Geosciences and Engineering, Vol. 12, No. 1 (2024), pp. 100–118.
https://doi.org/10.33030/geosciences.2024.01.007

RECYCLING TECHNIQUES FOR CRYSTALLINE SILICON AND THIN FILM PV PANELS: AN OVERVIEW

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Abstract: Over the last few years there has been a growing trend towards using solar electricity as an alternative source of energy. In order to meet the world's projected energy needs, PV panel technology is a major alternative to fossil fuels. Due to the increase in production, PV panels with a lifetime of between 25 and 30 years are potential for photovoltaic waste over the next few years. The environmental damage caused by PV panels is significantly reduced when they are recycled. The recycling also contributes to the recovery of materials, some of which are rare in nature. The structure of the components that make up this paper. From 2050 onwards, the estimated PV waste projections for the world have been analyzed.

Keywords: *Solar energy, photovoltaic panel, components of PV panel, recycling*

1. INTRODUCTION

Originally utilized in space, solar photovoltaic (PV) energy technologies are now widely applicable anywhere electricity is needed. One of the most developed and promising methods for producing renewable energy is photovoltaic (PV) energy production. PV technology is a common way to generate power and is also environmentally friendly. After hydropower and wind power, which are currently the world's most popular renewable energy sources, solar energy technology is currently in third place (Paiano, 2015). PV energy sources also produce electricity with minimal emissions of carbon that contribute to global warming. Moreover, the amount of CO_2 emitted per kWh from fossil fuel-generated power ranges from 400 to 1000 g CO_2 equivalent, while silicon-based solar panels emit very little CO_2 (Shin et al., 2017). The comparison between CO_2 emissions in the production and recycling of photovoltaic (PV) panels reveals significant variations based on panel type and manufacturing process. In the production phase, the amount of CO_2 emitted varies by nation and panel type, with polycrystalline panels generally emitting around 17-182 kg CO_2 per 1 m^2. Conversely, recycling processes result in significantly lower emissions due to reduced energy and raw material requirements (Vellini et al., 2017). Overall, while PV panel production contributes to CO_2 emissions, recycling processes significantly reduce these emissions, highlighting the importance of sustainable practices in the solar energy industry. Solar energy is dependable, efficient, safe, and pollutant-free. As a result, PV technology has a very promising future for meeting global energy demands. Solar PV power has been used more often over the last few decades. PV panels have a sizable market today and have the ability to generate sustainable energy on a global scale. Furthermore, it is anticipated that PV-generated electricity will overtake other worldwide energy sources as the dominant energy source within the current century (Xu et al., 2018). The growth of renewable capacity over the next five years will happen far more quickly than was predicted even a year ago. According to IEA's projection, renewables will grow by about 2400 GW over 2022–2027, which is equivalent to China's whole installed electricity capacity at present. This represents IEA's highest-ever upward revision and an acceleration of 85% from the prior five years and approximately 30% above the prediction in the previous year's report. Over 90% of the increase in the world's electrical capacity is expected to come from renewable sources during the projection period (Paiano, 2015). As a result, a sustainable plan for the removal of outdated solar panels is required for the growth of PV module recycling as a multidisciplinary field of study. Examining the available technologies can be useful in controlling and assessing the EoL PV modules (Mahmoudi et al., 2019). Developing low-cost recycling technology is essential for the developing PV sector in order to ensure the sustainability of PV at high deployment stages. Concurrently with these new technologies' quick commercialization. In an effort to reduce the detrimental effects of the continuous increase in the volume of PV waste and to institute solar module recycling, the European Union (EU) has incorporated PV waste into the new Waste of Electrical and Electronic Equipment (WEEE) directive (D'Adamo et al., 2017).

2. COMPONENTS OF PHOTOVOLTAIC PANELS

A solar panel, a battery or battery pack, and a solar controller are the three main components of a conventional solar power system. An inverter is required as part of the arrangement whether the output power is 110 V (AC) or 220 V (AC). Heat is produced as a result of the low energy waves that the PV modules have effectively collected, and shortwave irradiance from the sun is directly transformed into electricity by the semiconductor component of the PV cell. A photovoltaic system's internal components and exterior environmental conditions can affect how much power and current a solar cell can produce. Numerous elements, including installation, PV system, cost, and environmental considerations, influence the operation of solar systems and the power they produce. The two primary categories of solar panels available on the market are crystalline silicon and thin-film silicon (Artaş et al., 2023). Silicon, both monocrystalline and polycrystalline, is the most common material used to make PV panels. Solar arrays are equipped with crystalline silicon panels, which offer excellent recycling capacity. The primary goal of thin-film solar panels is cost reduction; these panels appear uniform but have extremely poor efficiency. Solar radiation is directly converted into electrical energy by solar panels through the use of the photovoltaic effect of the semiconductor material in the panel. A few solar cells connected in series make up the PV panel, which is the fundamental part of the system. The battery group's job is to store the energy released during panel illumination so that it can be supplied to the load whenever needed. The controller's job is to automatically guard against overcharging the battery. Transforming direct current into alternating current is the inverter's job. The fundamental power producing components of a solar power system are solar panels (Xu et al., 2018).

The typical PV panel components listed below are presented in *Figure 1* (Krebs & Frischknecht, 2022). Aluminum (Al) frame, Tempered glass, Solar cells, EVA Film (ethylene/vinyl acetate copolymer), Backsheet (TPT, Topotecan Hydrochloride), and Junction box.

