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Solar panels problem after end-of-life and waste management (SWOT analysis for the global directives of PV's waste management)

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ABSTRACT

Photovoltaic energy is a well-known term nowadays, and with the continuous increase in PV demand, it has become necessary to consider the other sides that may affect the success of it, which is considered one of the real effects on the environment. The PV waste has started to create a large issue with the absence of administrative procedures in many countries. Despite the estimated life of photovoltaic panels being between 20 and 30 years, many units have already started to stop working. However, research indicates the total cost of new materials to manufacture a PV panel is around USD 90 per square meter, compared to USD 13.62 for the costs of recycling a PV module. The regulations disclosed that the problem of EoL for PV modules and their management is still not considered an issue in many countries. Therefore, SWOT analysis was used to evaluate the EoL management of waste PV modules in three regions in Washington, California, and the European Union's WEEE Directive. This study presents recommendations to strengthen regulations to manage the problems of the EoL waste, and open the way for countries and the private sector to realize the responsibility that may affect the environment.

KEYWORDS

PV problems, solar panels waste, PV recycling, global PV waste directives, waste management, SWOT analysis

1. INTRODUCTION

Photovoltaic energy production is accelerating all over the world, in order to reduce emissions from traditional sources that affect the increase in global warming. Many traditional energy sources are being replaced by photovoltaic energy at present in line with the world's view toward maintaining sustainable development and reducing global warming [1]. PV capacity has been produced in the United States at around 80 GW by 2020, and this number is likely to increase by 2050 to approximately 3,200 GW [2]. However, the cumulative volume of e-waste is likely to increase to 200,000 tons by 2030 and over seven million tons by 2050 [3]. Although photovoltaic energy is considered friendly to the environment, it is not without flaws, as the large use and installation of solar panels leads to an increase in waste generated after the EoL, and thus direct impact on the environment [4].

PV panels do not last forever, the life of solar panels ranges between 25 and 30 years, and most distributors rely on an average of 20 years, which means that the panels that were installed in the early 21st century have almost stopped working. Over time, more PV modules will stop working, which will result in millions of tons of waste metal, glass, and various materials [5]. Although PV units last between 20 and 30 years of life, and manufacturers provide guarantees during this period, this does not mean that PV cells will last beyond the shelf life, as the guarantees provide that energy production will not decrease by about 20% of the electricity production during the life of the project, but it does not guarantee what will

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happen after its completion, as the electrical units corrode due to various weather factors and the color of the manufactured metal changes, thus leading to a decrease in efficiency, and this is what led to the failure to sign work agreements with solar energy units In satellites [6]. The reason for the stop of PV units to work is due to the decrease in the efficiency of PV cells, which originally may reach at best 20%, and the decrease in efficiency leads to the units becoming unable to keep up with the operating costs and compensate them with the amount of solar production, and then the accumulated waste stops working [7].

It is important to look at the negative part of the PV projects as well as the waste formed from the panels after the end of the project life that is considered to be very large and poses a threat to the environment. This is what the world will turn to in the coming years - try to find solutions before a major catastrophe occurs and leads to countless environmental problems. A part of the problem is that the PV panels were assembled with adhesives and other sealants to maintain their performance, but this made them difficult to disassemble, in addition to being made of many materials, some of which may be dangerous. Despite this, many companies, including ECS, are working extensively to recycle PV modules, in an attempt to reduce the risk of PV accumulation expected to reach millions of tons resulting from the expected operation of solar panels [5]. In the attempt of some organizations and countries to recycle photovoltaic modules after they stop working, the recycling rate is estimated at only 10% of the total solar modules that have expired [8].

Some countries are reluctant to set strict guidelines and policies for managing and recycling of EoL waste of PV units, because they see that deepening in this issue could lead to classifying it as among hazardous waste, tarnishing the reputation of PV technology, which many consider as a safe solution to preserve the environment and provide clean energy. As a result, the efforts of this paper target countries and emerging companies that wish to start implementing plans for waste management of PV units after the EoL, based on previous experience, by highlighting the main aspects and points of some of the directives adopted by some countries and international organizations to manage this issue, in clarifying the strengths, weaknesses, opportunities, and threats that some countries face during the implementation and development of the best methods for some of the policies used to solve this issue.

