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Life cycle assessment of polycrystalline solar panel production in Iran

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Abstract

In recent decades, global energy demand and environmental pollution have been steadily rising. The power sector is one of the major sources of global environmental pollution. Hence, it is necessary to pay more attention to renewable energy resources. In order to identify the best scenario for construction of a renewable power plant, it is necessary to examine all scenarios from all environmental aspects. Life cycle assessment methodology can be a useful tool for this purpose. In this research, life cycle of polycrystalline solar panel production in Iran is assessed. Primary energy consumption, global warming potential, acidification potential and eutrophication potential for panel and also cell manufacturing is assessed and the share of each panel component in all impact categories is presented. The primary energy demand is calculated as 15.4 MJ/W_P and GWP, AP and EP are calculated as 1.4356 kg CO_2-equiv. /W_P, 0.006 kg SO_2-equiv. /W_P and 0.0013 kg PO_4^{3-}-equiv. /W_P respectively. Transportation of panel components to the panel manufacturer is modelled in detail, results show that its contribution to life cycle primary energy consumption and environmental pollution is negligible. The results of this study can be used to identify critical points of the manufacturing life cycle and also to make decisions for the development of photovoltaics in Iran.

Keywords: Life cycle assessment; Polycrystalline solar panel; GHG emissions

Introduction

Global energy demand trends show a steady increase over the years [1], according to the latest statistics provided by the International Energy Agency in 2018, fossil fuels account for 81% of the world's primary energy supply [1]. Listed items alongside problems such as climate change, water pollution and scarcity, resource depletion and other environmental damages, makes the development of renewable energy knowledge and technologies and any other efforts to managing these dilemmas to an inevitable necessity.

Worldwide electricity generation accounts for 42% of greenhouse gas emissions, 48% of sulphur dioxide emissions and 64% of coal and 40% of natural gas consumption [1]. According to the outlook set by the International Energy Agency to tackle global warming and achieving sustainable development goals, greenhouse gas emissions need to be reduced by 90% by 2050, this implies reducing carbon dioxide emissions from 13 Gt per year to 1.4

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Gt [2]. It is furthermore necessary to increase the share of wind and solar power plants in global electricity generation by 9.3 times by 2040 to achieve the sustainable development horizon. If this prospect occurs, wind and solar power plants will account for 38% of total electricity generation [1]. In this regard, many governments have adopted policies that will accelerate and facilitate the development of electricity through low-carbon technologies [3].

Currently, photovoltaic and wind technologies account for 23% of total renewable electricity generation, followed by hydro-electricity generation with a share of 64% [4, 5]. It should be noted that the installed capacity of photovoltaic systems experienced a 50-fold increase between 2007 and 2017 and their share in global electricity generation increased from 0.03% in 2006 to 1.3% in 2016 [4, 5].

According to latest statistics released by the Iranian Ministry of Energy by the end of the solar year 1397, only about 1% of the country's electricity is generated by renewable energy sources [6]. This represents a significant difference with the sustainable development approach outlined by the International Energy Agency. Therefore, the study and development of renewable energy industry in Iran should be considered as an essential necessity.

Constructing a renewable power plant under any circumstances does not necessarily mean clean energy production and cannot be considered more appropriate than other electricity generation scenarios. In other words, changing point of view and paying attention to all the stages in the production, installation, commissioning and operation of power plant components can indicate significant pollutant emissions and remarkable energy consumption. Therefore, it is imperative to employ a tool that be able to calculate the total energy and resource consumption and pollutant emissions at all stages of power plant construction [7, 8].

Among the methods available to measure the environmental aspects of a product or process, Life Cycle Assessment (LCA) is one of the leading approaches that can estimate cumulative environmental impacts arising from all stages of a product or process life cycle [9].

Several studies have been carried out on life cycle assessment of photovoltaic power plants from various aspects. Life cycle assessment of a 4.2 kW_P grid-connected photovoltaic system mounted on a building rooftop at the University of Murcia is conducted by Valverde et al. [10]. All components of the system including panel, inverter, battery, structure and cable are considered, energy consumption and impacts on global warming are investigated. The Energy Pay-back Time (EPBT) is found to be 9.08 years and the specific CO_2 emissions is calculated as 131 g/kWh. Sumper et al. performed a life cycle assessment on a 200 kW_P roof top photovoltaic system with polycrystalline silicon modules [11]. The authors evaluate the net energy pay-back and greenhouse gas emission rates. The EPBT is between 3.5 and 5 years, depending on the irradiation.

