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Environmental and Economic Impact Assessments of a Photovoltaic Rooftop System in the United Arab Emirates

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Abstract: The shift toward renewable energy resources, and photovoltaic systems specifically, has gained a huge focus in the past two decades. This study aimed to assess several environmental and economic impacts of a photovoltaic system that installed on the rooftop of an industrial facility in Dubai, United Arab Emirates (UAE). The life cycle assessment method was employed to study all the flows and evaluate the environmental impacts, while several economic indicators were calculated to assess the feasibility and profitability of this photovoltaic system. The results showed that the production processes contributed the most to the environmental impacts, where the total primary energy demand was 1152 MWh for the whole photovoltaic system, the total global warming potential was 6.83×10^{-2} kg CO_2-eq, the energy payback time was 2.15 years, the carbon dioxide payback time was 1.87 years, the acidification potential was 2.87×10^{-4} kg SO_2-eq, eutrophication potential was 2.45×10^{-5} kg $PO_4{}^{3}$-eq, the ozone layer depletion potential was 4.685×10^{-9} kgCFC-11-eq, the photochemical ozone creation potential was 3.81×10^{-5} kg C_2H_4-eq, and the human toxicity potential was 2.38×10^{-2} kg1,4-DB-eq for the defined function unit of the photovoltaic system, while the economic impact indicators for the whole system resulted in a 3.5 year payback period, the benefit to cost ratio of 11.8, and 0.142 AED/kWh levelized cost of electricity. This was the first study to comprehensively consider all of these impact indicators together. These findings are beneficial inputs for policy- and decision-makers, photovoltaic panel manufacturers, and photovoltaic contractors to enhance the sustainability of their processes and improve the environment.

Keywords: life cycle assessment (LCA); photovoltaic panels (PV); environmental impact assessment; economic impact assessment

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1. Introduction

Electricity consumption is an indicator of the industrial and economic growth for countries. This is apparent in China, which has the greatest contribution of the world's industrial production, with an approximate contribution of 28% in 2019. The increase in global electricity demand from 1990 to 2019 was 228% [1], but it is forecasted by the International Energy Agency (IEA) to increase by more than 50% in 2030 [2]. The harmful environmental impacts of this continuously increasing demand are inevitable with the current main dependence on conventional energy resources [3] such as climate change and global warming due to massive greenhouse gas emissions. Thus, the dependence on renewable and clean energy resources has become one of the top priorities and visions for all countries [4].

Consequently, governments worldwide have invested significantly in regulating and adopting renewable energy resources to mitigate the risk of global warming and enhance the quality of the environment. Additionally, based on the current achievements and potential plans in generating electricity from renewable resources, the contribution of these resources is expected to reach 50% of the total energy generation between 2020 and 2025 [5]. This can be noticed from the published statistics by the International Renewable Energy Agency (IRENA) on the global trends in renewable energy from 2010 to 2020, which approached an ~2800 GW installed capacity in 2020 [6]. Additionally, the largest contributing regions in renewable energy projects are in Asia, which has 45.95% of the global total installed capacity with 1286 GW [7]; this is because China is the largest consumer and has put numerous efforts to decrease the use of conventional resources and depend on renewable resources.

Solar energy is a type of renewable energy resource that is plentiful, inconsumable, free, and safe [8]. Furthermore, it is known for its simplicity and effectiveness compared to other resources [9], in addition to the evolving technology that has led to a remarkable reduction in costs and promoted the use of solar energy [10]. The total contribution of solar energy is expected to reach 31% of total renewable energy resources in 2030 [11]. The latest updated statistics in 2020 showed that the top ten countries that contributed the most to the installation of solar energy projects were China, the USA, Japan, Germany, India, Italy, Australia, Vietnam, the Republic of Korea, and Spain.

Although there has been a noticeable shift toward renewable energy, the impact of climate change is still a global challenge and a major environmental risk. The main impact of climate change is global warming [12], which refers to the slow and gradual increase in the temperature of the Earth's atmosphere due to the increase in the heat hitting the Earth from the Sun and being trapped in the atmosphere (infra-red radiation) instead of being radiated into outer space,, which happens due to greenhouse gas emissions [13].

Greenhouse gases include several gases such as carbon dioxide (CO_2), which is the most popular gas as it is common and usually used to measure the global warming and other environmental impacts. It mainly results from burning fossil fuels, tree products, solid waste, and soil degradation, fluorinated gases including perfluorocarbons and hydrofluorocarbons, which are long-lasting and very warming gases, and result from several household, industrial, and chemical activities. Methane, which has a warming effect that is 28–36 times the effect of CO_2, results from the production and transportation processes of natural gas, oil or coal, the anaerobic decay of organic waste, livestock, and agricultural practices, nitrous oxide (NO_x), which lasts for long period of time in the atmosphere, the combustion of fossil fuel and soil waste, industrial activities, and agricultural practices. Sulphur hexafluoride, which lasts for thousands of years in the upper atmosphere, is used in specialized medical procedures and water vapor [12–15]. Another component that causes global warming is black carbon (BC), which are very small carbon particles ($PM_{2.5}$ and PM_{10}) that result from the incomplete combustion of biofuel, fossil fuels, and biomass. These particles can absorb the heat of the Sun a million times more than CO_2 [12]. However, several sectors contribute to greenhouse gas emissions, but the energy sector is responsible for approximately 72% of the total greenhouse gas emissions and 31% of the energy sector demand is to generate electricity and heat from non-renewable resources [16]. This highlights the importance of focusing on using renewable energy resources to cover the electricity and heating demands.

In the context of the United Arab Emirates (UAE), electricity consumption is rapidly increasing with an overall growth of approximately 310% in the past twenty years [17]. While dependence on renewable energy resources took place in 2013 with a noticeable boost in 2019 [18], such a boost was attributed to the proven feasibility of the initially installed PV systems accompanied by the rapid increase in the registered PV contracting companies, which led to significant growth in the market of PV systems. In addition, numerous milestones have been adopted and achieved by the UAE regarding the renewable energy sector such as having the headquarters for the International Renewable Energy Agency (IRENA), hosting the annual World Future Energy Summit, establishing the Emirates Nuclear Energy Corporation (ENEC), and launching the Energy Strategy 2050, which aims to increase the share of clean energy by 50% [19]. Furthermore, the UAE's greenhouse gas emissions per capita have reached 21.26 tons, where electricity and heat are the main contributing sectors with a total share of 88.2 million tons [20].

To evaluate PV systems worldwide, it is crucial to evaluate the energy generated by these systems, the energy consumed throughout the life cycle of these systems, and their environmental and economic impacts. This can be achieved by conducting a life cycle assessment (LCA), which is a standardized and systematic method for calculating the environmental impacts during the life cycle of systems [21–23]. In addition, LCA helps policy and decision-makers by mapping and highlighting the environmental impacts and the main contributors to the global warming problem [22,24–27].

As the UAE moves toward a net zero strategy, this paper aimed to assess the environmental and economic impacts of a PV system using several environmental and economic indicators such as the CO_2 payback time (CO_2PBT), energy payback time (EPBT), global warming potential (GWP), acidification potential (AP), ozone layer depletion potential (ODP), human toxicity potential (HTP), photochemical ozone creation potential (POCP), eutrophication potential (EP), payback period (PBP), benefit to cost ratio (BCR), and levelized cost of electricity (LCOE) using as a case study a multi-crystalline (poly) PV system installed on a rooftop of an industrial facility in Dubai, UAE. The rest of this paper is organized as follows. A literature review of the relevant studies is presented in Section 2, followed by the methodology in Section 3, then the results are summarized in Section 4. Section 5 includes the discussion, and finally, Section 6 includes our conclusions and future work.

2. Literature Review

A LCA is "the compiling and evaluation of the inputs and outputs and the potential environmental impacts of a product system during its lifetime", as defined by the international organization of standardization (ISO) [28,29], where inputs represent the required resources and outputs are emissions to air, soil, and water. LCA helps in determining the environmental hotspots throughout the life processes and accordingly assists in improving the processes and making them more environmentally friendly.

The first research work that studied the environmental impacts of PV systems was back in 1970 by [30], where the total energy used to produce PV solar cells was assessed, and it was concluded that the EPBT for monocrystalline PV solar cells was 12 years, which was almost half its lifetime (25 years). Most of the conducted studies focused on greenhouse gas emissions and their consequences on the environment, especially their impact on climate change and global warming [31–33]. For instance, [34] assessed the life cycle of a PV project and found that the greenhouse gas emissions would approximately reach 16g CO_2-eq/kWh over 50 years, while the EPBT for the same project was 0.9 years, which was less than 3% of the project's lifetime. Furthermore, different production processes of PV panels result in different environmental impacts that might be related to the raw materials used, the technology used, or manufacturing equipment, therefore, some researchers considered particular processes when they conducted a LCA for PV panels [35–37].

An interesting recent review paper focused on the life cycle assessment for the generation of three PV panels including silicon-based PV panels, thin-film PV panels, and PV panels that are produced by thin-film cells but using new technologies based on nanometers as well as inorganic, organic, or semi-organic materials [38]. However, the literature lacks studies that have considered the acidification potential, biological toxicity, or eutrophication potential, and only a few researchers have examined these environmental indicators [35,39–42]. In addition, recovering, recycling, and decommissioning stages were rarely considered in the previously conducted studies [43–45].

