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Environmental impact assessment of solar panel production and recycling in Southeast Asia

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ABSTRACT

Southeast Asia is world's second largest solar photovoltaic (PV) panel manufacturing region after China. The increases in panel production, domestic installation and end-of-life disposal are resulting in environmental impacts across the region. In particular, appropriate waste disposal methods within Southeast Asia, coupled with assessments of their environmental impacts are ever more critical. While many studies have assessed the environmental impacts of production and waste recovery, those for panels produced in Southeast Asia have received limited attention. This paper aims to assess the environmental impacts of the production and waste recovery of PV produced in Malaysia, Singapore, Thailand and Vietnam, through a cradle-to-grave life cycle assessment (LCA) with intermediate materials produced in China, and two waste recovery methods: laminated glass recycling facility (LGRF) and full recovery end-of-life photovoltaic (FRELP). The results show that the climate change potential of solar panels produced in Southeast Asia range from 10,442 to 10,976 kgCO_2-eq per tonne of modules, compared to 11,052 kgCO_2-eq in China. Waste recovery methods can lower the environmental impacts of solar panels across all impact categories when considering the avoided impacts from the recovery of materials. The reductions were most pronounced for climate change and metal depletion potential. Higher recovery yields would also result in reduced environmental impacts. In conclusion, this paper indicates that a supply chain that includes Southeast Asian PV assembly is a lower carbon option to the prevailing supply chain, especially when enhanced with effective waste recovery policies.

1. Introduction

The demand for solar photovoltaics (PV) has increased significantly over the past decade to meet global decarbonisation efforts. Demand is expected to continue growing, particularly with a recent international commitment to triple the global installed capacity of renewables to at least 11,000 GW by 2030 (COP28, 2023). Under the 'global net zero by 2050' roadmap, more than 600 GW of PV is to be installed annually (IEA, 2021b).

The annual manufacturing capacity addition for PV was 639 GW in 2022, with 1262 GW of announced additional capacity (IEA, 2021b). After China, Southeast Asia has become the world's second largest producing region for solar cells and modules. Together, Malaysia, Singapore, Thailand and Vietnam account for 11.6 % and 12.2 % of the global PV manufacturing capacity of cells and modules respectively (IEA-PVPS, 2022a).

At the same time, the uptake of solar power in Southeast Asia has also increased in the last decade - from 0.03 MW in 2006 to 24.11 MW in 2021 (EMBER, 2023). However, the total share of solar PV in the electricity generation in the region is still low, at only an average of 2.1 % (EMBER, 2023). ASEAN has also announced an ambition of ensuring that at least 23 % of the total energy mix in the region will be supplied from renewable energy by 2025 (ACE, 2022). Given the relatively slow adoption rate of solar PV in the Southeast Asia region and the region-wide ambition to increase the installation capacity, the production and deployment of solar modules in the region is likely to increase greatly within the next decade.

This growth in PV production and adoption is likely to have

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considerable impacts throughout its lifecycle. First, on the production side, concerns about ensuring cleaner product supply chains is becoming more prevalent. Given that each country uses different energy sources to generate electricity, which drives the PV production process, the environmental impact of PV production also differs across countries. Hence, assessing and comparing these impacts is crucial. Second, the global generation of PV waste is estimated to rise dramatically – to 1.7 million tonnes in 2030, rising to 60 million tonnes by 2050 (IRENA, 2016). In several countries, regulations and policies are currently in place or being developed to manage the flow of waste panels. However, landfilling and incineration remain the main options for PV waste treatment, unless recycling is mandated through policies for the end-of-life treatment of panels (IEA-PVPS, 2022). Thus, end-of-life PV treatment and its environmental impacts need to be assessed, highlighting the urgent need to recover critical minerals in panels, such as copper, aluminium and silver. Assessments for Southeast Asia are particularly crucial because of the high volume of module production, projected uptake of solar power, and potentially large stream of PV waste.

Numerous studies have assessed the environmental impact of the PV life cycle using the LCA's cradle-to-grave approach; however, studies on the link between PV production and recycling, particularly types of end-of-life treatment, are limited. Studies on the environmental impact of PV production have focused on China (Chen et al., 2016; Yang et al., 2015) but have not explored the types of disposal treatment. Southeast Asia's PV manufacturing has been explored; however, recycling treatment has not been elaborated upon (Yuan et al., 2024). Meanwhile, literature on the environmental impacts of recycling commonly focusses on this issue exclusively, without discussing the production phase. LCA end-of-life PV assessment have been extensively employed to investigate the environmental impacts of various end-of-life treatments in different geographical contexts, such as Europe (Latunussa et al., 2016), Australia (Singh et al., 2021) and India (Sharma et al., 2023). However, to the best of our knowledge, research linking the environmental impact of PV production with recycling treatment in Southeast Asia remain understudied.

The paper aims to estimate the environmental impacts of the production and end-of-life treatment methods of monocrystalline silicon PV within Southeast Asia through a cradle-to-grave life cycle assessment. The analysis consists of three steps. First, the environmental impacts from the production of PV in China with downstream processes taking place in Malaysia, Singapore, Thailand and Vietnam are estimated. The five countries are assessed because they have a significant share of PV manufacturing capacity. Monocrystalline silicon PV is selected because it currently has the highest market share in the PV market (IEA, 2022). Second, two end-of-life pathways for waste panels in Southeast Asia are analysed: waste recovery with a laminated glass recycling facility (LGRF) and a full recovery end-of-life photovoltaic (FRELP). Finally, the avoided environmental impacts from recovering and recycling the waste fractions are quantified. The novelty of this work is that it presents an impact assessment of the PV production link with different recycling treatments, with a comparative analysis in China and multiple countries in Southeast Asia. Moreover, both China and Southeast Asia have set goals for carbon neutrality by certain years, making it crucial to include scenario analyses that consider changes in grid emission factors (i.e., the amount of carbon emissions per unit of electricity generated).

This study contributes to research on the environmental impacts of circular solar PV policies in Southeast Asia. The results from this paper offer evidence on the environmental impacts of developing new global supply chains for PV panels. In particular, with mounting concerns about PV supply chain concentration, there is likely to be a demand to expand Southeast Asian PV supply chains. This expansion is likely to shine a spotlight on the environmental impacts of these alternative supply chains. This paper indicates that these alternative supply chains offer lower carbon pathways for PV assembly. It also confirms the view that the emissions associated with these supply chains can be reduced through end-of-life policies that minimise the need for new resources.

The rest of this paper is organised as follows. Section 2 consists of a literature review, including the PV lifecycle, environmental impacts, and end-of-life PV recycling policies. Section 3 elaborates on the methodology which consists of the goal and scope, life-cycle inventory, and life-cycle impact assessment. Section 4 presents the results and scenarios, followed by a discussion in Section 5. Finally, Section 6 concludes the study.

2. Literature review

2.1. PV life cycle

2.1.1. Production

Different technologies for PV are currently adopted globally. Crystalline silicon (c-Si) panels have the largest market share, accounting for 95 % of global PV production in 2022 (Philipps, 2023). Global c-Si module production in 2021 was also mostly comprised of monocrystalline silicon panels at more than 90 %, whereas multicrystalline silicon panels only made up around 5 % (IEA, 2022).

The whole life cycle of a monocrystalline silicon PV begins with the refining of crystalline c-Si. The silicon is obtained from silica quartz, which is refined into metallurgical grade silicon (MG-Si). MG-Si is then refined into solar-grade silicon through the Siemens process. The polysilicon is then placed in a crucible and crystallised onto a seed crystal through the Czochralski process. The resulting monocrystalline silicon ingot is then sliced into wafers, which undergo a polishing, doping, and coating process. This process produces solar cells, which can be joined in 60 or 72-cell configurations to form one panel. The cells are layered with a back sheet made from ethylene vinyl acetate and tempered glass. A frame, which is typically made of aluminium, is then placed around the panel. The production processes can be seen in Fig. 1.

The global supply chain of PV production shows that at least 70 % of the production of c-Si panels takes place in China across all parts of the production process (IEA-PVPS, 2022a; US Department of Energy, 2022).

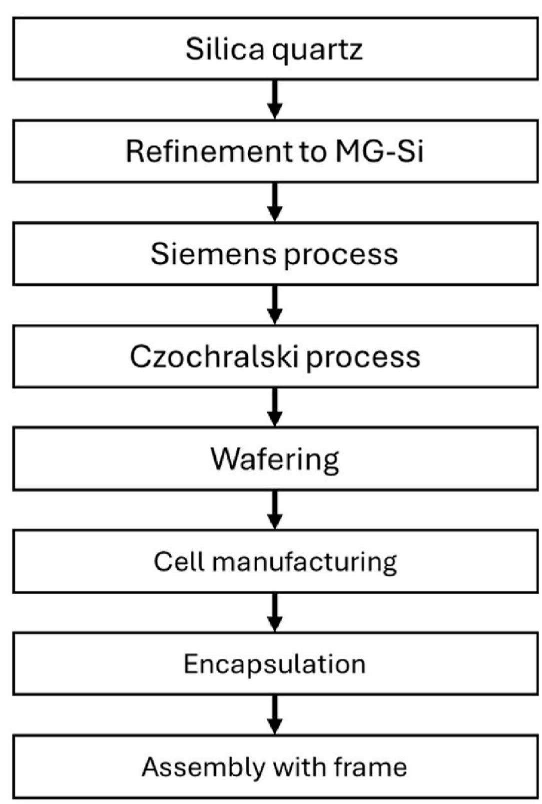

Fig. 1. The module production process for c-Si PV.

The production of polysilicon is concentrated in Xinjiang, China, while downstream processes mostly take place in Jiangsu, China, with the province taking up 33 % and 41 % of global and China's cell manufacturing capacity respectively. In module assembly, Jiangsu and Zhejiang make up 68 % of China's and 52 % of the global manufacturing capacity.

Outside of China, Vietnam and Malaysia are also significant producers of solar cells and modules for downstream processes such as cell production and module assembly. Singapore and Thailand also have major manufacturing capabilities for both processes and have significant global shares in the production of cells and modules, as seen in Table 1. Studies on the environmental impact of PV production have focused on China (Chen et al., 2016; Yang et al., 2015), and a comparative assessment of multiple Southeast Asian studies is lacking. Furthermore, previous studies have explored Malaysia, Thailand, and Vietnam (Yuan et al., 2024) but have not included Singapore, which has a share of manufacturing capacity of PV cell and module in Southeast Asia.

2.1.2. Operation and maintenance

The operations and maintenance phase is the longest phase in the PV life cycle (Mgonja and Saidi, 2017). The maintenance procedure of a PV system is the set of activities undertaken to preserve the operating conditions of a solar system by reducing its power degradation over its lifetime and effective maintenance practices ensure the system performs optimally. Three maintenance categories are explained according to Talayero et al. (2018): corrective maintenance, preventive maintenance and predictive maintenance.

Corrective maintenance refers to activities performed by trained technical teams to attend when the PV system undergoes a system failure, compromising system performance and downtime (Andrews et al., 2019). Preventive maintenance is considered one of the most crucial maintenance procedures where routine physical and visual inspections are carried out in order to identify faults that cause system failures (Andrews et al., 2019). Meanwhile, in predictive maintenance, instantaneous data and information are analysed comprehensively to verify the system performance and conduct anticipatory maintenance procedures to identify faults and eventually apply them accordingly (Abubakar et al., 2021). The expected lifetime of a solar system can perform at optimal levels for 25 years and beyond with effective maintenance procedures (Thangaraj and Velury, 2016).

2.1.3. End-of-life

While landfilling is a current end-of-life pathway for PV waste, the increase in material demand for future installations of PV makes landfilling an unsustainable option. Efforts have been made to recover materials from waste panels to ensure circularity during the life cycle of solar panels.

The laminated glass recycling facility (LGRF) and the full recovery end-of-life photovoltaic (FRELP) are two waste recovery methods explored in this study. These methods recover materials from waste panels for use in secondary refining and other applications. Aluminium and copper can be recovered and reused for PV applications without further refining. However, other recovered materials such as MG-Si and glass have lower purities than those required for PV and require further refining steps before they may be reused in PV. Faircloth et al. (2019) calculated the recovery yield of the LGRF process to be 77.8 %, whereas the FRELP process has a yield of 91 %.

Table 1
China and Southeast Asia's share of PV cell and module production in 2021.

Global PV cell manufacturing capacity		Global PV module manufacturing capacity	
Country	Global percentage share	Country	Global percentage share
China	81.2 %	China	75 %
Malaysia	5.4 %	Malaysia	3.7 %
Vietnam	3.6 %	Vietnam	6.8 %
Thailand	2.1 %	Thailand	1.2 %
Singapore	0.5 %	Singapore	0.5 %

Source: (IEA-PVPS, 2022a)

2.1.3.1. Laminated glass recycling facility (LGRF).

Recycling of crystalline silicon (c-Si) panels is largely done by glass recycling companies (IEA-PVPS, 2018), which is easier to carry out as waste modules can be recycled as a separate, smaller batch that suits its low waste flow.

