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Life cycle assessment of nano-silica coating for solar photovoltaic panel

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Abstract

Accumulation of dust, sand, water, or any pollution plume affects the efficiency of photovoltaic panels (PVs) by obstructing light transmittance to each PV module. This study prepared nano-silica with superhydrophobic and self-cleaning properties for coating on PVs. The Stöber process was used as a selective method to synthesize the nano-silica particles. Life cycle assessment was used to evaluate and compare the total environmental impact of coated and uncoated PV. The nano-silica coating was applied on PVs using a spraying technique and tested for efficiency in Pathum Thani and Chiang Rai provinces, Thailand. Centrum voor Milieukunde Leiden (CML) method, a common method for chemical products, was selected as the life cycle impact assessment method, which is commonly used for chemical products. The functional unit was defined as 1 kWh of electricity produced, with the lifetime of a PV being 25 years. The results showed that the efficiency improvement from the coating material could reduce the environmental impact by 2.08% compared to the uncoated PV. However, in the assessment, the impact on photochemical oxidation slightly increased from the additional chemical consumption for the nano-silica coating preparation.

Keywords: Life cycle assessment, Nano-silica, Photovoltaic panel, Stöber process, Superhydrophobic

1. Introduction

Global energy demand increases annually, and most countries meet such demand from fossil fuels, such as petroleum oil, natural gas, and coal [1]. Fossil fuels that produce energy using the combustion process are considered a primary source of air pollution in urban and industrial areas. Air pollution from such combustion contains various toxic gases, including carbon monoxide (CO), sulfur oxide (SOx), nitrogen oxide (NOx), and polycyclic aromatic hydrocarbons (PAHs), that are poisonous and can cause chronic diseases in the respiratory and cardiovascular systems [2,3]

Nowadays, most countries include renewable energy, such as solar, wind, hydropower, geothermal sources, and bioenergy, in the energy mix to minimize fossil fuel consumption. The United Nations General Assembly provides Sustainable Development Goals 7.2, which set targets for the inclusion of renewable energy in the global energy mix by 2030 and to improve energy coverage, especially in remote areas [4,5]. Solar photovoltaic cells are a trend in renewable energy and have rapidly expanded in the last decade. Solar energy is simpler for installation than other renewable energy with less equipment required in the system; therefore, it is compatible with space limitations. The photovoltaic panel (PV) can be placed in various areas exposed to sunlight [6]. However, dust or any other airborne particle are a main issue for PVs. The outer layer of a PV is made from glass, and its direct contact with the environment can become opaque due to dust particles that accumulate on the PV and can reduce the power conversion efficiency by approximately 30% [7-9]. Applying a PV coating with superhydrophobic properties can prevent the efficiency loss of solar energy by reducing dust and liquid remaining on the PV surface [10].

A coating material with a superhydrophobic property (water contact angle above 150 degrees) has been widely used to prevent liquid or dust settlement on the surface and is suitable for various surfaces, such as textile, wood, plastic, glass, and metal [11,12]. Although the superhydrophobic property has many benefits, such as self-cleaning that helps to keep the surface finish clean from dirt and or anti-corrosion, the liquids may penetrate the surface and oxidize internal structures [13]. The commercial coating material is typically made from waxes or silicones, but neither can eliminate oil stain. A fluorochemical is a commercial coating material that can remove oil stain from surfaces [14]. Nowadays, many research studies have reported on superhydrophobic coatings synthesized from nanoparticles because they can increase the contact angle, provide a durable coating, and have additional benefits, such as thermal and abrasion resistance [15,16]. Various research studies have reported that particle accumulation affects PV efficiency and that a coating can solve this problem. For example, Wayne & Hicks, 2021 [17] reported that particle accumulation on PV decreased the efficiency and could be solved by applying a hydrophobic coating. Jannatun et al, 2020 [18] applied a nano-silica coating on textiles and obtained high water repellency. Sanchez et al, 2013 [19] obtained a positive improvement in efficiency but did not describe the environmental impact. Whittaker & Heine, 2018 [20] found that some water repellents may be hazardous to the environment.

