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Photovoltaic Solar Cells and Panels Waste in Jordan: Figures, Facts, and Concerns

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Abstract: Even though the Kingdom of Jordan is moving in the right direction and adopting clean energy sources such as PV plants, the waste problem will eventually emerge within a few decades and will be an overwhelming issue if not addressed early on. According to reports, the installed PV capacity worldwide was around 410 GW in 2017 and is projected to increase to 5000 GW by 2050. Global solar PV waste is anticipated to reach between 5% and 15% of total generation capacity by 2030, with a 25-year average panel lifespan. This study aims to provide an estimation of the amount of PV waste expected within the next decade, and finally expand on the economic and environmental effects. Moreover, this paper's target is to explore the possible effects of PV waste materials in the northern part of Jordan, and the obtained results can be applied to other regions in Jordan. Information about renewable energy in Jordan, retrieved from databases of electricity companies, is utilized to reach an accurate estimation of the amounts of materials that will occur at the end of life. The solar PV panel end of life (EOL) management is a developing field that necessitates additional research and development The obtained findings, figures, and facts about the photovoltaic solar energy sector presented in this study highlight the urgency to develop a suitable system for the collection and management of photovoltaic modules at their end of life.

Keywords: PV; solar cells; waste; renewable energy; Jordan

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1. Introduction

Although the global benefits of the increased use of solar cells for power generation are enormous, photovoltaic solar panels at the end of life (EOL) may become a source of hazardous waste. It was reported that by 2017, the global installed PV capacity was around 410 GW, and it is expected to rise to 5000 GW by 2050. With an average panel lifetime of 25 years, global solar PV waste is expected to be between 5% and 15% of total generation capacity by 2030.

Jordan is considered to be a hydrocarbon-poor country, and it is known to import more than 90 percent of its energy. However, Jordan's geographic location is in the world's high solar belt, where the average solar insolation ranges between 5 and 7 kWh/m^2/day. Moreover, Jordan's climate conditions offer more than 300 sunny days per year [1]. Given these facts, it is expected that Jordan could fully rely on clean energy and could also export solar power to other regions in the world [2]. Therefore, solar as renewable energy (particularly solar PV) can be the future of the energy sector in Jordan; consequently, this has motivated the government to encourage the usage of PV solar energy. According to the national energy strategy of Jordan, renewable energy will contribute more than 20 percent of the kingdom's total energy mix in the year 2020, and toward 100% in 2050 [2].

Different solar PV plants, with a capacity ranging from a few kilowatts to hundreds of megawatts, were built in different regions of Jordan in the last decade [3]. Currently, approximately more than 1.2 GW of solar PV plants have been installed in different locations in Jordan [1]. Different entities and facilities across the country, such as hospitals, houses, hotels, and other industries and educational facilities, are installing solar PV systems [1]. The capacity of the installed plant depends on energy consumption in the facility and the available budget. While most houses preferred to install a small plant's capacity (a few kilowatts), institutions and industries installed larger ones with higher capacities of up to 100s MGW. The high trend in the utilization of solar energy prompted the private sector and investors to install high plant capacities such as Bainona (200 MW), Maan Sun (52 MW), Hosha (61 MW), and Mafraq (51 MW). According to the database of MoE, renewable energy contributes to the national energy budget with 1130 MW in 2018 and will reach more than 2400 MW in 2021.

Despite the appealing features of PV plants as a source of clean energy, it is not a completely benign technology. While solar PV energy can guarantee zero gas emission during its operational lifetime, the amount of waste produced after its end of life (EoL) raises tremendous concerns. The primary concern regarding solar PV cells and panels is when they expire or need replacement, which is not the case in Jordan yet. Because the panels currently distributed in Jordan, whether in small-scale or large-scale plants, have not reached their EoL yet, this problem has not gained attention. In addition, Jordan regulations have not provided a safe approach to managing and disposing of PV waste. When PV panels in large-scale plants eventually reach their EoL, their waste will be a burden. The more concerning source of PV panel waste, however, is small-scale plants since they can be disposed of sporadically at different locations and times. This will eventually lead to unseen and slow contamination, which can lead to widespread and long-term harmful impacts on the environment, human health, and water resources. Figure 1 shows samples of malfunctioned PV panels that are disposed of sporadically in the northern region of Jordan at the Al-Albayt 3.2 MW PV energy facility location.

Figure 1. PV panels that are disposed of sporadically in the 3.2-megawatt capacity PV plant located in the north of Jordan (courtesy of Energy Department/Al-Albayt University).

