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The dilemma in energy transition in Malaysia: A comparative life cycle assessment of large scale solar and biodiesel production from palm oil

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ABSTRACT

Energy transition to renewable energy is a current global trend. Being the world's second-largest palm oil and third-largest solar photovoltaic cells producer, Malaysia prioritizes palm biodiesel as biofuel and large scale solar as renewable energy sources. Nevertheless, disputed issues such as land occupation and embodied environmental impacts of both technologies are not backed with data-driven evaluation from a life cycle perspective. This study compares the environmental impacts and identifies the environmental hotspots of palm biodiesel and large scale solar systems using life cycle assessment methodology under the same system boundary and functional unit (i.e., 1 MJ of energy). There are 18 impact categories and three damage assessments evaluated with ReCiPe 2016 via SimaPro 9.1. The large scale solar systems perform more favorably than palm biodiesel systems by 77% in all damage assessments. The environmental hotspots in palm biodiesel (i.e., fresh fruit bunch production and milling) and large scale solar systems (i.e., electrical installation) show environmental burdens up to 15–51% in human non-carcinogenic toxicity, human carcinogenic toxicity, global warming, marine ecotoxicity, water consumption, and fossil resource scarcity. Anthropogenic carbon dioxide emissions from fossil fuel usage and land transformation in palm biodiesel systems are of positive value when compared (i.e., 11 g CO_2/MJ PB) to large scale solar systems. The aluminum recycling in large scale solar systems and anaerobic digestion biogas plant in the palm biodiesel system can reduce the environmental impact between 4.13% and 25%. Policy implications are recommended for policymakers for better decision-making aligned with the national renewable energy implementation road map.

1. Introduction

Fossil fuels account for 81% of global primary energy consumption (WBA, 2020), contributing more than two-thirds of global greenhouse gas (GHG) emissions and other pollutants to the surrounding (Lee and Birol, 2020). Fossil fuels are still heavily used and accounting for 74.2% in the electricity sector and 92% in the transport sector in 2018 (WBA, 2020), leading to a shrinking supply of fossil fuels, increasing environmental deterioration (e.g., global warming) and pollution-related human health problems (Panahi et al., 2019). To mitigate the environmental impacts caused by fossil fuels, a paradigm shift in the global energy landscape contributed by solar photovoltaic (PV) and biofuel technologies is observed. The recent two decades observed the global energy transition towards both technologies in energy and transport sectors as renewable energy (RE) sources.

The global solar PV capacity in 2020 was about 707 GW, with a growth comprising 50% of the global RE capacity growth (IRENA, 2021). China has the world's leading PV capacity, which accounts for 32%, followed by the United States (13%) and Japan (12%) (Mathur et al., 2020). By 2040, the PV industry could contribute 12.6% of the world's electricity supply (Zhang et al., 2020). Meanwhile, biofuels blended in fossil fuels for the transport sector have been implemented in 66 countries (Dey et al., 2021). In 2018, biofuels from palm oil contributed more than 3% of the energy demand in the transport sector at a growing rate of 13%, reaching six times the total energy demand of this sector (WBA, 2020).

As solar energy and palm oil are exploitable, prospective, and widely used natural resources (Dey et al., 2021; Liu et al., 2019), these advantages have caught the attention of some countries with a tropical

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List of abbreviations

AD	: Anaerobic digestion
BOS	: Balance of system
CPKO	: Crude palm kernel oil
CPO	: Crude palm oil
FFB	: Fresh fruit bunch
FRS	: Fossil resource scarcity
GHG	: Greenhouse gas
GW	: Global warming
HCT	: Human carcinogenic toxicity
HnCT	: Human non-carcinogenic toxicity
LCA	: Life cycle assessment
LSS	: Large scale solar
ME	: Marine ecotoxicity
MGS	: Metallurgical grade silicon
Mono-Si	: Mono-crystalline silicon
Multi-Si	: Multi-crystalline silicon
NDC	: Nationally determined contribution
PB	: Palm biodiesel
PV	: Photovoltaic
RE	: Renewable energy
REDD+	: Reducing emissions from deforestation and forest degradation in developing countries
RPO	: Refined palm oil
SDG	: Sustainable Development Goals
SGS	: Solar grade silicon
UN	: United Nations
WC	: Water consumption

climate and nutrient-rich soil like Mexico (Pérez-Denicia et al., 2017), Nigeria (Giwa et al., 2017), Indonesia and Malaysia (IRENA, 2018). These countries strive for clean energy through large scale solar (LSS) and palm biodiesel (PB) technologies. However, LSS and PB technologies pose embodied environmental issues, including organic carbon loss through CO_2 emission, biodiversity destruction, and land deprivation (Prapaspongsa et al., 2017; Roddis et al., 2020). For example, large-scale land transformation in oil palm plantations was responsible for about 75% of peat forest loss in Peninsular Malaysia, Sumatra, and Borneo from 2007 to 2015, severely affecting the biodiversity system in Southeast Asia (Dhandapani et al., 2020). While more than 2,000 ha of grazing land have been occupied to build an LSS technology in Charanka Solar Park, India (Yenneti et al., 2016).

The LSS and PB industries face shared issues in their production stages namely potential GHG emissions from fossil fuels usage and land transformation, albeit of the potential of the technologies to relieve environmental impacts (Liu et al., 2019; Szulczyk and Khan, 2018). The LSS project has been criticized for extensive land transformation, using chemicals for maintenance, and producing solar panels that may cause environmental damage (Hernandez et al., 2014). Without appropriate disposal of decommissioned PV panels, the loss of conventional materials (e.g., aluminum and glass) and the leachate of hazardous materials (e.g., lead and cadmium) in PV panels can cause environmental impacts (Adamo et al., 2017). For PB technology, environmental impacts, such as global warming, acidification, and eutrophication, are incurred in oil palm plantations due to land transformation and overused fertilizers (Groesbeck and Pearce, 2018). The production of PB has also been strongly opposed by environmentalists, who believe that large-scale palm oil plantation has caused severe damage to tropical forests, leading to GHG emissions (Mukherjee and Sovacool, 2014).

To resolve the energy transition dilemma, life cycle assessment (LCA) methodology can be applied to quantify and identify the severity level of environmental impacts inflicted throughout the lifespan of these technologies (Méndez et al., 2021). Table A.1 in the Supplementary Material summarizes 11 LCA studies that evaluate PB system or LSS systems. An LCA study conducted in China identified that multi-crystalline silicon (multi-Si) production and PV panel packaging are the hotspots area that incurred the highest environmental impacts, while the PV cell production induces the most negative impacts in freshwater and marine aquatic ecotoxicity potentials (Yang et al., 2015). Rashedi and Khanam (2020) compared four PV technologies throughout their whole life cycle. They presented that mono-crystalline silicon (mono-Si) technology caused the most significant environmental burdens, followed by amorphous silicon, multi-Si, and cadmium telluride thin-film using the ReCiPe 2016 method. However, the GHG emissions from land transformation are not thoroughly investigated. For PB, Castanheira and Freire (2017) investigated palm oil imported from Colombia to produce biodiesel in Portugal, evaluating the impact of land transformation, fertilization plans, and biogas management at palm oil extraction mill. Southeast Asia countries such as Thailand (Prapaspongsa et al., 2017), Indonesia (Meijide et al., 2020), and the Philippines (Mae et al., 2020) had begun investigating the relationship between land transformation and CO_2 emissions in palm oil plantations. Results showed that CO_2 emissions from land transformation, which is usually assumed negligible, have study significance.

To the authors' best knowledge, no direct comparison study between LSS and PB from a life cycle perspective has been conducted as shown in Table A.1. Most of the literature only focused on evaluating one type of RE system and the GHG emissions from fossil fuels usage, neglecting the possible competition with the other RE options and potential threats of GHG emissions from land use change. Due to land disputes, inadequate financial resources, and environmental concerns for both LSS and PB technologies, the stakeholders are hesitant to prioritize these technologies in the national energy transition landscape. Consequently, a holistic data-driven study is necessary to investigate the life cycle environmental impacts of both technologies.