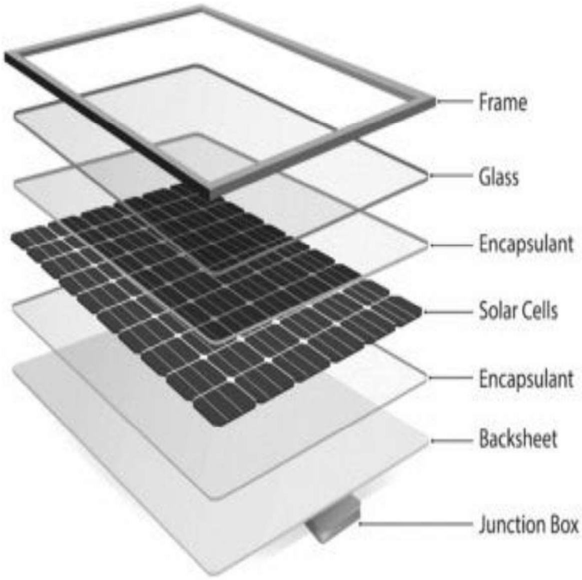

Figure 1
PV panel components (Krebs & Frischknecht, 2022)

With the advancement of technology and a more competitive industry, panels have grown tougher and lighter over time. It comes from mass reduction brought about by thinner glass sheets, frames, and layers as a result of optimized cell and panel designs. The composition of the materials used in PV panels has not changed significantly. Every link in the PV value chain makes it possible to produce more goods with a given amount of materials and resources. The goal of resource and material efficiency is to maximize environmental benefits while making sustainable use of the planet's finite resources. The mass/power ratio has been continuously declining over time as a result of material savings in PV panels and increased solar cell efficiency, as seen in *Figure 2* from IRENA (Weckend et al., 2016).

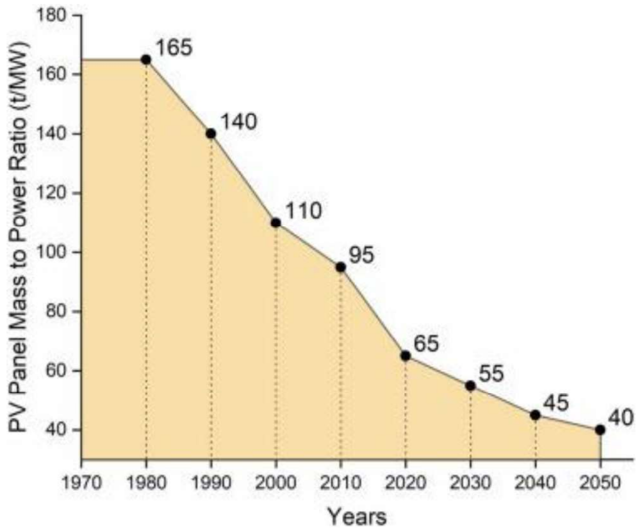

Figure 2

Decreasing of the mass/power ratio over the years (t/MW) (Weckend et al., 2016)

2.1. Crystal Silicon PV Panel

The earliest photovoltaic technologies are crystalline silicon PV panels, which currently hold a 92% market share (51% for polycrystalline and 41% for monocrystalline technologies when the global market is taken into account). In terms of crystalline silicon technology, monocrystalline silicon PV panels hold a 45% market share, while polycrystalline silicon PV panels hold a 55% share. Due to low productivity rates, production of a-Si products has been halted recently, and its market share is currently very small. Ninety-three percent of c-Si PV modules were made by Asian producers in 2021. With a share of 70%, China leads the way (Artaş et al., 2023).

2.1.1. Monocrystalline Silicon PV Panel

Using the Czochralski technique, which requires silicon to be in a molten state at 1400 ℃, first-generation monocrystalline silicon is formed as ingots. These solar cells are the most expensive of all solar cells and, in spite of their great lifetime and efficiency, demand a comparatively large energy expenditure for first-generation PV when compared to other technologies (Wang et al., 2014). PV cells are made primarily of semiconductor materials. A highly pure form of silicon is used to create monocrystalline silicon cells, which increases their photoelectric conversion efficiency. Compared to other solar cells, monocrystalline solar cells are more efficient, with an efficiency of above 20%. An additional benefit of monocrystalline cells is their extended longevity. For this kind of system, many manufacturers issue warranties of up to 25–30 years. Thus, from a financial standpoint, consumers typically choose polycrystalline solar panels as their primary PV panel type (Fernandes et al., 2016).

2.1.2. Polycrystalline Silicon PV Panel

A vital component in the manufacture of photovoltaic panels is polycrystalline silicon. The polycrystalline silicon solar cell has become increasingly more significant than the single-crystal silicon cell due to its simpler production process, which also makes it less expensive overall. Moreover, the efficiency of commercial polycrystalline silicon cells ranges from 13 to 19%. Cells that comprise several tiny silicon crystals are the building blocks of polycrystalline modules. Polycrystalline modules have an ice appearance due to many tiny crystals (Chen et al., 2011).

2.2. Thin-film PV Panel

Thin-film panels are 7% of PV panels. In terms of technology, silicon-based panels are simpler than thin-film panels. Thin-film panels are composed of massive materials such as polymer, glass, or metal that have thin layers of semiconductor material placed on them. There are two main types of thin-film technologies: CdTe (cadmium telluride) and CIGS (copper indium gallium selenide). With a laboratory efficiency of 21.0% for CdTe cells and 23.4% for CIGS cells, the cell efficiency is the greatest in thin-film technology. From 9% to 19%, the efficiency of CdTe modules has recently enhanced (Artaş et al., 2023).

2.2.1. CIGS (Copper-Indium-Gallium-Selenide)

Because of its many advantages, including easier fabrication processes and increased efficiency at the module and cell levels, the CIGS-based solar cell is regarded as one of the most promising thin-film solar cells. Simultaneously, because CIGS solar cells provide the user additional options of flexibility and low weight, they are excellent candidates for use in the manufacturing of thin-film cells. Alkali element post-deposition procedures, particularly those involving heavy alkali elements, have recently had a major impact on raising CIGS cell performance (Bouabdelli et al., 2020).

2.2.2. CdTe (Cadmium Telluride)

Both substrate and top sheet configurations are possible for the CdTe panel, with the top sheet variant being selected for higher than 17% efficiency. In thin-film cells, CdTe is crucial. According to some reports, CIGS panels cost about 30% more than CdTe technology. Thus, thin-film cells based on CdTe can yield a good efficiency/cost ratio (Nykyruy et al., 2019).

3. SOLAR PV PANEL WASTE PROJECTION

The number of waste streams from PV panels will rise as PV is deployed globally. For the years up until 2050 (Weckend et al., 2016).