Environmental footprint estimation of a grid-connected 20 MW_P capacity ground mounted PV system located in Felsőzsolca, Hungary is carried out by Szilágyi and Gróf [12]. Their results indicate that the production of photovoltaic modules account for around half of the total aggregated environmental impacts. The power plant reduces the environmental footprint by 75% compared to the Hungarian grid mix.

Pacca et al. compare polycrystalline silicon PVs with amorphous silicon in an installation of 33 kW roof top photovoltaic system [13]. The NER of polycrystalline modules is 2.7 and the EPBT is 7.4 year versus a ratio of 5.14 and 3.15 years for amorphous silicon. For the CO_2 emissions, the latter obtains 34.3 g CO_2-equiv. /kWh against 72.4 for the former.

Three different multi-Si PV technologies are compared by Luo et al. [14]. These three types are Aluminium back surface field (Al-BSF), Passivated emitter and rear cell (PERC) and PERC solar cells with the frameless double-glass module structure. The EPBTs are 1.11, 1.08 and 1.01 years, respectively, while their GHG emissions are 30.2, 29.2 and 20.9 g CO_2-equiv. /kWh, respectively.

A review of life cycle assessment studies of both off-grid and on-grid photovoltaic systems counting all components such as panels, inverters, structures, cables, connectors, etc. indicates that Up to 70% of primary energy consumption and pollutant emissions are related to panel production process [10, 12, 15-17]. Therefore, modelling of solar panel production process can be considered as the most essential part of the life cycle assessment of photovoltaic systems.

Review of previous studies shows that the transportation of components in solar panel production process has mainly been neglected, while the reason for this is not explained.

No publication has been found on an LCA of solar panel production as a major component of photovoltaic power plants specific to Iran. The objectives of this paper are to:

- Quantitatively assess the environmental impacts of solar panel manufacturing in Iran to provide a basis for energy policy-making process regarding the sustainable development.
- Identify the most important factors of energy consumption and environmental pollution in the panel manufacturing life cycle.
- Consider the panel components transportation to the panel manufacturer in Iran and evaluating its contribution to the life cycle primary energy consumption an environmental pollution.

2. Materials and Methods

2.1. Life Cycle Assessment

Life Cycle Assessment is a "cradle to grave" approach to evaluating systems, processes, products, and services. This methodology allows estimating the cumulative environmental impacts of all stages of the life cycle. In the present study, life cycle assessment was performed based on the methodology presented in ISO 14040 [9]. Based on this standard, assessment is performed in four main stages as follows:

- The goal and scope definition, at this stage the overall framework of the study is determined and functional unit and system boundaries are defined [9].

- Inventory analysis, which is the inventory of the total energy use, raw material use, air and water emissions and the total solid waste produced from the cradle-to-grave [9].

- Impact assessment, which tries to link each life cycle inventory to its related environmental impact(s) [18]. As stated in ISO 14042, life cycle inventory results are classified into impact categories, each with a category indicator [19].

- Interpretation, at this stage the findings from the impact assessment are considered to present consistent results based on the goal and scope of the study [9].

This study focuses on life cycle assessment of multicrystalline solar panel production in Fars, Iran. Production of a 320 W_P photovoltaic panel is considered as functional unit.

System boundary examined in this study is shown in Figure 1. The intended system boundaries cover all stages of the production chain, including raw material extraction, upstream and midstream processes, component fabrication and transportation.

2.2. Input data and assumptions

Technical specifications of the panel

Table 1 shows the technical specifications of the panel. The panel consists of six components: cell, EVA, backsheet, solar glass, frame, junction box.