Being the world's second-largest palm oil and third-largest solar PV cells producer, Malaysia is taken as a case study to compare the relative difference in environmental impacts between LSS and PB via LCA methodology. Considering the National Forestry Act 1984 and limited green technology tax incentives allocation, the Malaysian government faces a dilemma in transitioning lands to either LSS or PB systems (Salleh et al., 2020). Besides, the environmental hotspots of production stages that incurred the highest environmental impacts in these two technologies are yet to be identified thoroughly. By identifying the environmental hotspots, one can propose appropriate emissions reduction solutions to the technologies. The GHG emissions from Malaysia's land transformation are not comprehensively studied because of limited data availability and the lack of detailed real-time biodiversity systems studies (Rao and Mustapa, 2021). This study provides a life cycle quantitative approach to investigate the GHG emissions from the land transformation of LSS and PB technologies. It is hoped that this study can act as a reference to other countries such as Indonesia and the Philippines when determining the suitability of LSS and PB technologies application for an energy transition from the environmental perspective.

2. Materials and method

This study applies LCA methodology based on the ISO 14040 and ISO 14044 (ISO, 2006a; 2006b), with the following four steps: i) goal and scope definition; ii) life cycle inventory; iii) life cycle impact assessment; and iv) life cycle interpretation.

2.1. Goal and scope definition

This study aims to quantify and compare the environmental impacts from two types of RE systems (i.e., LSS and PB systems) and evaluates the hotspot stages in the systems within Malaysia's geographical boundary. The solar PV industry has been the fastest-growing RE sector in Malaysia due to high solar radiation levels ranging from 4.2 kWh/m^2 to 5.6 kWh/m^2 (Saleheen et al., 2021). Malaysia is the world's third-largest producer of solar PV cells and modules, and by 2050, PV energy is expected to increase to 13,540 GWh in the energy mix (Vaka et al., 2020). This study includes two types of PV technologies, namely multi-Si and mono-Si panels, as they are the most manufactured and widely used PV panels in Malaysia (IEA, 2017). Malaysia is the world's second-largest producer and exporter of palm oil after Indonesia. In 2020, the palm oil plantations covered 5.87×10^6 ha, and crude palm oil production (CPO) was 1.91×10^7 t (MPOB, 2020). An estimated 1.72×10^{10} L of PB can be produced from the CPO production to make up for the 1.1×10^{10} L of diesel consumed by the Malaysian transport sector in 2014 (Szulczyk and Khan, 2018).

Fig. 1 illustrates all production and product consumption stages with the input data (e.g., energy, water use, chemicals, transportation, and raw materials from nature) and output data (e.g., air, water, and soil emission, and final waste flow to landfill) in the baseline case of PB system (i.e., PB1) and LSS systems (i.e., LSS1 for multi-Si and LSS2 for mono-Si). The system boundary of both systems is synchronized as "cradle-to-grave" to ensure a fair comparison. The sub-stages within both system boundaries begin from the extraction of raw materials process to the consumption of the investigated product with the final waste flows to landfill (e.g., from nursery stage to transesterification with the final waste flows to landfill). The functional unit is standardized to 1 MJ energy generated from the respective technology (i.e., 1 MJ of electrical energy for LSS systems while 1 MJ of higher heating value for PB system) to ensure comparison uniformity and guide policymakers to select the most favorable system. It is worth noting that the primary energy demand in many countries including Malaysia is commonly represented and benchmarked with the unit of Joule. (IEA, 2021). The descriptions of these three main systems are as shown in Table 1.

2.2. Life cycle inventory (LCI)

Table 2 indicates the conversion factors for the functional unit in PB1 and LSS systems. The input data such as energy consumption, water usage, chemicals, transportation, raw materials from nature are collected. The output data include the air, water, and soil emissions at each stage, final flow waste, and the amount of co-product. The categorizations of input and output data are based on the different stages in the entire system to investigate the environmental hotspot areas.

The data for the PB1 system are sourced from MPOB official reports which are representative of Malaysia's palm oil industry and verified by the relevant palm oil stakeholders via interviews and on-site visits from 21 nurseries, 102 palm oil plantations, 12 palm oil mills, 11 refinery plants, and two PB plants in Malaysia, as cited under Table 2. In addition, peer-reviewed journals and the ecoinvent 3.7 database under Malaysia's environmental condition are selected to fill up the data gaps resulting from the MPOB official reports. Meanwhile, the collected data from LSS are based on the reference study (Rashedi and Khanam, 2020), sourced from comprehensive PV project investigations conducted by the Swiss Federal Office of Energy and localized using the thumb rules provided by local industry experts in the design of LSS in Malaysia. Table A.2 - A.4 in the Supplementary Material illustrate the detailed inventory data for PB1, LSS1, and LSS2 systems, which are converted to functional unit-based from raw data. The data is collected from similar data sources to minimize the data year gap and guarantee that the data is standardized in the methodology.

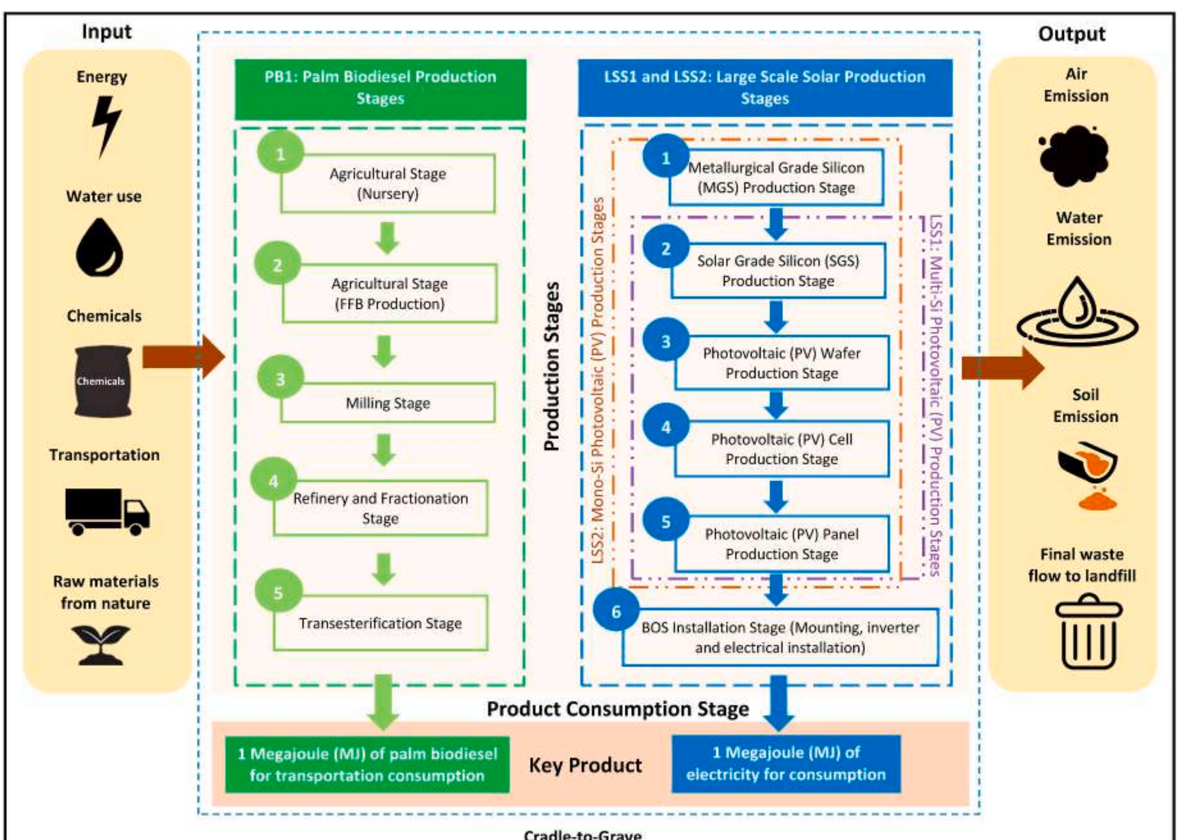

Fig. 1. System boundary of the palm biodiesel system (PB1) and LSS systems (LSS1 and LSS2).

Table 1
Description of PB1, LSS1, and LSS2 systems.

