Environmental and damage assessment of transparent solar cells compared with first and second generations using the LCA approach

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Abstract
With the development of different generations of solar cell (photovoltaic) technologies, extensive research has been conducted to evaluate their performances, applications, and cost benefits. Despite these technologies being known as green technologies compared with fossil fuels, however, their environmental problems and damages have not been assessed and compared systematically in their whole life cycle. In this study, the environmental effects of different solar cell generations are assessed and compared using the life cycle assessment approach. Environmentally speaking, the results obtained from the software indicate that the first (polycrystalline) and third (transparent Perovskite) generation panels cause the greatest ($1.43 \times 10^{-6}$ Daly) and least ($4.56 \times 10^{-7}$ Daly) damage to human health, respectively. In addition, these two generations of photovoltaic panels have the most significant and least negative influence on the ecosystem with $2.18 \times 10^{-8}$ and $7.05 \times 10^{-10}$ Species.Yr, respectively. Regarding the environmental effect of damage to the resources, the third and second (cadmium telluride) panels have the least damage with 0.027 USD2013 and 0.0184 USD2013, respectively. The most negative midpoint effect is associated with the marine ecotoxicity of 0.101 kg $1.4$-DCB by the second generation panels. Concerning global warming as the most critical consequence, all three panels also severely impact increasing the global warming index by 399, 164, and 134 (gCO$_2$ eq), respectively. Based on perovskite technologies that are being rapidly evolved with extensive applications, replacing this technology with the current generations is expected due to its less environmental impacts.

KEYWORDS
cadmium telluride panel, life cycle assessment, photovoltaics, polycrystalline panel, solar cell, transparent perovskite
INTRODUCTION

Among different types of renewable energies, solar energy has attracted the attention of many countries due to its eternity, relative sustainability, and easy accessibility. Specifically, solar energy has been extensively used for domestic and industrial applications to provide water heating for residential and industrial units, generate electricity, and air conditioning. Using solar cells to generate electricity is the most common form of exploitation of solar energy. The solar cells convert the absorbed solar irradiation into electrical energy due to internal semiconductors' interactions (photovoltaic [PV] effect).

Although in 2021, the world was still struggling to contain the corona pandemic, due to the fossil energy crisis caused by this disease, the demand for solar panels in 2021 by increasing 10% compared to the previous year, reached to 153.8 GW. This strong growth in solar panel demand can be attributed to projects postponed to 2021 due to the Coronavirus epidemic or rising glass prices, resulting in rising solar panel prices. China, the United States, Europe, and India control more than 70% of the photovoltaic market. 2021 marks the beginning of China's 5-year development plan, according to which projects without subsidies will be the main drivers of the country's solar energy market. The Chinese photovoltaic market is expected to demand 52 gigawatts of solar panels in the coming years. The US solar market will grow slowly, with small and commercial solar power projects delayed until 2022. With the extension of the solar investment tax credit, the long-term outlook for the US solar energy market is promising, and demand for solar panels is projected to reach around 24 GW by the end of 2022. In Europe, demand for solar panels in the European market increased in 2021 due to the support of green continental governments for solar energy. The solar panel market in Europe is projected to reach 27 GW this year. Emerging solar energy markets, including the Middle East and Latin America, are also notable. The solar energy market in the UAE, where large-scale solar projects will open this year, will see growing demand for solar panels. This increase in demand is also expected in Brazil and Chile. By glancing at the development of solar cell technologies, they can be categorized into three general generations, as Figure 1 shows.

Figure 2 indicates the efficiency of different solar cells as a function of the year various types of solar cells evolved in the first-ranked universities worldwide.

In 1976, the first generation of silicon solar cells, including amorphous silicones, was studied, as shown in Figure 2. As can be seen, the first-generation cells are still considered the most common and efficient cells, but the high cost of this generation has led to progressively developing the next generations and competing with the first-generation panel to capture the global market as much as possible. Another obvious point observed in this figure is that the efficiency trend of the cells is constantly improving. This means that the efficiency improves to compensate for the high production costs.

But, in this regard, the critical point is to select a suitable panel that is not only cost-effective with high performance but also eco-friendly. One of the methods to evaluate energy systems is the life cycle assessment method. Life cycle assessment (LCA) is one of the environmental assessment methods utilized today as a standard and widely used method in the environmental evaluation of processes, products, and services. In fact, as one of the environmental evaluation methods, LCA completes the third side of a sustainability assessment after doing techno-economic evaluations to guarantee...
environmental aspects as well as economic and technical ones. According to the previous discussions, several pieces of research have been conducted on using solar cells in architectural applications to enjoy clean solar energy; they present a remarkable performance in most cases.

Al-Otaibi et al. experimentally investigated the use of the second-generation panels of copper indium gallium selenide on a building’s rooftop. Obtained results indicated a remarkable performance factor equal to 75%–85% for these panels. They emphasized that using photovoltaic panels in buildings can be very appropriate and applicable. In another research, Kapsalis et al. studied the effect of PV panels on rooftops annually. They revealed the crucial mechanisms of PV to reduce the required demand for cooling and heating loads. The results showed that rooftop panels considerably affect the energy performance of the building, and there is a need for effective design to increase the energy produced by the panels for seasonal strategies.

