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Environmental Impact and Levelised Cost of Energy Analysis of Solar Photovoltaic Systems in Selected Asia Pacific Region: A Cradle-to-Grave Approach

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Abstract: Sustainability has been greatly impacted by the reality of budgets and available resources as a targeted range of carbon emission reduction greatly increases due to climate change. This study analyses the technical and economic feasibility for three types of solar photovoltaic (PV) renewable energy (RE) systems; (i) solar stand-alone, a non-grid-connected building rooftop-mounted structure, (ii) solar rooftop, a grid-connected building rooftop-mounted structure, (iii) solar farm, a grid-connected land-mounted structure in three tropical climate regions. Technical scientific and economic tools, including life cycle assessment (LCA) and life cycle cost assessment (LCCA) with an integrated framework from a Malaysian case study were applied to similar climatic regions, Thailand, and Indonesia. The short-term, future scaled-up scenario was defined using a proxy technology and estimated data. Environmental locations for this scenario were identified, the environmental impacts were compared, and the techno-economic output were analysed. The scope of this study is cradle-to-grave. Levelised cost of energy (LCOE) was greatly affected due to PV performance degradation rate, especially the critical shading issues for large-scale installations. Despite the land use impact, increased CO_2 emissions accumulate over time with regard to energy mix of the country, which requires the need for long-term procurement of both carbon and investment return. With regards to profitably, grid-connected roof-mounted systems achieve the lowest LCOE as compared to other types of installation, ranging from 0.0491 USD/kWh to 0.0605 USD/kWh under a 6% discounted rate. A simple payback (SPB) time between 7–10 years on average depends on annual power generated by the system with estimated energy payback of 0.40–0.55 years for common polycrystalline photovoltaic technology. Thus, maintaining the whole system by ensuring a low degradation rate of 0.2% over a long period of time is essential to generate benefits for both investors and the environment. Emerging technologies are progressing at an exponential rate in order to fill the gap of establishing renewable energy as an attractive business plan. Life cycle assessment is considered an excellent tool to assess the environmental impact of renewable energy.

Keywords: solar photovoltaic; greenhouse gas emission; levelised cost of energy; energy payback time; return of investment

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Citation: Ahmad Ludin, N.; Ahmad Affandi, N.A.; Purvis-Roberts, K.; Ahmad, A.; Ibrahim, M.A.; Sopian, K.; Jusoh, S. Environmental Impact and Levelised Cost of Energy Analysis of Solar Photovoltaic Systems in Selected Asia Pacific Region: A Cradle-to-Grave Approach. *Sustainability* **2021**, *13*, 396. https://doi.org/10.3390/su13010396

Received: 16 November 2020
Accepted: 29 December 2020
Published: 4 January 2021

1. Introduction

Sustainability and policies promoting economic, financial, and social inclusion will have limited impact if they cannot be sustained. A regional economic forum for different economies or countries can be used to promote a balanced, inclusive, sustainable, innovative, and secured growth by accelerating regional economic integration. The policy commitments and agreements are a good start for such a goal. However, the pursuit of an inclusive and sustainable community should not only end with official statements, but also requires implementation [1]. The Asia and Pacific region has been leading in this field, as reflected in its steady growth from a 60% share of global growth in renewable energy power generation (excluding hydro) in 2016 [2]. All Asia-Pacific Economic Cooperation (APEC) economies have individual energy or emissions intensity targets and have collectively set a target equivalent to reducing energy intensity by 45% between 2005 and 2035 [3]. However, the realities of funding and resources should be considered in the planning and implementation of projects. Likewise, policies that promote economic growth and stability are essential in ensuring a steady stream of financial resources that can be used to promote inclusive growth while convincing consumers of the value of such cost [4].

The current global average cost of electricity from utility-scale solar photovoltaic (PV) is USD 0.053/kWh [5]. This amount represents a 73% decrease since 2010 because of the fast pace of innovation, which has infused competitive pressure into the energy market. The overall reduction depends on drivers, such as balance-of-system (BOS), operation and maintenance, and capital costs. Given the effort of setting suitable policies in place, the cost of PV and renewables can decrease further in the near future [6]. Many countries in Asia have set individual energy and emission targets and adopted national renewable energy policies to achieve sustainability in every development sector [7]. The main drivers to strengthen solar PV cumulative capacity includes policies, regulations, programmes, and government support. These drivers will simultaneously increase the system flexibility, penetrating ambitious power market reform, installing new transmission lines, and the expansion of distributed generation. These new policies are expected to speed up deployment of solar energy [8]. Market and policy frameworks need to evolve in order to manage simultaneously these multiple objectives. Although the deployment timing and implementation transition uncertainty are high, if existing grid integration and infrastructure challenges are addressed, this uncertainty can be reduced with proposed federal tax reforms, international trade, and energy policies, which can have implications for the financial impact of renewables and alter their expansion over our forecast period [9].

Since 2014, China and Japan have long maintained a steady growth of renewable energy capacity compared with other countries in the region (Table 1). This commitment to renewable energy was encouraged by the United Nations' Sustainable Development Goals in fighting climate change and environmental deterioration [10]. China is working actively to meet its 40% energy intensity reduction target by 2025 (from its 2005 base) by expanding public transportation systems and strengthening fuel economy standards [11]. China expects the use of non-fossil primary energy to reach 20% by 2030 with a CO_2 reduction of 60–65% [12]. Malaysia is increasing the implementation of renewable energy, based on the example of countries leading in renewable energy capacity, especially those in northeast Asia [12]. Countries such as Japan, Republic of Korea, and Taiwan are committed to energy efficiency goals well beyond the 45% target. Japan has strengthened its energy efficiency measures by liberalizing its electricity and gas markets and setting a CO_2 reduction goal of 25% by 2030 from base emissions in 2013 [13]. Moving towards a greener future, countries set up goals and plans based on regional progress and targets. However, setting goals requires comprehensive analysis on the renewable technology and its implementation, in this case, solar photovoltaic (PV) systems.

An operating PV system has a significantly lower environmental and techno-economic impact compared to any electrical generation power plant, but the cost is higher. Thus, a thorough analytical foundation is needed to demonstrate the benefit of a PV system and provide reliable data for evaluation purposes for future development guidelines. This study aims to assess 6 PV systems characteristics from 3 different countries, namely, Thailand, Indonesia, and Malaysia. The three different types of systems include standalone, rooftop, and solar farm systems. The different PV systems will be analysed using life cycle assessment (LCA) and life cycle cost assessment (LCCA). Results are to be compared under functional unit of CO_2 equivalent emission per power generation (CO_2 eq/kWh) of a PV system, emission per square meter (CO_2 eq/m^2), and capital cost of system per power generation (USD/kWh) of the PV system.

Table 1. Total Solar Energy Capacity in Asia (2014–2018) [13].

Asia Countries	Total Solar Energy Capacity (MW)				
	2014	**2015**	**2016**	**2017**	**2018**
Brunei Darussalam	1	1	1	1	1
Cambodia	9	12	18	28	28
China	28,402	43,552	77,802	130,816	175,032
Chinese Taipei	620	842	1245	1768	2618
India	3518	5396	9647	17,873	27,098
Indonesia	42	51	58	59	60
Japan	23,339	34,150	42,040	49,040	55,500
Kazakhstan	5	57	57	59	209
Korea DPR	5	8	10	11	11
Korea Rep	2481	3613	4502	5835	7862
Malaysia	166	229	279	317	438
Philippines	23	165	759	886	886
Singapore	26	46	97	116	150
Thailand	1304	1425	2451	2702	2725
Viet Nam	5	5	5	8	106
Total	59,946	89,552	138,971	209,519	272,724

2. Methodology

Three types of PV systems were analysed for this comparison, solar farm, solar rooftop, and solar standalone system. An LCA and LCCA study is carried out in four distinct phases [14].

Phase 1: Goal and scope of study. The life cycle study is a process-based method that covers the entire system from cradle to grave. Within this scope, two different methods, experimental study and simulation tool approach, strengthen the data evaluation. The scope of the study assumed a 25-year lifetime for all PV systems and case studies were based on a two-year matured system (Figure 1).

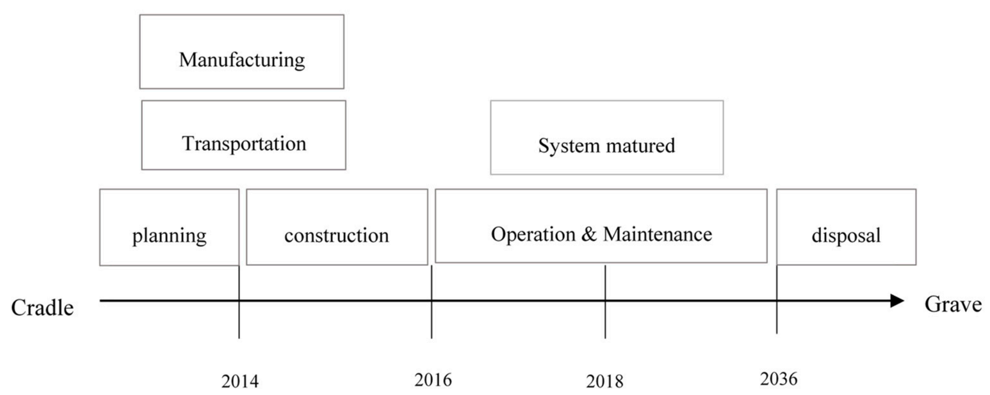


Figure 1. Photovoltaic (PV) systems life cycle timeline.

The system boundaries covered the eco-sphere and techno-economic effects, but not techno-sphere and social effects. This approach accounted for impacts only related to normal operations of processes and products, based on the assumption that no spill, accident, and/or natural disaster occurs throughout the entire process. The study estimated the effects based on the average maintenance and replacement of the three case studies [15].

Phase 2: Life cycle inventory (LCI). LCI is based on the identification and quantification assessment of the field in accordance with the environmental assessment methods [16]. The inventory data primarily include all materials and energy flows between life-cycle phases based on the designed framework [17]. Primary and secondary data were utilised to complete the inventory using the Ecoinvent database on SimaPro software. Data collection and calculations were associated with the functional system [18], emission per square meter (CO_2 eq/m^2), CO_2 equivalent emission per power generation (CO_2 eq/kWh) of a photovoltaic system, and capital cost of the system per power generation (USD/kWh).