Systems	Description
PB1[a]	The system consists of 4 main stages – Stage 1: Agricultural stage (Nursery and FFB production), Stage 2: Milling stage, Stage 3: Refinery and fractionation stage, and Stage 4: Transesterification stage. The land requirement of main and prenursery of palm seedlings included in this study are 0.87 m^2/y and 250.5 m^2/y, respectively. The system's expected life span is based on the maturity year of the oil palm plant, which is 25 years. A total of 102 oil palm plantations of 1.1 M ha with an average annual yield of 20.7 t/ha/y and planting density of 142 palm/ha is selected for this study. The soil nature of the plantation is mineral soil. The palm biodiesel production capacity of the system is assumed to be 60,000 t/y, with a product of 98% purity. At the milling stage, the operation capacity is at 270,000 t FFB/y. The product allocation between crude palm oil (CPO), palm kernels (PK), and palm shells (PS) is 61%, 25%, and 14%, respectively. The treatment process of by- and co-products (i.e., palm residues and general solid digestate) other than CPO is not considered as those are not the main product within the study scope. The primary emissions studied are mainly palm oil mill effluent (POME) and greenhouse gas (GHG). The chemical oxygen demand of POME is around 47,500–70,000 mg/L. Upon reaching the national discharge standard after being treated in an open ponding system, POME is released to natural waster bodies (DOE, 2009). The refinery and fractionation stage is assumed to produce an average of 45 kg palm fatty acid distillate (PFAD) in every t of processed CPO. The weight allocation of 95.5:4.5 is used in this study. The fractionation purity of the oil could reach up to 90%. As for transesterification, the weight allocation of the products, which are palm biodiesel and glycerol, is around 89.3:10.7. The treated wastewater in this stage fulfils the national effluent discharge standard (DOE, 2009), but the wastewater treatment process is not included in this assessment due to its negligible environmental impact (Tan et al., 2010).
LSS1[b]	The main stages included in the system are namely Stage 1: Solar grade silicon (SGS) production, Stage 2: Photovoltaic (PV) wafer production, Stage 3: PV cell production, Stage 4: PV panel production stage, and Stage 5: Balance of System (BOS) installation. 100% of multi-PV panels are utilized and installed on-site. The assumption on the system's energy yield is 1400 kWh/kW_p as recommended by local industrial experts. The expected life span for this system is 25 years. The sg-silicon produced in this study has 99.99% purity after undergoing the Siemens process. The quantity of chemicals and raw materials for the production of PV wafer, PV cell, PV panel are included in Table A.3. At the installation site, the inverter is assumed to own an efficiency of 93.5%. The electrical installation comprises lightning protection, fuse box, cabling in PV panel, cabling from PV panel to an inverter, and from the inverter to the electric meter. The land area of this LSS installation is assumed to be around 98 ha with 78 MW_p of electricity generation capacity. The operation of LSS is 14 h/d (7 a.m.–9 p.m.) with 0.02% annual loss in terms of operation hours.
LSS2[c]	With one additional stage as compared to LSS1, the key stages in the system are Stage 1: Metallurgical grade silicon (MGS) production, Stage 2: Solar grade silicon (SGS) production, Stage 3: Photovoltaic (PV) wafer production, Stage 4: PV cell production, Stage 5: PV panel production stage, and Stage 6: Balance of System (BOS) installation. The additional stage is due to the application of the mono-PV panel at the site. 100% of mono-PV panels are utilized and installed on-site. The assumption on the energy yield of the system is 1400 kWh/kW_p. as recommended by local industrial experts. The expected life span for this system is 25 y. The MGS produced from the reduction of extracted silica via thermal reaction with coke is 98% purity. The consequent production stages starting from SGS are assumed to be similar to LSS1 for a fair comparison.

[a] Important data and parameters of PB1 is mainly sourced from Muhammad et al. (2010), Zulkifli et al. (2010), Subramaniam et al. (2010), Tan et al. (2010), Wei et al. (2010) and, Aziz and Hanafiah (2020).
[b] Important data and parameters of LSS1 is mainly sourced from Rashedi and Khanam (2020) and on-site interview.
[c] Important data and parameters of LSS2 is mainly sourced from Rashedi and Khanam (2020) and on-site interview.

The calculation and modeling of the avoided products (i.e., palm biodiesel and electricity) of the investigated systems are based on the market substitution data of diesel fuel and conventional electricity sources in ecoinvent database as elaborated in Appendix B of the Supplementary Material. The assumed market substitution for both avoided products is of 1:1 ratio.

Table 2
The conversion factors for the functional unit in respective stages.

Stages	Functional unit (/MJ energy generated)	References
PB1: Palm Biodiesel System		
Oil palm seedling	2.71×10^{-5} unit[a]	Muhammad et al. (2010)
FFB	9.88×10^{-5} t	Zulkifli et al. (2010)
Crude palm oil (CPO)	3.19×10^{-5} t	Subramaniam et al. (2010)
Refined palm oil (RPO)	3.04×10^{-5} t	Tan et al. (2010)
Palm biodiesel	1.00 MJ	Wei et al. (2010)
LSS1: Multi-Si LSS System		
SGS	5.32×10^{-5} kg	Rashedi and Khanam (2020)
PV wafer	4.10×10^{-5} m^2	
PV cell	3.87×10^{-5} m^2	
PV panel	4.35×10^{-5} m^2	
Slanted mounting installation	4.24×10^{-5} m^2	
LSS2: Mono-Si LSS System		
MGS	4.24×10^{-5} kg	Rashedi and Khanam (2020)
SGS	3.75×10^{-5} kg	
PV wafer	4.24×10^{-5} m^2	
PV cell	4.00×10^{-5} m^2	
PV panel	4.34×10^{-5} m^2	
Slanted mounting installation	4.20×10^{-5} m^2	
LSS1 & LSS2: Balance of System (BOS) stage		
Electrical installation	5.71×10^{-6} unit[b]	Rashedi and Khanam (2020)
Inverter, 1000 W	5.71×10^{-6} unit[b]	

[a] The number of seedlings needed to generate 1 MJ of energy in the nursery stage.
[b] The number of electrical installation/inverter needed to generate 1 MJ of energy in the BOS stage.

2.3. Life cycle impact assessment (LCIA)

The data collected in Section 2.2 are further characterized using SimaPro 9.1 with the ReCiPe 2016 impact assessment method, which combines the advantages of the midpoint method of CML-IA and the endpoint approach of Eco-indicator 99 (Castanheira and Freire, 2017; Rashedi and Khanam, 2020). Eighteen impact categories and three damage assessments (i.e., human health, ecosystem quality, and resources) are evaluated in this study as displayed in Fig. A.1 in the Supplementary Material. This study's selection of impact categories also aligns with the solar energy systems and PB LCA studies conducted by Huang et al. (2017) and Castanheira and Freire (2017), respectively. The six impact categories, namely human non-carcinogenic toxicity (HnCT), global warming (human health and terrestrial system) (GW), human carcinogenic toxicity (HCT), marine ecotoxicity (ME), water consumption (WC), and fossil resource scarcity (FRS), which highlighted in yellow in Fig. A.1 in the Supplementary Material, are selected for in-depth analysis and discussion because these six impact categories account for more than 6% of the overall environmental burden for their aggregated damage assessment (i.e., human health, ecosystem quality, or resource) in this study. Eq. (1) demonstrates the method of selecting these six significant impact categories in the respective damage assessment:

$$IC_x\% = \left(\mathrm{IC_x} \div \sum IC_y\right) \times 100\% \quad \text{(Eq. 1)}$$

where:

$IC_x\%$ = Environmental damage percentage of x impact category result under y damage assessment

x = Investigated impact category (18 impact categories)
y = Investigated damage assessment (three damage assessments)
IC_x = Environmental damage value of x impact category result under y damage assessment
$\sum IC_y$ = Sum of the impact categories under y damage assessment

To determine the net environmental load resulting from the production and product consumption stages in the studied systems (i.e., PB1, LSS1, and LSS2), the net environmental value, ΔE, is developed and calculated as shown in Eq. (2).

$$\text{Net environmental value,} \ \Delta E = E_c + E_p \quad \text{(Eq. 2)}$$

where:

E_c = Environmental load from product consumption stage
E_p = Environmental load from production stages

A positive net value signifies environmental burden, while a negative net value indicates environmental benefit.

2.4. Life cycle interpretation

CO_2 emissions from fossil fuel usage and land transformation are further investigated in each stage of the three selected systems to compare the impact of global warming caused by fossil fuel consumption and arable land. The CO_2 emissions from land transformation are quantified based on the relevant conversion factors (i.e., 135.22 kg C/ha and 490.66 kg CO_2/ha of arable land) in Malaysia obtained from the ecoinvent 3.7 database. Arable land is presumably used for both systems as the land type is the most common and popular option in perennial agriculture (Olaniyi et al., 2013) and industrial development (Mohammed et al., 2015). Meanwhile, the CO_2 emissions from fossil fuel usage are estimated based on the carbon emission factors for PB system (i.e., 64.5 g CO_2/PB) and the displaced electricity factor of LSS systems (i.e., 0.20 kWh/MJ electricity). Further details on the calculation and modeling of the emissions can be found under Appendix B in the Supplementary Material. The environmental impacts and hotspot stages are evaluated by conducting a scenario analysis in PB1 and LSS systems to address the environmental load produced by the RE systems. The scenario analysis includes various locations of crude palm kernel oil (CPKO), anaerobic digestion (AD) in PB systems, and aluminum recycling in LSS systems. Further description and analysis of the scenario analysis are elucidated in Section 3.5.