Therefore, the efforts of this paper target countries and emerging companies that wish to start implementing plans for waste management of photovoltaic units after the end of their life based on previous experiences, by highlighting the main aspects and points of some of the directives adopted by some countries and international organizations to manage this issue, by clarifying the SWOT analysis (strengths, weaknesses, opportunities, and threats) that some countries face during the implementation and development of the best methods for some of the policies used to solve this issue. In addition, the most important point for countries that have established directives to solve this problem is how to dispose of PV cells after the end of their useful life without any impact to the environment. Where it is important for the start-up countries in this field that wish to develop recommendations for managing PV waste to provide adequate infrastructure for the large number of PV waste that will be formed in the future, and to make tax and commercial facilities for internal companies and foreign investments to work towards the establishment of an integrated system suitable for all parties. In addition, a prior agreement before sale is concluded between the companies and the owners on how to return the PV cells after EoL.

1.1. Problem statement

Many countries are searching now for the best techniques to decrease the depletion of traditional energy sources and replace them with clean and continuous energy sources. But the lack of attention and focus on an important topic which is the impact on the environment that will occur after the end-of-life span for the PV modules will lead to the failure of this technology. The problem of the end of life comes with increasing the waste resulting from the PV modules with no serious actions to manage this issue and start recycling in many countries around the world.

This paper aims to model the factors behind solar cells' recycling waste in the countries' environment by analyzing SWOT analysis of the main points of the countries' directives and visions on how to manage the PV waste issue and recycling process, in addition to giving recommendations that could improve the situation.

2. LITERATURE REVIEW

2.1. Solar panel components

It is important to understand what the solar modules consist of and their working principle to be able to go deeper into the recycling stage and know the obstacles that they may face. Solar cells, or what is known as PV cells, consist of very thin layers of semiconductor materials that convert sunlight into electricity, as the least amount of solar energy emitted by the sun reaches the Earth equivalent to 89,300 TW [9, 10]. The main component of PV cells is silicon, which began to be used nearly 80 years ago in areas far from big cities to be used to generate electricity through solar radiation, those cities that are difficult to reach with conventional electricity. However, many other materials have been found to be used instead of silicone, but they may be of higher cost, lower efficiency, or rare to find [11]. Silicon is used as one of the basic components in solar cells, although it is considered a non-ideal material from solid-state physics viewpoint, but it is less expensive and abundant compared to other materials such as gallium arsenide (GaAs), which is an ideal semiconductor material that requires only 1 mm of crystal to absorb about 90% of light compared to 100 mm of crystalline silicon [12].

Before we start the discussion about PV waste and its recycling, it is necessary to clarify the production method that is used most frequently to produce solar panels. PV modules consist of many parts and materials that pass through a set of stages to obtain the final shape of the photovoltaic chip. The carbonate is reduced to silicate in the furnace using the arc, and then the resulting gases break the bond of silicon with oxygen through a reaction that absorbs heat from the carbon component; then the metal, which is a semi-metallic substance, is pulled out and melted with the impurities deposited at the bottom, leading to the purification process, in turn, the chips are picked up after that. However, very diaphanous hardened glass is used as a solid base and other substances are placed on the upper layer [13]. As shown in Fig. 1, the supply chain of the photovoltaic panel shows the original material to reach the final shape of the cell through some manufacturing processes, the process of obtaining metal-grade silicon begins and the alloy is formed from Poly-silicon to produce the wafer, and then the photovoltaic unit is completed after the formation of the cell. [14].

2.2. PV efficiency

Efficiency is the most commonly used parameter to compare the performance of photovoltaic cells. Efficiency is defined as the ratio of the energy produced by the photovoltaic cell to the energy received by the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the intensity of the incident light from the sun and the temperature of the solar cell. The efficiency of photovoltaic panels depends on latitude and climate, which in turn determine the efficiency of solar modules in addition to the materials used in manufacturing, as the reflection of light from solar cells instead of absorption leads to a decrease in the resulting efficiency. Therefore, the efficiency of 20% of the amount of sunlight directed on the cell is 20% of the solar energy that is converted into electrical energy. However, the efficiency may differ from one solar cell to another, depending on various factors, and although the same solar radiation is shed on the same solar cells, the difference in design leads to the generation of a different value of energy. Some companies compete to try to reach the greatest possible efficiency, as the 21% efficiency of the solar cell achieves more energy than a cell with 14% efficiency. In addition, by 2021 the equivalent of about 40% efficiency has been reached. However, 22% of the capacity may already be sufficient for energy requirements [15].