The current research prepared a nano-silica coating with superhydrophobic and self-cleaning properties using the Stöber process and applied the coating onto the PV surface using a spraying technique. The efficiency of coating was measured by the daily electricity generation rate for coated versus uncoated PVs. However, efficiency evaluation based solely on the electricity production rate may not consider sufficient aspects; therefore, life cycle assessment (LCA) in the cradle-to-gate includes raw material acquisition, product manufacturing, and use phase (excluding the transportation and disposal phases) can be applied to evaluate the efficiency of a coating material based on its environmental impact. This research should expand the use of coatings in real situations and encourage more research into PV coatings.

2. Materials and methods

The research was divided into 3 parts that involved sequentially: 1) coating material and coated PV preparation; 2) efficiency evaluation; and 3) LCA evaluation of coated and uncoated PVs. The primary data consisted of raw material, energy consumption, efficiency evaluation, and LCA that were stored in the life cycle inventory (LCI) database. Figure 1 illustrates the methodology and the LCA boundary for this study.

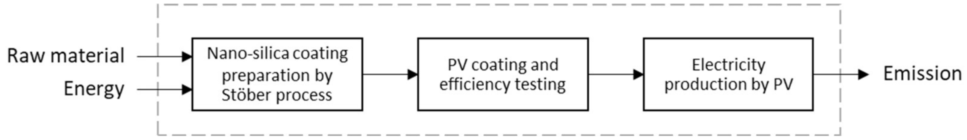

Figure 1 Methodology and LCA boundary (Cradle-to-Gate).

2.1 Preparation of coating material and coated PV

At first, the coating procedure and the materials were collected and processed using a pilot plant, which is relevant in LCA phase 2: inventory analysis. Then, the coating material was prepared from the pilot plant, as shown in Figure 2.

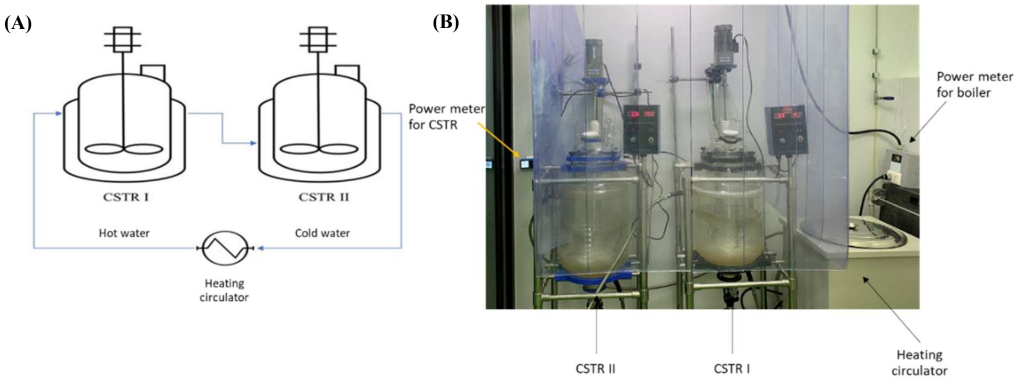

Figure 2 Nano-silica production system (A) diagram (B) pilot plant.

The production system operates under a batch process with 20 L normal operating capacity. The heating circulator heats water and transfers sequentially through the two continuously stirred tank reactor (CSTR) heating jackets. To observe the process more easily, the pilot-scale uses a glass CSTR instead of a stainless-steel CSTR that would be applied on a commercial scale and the thermal conductivity of the borosilicate glass is less than for a stainless-steel tank. However, the CSTR wall is thin compared to the thickness of the water in the jacket and the material in the reactor. Therefore, the coating preparation was assumed to have negligible impact on heat transfer due to material differences. The process structure, material, sources of energy consumption, and the preparation procedure are shown in Figure 3.