In addition, [46] studied the life cycle of a 1.2 kWp PV system using monocrystalline PV panels in Brazil for seven geographically different locations, where the decommissioning stage was not considered. It was found that the CO_2 emissions ranged between 14.54 and 18.68 g deCO_2-eq/kWh, while the EPBT ranged between 2.47 and 3.13 years. However, China, which is ranked as the largest PV panel manufacturer in the world, is currently facing major challenges in the recycling, reusing, or decommissioning processes of PV panels since many large-scale plants have reached their end of lifetime (25–30 years of operation) [47].

2.1. Environmental Indicators

To assess the environmental impacts of PV systems, EPBT, GWP, AP, EP, CO_2PBT, ODP, POCP, and HTP are the most applicable indicators and were considered in this study. Table 1 summarizes these indicators, and the following subsections discuss these indicators based on the reviewed literature.

Table 1. List of the considered environmental indicators in this study.

Indicator	Definition	Unit
EPBT	The time needed to recover the consumed primary energy throughout the life cycle of a system.	Years
CO_2PBT	The time needed to compensate for the CO_2 emissions throughout the lifetime of a system by the CO_2 reduction from the system itself.	Years
GWP	The absorption of light that the Earth radiates back due to the presence of greenhouse gas emissions, which causes global warming and climate change.	kg CO_2-eq.
AP	The presence of acidic elements in ecosystems.	kg SO_2-eq.
EP	The potential contribution of substances to the formation of biomass.	kg $PO_4{}^3$-eq.
ODP	The emission of substances contributes to ozone layer depletion in the stratosphere.	kg CFC-11-eq.
POCP	The creation of ozone and other reactive chemicals in the troposphere.	kg C_2H_4-eq.
HTP	The direct or indirect effect of toxic substances in air, soil, biota, or water on the health of humans.	kg 1,4-DB-eq.

2.1.1. Energy Payback Time (EPBT)

EPBT means the time when the energy consumed in producing, installing, maintaining, and recycling a system is compensated by the energy produced from the system [22,44,48]. For example, if the EPBT of a PV system that has an expected lifetime of 30 years is found to be 2 years, this implies that the needed energy for this system will be compensated in 2 years and the energy generated from the system is free energy for the remaining 28 years [49]. If the value of EPBT exceeds the lifetime of the PV panels, then the recovery of the energy consumed is impossible [50]. This indicator is commonly used as it represents the total input to the total output of the system, where interpretation is easily understood [36]. This has been the focus of several researchers as a result of a life cycle assessment for PV projects and products [51–54]. The resulting values of EPBT depend on several criteria such as the location of the system and the conversion efficiency of PV panels (the higher the efficiency, the shorter the EPBT) [44,53].

2.1.2. Global Warming Potential (GWP)

The consequences of GWP can be noticed in the form of different natural changes such as tornados, new harmful pests, droughts, diseases, rising sea levels, melting glaciers, etc. [12]. The quantification and analysis of GWP are carried out by converting each greenhouse gas emission to the CO_2 equivalent value. The main greenhouse gas emissions are CO_2 with GWP = 1, N_2O with GWP = 298, CH_4 with GWP = 25, and chlorofluorocarbon with GWP = 4750–14,400; all these quantities are based on a GWP of a 100 years [55]. For PV projects, the GWP impact mainly results from the production phase, which requires most of the energy used, however, the raw materials (silicon) can be recovered and reused after the lifetime of the cells [56,57].

2.1.3. Acidification Potential (AP)

This is mainly caused by anthropogenic activities and in the context of PV systems, the production process is the main contributor to AP, where the total AP of the PV panels is approximately 57% of the total AP from the PV system [57]. It occurs when a molecule donates hydrogen ions (H^+), where increasing the concentration of hydrogen ions will reduce the pH of the medium, increase the acidity, and negatively impact the biosphere. AP results mainly from the acidification chemicals that are emitted from fossil fuel combustion including SO_2, HCL, NOx, and NO_3 [57], and the values of AP differ according to different atmospheric environments and geographical characteristics [58].

2.1.4. Eutrophication Potential (EP)

Phosphorus, phosphate ($PO_4{}^3$), ammonia, nitrate, and nitrogen are the main contributors to EP, where the increase in nutrients will increase the production of biomass, which, in the case of aquatic systems, makes the water unsuitable for drinking [23]. Thus, EP damages the freshwater and marine water ecosystems, and it is attributed to the excessive growth of plants and algae as a result of increasing the associated growth factors [59,60]. Furthermore, it is harmful to terrestrial animals and plants as it disturbs the food web [61], affects the biodiversity in ecosystems, and in PV systems, EP is mainly caused by the production process of PV panels [57].

2.1.5. Ozone Layer Depletion Potential (ODP)

The depletion of the ozone layer makes it thinner and promotes the delivery of ultraviolet B radiation to the Earth, and it takes place every time an ozone molecule is reduced to oxygen. Ozone is important for the Earth's biosphere as it has benefits at stratospheric altitudes where it absorbs 99% of the harmful incoming UV irradiation, which accordingly protects the life on Earth. Therefore, if the ozone in lower altitudes is decreased, harmful UV radiation will penetrate and adversely impact the biosphere [57,59], which is dangerous for ecosystems and humans [23]. Brominated and chlorinated substances including CH_4, N_2O, and H_2O are the main contributors to ODP, where the risk of these substances lies in the fact that they have a long residence time in the atmosphere, which implies that ozone depletion will happen for a long time after the emissions [22,57]. For PV systems, the major contributor to ozone depletion is the production of PV cells [57]. Furthermore, the consumption of aluminum frames during the assembly process of PV panels is the main contributor to the ozone layer depletion potential, and it has been proven that decreasing the aluminum consumption by 10% during the assembly of PV panels would result in a 7.01% drop in the ozone layer depletion potential [36].

2.1.6. Photochemical Ozone Creation Potential (POCP)

The photochemical oxidation of volatile organic compounds (VOC) and carbon monoxide (CO) in the presence of nitrogen oxides and UV light creates ozone and other reactive chemicals in the troposphere [23,62]. Ethylene (C_2H_4) is the contributing substance to POCP. This indicator has been used by several LCA studies [63–66], and it has been proven that POCP has negative impacts on ecosystems, crops, and human health [23].

2.1.7. Human Toxicity Potential (HTP)

The HTP was initially proposed in [67]. The direct effect of the HTP occurs when drinking contaminated water or breathing polluted air, while the indirect effect of the HTP occurs when consuming plants or animals that have been affected by toxic substances from the environment. It is the most debated and uncertain indicator in the LCA, and 1,4 dichlorobenzene (1,4-DB) is the reference substance for human toxicity [23,68,69]. The severity of toxic substances depends on several criteria including exposure time and risk, the concentration of toxins, and the physical characteristics of humans [23,57]. Additionally, the excavation and processing of cadmium, aluminum, mercury, and magnesium promote spilling them out into the environment and increasing the HTP score [57]. Additionally, workers and consumers can have direct contact with these chemicals during their working or personal daily time [70], while for PV systems, the installation process on flat roofs is the main contributor to HTP [57].

2.2. Economic Indicators

The economic impact category is one of the sustainability assessment measures, and it is investigated before the execution phase to measure the feasibility and profitability of the project [71]. Although conventional/non-renewable energy resources are relatively cheaper than renewable ones [72,73], there is a continuous effort by manufacturers and planners to optimize the cost of renewable energy resources and make them profitable, in addition to providing environmentally acceptable solutions [74,75].

To assess the economic impact of PV systems, the generated electricity should compensate for the incurred cost including the capital, installation, operation, and maintenance costs, the levelized cost of electricity should be less than the current cost of electricity from the conventional resources, and the payback period should be as short as possible [76,77]. Table 2 summarizes the considered economic indicators in this study, and the following subsections discuss these indicators based on the reviewed literature.

Table 2. List of the considered economic indicators in the study.

Indicator	Definition	Unit
LCOE	The cost of electricity generated by the PV system considers all the associated costs during the system's lifetime.	AED/kWh
BCR	The comparison of the net generated profits to the net incurred costs.	Unitless
PBP	The time when all the incurred costs during the system's lifetime are recovered due to the generated profits from the system.	Years

2.2.1. Levelized Cost of Electricity (LCOE)

This indicator is mostly used to compare the cost of the generated electricity from PV projects (after deducting all the paid amounts for the materials, installation, operation, and maintenance) with the cost of electricity from the currently available resources (grid, diesel generator, etc.), which are non-renewable resources [78,79]. Accordingly, the lower the LCOE value, the higher profitability of the PV projects achieved and vice versa.