The EoL of PV modules has been studied from different perspectives such as economic analyses [4,5], impact on the environment [6–13], impact on water resources [14], impact on human health [15–17], soil contamination [8,18,19], and waste management methods [10,20–22]. Different scenarios in different countries have proposed or implemented management and mitigation approaches to PV panel waste [21,23–27]. PV panels are composed of several materials that can seep into the environment and water resources and prominently affect them, such as heavy metals [17]. Therefore, these impacts on the environment, water resources, and human health should be meticulously studied. Semiconductor materials are the main component that is used for the construction of commercial PV cells. Among the semiconductor materials used for the commercial production of PV cells, silicon is the most common one. Crystalline silicon-based PV cells are used in up to 90% of commercially installed PV cells. Other semiconductors and chemical materials such as copper indium selenide, cadmium telluride, and gallium arsenide, are used to construct different types of PV cells [14,28,29]. Even though silicon is not hazardous, silicon-based PV cells and panels contain other hazardous materials such as lead and tin. Other types of PV cells can contain more dangerous and cancerous materials such as cadmium [17].

Although the resources used in manufacturing solar PV panels comply with applicable regulations, these wastes must be properly disposed of and treated. As a result, solar PV panel EOL management is a developing field that necessitates additional research and development. The primary goal of this study is to provide an updated review of solar panel waste generation and a sketch of the current state of recovery efforts, policies on solar panel EOL management, and recycling. In addition, the study anticipates the base of solar panel recycling, recommending future directions for public policymakers.

Since crystalline silicon-based PV panels are dominant in Jordan, in this work, we focus on presenting figures and facts about the waste of crystalline silicon-based PV panels. To this end, this work is divided into five sections: Introduction (Section 1), Materials of and Mass Estimations of PV Cells and Panels (Section 2), Estimation of the Amounts of PV Waste in Jordan (Section 3), Discussion (Section 4), and Conclusions and Recommendations (Section 5).

2. Materials and Mass Estimations of PV Cells and Panels

Since silicon-based PV technology is the most common type, with a 90% market share [14], this section will be dedicated to estimating the mass and volume of the ingredient materials of silicon-based PV cells and modules. However, other types of thin-film PV cells require conscious attention since they contain more hazardous materials such as cadmium, chromium, copper, molybdenum, and arsenic [30].

PV cell manufacturing technology is evolving continuously, with efforts to enhance the efficiency of PV cells and reduce the cost/Wp. The current PV cell manufacturing practice focuses on reducing the amount of material composing PV cells. For example, the amount of silicon and silver in PV cells continuously decreases by reducing PV cell thickness and modifying the contact fingers. Other cell material amounts have also significantly reduced since 2010 [31]. There are different types of commercially employed crystalline silicon-based PV cell technologies, such as polycrystalline, monocrystalline, bifacial monocrystalline, bifacial polycrystalline, p-type PV cells, and n-type PV cells [31]. Each type of PV cell contains a varying amount of materials that typically depend on the type, technology of manufacturing, and year of production.

Figure 2 shows a simplified depiction of the typical crystalline silicon PV cells and the typical PV panels that are commonly installed in Jordan. Worth mentioning is that the front contacts of the typical crystalline silicon PV cell contain silver material. The intercell connectors in a panel are usually composed of lead-tin alloy. In the following sections, the materials composing PV panels and PV cells are addressed.

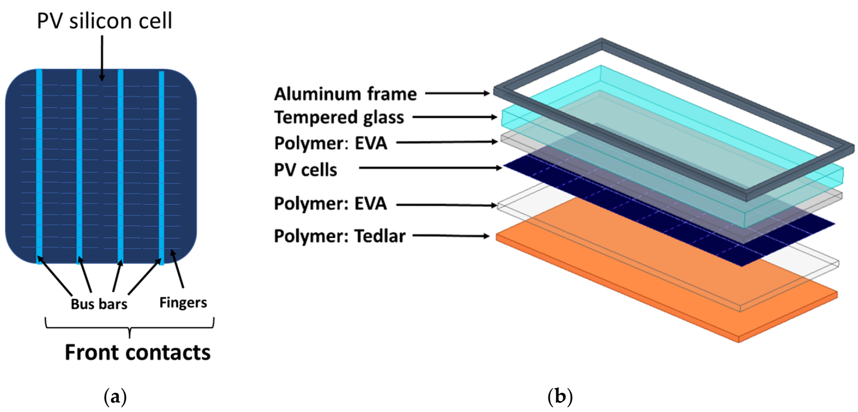

Figure 2. Simplified depiction illustrating the components of crystalline silicon PV cells (**a**) and a typical crystalline silicon PV panel (**b**).

2.1. Materials in PV Cells and Panels

Crystalline silicon-based solar PV panels are made from the following elements: glass, aluminum frame, ethylene-vinyl-acetate (EVA) copolymer transparent hermeticity layer, photovoltaic cells, installation box, Tedlar protective layer, and assembly bolts [32], which will be further explored in this section.