2.3. PV module end-of-life

The decrease in the efficiency of PV panels is a common occurrence, as the efficiency decreases every year and this leads to a decrease in the production of electrical energy until it reaches the minimum level of around 14% that makes the photovoltaic unit unable to provide the operating cost, and then it stops working, which called End-of-Life. According to reports issued by the National Renewable Energy Laboratory (NREL), the average annual energy loss for the cell is approximately 0.5%, and after approximately 25 years of operation, the unit reaches an efficiency limit that is not sufficient to continue operating, which leads to the photovoltaic units stopping working and turning into waste. The decline in efficiency is the largest during the first year, reaching an average of 2.5%, and gradually decreasing over time. Several factors lead to an annual decrease in the efficiency of solar units, the most important of which is the exposure of the panels to ultraviolet rays in addition to various weather factors, dust, failure, or the presence of workmanship problems [16].

2.4. PV waste

All attempts to try to stop or increase the life span of the photovoltaic panels fail and, in turn, the discontinued units are replaced with new units directly, which leads to an increase in PV waste annually, as the time interval between each project and another is very small, as direct replacement leads without the presence of sufficient time to dispose of the idle units to form photovoltaic waste [17]. According to a report published in 2016 by the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task12 and the International Renewable Energy Agency (IRENA) that it is expected PV waste in the world will increase from 1.7 to 8 million tons of accumulated waste in 2030, and the equivalent of 78 million tons in 2050 [18].

It is expected that nearly three and a half million tons of waste generated by 2030 will be collected from non-functioning PV modules only in China, which is one of the leading countries in the manufacturing and use of PV modules. According to researches, the largest amount of PV waste will be carbon steel at around 1.45 million tons, followed by 1.1 million tons of glass, then by plastic, aluminum, copper, silicon, and finally silver. However, it turns out that these numbers pose a real problem for the environment, but unfortunately there are very few places and stations equipped for recycling [19]. PV units contain 70% of glass and therefore 30% are different metal materials that can be recycled, whether silver, copper, or aluminum, but they need special procedures to be dismantled and recycled in the best way, as these metal materials have economic value, in addition to the environmental aspect because they contain a percentage of the total waste value [20].

2.5. PV modules recycling

The majority believes that the solution is to recycle photovoltaic materials, but the huge amount of units that will stop

Fig. 1. The supply chain for solar cell modules 'Own source'

working soon or that have already stopped is an obstacle to deal with, as most countries and companies are still not equipped to deal with these numbers [21]. The recycling rate of PV units in the world is estimated at only about 10% of the total amount, and the reason is due to the lack of sufficient organization and management to carry out the recycling process. In addition, the materials resulting from the recycling process, such as silicon, are considered to have no high value after recycling due to their availability, thus, the way to use waste cemeteries is considered the lowest cost [22]. However, recycling can be up to 80% of the photovoltaic cell weight [23].

The disposal of solar panel systems will become an issue if no solutions have been developed, compared to a large increase in PV production. Therefore, the development of waste solar unit recycling will be effective in solving this problem in the future. In Europe, chemical and thermal methods for photovoltaic re-cycling were extremely improved. The thermal method is done by separating the unit materials under 600 °C. The chemical method is to retrieve silicon particles out of PV cells, which can be re-utilized in PV units [24]. The PV Cycle, a non-profit organization, is considered one of the most important European organizations that aim to manage and dispose of waste resulting from the end of life of solar panels [25]. It has established many recycling facilities in Europe, and the recycling rate of crystalline silicon reached 96% for photovoltaic units, and this is a very high percentage and tremendous progress in the field of recycling within the European Union for electrical and electronic waste. The recycling method begins with the removal of all cables and boxes, including the frames of the PV modules. After that, all the different materials and units are separated [26]. In addition, SolarWorld, which is headquartered in Germany, uses a recycling method by thermal separation through a system called “input”. This process performs thermal analysis of the units by exposing the plastic materials to a temperature of 600 degrees Celsius, after which the solar cells and glass are separated manually, and then the glass and silicon cells are recycled to be used again. This process recovers 84% of the unit weight, 90% of the glass, and 95% of the semiconductor materials including the most widely used crystalline silicon. However, it can reach 98% of the recovery and recycling of unbroken cells depending on the conditions of the units and the thickness of the cells [27].