Three types of PV balance-of-system (BOS) for the case study were identified. (i) Solar stand-alone, a non-grid-connected building rooftop-mounted structure (Figure 2), (ii) solar rooftop, a grid-connected building rooftop-mounted structure (Figure 3), (iii) solar farm, land-mounted structure (Figure 4).

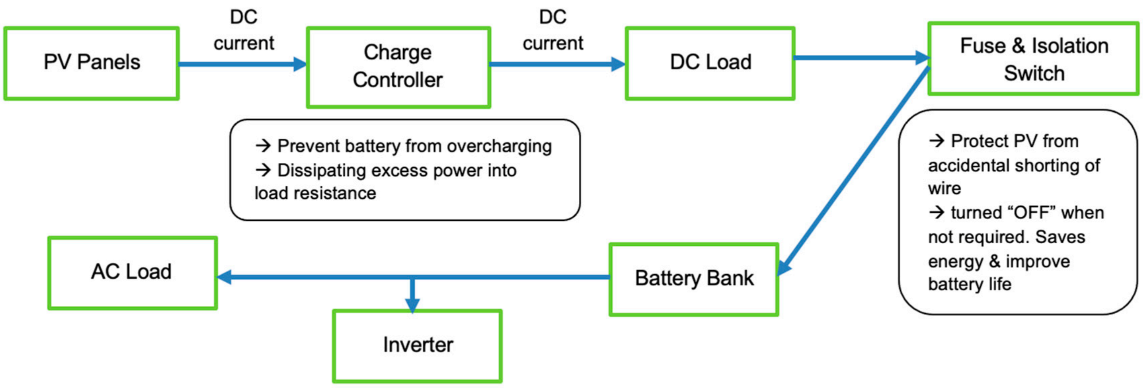


Figure 2. Solar standalone system balance-of-system (BOS).

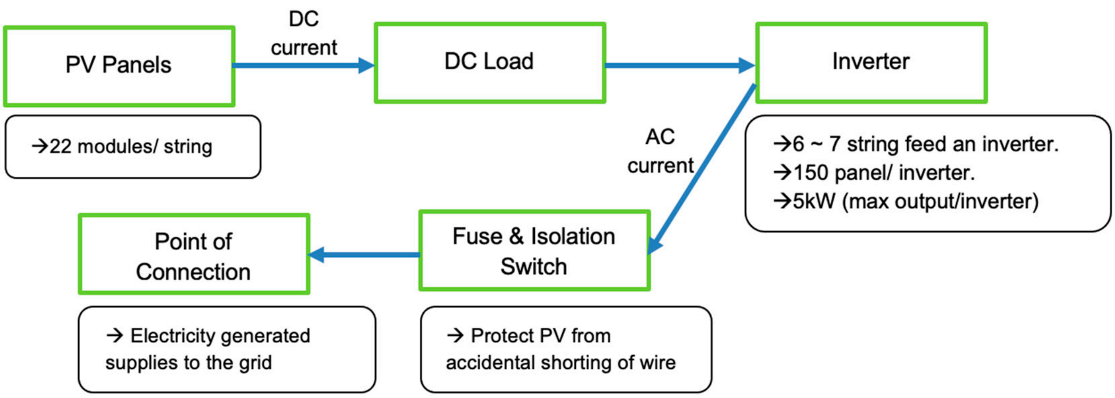


Figure 3. Solar rooftop system BOS.

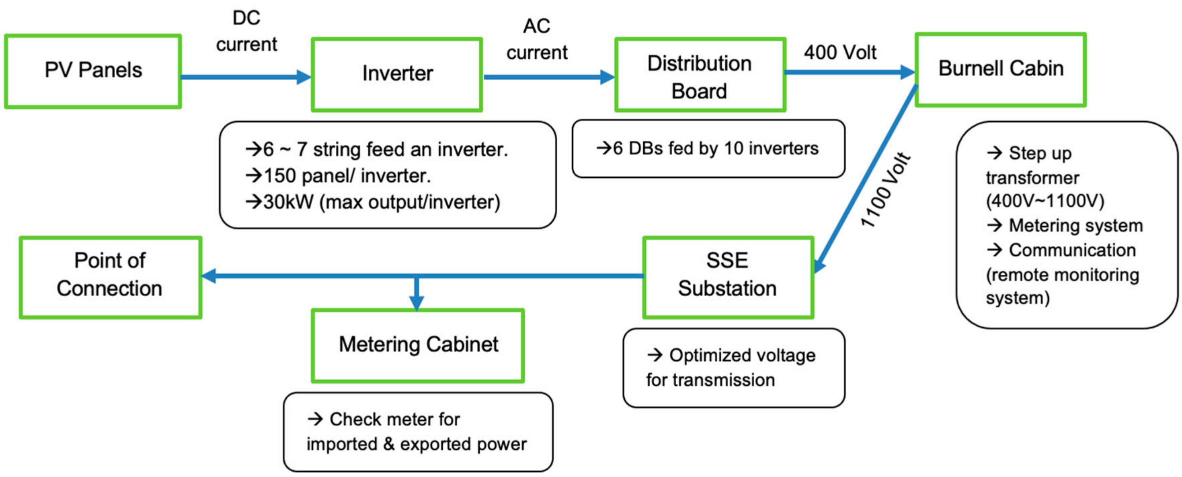


Figure 4. Solar farm system BOS.

The whole standalone system is connected to a string that holds 20 PV modules due to its low peak power. The generated DC current passes through the charge controller, which prevents the battery from being overcharged and dissipates excess power from load resistance. The fuse and isolation switch protect the PV from accidental shorting of wires and automate switching to off when PV is not generating electricity. The fuse and isolation switch are optional to the complete system, but its implementation can save energy and improve battery life. A battery bank is typical for a stand-alone system because it stores excess energy generated and allows flexible usage time at night. The stored electricity is directed to the DC load demand before being transferred to the inverter and converted into AC current for the AC load.

The BOS for a rooftop PV system can include one or more strings, in accordance with market demand. The generated DC current is converted into AC through the inverter, which can uphold about 6 to 7 strings. If the system production is sufficient, a distribution board is needed for load power distribution that can be fed by 10 inverters. If the power production fails to reach up to 10 inverters, a distribution board is unnecessary and is connected via a stand-alone system. A substation is set to a 11 kV switchgear to manage the system voltage before electricity export to the grid. If necessary, a transformer can be included in the loop before exporting the electricity.

The BOS for the solar farm uses an entirely different system due to the large volume of electricity management. The system utilizes a distribution board and a Burnell Cabin bundle, which includes a step-up transformer, a metering system, and a communication or remote monitoring system. These bundles handle large voltage efficiently. A substation is required as a switchgear to manage the system voltage before exportation to the grid. A metering cabinet is needed to record the imported and exported power. Finally, the power reaches the point of connection to the main national grid.

Phase 3: Life cycle impact assessment (LCIA). LCIA was separated into two parts; energy and emission impact analysis and economic fluctuation impact analysis. The results were combined and further refined for discussion. The various system parameters were normalized under the specified functional unit in Phase 2.

(a) Energy and emission impact analysis

Cumulative Energy Demand (CED) is the aggregate energy used during systems life cycle production. Energy payback is the energy produced by RE technology for the 25-year lifetime of the system, divided by the energy consumed to initially manufacture the system itself. The energy payback time (EPBT) is calculated based on the following Equation (1) [19]:

$$\text{EPBT} = \text{CED (MJ)}/\text{LEP (MJ)}, \quad (1)$$

$$\text{CED (MJ)} = E_M + E_T + E_I + E_D, \tag{2}$$

Localized energy production (LEP) is the cumulative energy produced by the PV system for 25 years. Cumulative energy demand (CED) in Equation (2) is the energy consumed during; manufacturing phase (E_M), transportation phase (E_T), installation phase (E_I), and disposal phase (E_D). The energy consumed to manufacture PV system is based on country grid electricity mix. Greenhouse gas (GHG) emission rate from the grid electricity mix can be calculated as Equation (3) below [20]:

$$\text{GHG emission rate}\left(\frac{gCO_2}{kWh}\right) = \frac{\text{Total GHG emission during life cycle}\ (gCO_2)}{\text{Annual power generation}\left(\frac{kWh}{year}\right) \times \text{Lifetime (year)}}. \tag{3}$$

The avoided GHG emission (CO_2 equivalent emission/kWh) of the PV system that produce clean energy to the grid for 25 years can be calculated with Equation (4):

$$G = \frac{W}{I \times \eta \times PR \times LT \times A}. \tag{4}$$

Where I is irradiation (kWh/m^2/year), η is conversion efficiency, PR is the performance ratio, LT is PV lifetime (year), and A is the area of module (m^2). Emission reduction (ER) refers to the difference between baseline and project emissions when the same amount of power is generated.

$$\text{ER (emission reduction)} = \text{BE (baseline emission)} - \text{PE (project emission)}, \tag{5}$$

$$BE = E_G \times EF_{grid}, \tag{6}$$

BE is the amount of emissions generated by the country grid electricity mix when generating the same amount of power as the PV power plants; PE is the quantity of emissions generated by PV power plants, which is zero; E_G is the annual electricity generation of the PV system project, (MWh/year); and EF_{grid} is the combined emission factor for the grid, (tCO_2/MWh) [21].