2.1.1. Aluminum

Aluminum is used in manufacturing the PV cell itself and as a holding frame for PV panels. Figure 3 shows the projected trend of the amount of aluminum used per cell over 10 years. A decrease in the amount used can be observed. In 2019, there is approximately 0.9 g of aluminum per cell, and it is expected to decrease to 0.681 g/cell in 2030. By assuming the 5.0 Wp capacity of the cell, the mass/Wp of aluminum would be approximately 0.18 g/Wp. This assumption is considered for all other types of installed PV cells in Jordan since 2013.

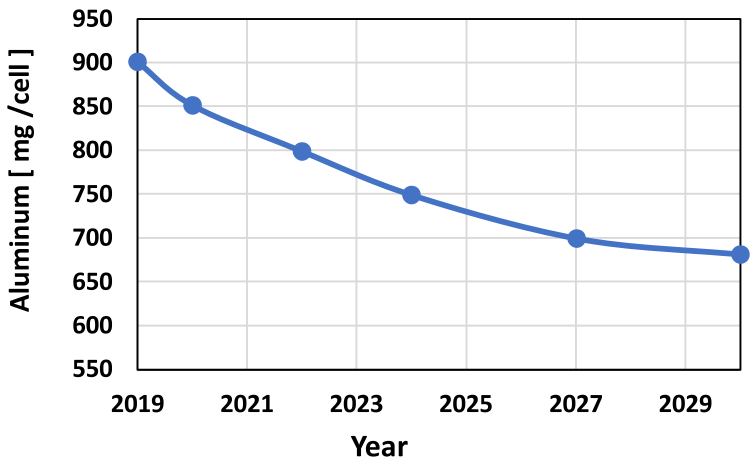

Figure 3. Trend for remaining aluminum per cell with 158.75 × 158.75 mm cell size of p-type monofacial crystalline silicon PV cell, as redrawn from [31].

2.1.2. Silver

As discussed earlier, the amount of silver in a silicon-based PV cell has been decreasing with the reduction in thickness of the cell and the modification of the contact fingers [31,33]. The amount of silver per cell has significantly decreased since 2010 [31]. Figure 4 expresses the projected trend of the amount of silver used in a typical PV cell, which is expected to continue decreasing. Based on the amount of silver in a PV cell in 2019, the estimated silver mass/wp is 0.1 g/cell, which is equivalent to 0.02 g/Wp. This estimate is based on the enhanced efficiency of PV cells and the reduced thickness of the silicon-based PV cells reported in the literature up until 2019 [31]. Similar to aluminum, in this study we consider the minimum reported mass/Wp of silver. In this manner, we guarantee that the total estimated amount of silver in PV panel waste would not be less than the reported value in this study.

2.1.3. Lead and Tin

In today's market, soldering that contains lead (Pb) is the standard interconnection technology for solar cells in module manufacturing [31]. Lead has been a basic metal in PV panel manufacturing, and typically each 60-cell crystalline silicon solar panel manufactured today contains up to 12 g of lead [34]. The silicon wafer-based modules often contain lead in the cell metallization layer around 2 g of lead per 60-cell PV panel and the solder approximately 10 g of lead [34]. Based on this information, the estimated average of lead mass/Wp, assuming the 60-cell panel has a capacity of 300 wp, is 0.04 g/Wp. The amount of tin utilized in the standard interconnections is approximately double that of the lead; therefore, it can be estimated that the mass/Wp of tin is 0.08 g/Wp.

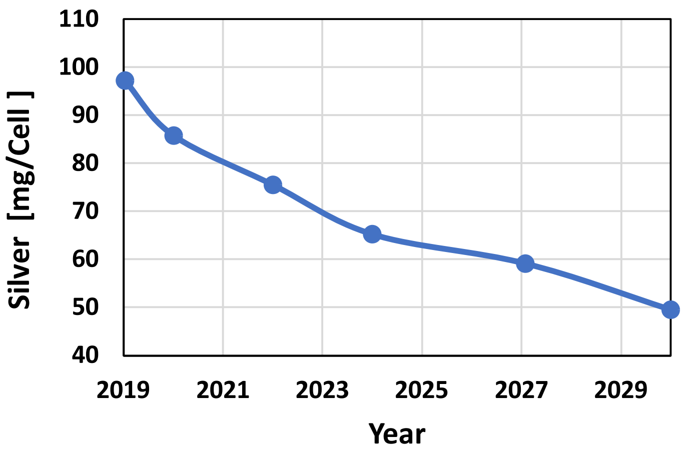

Figure 4. Trend for silver remaining on crystalline silicon-based PV cell (monofacial p-type) with dimensions of 158.75 × 158.75 mm, as redrawn from Ref. [31].

2.1.4. Dopant Materials

The most common dopant materials in crystalline silicon-based PV cells are phosphorus, boron, and arsenide. PV panels and cells are composed of minimal amounts of these materials in comparison to other metals. However, these materials should be given high attention since they can leach out of PV waste to soil and the environment. Their role in PV cells should emerge in waste management processes.