In an analytical study, Martinopoulos et al. investigated the environmental effects of a 4 kW regular PV system applicable for a building by implementing a cradle-to-grave LCA. The results indicated that although residential PV systems have relatively low environmental effects during their life cycle, they can perform better depending on their installation location and the quality of the local electricity. Environmental discussions have attracted much interest in recent years. In this regard, Gerbinet et al., by researching the literature on PV panels, concluded that silicon panels had been reviewed more frequently compared to different new types of panels like organic ones. They also realized that most studies are conducted on energy indices like the energy payback time (EPBT) index and climate changes like the CO₂ emission index. Peng et al. reexamined the EPBT performance of the energy and the environmental effects of the solar PV systems through a complete revision in the amount of greenhouse emission released from PV panels and the years required for these panels to provide a specified amount of energy. They implemented LCA for five conventional systems, including single crystal (mono-Si), polycrystalline (multi-Si), amorphous silicon (a-Si), cadmium telluride thin film, and Copper-Indium-Gallium-selenium (CIS or CIGS) thin film. The results showed that the cadmium telluride system environmentally outperforms the other four types in terms of EPBT index and greenhouse gas (GHG) emission due to lower technological requirements during LCA and relatively higher efficiency.

The mono-crystal system (mono-Si) shows the worst performance because of its high energy intensity during the generation procedure of solar cells. Wu et al. carried out an analytical investigation to examine the GHG emitted from a power plant comprised of polycrystalline silicon panels and a fossil fuel one generating...
identical power using the LCA. Their results showed that the emission from these power plants was 36.75 and 975.2 gCO₂-eq/kWh, respectively.²¹ Thenakis and Kim studied a 25 MW/yr power plant with cadmium telluride photovoltaic panels. By employing the LCA method, they found that the greenhouse gas emission would be 24 gCO₂-eq/kWh for every kWh of energy produced in this complex.²²

Based on the discussion mentioned earlier and the studies that overlooked the novel technologies of the solar panels, this study aims to assess the LCA of different generations of photovoltaic panels for residential applications in North America and Edmonton city in Canada. This study reviews the environmental effects of the product’s life cycle in East Asia because these technologies are produced there and the environmental impacts of consumption on another continent in the world. For this purpose, each generation’s most common industrial type is chosen and analyzed in this study.

2 | METHODOLOGY

Figure 3 displays the main phases of the LCA analysis. Based on the ISO14040-44 standard, the most critical parameters of LCA analysis are as follows; the list of parameters is completed depending on the area of study. The methodology consists of 5 subsections. The first three parts (functional unit, assessment range, and technical framework and scope) are considered as the first stage of LCA (goal and scope definition). The fourth and fifth sections which are scenario description and assumptions and limitations are considered the inventory analysis. Interpretation is flowed in all of the processes and appears in each stage and with the impact assessment driven from ISO 14042 which is the results part, all of the four stages of a life cycle assessment are formed and completed.

2.1 | Functional unit

Given the products are PV panels, energy is one of the suitable functional units, which can be selected. Therefore, in this study, the energy unit, that is, 1 kWh, is chosen as a criterion to compare and analyze the results.

2.2 | LCA types (assessment range)

Depending on the goal and application range of the study, the LCA is divided into four categories as shown in Figure 4, which include: cradle-to-grave, cradle-to-gate, gate-to-gate, and cradle-to-cradle LCA.

Based on the studied system, it seems that the cradle-to-gate type is the most suitable range to analyze because the perovskite cells are in the research stage and entering the market. So there has been no research conducted on this subject of disposal and recycling to analyze the data in the life cycle.

2.3 | Technical framework and scope

One of the main parts of any LCA analysis is the goal and scope part. This part is formed of some steps. In the first step, it is required that a general schematic of the flowchart and system studied is presented (see Figure 5).

The inputs, outputs, losses, and system boundaries are indicated in Figure 5. This figure presents a big picture of all processes occurring in the life cycle of a system. It is worth mentioning that the broad overview depicted in Figure 5 is still valid when using different systems. In this situation, only raw materials, processes, and the construction method might change while other parts of the system boundary remain unchanged.

After defining the goal and scope of the project, collecting and preprocessing the data are implemented to quantify the inputs and the outputs of the product life cycle. Inventory is the primary step of the LCA method. Accurate data acquisition is performed while data scarcity can be the most significant challenge in this phase.²⁵

In the next step, obtained results are analyzed. The life cycle impact assessment (LCIA) is a part of LCA whose goal is to receive and assess the magnitude and
FIGURE 4  A schematic of different LCAs types. LCA, life cycle assessment.