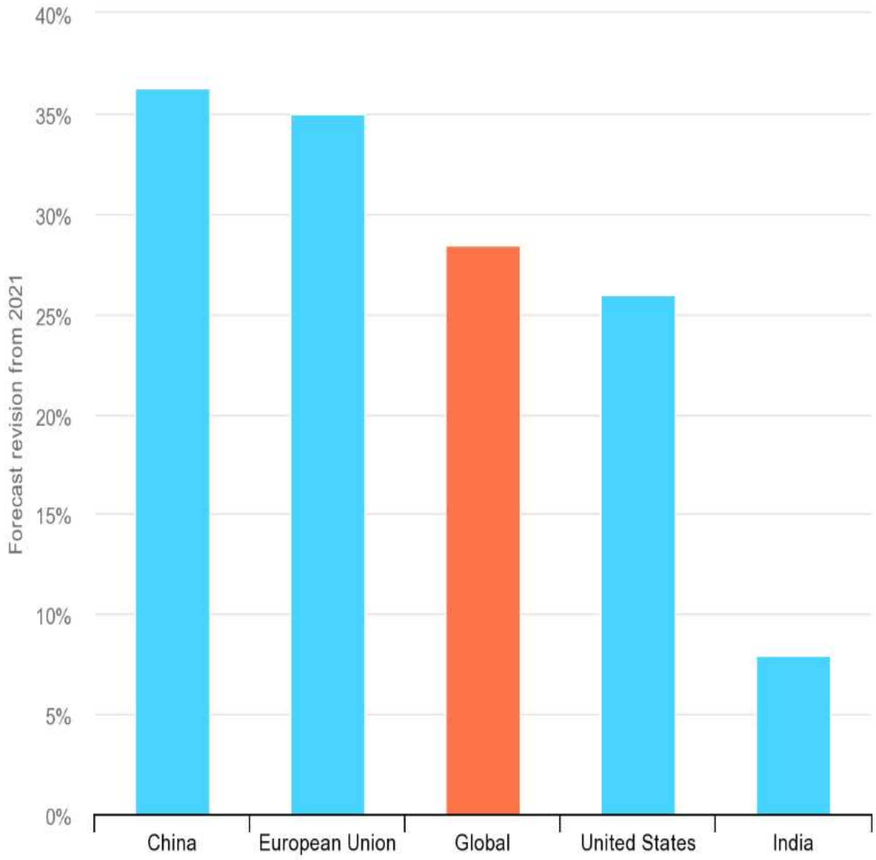

Figure 3

Upward revisions to renewable capacity expansion forecasts from Renewables 2021 to Renewables 2022 (Weckend et al., 2016)

Figure 4 displays the market share of solar panels by technology group. The number of fully connected PV panels is currently rapidly increasing. Given that solar panels typically have a 25-year useful life, rapid expansion is predicted in the upcoming years. Nonetheless, it is anticipated that by 2050, the entire amount of EOL PV panels would be 9.57 million tons. In 2014, silicon-based c-Si panels held a 92% market share, followed by CdTe-based panels at 5% and copper indium gallium (CIGS) at 2%. The remaining 1% of the market was occupied by panels made of other materials, such as dye-sensitized, CPV, and organic hybrids. Between 2014 and 2030, the market share of c-Si PV panels is expected to drop from 92% to 44.8% (Bouabdelli et al., 2020) (Nykyruy et al., 2019). Over the same time span, third-generation PV panels are expected to increase from a base of 1% in 2014 to 44.1% (Chowdhury et al., 2020).

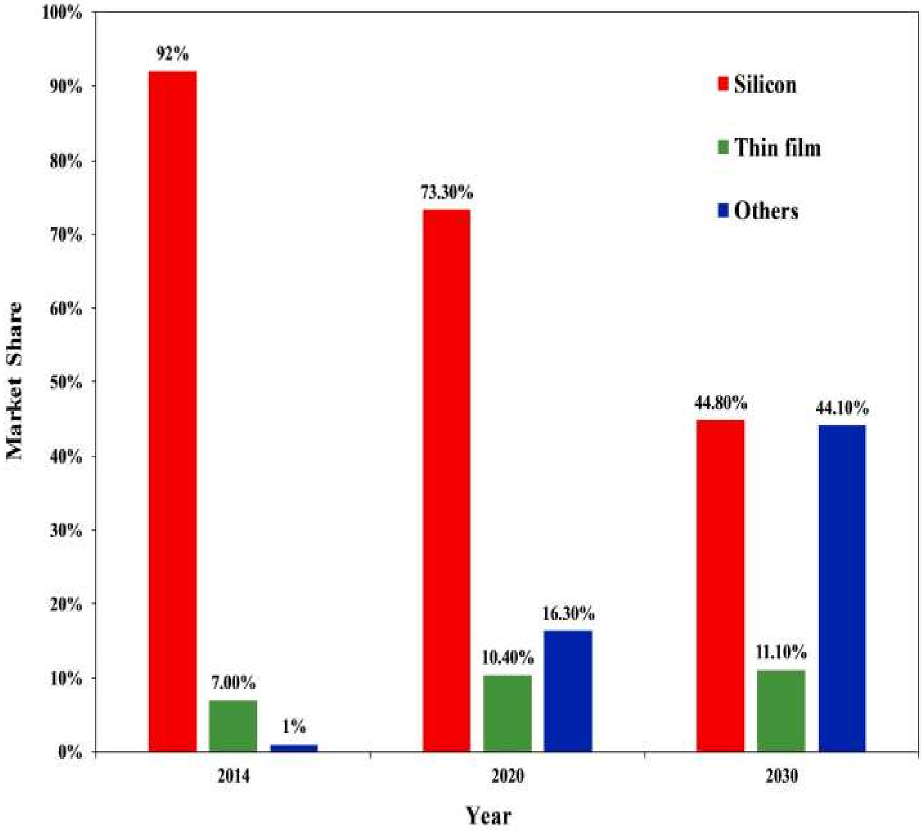

Figure 4
Market share of PV panels by technology type (2014–2030)
(Chowdhury et al., 2020)