(b) Economic fluctuation impact analysis

Economic analysis is a time-dependent formula with a variety of variables, including the discount factor, time-variant failure probability at time, single present value factor, and annuity present value factors. The levelised cost of energy (LCOE) as shown in Equation (7) only considers the cost of the life cycle and the amount of energy generated; it can eliminate favouritism or bias between technologies [22].

$$LCOE = \frac{LCC}{LEP}. \tag{7}$$

LEP is the amount of energy generated by the PV power plant for 25 years. A low value of LCOE is preferred because it shows that a small amount of money is needed to produce one unit of energy. The overall cost of the project (LCC) is calculated with Equation (8) [23]. This cost is influenced by several parameters, such as investment (C_I), operating, maintenance and repair (C_{OMR}), replacement (C_{rep}) and other costs (C_O), and residual value (C_{res}). LCC analysis is an analysis based on a baseline case study and uses an assumption value to forecast future value. In this study, electricity price changes are not considered since LCC uses a discounted rate to be able to compare the results over three different regions.

$$LCC = C_1 + C_{OMR} + C_{rep} + C_O - C_{res} \tag{8}$$

The payback period is the number of years required to recover the initial investment or early outflow. A short PB period is highly coveted, because capital gains will be available early and will reduce the risk of the investment. The equation below was used to obtain the refund period. PB was calculated by using the following Equation (9) [24]:

$$PB = (n - 1) + \left[\frac{(C_1 - \text{Cumulative cash flow before n})}{\text{Current cash flow n}}\right] \quad (9)$$

For this calculation, n is the recovery year when annual cash flow exceeds the initial investment. Two types of PB periods were included in the economic analysis: a simple PB period (SPB) and the discounted PB period (DPB). The SPB period ignores the time value of money, whereas the DPB period of the discount considers the time value of money.

Phase 4: Interpretation. Data validation and verification were conducted thoroughly with the reference flow, as stated in the system boundaries, ISO standards for environmental and policy guidelines, Ecoinvent database for material value and environmental impact assessment [25].

Economic differences between regions were compared in terms of regional policy standards, regional tariff extraction and financial rate levelling (Figure 5). The values were assessed and calculated based on the benefits received for the power generated based on market economies [26]. Impact assessment results were interpreted based on GHG emissions and financial outcomes without considering geographical impact due to noncomparable bases.

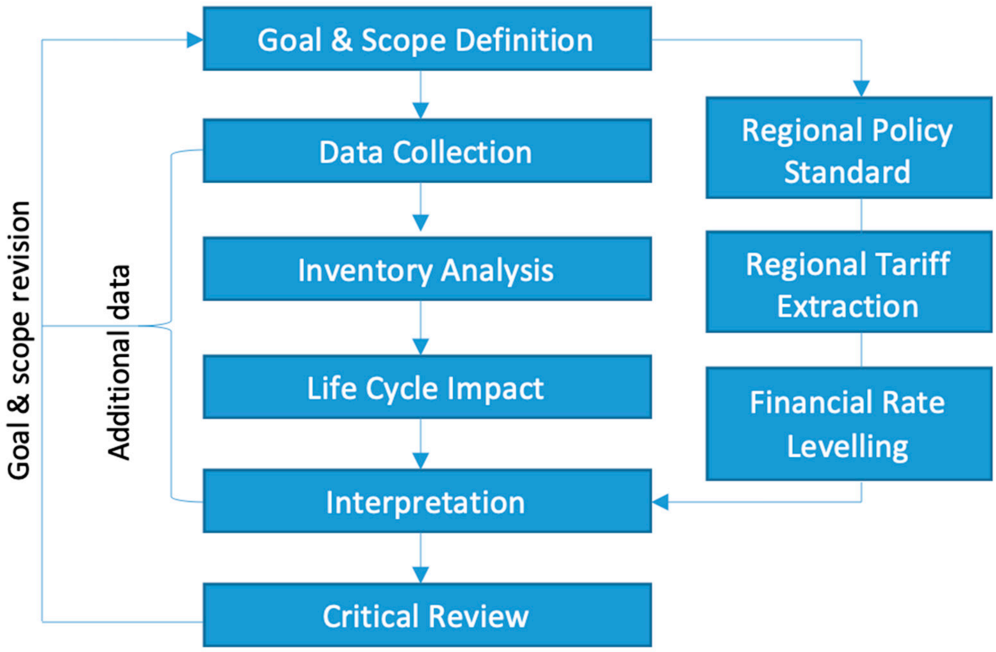


Figure 5. Study framework.

Selected Case Studies

Economic fluctuation analysis was normalized with a basis of comparison for purposes between country economies, which have variety of market value. In the assessment of variation of the systems and product market value during the selected timeline, the case study systems were expected to fulfil all the listed criteria below:

i. A two-year matured system;
ii. Location in Asian countries with a tropical climate;
iii. Commercial system owned by an individual or single company;
iv. The use of a crystalline-based (monocrystalline/polycrystalline) or amorphous PV system only.

The criteria listed above are applied to typical systems implemented in numerous countries due to their long-established results and trust by consumers. Two other economies, namely, Thailand and Indonesia, were selected within the APEC region for comparison with Malaysia. These countries were selected not only because of their tropical climate, but also because of their closely related energy resources, which drive the policies in a similar direction. The introduction of PV in these neighbouring countries is also growing at a constant rate and comparable to that of Malaysia. Figures 6–8 show the energy mix for Malaysia, Indonesia, and Thailand. The energy mix of the country is a key factor that affects the type of energy consumed during an entire system life cycle.

The case studies chosen are as shown in Table 2. Case 1 is located in Malaysia with an annual average radiation of 1571 kWh/m^2/year. The standalone PV system was installed on the roof of a single-story house in 2015. The system consists of 12 polycrystalline panels which cover an effective area of 19.22 m^2. The power capacity of Case 1 is 3.0 kWp and the PV system was installed by the owner to support renewable energy development.

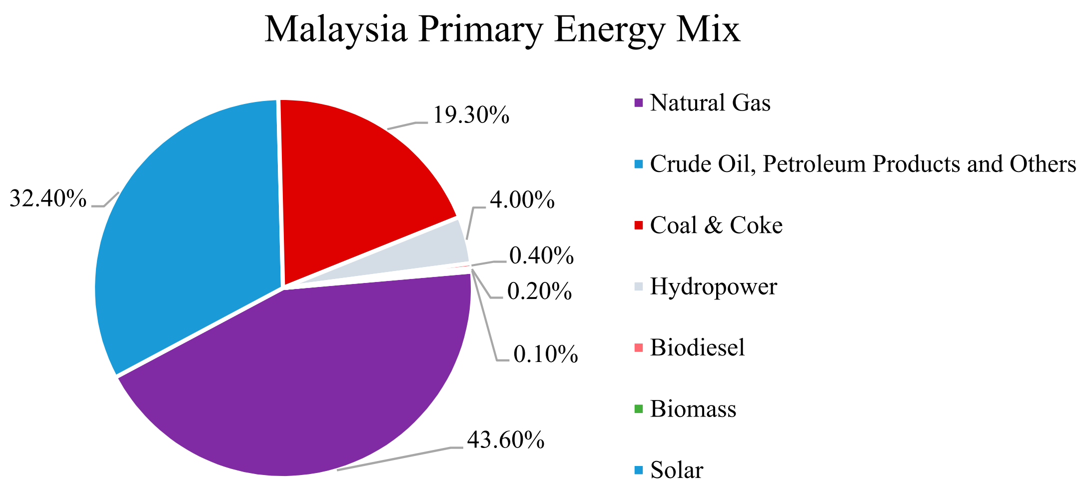


Figure 6. Malaysia primary energy mix. Source: [27,28].

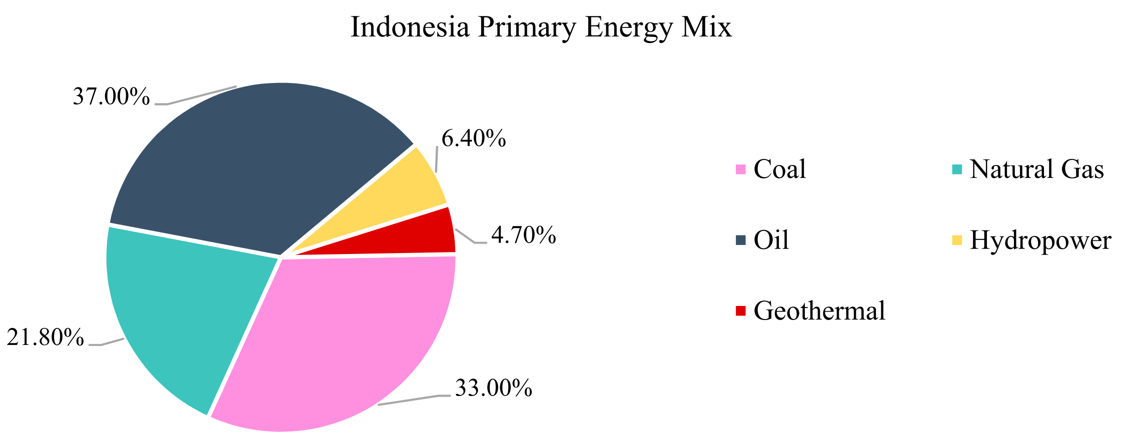


Figure 7. Indonesia primary energy mix. Source: [27,28].

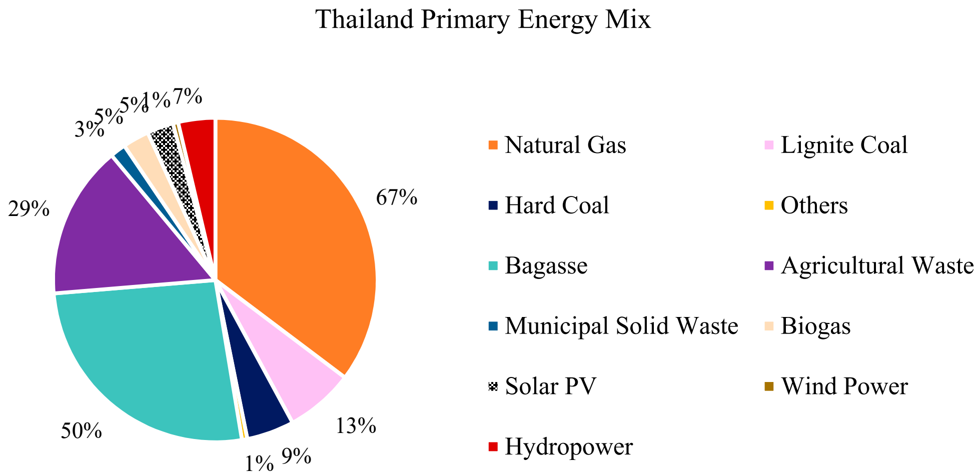
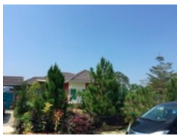


Figure 8. Thailand primary energy mix. Source: [27,28].

Table 2. Selected case studies in Asia.