FIGURE 5  The process and details of a photovoltaic (PV) panel

FIGURE 6  The schematic of the panels

FU300P (Polycrystalline panel)   GE. CdTe78 (CdTe panel)   infinityPV.AM1.5 (Perovskite panel)
### Table 1
The characteristics of the selected panels

|                         | Polycrystalline panel (GEN1) | CdTe panel (GEN2) | Perovskite panel (GEN3) |
|-------------------------|-----------------------------|-------------------|-------------------------|
| Dimensions (m)          | $2 \times 1 \times 0.04$    | $1.2 \times 0.6 \times 0.0075$ | $0.1 \times 0.1 \times 0.000003$ |
| Weight (kg)             | 22.5                        | 13                | 0.04                    |
| Efficiency (%)          | 16                          | 11                | 7                       |
| Brand/country           | FU300P/China                | GE. CdTe78/China  | infinityPV. AM1.5/China |
| Nominal power (W)       | 300                         | 70                | 120                     |
| Power generation per ft² (W) | 10                       | 7                 | 4.4                     |
| Panel area needed to produce 1 KWH (m²) | 9                         | 12.86             | 20.45                   |
| Weight of panels to generate 1 kWh (kg) | 101.25                    | 232.19            | 84.87                   |

**Figure 7**
The manufacturing processes of silicon-based photovoltaic (PV) modules.
importance of the potential environmental consequences caused by the life cycle of that product. The LCIA uses the information obtained from the inventory step of the life cycle. LCIA converts the quantitative results of the inventory analysis part into qualitative and apprehensible results to help in understanding the environmental effects of the system studied. Therefore, firstly the grouping, and secondly, the normalization and weighting steps are done.

The last step of the LCA analysis is to analyze the problem, including modeling and collecting information related to technical processes, pertinent streams (products and wastes), and primary streams (natural resources) during the life cycle. The streams and information are normalized by a 1 kWh functional unit as an interpretation of the output.

2.4 | Inventory analysis

As mentioned earlier, PV panels consist of three different generations, each of which has its exclusive technology. Hence, in this study, one sample from each generation is chosen to determine their environmental effects. Figure 6 presents model schematics; Table 1 reports the weight and characteristics for energy units (1 kWh).

![Diagram of PV panel manufacturing processes]

The design process, manufacturing, and fabrication of the panels are analyzed in Figures 7–9, respectively. Figure 7 belongs to the first-generation panels indicating the following processes: quartz reduction, purification of metallurgical grade silicon, electric or solar silicon production, making single- and/or polycrystalline silicones, and wafer resection, cell production, and laminated panel fabrication.

For the second-generation panels (cadmium telluride and copper indium selenium, CIS), the photoactive P/N junction forming of two semiconductors compounds of CdTe and CdS are directly deposited in very thin layers on a clean glass substrate using the vapor deposition method. The series connection of the adjacent P/N conductors is accomplished by a series of automated laser and mechanical processes. Then a second protective glass plate is added at the top to form the finished module. The production flowchart of the second-generation panels is given in Figure 8.

The production process of the modules based on the third-generation panels (transparent Perovskite) is illustrated in Figure 9. First, CuO electrical displacement is conducted. After that, this module is baked at 100°C for 10 min. Then, the module is coated with a MAPbI3 and PCBM spin coating. Eventually, evaporated silver metal is blown into it. After creating the perovskite module, the
other manufacturing stages are similar to the second-generation panels.

After selecting the final options to analyze each generation, it is necessary to investigate the mass balance of each panel at the next step. For this purpose, the portion of every single material used should be identified separately for each panel. In this regard, the percentage portion of each material in the panel structure is presented in Figure 10.

After finding thickness percentages based on Figure 10, the mass calculation of each material is carried out according to the dimensions given in Table 2.
2.5 Assumptions and limitations

Every three generations of these panels are produced in China, and the end consumer is in Canada. Thus, it is assumed that the panels’ transportation between the two countries is carried out by sea transit, cargo ships from China to the loading site (Vancouver Harbor), and train transit to the construction site (Edmonton City). Perovskite transparent panels have not been fully commercialized yet, but this study ignores this problem.

3 RESULTS AND DISCUSSION

3.1 The first-generation panel (polycrystalline)

The 18-tuple environmental effects of the first-generation panels are shown in Figure 11A. This diagram relatively indicates the percentages of the materials formed in each of the life cycle stages on the specific environmental effects. As can be seen, the glass used in these panels has relatively the most negative impacts on the stratospheric ozone depletion and human noncancerous toxicity equal to 28.9% and 23.7%, respectively. It also positively affects ionizing radiation, leading to the environmental effect reduction of this part by 3.35%. The a-si part of these panels has the highest adverse effects on human carcinogenic toxicity and the ionizing radiation equal to 33.2% and 30.5%, respectively. The silicon wafer part of the panels has the strongest negative influences on water consumption and soil pollution, equivalent to 83.5% and 75.9%, respectively. Metallization and the metal used behind the panels have environmental effects on marine pollution and human noncancerous toxicity equal to 57.9% and 51.9, respectively. Shipping also has the highest impact on terrestrial acidification and fine particular matter formation, equal to 1.16% and 0.7%, respectively. Road transport also causes environmental effects on the ozone, human health damage by 0.54%, and environmental damage equal to 0.53%. During these panels’ life cycles, electricity consumption significantly affects global warming and ozone, and human health by 11.5% and 11.2%, respectively.