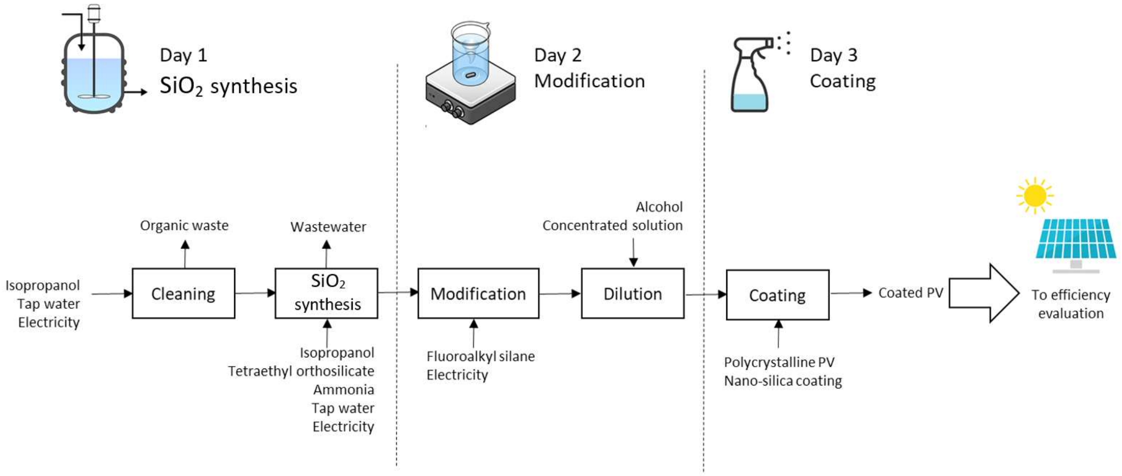

Figure 3 Process flow diagram of nano-silica coating (pilot-scale).

2.2 *Cleaning*

CSTRs must be cleaned before use in coating preparation. Isopropanol is stirred in each CSTR (400 rpm, at room temperature) for 15 min. Then, the bottom valves are opened to discharge isopropanol from both CSTRs. The isopropanol can be reused for cleaning three times; therefore, the total amount of isopropanol for LCA evaluation is one-third of the actual isopropanol used.

2.3 *SiO_2 synthesis*

SiO_2 nanoparticles are synthesized using the Stöber process (Figure 4). For the base reactant, tetraethyl orthosilicate (TEOS) is dissolved in isopropanol in each CSTR and stirred (450 rpm, 60°C). After 30 min, ammonia is added to each CSTR and more is added at two 30 minutes intervals. The CSTR is continually stirred overnight (approximately 15 hours.)

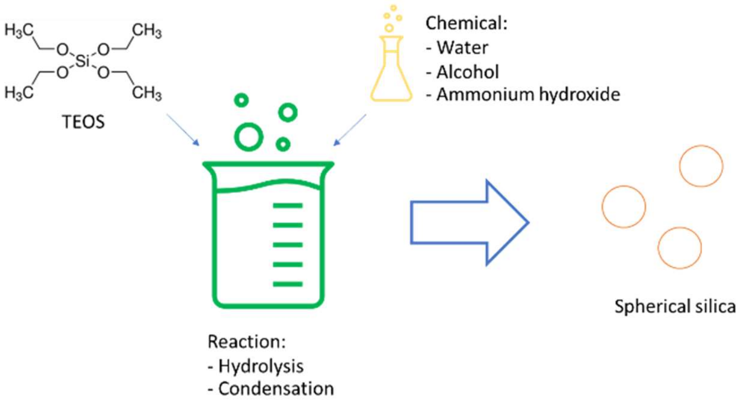

Figure 4 Stöber process.

The Stöber process is widely used to synthesize spherical silica on both laboratory and industrial scales. The process reacts TEOS with alcohol (commonly methanol, ethanol, or propanol) and distilled water under hydrolysis and condensation [21,22]. As a result, spherical silica beads are formed as various nano-sized particles involving the concentration of ammonium hydroxide, as a base catalyst [23].

2.4 Modification

After the overnight reaction, the SiO_2 solution is cooled by changing the circulator water approximately three times until the temperature decreases to about 40°C. Then, the solution is discharged via the bottom valve into a glass container. Next, the solution is placed on a hot plate and mixed with fluoroalkyl silanes (FAS) with magnetic stirring for 1 hour to obtain the concentrated solution.

2.5 Dilution

The SiO_2 solution can be stored as a concentrated solution to minimize the required storage area; it must be diluted before use. Typically, a 1:9 ratio of SiO_2 solution-to-alcohol is used for glass coating, followed by magnetic stirring (400 rpm, ambient temperature) for 15 min. This was applied in the current study.

2.6 Coating

This research study was conducted on a small scale; therefore, the PV was coated using a hand-spray bottle. A coating batch was sufficient for 750 panels (2 m^2 panel size). Thus, the total surface area was 1,500 m^2.