3. Results and discussion

This section is divided into six subsections, where the first and second sub-sections analyze the impact assessment and endpoint of both technologies. Section 3.3 identifies and elaborates the environmental hotspots in the respective systems, while Section 3.4 presents a scenario analysis involving material recovery processes in the respective base case scenarios for LSS and PB to address the research gaps raised in the literature review. Policy implications and development (i.e., Section 3.6) based on the study results are elaborated to highlight the significance of the study in RE policymaking before concluding the study in the Conclusion section.

3.1. Impact assessment comparison of PB1 and LSS systems

The environmental loads of all assessed impact and damage assessment in essential stages of LSS and PB are tabulated under Tables A.5 – A.7 and presented in Fig. A.2 in the Supplementary Material. According to the impact and damage assessment results presented in Figs. 2 and 3, the investigated system with the highest net environmental load (i.e., net environmental burden and net environmental benefit for positive and negative values, respectively) is set at 100% as the control basis. The following six impact categories of the characterization method ReCiPe 2016, selected from Section 2.3, are arranged in ascending environmental impact magnitude order under respective damage assessment in Sections 3.1.1 to 3.1.6.

3.1.1. Human non-carcinogenic toxicity (HnCT)

As portrayed in Fig. 2, the LSS systems (i.e., LSS1 and LSS2) outperform the PB1 system approximately by 27.3% (i.e., -4.11×10^{-7} DALY/MJ energy) and 20.2% (-2.99×10^{-7} DALY/MJ energy) in net environmental benefit, respectively. The electrical installation and FFB production produce the highest HnCT impact in LSS systems and PB1 system, respectively. The electrical installation stage is 14% higher than the FFB production stage. This is due to the zinc emission from copper materials (96% of HnCT from electrical installation) and chemical fertilizer application (88% of HnCT from the FFB production stage).

3.1.2. Global warming (GW)

PB1 system induces the most significant GW in human health and terrestrial ecosystem through milling stage and FFB production,

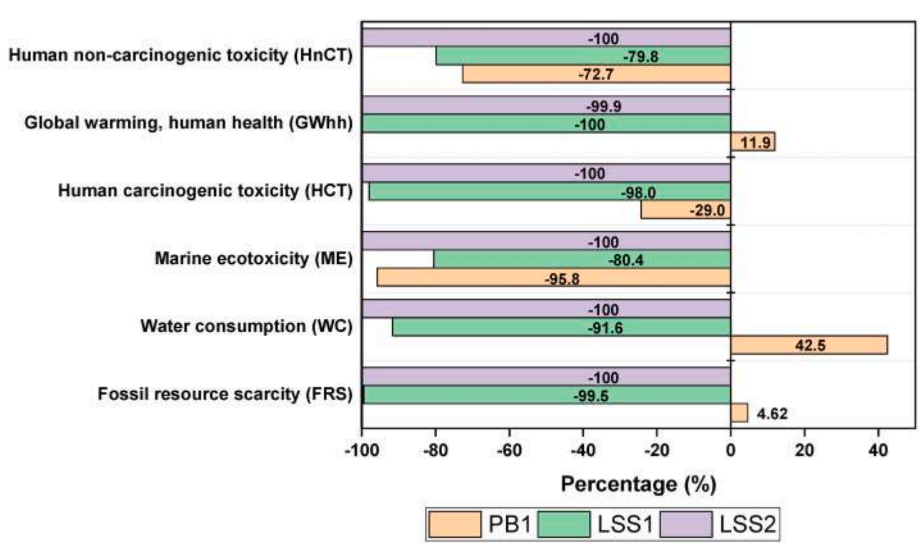

Fig. 2. The critical impact assessment for PB1, LSS1, and LSS2 systems. Positive percentage value represents net environmental burden, whereas negative percentage value represents net environmental benefit.

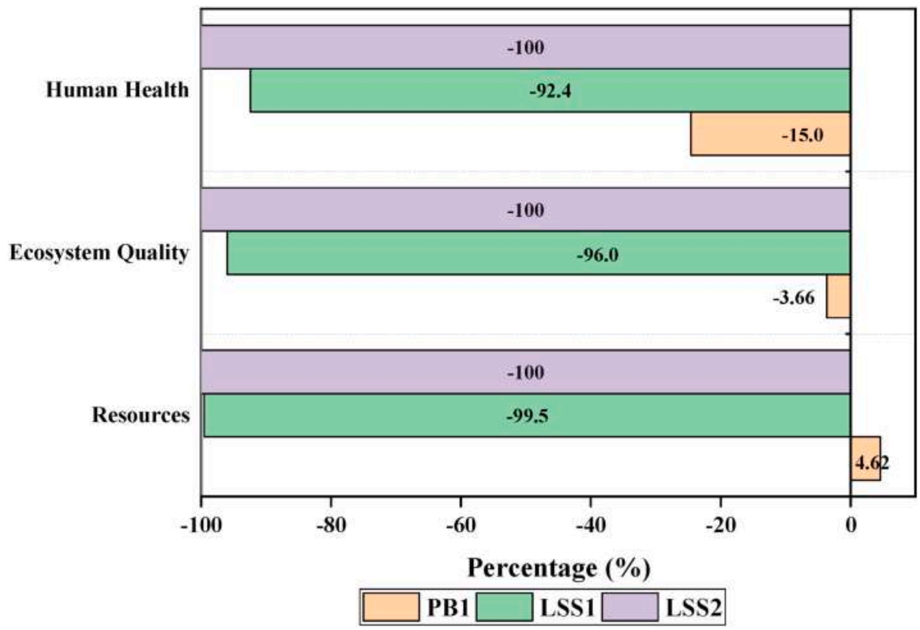

Fig. 3. The damage assessment of PB1, LSS1, and LSS2 systems. Positive percentage value represents net environmental burden, whereas negative percentage value represents net environmental benefit.

occupying the top 66 percentile of GW among the other production stages of PB1 and LSS systems. Meanwhile, the production stages of LSS systems range below the bottom five percentile of GW, with the SGS production stage for mono-PV panel amounting to the highest GW (4.73–4.79%) in LSS systems. Bearing the highest environmental burden among the other systems, the product consumption of the PB1 system could not fully offset the GW impact from production stages, contributing 12% (i.e., 2.11×10^{-7} DALY/MJ energy, 4.24×10^{-7} species. yr/MJ energy) of environmental burden in terms of human health and ecosystem. The production consumption of LSS systems oppositely discount 9- to 13-fold of GW impact of production stages.

3.1.3. Human carcinogenic toxicity (HCT)

For HCT, the PB1 system shows lower environmental relief than LSS systems by roughly 69% (i.e., -6.26×10^{-7} DALY/MJ energy), as elucidated in Fig. 2. The Cr^{4+} elements in the milling and FFB production stages are responsible for almost one-third of HCT production in the studied systems. The slanted mounting setup for PV panels and the PV panel production stage are ranked after those stages contributing to Cr^{4+}. The product consumption stage cuts off 98% and 343–383% of HCT in PB1 and LSS systems.

3.1.4. Marine ecotoxicity (ME)

Despite LSS1 systems showing higher environmental benefits than PB1 system, as opposed to the results in other ecosystem quality impact categories, the electrical installation of the LSS systems generates the highest impact in ME (22%) due to copper application for installation, followed by the FFB production in PB1 system (16%) resulting from chemical fertilizer application. These two stages contribute 1.49–1.80 mg Zn emissions per MJ product, totaling up to 38% of the production stages in both systems. Surprisingly, the LSS2 system showed 15% lower environmental benefit (i.e., -1.06×10^{-10} species. yr/MJ energy) than PB1 as biofuel consumption in PB1 alone countered 1.75 times of ME in production stages.

3.1.5. Water consumption (WC)

The environmental loads caused by the WC of the milling stage for the sterilization process and FFB production stage for irrigation in the PB1 system are twice that of the entire production stages in LSS1 and LSS2. The overwhelmingly high environmental load (i.e., 42.5% net environmental burden) of WC in PB1 system is due to the water consumed for steam and energy generation from fossil fuel usage.