The aluminium frame and junction box of the solar module are first detached manually, followed by shredding of the bare laminates. The impurities are then manually pre-sorted before the shredded PV is crushed more finely to facilitate the sorting of the waste fractions. The ferrous components of the PV module are then sorted from the non-ferrous metals such as copper and aluminium through eddy-current separators. Other nonmetal fractions such as glass, porcelain and ceramics are then separated from the waste module. The remaining waste modules undergo sieving to separate glass and polymer. The resulting outputs of the LGRF process that undergo a secondary refinement for other applications are glass cullet, copper and aluminium. The other waste fractions are either landfilled or incinerated. Fig. 2 shows the process flows for the LGRF method.

2.1.3.2. Full recovery end-of-life photovoltaic (FRELP) process.

The FRELP process was a pilot-scale recycling facility run by the Italian company Sasil S.p.A. that was dedicated to optimising the recovery and quality of materials from c-Si PV. The company acts as a raw material supplier for glass production and participates in initiatives for the recovery and treatment of glass from industrial waste. The FRELP process was developed with PV CYCLE as a pilot study to optimise the recovery of waste fractions from PV panels.

The collected PV are unloaded and moved to the dismantling process by a conveyor belt. The edges of the aluminium frame are cut, followed by the removal of the frame. Cables are also detached from the module by a mechanical arm. Any plastic cabling material that is removed with the cables is incinerated later on. The remaining PV sandwich undergoes a separation process, where the glass layer is detached from the sandwich. This results in pieces of PV glass and the remaining sandwich.

The foil components and PV cells are then cut more finely and brought to an incineration site. The bottom ash from this incineration process, which makes up 40 % of the input mass, is then sent back to the recycling facility. The remaining aluminium connector residues are then collected from the ash through a sieving process. Following this, the ash undergoes an acid-leaching step with water and nitric acid. The acid leaching dissolves the metals while leaving the silicon from the PV cells in the residue. A vacuum filtration process then recovers the silicon fraction, whereas the filtrate is treated with electrolysis to recover the silver and copper, which also releases NOx gases amounting to around 2 kg per tonne of PV waste.

Calcium hydroxide is added to the remaining acid to neutralise the mixture. The mixture is then filtered to separate the liquid waste from the residue, which is classified as hazardous waste. The wastes are then landfilled in their respective landfills. The steps are summarised in Fig. 3.

2.2. End-of-life PV recycling policies

Policies are a key driving force in the implementation of waste recovery and treatment methods for PV waste. A combination of regulations and waste classification have been adopted globally to enforce appropriate waste treatment methods. In the EU, the Waste Electrical and Electronic Equipment Directive 2012/19/EU was amended to include solar panels in the list - mandating that all panel manufacturers and distributors to assume responsibility for the take-back and recycling of waste panels or to participate in a producer compliance scheme (IEA-PVPS, 2017b; IRENA, 2016; Jain et al., 2022). South Korea also

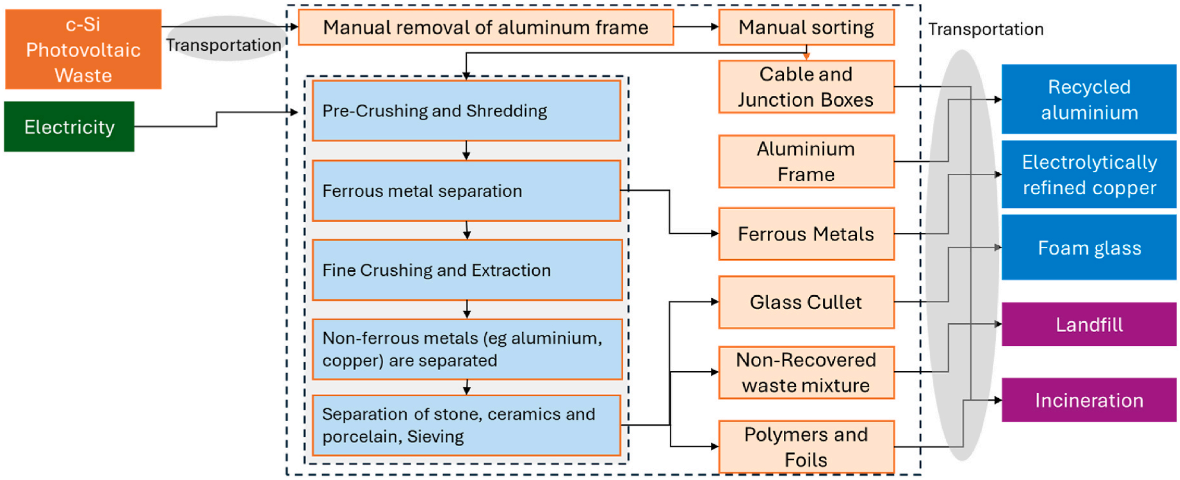

Fig. 2. The process flow for the LGRF process, based on IEA-PVPS (2017a).

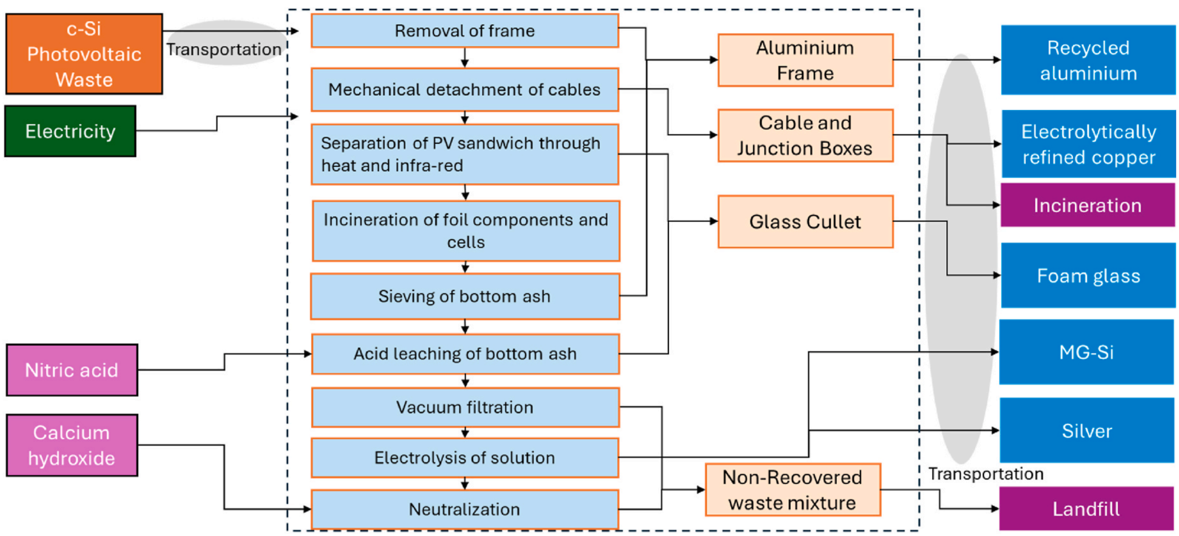

Fig. 3. The process flow for the FRELP waste recovery method, based on IEA-PVPS (2017a); Latunussa et al. (2016).

implemented mandatory recycling of PV in 2023 under the Eco-Assurance System to reduce the environmental loads of PV waste. The amount of mandatory recycling is annually calculated based on panel sales from the previous year. In Japan, a roadmap for waste management for panels was developed in 2016 and plans to promote them were announced in 2023 (Munosuke, 2022). In Washington State, United States, guidelines for end-of-life PV in which manufacturers, importers, and retailers must finance the takeback and recycling of PV at no cost to owners have also been implemented (Quinn, 2022; State of Washington Department of Ecology, n.d.). These policies have been implemented in different countries quite recently; therefore, data on the few existing PV recycling facilities are still limited. As advancements in panel recycling continue, more updated data is anticipated in the future (Singh et al., 2021; Halog and Mcgavin, 2024).

Progress in the implementation of recycling policies varies across Southeast Asian countries. The Singapore government introduced the Resource Sustainability Act in 2020, which states free take-back services must be carried out by all producers of PV, followed by disposal or recycling with licensed waste collectors or recyclers (Ministry of Sustainability and Environment, 2020). In Vietnam, the Law on Environmental Protection took effect from 1 January 2022 onwards, necessitating businesses to conduct their own recycling processes for products with “recyclable value” or opt to pay a premium to the government-managed fund, which will conduct its own recycling programme (Burke et al., 2021). Malaysia is yet to classify end-of-life PV as electronic waste, which has three broad categories and prohibits landfilling (Department of Environment Malaysia, 2010). In addition, Malaysia faces complex challenges in adapting current waste recovery and treatment methods for PV (Yu et al., 2023). Similarly, there are no regulations on end-of-life PV in Thailand (Limmanee et al., 2023). End-of-life treatment methods for grid-scale floating solar projects for the country are currently limited to landfilling or incineration (Meas, 2021).

The literature review indicates that an increase in uptake of solar for decarbonisation efforts and the resulting projected waste PV volumes has implications on the environment, particularly considering the resource demand and lack of circularity of panels. Such environmental impacts from the production of panels will affect Southeast Asia as production volumes increase. Indeed, Southeast Asian waste recovery methods and policies for PV panels are limited and studies that assess the environmental impacts of waste treatment in the region have yet to account for the impacts that arise from production. This paper bridges this gap through a life cycle assessment of the production and end-of-life methods in Southeast Asia.

2.3. Environmental impacts

Solar power generation is steadily increasing, and there is growing interest in the environmental impacts occurring throughout the whole life cycle of Solar PV. The life cycle can be broadly divided into the stages of solar module production, operation, and end-of-life.

Firstly, even with relatively clean energy used, the impacts arising from the production of the panels are not negligible. Ito et al. (2016) indicated that, across all PV technology types, the largest contributor to greenhouse gas (GHG) emissions was the production of the PV modules. Within the panel production phase, the purification of MG-Si to solar grade silicon contributed the most to the cumulative energy demand, particularly due to the high amount of electricity required (Fukurozaki et al., 2012; Hou et al., 2016). Similarly, Abuzaid and Samara (2022) conducted an environmental impact assessment by installing PV produced in Jordan throughout the entire lifecycle of the system on a rooftop solar system in the UAE. Their findings showed that the production of polysilicon had the highest contribution to the environmental impacts across all impact assessment factors. This was attributed to the high demand for fossil-fuel intensive electricity from the Jordanian grid. Bondoc (2023) also ascertains that fossil-fuel based electricity and metal production lead to the high human carcinogenic toxicity, freshwater toxicity and marine ecotoxicity associated with panel production since the main components of solar modules include metals such as glass, aluminium, and copper.

Second, GHG emissions during the operation of PV solar power plants are significantly lower compared to traditional fossil fuel power plants. It was observed by Fthenakis and Kim (2010) that little attention has been shown for the emissions associated with the operations phase of PV systems, as quantifiable information is minimal. However, Fukurozaki et al. (2013) concluded that the use phase of the PV is almost negligible.

Lastly, regarding the end-of-life treatment of PV, Oteng et al. (2023) concluded that landfilling has the highest environmental burdens, and the burdens are alleviated with increasing recycling obligations – as did Fthenakis (2000) and Corcelli et al. (2018). Sharma et al. (2023) found that recycling the recovered materials can result in an impact reduction of up to 70 % in the forthcoming production phase. An experimental recycling method also concluded that the net environmental impacts are already beneficial when only the aluminium frame and junction box are recycled, and the benefits increase when the recovery yield rises (Dias et al., 2022). These environmental benefits are further amplified when the recovery yield of the recycling processes increases, and when other valuable fractions such as MG-Si and silver are included (Faircloth et al., 2019). The recovery of silver, aluminium and silicon were also crucial in influencing the environmental benefits of recycling waste panels (Maani et al., 2020).

Based on previous studies and local cases, we highlight the need for new research. First, it is necessary to estimate the environmental impact of the power demand resulting from solar module production. China dominates solar module production. However, recently, some stages of PV module production have been shifting to Southeast Asia. Estimating the environmental impact of this shift is crucial, as previous studies have emphasised the significant power demand in solar module production. Both China and Southeast Asia aim for carbon neutrality within the next few decades, and it is essential to incorporate scenario analyses reflecting changes in grid emission factors. Second, it is necessary to estimate the environmental impact reductions achievable by recovering valuable materials from waste panels. While many countries with increased solar power generation have established policies and regulations for solar waste management and are preparing for waste processing, Southeast Asia still has limited policies on solar waste management. Thus, research is needed to estimate how much environmental burden can be reduced by recovering materials from waste solar panels.