Photovoltaic units are made from different and complex materials that are difficult to handle and recycle, due to the type of materials that may be toxic as a result of recycling by using chemical or thermal methods, and other materials that have been glued tightly during manufacturing to prevent leaks and therefore impossible to disassemble without being broken. However, there are many processes used to recycle PV modules that include mechanical, thermal, or chemical delamination. The PV modules are disassembled and cracked using mechanical processes, or by using special acids the most important elements in the composition of the modules can be melted and separated, including silicon, which is widely used as a semiconductor material. In addition, precious metals are also separated through thermal systems that burn and melt materials, or by using acidic substances are used to dissolve and separate different parts of solar modules [28].

Table 1 shows several retrieved materials, outputs, and chemical and energy-consuming amount through various PV units by using the three recycling approaches, mechanical, thermal, and chemical methods. Thermal dissociation has the advantageous ability of recovering entire materials with a higher re-use rate. Although the procedure can use more energy and show less productivity, mechanical dissociation seems applied based on the current recycling basic structure for greater productivity. A thermal procedure also eliminates concerns about flaring fluoride back sheets and carbon-dioxide emissions. Nevertheless, efficacious filtering of glass, plastic, and PV cells after smashing can be more challenging. In addition, the amounts and productivity of the present chemical dissociation still require development and, in addition, the chemical material used still presents real issues to the environment and humans, making it not yet applicable in the manufacture [29–31].

2.5.1. Thermal treatment in PV module recycling. Before performing unit analysis using the thermal method, mechanical methods of cracking and separating outer boxes, circuit breakers, and connections are used. After the mechanical separation is completed, the materials are exposed to a high temperature of 600–650 degrees Celsius to separate the plastic materials from the glass and crystalline silicon, in addition to the existing silver, which is the most important material resulting from the recycling process [31].

Thermal method is better than the chemical in that it can make a full removal of encapsulating, and it is simple and economical. In addition, it does not contain the problem of solvent and its cost, but its disadvantages are the emission of gas during the decomposition of materials, and high energy requirements. However, this method is more efficient, simpler and easier to use than the chemical method [32].

2.5.2. Chemical treatment in PV module recycling. The method of chemical separation of photovoltaic units depends on such chemicals as tetrahydrofuran (THF), HNO3, and Ca(OH)2. After separating some materials by the

Table 1. Comparison of three major module delamination methods [28]

	Chemical analyses	Thermal analyses	Mechanical analyses
Products	Good or damaged surface and other solar panel parts	Good or damaged surface and other solar panel parts	SI and metal powder mixture (in some cases with plastic), damaged glass
Throughput rate	Very low	Low	High
Consumption	Very high	High	Low

mechanical method, the majority of other materials remain conjoined, and here comes the role of the chemical method in separating them from each other [31]. The advantages of the chemical process are less cell damage and good recovery of glass, but it is insufficient without other methods, requires a longer time, and harmful emissions and wastes in addition to the high price of solvents [33]. Therefore, it is recommended to use the thermal method after performing the initial separation using the mechanical method.

2.6. Comparing the cost of new materials to recovered materials

Despite the many important environmental aspects of moving towards managing photovoltaic waste recycling, the economic aspect also plays an important role, as it is important to consider the difference between new units and materials and those recycled, especially concerning private and external costs. The private and external costs of the units to be recycled consist of 3 sections: the first is recycling, the second is transport, and the third is disposal. As for the private costs, the cost of the first part is the cost of investment and treatment, and for the second part, it is the cost of diesel fuel, while the third part is the tipping fee of landfilling. As for the external costs, the cost is distributed over the emissions resulting from recycling, transportation, and incineration.