Table 1. Technical specifications of the panel

Item	Description
Module Dimensions	1956 × 992 × 40 mm
Solar Cells	Polycrystalline 156.75 × 156.75 mm
Number of cells per module	72 cells (6 × 12)
Maximum power at STC* (P_{max})	320 W_P
Efficiency	16.5 %
Weight	22 kg
Operation life	25 years

*STC: Standard Test Condition; Irradiance 1000 W/m^2, Cell Temperature (25±2) °C, AM1.5 acc. to IEC 60904-3

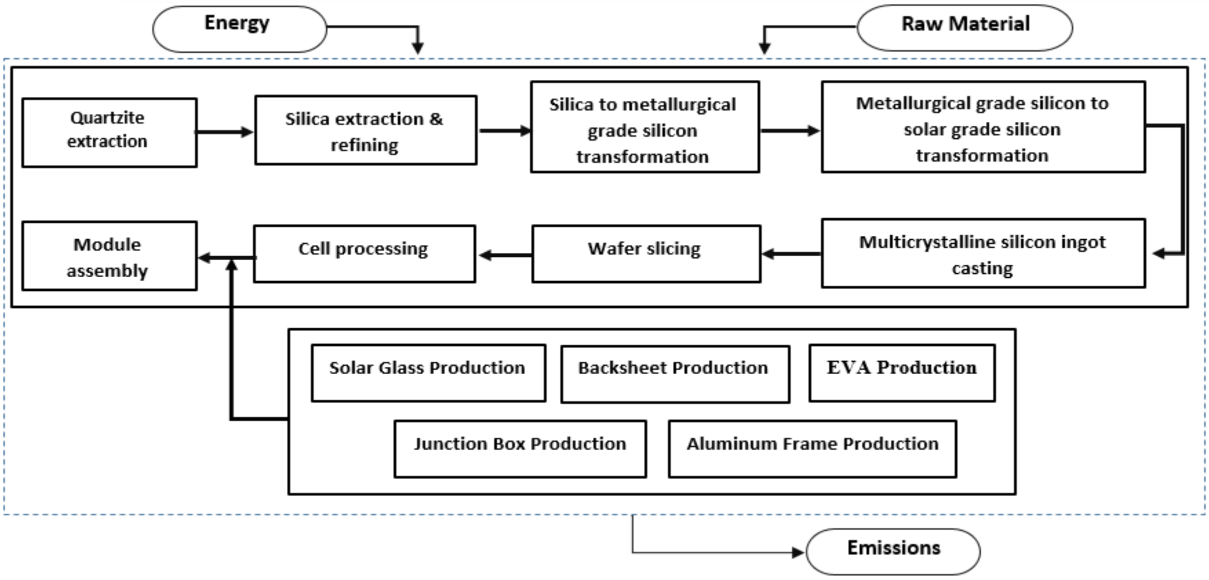


Figure 1. Life cycle assessment boundary

Panel components are mainly manufactured in various Chinese companies and imported to Iran. Other components are manufactured by Iranian companies and assembly is carried out at the mentioned factory.

Silica extraction

Silica (Silicon dioxide) is the main primary source of silicon production, which is one of the key ingredients in production of electrical equipment. Silica is mainly produced by the processing and refining of quartzite or sandstone. Silica extraction can be considered as the beginning step in the solar cell production process [20].

Metallurgical silicon production

At this stage, Silica is converted to silicon. This stage is a costly process in which considerable energy is consumed. The silicon produced at this stage has a purity of about 98%, which is mainly used in steel and aluminium industries. This product is called "metallurgical silicon" and does not have sufficient purity for use in the solar cell industry [21]. This process is mainly carried out during the reducing reaction between quartzite powder and coal in an electric arc furnace [22].

Since the cells used in the solar panel being assessed are produced in China, the life cycle inventory data of this process were extracted from Ye et al.'s, research [23].

Solar grade silicon production

Different methods exist to obtain solar-grade silicon. Because the most widely used method for producing solar grade silicon is the "modified Siemens process", this process is taken into account for modelling the panel production in this study. Life cycle inventory data for this stage is obtained from the research of Fu et al. [24].

Polycrystalline silicon ingot and wafer production

At this stage, the pure silicon produced in the previous stage is melted and the ingots with new crystal structure are produced. The production of ingots can be done by casting or a process known as the "Czochralski process ", the latter being used for the production of monocrystalline ingots [25]. Later, the ingots were cut into thin layers called "wafer". In this study, the wafer thickness is considered 220±20 μm based on the information provided by the cell manufacturer.