2.2.2. Benefit–Cost Ratio (BCR)

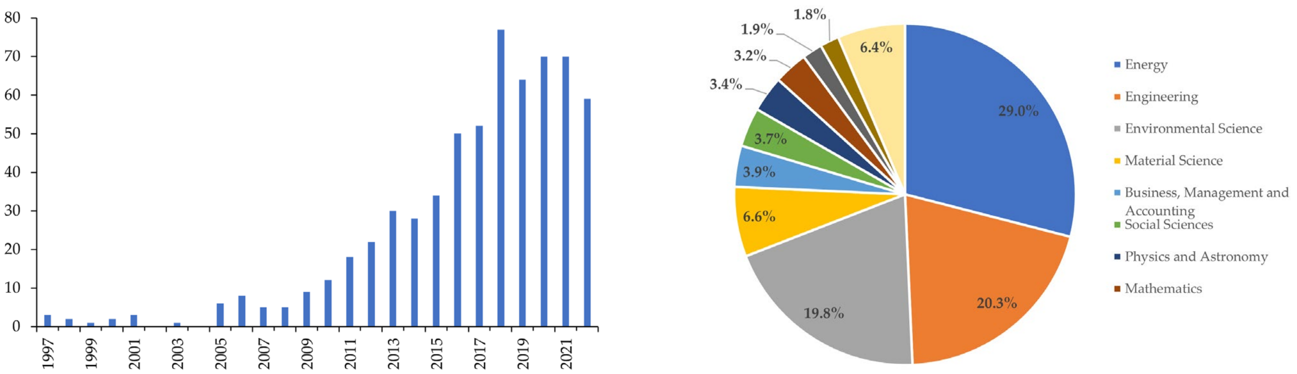
This indicator represents a profitability measure based on cost–benefit analysis, and assesses the economic success of projects by comparing the present generated benefits from the project (as monetary value) to the present incurred costs in the project [80,81]. If the resulting value of BCR is more than 1, then the project is profitable, the net present value will be positive, and the internal rate of return will be above the considered discount rate, but, if the BCR equals 1, this implies that the project is neither profitable nor lossy and the expected profits will equal the incurred cost, while a value of BCR that is less than 1 indicates a non-profitable project as the costs are going to be higher than the generated profits [82].

2.2.3. Payback Period (PBP)

The PBP is one of the widely used indicators for assessing projects [83], and takes into account the whole invested cost along with the positive and negative cash flows during the project lifetime to assess the profitability and feasibility of projects by knowing the period (in years) where a breakeven point is achieved when the net cashflow compensates the total invested cost [82,84].

Based on the reviewed literature, this study earns a significant position amongst the conducted studies as it considers many indicators from both the environmental and economic perspectives, where most of the input and output flows for the production processes considered as the main contributors to the environmental impacts in PV systems were measured directly in the production facilities (primary data), which resulted in more accurate findings in this study.

In terms of publications, there were 631 published studies in the world where environmental impact assessment and LCA were investigated for PV systems as per Scopus research analysis, which is categorized as one of the premium databases and peer-reviewed journals [85,86]. Figure 1a shows the conducted studies per year in this area, where it can be clearly noticed that the trend of research continuously increased with an insignificant drop in 2019. Furthermore, most of the conducted studies focused on the energy, engineering, and environmental areas, as illustrated in Figure 1b which supports the aim and application of this study as it focuses on the engineering, energy, and environmental aspects. In the UAE, the literature lacks environmental and economic impact assessments for PV systems, as only seven studies have been published. This might be related to the fact that these technologies are relatively new in the UAE in terms of the operational phase. However, with the numerous governmental and private initiatives toward renewable energy and PV systems as well as the rapid increase in installed capacity, there is a huge potential for such research topics in the UAE.



(**a**) (**b**)

Figure 1. Published work in environmental impacts for PV systems. (**a**) Documents per year, and (**b**) documents per subject area. Source: [85].

In addition, we selected polycrystalline PV panels instead of other available PV technologies, as this type is widely used worldwide and in the UAE due to its overall high-performance measures and values of the levelized cost of generated electricity (LCOE) [38,87]. Furthermore, most of the relevant studies in the literature have considered few environmental impact indicators (two or three indicators), where the EPBT, GWP, and CO_2PBT were mainly considered. Thus, covering numerous indicators in this study (CO_2PBT, EPBT, GWP, AP, ODP, HTP, POCP, and EP) as well as including economic impact assessment signifies the contribution of this study in this field, in addition to involving several processes other than the production of PV panels.

Consequently, to achieve the aim of this study, the authors studied the involved processes in the PV system's lifetime using a polycrystalline PV system installed on the rooftop of an industrial facility in Dubai, UAE to evaluate the environmental and economic impacts based on the input and output flows for all of the considered processes, analyze the resulting environmental and economic indicators, and set beneficial findings for the involved entities that can be used in related policies, strategies, and practices.

3. Materials and Methods

The methodology of this study was built based on the reviewed literature to identify the environmental and economic impacts to be considered, as some of the research questions were answered by the literature. Therefore, the methodology began with reviewing some of the previously conducted studies, then a set of sequential steps that included defining the assumptions of this study, providing details about the PV system location, type, and components, building the LCA framework, and conducting an economic impact assessment for the selected PV system were followed, as illustrated in Figure 2.

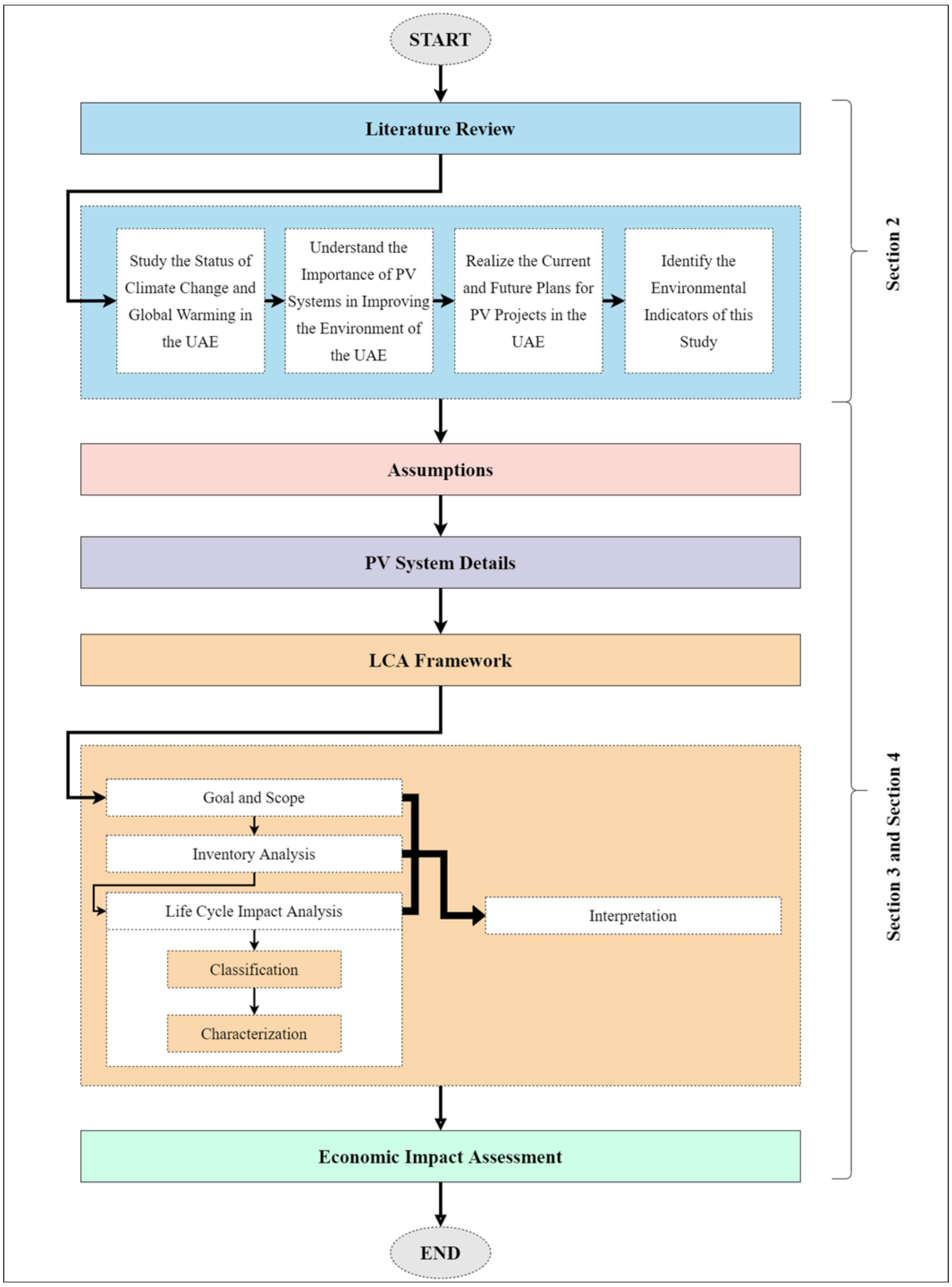


Figure 2. Methodology framework.

3.1. Assumptions

The following subsections represent the main assumptions that this study is based on.

3.1.1. System Boundary

Several cut-off criteria can be used to define the system boundaries and determine what are the included or excluded processes. In this study, the contribution of processes to the environmental impact and availability of data were used as cut-off criteria. Accordingly, the considered processes in this LCA study included the production of PV panel components, the production and assembly of PV panels, the transportation from the manufacturing plant to the site where the system will be installed, which was assumed to be one way (from the manufacturing plant in Amman, Jordan to the industrial facility in Dubai, UAE), the installation process, and the operation process, where the production of PV panels proved its significance in such assessment methods [57].

Additionally, the operation process was assumed to have insignificant environmental impacts as the resources (inputs) and emissions/wastes (outputs) are negligible in this phase when they are compared to the associated production phases; thus, the system was assumed to have zero discharges during the operation phase, while the installation phase was attributed to mounting the aluminum frame and PV panel on the roof and the electrical installation of the inverter and electrical components, where the emissions to air as well as solid wastes were estimated [36,46,88].