2.1.5. Silicon

Since silicon-based PV cells make up 90% of the total solar PV market, manufacturing technologies are subject to advancement. These advanced technologies lead to reducing the amount of silicon in a PV cell along with the enhancement of the cell's efficiency. Figure 5 illustrates the projected trend for the thickness of crystalline silicon PV cells over 12 years. The typical thickness of the p-type wafers in 2019 is around 170 µm, and based on the area of the cell and its efficiency (approximately 20%), the silicon mass/Wp is estimated to be 1.98 g/Wp.

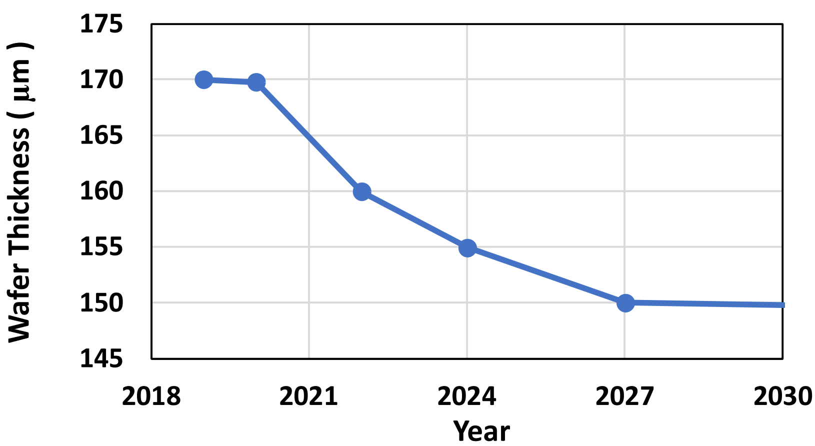

Figure 5. Trend for wafer thickness of the crystalline silicon-based PV cells (monofacial p-type) with dimensions of 158.75 × 158.75 mm, as redrawn from Ref. [31].

2.1.6. Copper

Copper is used in the photovoltaic system up to 40 times more than used in fossil fuel per energy unit generation. It was reported that about 5.5 tons of copper are used for the generation of one MW by PV solar system. Cooper is used in interconnected modules, earthing grids, DC and AC cables, inverter electronics, ribbons, and transformer windings [35].

It was estimated that about 72% of the copper used in PV systems can be recycled in the form of cables, interior parts, and primary materials. Based on the available data, 3.96 g/Wb will be used to calculate and estimate the copper waste amounts [29].

2.2. Glass and Polymers

Glass composes approximately 74% of the weight of a typical crystalline silicon PV panel [36]. A typical 60 PV cell panel of 300 Wp capacity would weigh on average 20 kg, meaning that the glass material mass is ~49.3 g/Wp.

EVA and Tedlar polymers: The PV cells in a typical crystalline silicon-based PV panel are usually encapsulated between two layers of EVA (ethylene-vinyl acetate). A Tedlar sheet usually backs the assembly of the encapsulated PV cells. EVA and Tedlar polymers compose a significant amount of traditional silicon-based PV panel weight, with EVA of 6.5% and PVF of 3.6% [36]. These polymers' estimated mass/power is ~7.4 g/Wp for a typical crystalline silicon PV panel. Table 1 summarizes the materials composing the commercial PV cells and panels.

Table 1. Estimated mass/Wp of the materials composing typical commercial crystalline silicon-based PV panels (typical silicon-based PV panel of 60 cells, an average weight of 20 Kg, and 300 Wp capacity are adopted for estimating values in this table).

Material	Gram/Wp *	Notes
Silicon	~1.47–~2.08 [31]	We consider the value of 1.47 g/Wp
Lead	~0.04–0.06 [34]	We consider the value of 0.04 g/Wp
Tin	~0.08–0.12 [37]	We consider the value of 0.08 g/Wp
Silver	~0.02–0.05 [31,33]	The median silver paste consumption for one solar cell has decreased from 0.3 g/cell in 2010 to 0.1 g/cell in 2019. We consider the value of 0.02 g/Wp, based on the reported amounts in 2019 [31].
Copper	~3.96 [29]	This amount includes wiring and cables of a PV system, including that amount inside PV cells and panels.
Aluminum (PV cell)	~0.18 [31]	This represents the amount of remaining aluminum on a PV cell
Aluminum (panel frame)	~6.87 [36]	This represents the amount of aluminum in the holding frame of a panel
Glass	~49.30 [36]	
EVA and Tedlar	~7.40 [36]	
Phosphorous		A very little amount: should be considered for leaching, and when managing the waste of PV cells
Arsenide		
Boron		

* All of these values are estimated by assuming the lowest mass/Wp of the materials as reported by the latest PV cell manufacturing technology up to 2020.