Cell production

During heat treatment and chemical reaction, a very thin layer of wafer surface is removed for the purpose of repairing the damage caused during cutting. The grey surface of the wafer turns blue and irregular pattern of pyramids is created on the wafer surface to absorb more radiation [25].

Since silicon is a semiconductor and the nature of photovoltaic phenomenon is based on free electrons transfer in different parts of a semiconductor, in a process known as "Doping" some impurities penetrate the wafer surface at a reaction temperature of 850 - 900 °C to form semiconductor n-type layer

[25]. In this study, based on the most widely used industrial method, phosphorus doping is considered to create p-n junction. Based on information provided by the cell manufacturer, the cell surface is covered with silicon nitride anti reflection coating. The weight of the cell used in the panel is 11.5±0.5 g. Electricity and material consumption for producing the panel, including all mentioned stages is presented in Table 2.

Table 2. Life cycle material and electricity consumption for the cell production [a]

Material	Amount	Unit
Acetic acid (98%)	0.6	kg
Aluminium	0.38	kg
Ammonia	0.348	kg
Argon	10.5	kg
Compressed air	47.81	m^3
Electricity	3155.49	MJ
Ethanol (97%)	0.23	kg
Flat glass (uncoated)	2.47	kg
Hydrochloric acid (30%)	5.5	kg
Hydrogen	0.5	kg
Hydrogen fluoride	1.094	kg
Hydrogen peroxide (50%)	0.44	kg
Natural gas	0.59	kg
Nitric acid (50%)	1.45	kg
Nitrogen	78.78	kg
Phosphoric acid (85%)	0.00931	kg
Potassium hydroxide	2.76	kg
Quicklime	6.52	kg
Sand quartz	15.37	kg
Silicon (metallurgical grade)	6.08	kg
Silicon carbide	0.238	kg
Silicon tetrachloride	8.29	kg
Silver	0.068	kg
Sodium hydroxide (50%)	4.85	kg
Steam	418.75	kg
Steel wire rod	17.11	kg

[a] Derived from Ref. [20,21,23-26]

Other panel components

In order to fix solar cells and to protect them against environmental damages, they are encapsulated by a very thin, transparent layer of ethylene vinyl acetate, which is called "EVA Sheet". This component is modelled based on the manufacturer's information and Ecoinvent database (version 3) [26].

"Solar Backsheet" is the last layer at the bottom of the solar PV panel and is typically made of a polymer or a combination of polymers. This layer can protect the panel from moisture, dirt, dust and other particles. According to information provided by the manufacturer, this component is made of three layers of equal thickness, the middle layer being polyethylene terephthalate and the other two layers being polyvinyl fluoride. This component is modelled based on the manufacturer's information and Ecoinvent database (version 3) [26].

"Junction Box" can be considered as a tool to connect a panel to the network or other panels. This component is modelled on the basis of manufacturer's information, Ecoinvent database (version 3) [26] and guidelines developed by the International Energy Agency for Life Cycle Assessment of Photovoltaic Systems [27].

The frame used in the panel production is made of silver anodized aluminium alloy which is manufactured in Iran. Hence, this component is modelled on the basis of research that have assessed the life cycle of extruded aluminium production in Iran [28].

Anti-Reflective tempered solar glass is used in the panel production. This component is modelled on the basis of manufacturer's information and Ecoinvent database (version 3) [26]. Specifications of solar panel components is presented in Table 3.

Table 3. Technical specifications of the panel components

Component	Material	Description	Manufacturing Country
Frame	Silver Anodized Aluminium Alloy (Aluminium Alloy: 6063)	Longitudinal side: 0.833 kg Transverse side: 0.456 kg	Iran
EVA	Ethylene-vinyl acetate	Thickness: 0.5 mm Density: 0.96 g/cm^3	China
Backsheet	Polyvinyl fluoride, Polyethylene terephthalate	Thickness: 315 μm	China
Solar Glass	Tempered Glass+ Anti-Reflection Coating	Thickness: 3.2 mm Density: 2.4872 g/cm^3	China
Junction Box	Polypropylene	Weight: 350 g	China

Transportation

The exact location of all panel components manufacturers in Iran and China is specified by contacting these companies and the type of transportation at all stages is determined. Next, the distances are measured using Google Maps, transportation is modelled and its environmental aspects are assessed. Ecoinvent database (version 3) [26] has been used for inventory analysis of transportation.