The excluded processes in this study were as follows. (i) Recycling and decommissioning, as the UAE has recently started adopting PV grid-connected systems, and regulations were announced in 2014. Therefore, for such systems, the lifetime is 25–30 years. Currently, there is no information or useful details regarding the recycling or decommissioning processes for PV systems in the UAE. However, the government has set targets for sustainability, and recycling in general that are related to sustainability and a circular economy, which is now taking place in several sectors. However, regarding the PV system, none of the currently installed PV systems have been operating for their whole lifetime, which justifies the lack of relevant information about the recycling system. Additionally, other countries have adopted several recycling/reusing methods for PV panels such as using the aluminum frames for newly produced panels or using the glass for facades. (ii) The maintenance process, as for such types of installation on an included roof, requires minimal maintenance and has almost no environmental impacts; the dust will not accumulate on the panels due to gravity, which implies that frequent cleaning is not required; in addition, the production and performance warranties of the PV panels equal the project lifetime (no replacement required). (iii) Balance of system components (BOS), as their contribution to environmental impacts of a PV system are insignificant compared to PV panels, especially for rooftop projects [36]. BOS includes mounting structures, cables (earthing, AC, and DC), inverters, breakers, and connectors [89]. Figure 3 shows the system boundary for this study.

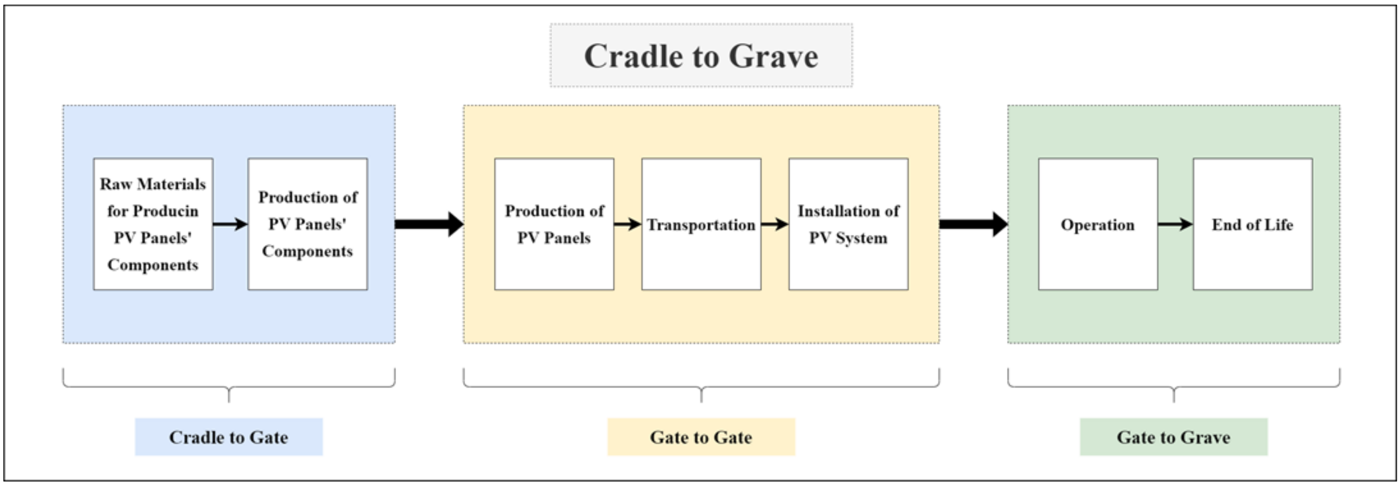


Figure 3. System boundary—LCA for a PV project in the UAE.

3.1.2. Function Unit

The function unit is the unit that makes the studies comparable, and it is crucial to define the function unit when conducting a comparative analysis [90]. For this study, the function unit was one polycrystalline PV panel that had a power capacity of 330 Wp and a mass of 22.16 kg.

3.1.3. Project Site

The PV system is installed on the rooftop of an industrial facility in Dubai, UAE. The facility is located in the Dubai Investment Park (DIP), as illustrated in Figure 4, which shows the top-view of the installed PV panels and the distribution of the PV panels on the roof as per the as-built drawings, with a latitude of 24.98°N and a longitude of 55.18°E. In this system, 1080 PV panels are connected to the grid of Dubai (DEWA) to generate electricity from the Sun. Their total mass is 23,932.8 kg, where the front glass component contributes to approximately 68% of the total mass of the PV panels. The area utilized by the PV panels is 1848.75 m^2.

(**a**) (**b**)

Figure 4. PV project site. (**a**) PV site top-view, and (**b**) distribution of the PV panels.

3.1.4. Installation Type

The PV system is mounted directly on the rooftop of the facility, having the same orientation as the corrugated sheets that are already installed on the rooftop. This type of installation has many advantages such as assuring the best utilization of the available area with the panels; providing a heat-insulation layer on the roof, which positively impacts the consumption of the air conditioning unit and reduces the associated negative environmental impacts; avoids the use of harmful materials and processes to the environment such as galvanized steel, concrete foundation, and excavation is not used; and a lower initial cost than other types of installation such as ground-mounted PV systems, elevated PV systems, or car parking PV systems.

3.2. PV System Details

The details of the selected PV system include the system components, the contribution of each raw material in the production of the PV panels, and the technical characteristics of the selected PV panel.

3.2.1. System Components

The PV system components consisted of PV panels and BOS, where the latter included all other equipment, except for PV panels, such as inverters, cables, mounting structures, electrical breakers, AC distribution boards, etc. [38]. Table 3 summarizes the components of the PV system considered in this study.

Table 3. PV system components.

No.	Component	Unit	Quantity	Description
1	PV Panels	pcs	1080	Polycrystalline—72 Cells—330 Wp
2	Inverters	pcs	6	String Inverters—Three Phase 50 kVA
3	Connectors	pcs	290	MC4
4	Mounting Structure	pcs	1080	Aluminum C-Profiles
5	Monitoring system	pcs	1	Weather Station, Sensors, and Datalogger
6	DC Cables	m	15,300	Solar Cable—6 mm^2
7	AC Cables	m	60	XLPE/PVC—4C—35 m^2
8	Earthing System	set	1	DC and AC
9	AC Combiner Box	pcs	1	Including Meter Cabinet and Breakers
10	Supporting Equipment	set	1	Cable Trays, Sundries, and Safety Lines

3.2.2. Raw Materials for Producing PV Panels

Since the production of PV panels was the considered production process in this study, as stated in the assumptions, it is important to show the contribution of each raw material in the production of PV panels. Table 4 shows all the raw materials along with their weight in the production of the selected PV panel, where the weight of each PV panel was 22.16 kg. This flow of materials to produce PV panels was defined as the reference flow, which measures the materials needed to define the function unit. These materials will be discussed in more detail in the life cycle inventory section.

Table 4. Raw material contribution in the selected PV panel.

No.	Component	Quantity	Weight "kg"		~"%"
			For (1) PV Panel	For (1080) PV Panels	
1	Front Glass	1	15.10	16,308.00	68.0%
2	PV Cells	72	0.75	810.00	3.4%
3	Ribbon Set	1	0.51	550.80	2.3%
4	Ethylene Vinyl Acetate (EVA) Sheet	2	1.52	1641.60	6.9%
5	Back Sheet	1	0.98	1058.40	4.4%
6	Junction Box with Cables	1	0.24	259.20	1.1%
7	Aluminum Frame	1	2.90	3132	13.1%
8	Adhesive Silicon	1	0.16	172.8	0.8%

3.2.3. Technical Characteristics of the PV panel

The selected PV panel was made of 72 cells of polycrystalline silicon, where 1080 PV panels were installed in this system to make a total installed capacity of 356.4 kWp. Table 5 summarizes the electrical, physical, thermal, material, and other characteristics. The electrical characteristics were measured at controlled testing conditions that are known as standard test conditions (STC) [91] and include (i) irradiance of 1000 W/m^2, (ii) ambient temperature of 25 °C, and (iii) air mass of 1.5. The electrical characteristics of the PV panels are given based on these controlled conditions.

The LCA framework consists of four steps, as shown in Figure 1 [28,29]. The goal of this study was to evaluate the environmental impact of the defined function unit installed on a rooftop of an industrial facility in Dubai, UAE, while all of the processes were defined and modeled along with their inputs and outputs to calculate the life cycle inventory (LCI) in the inventory analysis step. Appendix A shows the list of flows with thee inputs and outputs for the production processes for the selected PV panel.

Table 5. Technical characteristics of the selected PV panel.

	Electrical Characteristics (STC).		
No.	**Characteristics**	**Unit**	**Value**
1	Open Circuit Voltage—VOC	V	45.75
2	Short Circuit Current—ISC	A	9.19
3	Maximum Power Voltage—Vmpp	V	37.52
4	Maximum Power Current—Impp	A	8.80
5	Maximum Power—Pmax	W	330
6	Module Efficiency—η	%	16.9
	Physical Characteristics		
No.	Characteristics	Unit	Value
1	Module Dimension	mm	1968 × 990 × 40
2	Module Weight	kg	22.16
	Thermal Characteristics		
No.	Characteristics	Unit	Value
1	Voltage Temperature Coefficient—βVoc	%/°C	−0.32
2	Current Temperature Coefficient—αIsc	%/°C	+0.05
3	Power Temperature Coefficient—γPmp	%/°C	−0.40
4	Nominal Operating Cell Temperature—NOCT	°C	45 ± 2
	Material Characteristics		
No.	Characteristics	Value	
1	Cells Per Module	72 (12 × 6)	
2	Cell Type	Grade A, Polycrystalline	
3	Cell Size	156.75 × 156.75 mm	
4	Front Surface	Anti-Reflection Coated Tempered Glass	
5	Front Surface Thickness	3.2 mm	
6	Encapsulant	PID Free EVA	
7	Back Cover	Back Sheet	
8	Frame	Anodized Aluminum	
9	Junction Box	IP 68, 3 Bypass Diodes	
10	Connector and Cable	MC4 Interconnection, 1.2 m	
11	Fire Classification	Type I	
	Other Characteristics		
No.	Characteristics	Value	
1	Positive Power Tolerance	Up To 3% Extra Output	
2	Annual Degradation	−0.7%	

Next, the results from the LCI were used to calculate the life cycle impact assessment (LCIA), where the significance and amount of the potential environmental impact of the processes were defined. It is mandatory to classify the emissions by assigning each to the related impact category and then characterizing the emissions by converting them to a reference unit of measurement using a pre-defined characterization factor [28,29]. In this study, TRACI 2.1 was used for the characterization factors. Finally, the interpretation takes place in the environmental hotspots and draws conclusions and recommendations.