| TABLE 2 | The mass of each material in different panels (for generation 1 kWh energy) |
|------------------|------------------|------------------|------------------|------------------|
| **Polycrystalline panel (GEN1) 9 (m²)** | **Material** | **Volume fraction (%)** | **Density (kg/m³)** | **Mass fraction (%)** | **Mass (kg)** |
| | | | | | |
| | glass | P-Type a-si | i-Type a-si | n-Type a-si | Silicon wafer | Back contact (Ag) |
| | | 97 | 0.1 | 0.8 | 0.1 | 1 | 1 |
| | | 2500 | 2328 | 2328 | 2328 | 2330 | 10,490 |
| | | 86.8 | 0.085 | 0.68 | 0.085 | 0.85 | 11.5 |
| | | 98.88 | 0.186 | 0.69 | 0.186 | 0.86 | 1.16 |
| **CdTe panel (GEN2) 12.86 (m²)** | | |
| **Material** | **Volume fraction (%)** | **Density (kg/m³)** | **Mass fraction (%)** | **Mass (kg)** |
| | | | | |
| | glass | Sno2 | Zno | n-Cds:o | p-CdTe | Back contact (Ag) |
| | | 95.5 | 0.3 | 0.03 | 0.015 | 3.55 | 0.65 |
| | | 2500 | 6950 | 5610 | 4826 | 5850 | 10,490 |
| | | 83.7 | 0.75 | 0.06 | 0.025 | 7.4 | 8 |
| | | 202.43 | 2.73 | 0.139 | 0.06 | 19.18 | 7.66 |
| **Perovskite panel (GEN3) 20.45 (m²)** | | |
| **Material** | **Volume fraction (%)** | **Density (kg/m³)** | **Mass fraction (%)** | **Mass (kg)** |
| | | | | |
| | glass | ITO | PEDOT: PSS | Perovskite | Fullerene | BCP | Back contact (Ag) |
| | | 76 | 4 | 2 | 12 | 3 | 2.5 |
| | | 2500 | 1060 | 3910 | 1650 | 1100 |
| | | 65 | 9.9 | 0.7 | 16.2 | 1.8 | 0.95 |
| | | 55.11 | 8.91 | 0.63 | 13.79 | 1.45 | 0.81 |
Figure 11B is obtained by normalizing the environmental effects of the first-generation panels. As shown in this figure, the highest environmental impacts of the polycrystalline panels belong to marine and freshwater ecotoxicity and human cancer. The most elevated role in these areas is associated with the metallization part of the panels. Based on the importance of global warming, the tree diagram of the influential factors in this part is also depicted in Figure 12. As can be seen, the highest effect associated with the silicon wafer of
these panels. The life cycle of these panels with a mass of 101.25 kg and an area of 9 m² made of polycrystalline for electricity production of 1 kWh results in 0.46 kg CO₂ emission in the air.

The entire environmental effects can be categorized into three general parts: human health, ecosystems, and resources to facilitate management analyses and policy-making. Figure 13 indicates the relative percentage of the materials formed at different life cycle stages for the first-generation panels and their normalized form in these three parts. As shown in this figure, the silicon wafer in these panels has the highest adverse effects on human health, and pollution of ecosystems and resources with the proportion equal to 42.4%, 50.5%, and 44.7%, respectively. These considerable numbers are associated with the 24-step production process of silicon wafers.37

According to the normalized form, the entire environmental effects of the first generation, the polycrystalline panels significantly affect human health.

3.2 | The second-generation panel (thin layer)

The 18-tuple environmental effects of the second-generation panels are indicated in Figure 14A. This diagram relatively shows the percentages of the materials formed in each of the life cycle stages on the specific environmental effects. As can be seen, the glass used in these panels has the most relative negative effects on the reduction of terrestrial ecotoxicity and the stratospheric ozone depletion equal to 87.6% and 67.3%, respectively; it also has positive effects on the ionizing radiation, leading to environmental effects reduction of this part equal to 84.6%. Metallization and the metal utilized behind the cadmium telluride panels have the highest environmental negative effects on marine and freshwater ecotoxicity by 70.1% and 61.9%, respectively. Shipping these panels has the highest impact on fine particular matter formation, ozone, and human health by a portion of 2.87% and 2.2%, respectively. These panels’ road transport also has the highest environmental effects on fossil resource scarcity and ionizing radiation equal to 3.06% and 2.34%, respectively. The energy consumption during the life cycle of the cadmium telluride panels has the highest negative effects on global warming and ionizing radiation by 39.9% and 33.8%, respectively.

According to Figure 14B, by normalizing the environmental effects of the second-generation panels, the highest environmental effects of the cadmium telluride panels contribute to marine and freshwater ecotoxicity and human noncarcinogenic toxicity; most of these scopes is allocated to the metallization part of the panels.