Impact assessment

Primary energy consumption is one of the impact categories considered in this study. Cumulative Energy Demand (CED) is used to calculate the whole life cycle primary energy input, this includes the direct uses as well as the indirect consumption of energy due to the use of, e.g. construction materials or raw materials. This method has been firstly developed in the early seventies after the first oil crisis [29, 30].

Global warming is one of the major global issues in today's world that causes rising average global temperatures, sea level rise, climate change, melting glaciers and numerous ecological impacts [31]. This environmental issue is considered as one of the impacts categories in this study.

Acidification is another global environmental problem that has been assessed in this study. Acidification refers to the release of any acidic substances into the atmosphere, which can subsequently enter water and soil, resulting in the death of living organisms in aquatic ecosystems, vegetation loss, and soil fertility decline [32].

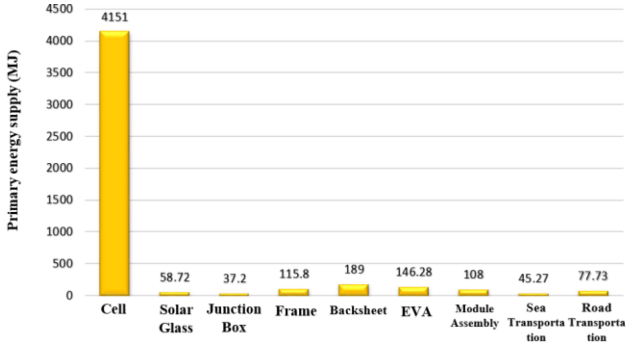
Eutrophication is also considered in this study. This impact category can be defined as an undesirable explosion of living aquatic-based organisms in lakes, enclosed bays and estuaries that results in oxygen depletion that can destroy an aquatic ecosystem. It could be regarded as the most important environmental issue caused by phosphorus losses [33].

CML 2001 methodology is utilized for environmental impact assessment. This method is developed by the Institute of Environmental Sciences, Leiden University, The Netherlands [34]. Simapro 9 is used for life cycle modelling in this research [35].

3. Results & Discussion

The total primary energy consumption- from renewable and non-renewable resources- for panel production is calculated as 4929 MJ of which 4806 MJ is related to the panel manufacturing process, including all stages from raw material extraction to panel production, and 123 MJ is related to the transportation.

In order to compare the solar panel manufacturing with the others, it is appropriate to provide the primary energy consumption for manufacturing the panel per its peak power generation. This is calculated as 15.4 MJ/W_P. Life cycle primary energy consumption for the panel manufacturing is presented in Figure 2.



Transportation of panel components from Iranian and Chinese manufacturers accounts for 2.52% of primary energy consumption. As mentioned, this case is usually neglected in previous studies while the reason is not explained. Calculated share for transportation indicates that the estimates considered in previous studies can be largely acceptable.

The results presented in Figure 2 show that the solar cell production life cycle accounts for 84.21% of the total primary energy consumption. Therefore, it is necessary to assess the life cycle of cell production separately. Figure 3 displays the life cycle primary energy consumption for manufacturing the polycrystalline solar cell.

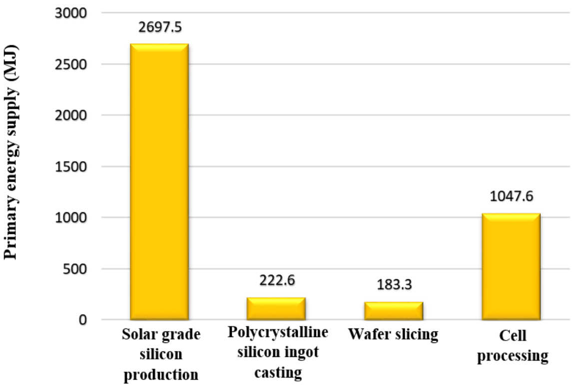


Figure 3. Life cycle primary energy supply

The results presented in Figure 3 show that the process of producing purified silicon for the production of solar cells and the process of converting polycrystalline wafers into cells account for 65% and 25.24% of the total primary energy consumption for the polycrystalline cell production and also account for 54.72% and 21.25% of the total primary energy consumption for panel production, respectively.

