CrossRef]
55. Ming, T.C.; Ramli, N.; Lye, O.T.; Said, M.; Kasim, Z. Strategies for decreasing the pour point and cloud point of palm oil products. *Eur. J. Lipid Sci. Technol.* **2005**, *107*, 505–512. [CrossRef]
56. Mukherjee, I.; Sovacool, B.K. Palm oil-based biofuels and sustainability in Southeast Asia: A review of Indonesia, Malaysia, and Thailand. *Renew. Sustain. Energy Rev.* **2014**, *37*, 1–12. [CrossRef]
57. Tan, C.; Man, Y.C. Differential scanning calorimetric analysis of palm oil, palm oil based products and coconut oil: Effects of scanning rate variation. *Food Chem.* **2002**, *76*, 89–102. [CrossRef]
58. Teh, S.S.; Ong, A.S.H.; Mah, S.H. Recovery and utilization of palm oil mill effluent source as value-added food products. *J. Oleo Sci.* **2017**, *66*, 1183–1191. [CrossRef]
59. Awalludin, M.F.; Sulaiman, O.; Hashim, R.; Nadhari, W.N.A.W. An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1469–1484. [CrossRef]
60. Bazmi, A.A.; Zahedi, G.; Hashim, H. Progress and challenges in utilization of palm oil biomass as fuel for decentralized electricity generation. *Renew. Sustain. Energy Rev.* **2011**, *15*, 574–583. [CrossRef]
61. Basri, M.F.; Yacob, S.; Hassan, M.A.; Shirai, Y.; Wakisaka, M.; Zakaria, M.R.; Phang, L.Y. Improved biogas production from palm oil mill effluent by a scaled-down anaerobic treatment process. *World J. Microbiol. Biotechnol.* **2010**, *26*, 505–514. [CrossRef]
62. Oswal, N.; Sarma, P.; Zinjarde, S.; Pant, A. Palm oil mill effluent treatment by a tropical marine yeast. *Bioresour. Technol.* **2002**, *85*, 35–37. [CrossRef]
63. Mekhilef, S.; Barimani, M.; Safari, A.; Salam, Z. Malaysia's renewable energy policies and programs with green aspects. *Renew. Sustain. Energy Rev.* **2014**, *40*, 497–504. [CrossRef]
64. Shafie, S.M.; Mahlia, T.M.I.; Masjuki, H.H.; Andriyana, A. Current energy usage and sustainable energy in Malaysia: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4370–4377. [CrossRef]
65. Sovacool, B.K.; Drupady, I.M. Examining the small renewable energy power (SREP) program in Malaysia. *Energy Policy* **2011**, *39*, 7244–7256. [CrossRef]
66. Umar, M.S.; Jennings, P.; Urmee, T. Strengthening the palm oil biomass renewable energy industry in Malaysia. *Renew. Energy* **2013**, *60*, 107–115. [CrossRef]
67. Umar, M.S.; Jennings, P.; Urmee, T. Sustainable electricity generation from oil palm biomass wastes in Malaysia: An industry survey. *Energy* **2014**, *67*, 496–505. [CrossRef]
68. Haris, A.H. Renewable Energy Bill and Subsidiary Legislations, Ministry of Energy, Green Technology and Water. 2011. Available online: Seda.gov.my (accessed on 13 March 2019).

69. Aziz, N.I.H.A.; Hanafiah, M.M.; Gheewala, S.H. A review on life cycle assessment of biogas production: Challenges and future perspectives in Malaysia. *Biomass Bioenergy* **2019**, *122*, 361–374. [CrossRef]
70. Abdurahman, N.; Rosli, Y.; Azhari, N. The performance evaluation of anaerobic methods for palm oil mill effluent (POME) treatment: A review. In *International Perspectives on Water Quality Management and Pollutant Control*; Quinn, N.W.T., Ed.; IntechOpen: London, UK, 2013; pp. 87–106.