3. Estimation of the Amounts of PV Waste in Jordan

3.1. Study Area

The north region of Jordan (study area) is situated 65 km to the north of the capital, Amman. It is situated northwest of the Hashemite Kingdom of Jordan. It covers an area of approximately 29,000 km^2, as detailed in Figure 6, and its population reaches about 309,400 (Table 2). This area mainly consists of four governorates (Irbid, Mafraq, Jerash, and Ajloun) and is located between 223 and 187° east and 226 to 321° north, according to the Palestine Grid.

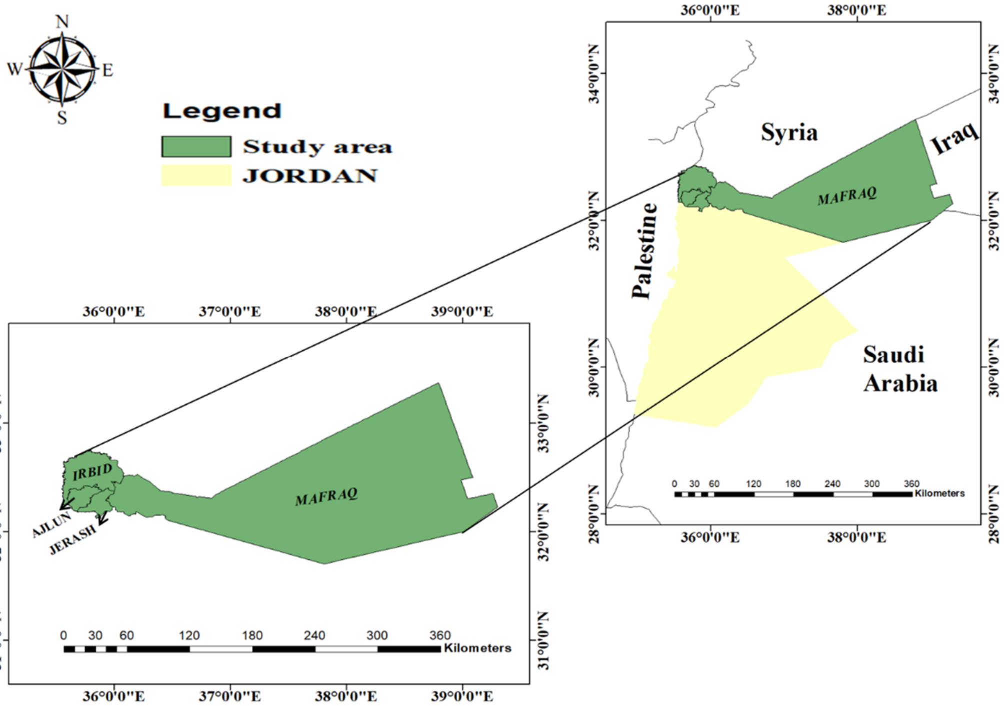

Figure 6. Location map of the study area.

Table 2. North governorates populations in 2020.

	Population	Households
Irbid	2,003,800	402,532
Mafraq	622,500	120,574
Jerash	268,300	52,965
Ajloun	199,400	39,579
Total	3,094,000	615,650

The installed PV capacity has grown extensively since 2013 in the northern region of Jordan, as shown in Figure 7. It is clear that the installed PV capacity increased significantly from 0.45 MW in 2013 to 102.7 in 2017 and 496 MW in 2020.

Since it is difficult to track all the types of silicon-based PV cells that are installed in Jordan and the exact materials composing each type, the reported data in the 2019 literature will be used as a baseline for the estimations in this work. The estimated PV waste depends on two assumptions: the lifetime of PV solar panel is 20 years, and the estimated quantities represent the lowest amounts of PV panel waste at their EoL. This estimation will be sufficient to extract conclusions about PV waste and could be considered as a guideline to address suitable mitigation and management approaches.

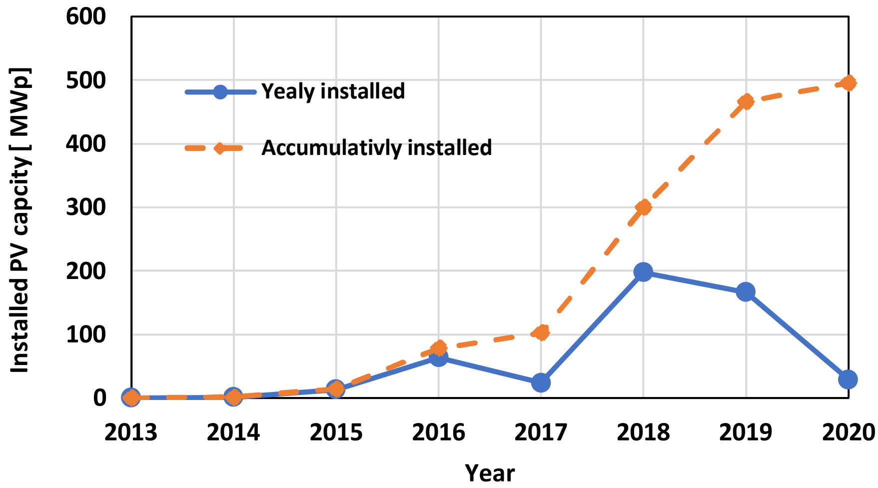

Figure 7. Yearly and accumulative solar PV power capacity in the northern region of Jordan.