According to estimates from the International Renewable Energy Agency (IRENA), there were over 250,000 metric tons of discarded solar panels in the world by the end of 2016 (Huang et al., 2017). Lead (Pb), cadmium (Cd), and numerous other dangerous substances are present in the solar panels and cannot be eliminated even if the panel breaks completely. The Japanese Environment Minister warned in November 2016 that the nation lacked preparations to properly and safely dispose of the 10,000–800,000 tons of solar panel waste produced year in Japan by 2040 (Yi et al., 2014). According to a recent statement, Toshiba Environmental Solutions estimates that it will take roughly 19 years to reprocess all of Japan's huge solar waste that is created by 2020. By 2034, the annual garbage will have increased 70–80 times compared to the year prior to 2020 (Yi et al., 2014). There are now two commercially accessible types of PV recycling technology, although additional technologies are being investigated. Thin film technology employing either CdTe or CIGS technology is the second-largest market segment, followed by panels produced using c-Si technology. Because of their distinct module architectures, the recycling procedures for c-Si PV panels differ from those used for thin film PV panels (Smith & Bogust, 2018). One significant difference is that the goal of removing the encapsulant from the compound photovoltaic modules' layered structure is to retrieve the substrate glass and quilted glass, which house the semiconductor layer. Thus, the goal of recycling c-Si modules is to separate the glass and retrieve the Si cells along with other metals. The process used to recycle Si-based PV panels involves layer separation, which calls for the removal of the panel's encapsulant and the Si cells themselves in order to recover the metals (Kurinec, 2018).

3.1. Causes of solar PV panel failure

New solar panels should have comparatively few problems, with minor erosion (0.5–5%) being the most common; the main causes are subpar design and manufacturing flaws. According to *Figure 5*, there are various reasons for panel failure, including problems with grounding and electrical equipment such charge controllers, junction boxes, fuse boxes, and cabling. Early on in its manufacture, solar panels experienced incoherency from broken solar cells and deterioration of the colorless ethylene vinyl acetate (EVA) anti-reflective coating layer that was added to the glass (Chowdhury et al., 2020).

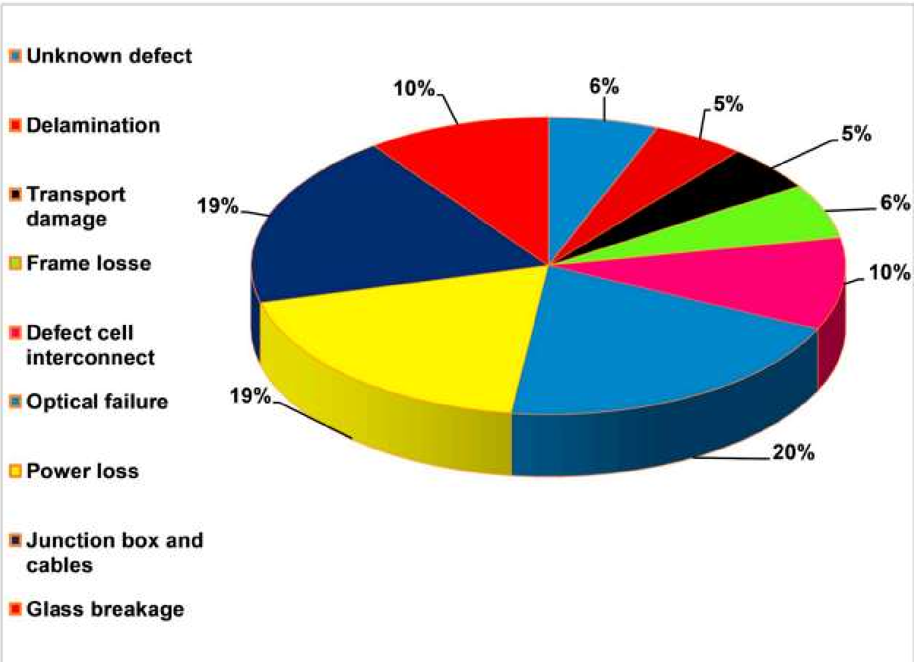

Figure 5
PV panel failure rates according to customer complaints (Chowdhury et al., 2020)

Over the course of the first 12 years of operation, a number of factors contributed to failures, including repeated load cycles brought on by wind, snow, and temperature variations that resulted in degradation, contact defects in junction boxes, glass breakage, burst frames, cell interconnection breaks, and issues with the diodes linked to an increased rate of interconnectors and cell degradations. According to earlier studies, microscopic cracks and failures accounted for 40% of PV panel failures. Since 2008, when thin cell panel production started, this explanation has become the most prevalent in more recent panels (Weckend et al., 2016).

4. COMPARISON OF THE AMOUNT OF CO2 EMISSIONS OCCURRING IN PHOTOVOLTAIC PANEL PRODUCTION AND RECYCLING

Since solar energy produces fewer carbon emissions than other energy production techniques, it is seen as an ecologically beneficial means of producing electricity. However, these techniques not only use energy but also have an impact on the environment, either directly or indirectly. several procedures, such as the procurement and processing of certain materials utilizing chemicals in manufacturing. However, even though adding panels to solar power plants produces energy, doing so damages the environment and releases some CO_2 emissions into the atmosphere. PV technology is receiving a lot of attention, which is causing it to advance gradually and produce many panels with higher performance (Yildiz et al., 2020). The raw materials used and differences in the manufacturing process cause the quantity of CO_2 emissions to vary based on the type of solar panel. By 2050, using more than 8500 GW of solar energy may provide more than 25% of the world's electrical needs and perhaps save significant CO_2 emissions (4.9 Gt CO_2). This illustrates how energy efficiency measures and renewable energy sources may reduce CO_2 emissions by 21% of the total. Up to 2050, photovoltaic technology has the largest potential to reduce CO_2 emissions of all low-carbon options. The primary reason for this is the significant growth of solar energy, which has supplanted conventional power generating methods with the finest technological solutions and sufficient resource availability at better resource areas (Gielen et al., 2019).

Due to advancements in the photovoltaic sector and rising demand, CO_2 emissions from the manufacture of solar panels have nearly quadrupled globally to 51,900 kilotonnes of carbon dioxide in 2021, or around 0.15% of all energy-related emissions worldwide. However, improvements in material and energy efficiency as well as lower emissions from the production of power have offset increases in CO_2 emissions in several nations (Abdelilah et al., 2022). This section looks at the CO_2 emissions produced during the manufacturing and recycling of CdTe and polycrystalline panels, as well as the variations in their amounts. Currently, the study is concentrated on CdTe and polycrystalline panels because CdTe PV technology contains toxic materials like gallium, arsenic, cadmium, lead, and selenium, which pose serious environmental and health risks if not properly managed at the end of their life cycle (European Commission, 2011). Additionally, polycrystalline panels, which include high-value c-Si PV modules, are significant due to the economic impact of materials like silver and aluminum, with silver contributing the most to revenue due to its high market price and aluminum being important because of the large quantity used in frames (Hocine & Samira, 2019).