Table 2 indicates the total cost of new materials to manufacture a square meter of a PV panel is approximately USD 90 per square meter, compared to USD 13.62 for the private and external costs of recycling a PV module. The reasons for the great difference between the two costs are that the new materials include the initial cost of machines and equipment that are used to extract materials from nature, while the recycled materials do not need this additional cost. In addition, the cost of purchasing new materials for building a photovoltaic unit per square meter is much more than the cost of purchasing materials for recycling, such as silver that goes into building crystalline silicon panels, which is extracted from nature, but in the case of recycling it is obtained from recycled materials and not re-extracting them from minerals in nature. In general, the cost of extracting materials from nature and building PV modules is much more than what is extracted from recycling. In addition, the cost of reselling recycled products is lower, which makes it a positive cost and a win-win for all parties from the factory and seller to the customer [34, 35].

3. ENVIRONMENTAL RISK

The waste of photovoltaic units after the EoL forms large areas of land, and this leads to incorrect exploitation of natural lands, in addition to the emissions of various materials that may interact with time in the presence of various factors such as direct water precipitation on it. The lack of suitable solutions to this problem and the lack of equipped places to accommodate large quantities of expired solar cells will lead to multiple problems that can be likened to building large cities that are unlivable which affect the environment. However, more than 90% of the PV units are glass, polymers, and aluminum, which are classified as non-hazardous materials to the environment, but there are other materials such as silver, tin, and lead in addition to other metals, which are classified as dangerous to the environment, and may cause health and environmental problems over time [36–38].

Table 2. Total cost of recovered material vs. original materials

	Private Cost $/1m^2	External Cost $/1m^2
Virgin Materials	46.56	42.97
Recovered Materials	6.72	5.71

There is a large amount of lead equivalent to 12.67 g in each panel, which weighs about 22 kg, and this percentage is considered high and its disposal must be managed well. Research indicates that between 13% and 90% of the amount of lead present in each broken unit is leaked by rainwater and other factors, and some of these metals are classified as dangerous such as lead, chromium, nickel, and tin. Therefore, there are predictions of risks posing large quantities of lead (30 tons) and cadmium (2.9 tons) for the year 2050, which poses a threat to the environment [39].

3.1. Global PV waste regulations

As discussed in the previous points, the waste generated from the end of life of photovoltaic units will increase significantly and rapidly after 2030, which will lead countries to move towards establishing PV recycling regulations to manage the collection and recycling of solar cells in a necessary and safe manner that contributes to preserving the environment. Stakeholders cannot be left facing these challenges alone, so it is imperative that they participate in every step of the PV lifecycle to work together toward facing this challenge. Therefore, some policies and guidelines have been developed that will be effective to address the problem of end-of-life of solar cells through the appropriate implementation of these regulations [40].

In this section, some of the most important points for managing photovoltaic waste in some different regions will be reviewed, such as the European Union Directive on Waste Electrical and Electronic Equipment (WEEE), and some of the leading states in the area of solar power in the USA such as Washington and California.

3.1.1. Waste electrical and electronic equipment directive (EU's WEEE). European Union has put one of the main directive scopes based on the WEEE directives to rid of the waste that originates from electronics and electrical equipment. The main reason for this directive is to effectively address electrical and electronic waste in the 28 member states of the European Union and adds responsibility to stakeholders and also to address and manage these wastes [41]. According to the WEEE directives, all manufacturers are legally responsible for the proper management of waste electrical or electronic products that they manufacture, regardless of where the manufacturing facility is located. The WEEE Guidelines contain all effective and detailed guidelines for collecting, recovering, and recycling products with due regard to the environment and public health [42].

The first WEEE Directive came into work in 2003, even though it did not contain sufficient and comprehensive guidance for the management and treatment of the wide and varied volume of waste PV modules. In 2012 and according to a proposal from the European Union Commission, the directives were revised extensively and significantly to include end-of-life management of PV units. The amended WEEE Directive entered into force on August 13, 2012, and began to be implemented in member states within a new legal framework for waste PV units, under the name (WEEE EU/2012/19 Directive) [40].