Gabi software was used to conduct this LCA based on the collected information on all the considered processes. However, all the environmental impact factors can be calculated using defined mathematical equations that are related to the assigned emissions for each impact factor.

4. Results

The following subsections summarize the results of the environmental and economic impact assessments.

4.1. Environmental Impact Assessment

The results of the analysis for each environmental indicator are discussed in the following subsections.

4.1.1. Primary Energy Demand, EPBT, and CO_2PBT

From the analysis, it was found that the production process of polysilicon contributed to approximately 50% of the total primary energy demand, followed by the production process of a PV panel and the production process of PV cells, while other processes had an insignificant contribution to the total primary energy, as shown in Figure 5. The performance ratio of this PV system, which was measured by considering the heat, cables, soiling, and inverter losses, is 75.04%, while the peak sunshine hours in the UAE is approximately 5.84 h/day, the lifetime of the PV system is 25 years, and using the total primary energy required for the whole PV system of 1,151,690.5 kWh (1152 MWh), the EPBT will be 2.15 years, which implies that 2.15 years are needed to recover the energy consumed in the PV system during its lifetime (25 years). In other words, the energy produced from the PV system for the remaining years (22.85 years) is free. Moreover, the calculated CO_2PBT was 1.87 years, which means that 1.87 years are needed to recover the CO_2 emissions of this PV system by the reduction of CO_2 emissions gained from the operation phase of the system.

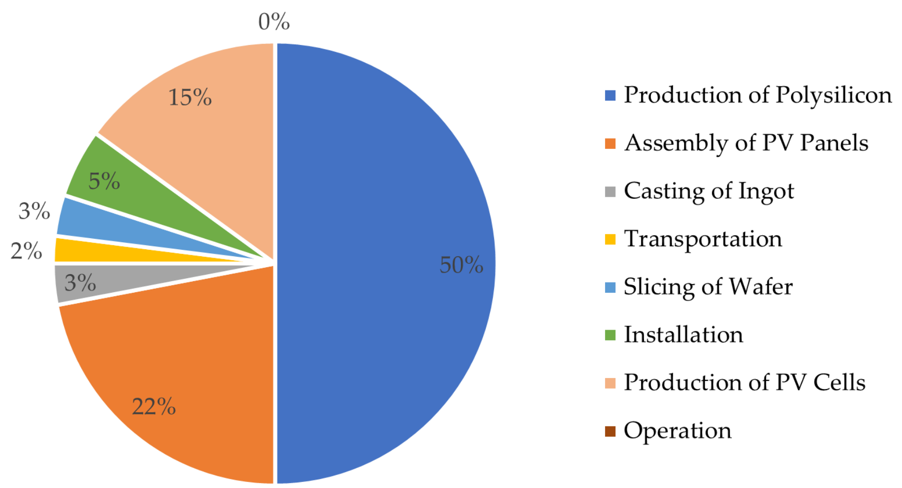


Figure 5. Contribution percentage of each process to the primary energy demand.

4.1.2. Global Warming Potential (GWP)

The GWP of this PV system was 6.83×10^{-2} kg CO_2-eq, where the production process of polysilicon contributed to approximately 40% of the total GWP, followed by the production process of a PV panel and the production process of PV cells. These production processes depend on electrical energy from the grid, where conventional energy resources are used to generate and supply electricity. In addition, the production process of the aluminum frame of PV panels is attributed with an abundant amount of CO_2 emissions, which justifies the remarkable contribution of these production processes to the GWP. Figure 6 represents the GWP for each process within the defined system boundary.

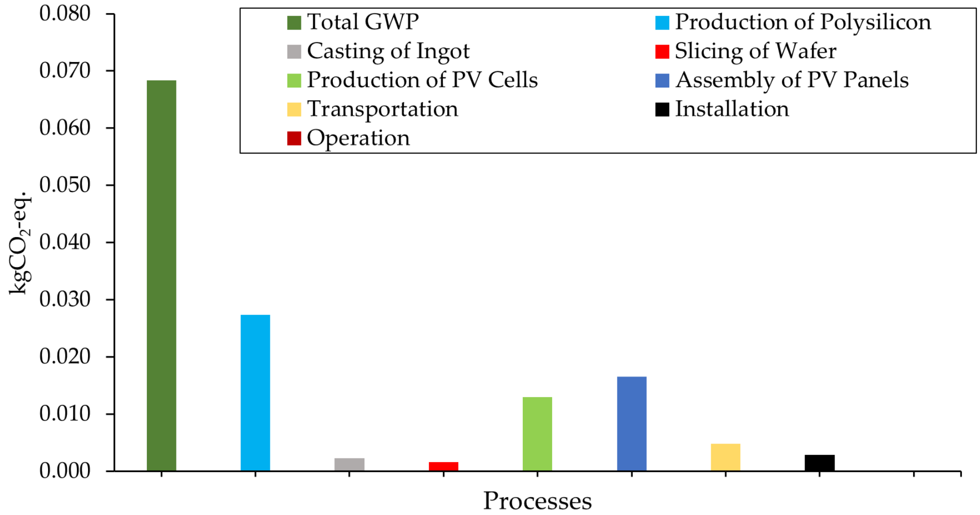


Figure 6. Global warming potential.

4.1.3. Acidification Potential (AP)

The AP score for this PV system was 2.87×10^{-4} kg SO_2-eq, where the production process of polysilicon contributed to more than 50% of the total calculated AP, followed by the production process of PV cells and the production process of a PV panel. As is the case of the calculated GWP, the contribution of the consumed electricity in the production processes led to this result, as it depends mainly on non-renewable energy resources. Figure 7 illustrates the AP score for each process within the defined system boundary.

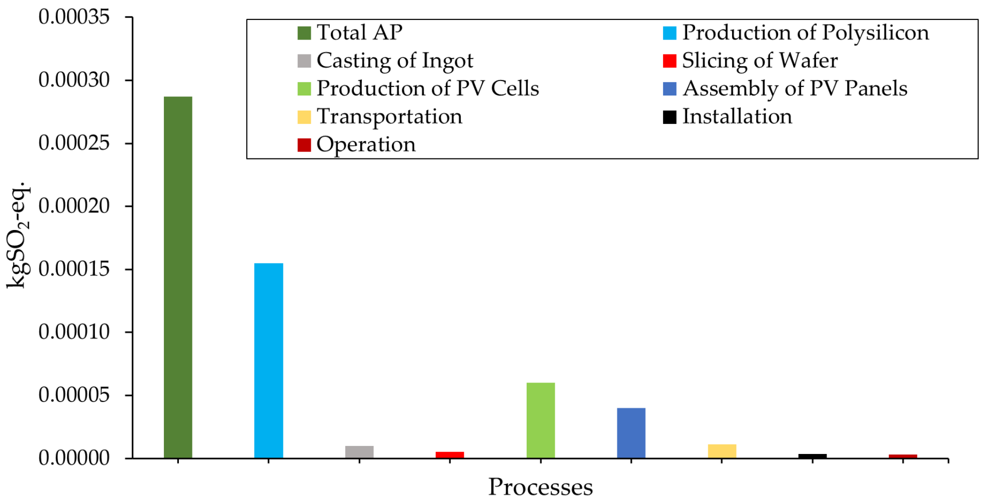


Figure 7. Acidification potential.

4.1.4. Eutrophication Potential (EP)

The EP score for this PV system was 2.45×10^{-5} kg $PO_4{}^3$-eq., where the contribution of the processes was similar to the case of AP, the production process of polysilicon contributed to more than 45% of the total calculated AP, followed by the production process of PV cells and the production process of a PV panel. Figure 8 illustrates the EP score for each process within the defined system boundary.

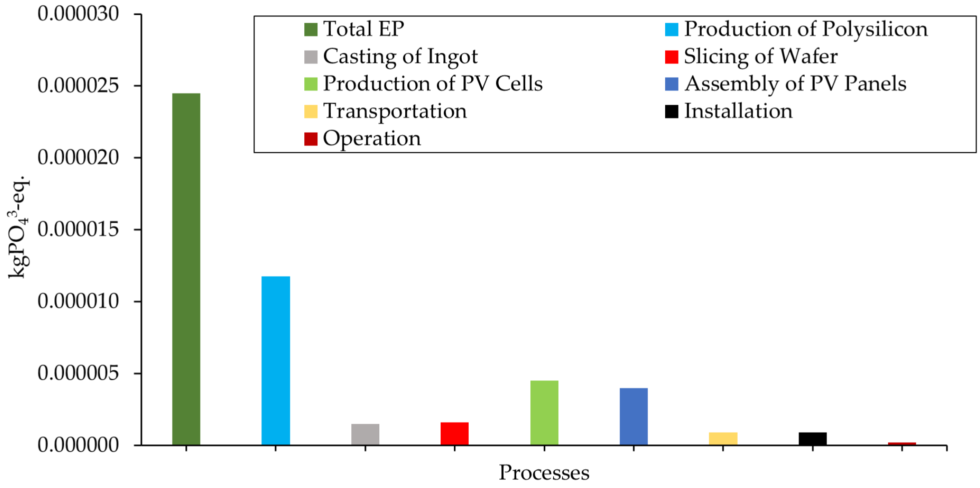


Figure 8. Eutrophication potential.