Global Warming Potential (GWP) during the panel production life cycle is calculated as 459.4 kg CO_2-equiv. which can be presented as 1.4356 kg CO_2-equiv. /W_P according to the panel peak power generation. Transportation with a share of 1.72% of total GWP accounts for 7.9 kg CO_2-equiv. for each panel. Figure 4 shows the life cycle global warming potential.

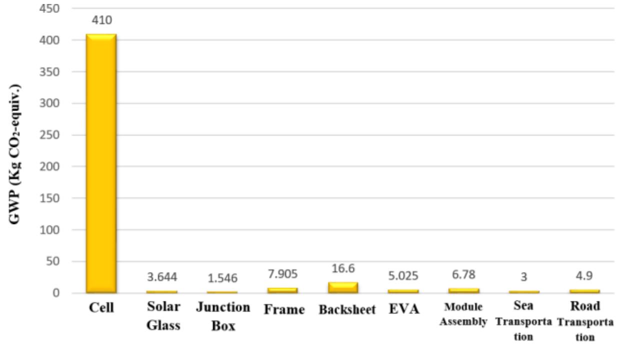


Figure 4. Life cycle global warming potential

Acidification Potential (AP) for the PV panel is 1.93 kg SO_2-equiv. which can be presented as 0.006 kg SO_2-equiv. /W_P. Transportation with a share of 4.12% of total AP accounts for 0.07954 kg SO_2-equiv. for each panel. Life cycle acidification potential is illustrated in Figure 5.

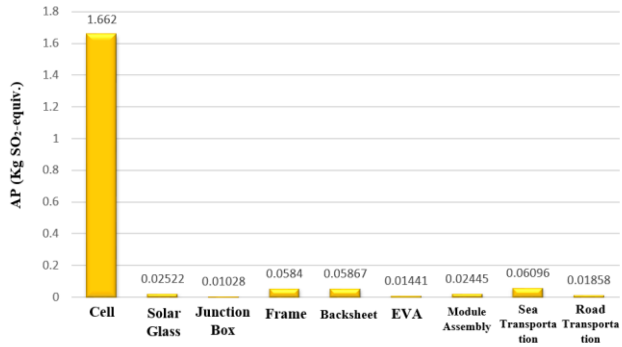


Figure 5. Life cycle acidification potential

The panel production Eutrophication Potential (EP) is calculated as 0.4141 kg PO_4^{3-}-equiv. which can be presented as 0.0013 kg PO_4^{3-}-equiv. /W_P. Transportation with a share of 2.57% of total EP accounts for 0.01065 kg PO_4^{3-}-equiv. for each panel. Life cycle eutrophication potential is presented in Figure 6.

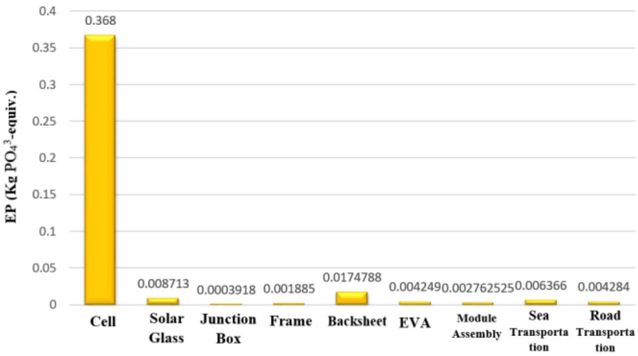


Figure 6. Life cycle eutrophication potential

Base on the results above, cell production has the largest share of energy consumption and environmental pollution. Therefore, efforts to increase productivity in this sector have a higher priority than other components.

In addition to the case of primary energy consumption related to transportation, emissions of pollutant at all stages of the life cycle shows that regardless of this item, does not cause much damage to the accuracy of modelling.