3. Methodology

Life cycle assessment (LCA) is a tool to analyse the environmental impacts of a product or service across its life cycle, including production, consumption and end of life. The LCA for the PV module is conducted in accordance with the relevant ISO14040 and ISO14044 standards, which provide guidelines and structure to how the LCA study is conducted. There are four steps - defining the goal and scope, inventory analysis, impact assessments and interpretation. The first three steps are presented sequentially in Section 3.1 to 3.3. The interpretation step has been carried out throughout the course of the study by ensuring the reliability of the inventory and the robustness of the findings in relation to other existing literature.

3.1. Goal and scope

The goal of this study was to determine the environmental impacts of solar PV throughout its entire life cycle in four selected Southeast Asian countries. The scope focuses on the manufacturing and end-of-life phases of the PV module, with the system boundary shown in Fig. 4. The expansion of the system to include the environmental benefits from avoiding the primary production of recovered materials is also conducted to further evaluate the impacts of PV outside of its life cycle. The impacts have not been aggregated in relation to the electricity generated from the panels to focus on the impacts from the production of the panels and potential reduction from waste recovery methods, where the majority of the impacts arise.

This study analysed two end-of-life treatment methods, LGRF and FRELP which occur in Malaysia, Singapore, Thailand and Vietnam. This includes waste recovery from the treatment methods and post-recovery refinement of recovered materials. The functional unit for this study was determined to be one tonne of PV panel, which has also been adopted in similar studies by Faircloth et al. (2019), IEA-PVPS (2017a) and Latunussa et al. (2016).

3.2. Life cycle inventory

The inventory data consists of two parts: the manufacturing process and end-of-life phase. The first part is an inventory of the manufacturing process of monocrystalline silicon panel. The data is obtained from IEA's PVPS Task 12, which provides an inventory of c-Si manufacturing processes from PV LCA experts in Asia (Frischknecht et al., 2020). Frischknecht et al. (2020) assumes 11 kg of material per m^2 of solar panel. This paper assumes the production of a monocrystalline PV, with polysilicon and wafer production occurring in Xinjiang, China. Within polysilicon production, the Siemens method is used in the refining of polysilicon.

Further downstream processes such as cell manufacturing and module assembly take place in Malaysia, Singapore, Thailand, and Vietnam. A model for the production of panels, with all processes taking place solely in China is also created as a baseline. Transportation is not included within the system boundary for assessment as results from earlier studies indicate that the environmental impacts from transportation are negligible (less than 3 %) compared to the production of the panels (Faircloth et al., 2019; Fukurozaki et al., 2012; Singh et al., 2021).

The second part of life cycle inventory is related to the end-of-life phase. The end-of-life waste treatment methods are categorised into two different recovery methods: waste recovery through the LGRF method, followed by treatment of recovered waste fractions, and waste recovery through the FRELP method followed by treatment of recovered waste fractions.

The inventory and waste flows for the LGRF process were obtained from empirical surveys conducted by IEA-PVPS (2017a). Information from Maltha BE, a Belgian laminated glass recycling plant that conducts

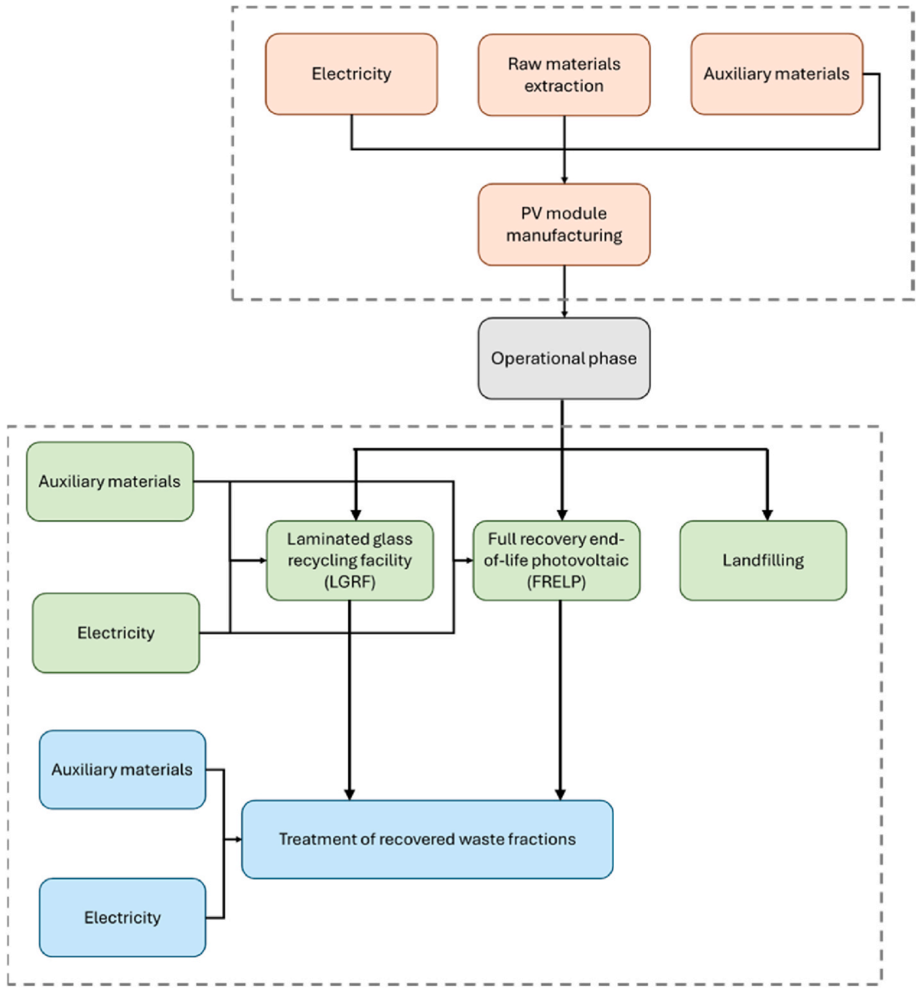

Fig. 4. The system boundary used in the LCA study.

recycling in discrete batches, was used in the analysis. The electricity consumption in the survey ranged from 46 to 84 kWh per tonne of PV waste, where 46 kWh/tonne was assumed to be the consumption at an optimal level. This analysis used the median within this range, which is calculated to be 65 kWh per tonne. While Maltha's recycling process conducts the frame and junction box removal in a separate location from the downstream processes, this assumes that the entire LGRF process is carried out solely in one facility.

The inventory and waste flows for the FRELP method were provided by Latunussa et al. (2016) under a collaborative study with PV Cycle, the developer of the FRELP method. Supplemental information from the IEA PVPS Task Force 12 for the FRELP waste recovery method developed by Sasil S.p.A (IEA-PVPS, 2017a) was also used.

The inputs and outputs from the LGRF and FRELP process are summarised in Tables 2 and 3.

Table 2
The inputs and outputs from the LGRF waste recovery method.

Input	Quantity	Unit	Output	Quantity	Unit
Solar waste	1000	kg	Glass cullet	640	kg
Electricity	234	MJ	Aluminium	135	kg
Diesel	92.25	MJ	Copper	2.60	kg
			Landfilled materials	72.40	kg
			Materials for incineration	150	kg

Sources: (Faircloth et al., 2019; IEA-PVPS, 2017a)

Table 3
The inputs and outputs from the FRELP waste recovery method.

Input	Quantity	Unit	Output	Quantity	Unit
Solar PV waste	1000	kg	Glass cullet	686	kg
Electricity	408.78	MJ	Aluminium	182.64	kg
Diesel	42.07	MJ	Copper	4.38	kg
Calcium hydroxide	36.50	kg	MG-Si	34.68	kg
Nitric acid	7.08	kg	Silver	0.50	kg
Water	309.71	kg	Hazardous sludge (for landfill)	50.25	kg
			NOx	2	kg
			Wastewater treatment	306.13	kg
			Materials for landfill	16	kg

Sources: (IEA-PVPS, 2017a; Latunussa et al., 2016)

3.3. Life cycle impact assessment (LCIA)

This study considers nine impact categories in the LCIA of the environmental impact of PV manufacturing and end-of-life treatment of waste panels. Midpoint impacts from ReCiPe are used to characterise the impact categories. Engagement with stakeholders within the renewable energy industry outlined impact categories of interest, which narrowed down the eighteen ReCiPe midpoint categories to eight: climate change potential, fine particulate matter formation potential, fossil depletion potential, freshwater eutrophication potential, human toxicity (cancer) potential, human toxicity (non-cancer) potential, metal depletion potential, terrestrial ecotoxicity potential. Cumulative energy demand

(CED) was also separately included in the categories assessed. The justifications for the usage of the nine categories are summarised in the Appendix. The assessment of manufacturing processes is modelled in GaBi, using the Ecoinvent 3.9 database, using electricity mixes for Malaysia, Singapore, Thailand, Vietnam, and China. End-of-life waste recovery methods are also modelled in GaBi using electricity mixes from Malaysia, Singapore, Thailand and Vietnam.

4. Results and scenarios

4.1. Results

The environmental impacts of producing one tonne of solar panels are presented in Table 4. For ease of reference, the countries have been abbreviated as such: China (CN), Malaysia (MY), Singapore (SG), Thailand (TH) and Vietnam (VN). Focussing on the production of the PV panel, panels with downstream processes in Southeast Asia are lower in climate change potential and terrestrial ecotoxicity potential than China. However, Malaysia and Vietnam, which hold the highest shares of production in the region, produce panels with higher fine particulate matter formation potential, freshwater eutrophication potential and human toxicity potential (cancer and non-cancer) than China. Panels with downstream processes in Thailand are higher than those fully produced in China in fine particulate matter formation, freshwater eutrophication potential, human toxicity potential (cancer and non-cancer) and metal depletion potential. Those with downstream processes in Singapore are lower across all impact categories compared to China, except for metal depletion potential. As a reminder from Table 1, Malaysia and Vietnam are responsible for 3.6 %–6.8 % of global cell and module manufacturing capacity, while Thailand is closer to 2 % and Singapore is around 0.5 %. Based on Figs. 5 and 6, the emissions from electricity generation in China were the largest contributor to climate change potential and energy use. For terrestrial ecotoxicity, the production of copper was the main source for all countries assessed, followed by the cell production process and aluminium alloy production, as seen in Fig. 7.

Two waste recovery methods were assessed: LGRF or laminated glass recycling facility, and FRELP or full recovery end-of-life photovoltaic. For the end-of-life waste recovery methods, it is seen that the LGRF method has lower impacts than the FRELP method for all impact categories and countries, due to the lower amount of electricity consumed and lower amounts of recovered waste that was recycled. When the avoided environmental impacts from recovering the waste fractions are included, the net environmental impacts are reduced across all impact categories. The inclusion of the avoided environmental impacts resulted in the net impact of the FRELP method being lower than the LGRF method.

It is also worth noting that waste recovery with the LGRF and FRELP methods leads to significant avoided impacts in metal depletion potential compared to the other impact categories. Based on Fig. 8, the avoidances from the recovery and recycling of waste fractions led to a reduction of at least 44.25 % and 127 % for the LGRF and FRELP methods for all countries due to the higher recovery yield and ability to recover additional materials like silver and MG-Si. A correlation between the recovery yield and the reductions in environmental impacts due to avoidances were observed for fine particulate matter formation potential, fossil depletion potential, freshwater eutrophication potential and human toxicity potential (cancer and non-cancer). The FRELP process led to higher reductions compared to the LGRF across these categories, with the highest reductions observed in Malaysia for fine particulate matter formation potential and freshwater eutrophication potential, and in Thailand for fossil depletion potential and human toxicity potential (cancer and non-cancer). Further details on the results for these categories can be seen in the Appendix. However, for terrestrial ecotoxicity, the recovery of waste fractions did not lead to significant reductions, as seen in Fig. 7.

4.2. Scenario analysis

As observed in Table 5, electricity generation contributes significantly environmental impacts such as climate change potential, fine particulate matter formation potential, fossil depletion potential, and freshwater eutrophication potential. However, China and the Southeast Asian countries in this study have also set out ambitious plans to decarbonise their power sector within the next few decades. Therefore, provided progress is made towards these targets, the electricity grid emissions for each country will change due the increasing share of renewable energy in electricity generation, which will lead to lower environmental impacts in the life cycle of the PV panels (APEC, 2022).

Hence, five scenarios were identified for further analysis of the potential change in impacts. Given the direct role decarbonisation plays in electricity generation, this section focussed on how changes in grid emission factors affect overall impacts via the climate change potential. 5 % reductions are used as a near-term estimation of a decarbonised power sector, whereas 25 % was taken as a long-term estimation of a grid energy mix with more aggressive integration of renewables. The five scenarios selected are.