3.1.6. Fossil resource scarcity (FRS)

FRS in PB1 system contributes 4.62% (4.67×10^{-10} USD2013/MJ energy) of the environmental burden. The fossil fuels demand at the milling stage (51%), FFB production stage (15%), and transesterification stage (13%) of PB systems account for 79% of the entire production stages of PB1 system. The biofuel consumption in the PB1 system can reduce up to 90% of FRS. Although the FRS of LSS systems is relatively insignificant compared to the PB1 system, the SGS production of mono-PV panels carries the highest FRS (3.8%) among other LSS stages.

3.2. Damage assessment comparison of PB1 and LSS systems

LSS systems exhibit higher environmental benefits (up to 77%) than the PB1 system for damage assessment (i.e., human health, ecosystem quality, and resources), as shown in Fig. 3. The product consumption of LSS systems has approximately two times greater environmental benefits than PB1 system; therefore, the resulting net environmental values from the LSS systems are typically higher than PB system in human health and ecosystem quality, except that PB1 system causes net environmental burden in resource scarcity. The accumulated human health damage from GW and HCT in the production stages is the primary factor of low environmental benefit (i.e., −15.9%) in the PB1 system. ME and WC are the key impact categories that induce lower environmental benefits for ecosystem quality in the PB1 system (i.e., −10.9%). Despite the environmental benefits from the product consumption stage, PB1 system could not wholly offset the environmental burden to resource scarcity due to tremendously high FRS, as illustrated in Fig. 2.

3.3. Environmental hotspots in PB and LSS production stages

The environmental hotspots are the production stages identified with considerable environmental impact load (occupy at least one-fifth of the overall environmental impact load caused by production stages) within PB and LSS systems. Fig. 4 illustrates the respective environmental hotspots in PB and LSS systems.

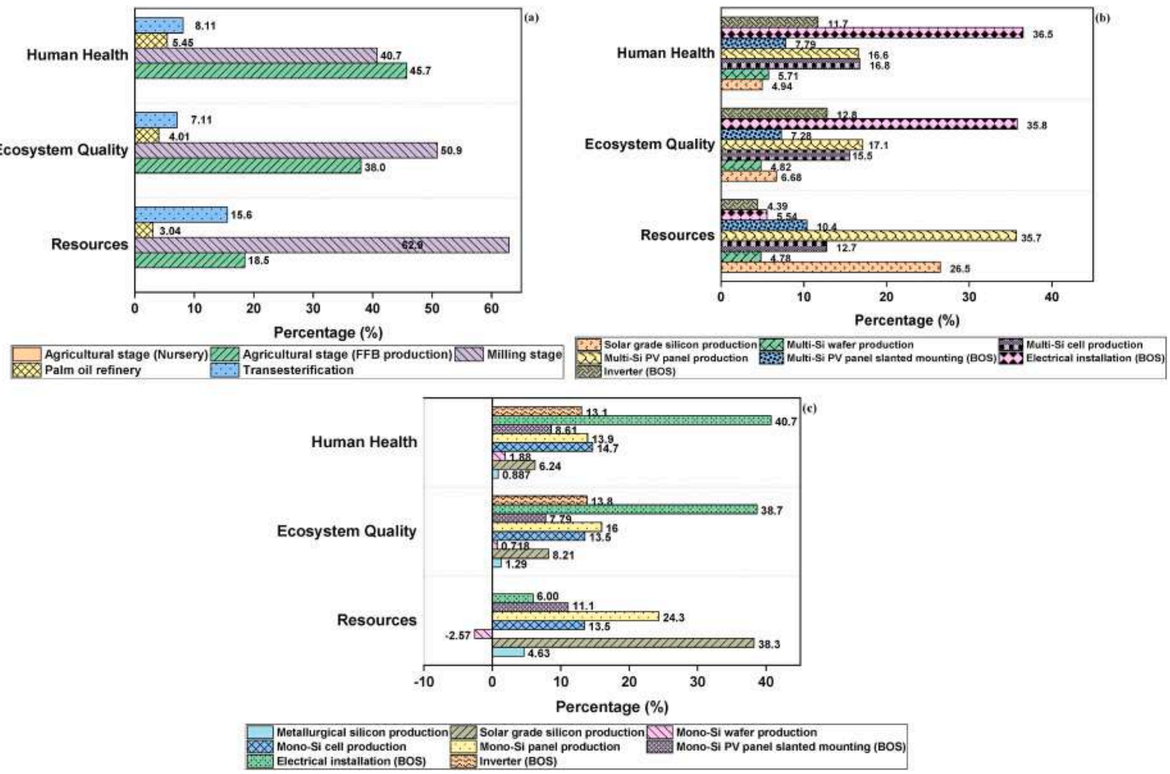

Fig. 4. The environmental hotspot contribution analysis in production stages of (a) PB system, (b) LSS1 system, and (c) LSS2 system. Positive percentage value represents environmental burden, whereas negative percentage value represents environmental benefit.

3.3.1. PB1 production

FFB production stage and milling stage of PB1 account for 81–89% of the overall environmental impact load in human health, ecosystem quality, and resources under production stages, as illustrated in Fig. 4. The applications of chemical fertilizers, transportation, and fossil fuel consumption are the dominant contributors behind both stages' substantial environmental impact load. Owing to the heavy proportion of heavy metal emissions from chemical fertilizers application, the environmental load of the FFB production stage across the assessed impact categories are exceptionally high, showing symmetry with the study conducted by Lee and Ofori-Boateng (2013). The environmental load of the milling stage is relatively substantial due to the heavy proportion of GHG and heavy metals emissions from steam production for the fruit bunch stripping process. The inclusion of PB consumption (product consumption) based on Malaysia's context counters almost 89% of damage to resource scarcity, offsetting 126% and 120% of damage to human health and ecosystem quality, respectively.

3.3.2. LSS1 and LSS2 production

Contrary to PB1, the stages in LSS1 and LSS2 show a relatively fair distribution of environmental load within the bounded system. The stages in both LSS systems are subcategorized into the production stages and BOS installation stages to systematically rank the environmental hotspots within the system. The production stages are the stages apart from BOS installation stages within the bounded system. Fig. 4(b) and (c) depict that the damage caused by the production stages upon resource scarcity outweighs that of the electrical BOS stages almost four times due to extraction of minerals (silicon) for production stages.

LSS2 performs better than LSS1 among the three damage assessments. Although mono-Si PV system is commonly perceived as causing a higher environmental burden than multi-Si due to higher energy requirement for processing (Peng et al., 2013), the fewer chemical applications in processing based on collected data and recycling of chemicals have significantly reduced the system's environmental burden. On average, LSS2 demonstrates a slightly lower environmental impact on the overall impact than LSS1, with a reduction ranging from 1.08 to 1.20%.

3.4. Anthropogenic CO_2 emission from fossil fuels usage and land transformation

Results in Section 3.2 reveal that GW incurs a significant environmental load in human health and ecosystem quality among the rest. Out of the GHG emissions, only CO_2 is prioritized in this study for analysis based on the result outcomes (i.e., CO_2 is made up above 90% of GW). Anthropogenic GHG emissions are the GHG emissions linked to human economic activities, primarily originating from fossil fuel usage and forestry development (Wang et al., 2018). The Ministry of Science, Technology and Innovation reported that anthropogenic GHG emissions are mainly contributed from energy (80%), followed by waste (9%), industrial processes and product use (6%), and agriculture, forestry, and other land use (4%) in 2014 (MESTECC, 2018). To accelerate the effort for climate change mitigation in Malaysia, it is essential to address the anthropogenic GHG emissions from the aforementioned sectors.

The anthropogenic CO_2 emissions resulting from fossil fuel usage and land transformation of different stages in PB1 and LSS systems are tabulated in Table 3. By including the production stage, the CO_2 emissions from the land transformation in both systems do not reduce drastically, contrary to that from fossil fuels usage. The displacement of conventional electricity sources and diesel fuel with product consumption in both systems respectively can offset the fossil fuel consumption for energy and industrial processes (i.e., production stages) significantly by 0.8–15 times. Meanwhile, the CO_2 from land transformation is meagre, around 0.004–0.2 times fossil fuel usage.

The PB1 system generates positive CO_2 emissions (11 g CO_2/MJ PB) compared to LSS1 and LSS2. The milling stage contributes the most significant CO_2 emissions portion (i.e., 70% of the total CO_2 emissions per product in PB1 production stages) from fossil fuel usage and while

Table 3
The anthropogenic CO_2 emissions from PB1, LSS1, and LSS2 systems.