Given the importance of global warming, the tree diagram of the influential factors on this part is illustrated in Figure 15 as well. As can be seen, the highest effect is attributable to the energy consumption during the life cycle of these panels. The life cycle of these panels with a mass of 232.19 kg and an area of 12.86 m² made of cadmium telluride panel for electricity production of 1 kWh leads to 0.21 kg carbon dioxide emission in the air.

The whole environmental effects can be divided into three general parts of human health, ecosystems, and resources to facilitate management analyses and policy-making. Figure 16 indicates the relative percentage of the materials formed at different stages of the life cycle of the second-generation panels and their normalized form in these three parts. As can be seen, the highest adverse effects on human health are related to metallization and the metal used in these panels with 46.6%; this factor has a top portion in the pollution of the ecosystems with 40.3%. The manufacture of cadmium telluride PV panels
usually has an effect of 37.6% on resources compared to the other components of these panels throughout its life cycle.

Based on normalizing the general environmental effects of the second-generation panels, it is clear that the highest environmental effects of the cadmium telluride panel target human health.

3.3 | The third-generation panel (organic)

The 18-tuple environmental effects of the third-generation panels are indicated in Figure 17A. This diagram relatively shows the percentages of the materials formed in each of the life cycle stages on the specific
environmental effects. As can be seen, the glass used in these panels has the most harmful effects on terrestrial ecotoxicity and stratospheric ozone depletion with 83.4% and 55.1%, respectively; it also has positive effects on ionizing radiation equal to 84.6%. Metallization and the metal utilized behind the Perovskite transparent panels have the highest environmental negative impacts on marine and freshwater ecotoxicity and human non-carcinogenic toxicity with 64.3%, 55.7, and 55.7%, respectively. Shipping these panels has the highest effect on terrestrial ecotoxicity and fine particular matter formation in the air, by 2.58% and 1.96%, respectively.

FIGURE 14  (A) The 18-tuple environmental effects of the second-generation panels and (B) the normalized form
These panels’ road transport also has the highest environmental effects on fossil resource scarcity and terrestrial ecotoxicity with 1.56% and 1.4%, respectively. The energy consumption during the life cycle of the third-generation panels has the highest negative effects on global warming and ionizing radiation by 80.2% and 79.9%, respectively.

According to Figure 17B, by normalizing the environmental effects of the first-generation panels, the highest environmental effects of the third-generation panels are on the marine and freshwater ecotoxicity and human non-carcinogenic toxicity that most of these scopes are allocated to the metallization part of the panels. Given the importance of global warming, the tree diagram of the influential factors on this part is illustrated in Figure 18 as well. As can be seen, the highest effect is attributable to the energy consumption during the life cycle of these panels. The life cycle of these panels with a mass of 84.87 kg and an area of 20.45 m² made of Perovskite transparent panel for electricity production of 1 kWh results in 0.17 kg carbon dioxide emission in the air.

The whole environmental effects can be divided into three general parts of human health, ecosystems, and resources to facilitate management analyses and policymaking. Figure 19A indicates the relative percentage of the materials formed at different stages of the life cycle of the third-generation panels and their normalized state in these three parts. According to this figure, the highest negative effects on human health are related to the energy consumption during the life cycle of these panels with 48.1%; also, this factor has a maximum portion in the pollution of the ecosystems with 63.5%. The manufacture of Perovskite PV panels generally has an 82% effect on the resources compared to the other factors forming these panels during their life cycle.

Figure 19B is obtained by normalizing the general environmental effects of the third-generation panels. As can be seen, the highest environmental effects of Perovskite PV panels are on human health.

### 3.4 Comparison of three generations of PV panels using their LCA

Figure 20 displays a comparison of the 18-tuple environmental effects for every three generations of PV panels. As can be seen, the polycrystalline panels have a more destructive impact on global warming, stratospheric ozone depletion, ionizing radiation, fine particulate matter formation, ozone, and human health, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, human carcinogenic toxicity, land use, fossil resource scarcity, and water consumption. In addition, the cadmium telluride panels also have a more destructive role in freshwater ecotoxicity, marine ecotoxicity, and human noncarcinogenic toxicity. According to this figure, the Perovskite transparent panels have lower environmental effects than the other ones apart from the considerable impact on the depletion of the mineral resources.

Figure 21 is obtained by normalizing the diagrams of Figure 20. According to this figure, the highest environmental adverse effects of three generations of PV panels are associated with marine and freshwater ecotoxicity. This is due to the metallization of the behind and the panels’ frame; this is caused by the metallization process, including silver extraction to installation on the panels.
The highest negative effects for the first generation are on the two factors mentioned above and then human noncarcinogenic toxicity. Like the first generation, the highest effects are on the two aforementioned factors and then human noncarcinogenic toxicity; likewise, the third-generation panels are similar to the second one but with more limited values.

To easily compare three generations of solar panels, the entire environmental effects can be divided into three general parts of human health, ecosystems, and resources. Figure 22 indicates the ranking of the maximum portion from the highest to the lowest impact on human health and the ecosystem, which is as follows: (1) polycrystalline, (2) cadmium telluride, and (3) Perovskite transparent panels. Moreover, on the subject of negative effects on the resources, the first and third-generation panels are almost equal, and the second-generation panels have lower effects.
Figure 23 is obtained by normalizing Figure 22 to show the absolute portion of each panel on environmental factors. It is clear that every three PV panels generally have more proportion of damage to human health.