It is projected that by the end of the year 2032, an overwhelming amount of PV waste material will be produced since this is when many of the PV panels in Jordan will reach their end of life. However, PV waste production is not limited to this projected year only. Jordan could witness PV waste in small quantities from as early as this year due to the maintenance process and installation. In the following section, the estimated amounts of significant PV waste projected to be produced will be presented.

However, a rough estimation of the amount of waste from the solar PV plants in Jordan, installed until 2020, shows a tremendous amount of waste materials that will emerge within a few years. Table 3 shows the annual and cumulative PV power installed in the northern region of Jordan (2013–2020) (MWp) and the amount of waste after the EoL of PV panels, assuming the minimum mass/Wp as ~66.6 g/Wp.

Table 3. Annual and cumulative PV power installed in the northern region of Jordan (2013–2020) (MWp) and the amount of waste after the EoL of PV panels.

Year	Capacity (Megawatt Peak)	EoL Year	PV Waste Mass (Metric Tons)	PV Waste Volume (m^3)
2013	0.4625	2033	~30.80	~83.25
2014	1.3552	2034	~90.25	~243.94
2015	13.2390	2035	~881.72	~2383.02
2016	63.8060	2036	~4249.48	~11,485.08
2017	23.8450	2037	~1588.10	~4292.10
2018	197.6600	2038	~13,164.16	~35,578.80
2019	166.4800	2039	~11,089.57	~29,966.40
2020	28.9610	2040	~1928.80	~5212.98
Total	495.81		33,022.88	89,245.80

The average dimensions of a commercial PV panel with 72 silicon PV cells and a peak power generation capacity of 300–375 watts is ~199.0 × 99.0 × 3.0 cm. Therefore, the volume per watt of a typical commercial crystalline silicon-based PV panel is between $\sim 1.8 \times 10^{-4}$ to $\sim 1.96 \times 10^{-4}$ m^3/Wp. Taking these data into consideration, the volume of PV panel waste that would emerge in the northern region of Jordan (up until 2040) is at least $\sim 89.25 \times 10^3$ m^3. If all of these PV panels were to be stacked, they would create a cubic building-like structure with a base area of 41 × 41 m and a height of 41 m. Additionally, if all PV panels would have the minimum weight per watt of commercial PV panels, the estimated average weight for them would be $\sim 33 \times 10^3$ metric tons.

The amount of silver and silicon per unit of energy generation is decreasing with the advancement of PV cell manufacturing technology. Aassuming the minimum reported weight/Wp for silver, the estimated amount of silver in PV waste will be at least 9.0 metric tons, as shown in Table 4. This amount of silver as a part of PV waste is economically appealing. However, considering the cost of extracting this amount of silver needs an economic analysis before deeming it feasible to extract.

Table 4. The estimated amounts of the materials in PV panel waste in the north of Jordan.

Year	Material Weight (Kg)								
	Al	**Al Frame**	**Si**	**Ag**	**Glass**	**Polymers**	**Cu**	**Sn**	**Pb**
2033	83	3177	679	9.25	22,801	3422	1831	37	74
2034	243	9310	1992	27.1	66,811	10,028	5366	108	216
2035	2383	90,951	19,461	264.78	652,682	97,968	52,426	1059	2118
2036	11,584	438,347	93,794	1276.12	3,145,635	472,164	252,671	5105	10,210
2037	4292	163,815	35,052	476.90	1,175,558	176,453	94,426	1908	3816
2038	35,579	1,357,924	290,560	3953.20	9,744,638	1,462,684	782,733	15,813	31,626
2039	29,966	1,143,717	244,725	3329.60	8,207,464	1,231,952	659,260	13,318	26,636
2040	5213	198,962	42,572	579.22	1,427,777	214,311	114,685	2317	4634
Total	9343	3,406,203	728,838	9916	24,443,368	3,668,984	1,963,402	39,665	79,330

The estimated amount of Al, Al frame, Si, Ag, Glass, Polymers, Cu, Sn, and Pb waste in 2033 will be 83, 3177, 679, 9.25, 22801, 3422, 1831, 37, and 74 kg, respectively, as shown in Table 4. During the period 2033, all materials waste will increase by about 6161%.