2.7 Efficiency evaluation

This research used polycrystalline PVs with a square size of 2 $m^{2,}$ and a maximum electricity output of 330 W. The test sites were outdoor areas, fully exposed to sunlight in Pathum Thani and Chiang Rai provinces, Thailand. Any electricity produced was measured by the installed wattmeter in each PV. However, as this study was conducted at a small scale, the coating was applied to the PV surface using hand spraying and this was assumed to require no measured energy. However, on a commercial scale, an electrical spraying machine would be required to coat large surfaces.

2.8 Life cycle assessment

LCA was used to evaluate the nano-silica coating through its environmental impact as standardized by ISO14040-Definition of Life Cycle Assessment and ISO14044:2006-Requirement and guide of Life Cycle Assessment. The LCA consisted of 4 main stages: goal and scope, LCI, life cycle impact assessment (LCIA), and interpretation.

2.9 Goal and scope

The goal and scope described the detail of products and services. A functional unit (FU) was used as the physical unit for calculations based on mass (g, kg) or energy (kW, kJ), according to the produced amount of product or service. The system boundary was the study scope, including material acquisition, product manufacturing, transportation, use, and disposal, also called a “cradle-to-grave” analysis [24].

The goal of this study was to compare the environmental impact of coated PVs with uncoated PVs. The system boundary covered, including raw material acquisition, manufacturing, and the use phase (electricity production) also called “cradle-to-gate”. Disposal and transportation were not considered in this comparative study. The electricity production of PV used the efficiency of PV to calculate the electricity during the lifetime of the PV. Figure 5 illustrates the system boundary of the study.

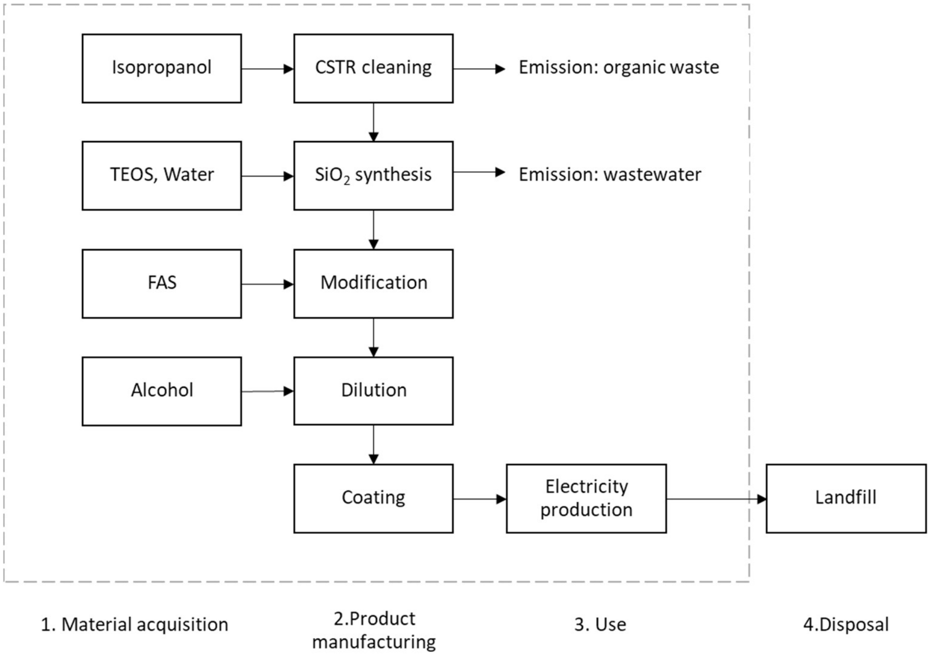

Figure 5 System boundary of LCA evaluation.

The functional unit was defined as 1 kWh electricity produced from coated and uncoated PVs over a typical lifetime of 25 years [25]. The coating durability was assumed to be 1 year, so the total coating time for the whole product life cycle was 25 times.

2.10 Life cycle inventory

Typically, the flow of materials and energy involved in a product or service (raw materials, sub-components, assembly parts, waste) within the system boundary is collected in inventory analysis. Then, the details are calculated from the processing to the functional unit before proceeding to the impact assessment. The process flow diagram with stream details and amounts is also compiled in this stage [26].

The inventory data of nano-silica coating were collected as primary data and included the amounts of raw materials, energy, and emissions. The database used in the inventory analysis used the Ecoinvent V3.05 database and the Thai National LCI Database (electricity and tap-water) for material acquisition.