1. Business-as-usual (BAU), where the grid emission factors do not change;
2. China reduces its grid emission factor by 5 % (CN5);
3. China reduces its grid emission factor by 25 % (CN25);
4. China and the ASEAN member states reduce their grid emission factors by 5 % (CN5-SEA5);
5. China and the ASEAN member states reduce their grid emission factors by 25 % (CN25-SEA25).

The effects of the reductions in grid emission factors on the climate change potentials of the LGRF and FRELP processes in the respective Southeast Asian countries are plotted in Fig. 9. A more comprehensive list of the results can be found in the Appendix.

For the CN5 scenario, the reduction of climate change potential is approximately 2.1 % for the LGRF and FRELP methods for all countries, relative to the BAU. Under the CN25 scenario, the climate change potential is reduced by 10.4 %–10.9 % for both waste recovery methods for all countries. Scenarios where both China and the Southeast Asian

Table 4
The environmental impacts of producing one tonne of solar modules by country.

Impact Category	Units	CN	CN-MY	CN-SG	CN-TH	CN-VN
Climate change potential	kg CO_2-eq	11,052.08	10,975.86	10,442.31	10,899.64	10,747.20
Fine particulate matter formation potential	kg PM2.5-eq	20.27	21.72	18.60	19.36	20.58
Fossil depletion potential	kg oil-eq	3201.29	3216.54	3079.34	3178.43	3109.83
Freshwater eutrophication potential	kg P. eq	2.62	2.97	2.42	3.13	2.77
Human toxicity potential (cancer)	kg 1,4-DCB eq	618.15	631.87	589.95	633.40	618.92
Human toxicity potential (non-cancer)	kg 1,4-DCB eq	14,405.82	14,710.70	13,948.49	14,710.70	14,482.04
Metal depletion potential	kg Cu-eq	66.08	66.01	66.08	66.39	66.01
Terrestrial ecotoxicity potential	kg 1,4-DCB eq	50,610.91	50,382.25	50,153.59	50,458.47	50,458.47
Cumulative energy demand	MJ	156,253.57	157,015.79	150,155.87	155,491.36	153,204.72

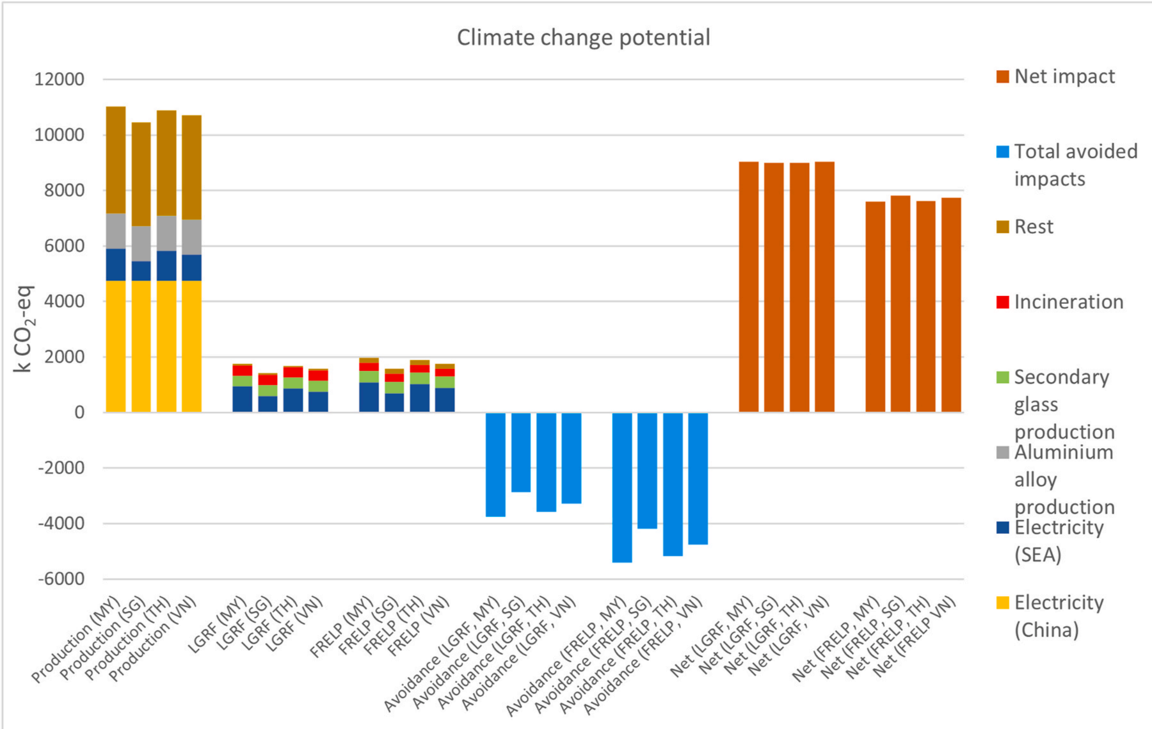

Fig. 5. The climate change potential of the production and end-of-life processes for PV panels in Southeast Asia.

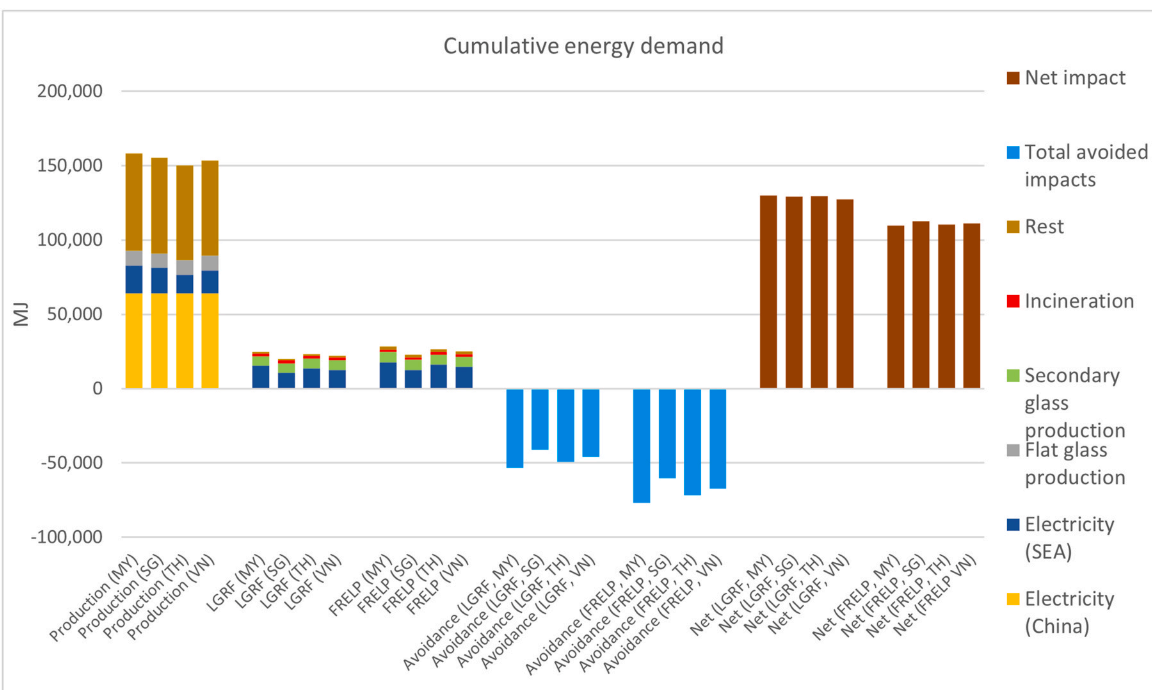

Fig. 6. The cumulative energy demand of the production and end-of-life processes for PV panels in Southeast Asia.

economies decreased their grid emissions also indicated a slightly higher reduction. Compared to the CN5 scenario, the CN5-SEA5 scenario presented reductions in climate change potential of approximately 2.5 % across all economies and waste recovery methods. Decreasing the grid emission factor by 25 % for China and the Southeast Asian countries (CN25-SEA25) also resulted in reductions of around 12.3 %–12.8 %.

In the four Southeast Asian economies, in scenarios where only China has decarbonised its grid (CN5 and CN25), the highest reductions in climate change potential were observed in Singapore, due to the higher grid emission factors for the other Southeast Asian economies. Malaysia and Thailand, which had the lowest reductions, have higher grid emission factors compared to Vietnam and Singapore, as shown in Table 6. A reduction in the grid emission factor for China, therefore, has a relatively lower impact for the life cycle of panels produced in Malaysia and

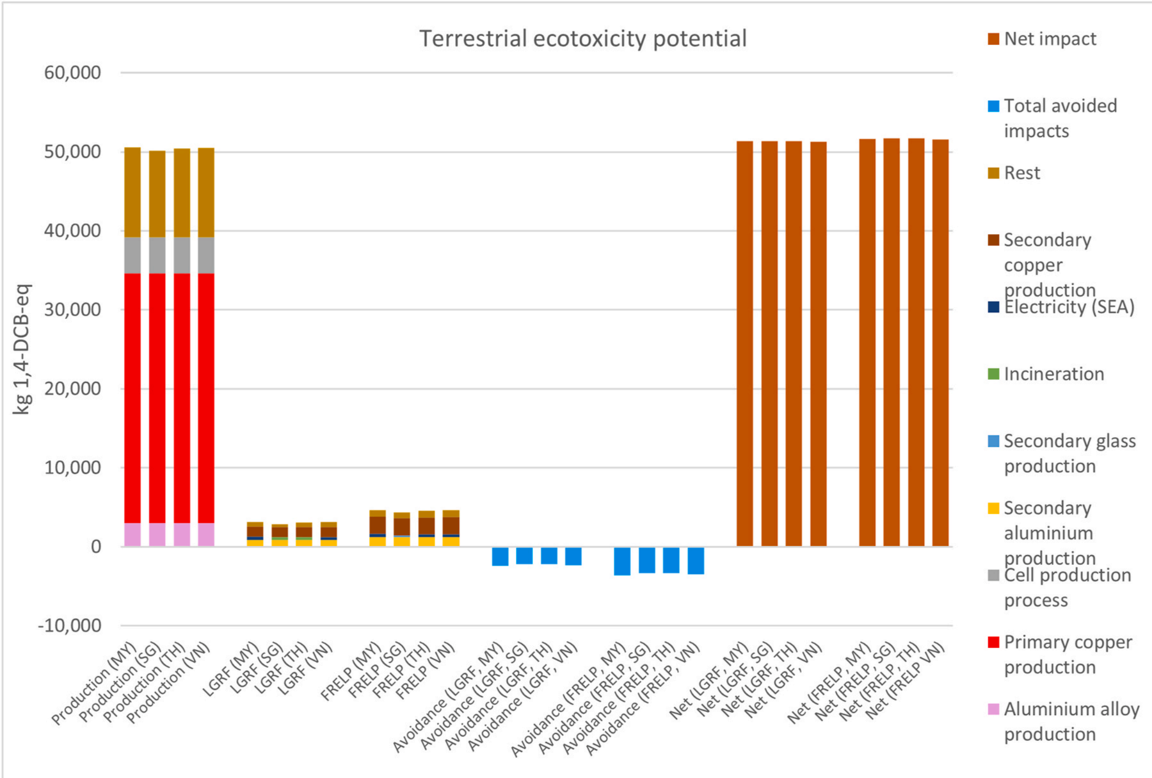

Fig. 7. The terrestrial ecotoxicity potential of the production and end-of-life processes for PV panels in Southeast Asia.