4.1.5. Ozone Layer Depletion Potential (ODP)

The ODP score for this system was 4.685×10^{-9} kg CFC-11-eq., the most influential process in this score was the production of a PV panel, which contributed to more than 70% of the total ODP score, followed by the production process of polysilicon, which contributed to approximately 20% of the total ODP, while other processes had an insignificant impact. This was mainly due to the production process for the aluminum frame of the PV panel and the consumed electricity during the whole production process, which is originally generated from non-renewable energy resources. Figure 9 represents the ODP score for each process within the defined system boundary.

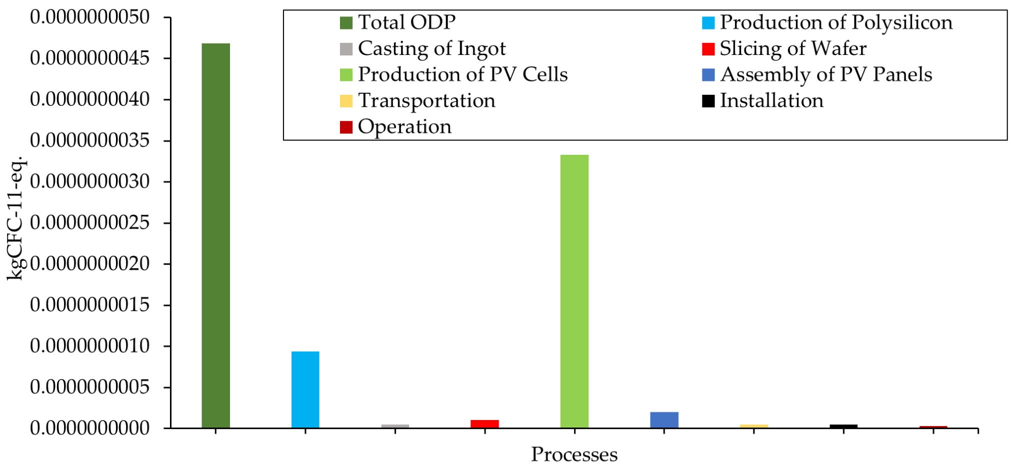


Figure 9. Ozone layer depletion potential.

4.1.6. Photochemical Ozone Creation Potential (POCP)

The POCP score for this system was 3.81×10^{-5} kg C_2H_4-eq., similar to most of the discussed environmental indicators. The production of polysilicon, PV cells, and the PV panel were the most influential processes in the total POCP score. This was due to the non-renewable source of electricity at the production plants and the aluminum frame production process. Figure 10 shows the POCP score for each process within the defined system boundary.

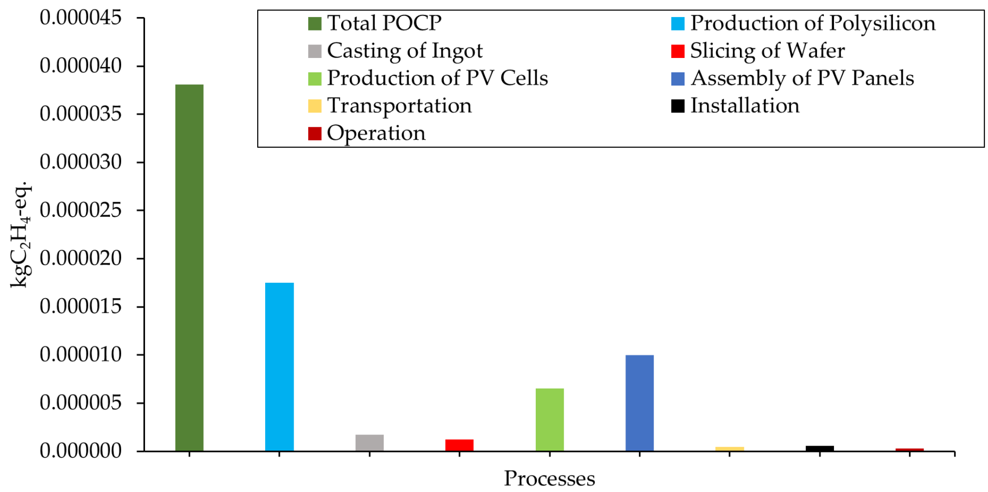


Figure 10. Photochemical ozone creation potential.

4.1.7. Human Toxicity Potential (HTP)

The HTP score for this system was 2.38×10^{-2} kg 1,4-DB-eq., where the production of polysilicon was responsible for more than 30% of this score, followed by the slicing process of the wafer with approximately 25%, and the production of PV panels with approximately 20%, while each one of the remaining processes had an insignificant contribution, as illustrated in Figure 11.

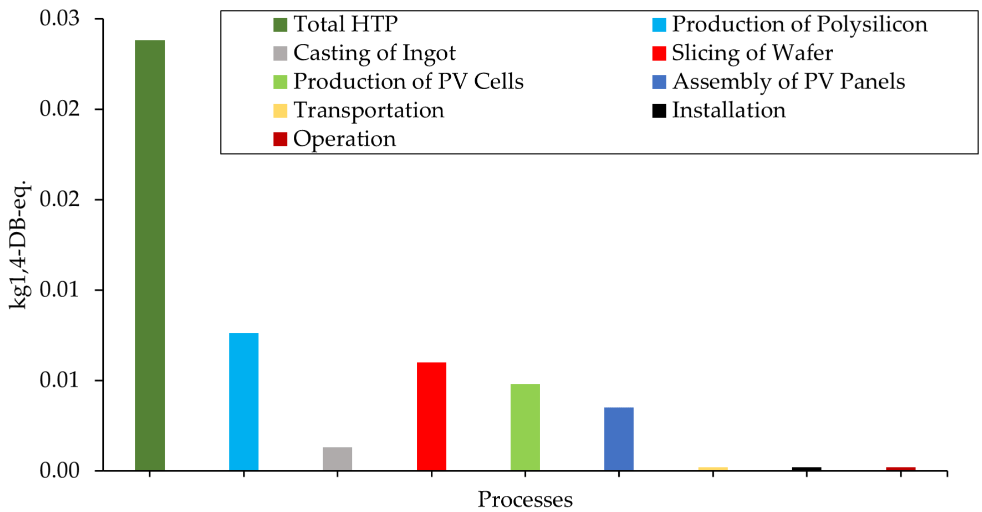


Figure 11. Human toxicity potential.

4.2. Economic Impact Assessment

Considering the electricity consumption for the facility before installing the PV system, the electricity tariff for the industrial sector in Dubai is DEWA (Dubai Electricity and Water Authority) and including the additional charges (value-added tax and fuel charges) [92], the discount rate (%), and the projected generation of the PV system based on the estimated losses during the operation, and the degradation in the performance of the PV panels, Table 6 can be constructed, and the achieved monetary savings (AED) considering all of the incurred costs during the project lifetime will equal AED 10,520,372 at the end of the PV project's life.

Table 6. Annal generation and savings for the selected PV project.

Year	Annual Generated Electricity (kWh/Year)	Approx. Yearly Savings (AED)
1	535,670	243,729
2	531,920	254,125
3	528,196	264,963
4	524,499	276,264
5	520,827	288,046
6	517,181	300,331
7	513,561	313,141
8	509,966	326,496
9	506,396	340,421
10	502,852	354,940
11	499,332	370,078
12	495,836	385,862
13	492,366	402,319
14	488,919	419,478
15	485,497	437,369
16	482,098	456,023
17	478,723	475,472
18	475,372	495,751
19	472,045	516,895
20	468,740	538,940
21	465,459	561,926
22	462,201	585,892
23	458,966	610,880
24	455,753	636,934
25	452,563	664,100
Total	12,324,937	10,520,374

Using the aforementioned economic metrics, the LCOE for this project can be calculated using the following equation [59,60]. The LCOE equals 0.142 AED/kWh, which is ~31.4% of the current industrial tariff at DEWA (0.452 AED/kWh), indicating the high economic feasibility of the project.

$$\mathrm{LCOE} = \frac{\sum_{i=0}^{N}\left[\frac{I_i+O_i+F_i-TC_i}{(1+r)^i}\right]}{\sum_{i=0}^{N}\left[\frac{E_i}{(1+r)^i}\right]}$$

I_i is the capital cost in year i (currency). O_i is the operation and maintenance cost in year i (currency). F_i is the cost of used fuel in year i (currency). TC_i is the tax credits or insurance cost on year i (currency). R is the considered discount rate (%). E_i is the generated electricity from the PV system in year i (kWh). N is the economic lifetime of the PV system (years).