The comparison of the cost to produce 1 KWH energy for each panel from the perspective of LCA, the efficiency of market-based solar panels, and the three main endpoint normalized environmental impacts of them is shown in Table 3.
In this study, according to the growing concerns of the international communities on the subject of environmental pollution replacing conventional fossil energy resources with renewable energy as clean resources, we tried to achieve the goals of green building as the newest solution to environmental pollution reduction using the LCA method. To this end, PV panels to use solar energy as a clean, inexpensive, and accessible energy source to provide the energy for the building, which settles in Canada, are introduced. In this regard, these systems are briefly presented at first, and a candidate is selected from each generation to be compared. In the following step, the information related to the raw materials, and discussions related to the construction and transportation of the polycrystalline, cadmium telluride, and Perovskite panels are prepared for 1 kWh energy as a functional unit. Finally, the collected information is applied to sima pro software to analyze the environmental effects of each panel under study using the LCA method. Different parts and inputs of the software are completed by relying on the assumptions and limitations based on data collected within the framework of the chosen functional unit and energy balance. From the point of environmental view, the results obtained from the software are as follows:

- The amount of the 18-tuple environmental effects of the first generation panels (polycrystalline) includes the global warming (0.399 kg eq), stratospheric ozone depletion (0.00000281 kg CFC11 eq), ionizing radiation (0.0344 kBq Co-60 eq), ozone formation and damage to human health (0.00113 kg NOx eq), fine particular matter formation (0.00932 kg PM2.5 eq), ozone formation and terrestrial ecotoxicity (0.00117 kg NOx eq), terrestrial acidification (0.00176 kg SO2 eq), freshwater eutrophication (0.000377 kg P eq), marine eutrophication (0.000025 kg N eq), terrestrial ecotoxicity (6.51 kg 1,4-DCB), freshwater ecotoxicity (0.0447 kg 1,4-DCB), marine ecotoxicity (0.0763 kg 1,4-DCB), human carcinogenic toxicity (0.031 kg 1,4-DCB), human noncarcinogenic toxicity (1.56 kg 1,4-DCB), land use occupation (0.0108 m2a crop eq), natural resource scarcity (0.0261 kg Cu eq), fossil resource scarcity (0.101 kg oil eq), and water consumption (0.00916 m3). The associated negative effects of these panels on three main categorizations of the environmental effects are as follows: human health (0.00000143 DALY), ecosystem (2.18E-8 species.yr), and resources (0.0276 USD2013).

- The amount of the 18-tuple environmental effects of the second generation panels (cadmium telluride) includes the global warming (0.164 kg eq), stratospheric ozone depletion (0.000000267 kg CFC11 eq), ionizing radiation (0.0344 kBq Co-60 eq), ozone formation and damage to human health (0.000718 kg NOx eq), fine particular matter formation (0.000525 kg PM2.5 eq), ozone formation and terrestrial ecotoxicity (0.000727 kg NOx eq), terrestrial acidification (0.00129 kg SO2 eq), freshwater eutrophication (0.000362 kg P eq), marine eutrophication (0.000118 kg N eq), terrestrial ecotoxicity (2.65 kg 1,4-DCB), freshwater ecotoxicity (0.0598 kg 1,4-DCB), marine ecotoxicity (0.0101 kg 1,4-DCB), human carcinogenic toxicity (0.0165 kg 1,4-DCB), human noncarcinogenic toxicity (2.13 kg 1,4-DCB), land use occupation (0.00796 m2a crop eq), natural resource scarcity (0.0413 kg Cu eq), fossil resource scarcity (0.213 kg oil eq), and water consumption (0.00916 m3). The associated negative effects of these

**FIGURE 18** The tree diagram of the influential factors on global warming

**CONCLUSION**
panels on three main categorizations of the environmental effects are as follows: human health (0.00000102 DALY), ecosystem (1.23E-8 species.yr), and resources (0.0184 USD2013).

- The amount of the 18-tuple environmental effects of the third generation panels (Perovskite transparent) includes the global warming (0.134 kg eq), stratospheric ozone depletion (0.000000924 kg CFC11 eq), ionizing radiation (0.0021 kBq Co-60 eq), ozone formation and damage to human health (0.00044 kg NOx eq), fine particular matter formation (0.000281 kg PM2.5 eq), ozone formation and terrestrial ecotoxicity (0.000443 kg NOx eq), terrestrial acidification (0.000662 kg SO2 eq), freshwater eutrophication (0.000111 kg P eq), marine eutrophication (0.00000417 kg N eq), terrestrial ecotoxicity (0.789 kg 1,4-DCB), freshwater...
ecotoxicity (0.0164 kg 1,4-DCB), marine ecotoxicity (0.0101 kg 1,4-DCB), human carcinogenic toxicity (0.00681 kg 1,4-DCB), human noncarcinogenic toxicity (0.575 kg 1,4-DCB), land use occupation (0.00316 m²a crop eq), natural resource scarcity (0.0991 kg Cu eq), fossil resource scarcity (0.0283 kg oil eq), and water consumption (0.000516 m³). The associated negative effects of these panels on three main categorizations of the environmental effects are as follows: human health (0.000000456 DALY), ecosystem (7.05E-8 species.yr), and resources (0.0270 USD2013).