Stages	Fossil fuel emissions	Land transformation emissions
	mg CO_2/MJ energy generated	
PB1		
Agricultural stage (Nursery)	1.05[a]	3.37
Agricultural stage (FFB production)	8,670	2,440
Milling stage	32,300	7.08
Refinery and fractionation stage	1,650	3.73
Transesterification stage	3,260	2.77
Biofuel produced for transportation consumption	−37,100[3]	−266
Net emission of the system[b]	**8,781**	**2,440**
LSS1		
SGS production	2,660	9.29
PV wafer production	604	3.21
PV cell production	1,280	3.84
PV panel production	2,980	14.8
PV panel slanted mounting (BOS)	1,600	6.18
Electrical installation (BOS)	372	91.6
Inverter (BOS)	366	0.738
Electricity generated for consumption	−150,000	−572
Net emission of the system	**−140,138**	**−442**
LSS2		
MGS production	543	1.46
SGS production	3,420	12.2
PV wafer production	−132	0.969
PV cell production	1,180	4.04
PV panel production	2,530	3.63
PV panel slanted mounting (BOS)	1,580	6.13
Electrical installation (BOS)	372	91.6
Inverter (BOS)	366	0.738
Electricity generated for consumption	−150,000	−572
Net emission of the system	**−140,141**	**−451**

[a] The positive value emission signifies the emission released, while the negative value emission represents the emission avoided. Avoided emission is the emission substituted by other RE alternatives emitted initially from conventional fossil fuels (i.e., coals, oil, natural gas).
[b] The net emission of the system is the summation of emission from production stages and product consumption stage.

the FFB production stage is the primary source for CO_2 emissions (i.e., 90% of the total CO_2 emissions per product in PB1 production stages) from land transformation. Meijide et al. (2020) reported that the biodiesel produced from the second rotation cycles palm planting or palm established on degraded land is around 30–50 g CO_2-eq/MJ PB, which is around 3 to 5 times of the obtained results. The result deviation is largely contributed by the higher CO_2 emission from biofuel consumption and land use change.

For LSS1 and LSS2 systems, SGS production and PV production are the main perpetrators of CO_2 emission in fossil fuel usage and land transformation. The CO_2 emissions relief (i.e., −132 mg CO_2/MJ) of PV wafer production in LSS2 contribute a 1.3% reduction via recycling processing chemicals (i.e., silicon carbide and triethylene glycol) and fewer chemicals applications. Interestingly, although LSS2 has better environmental performance, this system's CO_2 emissions SGS production are 1.3 times higher than that of LSS1 due to the accumulation of processing chemicals.

The Malaysian government is ambitious to reduce anthropogenic GHG emissions by 45% based on the benchmark value (i.e., 288,663 Gg CO_2-eq) in 2005 (MGTC, 2017). Considering 9×10^5 t/y of PB production and 875 MW_p, of LSS capacity, the product consumption stage of PB1 and LSS systems can reduce the national GHG emissions by 0.28% and 0.79%, respectively. Aside from that, the stages identified with alarming CO_2 emission rates should be addressed with suitable solutions to further reduce emissions at production stages. The corresponding material recovery processes are retrofitted under simulation at the highly affected environmental hotspots for further analysis, as suggested in Sections 3.5.1–3.5.3.

Considering the lack of concerns on the CO_2 emission from land transformation, carbon storage and sequestration technologies such as soil carbon sequestration (i.e., agricultural waste as bio-fertilizers, diverse replanting) should be integrated with FFB production stage in PB1 (Prapaspongsa et al., 2017) and site installation stage in LSS systems (Groesbeck and Pearce, 2018). Restoration of soil carbon stock through organic fertilizers application and replanting in agricultural sectors can replenish the soil carbon loss during land exploitation (Salleh et al., 2020). Landscape conditions and soil carbon stock can be improved by cultivating more greeneries at the LSS site (Groesbeck and Pearce, 2018). Besides, reducing CO_2 emissions from land transformation can benefit GW, WC, and FRS (Zhu et al., 2010), which is essential to accomplish the key goals of the National REDD + programme initiated by the UN, such as reduced soil organic carbon loss, protection of varying ecosystems and thorough study on land use.

3.5. Scenario analysis of PB1 and LSS systems

The description of each scenario is tabulated in Table 4, while the additional information of the case scenarios is added in Table A.8 in the Supplementary Material. Eight scenarios, of which five alternative scenarios are created among the three baselines scenarios (i.e., PB1, LSS1, and LSS2) are illustrated in Fig. A.3 in the Supplementary Material.

Fig. 5 illustrates the scenario analysis results. The net environmental value (i.e., δE), described in Eq. (2), is represented with a black dot to elucidate each scenario's total net environmental load.

3.5.1. Baseline scenario and alternative scenarios in PB1 system

The baseline scenario (i.e., PB1-CPKOport-NoAD) appears as the worst-case scenario, bearing the most overall environmental burden among the other PB1 scenarios. Under ascending order, the total net environmental loads of PB1 scenarios are as followed: PB1-CPKOport-NoAD, PB1-CPKOport-AD, PB1-CPKOmill-NoAD, PB1-CPKOmill-AD. Approximately 2.31–6.75% of the percentage difference is found in the alternative scenarios with the baseline scenario as control. The integration of the CPKO plant and AD biogas plant is an efficient combined material recovery process in relieving environmental at the milling stage (Loh, 2017) by reducing 2.91–6.75% of human health damage, 3.12–6.03% of ecosystem quality damage, 2.31–4.70% of resource

Table 4
Description of case scenarios in scenario analysis.

Abbreviation of case scenario	CPKO plant at port	CPKO plant at mill	AD biogas plant[a]	Aluminum recycling[b]
PB1-CPKOport-NoAD (Baseline scenario)	√[c]	No[d]	No	N/A[e]
PB1-CPKOmill-NoAD	No	✓	No	N/A
PB1-CPKOport-AD	✓	No	✓	N/A
PB1-CPKOmill-AD	No	✓	✓	N/A
LSS1-NoRec (Baseline scenario)	N/A	N/A	N/A	No
LSS1-Rec	N/A	N/A	N/A	✓
LSS2-NoRec (Baseline scenario)	N/A	N/A	N/A	No
LSS2-Rec	N/A	N/A	N/A	✓

[a] The electricity generated from the AD biogas plant (i.e., POME treatment process) is used to cater for the need of the mill.
[b] The facility recycles 100% of the aluminum waste generated from PV panel production and mounting stages.
[c] "√" refers to including the corresponding stage.
[d] "No" refers to not including the corresponding stage.
[e] "N/A" refers to the corresponding stage not applicable.