71. Ahmed, Y.; Yaakob, Z.; Akhtar, P.; Sopian, K. Production of biogas and performance evaluation of existing treatment processes in palm oil mill effluent (POME). *Renew. Sustain. Energy Rev.* **2015**, *42*, 1260–1278. [CrossRef]
72. Wu, T.Y.; Mohammad, A.W.; Jahim, J.M.; Anuar, N. Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes. *J. Environ. Manag.* **2010**, *91*, 1467–1490. [CrossRef]
73. Yuniarto, A.; Noor, Z.Z.; Ujang, Z.; Olsson, G.; Aris, A.; Hadibarata, T. Bio-fouling reducers for improving the performance of an aerobic submerged membrane bioreactor treating palm oil mill effluent. *Desalination* **2013**, *316*, 146–153. [CrossRef]
74. Durham, B.; Mierzejewski, M. Water reuse and zero liquid discharge: A sustainable water resource solution. *Water Sci Tech. Water Supply* **2003**, *3*, 97–103. [CrossRef]
75. Heins, W.; Schooley, K. Achieving zero liquid discharge in SAGD heavy oil recovery. *J. Can. Petrol. Technol.* **2004**, *43*, 1–8. [CrossRef]
76. Katsoyiannis, I.; Castellana, M.; Cartechini, F.; Vaccarella, A.; Zouboulis, A.; Grinias, K. Application of zero liquid discharge water treatment units for wastewater reclamation: Possible application in marine ports. In *Sustainable Development of Sea-Corridors and Coastal Waters*; Springer: Cham, Switzerland, 2015; pp. 39–45.
77. Mu, C.; Lin, W.; Zhang, M.; Zhu, Q. Towards zero discharge of chromium-containing leather waste through improved alkali hydrolysis. *Waste Manag.* **2003**, *23*, 835–843. [CrossRef]
78. Wang, J.; Mahmood, Q.; Qiu, J.P.; Li, Y.S.; Chang, Y.S.; Chi, L.N.; Li, X.D. Zero discharge performance of an industrial pilot-scale plant treating palm oil mill effluent. *BioMed Res. Int.* **2015**, *2015*, 1–9. [CrossRef]
79. Rajakumari, S.P.; Kanmani, S. Environmental life cycle assessment of zero liquid discharge treatment technologies for textile industries, Tirupur: A case study. *J. Sci. Ind. Res.* **2008**, *67*, 461–467.
80. Grant, S.B.; Saphores, J.D.; Feldman, D.L.; Hamilton, A.J.; Fletcher, T.D.; Cook, P.L.; Stewardson, M.; Sanders, B.F.; Levin, L.A.; Ambrose, R.F. Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability. *Science* **2012**, *337*, 681–686. [CrossRef]
81. Madaki, Y.S.; Seng, L. Pollution control: How feasible is zero discharge concepts in Malaysia palm oil mills. *Am. J. Engineer. Res.* **2013**, *2*, 239–252.
82. Tong, T.; Elimelech, M. The global rise of zero liquid discharge for wastewater management: Drivers, technologies and future directions. *Environ. Sci. Technol.* **2016**, *50*, 6846–6855. [CrossRef]
83. Weidema, B.P.; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Vadenbo, C.; Wernet, G. *Overview and Methodology: Data Quality Guideline for the Ecoinvent Database Version 3*; Ecoinvent Report 1 (v3); The Ecoinvent Centre: St. Gallen, Switzerland, 2013.
84. Durlinger, B.; Tyszler, M.; Scholten, J.; Broekema, R.; Blonk, H.; Beatrixstraat, G. Agri-footprint: A life cycle inventory database covering food and feed production and processing. In Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector, San Francisco, CA, USA, 8–10 October 2014; pp. 310–317.
85. Norris, G.A. *Simapro Database Manual: The Franklin US LCI Library*; Pré Consultants and Sylvatica: Amersfoort, The Netherlands, 2004; pp. 1–30.
86. Huijbregts, M.; Steinmann, Z.; Elshout, P.; Stam, G.; Verones, F.; Vieira, M.; Hollander, A.; Zijp, M.; Van Zelm, R. *Recipe 2016: A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization*; RIVM Report 2016–0104; National Institute for Human Health and the Environment: Bilthoven, The Netherlands, 2016.
87. ISO 14044. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines, European Committee for Standardization*; International Organization for Standardization ISO Central Secretariat: Geneva, Switzerland, 2006.
88. Lee, K.E.; Mokhtar, M.; Mohd Hanafiah, M.; Abdul Halim, A.; Badusah, J. Rainwater harvesting as an alternative water resource in Malaysia: Potential, policies and development. *J. Clean. Prod.* **2016**, *126*, 218–222. [CrossRef]

89. Loh, S.K.; Lai, M.E.; Ngatiman, M.; Lim, W.S.; Choo, Y.M.; Zhang, Z.; Salimon, J. Zero discharge treatment technology of palm oil mill effluent. *J. Oil Palm Res.* **2013**, *25*, 273–281.
90. Tabassum, S.; Zhang, Y.; Zhang, Z. An integrated method for palm oil mill effluent (POME) treatment for achieving zero liquid discharge: A pilot study. *J. Clean. Prod.* **2015**, *95*, 148–155. [CrossRef]
91. International Energy Agency. *CO_2 Emissions from Fuel Combustion—Highlights*; International Energy Agency: Paris, France, 2017.