2.11 Life cycle impact assessment

LCIA evaluates the environmental impact of all components in the inventory analysis, including raw material consumption and emissions [27]. The results are represented as a midpoint and endpoint. The LCIA in this study used the Centrum voor Milieukunde Leiden-impact assessment (CML-IA) baseline V3.05 method in the SimaPro software, which is commonly applied for chemical products. The CML method (designed by Center of Environmental Science of Leiden University) provides 10 midpoint impact categories: abiotic depletion(kg PO_4 eq and kg SO_2 equivalent (eq)), global warming (GWP100a; kg C_2H_4 eq), ozone layer depletion (ODP; kg 1,4-dichlorobenzene (DB) eq), human toxicity (kg 1,4-DB eq), freshwater aquatic ecotoxicity (kg 1,4-DB eq), and marine aquatic ecotoxicity (kg 1,4-DB eq), terrestrial ecotoxicity (kg chlorofluorocarbon (CFC)-11 eq), photochemical oxidation (kg CO_2 eq), acidification Megajoule (MJ), and eutrophication (kg Sb eq) [28,29]. The normalization results are used to compare the total impact for all impact categories. The normalization factor used in the study was the World, 2000 dataset covering global average values to normalize the midpoint results [30].

2.12 Interpretation

Interpretation summarizes and checks the completeness of the goal and scope, LCI, and LCIA [31]. Then the conclusion and recommendations of this study can be detailed. The LCIA results were analyzed based on contribution analysis to gain insight into coating material and environmental hotspots from relevant materials.

3. Result and discussion

3.1 Preparation of coating material and coated PV

The pilot plant produced 200 L of nano-silica coating which was sufficient for 1,500 m^2 of PV. The approximate density tested by weighing was 810 g/L. In this case, the testing site installed 2 m^2 PVs that were scheduled for recoating after 25 years. The nano-silica coating after overnight mixing and during PV application is shown in Figure 6.

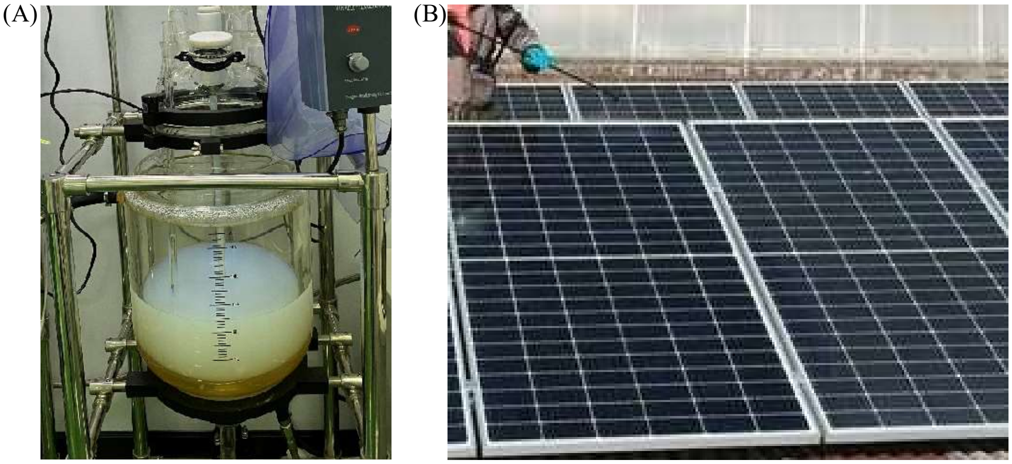

Figure 6 (A) Concentrated nano-silica coating (B) Nano-silica application on PV using hand spraying technique.

The coating material required was calculated using the equation:

$$\begin{aligned}\text{Total coating required (mass)} &= \rho_{\text{Coating}} \times V_{\text{Coating}} \\ &= \rho_{\text{coating}} \left(A_{\text{PV}} \times \frac{V_{\text{Pilot plant}}}{A_{\text{Pilot plant}}} \right) \times 25 \text{ (times)} \\ &= 810 \frac{g}{L} \left(2\text{ m}^2 \times \frac{200\text{ L}}{1500\text{ m}^2} \right) \times 25 = 5.41\text{ kg}\end{aligned}$$

where,
ρ_{Coating} = Coating density
APV = PV surface area
$V_{\text{Pilot plant}}$ = Coating volume per batch
$A_{\text{Pilot plant}}$ = Applicable area per batch

The total coating required was used to calculate the mass of material and energy used for coating production in inventory analysis.

