



TeraCale: Integrated laser irradiation and chemical etching with IoT automatization as a solution for sustainable crystalline-silicone photovoltaic panel waste recycling system

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ABSTRACT

Background: The rapid expansion of global renewable energy capacity resulted in a significant increase in crystalline-silicon (c-Si) photovoltaic (PV) panel installations, which are projected to generate up to 78 million tonnes of end-of-life (EoL) waste by 2050. Existing recycling methods, including pyrolysis, mechanical shredding, and organic solvent dissolution, are often associated with high energy demands, toxic emissions, and the risk of damaging valuable solar cells. This study aims to present TeraCale, an innovative recycling system that integrates laser irradiation and chemical etching with Internet of Things (IoT) automation to deliver a sustainable and economically viable solution for c-Si panel waste. **Methods:** This study is formulating the idea of innovation by collecting and analyzing the data from various journals. The methodology comprises a three-stage treatment process, such as initial hydraulic dismantling of frames using Programmable Logic Controllers (PLC) for real-time monitoring; subsequent separation of ethylene vinyl acetate (EVA) and glass layers using nanosecond and pulsed optical fiber lasers; and chemical etching with NaOH, HNO₃, and H₃PO₄ to recover high-purity metals. **Findings:** The study indicates that this integrated approach can achieve a silicon yield of 99.9984% and generate a total recycling profit of approximately 185.43 USD per kilogram of solar cells. The results demonstrate that automating the separation process significantly reduces manual labor and environmental risks while maximizing material recovery value. **Conclusion:** TeraCale constitutes a critical advancement in circular economy practices for the solar industry, effectively supporting Sustainable Development Goals 7 and 12. **Novelty/Originality of this article:** The novelty of this work is demonstrated by the unique combination of selective laser debonding and IoT-driven automation, providing a high-precision alternative to conventional destructive recycling techniques.

KEYWORDS: chemical etching; laser irradiation; PV panel; recycle.

1. Introduction

Based on data from the IPCC (2023), global greenhouse gas (GHG) emissions in 2030 are projected to cause severe global warming, exceeding 1.5°C during the 21st century and will further complicate efforts to limit warming below 2°C if no subsequent action is taken. A global temperature increase of up to 1.5°C is expected to cause more intense flooding and

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rainfall, while an increase of 2°C or more could cause significant agricultural and ecological droughts (IPCC, 2023). Global warming is inextricably linked to the impact of human activities, particularly those that produce GHG emissions in the form of CO₂ and methane. If left unchecked, global warming will continue and increase significantly. Therefore, reducing greenhouse gas emissions to achieve net zero emissions is a matter of high urgency. The transition to renewable energy presents a key solution to reducing these emissions. Supported by public awareness of the increasingly threatening climate crisis, the use of renewable energy has continued to increase on a global scale over the past few decades. According to the Renewable Capacity Statistics 2025 report from the International Renewable Energy Agency (IRENA), global renewable energy capacity has nearly quadrupled since 2015 and will meet 46% of global energy demand by 2024. This phenomenal growth encompasses various types of renewable energy, including solar, wind, hydro, and bioenergy.

One form of renewable energy that has proven to be considerably significant in reducing carbon emissions is solar energy. One gigawatt of installed photovoltaic (PV) solar panel capacity can reduce about 1.5 million tonnes of carbon dioxide (Mt CO₂) per year from coal-fired power plants (IEA, 2020a). Photovoltaic (PV) technology is a technology that converts solar energy into electrical energy using solar cells. Global installed solar power capacity was initially only around 40 GW in 2010. This figure has increased more than 45-fold in 2024 to more than 1.8 TW (IRENA, 2025). In addition to being driven by increased awareness of the need for clean energy sources, lower costs have also made solar energy more competitive compared to conventional electricity sources. Policy support and incentives also play an important role in driving the growth of the solar power industry. Many countries, including Vietnam, China, and European Union countries, have implemented feed-in tariffs, net metering programmes, or other supportive measures to encourage the installation of PV systems (Hassan et al., 2024). By 2050, solar technology is projected to have an installed capacity of 4.5 TW and be capable of meeting (Ali et al., 2024a). The massive use of solar technology simultaneously increases with the amount of waste the industry produces. Thus, the projected waste from solar panels are predicted to reach 8 million tonnes by 2030 and 78 million tonnes by 2050 (IRENA & IEA-PVPS, 2016).