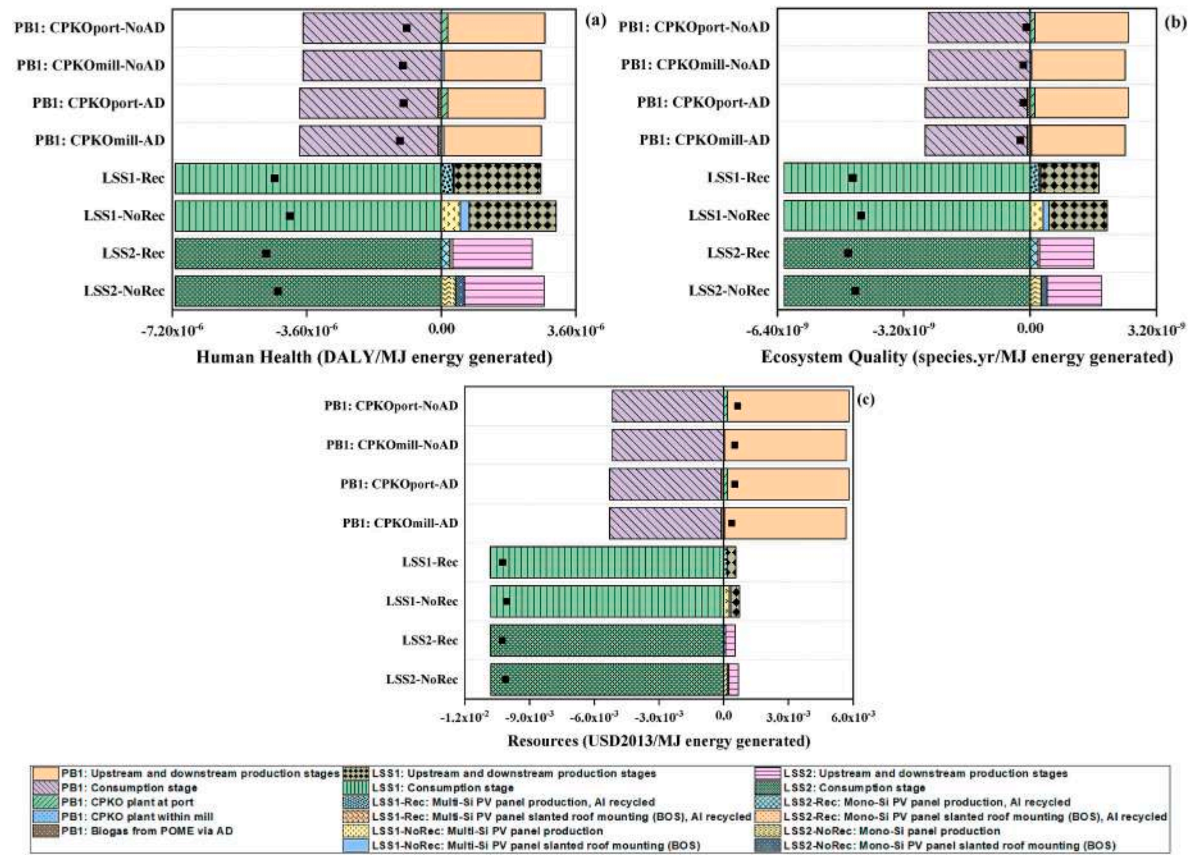

Fig. 5. The scenario analysis of PB1, LSS1, and LSS2 systems based on damage assessment: (a) human health, (b) ecosystem quality, and (c) resources scarcity.

scarcity. Further improvement can be made by fully utilizing the solid palm waste as an energy source at the milling stage, inadvertently minimizing the reliance on fossil fuels in the FFB steam stripping process (Phuang et al., 2021). GW is relieved by 6% upon the installation of material recovery processes.

3.5.2. Baseline scenario and alternative scenarios in LSS systems

LSS1-NoRec and LSS2-NoRec are the baseline scenarios for LSS1 and LSS2, respectively. Similar to the PB system, the baseline scenario is the worst-case scenario as compared to alternative scenarios. Under ascending order, the total net environmental loads of all LSS scenarios are as follows: LSS1-NoRec, LSS2-NoRec, LSS1-Rec, LSS2-Rec. LSS2 outperforms LSS1 by 7–10% across the assessed scenarios regarding human health, ecosystem quality, and resource scarcity. Approximately 10–25% of the percentage difference is found in the alternative scenarios with the baseline scenario as control. Aluminum recycling shows efficacy as a material recovery process to relieve environmental at PV panel production and slanted mounting installation stages (Xu et al., 2018), reduced 11–13% of human health damage, 10–11% of ecosystem quality damage, 22–25% of resource scarcity. The material recovery process reduces the environmental burden under GW by 40%. A high-value recycling approach such as the recovery of rare materials (i.e., silver) and materials with high embedded energy value (i.e., silicon and solar glass) is recommended for greater environmental benefit, especially in resource scarcity (IRENA and IEA-PVPS, 2016).

3.5.3. Comparison between PB1 and LSS systems

A comparison study is made between the best-case scenario and worst-case scenario of the PB1 and LSS systems. In Fig. 5(a) and (b), the best and worst-case scenario of the LSS system outstands that of the PB1 system, seven-to ten-fold from the human health and ecosystem quality perspective. Howbeit, the PB1 system's damage potential to resource scarcity is not entirely offset in both worst and best-case scenarios (i.e., the net environmental value of the case scenario is positive). The environmental relief of the PB1 system is inferior to the LSS system, primarily due to the immense fossil fuel demand at the FFB production and milling stage.

3.6. Policy implications and development

Among the 17 global sustainable development goals (SDG), 7 of the SDGs are strongly related to climate change as quantified using the Nationally Determined Contribution (NDC)-SDG Connections Tool (Janetschek and Iacobuta, 2019), indicating the vast influence of climate change in other global issues like food security, water sanitation, and clean energy transition as elucidated in Fig. 6. As one of the 196 countries that ratified the Paris Agreement to commit for climate change mitigation, Malaysia has shown a massive interest in blending this effort within the nation's energy and economic policymaking, which subsequently pledged to NDC and launched numerous national policies to develop LSS and PB. Based on the calculations in Appendix B, 34 GW_p (39 times of the installed capacity) LSS or 1.01×10^8 t/y (112 times of the existing operating capacity) of PB are required to achieve the 45% national carbon intensity reduction specifically in the energy sector. LSS and PB technologies have great potential in helping the government to deliver commitments towards Renewable Energy Transition Roadmap 2035 and Paris Agreement. Malaysia's Sustainable Energy Development Agency has rolled out various schemes and incentives, including the LSS project, aiming to achieve 1 GW operational by 2020 (Laajimi and Go, 2019). Besides, Malaysia implemented a 10% PB and 90% petrol diesel mandate (B10) for the transport sector in 2019 (Phuang et al., 2021). A total capacity of 875 MW_p LSS and 9×10^5 t/y of PB plants are being operated throughout Malaysia as of 2018, expecting a breakthrough of 1634 MW_p and 1M t/y respectively upon completion (Energy

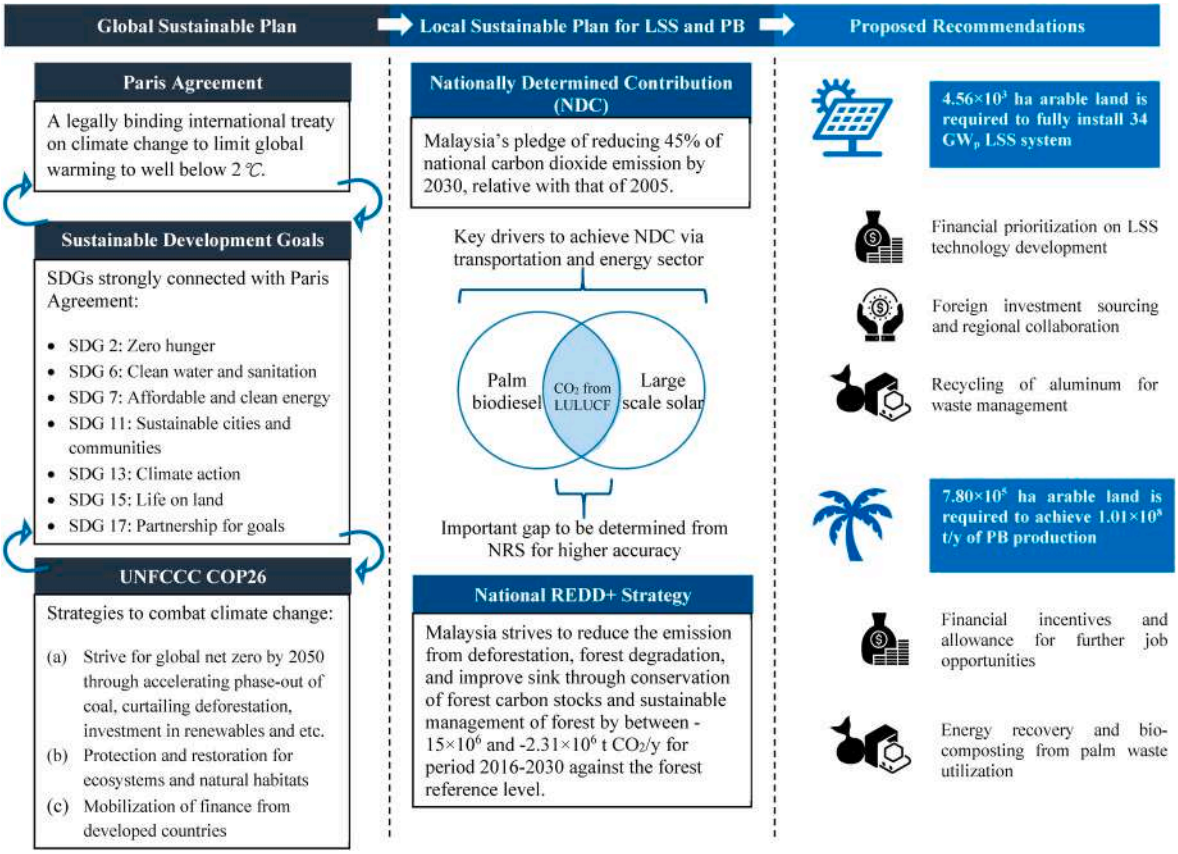

Fig. 6. The energy policy formulation and adaptation related to PB and LSS in Malaysia.