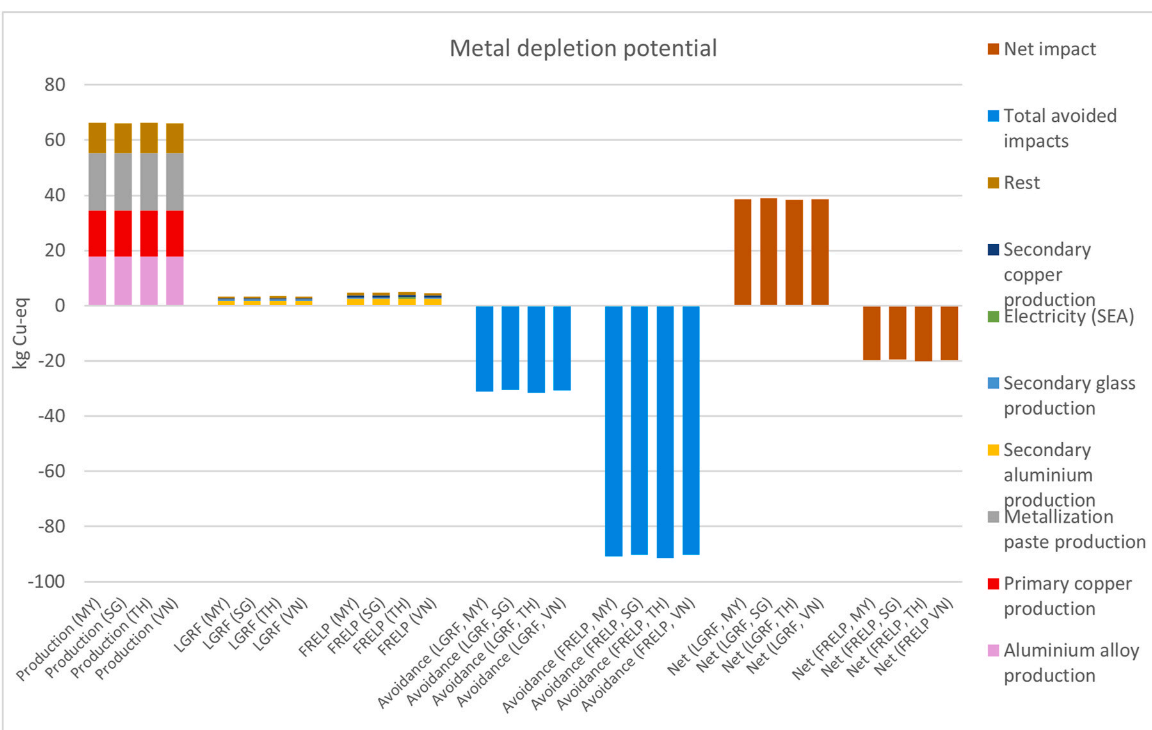

Fig. 8. The metal depletion potential of the production and end-of-life processes for PV panels in Southeast Asia.

Table 5
The average percentage contribution of electricity generation among the four Southeast Asian countries across specific impact categories.

Environmental impact category	LGRF	FRELP
Climate change potential	52.60 %	51.79 %
Fine particulate matter formation	44.76 %	43.68 %
Fossil depletion	52.30 %	51.34 %
Freshwater eutrophication potential	46.11 %	45.19 %

Thailand. The decarbonisation of the Southeast Asian grids in addition to China's (CN5-SEA5, CN25-SEA25) further substantiates this observation: the reductions in climate change potential for Malaysia and Thailand are the highest under these two scenarios.

It should be noted that the reduction of the grid emission factors for China and the Southeast Asian economies does not lead to an equivalent reduction in the climate change potential during the life cycle of the panel. Conclusively, decarbonising the grids can reduce the environmental impacts of the panel during its life cycle to a limited degree.

5. Discussion

Across the life cycle of PV, manufacturing and end-of-life treatment are deemed critical for determining their overall environmental impact. Regarding the production of PV, the differences in climate change potential across the five countries can be attributed to electricity mixes. It was observed that panels with downstream processes in Southeast Asia all had a lower climate change potential than those produced in China. This highlights the opportunity to follow a low-carbon pathway by manufacturing and assembling PV in Southeast Asia. This could also alleviate China's current market dominance.

However, attention should also be given to other impact categories where panels produced in Malaysia and Vietnam are higher than those in China, as stated in Section 4.1. Malaysia and Vietnam, which are responsible for the largest share of cell manufacturing and panel assembly in the region, have electricity mixes dominated by coal and natural gas. Coal comprises the majority of electricity mixes in China, Malaysia, and Vietnam, at 63.0 %, 47.9 %, and 32.5 %, respectively (IEA, 2021a). While the share of coal in China is higher than Malaysia or Vietnam, China's usage of other fossil fuels, particularly natural gas, is limited to 3.2 % in the electricity mix, compared to 32.8 % and 10.5 % for Malaysia and Vietnam respectively. Conversely, Thailand and Singapore have electricity mixes where natural gas, a relatively 'cleaner' fuel, makes up the largest share, which results in the lower environmental impacts for panels produced in these countries. For each environmental impact category, the different impact factors from generating 1 kWh of electricity are presented for each country in Table 6.

The breakdown of the climate change potential and CED from producing the PV indicate a large contribution from the polysilicon and cell manufacturing processes, as observed in Figs. 5 and 6. This aligns with the findings from Hou et al. (2016) and Abuzaid and Samara (2022). This is observed regardless of the country of production, as observed in Gan et al. (2023), who compared the greenhouse gas emissions for solar panels fully produced in the USA compared to China. The scenario analysis indicates that decarbonising the grids of the producing countries by 5 % in each country does not lead to equivalent reductions in the climate change potential of the panels and only achieves around 2.5 % reductions in climate change potential. This is consistent with the sensitivity analysis from Chen et al. (2016), who also reported that a 5 % reduction in electricity consumption leads to a 3 % reduction in climate change potential for panels produced in China. This suggests that

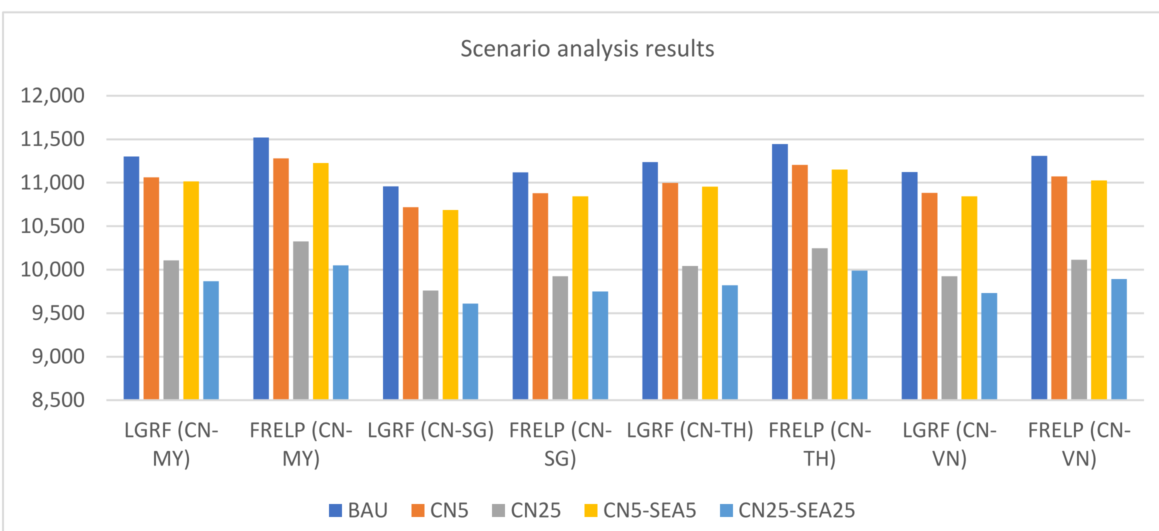

Fig. 9. The results from the scenario analysis based on the 2 scenarios.

Table 6
The impact factors for the production of 1 kWh of electricity in each country.

Impact Category	Units	CN	MY	SG	TH	VN
Climate change potential	kg CO_2-eq	1.01	0.806	0.514	0.750	0.653
Fine particulate matter formation potential	kg PM2.5-eq	0.00156	0.00212	0.000125	0.000629	0.00144
Fossil depletion potential	kg oil-eq	0.277	0.271	0.199	0.251	0.209
Freshwater eutrophication potential	kg P. eq	0.000180	0.000363	0.0000107	0.000449	0.000238
Human toxicity potential (cancer)	kg 1,4-DCB eq	0.0302	0.0328	0.00516	0.0332	0.0241
Human toxicity potential (non-cancer)	kg 1,4-DCB eq	0.423	0.532	0.0290	0.541	0.383
Metal depletion potential	kg Cu-eq	0.000329	0.000313	0.000259	0.000459	0.000216
Terrestrial ecotoxicity potential	kg 1,4-DCB eq	0.442	0.332	0.0968	0.265	0.304
CED	MJ	14	13.2	9.27	11.9	10.8

decarbonisation efforts beyond the electricity grid are required in the entire supply chain. The results of this study also show that, by considering the avoided environmental impacts of waste recovery, the overall environmental impacts are lowered in every impact category. Recovering a material can prevent the production of the material it replaces (Söderman, 2003). Our analysis supports the findings of previous research on end-of-life PV waste in India (Sharma et al., 2023) and Australia (Singh et al., 2021) Noticeable reductions in impact are related to mineral resource scarcity, marine ecotoxicity, land use, freshwater ecotoxicity, and human carcinogenic toxicity. PV recycling can significantly decrease the impact of the PV manufacturing by up to 70 %.

To assess the robustness of our findings, we compare our results associated with the LGRF and FRELP process for Thailand to an LCA study conducted by Faircloth et al. (2019). The study reported the net climate change potential to be −3200 kgCO2e and −4500 kgCO2e respectively, in comparison to our study (−1890.57 kgCO2e for LGRF and −3285.16 for FRELP). While Faircloth et al. (2019) considers the environmental benefits from incineration with energy recovery, our study does not include energy recovery in the incineration process. Other reasons for the differences are also due to different refining pathways for the recovered materials.

A higher recovery yield and the recovery of other fractions such as silver were key factors for the higher avoided impacts observed in the FRELP method than the LGRF method, particularly for the metal depletion potential. The avoided impacts led to an overall lower net impact for the assessed impact categories despite the higher impacts for the method itself. Technology advancements that increase the recovery yield from PV can therefore increase the avoided impacts and alleviate the resource intensity of PV panels. However, the avoided impacts for both waste recovery methods are minimal in decreasing the net impacts for terrestrial ecotoxicity potential due to the high impacts from the production of primary copper in the production of the PV panels, as seen in Fig. 7. However, the impact associated with the production of secondary copper in the LGRF and FRELP method was lower than the production of primary copper by more than 93 %. Therefore, increasing the share of recycled copper in production of panels can therefore further reduce the terrestrial ecotoxicity potential in the life cycle of the PV panels.

Feeding the recovered waste fractions back into the production of PV panels can alleviate the environmental impacts of the life cycle itself. Malaysia and Vietnam have established manufacturing capacities for aluminium. Copper refining capacity from concentrates is also established in Malaysia and Thailand. The production of primary aluminium was within the top three contributors for climate change potential, terrestrial ecotoxicity potential and metal depletion potential for all countries. The production of primary copper was also the largest contributor to terrestrial ecotoxicity and within the top three contributors to metal depletion potential. As the environmental impacts of producing secondary copper and aluminium are lower than their primary counterparts (Hong et al., 2012; Jingjing et al., 2019), feeding the recycled metals back into the production process can reduce the environmental impacts within the production of the PV panels.

6. Conclusion

This study used a life cycle assessment to determine the environmental impacts of mono-Si PV module production and recycling in four countries in Southeast Asia: Malaysia, Singapore, Thailand, and Vietnam, with intermediate materials from China. Given the region's growing importance in world PV manufacturing, this understanding will be of value in assessing the environmental impacts of the low-carbon transition and in the role recycling can play in minimising those impacts.

The findings from the production of PV panels in Southeast Asia show that panels produced in Southeast Asia are lower in CED and climate change potential, and most of these were contributed from the production of polysilicon. A scenario analysis found that decarbonising the electricity grid did not lead to reductions of the same magnitude in the climate change potential of the panels. In the recycling methods, higher recovery yields led to lower net environmental impacts for the life cycle of the PV panels, particularly for metal depletion potential, CED and climate change potential. While the recycling methods did not significantly alleviate the net terrestrial ecotoxicity potential, including recycled copper in the production phase considerably reduces it. While our findings align with similar studies on the environmental impact of manufacturing and recycling solar PV, we acknowledge that the study is limited in its assessment due to the assumptions of the relevant technologies and their efficiencies, which may differ in real practice.

More broadly, given Southeast Asia's growing importance in the world PV manufacturing, the results indicate that a supply chain that includes Southeast Asian solar PV assembly can be a lower carbon option to the prevailing supply chain. They also confirm the view that huge carbon dioxide savings can be achieved through end-of-life policies that minimise the need for new resources. Indeed, proper waste recovery methods and management coupled with appropriate decarbonisation pathways can support Southeast Asia in its role as a PV producing region.

This role might become of even greater significance if economies seek to diversify their sources of supply and avoid over-dependence on a single source for their low carbon energy transition. With this in mind, it becomes valuable to identify the environmental impacts of developing alternative supply chains with an aim to minimise both security of supply and the overall environmental impact of electricity generation - potentially reducing the resistance to and accelerating the global low carbon transition. Future research that assesses the whole-life environmental impacts of PV panels, including the electricity generation on a per-kWh basis, will provide an opportunity for comparison across power generation technologies.