4.1. Average Amount of CO_2 Emissions in Polycrystalline PV Panel Production

The usage of a certain quantity of energy at each stage of the production of solar panels results in either direct or indirect CO_2 emissions. In the nations that produce PV panels, the quantity of CO_2 emissions emitted during the production of 1 m^2 of polycrystalline PV panels has been estimated roundly. Various CO_2 emission amounts have been observed in each nation during the production of a 1 m^2 polycrystalline panel.

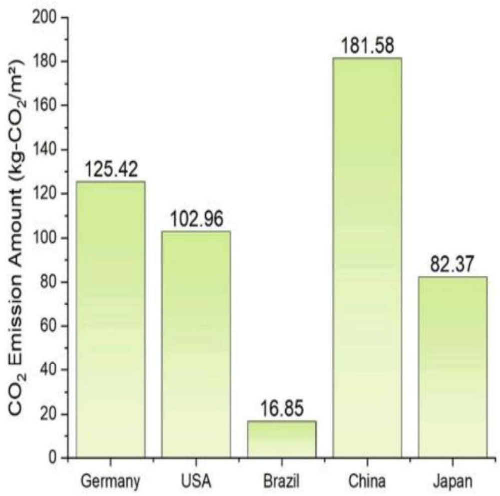

Figure 6

This is the distribution of the average amount of CO2 emissions released to the environment in the production of polycrystalline PV panels by country (Gökhan et al., 2020)

The estimated CO_2 emissions, as shown in *Figure 6*, are as follows: approximately 125 kilogram CO_2 in Germany, approximately 102 kg CO_2 in the USA, approximately 17 kg CO_2 in Brazil, approximately 83 kg CO_2, and approximately 182 kg CO_2 in Japan and China (Yildiz et al., 2020).

4.2. Average CO_2 Emission Amount During Recycling of Polycrystalline PV Panel

PV panels that are recycled contribute significantly to the output of new panels. Due to the fact that many recycled panel methods use fewer raw materials (Müller, 2006). When comparing the recycling process to the normal process, which involves procuring silicon and manufacturing sheets, relatively few raw materials are used.

Lower CO_2 emissions are produced by the recycling process as it requires a lot less energy and raw materials than the conventional method from silicon supply to sheet production (Yue et al., 2014). The recyclable panel serves as the primary source of raw materials for the backsheet's manufacturing. By using this process, 0.888 m^2 of polycrystalline solar panels are produced, assuming that a 1 m^2 polycrystalline panel is recycled. This process consumed 21.1 kWh of energy. Because energy usage generates indirect CO_2 emissions, it varies between nations by 2.20–20.47 kg-CO_2. The countries' CO_2 emission levels are displayed in *Figure 7*. The computation's result indicates that the production of recycled panels and non-recyclable panels results in significantly different CO_2 emissions. These findings demonstrate the significance of recycling.

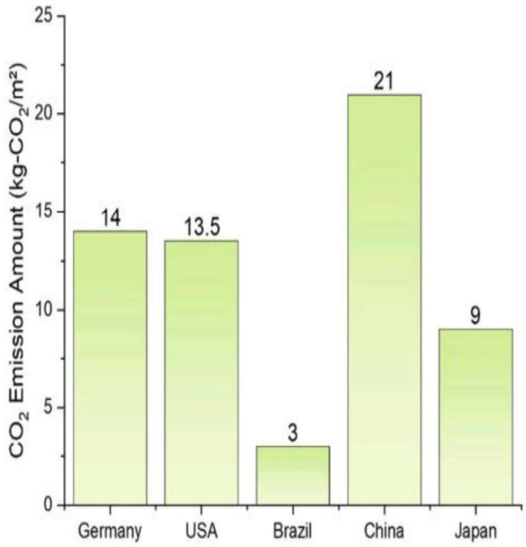

Figure 7

The amount of CO2 emission during the recycling of the polycrystalline panel
(Yildiz et al., 2020)

4.3. Average Amount of CO_2 Emissions in CdTe PV Panel Production

1.25 kWh of electricity are needed for the cadmium purification process in order to produce 1 kilogram of cadmium. Consequently, CO_2 emissions in the range of 0.11–1.21 kg-CO_2 are seen when five nations are compared. The energy required in the semiconductor cadium manufacturing process is 3.86 kWh after purification. Emissions of CO_2 into the atmosphere during this process range from 0.35 to 3.74 kg-CO2. Utilizing 0.0425 kWh of energy, 0.646 kg of semiconductor cadmium and 0.419 kilogram of hydrochloric acid react to make 1 kg of $CdCl_2$. Low CO_2 emissions of around 0.3–41.23 g-CO_2 are produced by this technique. Following this technique results in the production of CdS using 0.004 kWh of energy and insignificant CO_2 emissions for the process within the range of 0.00036−0.00388 g-cCO_2 (Corcelli et al., 2017). A little amount of CO_2 emissions, between 3.87 and 41.71 g-CO_2, are produced during the 0.043 kWh of power consumed in the tellurium procurement process that is necessary for the production of PV panels. CO_2 emissions range from 0.98 to 10.56 kg-CO_2 throughout the process of turning tellurium into semiconductor tellurium. The environmental CO_2 emissions linked to the production of CdTe PV panels are broken out by nation in *Figure 8*. Based on data from five nations, the CO_2 emission quantity of 1 m^2 CdTe PV manufacturing was computed. Various CO_2 emission amounts have been observed in each nation during the manufacture of 1 m^2 CdTe PV panels.

Furthermore, when the production of a 1 m^2 CdTe PV panel is compared to that of a 1 m^2 polycrystalline PV panel, the CdTe PV panel is determined with values that result in lower CO_2 emissions (Yildiz et al., 2020).