The BCR can be calculated by dividing the net present value of the net positive cashflow by the net present value of the net negative cashflow [59,60], as shown in the following equation. The BCR equals 11.8, and since it is greater than 1, it indicates a high feasibility and profitability.

$$\mathrm{BCR} = \frac{\mathrm{NPV}_{\text{net positive cashflow}}}{\mathrm{NPV}_{\text{net negative cashflow}}}$$

Finally, the payback period can be calculated using the following equation [59,60]. The PBP of this PV project was 3.5 years, which was 14% of the project lifetime, as illustrated in Figure 12.

$$\mathrm{PBP} = \frac{\mathrm{NPV}_{\text{net positive cashflow}}}{\mathrm{NPV}_{\text{net negative cashflow}}}$$

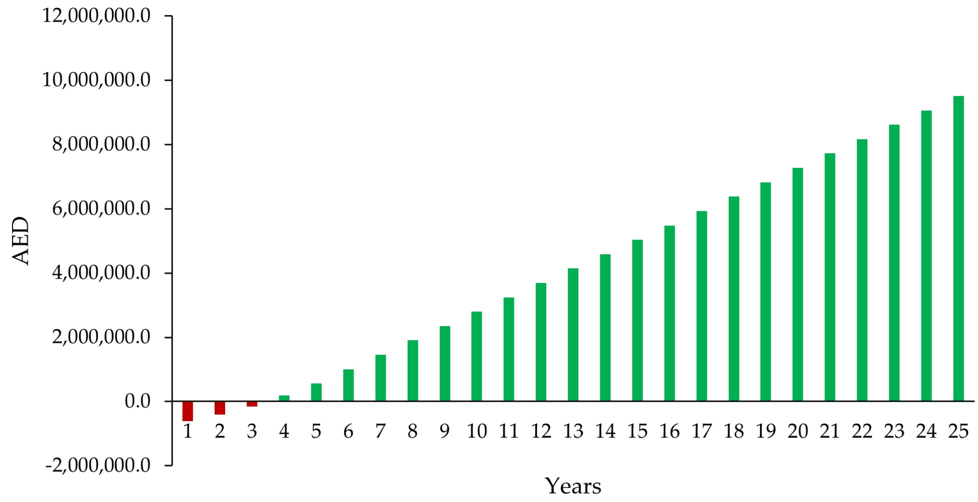


Figure 12. Payback period for the PV project.

Additionally, installing PV panels on such types of roofs is considered the most feasible option, as the required structure for installing the panels is the least among other types of installation. In this installation, the panels are laid on the corrugated sheet by using aluminum rails that are fixed on the roof through and linked to the existing rails that carry the corrugated sheet. Therefore, the capital cost is significantly reduced, which results in improving the feasibility of the project. However, there is a limit on the size of the PV system where below this limit the system would be feasible. Setting this limit takes into consideration several vital factors including the average electrical consumption, the associated maintenance, the available area for installation, cost per kWp installed, etc. For this PV system, the installed size is 356.4 kWp in terms of the maximum capacity that can be installed on the roof area considering empty spaces for access, cleaning, and maintenance. However, installing a PV system that is less than 185 kWp for this project would be unfeasible, as the LCOE will be higher than the prevailing tariff (AED/kWh), would cover less than 40% of the consumption, and increase the payback period by an additional 5 years. In terms of the environmental effects, previous studies suggested that PV systems are defined as emission-free energy systems [93], and the adverse environmental impacts are usually linked to the production processes regardless of the system size.

5. Discussion

The study revealed that the main environmental damage due to PV panels occurred during the production processes of polysilicon, PV cells, and PV panels due to the high-demand on-grid electricity that is generated from non-renewable resources as well as the associated greenhouse gas emissions from producing the polysilicon material, slicing the wafers, producing the aluminum frames, and assembling the panels. Based on the results in Section 4, it was noticed that all of the considered environmental impact indicators have been examined for the processes within the defined system boundary. Each indicator has shown significance based on the emissions resulting from each flow. The total primary energy demand in this study was mainly through the use of grid electricity, which is derived from conventional/non-renewable energy resources and mostly incurred in the production of polysilicon, PV cells, and PV panels. Therefore, optimizing the production processes will result in better primary energy demand values, which will accordingly decrease the energy payback time. This has also been highlighted by [44], where the impact of optimizing the production processes and providing PV panels with higher efficiency would certainly result in lower energy payback times.

Similarly, these production processes contribute to most of the global warming potential, acidification potential, eutrophication potential, human toxicity potential, ozone layer depletion potential, and photochemical ozone creation potential. This is attributed to carbon dioxide, sulfur dioxide, nitrate, nitrogen oxides, nitrous oxide, ammonia, silicon tetrachloride, phosphate, non-methane volatile organic compounds (NMVOC), selenium, and other greenhouse gas emission from the high demand on electricity (grid) in production processes. These findings are in line with the findings in similar studies in Korea, Thailand, and China [23,36,44,56,59,61,94–97]. For example, the production of ultrapure silicon has a high energetic cost and releases chlorinated gases to the atmosphere, which results in adverse environmental consequences [98].

However, the operation phase has a negligible environmental impact on the selected PV system, as shown in the Results section, which is supported by a few previously conducted studies where the contribution of the operation phase was found to be insignificant in the overall impact assessment indicators [36,46,88].

When assessing the influence of transportation of the PV panels, it has been shown that the impact could be considered insignificant as the panels used in this study were transported from Jordan to the UAE through land freight, which has a considerably lower negative impact on the environment and cost compared to other exporting destinations such as China, Europe, or the USA. These findings are highly influenced by the geographical location, installation type, materials used, the origin of the materials, etc.

Furthermore, a comparison of the findings for all of the selected environmental impacts was conducted to highlight the significance of each environmental indicator in each process. This was carried out by normalizing the results for all indicators and then comparing them across all of the processes. Figure 13 shows the normalized environmental impacts for the considered processes of the function unit, where it can be noticed that the environmental impact indicators for the operation phase were negligible, while the installation, transportation, slicing of the wafer, and casting of ingots had a small influence on the selected environmental impacts. However, the production of polysilicon, PV cells, and PV panels had the most significant influence on the environmental impacts, where they contributed to 83.5% of the total GWP, 91% of the total AP, 84.5% of the total EP, 95% of the total ODP, 92.3% of the total POCP, and 69.8% of the total HTP.

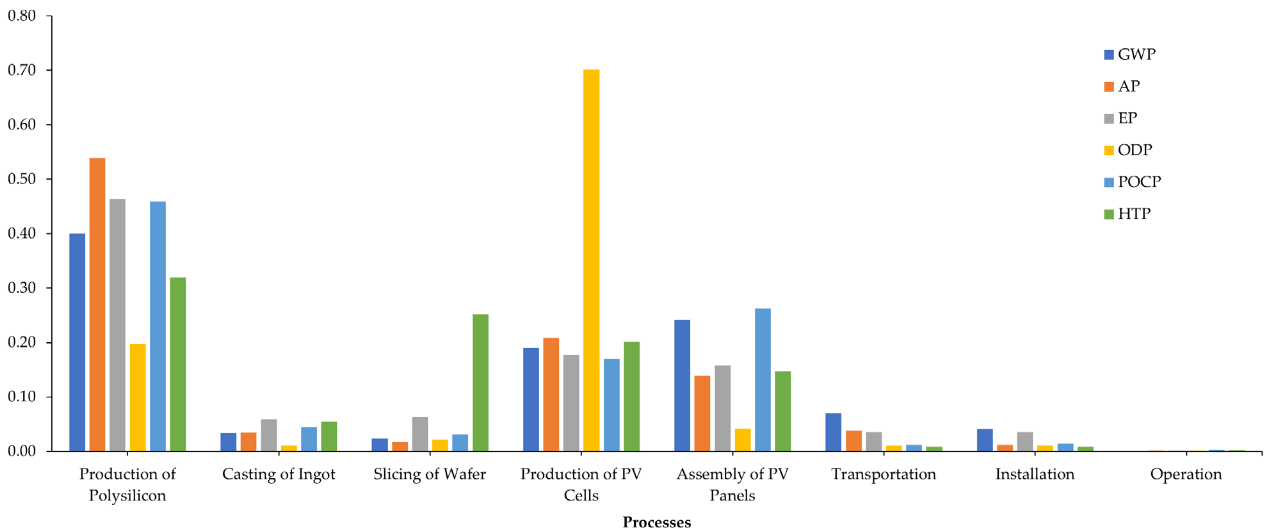


Figure 13. Normalized environmental impacts for all processes.

Regarding the economic impact of this PV system, it can be noticed from the results that the selected economic indicators showed high profitability and feasibility values, where for such a long project lifetime (25 years), the capital investment cost including the material, installation, and operation costs will be recovered within 3.5 years of operation, which promotes adopting PV systems to generate electricity in the UAE. Moreover, with the anticipated increase in the grid electricity tariff, the PBP would be less than 3.5 years. Additionally, the benefit-to-cost ratio for this project was calculated based on the net present value (positive and negative) and resulted in a high value of 11.8, which implies a profitable project. Finally, the levelized cost of electricity was 0.142 AED/kWh, while the current electricity tariff in DEWA for the industrial sector is 0.452 AED/kWh. It is apparent from the results that generating electricity from the PV system is definitely more feasible than relying on the grid, even though the dependence on the PV system is partly due to area limitations that would restrict installing a PV system that covers all of the consumption. These findings were based on comparing the electricity generated from the system with the electricity withdrawn from the grid, so the results would differ and become more feasible if they are compared with other sources of electricity such as diesel generators that are used on several islands and remote areas in the UAE.