CRediT authorship contribution statement

Kendra H.Y. Ho: Visualization, Investigation, Writing – review & editing, Software, Validation, Conceptualization, Writing – original draft, Methodology. **Alvin W.L. Ee:** Validation, Methodology, Formal analysis, Supervision, Data curation, Writing – review & editing, Visualization, Software, Conceptualization, Writing – original draft, Resources, Investigation. **Minhee Son:** Visualization, Writing – original draft, Writing – review & editing. **Sita Rahmani:** Writing – original draft, Writing – review & editing, Visualization. **Faadhil Mohamed Liyaff:** Visualization, Writing – original draft, Writing – review & editing. **Roger Fouquet:** Writing – original draft, Writing – review & editing, Supervision, Visualization, Project administration, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146277.

Appendix

Table A1
The life cycle impact categories used in the study and the rationale for their usage.

Impact category	Definition	Justification
Climate change	Potential global warming due to emissions of greenhouse gases	High volume of electricity usage to produce panels, which may be fossil-fuels intensive
Fine particulate matter formation	Release of fine particulates at ground level, which affect human health	Burning of fuels for energy releases fine particulate matter
Fossil depletion	The depletion of fuel resources	Current grid mixes use fossil fuels
Freshwater eutrophication	Enrichment of freshwater ecosystem due to excess nutrients	Wastewater from the production and waste recovery methods release emissions into water that increase freshwater eutrophication
Human toxicity	Impact of emission of toxic substances on humans	Production requires the mining of heavy metals that lead to human toxicity
Metal depletion	The depletion of natural metals resources	High use for metals for usage in solar panels
Terrestrial ecotoxicity	Damages to terrestrial ecosystem due to the release of emissions	Mining activities for metals used in panels releases emissions that affect terrestrial ecotoxicity
Cumulative energy demand	Direct and indirect energy use throughout the life cycle.	The high energy demand for the production and end-of-life treatment methods for solar panels

Table A2
The environmental impacts from the LGRF and FRELP waste recovery methods.

	Malaysia		Singapore		Thailand		Vietnam	
	LGRF	FRELP	LGRF	FRELP	LGRF	FRELP	LGRF	FRELP
Climate change potential	1750.00	1970.00	1410.00	1570.00	1690.00	1890.00	1570.00	1760.00
Fine particulate matter formation potential	2.88	3.61	0.56	0.92	1.15	1.60	2.09	2.70
Fossil depletion potential	517.00	591.00	432.00	493.00	493.00	564.00	444.00	507.00
Freshwater eutrophication potential	0.57	0.65	0.16	0.18	0.70	0.80	0.43	0.49
Human toxicity potential (cancer)	96.30	115.00	64.20	77.30	96.80	115.00	86.30	103.00
Human toxicity potential (non-cancer)	1630.00	2270.00	1050.00	1590.00	1640.00	2290.00	1460.00	2070.00
Metal depletion potential	3.40	4.78	3.34	4.70	3.57	4.97	3.29	4.65
Terrestrial ecotoxicity potential	3170.00	4660.00	2900.00	4340.00	3100.00	4570.00	3140.00	4620.00
CED	24,700.00	28,300.00	20,100.00	23,000.00	23,200.00	26,600.00	20,000.00	25,200.00

Table A3
The avoided impacts from recycling the recovered materials from the LGRF and FRELP waste recovery methods.

	Malaysia		Singapore		Thailand		Vietnam	
	LGRF	FRELP	LGRF	FRELP	LGRF	FRELP	LGRF	FRELP
Climate change potential	3753.79	5416.21	2861.12	4185.49	3580.57	5175.16	3280.64	4764.57
Fine particulate matter formation potential	8.70	12.28	2.60	4.47	4.16	7.18	6.62	9.99
Fossil depletion potential	1096.95	1578.38	873.83	1271.80	1035.03	1493.48	906.44	1316.40
Freshwater eutrophication potential	1.28	2.58	0.20	1.10	1.61	3.03	0.90	2.05
Human toxicity potential (cancer)	129.85	201.72	45.40	85.69	131.17	203.54	103.35	165.32
Human toxicity potential (non-cancer)	2043.91	10,847.41	500.85	8727.89	2065.34	10,877.78	1583.79	10,216.06
Metal depletion potential	31.04	90.79	30.52	90.17	31.49	91.40	30.66	90.27
Terrestrial ecotoxicity potential	2395.23	3625.22	1670.68	2631.12	2183.57	3336.41	2302.05	3498.94
CED	53,200.00	77,042.08	41,145.20	60,455.82	49,269.40	71,643.06	46,028.40	67,183.90

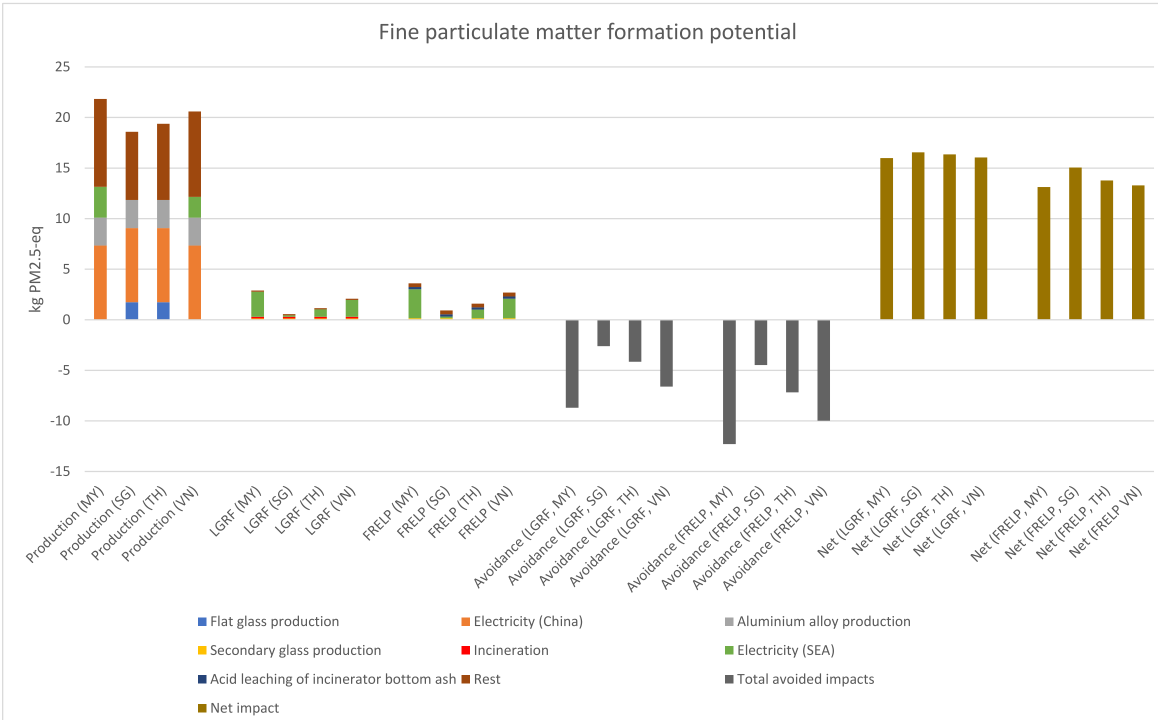

Fig. A1. The fine particulate matter formation potential of the production and end-of-life processes for PV panels in Southeast Asia.

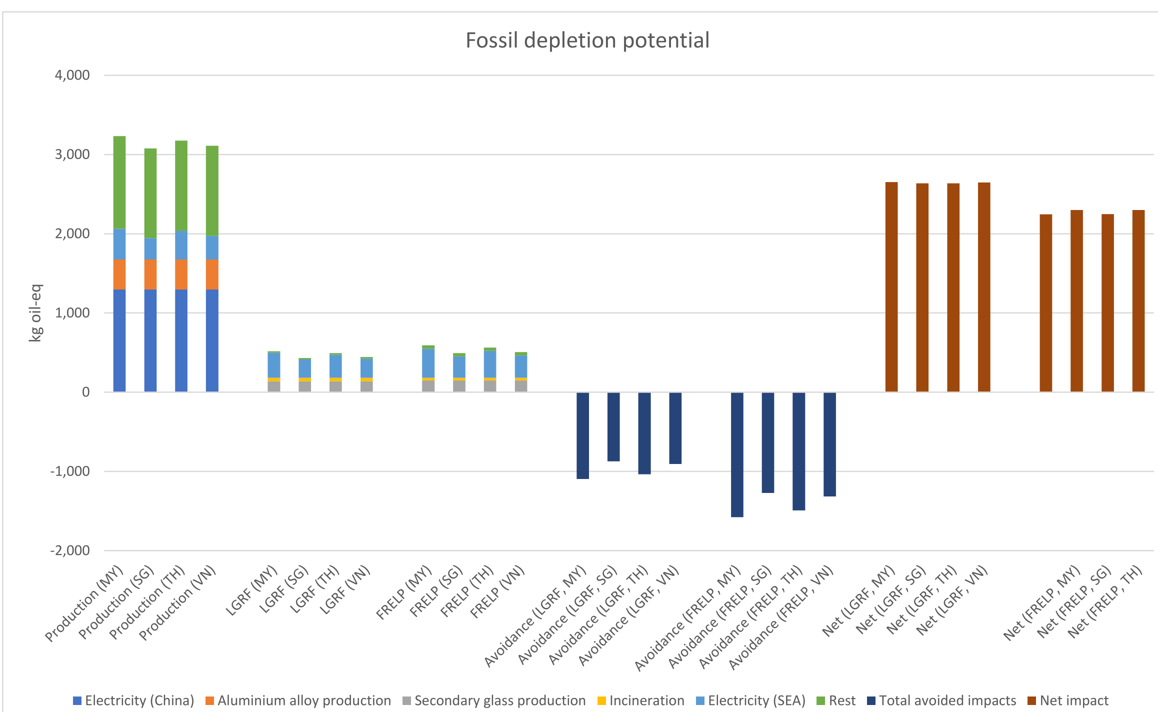

Fig. A2. The fossil depletion potential of the production and end-of-life processes for PV panels in Southeast Asia.

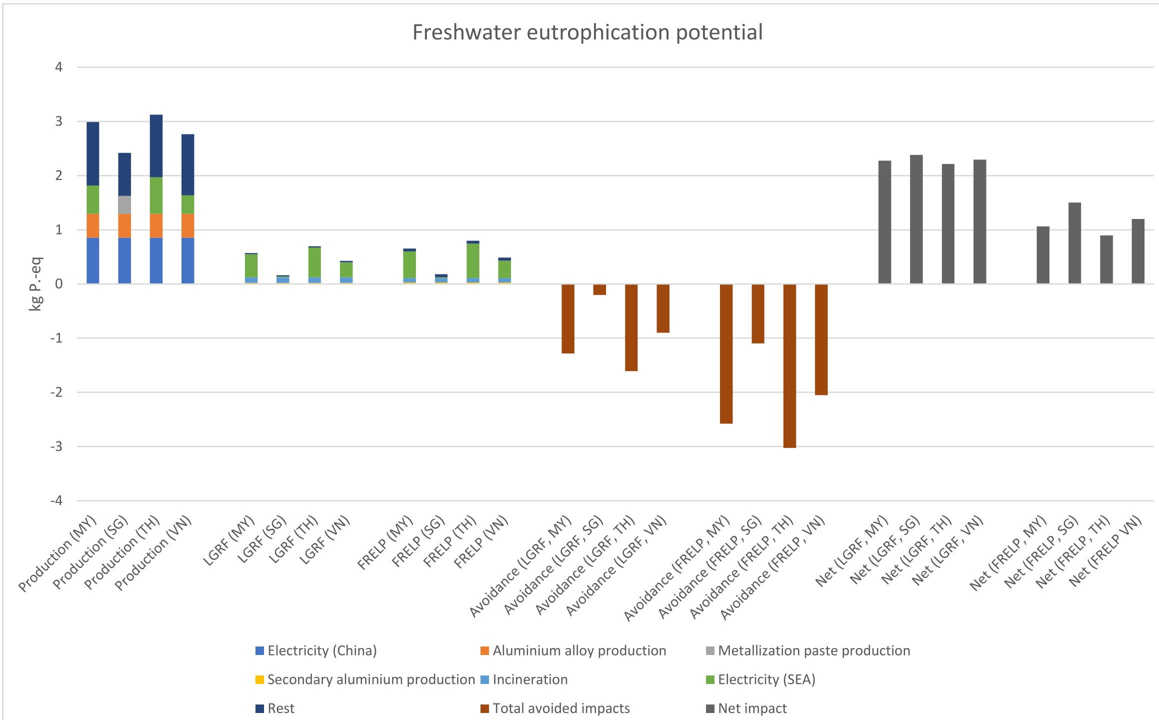

Fig. A3. The freshwater eutrophication potential of the production and end-of-life processes for PV panels in Southeast Asia.