One of the most important WEEE directives related to photovoltaic units was that product manufacturers are legally responsible for establishing sound management of the product's life and after the life span of their products regardless of the location of the facility, in addition to encouraging cooperation between companies and recycling plants. Measures should be implemented and taken by the member states for environmental design capacity, which would allow for the reuse of waste generated from electrical and electronic equipment. Moreover, manufacturers are allowed to use waste electrical and electronic equipment in industries unless it affects the environment or safety requirements [43].

3.1.2. The management program of Washington State's PV unit. The Washington state legislature passed Senate Bill 5939 in 2017, which aims to modify tax spurs that hearten an increase in sustainable local renewable power manufacturers (S.B. 5939, 65th Leg., 3rd Spec. Sess. (WA) [2018]). In 2020, this law was modified as per Section 1 of the House of Representatives Bill No. 2645, bearing in mind that Section 2 of the bill was repealed by the Governor [44].

A part of the project was to set up a complete program for the supervision and recovery of PV modules by having the manufacturers finance and implement a plan to take back the PV modules after their end of life sold after July 1, 2022, without placing any additional costs on the owner of the PV modules [45]. As of July 1, 2023, a condition for the sale or offer of sale of PV modules becomes approval of the take-back plan developed by the manufacturer, distributor, or retailer for the supervision of PV modules from the Washington Department of the Environment [46].

3.1.3. California's universal waste regulations. The California Department of Toxic Substances Control (DTSC) responsible for protecting people and the environment from toxic substances has issued Regulation No. R-2017-04, in 2020, which in turn manages discarded PV module waste as a global waste, which has toxicity characteristic of hazardous waste in California [47]. California's global directives of waste contain determination, recording, carriage, handling, stockpiling, and hazard demands that are minimal rigorous than California's hazardous waste regulations. Some of the regulations define management standards for the different levels that include treatment, the goal of which is to safely manage and conduct the treatment process by global waste processors who do not have the hazardous waste facility they need to obtain, based on the regulation number (Code Regs. 66273.75) [48].

Declarations of the DTSC Global Waste Regulations include following annual reporting and record-keeping instructions, such as notifying the DTSC of information about the types of PV modules that are being collected and indicating if more than 5,000 kg of PV modules are to be collected at the same time, based on the regulation number (Cal. Code Regs. tit. 22 § 66273.32). Before transferring the photovoltaic units to the facility that will dispose of them, they must be assembled and stored for up to one year, based on the regulation number (Cal. Code Regs. tit. 22 § 66273.35). In addition, the PV modules should be dismantled including metal frames without breaking the glass covering the photovoltaic panels, based on the regulation number (Cal. Code Regs. tit. 22 § 66273.72) [48].

4. SWOT ANALYSIS OF GLOBAL ACTIONS

The study of all the previous research focused on PV EoL waste and how it could impact the environment, and the ways that are used to recycle it. In addition, the directives and legislature of some countries and regions in how they deal with PV EoL waste, such as Washington, California, and EU's WEEE directives have been analysed.

The next section aims to introduce some of the main policies and recommendations that some countries use, regarding EoL PV waste management and recycling, by using SWOT analysis to introduce the internal points of strengths, and weaknesses, and the external points of opportunities, and threats.

These instructions and policies help create a SWOT analysis for some countries' legislations and directives on the three regions (EU's Waste from Electrical and Electronic Equipment Europe (WEEE) directives, Washington, California). The strengths, weaknesses, opportunities, and threats (SWOT) analysis criteria emanated from the legislations and directives of the countries that mentioned in the previous points based on the main aspects of the PV EoL management policy.