A comparison between some of the results obtained in this study and other similar studies is presented in Table 4. Comparing the results shows a very good match in some cases and a big difference in some others. This difference can be attributed mainly to the nature of the life cycle assessment method, since the boundaries of analysis and the parameters involved determine the results of a life cycle assessment study. For example, in a study by Xu et al. wiring, inverter, and holder is considered and so, a larger GWP was calculated [36].

In addition to the above, the inherent trend of technology development, the way raw materials are supplied, the differences in production processes, different locations of production and some other reasons have made these differences. For this reason, it can be said that the results of a life cycle assessment study cannot be fully generalized to all other similar cases.

The panel components contribution to primary energy consumption and environmental pollution indicates that they do not have the same share in all impact categories. Therefore, it can be said that the selection of environment friendly scenario for solar panel production cannot be done only based on one impact category. It seems that the life cycle assessment methodology- especially the endpoint methods- can be very effective for finding the most appropriate process.

4. Conclusions

Increasing rate of environmental damage across the planet is undeniable. The electricity industry is one of the main causes of these environmental issues. That is why the development of renewable electricity industry needs to be considered not as a useful proposition but as an inevitable necessity.

If the energy industry policymaker decides to construct renewable power plants in a region or to support the constructers of renewable power plants in the same region, there are a variety of options among

Table 4. Comparison of life cycle primary energy supply and environmental pollution with similar studies

Item	Comparison Criteria	Present study	Other researches			
			[37]	[38]	[36]	[39]
Primary Energy	MJ/ m^2 module	2540.72	-	-	-	4944.44
GWP	Kg CO_2-equiv. /W_P	1.4356	-	1.44	2.06	-
	kg CO_2-equiv. /kg module	20.88	27.2	-	-	-
AP	Kg SO_2-equiv. /W_P	0.006	-	-	0.02	-

the types of power generation methods and how to construct them. In such a situation, it seems necessary to make use of a tool which be able to identify the most suitable scenario. Evidently, the life cycle assessment methodology with the approach of cradle to grave analysis can provide the needs.

Iran has very good conditions for solar power generation. Efficient policymaking for the development of solar power industry and achieving the goals of sustainable development requires a thorough assessment of all environmental aspects of solar power plant construction.

Among the various methods of solar power generation, photovoltaic systems have a much larger market share due to their flexible characteristics. The literature review shows that among the components of a photovoltaic plant such as panels, inverters, cables, connections, holders, electrical enclosures, etc., the life cycle of photovoltaic panel production has the largest share of energy consumption and environmental pollution in the life cycle of power plant construction. For this reason and also due to lack of related research in Iran, the life cycle of photovoltaic panel production in one of the Iranian factories was assessed in this study. The main results of this study are as follows:

• Primary energy consumption, global warming potential, acidification potential and eutrophication potential of manufacturing the panel during its life cycle is assessed. The primary energy demand is calculated as 15.4 MJ/W_P and GWP, AP and EP are calculated as 1.4356 kg CO_2-equiv. /W_P, 0.006 kg SO_2-equiv. /W_P and 0.0013 kg PO_4^{3-}equiv. /W_P respectively. Results shows that the life cycle of cell production has the largest share of energy consumption and environmental pollution. Also, the share of panel components in all impact categories is not the same. This result suggests that the life cycle assessment methodology can be a very efficient tool for multi-aspect decision making. Comparing the results with similar studies in other countries show a very good match in some cases and a big difference in some others. This can be attributed to the important role of the case study on the results of a life cycle assessment, as well as, it can be said that the results of a life cycle assessment study cannot be fully generalized to all other similar cases.

• Transportation of panel components from the manufacturer to the assembly site was investigated in this study. This item had been generally neglected in previous research. The results show that the share of this item in primary energy consumption and environmental pollution is less than 5%, and regardless of that, does not cause much damage to modeling accuracy.

• The results of this study can be used to compare the justification of the construction of photovoltaic power plants in Iran compared to other types of power plants.

• In addition to identifying critical points in the production of solar panels, the results of this study can be used to compare the feasibility of constructing photovoltaic power plants in Iran to other types of power plants. This can be useful for policy making and selecting the appropriate renewable power generation scenario.

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