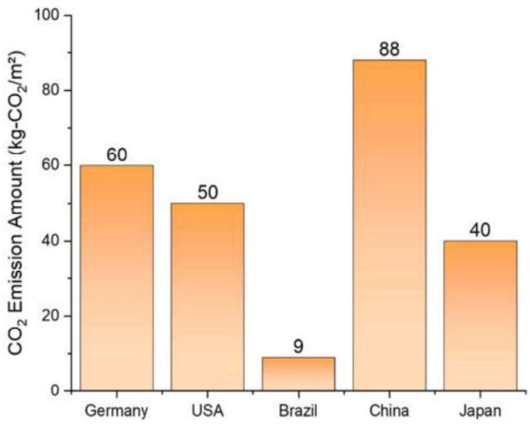

Figure 8
Distribution of the average amount of CO2 emissions released to the environment in CdTe PV panel manufacturing by country (Yildiz et al., 2020)

4.4. Average CO_2 Emission Amount During Recycling of CdTe PV Panel

Roughly 90% of CdTe photovoltaic panels that are recycled are retrieved. This makes the process of fabricating CdTe photovoltaic panels relatively easy and resource efficient. Analyzing the recycling of a 1 m^2 CdTe PV panel reveals that the procedure results in the discharge of 0.0412 kg of CdTe PV panel. In this procedure, 4.4 kWh of energy are consumed, and as a result, indirect CO_2 emissions vary from 0.4 to 4.27 kg-CO_2 (Vellini et al., 2017). The quantity of CO_2 emissions that each nation has released into the atmosphere as a result of recycling CdTe photovoltaic panels is displayed in *Figure 9*. The manufacturing of CdTe PV panels and recycled panels is seen to produce notably different CO_2 emissions and non-recyclable panels. Research has demonstrated that every type of photovoltaic panel provides notable energy savings during production, which in turn leads to substantial reductions in

CO2 emissions through recycling (Yildiz et al., 2020). Despite the fact that cadmium is one of the most toxic substances known to man, a CdTe panel has lower primary energy consumption, an EPBT value, and all other impact potentials because of the recycling process, which guarantees that a significant amount of CdTe semiconductor is supplied to the panel fabrication stage. Panel production is a simpler process than that of silicon panels. The findings demonstrate that although CdTe cells have a poorer energy efficiency than Si cells, they can compensate for this with benefits to the economics, environment, and energy (Vellini et al., 2017).

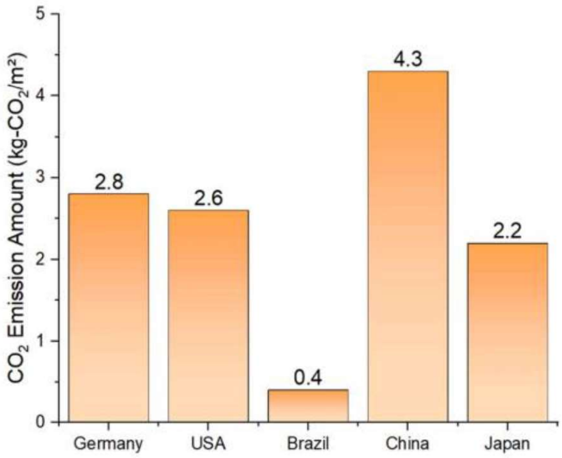

Figure 9
The amount of CO2 emissions during the recycling of CdTe panels
(Yildiz et al., 2020)

5. EXISTING METHODS OF THE RECYCLING PROCESS

5.1. Recycling Techniques of Crystalline Silicon PV Panels

Before the sandwich-sheet-like structure can be removed from crystalline silicon solar panels for recycling, a frame needs to be separated. Since each manufacturer has a different profile, size, and method of fastening, the frame is often disassembled by hand. The delamination of the EVA layer is the next stage in separating the silicon cell and glass. The waste panels enter at this point as a whole, and the EVA glass components are separated once they are separated (Artaş et al., 2023). There are two types of delamination techniques: chemical and thermal. Thermal treatments include fluidized bed heat treatment, pyrolysis, and electro-thermal heating. Chemical techniques include the use of solvent, nitric acid dissolution, ultrasonic irradiation, and solvent dissolution. Methods such as fluidized bed pyrolysis, electro-thermal heating, and nitric acid dissolution combine to yield silicon as one output and metal assemblages and transparent glass as the other. After delamination, glass components, crystalline silicon cells, and metal compounds move on to the material separation stage. Glass and metal compounds are produced as one output, and silicon cell chips are produced as the result of a combination of ultrasonic irradiation, solvent, solvent dissolution, and heat treatment. Chemical etching is the only method available for material separation in c-Si. This process mixes nitric, ethanoic, and hydrofluoric acids in the presence of bromine gas. Glass is helped to separate from silicon cells and metal compounds by this process (Maani et al., 2020).

5.2. Recycling Techniques of Thin Film PV Panels

Modules can be divided by cutting, crushing, or both, as well as by a thermal or solvent-based delamination process. The mechanical methods include hot wire cutting, hammer grinding, laser irradiation, and shredding. A life cycle study of laser irradiation and hot wire cutting cannot be performed at this time because there is no industrial instruction available. The sole thermal method requires heating the panels to 500 °C in a laboratory-scale oven for heat treatment. The procedure of wet and dry mechanical processing (abrasion) is used to separate the EVA from the glass and semiconductor material in thin-film components. Because of the more intricate structure of thin film panels, the delamination process takes a little longer for CdTe PV panels (Isherwood, 2022). However, material separation for thin films is a multi-step process with multiple moving parts. Abrasion is a wet mechanical process that uses friction and shear forces on the surface of the particles to be separated. Thin film fragments decompose into glass, semiconductors, and EVA as they wear. Glass and EVA are sifted during the sieving process used for this product. Substances finer than 150 µm, such as glass, are floated. The product then produces metal compounds, which are eliminated by dry etching or leaching. However, material separation for thin films is a multi-step process with multiple moving parts (Maani et al., 2020).