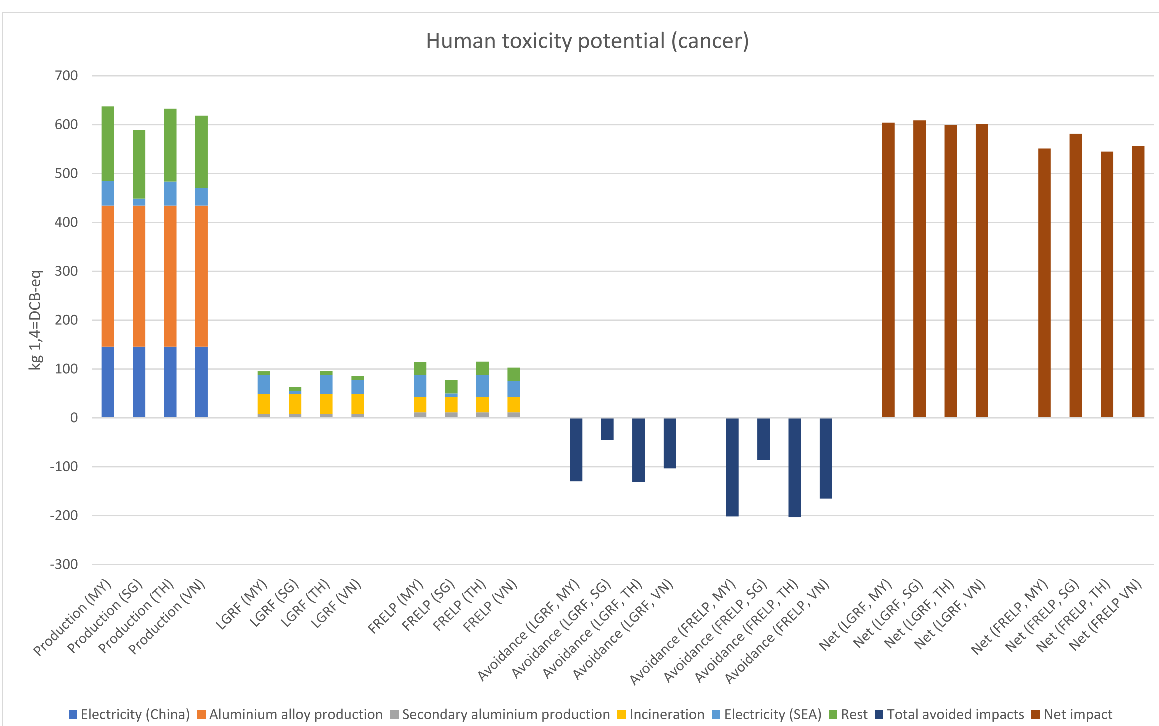

Fig. A4. The human toxicity potential (cancer) of the production and end-of-life processes for PV panels in Southeast Asia.

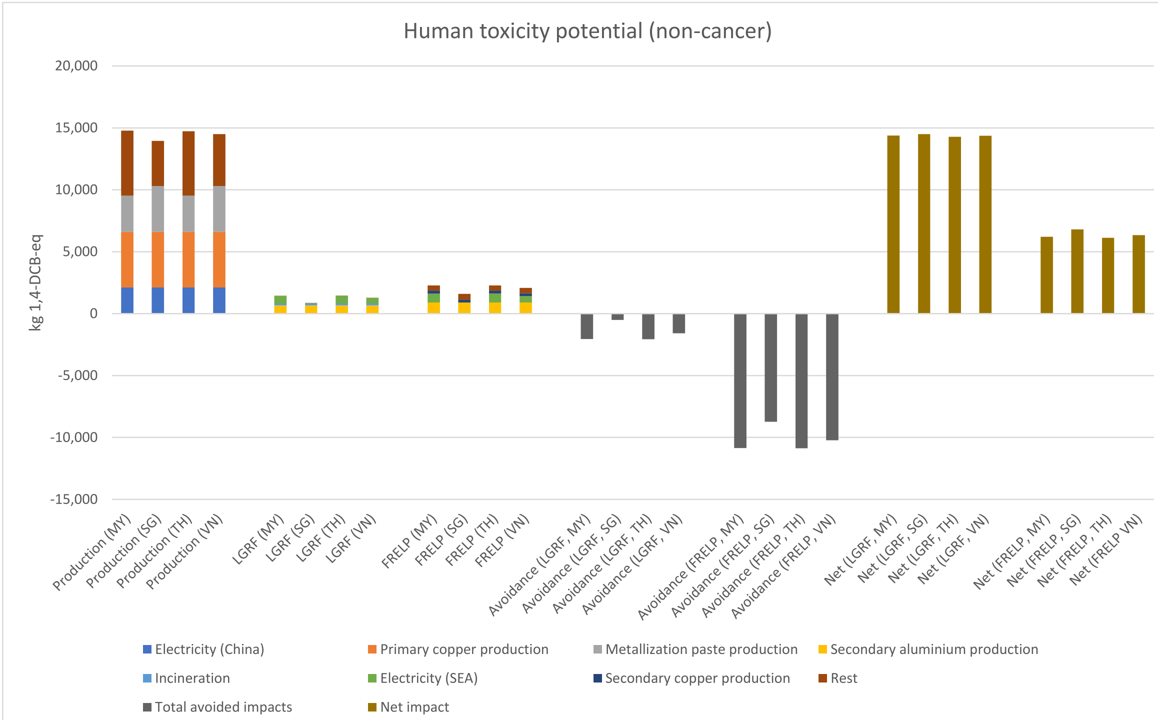

Fig. A5. The human toxicity potential (non-cancer) of the production and end-of-life processes for PV panels in Southeast Asia.

Table A4
The environmental impact of the production and end-of-life treatment of waste panels in Malaysia when the avoidances are included.

Impact category	Units	LGRF Total impacts	LGRF Total impacts with avoidance	LGRF Percentage change	FRELP Total impacts	FRELP Total impacts with avoidance	FRELP Percentage change
Climate change	kg CO_2-eq	12,802.08	9048.29	29.32 %	13,022.08	7605.88	41.59 %
Fine particulate matter formation	kg PM2.5-eq	24.68	15.98	35.25 %	25.41	13.13	48.34 %
Fossil depletion	kg oil-eq	3748.78	2651.83	29.26 %	3822.78	2244.40	41.29 %
Freshwater eutrophication	kg P. eq	3.56	2.28	36.03 %	3.64	1.06	70.82 %
Human toxicity (cancer)	kg 1,4-DCB eq	734.27	604.42	17.68 %	752.97	551.25	26.79 %
Human toxicity (non-cancer)	kg 1,4-DCB eq	16,416.92	14,373.02	12.45 %	17,056.92	6209.52	63.60 %
Metal depletion	kg Cu-eq	69.71	38.67	44.53 %	71.09	−19.70	127.71 %
Terrestrial ecotoxicity	kg 1,4-DCB eq	53,780.91	51,385.68	4.45 %	55,270.91	51,645.69	6.56 %
CED	MJ	183,240.21	130,040.21	29.03 %	186,840.21	109,798.13	41.23 %

Table A5
The environmental impact of the production and end-of-life treatment of waste panels in Singapore when the avoidances are included.

Impact category	Units	LGRF Total impacts	LGRF Total impacts with avoidance	LGRF Percentage change	FRELP Total impacts	FRELP Total impacts with avoidance	FRELP Percentage change
Climate change	kg CO_2-eq	11,852.31	8991.19	24.14 %	12,012.31	7826.82	34.84 %
Fine particulate matter formation	kg PM2.5-eq	19.16	16.56	13.59 %	19.52	15.04	22.92 %
Fossil depletion	kg oil-eq	3511.34	2637.51	24.89 %	3572.34	2300.53	35.60 %
Freshwater eutrophication	kg P. eq	2.58	2.38	7.90 %	2.60	1.50	42.20 %
Human toxicity (cancer)	kg 1,4-DCB eq	654.15	608.75	6.94 %	667.25	581.56	12.84 %
Human toxicity (non-cancer)	kg 1,4-DCB eq	14,998.49	14,497.64	3.34 %	15,538.49	6810.60	56.17 %
Metal depletion	kg Cu-eq	69.42	38.90	43.96 %	70.78	−19.39	127.39 %

(continued on next page)

Table A5 (*continued*)

Impact category		LGRF			FRELP		
	Units	Total impacts	Total impacts with avoidance	Percentage change	Total impacts	Total impacts with avoidance	Percentage change
Terrestrial ecotoxicity	kg 1,4-DCB eq	53,053.59	51,382.91	3.15 %	54,493.59	51862.47	4.83 %
CED	MJ	170,255.87	129,110.67	24.17 %	173,155.87	112700.05	34.91 %

Table A6
The environmental impact of the production and end-of-life treatment of waste panels in Thailand when the avoidances are included.

Impact category		LGRF			FRELP		
	Units	Total impacts	Total impacts with avoidance	Percentage change	Total impacts	Total impacts with avoidance	Percentage change
Climate change	kg CO_2-eq	12,589.64	9009.07	28.44 %	12,789.64	7614.48	40.46 %
Fine particulate matter formation	kg PM2.5-eq	20.51	16.35	20.27 %	20.96	13.78	34.24 %
Fossil depletion	kg oil-eq	3671.43	2636.40	28.19 %	3742.43	2248.94	39.91 %
Freshwater eutrophication	kg P. eq	3.82	2.21	42.07 %	3.92	0.90	77.11 %
Human toxicity (cancer)	kg 1,4-DCB eq	730.20	599.03	17.96 %	748.40	544.86	27.20 %
Human toxicity (non-cancer)	kg 1,4-DCB eq	16,350.70	14,285.36	12.63 %	17,000.70	6122.92	63.98 %
Metal depletion	kg Cu-eq	69.96	38.47	45.01 %	71.36	−20.04	128.09 %
Terrestrial ecotoxicity	kg 1,4-DCB eq	53,558.47	51,374.90	4.08 %	55,028.47	51,692.06	6.06 %
CED	MJ	178,691.36	129,421.96	27.57 %	182,091.36	110,448.30	39.34 %

Table A7
The environmental impact of the production and end-of-life treatment of waste panels in Vietnam when the avoidances are included.

Impact category		LGRF			FRELP		
	Units	Total impacts	Total impacts with avoidance	Percentage change	Total impacts	Total impacts with avoidance	Percentage change
Climate change	kg CO_2-eq	12,317.20	9036.56	26.63 %	12,507.20	7742.62	38.09 %
Fine particulate matter formation	kg PM2.5-eq	22.67	16.05	29.18 %	23.28	13.29	42.90 %
Fossil depletion	kg oil-eq	3553.83	2647.38	25.51 %	3616.83	2300.43	36.40 %
Freshwater eutrophication	kg P. eq	3.19	2.29	28.15 %	3.25	1.20	63.11 %
Human toxicity (cancer)	kg 1,4-DCB eq	705.22	601.87	14.65 %	721.92	556.59	22.90 %
Human toxicity (non cancer)	kg 1,4-DCB eq	15,942.04	14,358.25	9.93 %	16,552.04	6335.98	61.72 %
Metal depletion	kg Cu-eq	69.30	38.64	44.25 %	70.66	−19.61	127.75 %
Terrestrial ecotoxicity	kg 1,4-DCB eq	53,598.47	51,296.42	4.29 %	55,078.47	51,579.53	6.35 %
CED	MJ	173,204.72	127,176.32	26.57 %	178,404.72	111,220.82	37.66 %

Table A8
The climate change potential from the scenario analysis for all Southeast Asian countries and waste recovery methods.

	LGRF (CN-MY)	FRELP (CN-MY)	LGRF (CN-SG)	FRELP (CN-SG)	LGRF (CN-TH)	FRELP (CN-TH)	LGRF (CN-VN)	FRELP (CN-VN)
BAU	11,303.16	11,520.41	10,957.68	11,119.76	11,236.91	11,443.57	11,122.14	11,310.48
CN5	11,064.10	11,281.34	10,718.61	10,880.70	10,997.84	11,204.51	10,883.07	11,071.42
CN25	10,107.84	10,325.08	9762.35	9924.44	10,041.58	10,248.24	9926.81	10,115.15
CN5-SEA5	11,016.42	11,226.05	10,688.20	10,845.44	10,953.47	11,153.05	10,844.44	11,026.62
CN5-SEA25	9869.43	10,048.61	9610.31	9748.13	9819.73	9990.98	9733.66	9891.16

Data availability

Data will be made available on request.

References

Abubakar, A., Almeida, C.F.M., Gemignani, M., 2021. A review of solar photovoltaic system maintenance strategies. In: 2021 14th IEEE International Conference on Industry Applications (INDUSCON).