Case	Location	Annual Average Irradiation	No. of PV Panels and Model	Panel Effective Area	Power Capacity	Service Year
 Case 1	Malaysia (2′43′ N, 101′57′ E)	1571 kWh/m^2/year	12 unit SHARP Poly-Si-ND-235QCJ	19.22 m^2	3.0 kWp	2015
 Case 2	Thailand (18.7′ N 98.9′ E)	1672 kWh/m^2/year	2808 unit Solartron Polycrystalline SP250	4548.98 m^2	702 kWp	2011
 Case 3	Malaysia (5.22′ N 100.24′ E)	1685.39 kWh/m^2/year	1320 unit Polycrystalline	2138.4 m^2	200 kWp	2016
 Case 4	Thailand (18.7′ N 98.9′ E)	1672 kWh/m^2/year	32 unit Amorphous Silicon	51.84 m^2	2.5 kWp	2011
 Case 5	Malaysia (2.3 N, 102.3 E)	1571 kWh/m^2/year	29,092 unit Yingli PANDA Monocrystalline	47,129 m^2	8.0 MWp	2014
 Case 6	Indonesia (1.3 N, 116.3 E)	1888 kWh/m2/year	8568 unit Adyasolar SP240-24M Monocrystalline	13,880.16 m^2	2.0 MWp	2014

Next, Case 2 is located in Thailand. It is a standalone solar farm system which only generates electricity for the campus area and does not sell its excess electricity. The power capacity of the system is 702 kWp with 2808 polycrystalline panels over 4548.98 m^2. The system started operating in 2011 with an annual average irradiation of 1672 kWh/m^2/year. The standalone solar farm is considered a high-risk investment without any generated income. Its payback relies only on its electrical consumption savings over time.

Case 3 is located in Malaysia. The 200 kWp, polycrystalline PV system is mounted on the large rooftop of a factory. The 2138.4 m^2 flat rooftop area is now covered with 1320 photovoltaic panels since 2016. Annual average irradiation reaches 1685.39 kWh/m^2 /year. Although the system is expected to generate good income with a short payback period, the factory area appears to interfere with the effectiveness of PV production capability due to heavy dust accumulation on top of the panels. This could greatly affect the power generation and efficiency of the panel if it is not regularly maintained.

The fourth case study is located in Thailand and was installed in 2011. It is a small 2.5 kWp grid-connected system, mounted on the slanted-roof structure of an event hall. There are only 32 amorphous PV panels with an effective area of 51.84 m^2. The annual average irradiation is 1672 kWh/m^2/year, which is expected to be enough in supporting the small, rarely used event hall. The excess production of electricity on a non-event day can be sold to the grid for income.

Next, Case 5 is an 8.0 MWp solar farm system located in Malaysia and built in 2014. The system installation includes 29,092 highly efficient monocrystalline PV panels on vacant land. The 47,129 m^2 piece of land was bought and managed by a company, which adds to the investment cost. The annual average irradiation is 1571 kWh/m^2/year and the installation is expected to produce high power generation yields. The PV system is maintained and cleaned regularly to preserve its efficiency throughout the years.

Finally, Case 6 is located in Indonesia. The 2.0 MWp PV system started operation in 2014. It has 8568 monocrystalline panels installed on 13,880.16 m^2 of land. The annual average irradiation is 1888 kWh/m^2/year and it is expected to boost power output by using a transformer to maximized electricity generation. The PV system is owned partially by the government and is maintained regularly all year round. These are the 6 case studies selected for analysis using LCA and LCCA.

3. Results and Discussion

3.1. Environmental Impact

All graphs showed a similar pattern in which PV manufacturing dominates the total cumulative energy demand (CED) of any type of system. Normalized CED is the energy consumption based on installed system capacity and percentage of the mix; the difference is projected in Figure 9. The country energy mix is highly affected by energy consumption with respect to fossil fuels. Large-scale standalone solar farms typically require a massive BOS, but the case study included two systems that are not grid-connected only support a certain designated area, and whose energy is not for sale. Thus, the energy consumption is second to that of PV manufacturing in solar-farm case studies. This case is different from the small-scale standalone system in Case 1, where the decommissioning and disposal phase is greater than the BOS. The difference may be due to the need for disposal management that dominate in small systems. A typical solar system CED is mostly from the manufacturing PV phase (Cradle) (Figure 9).

According to the CED analytical results, PV manufacturing dominated the energy demand in all the case studies in the three countries surveyed. Energy input from country-grid electricity mix is an important factor that affects the CED of a PV system. All system CEDs derive mainly from PV manufacturing and emit high GHG emissions, especially for large-scale systems. However, the large-scale generation quickly covers the CED coupled with the use of amorphous technology PV, which accounts for the lowest manufacturing CED. According to Kourkoumpas et al., (2018) manufacturing of PV, specifically the ingot growing method, consumes the most energy, about 45% of the total primary energy [29].

The embodied energy of materials is highly correlated with the production of technology and components. The embodied energy content in a multi-crystalline silicon PV panel ranges between 1095–4312 kWh/m^2 and accounts for 85% of the PV module [30]. The value can be reduced depending on the clean energy mix of a country such as in Norway [31].

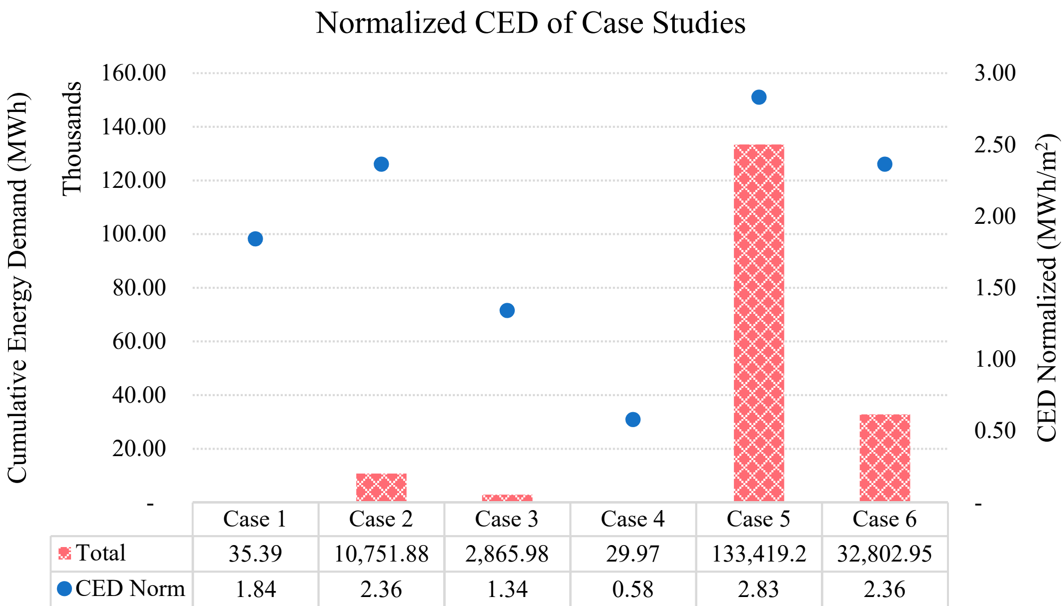


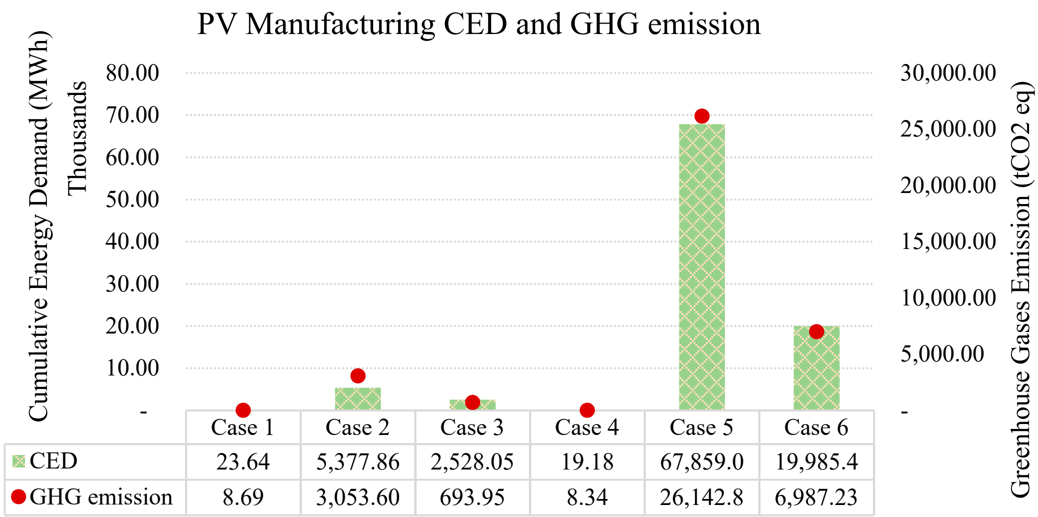
Figure 9. Normalized cumulative energy demand (CED) of case studies.

The embodied energy and carbon coefficients (Table 3) determine the embedded energy and embedded carbon of each material in a solar PV BOS. Mason et al. observed a 71% reduction in life cycle energy BOS requirements by using an advanced system design, which implies the potential for near-zero life cycle GHG emissions with future development [32]. Based on industrial fuel mix, multi-crystalline silicon (m-Si) panel uses 4750 MJ/m^2 in the manufacturing process, which is slightly higher than that of polycrystalline silicon (p-Si) panel (4070 MJ/m^2). This situation leads to a greater GHG emission impact of 0.242 tCO_2/m^2.

Table 3. Material embedded energy and carbon coefficient (Ice v2).