Commission, 2018).

LSS and PB remain the popular RE alternatives to combat climate change and achieve carbon neutrality in Malaysia. Despite the postponement due to the COVID-19 pandemic, the rollout of the B20 diesel mandate (i.e., a mandate to blend 20% PB in petroleum-based diesel) (The Star, 2021a) and LSS bidding (The Star, 2021b) in 2021 are not terminated as the government is planning to venture into the carbon trading market in the upcoming years (Bernama, 2021). The implementation of PB as biofuel and LSS for electricity generation is governed by the RE technologies respective policy framework. Fig. 6 illustrates the relationship between the global, local, and policy suggestions to achieve the 45% carbon reduction target based on the results obtained in the study. Stemming from the nation's pledge towards the global commitment in climate change combat, local policies and action plans to develop LSS and PB covers huge governances ranging from energy transformation, waste recovery, food security, water resources, biological diversity and forestry management.

The disconnection of main policy implementation steps (Chapman et al., 2016) in Malaysia, especially from the policy adaptation and legitimization step onwards, has exacerbated the sustainability and practicability of the national energy policy framework. Mohd Chachuli et al. (2021) applied data envelopment analysis to investigate the effectiveness of the RE policies transition in Malaysia. Due to the economic status of Malaysia as a developing country and the lack of economic models related to climate change (Rao and Mustapa, 2021), the adaptation and legitimization of RE policies are restricted by financial and technological barriers, which have always been the prior problem of renewables development in Malaysia. To effectively implement the B20 mandate and LSS according to Malaysia's current RE development circumstance, the financial allocation on LSS in terms of technology development, operation, and research should be prioritized in relevant energy policy framework compared to PB based on the study result. Nevertheless, the development of PB should not be neglected because of the high national palm waste generation of 5.2 × 10^7 t/y in 2017 (Hamzah et al., 2019) and the capability to account for 13% of GHG emissions reduction achievement in 2014 (MESTECC, 2018) via palm waste utilization.

For LSS, the allocation capacity of green technology incentives for LSS tender bidding, installation subsidies, Feed-in Tariff, and Net Energy Metering should be increased to reduce the levelized cost of electricity. A financial roadmap throughout the life cycle of LSS projects should be detailed in the energy policies (Sala et al., 2016), especially for the implementation of Renewable Energy Policy and Action Plan to enhance the confidence of financial investors and consumers towards LSS projects. For example, the integration of life cycle thinking (i.e., environmental impact assessment, economy and social life cycle assessment) with policy framework planning and implementation is being developed in the policy development of the EU commissions for problem anticipation and evaluation. The waste management (i.e., recycling of aluminum components) of LSS should be planned and subsidized to prevent mass disposal problems due to the sudden accumulation of PV waste in the future (Faircloth et al., 2019). The recycling of aluminum is proven to be significant in overcoming the environmental impacts of tailing from LSS systems, as captioned in Section 3.5.2, which can be potentially implemented via Act 672 JPSPN (Solid Waste and Public Cleansing Management Act, 2007). Foreign investment sourcing and regional collaboration are other potential options to expand the financial capacity for renewables development, as demonstrated via the recent MYR 4.25 × 10^{10} worth of investment from Risen Energy Co Ltd to Malaysia's PV manufacturing industry (Tan, 2021). Due to increasing demand, the recent price increment of PV modules worldwide shows that financial aid is vital to ensure stable LSS development (Azhar, 2021).

Green technology incentives such as Pioneer Status tax exemption and Investment Tax Allowance are vital for PB production in the implementation of Roundtable on Sustainable Palm Oil and Malaysian Sustainable Palm Oil, which catalyzes the circular economy realization of the palm oil industry. Lucrative allowance on technical support to integrate renewables in PB production should be awarded to increase job opportunities and increase the confidence of stakeholders (Chin et al., 2014). Control on the palm oil price fluctuation can effectively increase PB production, as government subsidization is not sustainable. Similarly, the waste management of the milling and FFB production stages in the PB system, such as the energy recovery and bio-composting from palm waste utilization, should be implemented meticulously to avoid reliance on landfills and relieve the environmental burden, as demonstrated in Section 3.5.1. The palm waste recovery plan should be coupled with agricultural waste management policies that are currently deficient in Malaysia. Green Technology Financing Scheme is another financial alternative to develop palm waste recovery which aims to provide funds to the eligible green businesses (GTFS, 2016). A study conducted by Hannan et al. (2018) revealed that the stakeholders are more willingly to switch to biomass-generated electricity (i.e., more than 50% from palm waste) under the SREP project, in which the generation up to 10 MW can be sold to TNB with a 21-year license agreement. The preference over biomass energy reflects that biomass co-firing is critical in developing energy decarbonization and greater bioenergy investments are required, as supported by the study of Mohd Idris et al. (2021).

According to the calculations in Appendix B with LCA results, 7.8×10^5 ha of plantation land is presumably required for 1.01×10^8 t/y PB while 4.56×10^3 ha of arable land for 34 GW_p LSS setup (i.e., totaling up to 2.38% of Malaysia's land area). Malaysia is committed to maintaining at least 50% of the country's land area with forest and tree cover, which is around 1.83×10^7 ha (MSTI, 2019). It is essential to enhance the technical improvement and financial allocation to investigate GHG emissions from land transformation under the National REDD + Strategy implementation. Improvised methodology, in-depth site investigation, and continuous monitoring of land transformation for anthropogenic economic activities and forestry management are essential to complement Malaysia's overall GHG emissions data gap. The CO_2 emission from various bio-systems is still vague (MESTECC, 2018). Therefore, it is crucial to determine the priority and the diversity of RE development based on its forestry land condition through policymaking. With the nation's determination to achieve carbon neutrality by 2050 as announced under 12th Malaysia Plan, the control of land use emission is another crucial area to be scrutinized.

4. Conclusions

This comparative study serves as a guide to national RE policymakers and relevant stakeholders to exhibit the RE transition landscape of the nation. The results reflect that LSS systems perform 77% better than the PB1 system, however, LSS2 performs better than LSS1 from the environmental perspective. FFB production stage and milling stage emerge as the severe environmental hotspots in PB1 due to chemical fertilizers application, transportation usage, and fossil fuels consumption, adding up to 81–88% of the total environmental impact of the PB production stages. For LSS systems, the mineral resource scarcity of production stages is four times the electrical installation stages in BOS. The electrical installation stages harbor the heaviest environmental impact for human health and ecosystem quality with the metal's application for installation (35–37%). The inclusion of product consumption stage in both LSS and PB systems has shown significant environmental impact offset with negative offset results in human health and ecosystem quality. Resource scarcity for PB system remains positive after the offset. The environmental hotspots in LSS and PB systems (i.e., FFB production stage, milling stage, and electrical installation stage) exhibited environmental impact up to 15–51% based on the significant impact categories selected for further investigation.

The CO_2 emissions from the land transformation of both systems are roughly 0.004–0.2 times that of fossil fuels usage. The main contributors of CO_2 emissions in LSS are SGS production and PV panel production. In contrast, the FFB production and milling stage contribute the most CO_2 in the PB system, totaling 41 g CO_2/MJ PB. LSS systems can reduce 40% of GW with aluminum waste recycling, while the PB system gains 6% of GW relief from installing the CPKO plant and AD biogas plant at the milling stage.

The overall study results link the concerns on the development allocation of LSS and PB to achieve the national carbon emission reduction RE targets. Although the LSS systems emerge as the more attractive option than the PB system from an environmental perspective, it should be emphasized that this study only focuses on evaluating the environmental impacts of both PB and LSS systems. Therefore, a more comprehensive study on life cycle costing for economic assessment and social aspect consideration can be included to increase the feasibility of this study and ensure a multidimensional comparison between two technologies. Since the primary energy source of both systems is solar energy, the concept of combining exergy analysis with LCA has the potential to enhance environmental sustainability from the aspect of exergoenvironmental analysis. Uncertainty and parametric sensitivity analyses for the culprits in environmental hotspots (i.e., fossil fuel usage and land use change factors) shall be considered to enhance the accuracy and reliability of the study outcomes.

CRediT authorship contribution statement

Zhen Xin Phuang: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Zuchao Lin:** Visualization, Formal analysis, Writing – original draft. **Peng Yen Liew:** Validation, Writing – review & editing. **Marlia Mohd Hanafiah:** Validation, Writing – review & editing. **Kok Sin Woon:** Supervision, Conceptualization, Validation, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131475.

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