3.2 Efficiency evaluation

The electricity evaluations took place at the test sites in Pathum Thani and Chiang Rai provinces, Thailand and were represented as real-time graphs, as shown in Figures 7(A) and 7(B). The test period was selected in the summer season during March 2020 because there was no rain expected during this period. Rain removes any dust covering on the surface of PVs and the result from coated and uncoated PVs would be similar, thus confounding the intended aim of the study to compare coated and uncoated PV surfaces. Furthermore, variations in daily rainfall would make it difficult to interpret any cleaning results.

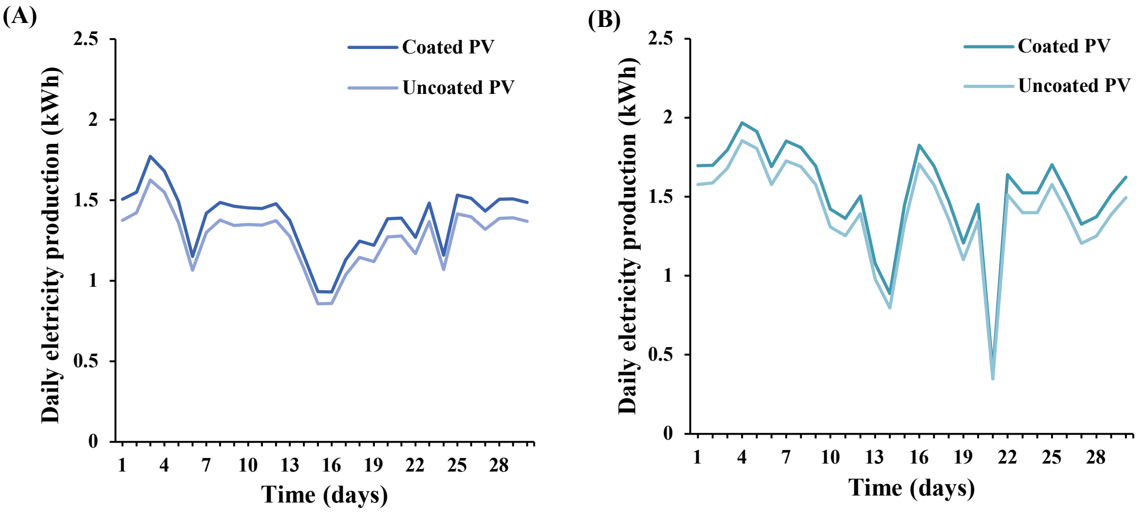

Figure 7 Daily electricity production (A) Pathum Thani (B) Chiang Rai sites.

The electricity production trends at the Pathum Thani and Chiang Rai sites were similar because both test sites were located in the same climatic area. According to Köppen's climate classification, Pathum Thani and Chiang Rai are tropical savanna areas (Aw). Each climatic area was determined based on seasonal precipitation and temperature patterns [32]. The daily electricity production depends on external factors, such as solar intensity, cloud cover, and temperature [33]. For example, Day 21 at the Chiang Rai site was interrupted by cloud cover due to unusual weather conditions; However, these did not affect the cleanliness of the PVs.

The daily electricity results were measured for 1 month, whereas LCA evaluated the environmental impact for coated and uncoated PVs for a complete life cycle, typically 25 years (Table 1). Therefore, it was necessary to average the electricity production at both sites to estimate the total electricity production over 25 years. Daily production from Figure 7 was applied for daily electricity production in the year, and was calculated based on degradation rate of 0.5% per year for crystalline silicon type panels [34,35].

The daily electricity production and total electricity produced during 25 years were calculated using the following equations:

$$E_{avg} = \frac{(E_i + E_{(i-1)})(0.995)+\ldots}{25} \quad ;1\leq i\leq 25$$

$$E_t = E_{avg} \text{ x } 365 \text{ (days) x } 25 \text{ (years)}$$

where,

E_{avg} = Average daily electricity production (kWh)
E_i = Average of daily electricity production in year i (kWh)
E_t = Total electricity produced (kWh)

Table 1 Average electricity production per day of coated and uncoated PVs at different test sites.