Materials	**Embedded Energy and Carbon Coefficient**			**Comments**
	EE (MJ/kg)	**EC (kgCO_2/kg)**	**EC (kgCO_2e/kg)**	**EE: Embedded Energy EC: Embedded Carbon**
Aggregate (general)	0.083	0.0048	0.0052	Industrial fuel consumptions
Aluminium (general)	155	8.24	9.16	Assumed ratio
Primary Glass	15.00	0.86	0.91	Includes CO_2 emission from primary manufacturing
Silicon	2355	-	-	
Lithium	853	5.30	-	
Water	0.01	0.001	-	
Plastic	80.50	2.73	3.31	Includes feedstock energy (EU)
Wire	36.00	2.83	3.02	
	MJ/m^2	kgCO_2/m^2		
Monocrystalline PV	4750	242		Industrial fuel mix
Polycrystalline PV	4070	208		

Energy consumption from PV manufacturing is approximately 60–70% of the entire life cycle in all types of PV systems. This energy consumption factor could lead to advancements in manufacturing methods and technological development. Various types of PV panels involve different production methods and energy consumption rates. Figure 10 shows that the CED of monocrystalline PV production is the highest, and that of polycrystalline PV and amorphous silicon is the lowest. This indicates that the type of PV used in the system contributes greatly to the energy impact factor. According to Ludin et al. (2018), the CED of thin-film PV is lower in terms of energy payback time PBT) in comparison with that of monocrystalline (m-Si) and polycrystalline (p-Si), with its consumption balanced to its production efficiency [33]. However, in terms of PV performance, p-Si was more efficient in solar conversion independent of the location. Annual conversion efficiency for m-Si and p-Si was around 12.8%, whereas that for a-Si reached 8% [34].



	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CED	23.64	5,377.86	2,528.05	19.18	67,859.0	19,985.4
GHG emission	8.69	3,053.60	693.95	8.34	26,142.8	6,987.23

Figure 10. CED of different types of solar panel manufacturing and greenhouse gas (GHG) emission by case study.

According to the CED of all case studies, the EPBT showed different patterns (Figure 11). Case 4 had the fastest EPBT of 0.7 years because the system consumed a small amount of energy, particularly from amorphous silicon manufacturing. Solar PV systems using thin-film panels are preferable due to their low EPBT periods, in addition to their low GHG emissions. GHG emissions (or GWP) is approximately 9.4–104 g CO_2-eq/kWh for polycrystalline PV systems, 44–280 g CO_2-eq/kWh for monocrystalline PV systems, and 15.6–50 g CO_2-eq/kWh for amorphous PV systems [35]. Energy PB is greatly influenced by various components used and activities during the life cycle phases, which include a 25-year lifetime. High energy PB years by Ecoinvent included the production of the relevant components, but even just including PV panel production results in a high global warming potential [36]. EPBT calculations are heavily influenced by the amount of sunlight received by a PV system. The more sunlight received, the more kWh the PV system will produce, and the faster the PV system will offset the energy it consumed to manufacture it. A 2006 study reported the EPBT of one to two years based on an average of 4.7 peak sun-hours received in southern Europe. If you live in a sunny climate, then the EPBT will be low. The current overall worldwide average EPBT is one to three years (rather than one to two years for southern Europe) and accounts for cloudy locations across the globe [37].

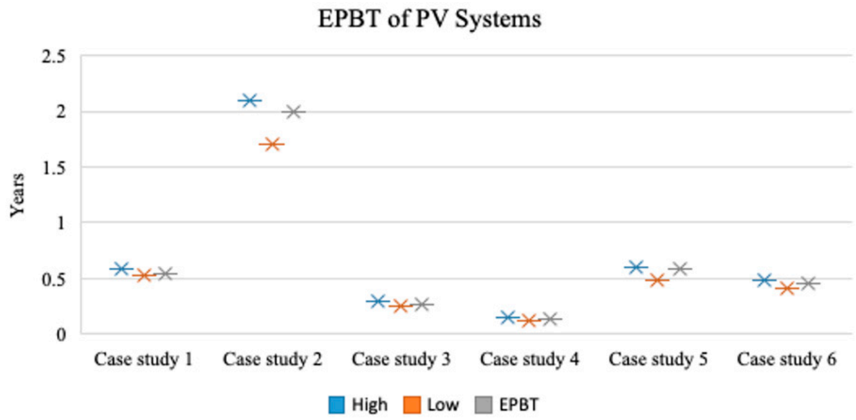


Figure 11. Energy payback time (EPBT) of PV systems varies based on maintenance energy investment.

Case 1 had the highest EPBT of 3.6 years, due to the large CED allocation in the battery energy storage system which entails a significant cost compared to a grid-connected system [38]. Solar-farm Cases 5 and 6 had the same EPBT range, which is 2.6–2.7 years, due to energy production. Although both solar farms achieved a high CED, their energy production was sufficient to compensate the consumed energy. Case 2, which resulted in the longest EPBT of two years, showed that a large-scale standalone solar farm required a large CED in construction and PV manufacturing. However, its energy generation was insufficient to cover its CED over a short time period. This value was also affected by its elevated energy consumption for operation and maintenance. The system maturity also played a role, as indicated by various improvement gap indicators, such as efficiency increment and conversion [39]. Case 3 exhibited a remarkable EPBT of 3.2 years for a commonly used polycrystalline technology, compared with the CED of 12.61 MJ/Wp and an EPBT of 2.2–6.1 years for multi-crystalline installation in China.

The GHG emission by the PV system capacity (Figure 12) showed that the ratio of GHG emitted over the PV system capacity normalized the comparison because the PV systems because they vary in size and total energy consumption. For a typical silicon solar PV technology, the GHG emission rate ranges between 29–671 g CO_2eq/kWh for m-Si. Meanwhile, the p-Si range is around 12.1–569.0 g CO_2eq/kWh [33]. The ratio for the entire system consistently ranged within 2.8–4.2. Magrassi et al. (2020) reported, 100 kWp m-Si PV plant emits 43 g CO_2eq/kWh compared to Case 3, 200kWp p-Si PV plant emits 569 g CO_2eq/kWh. The large difference in value could be due to manufacturing of PV and installation phase of the system [40]. A larger ratio means that a greater amount of GHG is emitted for a certain system capacity. For Case 2, the ratio was extremely high despite the comparably lower GHG emission compared with that of other large-scale solar farms. This result means that the system produces a large amount of GHG emissions over a small-scale system, either due to local PV manufacturing process or power peak of the PV panel itself.

Figure 13 shows the annual avoided GHG emissions by case study. The larger the system capacity installed, the greater the annual electricity generated, which replaces the regional electricity mix generated for the grid. This result supports the argument that a large-scale solar farm with high energy production is more viable than other small PV systems due to its carbon payback capability. A small-scale solar system is also viable over a long period, but its carbon emissions per 1 kWh production is extremely low [41]. Thus, carbon payback requires a long time. Moreover, GHG emissions over 1 MJ of energy consumption by each life-cycle phase shows that the manufacturing and disposal stages of the PV systems emit the highest amount of carbon emissions. The reasons are that both local manufacturing (particularly that of amorphous silicon) and the effect of the electricity grid mix has an increased value of GHG. The GHG emitted by monocrystalline PV manufacture is relatively high over 1 MJ of energy consumed, compared with that of polycrystalline PV [42].

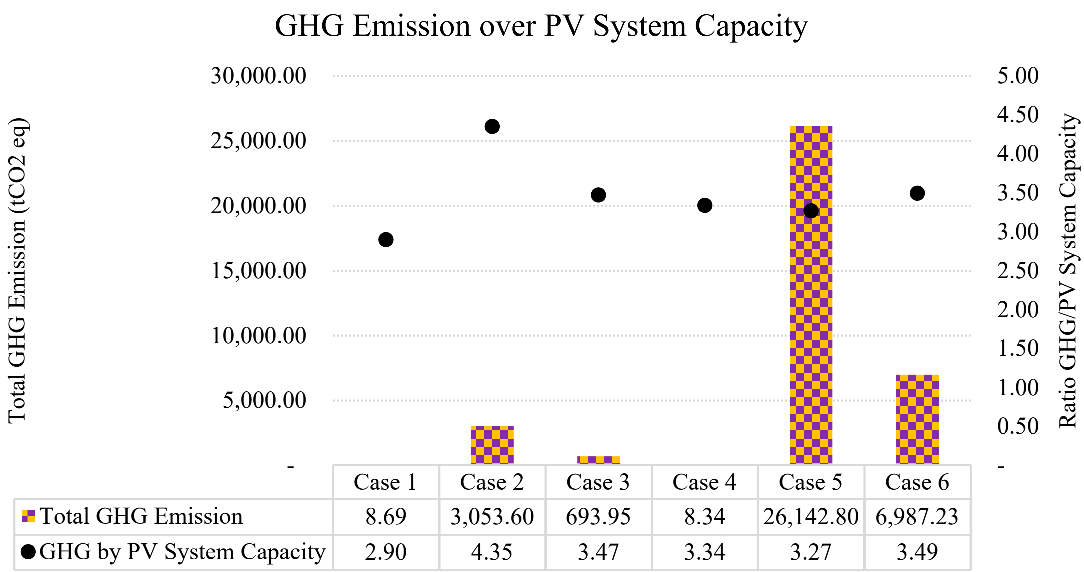


Figure 12. GHG emission normalized by PV system capacity.

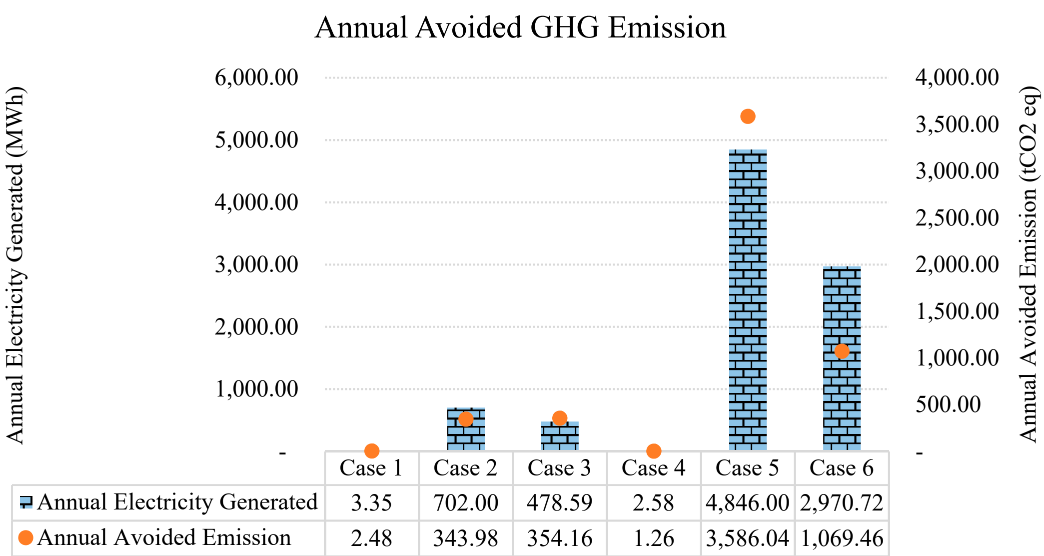


Figure 13. Case Studies annual avoided GHG emission.