- By comparing these three generations of PV panels through the LCA method, it is found that the third-generation panels (Perovskite transparent) outperform
FIGURE 22  The comparison of main parts of life cycle analysis for three generations of panels

FIGURE 23  The comparison of the normalized main parts concerning the LCA for every three generations of the panels. LCA, life cycle assessment.

TABLE 3  The comparison of the three generation of solar panels

|                         | Cost ($) | Efficiency (%) | Environmental effects on human health | Environmental impacts on ecosystems | Environmental effects on resources |
|-------------------------|----------|----------------|----------------------------------------|------------------------------------|----------------------------------|
| Polycrystalline panel   | 421.2    | 16             | 0.6                                    | 3.04E-02                           | 0.00979                           |
| Cadmium Telluride panel| 287.55   | 11             | 0.429                                  | 1.70E-02                           | 0.00641                           |
| Perovskite panel        | 102.2    | 7              | 0.191                                  | 9.77E-03                           | 0.00957                           |
compared to the other generations. The first-generation panels (polycrystalline), despite their high efficiency, have the worst environmental performance due to consuming more energy to build and employing more raw materials. The second-generation panels (cadmium telluride) have acceptable environmental performance in the other cases in comparison with the two other panels, apart from the three effects of freshwater ecotoxicity, marine ecotoxicity, and human noncarcinogenic toxicity, which have the highest amount compared to the other effects based on normalizing negative effects. Therefore, commercializing the third-generation panels is recommended.

- Employing the LCA method for energy systems makes it possible to compare the amount of CO₂ that emits into the air for the production of 1 kWh by different solar panel technologies. In terms of carbon emission, the best performance between these three panels is related to the Perovskite transparent panels, which have higher efficiency on average, about 55.6%, 100.75%, 279.16%, 62.91%, 11.03%, and 6.87% compared to the hydro, wind, nuclear, biomass, combined cycle, and coal power plants, respectively. Furthermore, these panels’ carbon emission is equal to 33.58% and 81.71% compared to the first and second generations of panels. This paper claims that PV technology, especially Perovskite transparent, is eco-friendly. Consequently, so much attention should be attracted to them more than ever for energy production policies in the world. Hence, future work and research should be conducted on the LCA of the other generations of technologies and the economic LCA (E-LCA) and social LCA (S-LCA) of these three generations.

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**REFERENCES**

1. Zahedi R, Seraji MAN, Borzuei D, Moosavian SF, Ahmadi A. Feasibility study for designing and building a zero-energy house in new cities. *Sol Energy*. 2022;240:168-175.
2. Dominguez A, Kleissl J, Luval J C. Effects of solar photovoltaic panels on roof heat transfer. *Sol Energy*. 2011;85(9):2244-2255.
3. Chahine K, Murr R, Ramadan M, Hage HE, Khaled M. Use of parabolic troughs in HVAC applications—design calculations and analysis. *Case Stud Therm Eng*. 2018;12:285-291. doi:10.1016/j.csite.2018.04.016
4. Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. *Renew Sustain Energy Rev*. 2011;15(3):1625-1636.
5. Rivera M, Rojas D, Fuentes R, Wheeler P. Development of solar energy in Chile and the world. 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). IEEE; 2021:2453-2457.
6. Sahu BK. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. *Renew Sustain Energy Rev*. 2015;43:621-634.
7. Brown MA, Tudawe R, Steimer H. Carbon drawdown potential of utility-scale solar in the United States: evidence from the state of Georgia. *Renew Sustain Energy Rev*. 2022;161:112318.
8. Kastanaki E, Giannis A. Energy decarbonisation in the European Union: assessment of photovoltaic waste recycling potential. *Renew Energy*. 2022;192:1-13.
9. Viana AG, Ramos DS. Outcomes from the first large-scale solar PV auction in Brazil. *Renew Sustain Energy Rev*. 2018;91:219-228.
10. Maghraby H, Shwehdi M, Al-Bassam GK. Probabilistic assessment of photovoltaic (PV) generation systems. *IEEE Trans Power Syst*. 2002;17(1):205-208.
11. Meng L, You J, Yang Y. Addressing the stability issue of perovskite solar cells for commercial applications. *Nat Commun*. 2018;9(1):1-4.
12. Moosavian SF, Borzuei D, Zahedi R, Ahmadi A. Evaluation of research and development subsidies and fossil energy tax for sustainable development using computable general equilibrium model. *Energy Sci Eng*. 2022;1-14.
13. Komninos I. Product Lifecycle Management. Urban and Regional Innovation Research Unit, Faculty of Engineering, Aristotle University of Thessaloniki; 2002.
14. Mohseni M, Moosavian SF, Hajinezhad A. Feasibility evaluation of an off-grid solar-biomass system for remote area electrification considering various economic factors. *Energy Sci Eng*. 2022;10:3091-3107.
15. Al-Otaibi A, Al-Qattan A, Fairouz F, Al-Mulla A. Performance evaluation of photovoltaic systems on Kuwaiti schools’ rooftops. *Energy Convers Manage*. 2015;95:110-119.
16. Kapsalis V, Karamanis D. On the effect of roof added photovoltaics on building’s energy demand. *Energy Build*. 2015;108:195-204.
17. Martinopoulos G. Are rooftop photovoltaics a sustainable solution for Europe? A life cycle impact assessment and cost analysis. *Appl Energy*. 2020;257:114035.
18. Borzuei D, Moosavian SF, Ahmadi A. Investigating the dependence of energy prices and economic growth rates with emphasis on the development of renewable energy for sustainable development in Iran. *Sustain Dev*. 2022;2284.
19. Gerbinet S, Belboom S, Léonard A. Life cycle analysis (LCA) of photovoltaic panels: a review. *Renew Sustain Energy Rev*. 2014;38:747-753.
20. Peng J, Lu L, Yang H. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renew Sustain Energy Rev*. 2013;19:255-274.
21. Wu P, Ma X, Ji J, Ma Y. Review on life cycle assessment of greenhouse gas emission profile of solar photovoltaic systems. *Energy Proc*. 2017;105:1289-1294.
22. Fthenakis VM, Kim HC. Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics. *MRS Online Proc Libr*. 2005;895(1):1-6.