	Daily electricity production (E_{avg}/ kWh)	Total electricity produced in 25 years lifetime (E_t/kWh)
Pathum Thani		
Coated	1.344	12,265
Uncoated	1.275	11,630
Chiang Rai		
Coated	1.430	13,045
Uncoated	1.322	12,068

The total amounts of electricity produced from the 2 testing sites averaged for LCA evaluation were 12,655 kWh for the coated PVs and 11,849 kWh for the uncoated PVs, with a 6.579% difference. The environmental performance was evaluated using LCA.

3.3 Life cycle assessment

3.3.1 Inventory analysis

The material and energy use for coated material production were collected as primary data. Other raw material information was collected as secondary data from databases, including Ecoinvent V3.05 and the Thai National LCI Database. 5.41 kg of nano-silica coating was sufficient for 12,655 kWh of electricity production. Thus, a functional unit (1 kWh of electricity production) consumed 0.000428 kg of nano-silica coating. Table 2 shows the primary data for coated and uncoated PVs per FU.

Table 2 Raw materials and energy consumption per functional unit (1 kWh of electricity production).

	Description	Quantity		Unit/kWh
		Coated PV	Uncoated PV	
Input				
SiO_2 material	Cleaning, SiO_2 synthesis	1.95	-	g
Electricity	CSTR, heating circulator	0.0020319	-	kWh
Tap water	Heating circulator	12.64	-	g
Fluoroalkyl silane	Modification	0.0158	-	g
Alcohol	Dilution	11.38	-	g
Polycrystalline PV	Coating	0.000158	0.000169	m^2
Output				
Emission-Organic waste	Cleaning	0.506	-	g
Emission-Wastewater	Heating circulator	9.48	-	g

The electricity consumption in all processes used Thai electricity from the Thai National LCI Database while others used the LCI database from Ecoinvent V3.5. In Table 2, coated PV minimized the PV size by 6.728% compared to the uncoated PV because of the former's higher efficiency. The hand spray bottle for PV coating would be substituted on a commercial scale by a marketed spraying machine which typically consumes 2 kW for 120 L/h coating ability. Electricity consumption for the spraying machine was calculated using the equation:

$$\begin{aligned} W &= \mathrm{P} \times \mathrm{t} = \mathrm{P} \times \frac{\mathrm{V}}{\mathrm{q}} \\ &= 2000\, W \, \frac{6.67\, L}{120\, \frac{L}{h}} \\ &= 111 \text{ kWh} = 0.111 \text{ kWh} \end{aligned}$$

where,

P = Spraying machine power
t = Time required
V = Coating volume for the life cycle
q = Spraying rate

The spraying machine consumed 0.111 kWh of electricity for coating the PV for a working life of 25 years, which produced 12,655 kWh of electricity. The spraying machine consumed 0.000009 kWh for 1 kWh of electricity production for coating the PVs or 0.04% more electricity consumption

3.3.2 Impact assessment and interpretation

The CML-IA baseline method was used for LCIA. The method can evaluate midpoint impacts (characterization results) and normalization results, which can be used to compare the total impact from products. Table 3 shows the characterization results of coated and uncoated PVs for all 10 impact categories.

Table 3 Characterization results (midpoint impact) of coated and uncoated PVs.

Impact category	Unit	Coated PV	Uncoated PV
Abiotic depletion	kg Sb eq	8.98×10^{-7}	9.56×10^{-7}
Abiotic depletion (fossil fuels)	MJ	3.35×10^{-1}	3.25×10^{-1}
Global warming (GWP100a)	kg CO_2 eq	2.86×10^{-2}	2.92×10^{-2}
Ozone layer depletion (ODP)	kg CFC-11 eq	3.88×10^{-9}	4.03×10^{-9}
Human toxicity	kg 1,4-DB eq	1.60×10^{-2}	1.67×10^{-2}
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	1.27×10^{-2}	1.33×10^{-2}
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.83	5.06
Terrestrial ecotoxicity	kg 1,4-DB eq	5.97×10^{-5}	6.22×10^{-5}
Photochemical oxidation	kg C_2H_4 eq	6.52×10^{-6}	5.93×10^{-6}
Acidification	kg SO_2 eq	1.18×10^{-4}	1.21×10^{-4}
Eutrophication	kg PO_4 eq	6.59×10^{-5}	6.88×10^{-5}

From Table 3, all the impact categories except abiotic depletion (fossil fuels) and photochemical oxidation for the coated PV were higher than for the uncoated PV, due to using the nano-silica material. Alcohol was the main material causing environmental impact. The nano-silica coating preparation consumed a high amount of alcohol to dilute the concentrated coating before applying it to the PVs. In the Ecoinvent v3.5 database, alcohol acquisition contains beryllium, nickel, selenium, vanadium, and cobalt and mainly affects abiotic depletion (fossil fuels) and photochemical oxidation. From this case, the selection of the solvent in the dilution process and the cleaning agent for the CSTR cleaning process may produce a lower environmental impact. Figure 8 shows the normalization results used to compare the total environmental impact of coated and uncoated PVs.