3.2. Economic Impact

Economic impact studies have been conducted on various products as a platform for evaluating value-to-money along the entire value chain [43]. The LCC and LCOE for all case studies is calculated based on different discount rates (2%, 4%, and 6%). From Figure 14, the LCC value decreased as the discount rate increased. All the case studies followed this trend, except for Case 3 whose LCC value increased as the discount rate increased. This anomaly is due to the total cost of operational, maintenance, and repair cost (C_{OMR}), replacement cost (C_{rep}) and residual value (C_{res}) at 2% (−USD 22,952.14), which are substantially less than those at 4% and 6%, −USD 4437.34 and USD 4673.74 respectively. Thus, at a 2% discount rate, the inflow of cash (C_{res} value) is greater than at 4% and 6% discount rates.

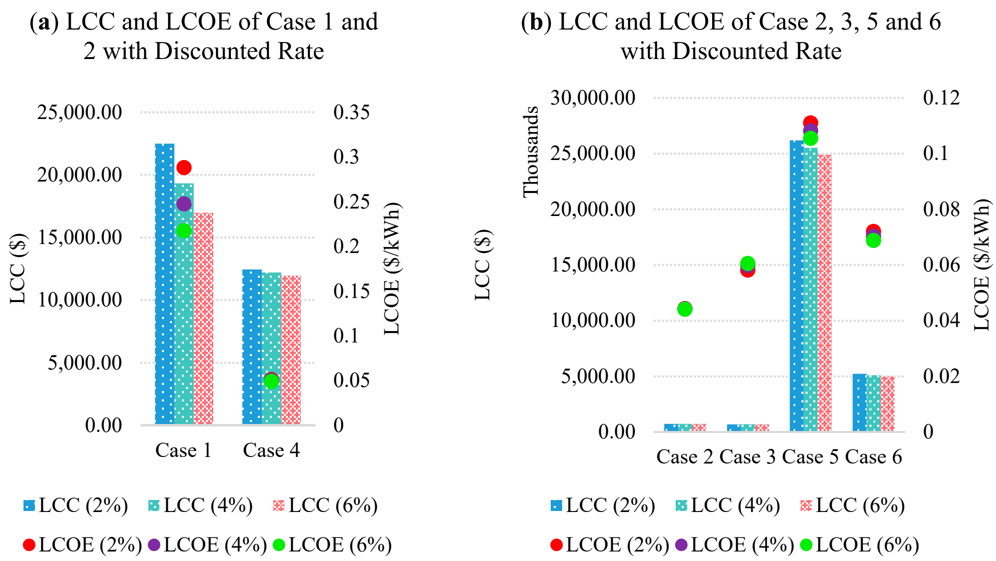


Figure 14. (**a**) Life cycle cost (LCC) and levelised cost of energy (LCOE) of case 1 and 4. (**b**) LCC and LCOE of case 2, 3, 5, and 6 based on different discount rates of 2%, 4%, and 6%.

The highest LCC values at 2%, 4%, and 6% is that of Case 5, followed by those of Cases 2, 3, and 6. Solar farms cost the most because they are primarily built-in large scale, thus requiring the purchase of land, cost for land clearing and management, building of facilities, road access, and other factors. For example, in Case 5, these costs consumed about 20% (USD 4,200,000.00) of the initial investment. As expected, large-scale PV systems need enormous quantities of PV modules, inverters, support structures, and electrical systems. These costs consumed USD 15,750,000.00, which is 75% of the initial investment cost. The same condition applies to Case 6 where PV modules and other BOS systems cost the most. On the other hand, the lowest LCC value was that of Case 4, followed by Case 1. This was due to the small amount of equipment for the Case 4 system compared with Case 3. The system for Case 4 consisted of 32 units of PV modules, an inverter and a charge controller. Meanwhile, the Case 3 system consisted of 1320 units of PV modules, eight inverters, and large BOS systems, which cost a considerable amount. Case 4 did not use batteries, although the quantity of PV modules (the most expensive component) was considerably greater than that of stand-alone case studies. Batteries contributed substantially to the LCC value because they need to be replaced every three-years given their lifetime.

Discount rates play an important role in the calculation of LCC and a similar role in LCOE. The smallest discount rate will contribute lower results in LCC and LCOE together [44]. Thus, a low discount rate improves the reduction of the overall cost of the PV system, reducing the cost of producing one unit of energy [45]. The LCOE for all case studies in Table 4 showed a comparatively higher value than the other categories of PV systems, that is, Case 1. The LCOE for Case 1 recorded values of 0.2881, 0.2475, and 0.2173 USD/kWh discount rate of 2%, 4%, and 6% respectively. A stand-alone system produces a high LCOE value because the cumulative energy generated (LEP) extremely low compared with their LCC value [46]. In this case, Case 1 produced 78,033.60 kWh throughout its lifetime, but the LCC value was extremely high (at 2%, 4% and 6%), thus resulting in a high LCOE value. However, the value is considered on the higher end among the other PV systems and comparable to the LCOE variety range of 0.06–0.12 USD/kWh of an implausible PV/T system, as summarized by Gu et al. (2018) [47].

The lowest LCOE value was observed for the rooftop PV system. Both cases showed good performance in LCOE values, especially Case 4. The rooftop PV system can achieve a low LCOE value because it can produce a large amount of LEP. For example, Case 4 can produce 243,552.50 kWh in its 25 years of operation compared with Cases 1, which produce 78,033.60 kWh, these values are notably low for their LCC. Meanwhile, Case 3 can produce 11,640,331.37 kWh, similar to a solar farm mounted on the roof of a building. Another reason that a rooftop can achieve low LCOE is their low LCC value compared with their LEP value. Rooftops require no land, thus saving a considerable amount in property investment. This condition eventually lowered the LCC value. Unlike solar farms, purchasing land results in an extra cost which contributes to the high LCC value.

Table 4. Findings summary main analysis.

	Life Cycle Cost, LCC (USD)			Levelized Cost of Energy, LCOE (USD/kWh)		
Discount Rate	**2%**	**4%**	**6%**	**2%**	**4%**	**6%**
			Stand-alone PV			
Case 1	22,480.70	19,310.94	16,959.09	0.2881	0.2475	0.2173
Case2	725,147.86	723,662.66	721,783.24	0.0443	0.0442	0.0441
			Rooftop PV			
Case 3	677,047.86	695,562.66	704,673.74	0.0582	0.0598	0.0605
Case 4	12,439.22	12,198.39	11,958.97	0.0511	0.0501	0.0491
			Solar farm			
Case 5	26,184,865.32	25,509,958.23	24,889,130.50	0.111	0.1082	0.1055
Case 6	5,218,893.56	5,100,949.46	4,988,828.95	0.072	0.0703	0.0688

The fastest simple payback (SPB) was recorded in Case 6, which presented a PB of 6.26 years, followed by Case 4 with 7.96 years, Case 3 with 8.45 years, Case 5 with 9.75, and Case 2 with the slowest PB period of 13.28 years (Table 5). For Case 1, PB was impossible to attain because the last year of operation, the 25th year of operation, the savings was USD 1624.55. USD 6650.00 is needed to attain SPB. As for discounted payback (DPB), according to Allouhi et al. 2020, the current market conditions in Morocco show that the economic analysis of the monocrystalline-Si/ polycrystalline-Si type system was the technology offering the longest discounted payback period with the 20-city average of 28.62 years [34]. In this study, the fastest DPB (6.76 years) was observed in Case 6 at a 2% discount rate, followed by Case 6 at 4% with DPB of 7.36 years, and Case 6 at 6% with DPB of 8.1 years. These values are comparable to the shortest DPB of 17.11 years for p-Si and 21.62 years for m-Si [34]. The slowest DPB was that of Case 2 at 6% (25.11 years). For others, their DPB averaged between 8–16 years. In standalone systems, the PB is long because their present value savings are remarkably low. Their savings reached roughly 24% of their initial investment on the 25th year of their operation. Thus, calculating DPB was impossible. The PV module cost must be lowered by 30% to make the LCOE and PB periods competitive to improve the PB of a PV system investment [22].

Table 5. Simple Payback (SPB) Period and Discounted Payback (DPB) Period.

	Simple Payback, SPB (Year)	Discounted Payback, DPB (Year)		
Discount rate	-	2%	4%	6%
Stand-alone PV	-			
Case 1	-	-	-	-
Case2	13.28	14.28	17.59	25.11
Rooftop PV	-			
Case 3	8.45	9.36	10.55	12.20
Case 4	7.96	8.77	9.80	11.22
Solar farm	-			
Case 5	9.75	10.98	12.69	15.32
Case 6	6.26	6.76	7.36	8.10

4. Policy Intervention

National policies and global collaborative actions play important roles in shaping industrial development and widening the energy security frontier based on abundant PV resources. Many studies considered newly raised economic and social issues related to the LCA of large-scale PV system installation. Cross-disciplinary interest in systematic innovations include building integrated renewable technology, smart city, and hybrid renewable technology systems [48–50]. Although renewables are progressively replacing high impact products from an environmental view point, the life cycle of PV systems shows that renewable energy still requires technological innovations to be more sustainable. Related strategies include the following:

- Whole system integration for optimal spatial consumption and impact trade-off balance on a temporal basis;
- Improvement of additional technology efficiency via low-energy consumption and low-toxic manufacturing;
- Design an optimal evaluation method that includes environment, circular economy, and social issues for renewable energy technology.