4.1. SWOT analysis of EoL PV waste management in Washington

The state of Washington relies in its recommendations and actions on the law established in 2017 by the legislature that aims to promote renewable energy and oversee the process of recovering panels from the owner after their life. In the previous stages, before the establishment of special laws that include recycling and effective management of waste from photovoltaic units, this waste was considered largely unimportant because the main focus was on creating technology that provides unconventional electrical energy. However, a study was made with the adoption of the maximum life of the units, which is 35 years of operation, the size of the units by 2047 will reach 1 metric ton [49]. Therefore, the system was established to manage these units after the end of their life. However, although there are great strengths and opportunities such as environmental preservation, permitting, and facilities regarding the classification of waste PV units indicated in Fig. 3, there are still some challenges, as these laws and recommendations include the units that have been sold after 2017. But there is still a question about the units before 2017, what is their fate? However, one of the recommendations that should be reconsidered to answer this question is to include the units that were sold before 2017 in these recommendations and laws and to increase the awareness of people and companies about these procedures to follow up on units that were sold before this period. The program is based on financing and recycling the panels at no cost to their owners, in addition to obligating manufacturers to follow the necessary standards for recycling. The program will include residential panels and large projects, where the range of uses for solar panels in homes is already large and it is important to take them into account. One of the objectives of the project is to reduce the environmental impact of the product and make its use safe even after the end of its life cycle [50]. The SWOT shown in Fig. 2 illuminates the inner and outer characteristics and is utilized to distinguish the suitable directive for EoL PV where it is a fit for the state of Washington but it should be changed according to each country or government to suit its policies and directives that focus on electronic waste and the management of the PV EoL waste. For example, one of Washington's main weaknesses is that these terms do not apply to the PV modules that have been sold after 2017, which make the older PV before 2017 accumulate as waste; that might not be one of the conditions in another country. On the other hand, similar directives might include the PV units sold before 2017 outside Washington.

Making facilities in Washington related to the recycling of waste PV units and not considering it as dangerous waste, allows for reducing the cost and uncertainty associated with classifying photovoltaic units as hazardous waste. This will contribute to providing external opportunities for foreign investors from other states for example, which consider the PV units as dangerous waste by transporting and recycling them inside Washington, which allows external investment.

4.2. SWOT analysis of EoL PV waste management in California

Based on regulation Number R-2017-04, that has been established in 2020 by the California Department of Toxic Substances Control (DTSC), and based on the policy and recommendations that are mentioned in the regulations section in turn to manage PV EoL waste, a SWOT has been created to focus on the main points in the end-of-life management of PV modules. As shown in Fig. 3.

California has a vision of reaching 100% clean energy by 2045, and one of the steps taken to reach this is the implementation of some necessary measures to reduce the spread of waste PV modules after EoL. California's main strength about PV waste reduction is to reduce the costs and liabilities of PV module waste compared to hazardous waste in general and to prevent its disposal instead of recycling. However, one of the important weaknesses is that in

Strengths	• Establishing laws aimed at environmental safety in a way that reaches 100%. • Stimulating the recycling of photovoltaic units. • Facilitating policies related to the recycling of photovoltaic units, and not linking them to the requirements of dangerous waste. • Reducing the cost of licenses related to the classification of photovoltaic units, as they are not dangerous waste.	**Weaknesses** • These terms apply only to PV units sold after 2017. • Very small photovoltaic units, such as lighting, this program may not be able to process completely.
Opportunities	• Financial revenues to finance the costs of the photovoltaic waste management program. • Competition between companies, due to the presence of facilities. • Direct cooperation between the manufacturer, supplier, and owner. • Increasing investment by internal and external competitors.	**Threats** • Manufacturers and suppliers may withdraw from selling PV units in the state because there are no similar requirements in other states.

Fig. 2. SWOT analysis of Washington end-of-life PV waste directives

Strengths	Weaknesses
• The vision is to reduce some of the costs and responsibilities related to the hazardous waste of photovoltaic units compared to the general hazardous waste. • Preventing the disposal of photovoltaic waste and instead recycling it after the end-of-life. • Contributes to achieving the state's goals of reaching 100% clean energy by 2045.	• In California, the use of chemical and thermal processing methods is not permitted. • It is not necessary to cancel a prior toxicological examination. • The regulation considers photovoltaic units to be toxic waste; it may be difficult to recycle them.
Opportunities	**Threats**
• Opening the way for new research in recycling methods. • Building an infrastructure ready to contain waste photovoltaic units.	• It may create assumptions that the waste of PV EoL is toxic and dangerous instead of being classified as solid waste only. • It may hinder the transportation and storage of PV as they should only transfer to approved facilities. • There may be opinions that the manufacturers of PV produce hazardous materials for the environment.

Fig. 3. SWOT analysis of California end-of-life PV waste directives

California it is not allowed to use chemical and thermal treatment methods, which are the most important recycling processes used for PV modules, and also to consider parts of PV modules as hazardous materials. Which, in turn, leads to creating threats of withdrawal of PV recycling companies from the region and their tendency to invest in other places. This may create new research opportunities in California to find effective and modern ways to recycle PV modules.