5.3. Challenges and future outlook

The future of PV solar panel recycling lies in a combination of physical and chemical technologies, as well as the use of light, water, and biodegradable auxiliaries (Palitzsch & Loser, 2018). Design for Recycling (DfR) and Design for Durability (DfD) are crucial in identifying optimal materials and geometries for more efficient recycling (Calì et al., 2022). The resource efficiency of PV recycling processes can be significantly improved, with high-efficiency processes able to recycle up to 83% of the waste panel (Ardente et al., 2019). The widespread adoption of advanced recycling techniques for PV solar panels faces several challenges. These include technological complexities, inadequate infrastructure, and economic hurdles (Gerold & Antrekowitsch, 2024). While proven recycling technologies exist, they need to be made more efficient and less complex, with reduced energy requirements and chemical use. The lack of economic viability and unfavorable policies also hinder the recycling process (Tao & Yu, 2015). The disposal of end-of-life PV modules in landfills or bulk recycling facilities can lead to environmental issues, highlighting the need for high-value closed-loop recycling (Yu et al., 2022). The impending surge in PV waste, combined with inefficient recycling technologies, poses a significant problem (Peplow, 2022). To address these challenges, concerted action is needed to drive the development of efficient and sustainable PV module recycling practices (Gerold & Antrekowitsch, 2024). The importance of reducing recycling costs and environmental impacts, while maximizing material recovery was emphasized by (Heath et al., 2020). This is echoed by (Xu et al., 2018) , who calls for the development of economically feasible and non-toxic recycling technologies. Both authors stress the need for adaptable recycling infrastructure to keep pace with technological advancements. (Tao & Yu, 2015) and (Lunardi et al., 2018) highlight the potential of recycling pathways and processes, but note the challenges in terms of process efficiency, energy requirements, and economic viability. They also emphasize the importance of regulatory frameworks and producer responsibility to support the PV recycling industry. These studies collectively point to the need for further research and development in the areas of cost-effective and environmentally friendly recycling technologies, efficient collection networks, and supportive regulatory frameworks.

6. CONCLUSIONS

In order to the development of photovoltaics to take place, a low production cost will have to be achieved given that there are plenty of cheap common energy sources available. The transition to a low carbon energy paradigm is also an important challenge for the environmental and economic sustainability of the PV supply chain, particularly at the module's end-of-life phase. At the same time, by managing photovoltaic modules at an end of its useful life, it will be possible to make substantial progress towards a Sustainable Solar Industry. It shall also ensure that appropriate waste treatment technologies and recycling and recovery strategies are adopted in relation to the decommissioning of photovoltaic power plants. Due to the growing use of PV panels and their production capacities, waste from these panels is expected to be a key issue within 10 years. This will make it more important than ever that they are recycled. Reprocessing is therefore likely to significantly improve the current situation, when PV modules are able to function for a period of 25–30 years without deterioration. Valuable materials are thrown in the landfill immediately after PV panels are disposed of. Significant profits can be obtained from recovering rare materials like tellurium and indium, precious resources like copper, silver, aluminum, silicon, and glass, and hazardous materials like lead, selenium, and cadmium, depending on their economic viability. The investigation concludes that the world should not become a dumping ground for photovoltaic panels over the next few years. The overview shows that careful planning for recycling will become indispensable as the most popular photovoltaic panels are approaching their end of life in the coming years.

REFERENCES

IEA (2022). *Special Report on Solar PV Global Supply Chains.* Paris, OECD Publishing. https://doi.org/10.1787/9e8b0121-en

Ardente, F., Latunussa, C. E., & Blengini, G. A. (2019, May). Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. *Waste Management*, 91, pp. 156–167. https://doi.org/10.1016/j.wasman.2019.04.059

Artaş, S. B., Kocaman, E., Bilgiç, H. H., Tutumlu, H., Yağlı, H., & Yumrutaş, R. (2023, June). Why PV panels must be recycled at the end of their economic life span? A case study on recycling together with the global situation. *Process Safety and Environmental Protection*, 174, pp. 63–78. https://doi.org/10.1016/j.psep.2023.03.053

Bouabdelli, M. W., Rogti, F., Maache, M., & Rabehi, A. (2020). Performance enhancement of CIGS thin-film solar cell. *Optik*, 216 (March), 164948. https://doi.org/10.1016/j.ijleo.2020.164948

Calì, M., Hajji, B., Nitto, G., & Acri, A. (2022). The Design Value for Recycling End-of-Life Photovoltaic Panels. *Applied Sciences*, 12 (18), 9092, https://doi.org/10.3390/app12189092

Chen, H., Chang, L., Jeng, M., & Lai, C. (2011). Solid-State Electronics Characterization of laser carved micro channel polycrystalline silicon solar cell. *Solid State Electronics*, 61 (1), pp. 23–28. https://doi.org/10.1016/j.sse.2011.02.005

Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews*, 27, 100431. https://doi.org/10.1016/j.esr.2019.100431

Corcelli, F., Ripa, M., & Ulgiati, S. (2017). End-of-life treatment of crystalline silicon photovoltaic panels. An emergy-based case study. *Journal of Cleaner Production*, Vol. 161, pp. 1129–1142, https://doi.org/10.1016/j.jclepro.2017.05.031

D'Adamo, I., Miliacca, M., & Rosa, P. (2017). Economic Feasibility for Recycling of Waste Crystalline Silicon Photovoltaic Modules. *International Journal of Photoenergy*, Vol. 2017, Article ID 4184676, p. 6. https://doi.org/10.1155/2017/4184676

El-Fayome, E., Abdelhamed, M. A., El-Shazly, A., Abouelatta, M., & Zekry, A. (2023). End Of Life Management Of Solar Panels. *40th National Radio Science Conference (NRSC)*, Giza, Egypt, 2023, pp. 286–293, https://doi.org/10.1109/NRSC58893.2023.10152958

European Commission (2011). *Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE directive.* Paris, France, Bio Intelligence Service, 86 p.

Hocine, L., & Samira, K. M. (2019). Optimal PV panel's end-life assessment based on the supervision of their own aging evolution and waste management forecasting. *Solar Energy*, 191, pp. 227–234. https://doi.org/10.1016/j.solener.2019.08.058

Kurinec, S. K. (ed.) (2018, December 3). *Emerging Photovoltaic Materials: Silicon & Beyond.* Beverly, Massachusetts, USA, Scrivener Publishing LLC, https://doi.org/10.1002/9781119407690

Fernandes, C. A. F., Torres, J. P. N., Morgado, M., & Morgado, J. A. (2016, September). Aging of solar PV plants and mitigation of their consequences. *2016 IEEE International Power Electronics and Motion Control Conference (PEMC)*, Varna, Bulgaria, pp. 1240–1247, https://doi.org/10.1109/epepemc.2016.7752174

Gielen, Dolf, Gorini, Ricardo, Asmelash, Elisa, Prakash, Gayathri, Leme, Rodrigo, (2019). *Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects.* A Global Energy Transformation: paper. Abu Dhabi, International Renewable Energy Agency.