3.2. Thin-Film PV Technology

Safety precautions must be taken with most types of thin-film PV panels since they contain hazardous and toxic materials. Unfortunately, accurate information about the amount of thin-film PV panels installed in Jordan is unavailable. However, by adapting the typical global percentage of usage of these thin films, which is around 10%, it is possible to assume that the amount of thin-film PV capacity installed in Jordan is 100 MW. According to [29], the amount of cadmium telluride (CdTe) required for PV module manufacturing is 91 tons/GWp. Therefore, the amount of CdTe in such types of PV panels waste could be estimated to be 9 metric tons. This raises many concerns about these materials, and so more attention should be paid to thin-film deployment and their waste. Some of the concerning factors are:

- Silicon-based PV panels have a leaching potential of approximately 4 g of lead per kilowatt installed, compared to approximately 23 g of cadmium per kilowatt installed for CdTe-based PV panels.
- Cadmium is considered approximately 10 times more hazardous than lead.
- The possible wide geographical distribution of such panels in different regions in Jordan will result in widespread and long-term environmental contamination and hazards to human health.
- Jordan has no policies or regulations regarding the procurement of thin-film PV panels or the management of their waste.

A rough estimation of the amounts of PV panels materials that would emerge is summarized in Table 4, which is based on the information about the installed PV plants up until 2020 in Jordan. It is worth mentioning that the estimated amount of PV waste is based on panel waste only. It does not include other PV plant component waste, such as electronic devices, holding structures, etc. Figure 8 further illustrates the PV waste accumulation rate as a time function in the northern Jordan region.

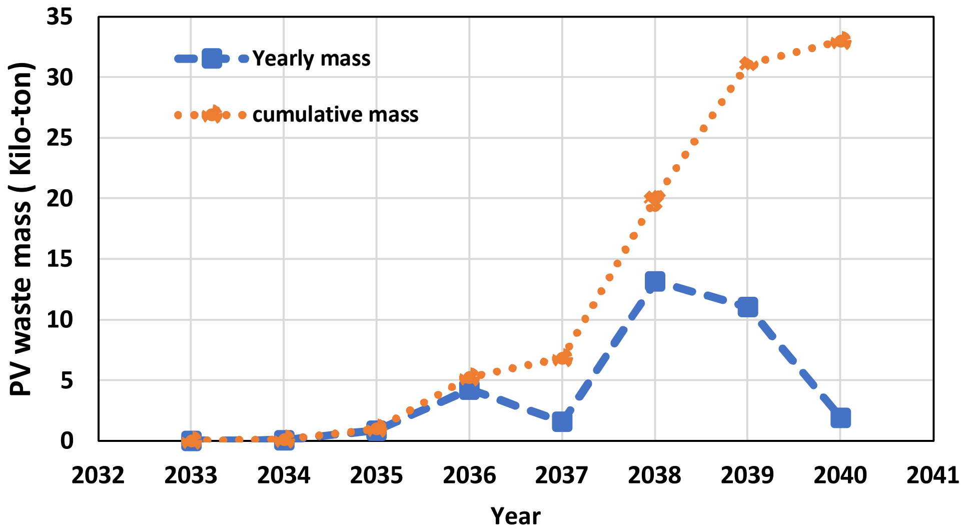

Figure 8. Estimated annual and cumulative PV waste mass that would emerge due to the already installed PV panels in the northern region of Jordan from (2012 to 2020).

4. Discussion

The estimated amount of PV panel waste in Jordan is significantly large and inevitable. As Figure 8 shows, the accumulated mass of PV waste can reach as high as 32 kilotons and a volume as high as 89,000 cubic meters, as shown in Table 3. Unfortunately, this amount of material can be spread out in the entire region since no regulations or laws are issued to control their disposal. Starting in 2032, massive amounts of PV waste will emerge. These amounts will gradually increase to reach a dangerous level in a few decades. The disposal of the waste gradually during the coming years and sporadically in the region would yield a highly negative environmental impact. Bearing in mind that the amount of PV waste, at the national level, would be triple that of the northern part of Jordan or more, the issue of PV waste cannot be considered a trivial problem.

Another aspect of the PV waste problem can be seen from the economic view. Turning a problem into an opportunity is a quite valid statement on the problem of PV waste. As Table 4 shows, there are large amounts of different materials in PV panel waste that have significant economic value.

4.1. Recyclable Materials and Economic Value

The different types of materials composing PV panels, such as glass, silicon, aluminum, silver, and copper, are recyclable. Some materials do not need a complicated process to extract from waste, such as aluminum and copper from connecting cables. Other materials require special processes to extract from waste, which requires extra cost and special facilities.

The price of the retrieved materials from PV waste can enhance the local economy and create jobs. On the other hand, the cost of the retrieval process of such materials can reduce their economic value, which might render retrieving precious materials unappealing. For example, the minimum silver amount available in PV waste in the first year would be around 9 kg. The accumulative quantity would be around 9.9 metric tons, as shown in Table 4. The price of such an amount of silver, at today's prices, would be ~5.4 million dollars. However, the cost of retrieving such an amount of silver should be considered. Regardless of the economic value, the environmental impact of non-retrieving silver from waste can be tremendously costly since silver can highly affect soil quality for agriculture. Therefore, processing and retrieving silver would not be a luxurious choice but a necessary action regardless of the cost.