4.3. SWOT analysis of EoL PV waste management of EU's WEEE directives

The WEEE Directive was created in 2012 and stands for Electrical Waste and Electronic Devices Directive and is a European Union Directive. The WEEE Directive was chosen because it serves as a reference and recommendations for member states regarding policies used in the disposal of electrical and electronic waste including photovoltaic units. The objective of the laws established to direct waste electrical and electronic equipment (WEEE) is the effective management of this waste through recollection and recycling to be used again after the end of its life.

According to the reference to the legislation and policies in the previous sections, the SWOT has been designed in Fig. 4 to cover the main points in the photovoltaic EoL management process of the WEEE Directives. In addition, the Directives of the European Union, which includes about 28 countries, aim to start a comprehensive program that guides participants and member states with regard to the management of electronic waste, as e-waste includes photovoltaic equipment, according to these directives. Customers' confidence should be taken into consideration in recovering expired equipment at least for free, with a commitment to electronic waste recycling, which makes it an important strength towards the disposal of photovoltaic end-of-life waste. This provides an opportunity to encourage people to search for ways to return these expired devices to the companies. Individuals and entities may face weaknesses represented in the difficulty of finding suitable facilities to return expired devices and the lack of a system for direct communication between companies and individuals to facilitate the process of return and recycling.

5. CONCLUSION AND RECOMMENDATIONS

Although there are regulations in some countries that contribute to managing the EoL of PV units, however, their implementation is still unclear. It is necessary to share responsibility among all parts of society, whether manufacturers, sellers, or owners in order to reach levels at which PV modules are completely environmentally friendly even after the end of their life. This study clarifies the procedures and regulations of three regions in Washington, California, and the EU's WEEE by using a SWOT analysis, which aims to clarify the different aspects of the directives, that differ from one region to another, as in Washington, these legislations are implemented for units sold after the year 2017 only, and in California, it is not allowed to use chemical or thermal recycling methods, which are the basis for recycling photovoltaic modules. However, non-attributing the waste of photovoltaic units to other dangerous waste is considered the most important recommendation and regulations referred to by some countries such as Washington to reduce effectively the recycling of waste photovoltaic units, thus reducing the cost of licenses and facilitating them as these wastes are not dangerous, which will lead to the success of the recycling process. However, the main issue is the lack of

Strengths	• Starting a program that directs the participants into e-waste. • Building a reference system for member states that allow waste disposal. • The accession of about 28 countries of the European Union to the system. • Considering customer trust redeem expired materials at least free of charge. • Commitment to recycling e-waste.	**Weaknesses** • Lack of a site or program that allows companies and recyclers to communicate directly. • The difficulty of finding suitable facilities to make people return the expired devices, taking into account the population density. As people may be available in multiple areas or far away. • Individuals cannot dispose of and recycle this waste individually with companies but must wait and work collectively.
Opportunities	• Open new recycling facilities. • Availability of new job opportunities. • Encourage people to search for ways to return the expired PV. • Helping the environment get rid of e-waste. • Companies restore or buy expired products to recycle them	**Threats** • Miscommunication between manufacturers and customers or those responsible for recycling. • Intense competition between companies may result in the exploitation of customers.

Fig. 4. SWOT analysis of EU's end-of-life PV waste directives

actual management of the end-of-life of photovoltaic panels. Therefore, it is recommended that a prior agreement be made between companies and owners on how to return the photovoltaic cells after the end of their life. In addition, it is appropriate to create a website that contains portals for manufacturers, distributors, and owners, to facilitate communication and management in the good disposal of waste photovoltaic units. However, the countries that want to start controlling this problem can make facilities for companies and internal and external investments, to start establishing factories and facilities to manage photovoltaic waste. Furthermore, the California Recycling Program forbids the disposal of PV waste and instead recycles it after its life span. Consequently, there is a law that prevents the disposal of these wastes without effective management.

These analyses are a starting point for developing countries in the field of managing the end-of-life of photovoltaic units, to start creating and developing the directives which will contribute to maintaining making this technology completely clean energy that contributes to maintaining a safe environment.

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