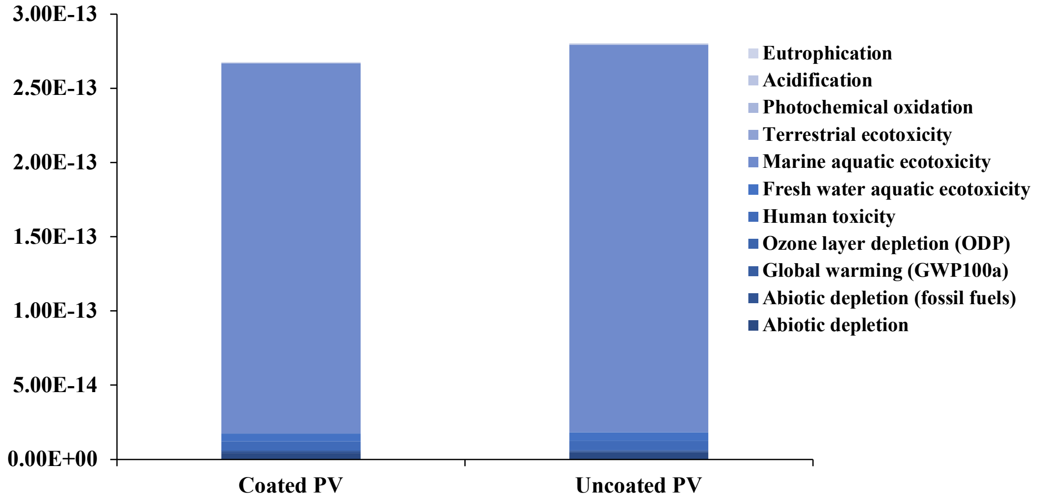

Figure 8 Normalization results for coated and uncoated PVs.

Figure 8 shows the normalization results that can be used to compare the total impact from all environmental impact categories of the products. The total environmental impacts of coated PV were reduced by 2.08% and 2.05% when the spraying machine was included.

Freshwater and marine aquatic toxicity were the main contributing classes for the PV cell products. A PV cell is made from silicon which originated from natural sand. However, the natural sand had to be purified before it could be used to produce PV cells. The silicon and PV cell manufacturing process involves a furnace that operates at high temperatures and consumes acid in the cleaning process and the high-temperature production requires high amounts of energy and results in a high environmental impact. Wastewater also contributes to waterborne emission. The modification process changed the circulating water repeatedly and drained it as wastewater. At a commercial scale, the process may require the installation of a cooling unit or a heat exchanger network to cool the system that could save on total electricity consumption.

4. Conclusion

The coating preparation had a positive effect on power generation efficiency and the environmental impact over the lifetime period of 25 years for the PVs. The analysis showed that the power efficiency of the coated PV increased by 6.579%, which positively affected production and the economics. Efficient power generation can help reduce the size of solar panel installations. The life cycle impact assessment showed that the total environmental impact of the coated PV was reduced by 2.08% compared to uncoated PV. The major impact categories of global warming (GWP100a), human toxicity, and eutrophication decreased by 2.18, 4.11, and 4.29%, respectively, if coated PVs were used compared to uncoated ones. The nano-silica coating mainly affected water resources, such as marine and freshwater aquatic ecotoxicity, due to the main contribution of alcohol. However, these impacts of the nano-silica coating were low compared to that for the PVs. Commercial-scale production with higher efficiency may reduce the contribution of SiO_2 materials; furthermore, the selection of an eco-friendly solvent may reduce the adverse impacts on water resources. Although PVs are a form of renewable energy and have zero operating emissions, further investigation is required regarding the environmental impact of their construction materials, achieving further efficiency improvement, and the disposal for end-of-life products.

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