The LCA and LCCA of PV systems (standalone, solar rooftop, and solar farm PVs) have produced distinctive results from the environment and economic points of view. The three economies analysed are still heavily dependent on traditional energy. Through their comprehensive target line-ups, governments in Asian countries have adopted various policies to further develop their own renewable energy policy interventions. These actions include agreements and unregulated laws that highlight incentives and carbon taxes to manage the increase in energy demand. However, a comprehensive analysis is required to assemble fragmented policies and regulations to achieve necessary goals [51]. Stakeholders and governments in Asia are responding to the growing pressures of growing population and increased energy demand by reviewing their existing policies to further stabilize energy and secure economic growth [51]. According to the RE market development, the cost of panels should decrease with the improved technology in the quickly growing PV installation market [49]. In addition, Malaysia has increased PV installation capacity due to attractive incentives offered by the government, such as Feed-in-Tariffs (FiT) and subsidies. These policies work as a catalyst and are crucial for PV implementation growth. The cost of system management could be reduced by improving electricity governance system, increasing clean energy investment and upgrading the grid system [52]. Grid-storage systems, when the grid is used for energy storage, is not considered in this study since the type of grid connection used in the case studies region is different. Grid connected PV systems usually manage electricity through the term import (buying) and export (selling) of electricity, without considering it as storage. The grid electricity market value is specified by region/country itself with governments incentives through RE policy interventions [53]. Public awareness of RE has gradually increased, and consumers are now searching for green incentives and tax exemptions for clean resource technology investments, which have further increased RE capacity to 2080 MW by 2020 and a target of 4000 MW by 2030 by Malaysia [54]. Correspondingly, the Malaysian climate change targets are the 35% reduction of GHG intensity by 2030 from the 2005 level with the increase to 45% reduction with enhanced international support [55].

Similarly, GDP growth in Indonesia is limited due to wildfires and other natural disasters that affect the country, an estimated Rp221 trillion allotted for renovation and recovery [56]. Thus, Indonesia focuses on achieving an electrification ratio of 99.7% by 2025. With the implementation of a PV business model that encourages self-consumption, Indonesia uses net billing as a market-based compensation mechanism. This mechanism supports consumer compensation based on the actual market value of the kWh consumed or injected onto the grid [13]. The costs for small-scale solar systems are lower than for large-scale solar ones. This condition promotes an increased societal interest in the technology with low investment despite geographical conditions. Therefore, risks are low because small-scale systems do not need to compete against wholesale electricity prices, but instead compete against the final cost of electricity facing consumers. Large-scale solar PV systems also face the challenge of grid connection, land acquisition, acquisition of relevant solar data and negotiation of long-term pricing agreements that are unsuitable for various backgrounds of consumers. Indonesia aims to reduce 26% and 29% of its GHG emission from business-as-usual (BAU) level by 2020. This target can be increased to 41% by 2020 with international support. Indonesia also plans to increase 23% and 31% of its renewable energy shares into the primary energy supply by 2025 and 2050, respectively [51].

Thailand renewables are significantly leading in bioenergy due to their abundant resources. Thailand is well-known for its abundant automobile and truck traffic, and its car ownership is expected to grow to an average of 32 cars per 1000 person [7]. Thus, Thailand needs to spur its RE consumption growth to 30% by 2036. This growth is assumed to include 20.11% renewable energy mix into the power generation share and 25.04% into transport fuel consumption [51]. Accordingly, Thailand aims to improve its green energy outlook for climate change by reducing energy intensity by 30% based on 2010 levels. The country also plans to reduce GHG emission by 20% from the 2030 BAU level and increase it to 25% with enhanced international support. Installation capacity relates to the number of PV panel produced. Based on the findings in this study, PV manufacturing contributed higher CO2 and GHG emissions in comparison to the other life cycle phases for all the PV systems. This phase also consumed the highest CED based on the country's electricity mix. Planning of system capacity size is crucial, given that the standalone system does not generate any income from the energy produced. The savings depend on the amount of energy consumed. Therefore, before installing a standalone system, a plan must be developed to calculate a suitable capacity size of the load system (for example, a house). The load energy consumption needs to be the same as the energy produced to maximize savings. The rooftop system is more viable as there is not a need to purchase land, as with large scale solar farms. Compared with solar farms, the rooftop system has a lower cost and LCOE, which are better than that of solar farm systems. If rooftops were as large as solar farms, increased amounts of energy can be produced to yield a low LCOE. Thus, more profits are gained, and the PB period of the system is shortened.

5. Conclusions

All case studies for each PV system in Malaysia, Thailand, and Indonesia were successfully conducted. According to the findings of this study, Case 4 had the fastest energy PB time of 0.14 years due to its low manufacturing energy consumption of amorphous silicon technology. The normalized CEDs for all cases were within the average range of 45 MJ/m^2 to 60 MJ/m^2. Comparison of different types of PV systems proves that manufacturing of products eventually dominates the CED of each system and influences the EPBT longevity overtime, in addition to those of efficiency and degradation factors on PV panel itself. Moreover, the GHG emission of PV system ratio to its total system capacity stays consistently within 2.8–4.2. The GHG emission/CO_2 eq. per 1 kWh of energy produced by the PV system shows whether the system produced enough green energy to cover its non-renewable mix electricity used to produce the system. Most of the case studies, except Cases 5 and 6, emitted more CO_2 compared with their production. However, whether the PV system requires considerable time to recuperate remains unclear.

Meanwhile, in the LCC and LCOE analyses, the best system was the rooftop PV system. Both cases of rooftop PV systems recorded the lowest value of LCC and LCOE. The LCOE value of Case 4 was the highest with 0.0491 USD/kWh, followed by Case 3 with 0.0582 USD/kWh. Case 6 (2%) showed the best performance in supplementary financial measures. Case 6 was the best in regards to the SPB and DPB analyses. Thus, the solar farm system is more feasible in this case compared with the rooftop PV system. For the rooftop PV system to be financially viable and to take advantage of its low LCC and LCOE value, it needs to be operated at a large scale (similar to solar farms) with increased capacity to achieve high energy production. However, for solar farms to be more cost-effective and achieve low LCOE value, the use of PV modules with degradation rates below 0.20% is highly recommended. National and regional policy interventions play important roles in supporting renewable energy growth and development in their implementation in Asia. The need to identify priorities, maintain stability and develop pathways for the renewable energy market is crucial to achieve the targets set up by various countries.

- Economies should widen their renewable energy roadmap by considering other adaptable policies and measures in the energy portfolio.
- Attractive programs and incentives are an excellent catalyst to improve public awareness and attract investments.
- Initializing the many energy scenarios in a decision-making platform achieves the highest potential for concerns of spatial installation and temporal market-driven trade-offs.

Author Contributions: Data curation, A.A.; investigation, N.A.A.A.; supervision, K.S.; validation, M.A.I. and S.J.; writing—original draft, N.A.L.; writing—review and editing, K.P.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors would like to acknowledge the support of publication works and expertise from the Economic Research Institute for ASEAN and East Asia (ERIA).

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

Abbreviations

AC	Alternating Current
BAU	Business-as-Usual
CO_2	Carbon Dioxide
DC	Direct Current
EPBT	Energy Payback Time
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCC	Life Cycle Cost
LEP	Local Energy Production
PB	Payback
RE	Renewable Energy
SPB	Simple Payback
m-Si	Monocrystalline
APEC	Asia Pacific Cooperation
BOS	Balance of System
CED	Cumulative Energy Demand
DPB	Discounted Payback
FiT	Feed-in-Tariff
GDP	Gross Domestic Product
LCCA	Life Cycle Cost Assessment
LCOE	Levelised Cost of Energy
LCIA	Life Cycle Impact Assessment
O&M	Operation and Maintenance
PV	Photovoltaic
SDG	Sustainable Development Goals
a-Si	Amorphous Silicon
p-Si	Polycrystalline