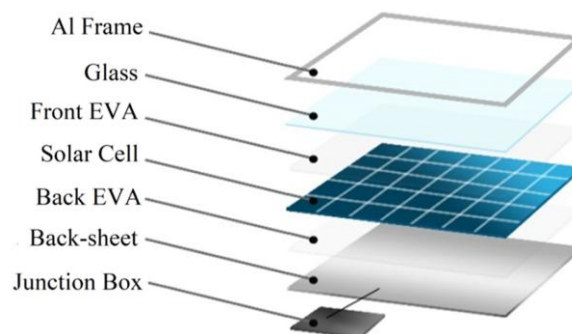


Fig. 1. Arrangement of crystalline silicon (c-Si) PV panels (Li et al., 2022)

The PV panels currently in use fall into two general categories: crystalline silicon (c-Si) panels and thin-film panels. c-Si panels are more commonly used because they have medium to high efficiency, so they are often applied to residential or commercial roofs. On the other hand, thin-film panels produce low efficiency but have lower production costs than c-Si, so they are rarely used on a large scale. Among the many types of PV panels currently available, monocrystalline (mono-Si) panels are the most widely installed due to their high efficiency (17%-22%) and long service life, which exceeds 25 years with proper maintenance (Kumari et al., 2022). The second most widely used type of PV panel is the polycrystalline (poly-Si) panel because it is more affordable with slightly lower efficiency (around 13-16%) than monocrystalline (Sugianto, 2020). Poly-Si panels are widely used in large-scale projects, such as solar farms, which consider cost per watt as a primary factor.

Although the production costs of both panels are relatively high, their high efficiency has enabled them to dominate the market. These mono-Si and poly-Si panels fall under the category of c-Si panels. c-Si panels are composed of several layers, namely an aluminium frame, a glass layer, a front Ethylene Vinyl Acetate (EVA) layer, solar cells, a back EVA layer, a back sheet, and a junction box where the cables are connected (Figure 1).

When the service life of PV panels has expired, various components within them can cause environmental problems if not handled properly. The EVA contained in PV panels is a thermoplastic polymer that is difficult to degrade and can cause the release of hazardous compounds if left untreated. Not only that, the back sheet in PV panels is also made of plastic that is difficult to recycle and fluorinated, so it has the potential to release corrosive gases, such as CO, CO₂, and COF₂, when burned (Wahman et al., 2023). In addition, hazardous metals, such as cadmium, lead, and various other types of polymers contained in PV panels can also have adverse effects on the environment and human health (due to their carcinogenic properties), especially on the respiratory system (Mayer et al., 2021).

Furthermore, with the 25-30 year estimated lifespan of PV modules, the adoption of PV panels as a sustainable energy source also raises new concerns, especially with the end-of-life (EoL) issue of PV panels. As installation capacity increases, the number of PV panels produced will also increase, as will the amount of EoL PV panel waste. If not handled properly, it is predicted that PV panel waste could accumulate to 78 million tonnes by 2050 (Figure 2) and potentially cause significant environmental impacts (Kwok et al., 2024). In addition, the disposal of PV panels in landfills also releases a number of toxic compounds that have a high chance to cause air and soil pollution. Therefore, an appropriate solution is needed to resolve the issue of PV panel waste.