23. Laurent A, Weidema BP, Bare J, et al. Methodological review and detailed guidance for the life cycle interpretation phase. *J Ind Ecol*. 2020;24(5):986-1003.

24. Parisi ML, Maranghi S, Vesce L, Sinicropi A, Di Carlo A, Basosi R. Prospective life cycle assessment of third-generation photovoltaics at the pre-industrial scale: A long-term scenario approach. *Renew Sustain Energy Rev*. 2020;121:109703.

25. Battisti R, Corrado A. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy*. 2005;30(7):952-967.

26. Nikkhah A, Khojastehpour M, Emadi B, Taheri-Rad A, Khorramdel S. Environmental impacts of peanut production system using life cycle assessment methodology. *J Clean Prod*. 2015;92:84-90.

27. Yu L-M, Man JX, Chen T, et al. Colorful conducting polymers for vivid solar panels. *Nano Energy*. 2021;85:105937.

28. Dobrzanski L, Szczensa M, Szindler M, Drygala A. Electrical properties mono- and polycrystalline silicon solar cells. *J Achiev Mater Manuf Eng*. 2013;59(2):67-74.

29. Kopyachenko L, Toyama T. Current–voltage characteristics and quantum efficiency spectra of efficient thin-film CdS/CdTe solar cells. *Sol Energy Mater Sol Cells*. 2014;120:512-520.

30. Moeini I, Ahmadpour M, Mosavi A, Alharbi N, Gorji NE. Modeling the time-dependent characteristics of perovskite solar cells. *Sol Energy*. 2018;170:969-973.

31. Moosavian SF, Zahedi R, Hajinezhad A. Economic, environmental and social impact of carbon tax for Iran: a computable general equilibrium analysis. *Energy Sci Eng*. 2022;10(1):13-29.

32. Sha WE, Ren X, Chen L, Choy WC. The efficiency limit of CH3NH3PbI3 perovskite solar cells. *Appl Phys Lett*. 2015;106(22):221104.

33. Birkmire RW, McCandless BE. CdTe thin film technology: leading thin film PV into the future. *Curr Opin Solid State Mater Sci*. 2010;14(6):139-142.

34. Tarr NG. A polysilicon emitter solar cell. *IEEE Electron Device Lett*. 1985;6(12):655-658.

35. Oladeji IO, Chow L, Ferekides CS, Viswanathan V, Zhao Z. Metal/CdTe/CdS/Cd1–xZnxS/TCO/glass: a new CdTe thin film solar cell structure. *Sol Energy Mater Sol Cells*. 2000;61(2):203-211.

36. Mungan ES, Lu C, Raghunathan V, Roy K. Modeling, design and cross-layer optimization of polysilicon solar cell based micro-scale energy harvesting systems. Proceedings of the 2012 ACM/IEEE international symposium on Low power electronics and design; 2012:123-128.

37. Zou X, Ji L, Ge J, Sadoway DR, Edward TY, Bard AJ. Electrodeposition of crystalline silicon films from silicon dioxide for low-cost photovoltaic applications. *Nat Commun*. 2019;10(1):1-7.

38. Tsang MP, Sonnemann GW, Bassani DM. Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Sol Energy Mater Sol Cells*. 2016;156:37-48.

39. Korsavi SS, Zomorodian ZS, Tahsildoost M. Energy and economic performance of rooftop PV panels in the hot and dry climate of Iran. *J Clean Prod*. 2018;174:1204-1214.

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