The recycling phase is not yet implemented or regulated in the UAE, as the market of PV is still new (not more than 6 years), but it is important to explore the dismantling, recycling, decommissioning, or reusing practices of PV panels and be ready with proper procedures that would not impact the environment negatively. A study by Bartie et al. (2021) explored the PV life cycles in terms of resource efficiency, circularity, and sustainability, presenting potential opportunities for the recovery of high-quality secondary resources [99]. Additionally, other studies have suggested the use of emerging materials and technologies to improve the use of solar energy. The study focused on enhancing the efficiency of photovoltaic devices such as hot-carrier solar cells, printable solar cell materials, multijunction, ultrathin, and intermediate band [100].

Additionally, the social aspect can be integrated into this sustainability assessment by conducting a qualitative study based on a representative survey using several social indicators such as job creation, human health, human welfare, ethic, awareness, and social acceptance, where the results will provide recommendations and suggestions to weak areas where the efforts should be focused to enhance the social sustainability of the PV project.

In general, the adaptation of renewable energy sources such as solar energy is a promising field, but its effects on the environment, especially at the production stage, should be carefully assessed to ensure minimal environmental impacts.

6. Conclusions

The UAE has announced its net zero strategy initiative in hopes of achieving net-zero emissions by 2050. As part of this initiative, solar energy dominates due to its regional potential. This study used a case study in Dubai and provides comprehensive environmental and economic impact assessments of a PV project considering a polycrystalline PV panel (330 Wp) as a function unit, where the production of raw materials, the production of PV cells, the production of PV panels, the transportation of PV panels from Jordan to Dubai, UAE, installation of the PV system, and the operation of the system were the included processes within the system boundary. It is clear that the main impacts to the environment from the PV panels are during their production, rather than their usage.

The findings of this study open the door to encouraging policymakers, PV manufacturing plants, and PV contracting companies to optimize the associated processes used for the production of the panels to enhance the sustainability of PV systems. Hence, it is recommended that the production processes, especially for the silicon, cells, frames, and panels, are optimized as well as incorporating renewable energy resources in their production plants to decrease the dependency on grid electricity.

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Data Availability Statement: Data supporting the reported results can be found in Appendix A.

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

Appendix A

Table A1. Flows for the production processes of the selected 330 Wp polycrystalline PV panel.

No.	Processes	Unit	Value
1	Metallurgical Smelting for Silicon		
1.1	Inputs		
1.1.1	Standard Coal	kg	14.85
1.1.2	Quartz Sand	kg	6.37
1.1.3	Graphite	kg	0.22
1.1.4	Tar	kg	0.22
1.1.5	Electricity	kWh	23.73
1.1.6	Water	kg	23.73
1.2	Outputs		
1.2.1	Silicon	kg	1.86
1.2.2	Slag from MG Silicon Production for Disposal	kg	1.39
1.2.3	Suspended Substances	kg	0.06
1.2.4	Carbon Dioxide to Air	kg	41.95
1.2.5	Carbon Monoxide to Air	kg	0.77
1.2.6	Nitrogen Oxides to Air	g	86.79
1.2.7	Silicon Dioxide to Air	kg	0.52
1.2.8	Sulfur Dioxide to Air	kg	0.21
1.2.9	Water	kg	23.10
2	Production of Polysilicon		
2.1	Inputs		
2.1.1	Trichlorosilane	kg	9.81
2.1.2	Metallurgical Silicon	kg	1.87
2.1.3	Silicon Tetrachloride	kg	2.60
2.1.4	Calcium Oxide	kg	2.09
2.1.5	Hydrogen	kg	0.17
2.1.6	Hydrofluoric Acid	kg	0.02
2.1.7	Hydrochloric Acid	kg	1.07
2.1.8	Chlorine	kg	1.94
2.1.9	Nitric Acid	kg	0.08
2.1.10	Nitrogen Gaseous	kg	23.00
2.1.11	Sodium Hydroxide	kg	1.40
2.1.12	Electricity	MJ	666.12
2.1.13	Steam	kg	108.55
2.1.14	Water	kg	2794.04
2.2	Outputs		
2.2.1	Solar Grade Poly Silicon	kg	1.79
2.2.2	Silicon Dust for Recovery	kg	0.29
2.2.3	COD to Water	g	25.23
2.2.4	Suspended Solids to Freshwater	g	16.75
2.2.5	Silica	kg	1.65
2.2.6	Chloride	kg	1.95
2.2.7	Trichlorosilane to Air	g	9.57
2.2.8	Chlorosilane to Air	g	8.42
2.2.9	Water (Evapotranspiration) to Air	kg	2021.91
2.2.10	Hydrogen Chloride to Air	g	10.09

Table A1. *Cont.*

No.	Processes	Unit	Value
2.2.11	Hydrogen Fluoride to Air	g	0.05
2.2.12	Silicon Tetrachloride to Air	g	2.69
2.2.14	Silicon Dust to Air	g	2.45
2.2.15	Nitrogen Dioxide to Air	g	1.13
3	Casting of Ingot		
3.1	Inputs		
3.1.1	Solar Grade Poly Silicon	kg	1.79
3.1.2	Quartz Crucible	kg	5.04
3.1.3	Silicon Carbide	g	20.08
3.1.4	Sodium Hydroxide	g	15.01
3.1.5	Argon	kg	3.66
3.1.6	Silicon Chloride	kg	silicon chloride
3.1.7	Compressed Air	m^3	6.11
3.1.8	Hydrofluoric Acid	g	61.67
3.1.9	Hydrochloric acid	kg	0.94
3.1.10	Electricity	MJ	53.29
3.1.11	Steam	kg	2.61
3.1.12	Water	kg	143.82
3.2	Outputs		
3.2.1	Poly Silicon Ingot	kg	1.71
3.2.2	Waste Quartz Crucible for Recovery	kg	5.04
3.2.3	Silicon Carbide	g	19.65
3.2.4	Waste Acid	g	107.48
3.2.5	Water (Evapotranspiration) to Air	kg	118.29
3.2.6	Hydrogen Fluoride to Air	g	0.20
4	Slicing of Wafer		
4.1	Inputs		
4.1.1	Poly Silicon ingot	kg	1.71
4.1.2	Steel Wire	kg	5.32
4.1.3	Glass	kg	0.83
4.1.4	Compressed Air	m^3	8.87
4.1.5	Detergent	kg	0.70
4.1.6	Silicon Carbide	g	55.85
4.1.7	Acetic Acid	kg	0.20
4.1.8	Electricity	MJ	7.35
4.1.9	Water	kg	156.68
4.2	Outputs		
4.2.1	Poly Silicon Wafer	kg	1.05
4.2.2	Silicon Scrap for Recovery	kg	0.61
4.2.3	Glue Residues for Disposal	g	75.09
4.2.4	Glass	kg	0.83
4.2.5	Chloride	g	1.98
4.2.6	Hydrogen Chloride	g	0.09
4.2.7	Nitrogen Oxides to Air	g	0.35
4.2.8	Acetic Acid	kg	0.20
4.2.9	Wastewater	kg	98.00
5	Production of PV Cells		
5.1	Inputs		
5.1.1	Poly Silicon Wafer	kg	1.05
5.1.2	Natural Gas	kg	0.17
5.1.3	KOH	kg	0.82
5.1.4	Nitrogen	kg	2.28

Table A1. *Cont.*

No.	Processes	Unit	Value
5.1.5	Nitric Acid	kg	0.74
5.1.6	Phosphoric Acid	g	3.14
5.1.7	Hydrofluoric Acid	kg	0.19
5.1.8	Hydrochloric Acid	kg	0.78
5.1.9	Ammonia	g	28.36
5.1.10	Aluminum	kg	0.16
5.1.11	Silver	g	18.14
5.1.12	Ethanol	kg	0.08
5.1.13	Electricity	MJ	189.64
5.1.14	Steam	kg	8.74
5.1.15	Water	kg	281.14
5.2	Outputs		
5.2.1	Poly Silicon Solar Cell	kW	0.33
5.2.2	NMVOC to Air	g	10.52
5.2.3	Nitrogen Oxides to Air	g	22.56
5.2.4	Hydrogen Fluoride to Air	g	1.30
5.2.5	Hydrogen Chloride to Air	g	1.50
5.2.6	Ammonia to Air	g	2.26
5.2.7	Water	kg	287.97
6	Assembly of a PV Panel		
6.1	Inputs		
6.1.1	Poly Silicon Solar Cell	kW	0.33
6.1.2	Aluminum	kg	4.46
6.1.3	Glass	kg	15.1
6.1.4	Isopropanol	g	5.24
6.1.5	Ethylene Vinyl Acetate Copolymer (EVA)	kg	2.30
6.1.6	Ethanol	g	17.69
6.1.7	Poly-Vinyl Fluoride Film (PVF)	kg	0.97
6.1.8	Poly-Ethylene Terephthalate (PET)	kg	0.97
6.1.9	Electricity	MJ	23.08
6.1.10	Steam	kg	5.22
6.1.11	Water	kg	38.99
6.2	Outputs		
6.2.1	PV Solar Panels	kW	0.33
6.2.2	Suspended Substances	kg	0.13
6.2.3	Activated Carbon for Recovery	g	19.87
6.2.4	Carbon Dioxide	g	205.59
6.2.5	Water (Evapotranspiration) to Air	kg	31.11
6.2.6	Water to Freshwater	kg	7.53

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