92. Energy Commission. 2016. Available online: https://www.st.gov.my/ (accessed on 3 January 2019).
93. Oh, T.H.; Hasanuzzaman, M.; Selvaraj, J.; Teo, S.C.; Chua, S.C. Energy policy and alternative energy in Malaysia: Issues and challenges for sustainable growth–an update. *Renew. Sustain. Energy Rev.* **2017**, *81*, 3021–3031. [CrossRef]
94. Mahlia, T. Emissions from electricity generation in Malaysia. *Renew. Energy* **2002**, *27*, 293–300. [CrossRef]
95. Shafie, S.; Mahlia, T.; Masjuki, H.; Ahmad-Yazid, A. A review on electricity generation based on biomass residue in Malaysia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 5879–5889. [CrossRef]
96. Lijó, L.; González-García, S.; Bacenetti, J.; Fiala, M.; Feijoo, G.; Lema, J.M.; Moreira, M.T. Life cycle assessment of electricity production in Italy from anaerobic co-digestion of pig slurry and energy crops. *Renew. Energy* **2014**, *68*, 625–635. [CrossRef]
97. Wang, Q.L.; Li, W.; Gao, X.; Li, S.J. Life cycle assessment on biogas production from straw and its sensitivity analysis. *Bioresour. Technol.* **2016**, *201*, 208–214. [CrossRef]
98. Roux, C.; Schalbart, P.; Peuportier, B. Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. *J. Clean. Prod.* **2016**, *113*, 532–540. [CrossRef]
99. Wang, J.; Mahmood, Q.; Qiu, J.P.; Li, Y.S.; Chang, Y.S.; Li, X.D. Anaerobic treatment of palm oil mill effluent in pilot-scale anaerobic EGSB reactor. *BioMed Res. Int.* **2015**, *2015*, 1–7. [CrossRef]
100. Ali, R.; Daut, I.; Taib, S. A review on existing and future energy sources for electrical power generation in Malaysia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 4047–4055. [CrossRef]
101. Khor, C.S.; Lalchand, G. A review on sustainable power generation in Malaysia to 2030: Historical perspective, current assessment, and future strategies. *Renew. Sustain. Energy Rev.* **2014**, *29*, 952–960. [CrossRef]
102. Jaramillo, P.; Griffin, W.M.; Matthews, H.S. Comparative life-cycle air emissions of coal, domestic natural gas, lng, and sng for electricity generation. *Environ. Sci. Technol.* **2007**, *41*, 6290–6296. [CrossRef] [PubMed]
103. Kumar, S.; Kwon, H.T.; Choi, K.H.; Hyun Cho, J.; Lim, W.; Moon, I. Current status and future projections of LNG demand and supplies: A global prospective. *Energy Policy* **2011**, *39*, 4097–4104. [CrossRef]
104. Tilton, J.E. *On Borrowed Time? Assessing the Threat of Mineral Depletion*; Routledge: New York, NY, USA, 2010; pp. 1–158.
105. International Gas Union. 2017. Available online: https://www.igu.org/ (accessed on 3 January 2019).
106. Hengeveld, E.J.; Bekkering, J.; Van Gemert, W.J.T.; Broekhuis, A.A. Biogas infrastructures from farm to regional scale, prospects of biogas transport grids. *Biomass Bioenergy* **2016**, *86*, 43–52. [CrossRef]
107. Trummer, D.R. Biomass-Fired CHP in Palm Oil Mills. In *Malaysian-Danish Country Programme for Cooperation in Environment and Sustainable Development (2002–2006)*; Royal Danish Embassy: Kuala Lumpur, Malaysia, 2001.
108. Cervi, W.R.; Lamparelli, R.A.C.; Seabra, J.E.A.; Junginger, M.; Van Der Hilst, F. Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment. *Biomass Bioenergy* **2019**, *122*, 391–399. [CrossRef]
109. Gigliucci, G.; Petruzzi, L.; Cerelli, E.; Garzisi, A.; La Mendola, A. Demonstration of a residential CHP system based on PEM fuel cells. *J. Power Sources* **2004**, *131*, 62–68. [CrossRef]
110. Parsaee, M.; Kiani, M.K.D.; Karimi, K. A review of biogas production from sugarcane vinasse. *Biomass Bioenergy* **2019**, *122*, 117–125. [CrossRef]
111. Pöschl, M.; Ward, S.; Owende, P. Evaluation of energy efficiency of various biogas production and utilization pathways. *Appl. Energy* **2010**, *87*, 3305–3321. [CrossRef]
112. Chin, M.J.; Poh, P.E.; Tey, B.T.; Chan, E.S.; Chin, K.L. Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia's perspective. *Renew. Sustain. Energy Rev.* **2013**, *26*, 717–726. [CrossRef]