Abuzaid, H., Samara, F., 2022. Environmental and economic impact assessments of a photovoltaic rooftop system in the United Arab Emirates. Energies 15. https://doi.org/10.3390/en15228765.
ACE, 2022. The 7th ASEAN Energy Outlook 2020-2050.
Andrews, R., Ara, A., Assmus, J.-H., Barandalla, D., Bartle, M., Beauvais, A., Beggi, A., Bernardi, E., Campbell, A., Campistron, C., 2019. Operation & maintenance best practice guidelines/version 4.0. In: SolarPower Europe: Operation & Maintenance Best Practice Guidelines, Version 4.0.
APEC. (2022). APEC energy demaand and supply outlook (eighth ed.) - Volume II. E. W. G. E. SOM Steering Committee on Economic and Technical Cooperation (SCE). https://www.apec.org/publications/2022/09/apec-energy-demand-and-supply-outlook-%288th-edition%29—volume-ii.
Bondoc, C.C.E., 2023. Feasibility and Environmental Life Cycle Assessment of Mono-Crystalline Silicon (Mono-Si) Solar Photovoltaic Panels with Recycled Vs. Non-recycled Materials. ProQuest Dissertations & Theses Global, United States – Pennsylvania (Publication Number 30485837) [M.Sc.S.E., Villanova University]. http://libproxy1.nus.edu.sg/login?url=https://www.proquest.com/dissertations-theses/feasibility-environmental-life-cycle-assessment/docview/2821575695/se-2?accountid=13876.
Burke, F., Nguyen, T.H., Nguyen, P.T.H., 2021. Vietnam: major changes in the new environmental protection law. https://insightplus.bakermckenzie.com/bm/attachment_dw.action?attkey=FRbANEucS95NMLRN47z%2BeeOgEFCt8EGQJsWJiCH2WAVfnLVn2ghRGDHGdtDl3rmJ&nav=FRbANEucS95NMLRN47z%2BeeOgEFCt8EGQbuwypnpZjc4%3D&attdocparam=pB7HEsg%2FZ312Bk8OIuOIH1c%2BY4beLEAeA%2BhCYIjlkek%3D&fromContentView=1.
Chen, W., Hong, J., Yuan, X., Liu, J., 2016. Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. J. Clean. Prod. 112. https://doi.org/10.1016/j.jclepro.2015.08.024, 1052-1032.
COP28, 2023. Global renewables and energy efficiency pledge. Retrieved 14 March 2024 from. https://www.cop28.com/en/global-renewables-and-energy-efficiency-pledge.
Corcelli, F., Ripa, M., Leccisi, E., Cigolotti, V., Fiandra, V., Graditi, G., Sannino, L., Tammaro, M., Ulgiati, S., 2018. Sustainable urban electricity supply chain – indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecol. Indic. 94, 37–51. https://doi.org/10.1016/j.ecolind.2016.03.028.
Department of Environment Malaysia, 2010. Guidelines for the Classification of Used Electrical and Electronic Equipment in Malaysia. Department of Environment, Malaysia. Department of Environment Malaysia Retrieved from. https://enviro2.doe.gov.my/ekmc/wp-content/uploads/2016/08/1403742193-Guidelines%20for%20the%20Classification%20of%20Used%20Electrical%20and%20Electronic%20Equipment%20in%20Malaysia.pdf.
Dias, P.R., Schmidt, L., Chang, N.L., Monteiro Lunardi, M., Deng, R., Trigger, B., Bonan Gomes, L., Egan, R., Veit, H., 2022. High yield, low cost, environmentally friendly process to recycle silicon solar panels: technical, economic and environmental feasibility assessment. Renew. Sustain. Energy Rev. 169. https://doi.org/10.1016/j.rser.2022.112900.
EMBER, 2023. Yearly electricity data. https://ember-climate.org/data-catalogue/yearly-electricity-data/.
Faircloth, C.C., Wagner, K.H., Woodward, K.E., Rakkwamsuk, P., Gheewala, S.H., 2019. The environmental and economic impacts of photovoltaic waste management in Thailand. Resour. Conserv. Recycl. 143, 260–272. https://doi.org/10.1016/j.resconrec.2019.01.008.
Frischknecht, R., Stolz, P., Krebs, L., Wild-Scholten, M.d., Sinha, P., 2020. Life cycle inventories and life cycle assessments of photovoltaic systems. https://iea-pvps.org/wp-content/uploads/2020/12.
Fthenakis, V., Kim, H.C., 2010. Life-cycle uses of water in US electricity generation. Renew. Sustain. Energy Rev. 14 (7), 2039–2048.
Fthenakis, V.M., 2000. End-of-life management and recycling of PV modules. Energy Policy 28 (14), 1051–1058. https://doi.org/10.1016/S0301-4215(00)00091-4.
Fukurozaki, S., Zilles, R., Sauer, I.L., 2013. Energy payback time and CO2 emissions of 1.2 kWp photovoltaic roof-top system in Brazil. Int. J. Smart Grid Clean Energy 2 (2), 1–6.
Fukurozaki, S.H., Zilles, R., Sauer, I.L., 2012. Energy payback time and CO2 emissions of 1.2 kWp photovoltaic roof-top system in Brazil. International Journal of Smart Grid and Clean Energy 2 (2). https://www.ijsgce.com/uploadfile/2012/1019/20121019125331523.pdf.
Gan, Y., Elgowainy, A., Lu, Z., Kelly, J.C., Wang, M., Boardman, R.D., Marcinkoski, J., 2023. Greenhouse gas emissions embodied in the US solar photovoltaic supply chain. Environmental Research Lettes 18.
Halog, A., Mcgavin, L., 2024, July. 2). Policy Design for solar waste management in a decarbonised, circular economy: A systematic review. https://sciencespo.hal.science/hal-04631714.
Hong, J., Zhou, J., Hong, J., Xu, X., 2012. Environmental and economic life cycle assessment of aluminum-silicon alloys production: a case study in China. J. Clean. Prod. 24. https://doi.org/10.1016/j.jclepro.2011.11.003.
Hou, G., Sun, H., Jiang, Z., Pan, Z., Wang, Y., Zhang, X., Zhao, Y., Yao, Q., 2016. Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. Appl. Energy 164, 882–890. https://doi.org/10.1016/j.apenergy.2015.11.023.
IEA-PVPS, 2017a. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe.
IEA-PVPS, 2017b. Trend 2017 in photovoltaic applications. https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_Trends_2017_in_Photovoltaic_Applications.pdf.
IEA-PVPS, 2018. End-of-Life management of photovoltaic panels: trends in PV module recycling technologies. https://iea-pvps.org/wp-content/uploads/2020/01/End_of_Life_Management_of_Photovoltaic_Panels_Trends_in_PV_Module_Recycling_Technologies_by_task_12.pdf.
IEA-PVPS, 2022. IEA PVPS Trends 2022 Figures and Tables.
IEA-PVPS, 2022. Status of PV module recycling in selected IEA PVPS task 12 countries. Report IEA-PVPS T12-24: 2022). https://iea-pvps.org/wp-content/uploads/2022/09/Report-IEA-PVPS-T12-24_2022_Status-of-PV-Module-Recycling.pdf.
IEA, 2021a. Countries and Regions: Electricity. https://www.iea.org/countries.
IEA, 2021b. Net zero by 2050: a roadmap for the global energy sector. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.
IEA, 2022. Special Report on Solar PV Global Supply Chains. I. E. Agency.
IRENA, 2016. End-Of-Life Management: Solar Photovoltaic Panels. IRENA, Issue. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09.
Ito, M., Lespinats, S., Merten, J., Malbranche, P., Kurokawa, K., 2016. Life cycle assessment and cost analysis of very large-scale PV systems and suitable locations in the world. Progress in Photovoltaics 24 (2), 159–174.
Jain, S., Sharma, T., Gupta, A.K., 2022. End-of-life management of solar PV waste in India: situation analysis and proposed policy framework. Renew. Sustain. Energy Rev. 153. https://doi.org/10.1016/j.rser.2021.111774.
Jingjing, C., Zhaohui, W., Yufeng, W., Liquan, L., Bin, L., De'an, P., Tieyong, Z., 2019. Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2019.03.020.
Latunussa, C.E., Mancini, L., Blengini, G.A., Ardente, F., Pennington, D., 2016. Analysis of Material Recovery from Silicon Photovoltaicc Panels.
Limmanee, A., Sitthiphol, N., Jaroensathainchok, S., Pluemkamon, R., Kotesopa, S., Udomdachanut, N., Hongsingthong, A., 2023. A survey of decommissioned photovoltaic modules from solar power plants in Thailand: performance and second life opportunities. IEEJ Trans. Electr. Electron. Eng. 18 (12), 1853–1994.
Maani, T., Celik, I., Heben, M.J., Ellingson, R.J., Apul, D., 2020. Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels. Sci. Total Environ. 735. https://doi.org/10.1016/j.scitotenv.2020.138827.
Meas, C., 2021. *Policy Proposals for Photovoltaic Waste Disposals of a Floating Solar Farm in Sirindhorn Dam, Thailand* [master's Thesis. Kyoto University. https://diving-rov-specialists.com/index_htm_files/env_31-policy-proposal-photovoltaic-waste-disposal.pdf.
Mgonja, C.T., Saidi, H., 2017. Effectiveness on implementation of maintenance management system for off-grid solar PV systems in public Facilities–A case study of SSMP1 project in Tanzania. Int. J. Mech. Eng. Technol. 8 (7), 869–880.
Ministry of Sustainability and Environment, 2020. The resource sustainability act. Ministry of Sustainability and Resources. Retrieved 13 March 2024 from. https://www.mse.gov.sg/resource-room/category/2020-07-30-resource-sustainability-act/.
Munosuke, K., 2022. 京都、使用済み太陽光パネルの「3R」推進、報告書を公表. Nikkei Business. https://project.nikkeibp.co.jp/ms/atcl/19/news/00001/02609/?ST=msb.
Oteng, D., Zuo, J., Sharifi, E., 2023. An evaluation of the impact framework for product stewardship on end-of-life photovoltaic modules: an environmental lifecycle assessment. J. Clean. Prod. 411. https://doi.org/10.1016/j.jclepro.2023.137357.
Philipps, S., 2023. Fraunhofer ISE: Photovoltaics Report 2022.
Quinn, M., 2022. 2022). With more solar panels entering the US waste stream, EPR policy and standards emerge. Waste Dive. https://www.wastedive.com/news/solar-pv-panel-epr-recycling-washington-nerc/632719/.
Sharma, A., Mahajan, P., Garg, R., 2023. End-of-life solar photovoltaic panel waste management in India: forecasting and environmental impact assessment. Int. J. Environ. Sci. Technol. 1–20. https://doi.org/10.1007/s13762-023-04953-2.
Singh, D., Kaur, J., Molinari, G., Bui, J., Soltani, B., Rajarathnam, G.P., Abbas, A., 2021. Life cycle assessment of disposed and recycled end-of-life photovoltaic panels in Australia. Sustainability 13 (19). https://doi.org/10.3390/su131911025.
Söderman, M.L., 2003. Including indirect environmental impacts in waste management planning. Resour. Conserv. Recycl. 38 (3), 213–241. https://doi.org/10.1016/s0921-3449(02)00149-0.
State of Washington Department of Ecology. (n.d.). *Solar Panels*. Retrieved 27 February 2024 from https://ecology.wa.gov/waste-toxics/reducing-recycling-waste/our-recycling-programs/solar-panels.
Talayero, A.P., Llombart, A., Casado, A., Melero, J., 2018. *Operation and Maintenance in Solar Plants: Eight Study Cases*.
Thangaraj, S., Velury, M., 2016. Importance of Operations and Maintenance in a Solar PV System. Imperial J. Interdiscip. Res. (Ijir) Great Lakes Inst. Manag. Gurgaon, India 2, 4.
US Department of Energy, 2022. Solar Photovoltaics Suply Chain Deep Dive Assessment.
Yang, D., Liu, J., Yang, J., Ding, N., 2015. Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade. J. Clean. Prod. 94, 35–45. https://doi.org/10.1016/j.jclepro.2015.02.003.
Yuan, L., Nain, P., Kothari, M., Anctil, A., 2024. Material intensity and carbon footprint of crystalline silicon module assembly over time. Solar Energy 269, 112336. https://doi.org/10.1016/j.solener.2024.112336.
Yu, H.F., Hasanuzzaman, M., Rahim, N.A., 2023. Recycling end-of-life photovoltaic modules in Malaysia: challenges and potential solutions. In: IOP Conference Series: Earth and Environmental Science. https://doi.org/10.1088/1755-1315/1261/1/012017.