Other materials, such as aluminum, contribute to a large bulk of waste as high as 3400 metric tons. The economic value of this amount of aluminum, at today's price, is

~7.4 million dollars. The aluminum of PV frames in waste can be used as a raw material for the industry or reused as frames for new PV modules. Likewise, silicon material, usually high-quality silicon, can be used as raw material or retreated and reused as PV cells for producing new PV panels.

Retrieving materials from PV panel waste goes through multiple mechanical, physical, and chemical processes that consume chemicals and energy. Different materials can be retrieved and recycled successfully through these processes, such as aluminum frames, glass, polymers, silicon, silver, and tin.

Depending on the method of management and recycling, energy consumption can vary. However, based on the excellent study of Ref. [38], an estimation of the required energy required for recycling PV waste materials is concluded as ~ 148 TWH. This amount would be consumed for recycling the whole estimated amount of waste during the long period of recycling processes. The ratio of energy/PV panels, assuming panels with 300 Wp capacity, is considered as reported by Ref. [38]. Nevertheless, conducting a comprehensive study on the optimal management and recycling method, particularly in Jordan, for energy, economy, and ecology aspects is under consideration by the work team.

4.2. Management Plant and Collection Areas

Due to the large volume that will emerge due to PV waste, two main issues arise. First, this waste cannot be disposed of sporadically around the areas where PV plants are installed, which is the current situation in Jordan. Therefore, specifying a collection area for PV waste becomes necessary. By specifying the collection area for PV waste, the widespread contamination of the environment due to PV waste can tremendously be reduced and controlled. Moreover, this action facilitates the utilization of waste economically. However, this action requires a PV waste collection mechanism and management plan and issuing regulations through law and bylaws to arrange waste disposing of and collection.

4.3. Environmental Impact and Regulation

Based on the reported amount of installed solar PV plants in the northern region of Jordan, the waste produced from these cells will contain at least ~9.9 metric tons of silver and ~24,000 metric tons of glass. The aluminum frame weighs at least 3400 metric tons, as stated in Table 4. The EVA and Tedlar encapsulation materials weigh almost 3600 metric tons. The significance of polymers in PV waste can be seen from multiple aspects: First the accumulated amounts of polymers from PV waste. Second is the impact of these polymers on the environment since such materials with continuous exposure to solar radiation can yield chemicals with a high toxic index [15]. Third is the economic potential that can arise from using these polymers if recycled. A photovoltaic solar power plant contains approximately 5.5 metric tons of copper per megawatt of power generation [19]. For the currently installed PV plants in the northern region of Jordan, this would yield ~2200 metric tons of copper. However, the minimum estimated copper in PV waste would not be less than ~1900 metric tons, as shown in Table 4.

Silver can leach into the environment and contaminate soil and water. Whether disposed of randomly or collected in collection areas, the leaching of silver is harmful to both soil and water. In addition, other hazardous metals and materials in PV waste such as lead and tin will be available in large quantities. For example, the accumulated amount of lead and tin in PV panels at their EoL will be ~79.3 and ~39.7 tons, successively. These amounts of lead are pretty concerning and, if leached into the environment, would have a tremendous long-term effect on environmental resources such as water and soil.

The volume and weight of PV waste, type of materials, distribution of PV plants, and hence their waste, collection, and management are pending issues that need serious attention in Jordan.

5. Conclusions and Recommendations

PV waste has many aspects to look at such as economic value, environmental impact, effect of materials on soil and water, and human health. Sporadic disposal of waste material can lead to wide environmental contamination and the leaching of hazardous materials into soil and water. Large amounts of such PV waste will emerge within a few years and require a cognizant and well-organized management scheme.

Since the problem of PV waste accumulation is slow and gradual, several preventive measures should be taken regarding PV waste management at the local and regional scale:

- First: Awareness about PV panels at their EoL between sectors that deal with PV energy, including companies, installers, legislators, etc.
- Second: Awareness of the emerging PV waste problem among decision-makers.
- Third: The importance of issuing laws, bylaws, and regulations that organize and enforce measures to manage and deal with PV waste safely and correctly.
- Fourth: Assigning an area, or areas, dedicated to PV waste accumulation for further treatment later.
- Fifth: Establish facilities that treat, recycle, or reuse PV waste after the EoL of panels.
- Sixth: Thin-film PV panels should be considered seriously when exporting, installing, and disposing of at their EoL.
- Seventh: In addition to typical crystalline PV panels, importing, installing, and waste management of thin-film PV panels are essential issues that need to be addressed by different sectors, particularly the legislation sector.
- Eighth: A comprehensive study needs to be conducted to determine Jordan's optimal management and recycling method for energy, economy, and ecology.
- The importance of PV waste and its management can be seen from many aspects: legislation, environmental, economic, social, and human health.

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