References

1. APEC Policy Support Unit. APEC Regional Trends Analysis Trade, Policy, and the Pursuit of Inclusion. 2018. Available online: https://www.apec.org/Publications/2018/05/APEC-Regional-Trends-Analysis (accessed on 12 May 2018).
2. APEC Energy Working Group. *APEC Workshop on Energy Statistical and Geographic Information Systems Summary Report*; APEC: Mexico City, Mexico, 2018. Available online: https://www.APEC-Workshop-on-Energy-Statistical-and-Geographic-Information-Systems.pdf (accessed on 12 May 2018).
3. APEC Policy Support Unit. Research Outcomes: Summary of Research Project 2017. Available online: https://www.apec.org/Publications/2018/05/Research-Outcomes---Summary-of-Research-Projects-2017 (accessed on 12 May 2018).
4. REN21 and Global Network of Research Partners. *Renewables 2017 Global Status Report*; REN21: Paris, France, 2017. Available online: https://www.ren21.net/wp-content/uploads/2019/05/GSR2017_Full-Report_English.pdf (accessed on 12 May 2018).
5. International Renewable Energy Agency. *Renewable Power Generation Costs in 2019*; International Renewable Energy Agency Agency: Abu Dhabi, UAE, 2020; Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019 (accessed on 12 May 2018).
6. ExxonMobil. *2018 Outlook for Energy: A View to 2040*; Energy Global News: Texas, TX, USA, 2018. Available online: https://www.aop.es/wp-content/uploads/2019/05/2018-Outlook-for-Energy-Exxon.pdf (accessed on 12 May 2018).
7. Ferroukhi, R.; Nagpal, D.; Hawila, D. *IRENA (2018), Renewable Energy Market Analysis: Southeast Asia*; Abu Dhabi, UAE, 2018. Available online: https://www.IRENA_Market_Southeast_Asia_2018.pdf (accessed on 12 May 2018).
8. Jäger-waldau, A. *PV Status Report 2016*; EU Science Hub: Luxembourg, 2016. Available online: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC103426/ldna28159enn.pdf (accessed on 12 May 2018).
9. International Renewable Energy Agency. *Renewable Power Generation Costs in 2017*; International Renewable Energy Agency Agency: Abu Dhabi, UAE, 2017.
10. International Renewable Energy Agency (IRENA). *Renewable Capacity Statistics 2019*; International Renewable Energy Agency Agency: Abu Dhabi, UAE, 2019.
11. UN. *The 2030 Agenda for Sustainable Development*; A/RES/70/1; UN: New York, NY, USA, 2015; Volume 16301, pp. 13–14. Available online: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed on 3 January 2020).
12. Bajracharya, I.; Bhattrai, N. Road Transportation Energy Demand and Environmental Emission: A Case of Kathmandu Valley. *Hydro Nepal* **2016**, *18*, 30–40. [CrossRef]
13. Frischknecht, R.; Fthenakis, V.; Kim, H.C.; Raugei, M.; Sinha, P.; Stucki, M. *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*; IEA PVPS: New York, NY, USA, 2015.
14. Ho, K.; Tang, D. Climate change in Malaysia: Trends, contributors, impacts, mitigation and adaptations. *Sci. Total Environ.* **2019**, *650*, 1858–1871.
15. European Commission—Joint Research Centre—Institute for Environment and Sustainability. *Framework and Requirements for Life Cycle Impact Assessment Models and Indicators*; European Commission: Luxembourg, 2010.
16. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; Van Zelm, R. *ReCiPe 2008*; The Netherlands, 2009; pp. 1–44. Available online: http://www.pre-sustainability.com/download/misc/ReCiPe_main_report_final_27-02-2009_web.pdf (accessed on 12 May 2018).
17. Rincón, L.; Castell, A.; Pérez, G.; Solé, C.; Boer, D.; Cabeza, L.F. Evaluation of the environmental impact of experi-mental buildings with different constructive systems using Material Flow Analysis and Life Cycle Assessment. *Appl. Energy* **2013**, *109*, 544–552. [CrossRef]
18. Verones, F.; Bare, J.; Bulle, C.; Frischknecht, R.; Hauschild, M.; Hellweg, S.; Henderson, A.; Jolliet, O.; Laurent, A.; Liao, X.; et al. LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *J. Clean. Prod.* **2017**, *161*, 957–967. [CrossRef] [PubMed]
19. Su, S.; Li, X.; Zhu, Y.; Lin, B. Dynamic LCA framework for environmental impact assessment of buildings. *Energy Build.* **2017**, *149*, 310–320. [CrossRef]
20. Christensen, C.B.; Barker, G.M. Effects of Tilt and Azimuth on Annual Incident Solar Radiation for United States Locations. In Proceedings of the International Solar Energy Conference. American Society of Mechanical Engineers, Washington, DC, USA, 21–25 April 2001; pp. 225–232.
21. Weidema, H.R.; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O.; Wernet, G. *Overview and Methodology, Data Quality Guideline for the Ecoinvent*; Swiss Centre for Life Cycle Inventories: Zurich, Switzerland, 2013; Volume 3.
22. Asian Development Bank. *Guidelines for Estimating Greenhouse Gas Emissions of Asian Development Bank Projects Additional Guidance for Energy Projects*; Asian Development Bank: Manila, Philippines, 2017.
23. Veríssimo, P.H.A.; Campos, R.A.; Guarnieri, M.V.; Veríssimo, J.P.A.; Nascimento, L.R.D.; Rüther, R. Area and LCOE considerations in utility-scale, single-axis tracking PV power plant topology optimization. *Sol. Energy* **2020**, *211*, 433–445. [CrossRef]
24. Reddy, V.R.; Kurian, M.; Ardakanian, R. Life-cycle Cost Approach (LCCA): Framework and Concepts. In *Environmental Education and Ecotourism*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2015; pp. 17–37.
25. Universiti Teknologi MARA. *Fundamentals of Finance*, 14th ed.; Universiti Teknologi MARA: Selangor, Malaysia, 2014.
26. Cellura, M.; Cusenza, M.A.; Longo, S. Energy-related GHG emissions balances: IPCC versus LCA. *Sci. Total Environ.* **2018**, *628–629*, 1328–1339. [CrossRef]

27. Jäger-Waldau, A.; Kougias, I.; Taylor, N.; Thiel, C. How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030. *Renew. Sustain. Energy Rev.* **2020**, *126*, 109836. [CrossRef]
28. Energy Commission. *Malaysia Energy Statistics Handbook 2017*; Energy Commission: Kuala Lumpur, Malaysia, 2018.
29. IRENA. *Renewable Energy Outlook: Thailand*; IRENA: Bangkok, Thailand, 2017.
30. National Energy Council. *Indonesia Energy Outlook 2016*; National Energy Council: Jakarta, Indonesia, 2016.
31. Kourkoumpas, D.; Benekos, G.; Nikolopoulos, N.; Karellas, S.; Grammelis, P.; Kakaras, E. A review of key environ-mental and energy performance indicators for the case of renewable energy systems when integrated with storage solu-tions. *Appl. Energy* **2018**, *231*, 380–398. [CrossRef]
32. Fthenakis, V.; Frischknecht, R.; Raugei, M.; Kim, H.C.; Alsema, E.; Held, M.; de Wild-Scholten, M. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity. *IEA PVPS Task* **2011**, *12*, 6–21.
33. IEA. *Tracking Clean Energy Progress*; IEA: Paris, France, 2012.
34. Kittner, N.; Gheewala, S.H.; Kamens, R. Life Cycle Considerations for Monocrystalline Photovoltaics in Thailand. *J. Sustain. Energy Environ.* **2012**, *3*, 143–146.
35. Ludin, N.A.; Mustafa, N.I.; Hanafiah, M.M.; Ibrahim, M.A.; Teridi, M.A.M.; Sepeai, S.; Zaharim, A.; Sopian, K. Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. *Renew. Sustain. Energy Rev.* **2018**, *96*, 11–28. [CrossRef]
36. Allouhi, A.; Saadani, R.; Buker, M.; Kousksou, T.; Jamil, A.; Rahmoune, M. Energetic, economic and environmental (3E) analyses and LCOE estimation of three technologies of PV grid-connected systems under different climates. *Sol. Energy* **2019**, *178*, 25–36. [CrossRef]
37. Sherwani, A.F.; Usmani, J.A. Life cycle assessment of solar PV based electricity generation systems: A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 540–544. [CrossRef]
38. Althaus, H.-J. Calculation of energy payback time of PV and its determinants. In Proceedings of the Swiss Photonics Workshop Dübendorf, Quantis, Switzerland, 22 October 2013.
39. Rossi, F.; Heleno, M.; Basosi, R.; Sinicropi, A. Environmental and economic optima of solar home systems design: A combined LCA and LCC approach. *Sci. Total Environ.* **2020**, *744*, 140569. [CrossRef]
40. Soares, N.; Bastos, J.; Pereira, L.D.; Soares, A.; Amaral, A.; Asadi, E.; Rodrigues, E.; Lamas, F.; Monteiro, H.; Lopes, M.; et al. A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. *Renew. Sustain. Energy Rev.* **2017**, *77*, 845–860. [CrossRef]
41. Magrassi, F.; Rocco, E.; Barberis, S.; Gallo, M.; Del Borghi, A. Hybrid solar power system versus photovoltaic plant: A comparative analysis through a life cycle approach. *Renew. Energy* **2019**, *130*, 290–304. [CrossRef]
42. Bazán, J.; Rieradevall, J.; Gabarrell, X.; Vázquez-rowe, I. Science of the Total Environment Low-carbon electricity production through the implementation of photovoltaic panels in rooftops in urban environments: A case study for three cities in Peru. *Sci. Total Environ.* **2018**, *622–623*, 1448–1462. [CrossRef]
43. Battaglia, C.; Cuevas, A.; De Wolf, S. High-efficiency crystalline silicon solar cells: Status and perspectives. *Energy Environ. Sci.* **2016**, *9*, 1552–1576. [CrossRef]
44. Atia, N.G.; Bassily, M.A.; Elamer, A.A. Do life-cycle costing and assessment integration support decision-making towards sustainable development? *J. Clean. Prod.* **2020**, *267*, 122056. [CrossRef]
45. Naves, A.X.; Fernández, A.; Fernández, A.I.; Cabeza, L.F.; Haddad, A.N.; Boer, D. Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector: A review. *Sol. Energy* **2019**, *192*, 238–262. [CrossRef]
46. Harvey, L.D. Clarifications of and improvements to the equations used to calculate the levelized cost of electricity (LCOE), and comments on the weighted average cost of capital (WACC). *Energy* **2020**, *207*, 118340. [CrossRef]
47. Narayan, N.; Chamseddine, A.; Vega-Garita, V.; Qin, Z.; Popovic-Gerber, J.; Bauer, P.; Zeman, M. Exploring the boundaries of Solar Home Systems (SHS) for off-grid electrification: Optimal SHS sizing for the multi-tier framework for household electricity access. *Appl. Energy* **2019**, *240*, 907–917. [CrossRef]
48. Gu, Y.; Zhang, X.; Are Myhren, J.; Han, M.; Chen, X.; Yuan, Y. Techno-economic analysis of a solar photovoltaic/thermal (PV/T) concentrator for building application in Sweden using Monte Carlo method. *Energy Convers. Manag.* **2018**, *165*, 8–24. [CrossRef]
49. Kunkel, S.; Matthess, M. Digital transformation and environmental sustainability in industry: Putting expectations in Asian and African policies into perspective. *Environ. Sci. Policy* **2020**, *112*, 318–329. [CrossRef]
50. Yu, H.J.J.; Geoffron, P. *Solar PV Market and Policies*; Elsevier BV: Amsterdam, The Netherlands, 2020; pp. 413–437.
51. Butler, R. Challenges and opportunities. *Worldw. Hosp. Tour. Themes* **2018**, *10*, 635–641. [CrossRef]
52. Erdiwansyah, R.; Mamat, M.S.; Sani, M.; Sudhakar, K. Renewable energy in Southeast Asia: Policies and recommendations. *Sci. Total Environ.* **2019**, *670*, 1095–1102. [CrossRef]
53. Phoumin, H.; Kimura, F.; Arima, J. Potential Renewable Hydrogen from Curtailed Electricity to Decarbonize ASEAN's Emisions: Policy Implications. *Sustainability* **2020**, *12*, 10560. [CrossRef]
54. Energy Commission. *Handbook Malaysia Energy Statistics*; Energy Commission: Kuala Lumpur, Malaysia, 2019.
55. Ambashi, M. *Key Messages: ASEAN Development and Innovation Strategy in the Era of New Industrialisation*; Economic Research Institute for ASEAN and East Asia: Jakarta, Indonesia, 2020; pp. 1–5.
56. Arnaoutakis, N.; Souliotis, M.; Papaefthimiou, S. Comparative experimental Life Cycle Assessment of two commercial solar thermal devices for domestic applications. *Renew. Energy* **2017**, *111*, 187–200. [CrossRef]