Gerold, E., & Antrekowitsch, H. (2024). Advancements and Challenges in Photovoltaic Cell Recycling: A Comprehensive Review. *Sustainability*, 16 (6), 2542. https://doi.org/10.3390/su16062542

Gökhan, Y., Etem, A., & Ceylan, İ. (2020). Investigation of life cycle CO_2 emissions of the polycrystalline and cadmium telluride PV panels. *Environmental Nanotechnology , Monitoring & Management*, Vol. 14 (June), 100343. https://doi.org/10.1016/j.enmm.2020.100343

Heath, G. A., Silverman, T. J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., & Wade, A. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. *Nature Energy*, 5 (7), pp. 502–510. https://doi.org/10.1038/s41560-020-0645-2

Huang, W. H., Shin, W. J., Wang, L., Sun, W. C., & Tao, M. (2017). Strategy and technology to recycle wafer-silicon solar modules. *Solar Energy*, 144, pp. 22–31. https://doi.org/10.1016/j.solener.2017.01.001

Isherwood, P. J. M. (2022). Reshaping the Module: The Path to Comprehensive Photovoltaic Panel Recycling. *Sustainability*, 14 (3), 1676, https://doi.org/10.3390/su14031676

Krebs, L., & Frischknecht, R. (2022). *Resource Use Footprints of Residential PV Systems*. IEA PVPS Task 12, International Energy Agency (IEA) PVPS Task 12, Report T12-22:2022. www.iea-pvps.org

Lunardi, M. M., Alvarez-Gaitan, J. P., Bilbao, J. I., & Corkish, R. (2018). A Review of Recycling Processes for Photovoltaic Modules. In: *Solar Panels and Photovoltaic Materials.* InTech, https://doi.org/10.5772/intechopen.74390

Maani, T., Celik, I., Heben, M. J., Ellingson, R. J., & Apul, D. (2020). Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels. *Science of the Total Environment*, 735, 138827. https://doi.org/10.1016/j.scitotenv.2020.138827

Müller, A., Wambach, K., & Alsema, E. (2006). Life Cycle Analysis of Solar Module Recycling Process. *MRS Proceedings*, 895. https://doi.org/10.1557/proc-0895-g03-07

Mahmoudi, S., Huda, N., Alavi, Z., Islam, T., & Behnia, M. (2019). Resources , Conservation & Recycling End-of-life photovoltaic modules: A systematic quantitative literature review. *Resources, Conservation & Recycling*, 146 (October 2018), pp. 1–16. https://doi.org/10.1016/j.resconrec.2019.03.018

Nykyruy, L. I., Yavorskyi, R. S., Zapukhlyak, Z. R., Wisz, G., & Potera, P. (2019). Evaluation of CdS/CdTe thin film solar cells: SCAPS thickness simulation and analysis of optical properties. *Optical Materials*, 92 (April), pp. 319–329. https://doi.org/10.1016/j.optmat.2019.04.029

Paiano, A. (2015). Photovoltaic waste assessment in Italy. *Renewable and Sustainable Energy Reviews*, 41, pp. 99–112. https://doi.org/10.1016/j.rser.2014.07.208

Palitzsch, W., & Loser, U. (2018). Integrated PV-Recycling-More Efficient, More Effective. *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, pp. 2272–2274, Washington D.C., USA, https://doi.org/10.1109/pvsc.2017.8521517

Peplow, M. (2022). Solar Panels Face Recycling Challenge. *ACS Central Science*, 8 (3), pp. 299–302. https://doi.org/10.1021/acscentsci.2c00214

Shin, J., Park, J., & Park, N. (2017). A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers. *Solar Energy Materials and Solar Cells*, 162 (September 2016), pp. 1–6. https://doi.org/10.1016/j.solmat.2016.12.038

Smith, Y. R., & Bogust, P. (2018). Review of Solar Silicon Recycling. In: Sun, Z. et al.: *Energy Technology 2018.* TMS 2018. The Minerals, Metals & Materials Series. Cham, Springer, pp. 463–470. https://doi.org/10.1007/978-3-319-72362-4_42

Tao, J., & Yu, S. (2015). Review on feasible recycling pathways and technologies of solar photovoltaic modules. *Solar Energy Materials and Solar Cells*, 141, pp. 108–124. https://doi.org/10.1016/j.solmat.2015.05.005

Vellini, M., Gambini, M., & Prattella, V. (2017). Environmental impacts of pv technology throughout the life cycle: Importance of the end-of-life management for si-panels and cdte-panels. *Energy*, Vol. 138, pp. 1099–1111, https://doi.org/10.1016/j.energy.2017.07.031

Weckend, S., Wade, A., and Heath, G. A. (2016). *End of Life Management: Solar Photovoltaic Panels.* United States: N. p. Web. https://doi.org/10.2172/1561525.

Xu, Y., Li, J., Tan, Q., Peters, A. L., & Yang, C. (2018). Global status of recycling waste solar panels: A review. *Waste Management*, 75, pp. 450–458. https://doi.org/10.1016/j.wasman.2018.01.036

Yıldız, G., Çalış, B., Gürel, A. E., & Ceylan, L. (2020). Investigation of life cycle CO_2 emissions of the polycrystalline and cadmium telluride PV panels. *Environmental Nanotechnology, Monitoring & Management*, 14, 100343. https://doi.org/10.1016/j.enmm.2020.100343

Yi, Y. K., Kim, H. S., Tran, T., Hong, S. K., & Kim, M. J. (2014). Recovering valuable metals from recycled photovoltaic modules. *Journal of the Air & Waste Management Association*, 64 (7), pp. 797–807. https://doi.org/10.1080/10962247.2014.891540

Yue, D., You, F., & Darling, S. B. (2014). Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy*, 105, pp. 669–678. https://doi.org/10.1016/j.solener.2014.04.008

Yu, H. F., Hasanuzzaman, M., Rahim, N. A., Amin, N., & Nor Adzman, N. (2022). Global Challenges and Prospects of Photovoltaic Materials Disposal and Recycling: A Comprehensive Review. *Sustainability*, 14 (14), 8567, https://doi.org/10.3390/su14148567