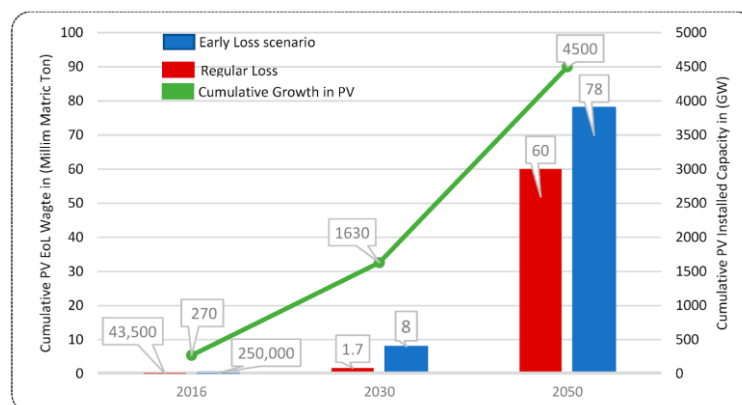


Fig. 2. Projected PV panel EoL waste generation between 2016 and 2050 (Ali et al., 2024b)

This long-standing issue has also become a task for researchers to find a solution. Various PV panel waste recycling methods have been developed previously to solve the EoL PV panel problem. However, these solutions also cause other problems, such as: Pyrolysis is a method of recycling end-of-life PV panel waste by heating the material in the absence of oxygen. Pyrolysis aims to break down organic components such as the front protective glass, release silicon-based solar cells, EVA adhesive layers, and junction boxes into simpler molecules such as gases, liquids, and solids. However, this pyrolysis method faces obstacles as it creates new problems because it requires a large amount of energy for processing. In addition, recycling PV panels using this method also produces harmful gas emissions and has the potential to degrade solar cells, thereby reducing their quality (Li et al., 2022).

The mechanical processing method involves several stages, namely shredding, high-voltage pulse, and milling. The shredding process is a mechanical process that aims to crush PV panels into smaller pieces using a shredder. Next, the high-voltage pulse process uses high-voltage electrical pulses to break down the layers of material in PV panels. Finally, milling is a further refinement process of the shredding results to release fine materials contained in glass or resin. Although it appears mechanical and has a fairly complex method,

this process also has shortcomings in the form of an imperfect separation process, the risk of metal emissions spreading into the atmosphere, and the potential for damage to solar cells (Tembo et al., 2021). In addition, the use of electrochemical technology in metal recovery is also considered ineffective due to the slow recovery process and difficulty in applying it on a large scale (Modrzynski et al., 2021). The organic solvent method in the PVA panel recycling process is a method that uses chemical solvents as the main ingredient to recycle PV panels containing complex organic compounds, such as resins and polymers. This method also has disadvantages, particularly in the dissolution of EVA, which produces large amounts of mixed organic waste with high toxicity. Furthermore, organic solvents integrated with ultrasound can cause the formation of toxic vapour compounds (Huang et al., 2023).

Reviewing the ineffectiveness of previous PV panel processing solutions, a more efficient and sustainable PV panel waste recycling method is urgently needed. To that end, the author offers a solution called TeraCale: Integrated Laser Irradiation and Chemical Etching with IoT Automatisasi as a Sustainable Crystalline-Silicon Photovoltaic Panel Waste Recycling System Solution. TeraCale integrates laser irradiation and chemical etching technologies to handle PV panel waste comprehensively, from component separation to the recovery of valuable metals in solar cells. The use of the Internet of Things (IoT) aims to optimize the laser irradiation separation process, increase work process efficiency through automation, and reduce human labour involvement, thereby creating a sustainable and economical PV panel recycling solution. Considering the potential for massive volumes of panel waste in the future, TeraCale focuses on the recovery of c-Si panels due to their high market dominance, making TeraCale's innovation highly relevant to the industry today. TeraCale's innovation is expected to support the realisation of Sustainable Development Goal (SDG) 12, Responsible Consumption and Production, by 2050.

2. Methods

2.1 Primary treatment

The PV panel recycling process by TeraCale consists of three stages, namely primary treatment, secondary treatment, and tertiary treatment, which can be visualised as a flowchart in Figure 3. Primary treatment includes separating the aluminium frame and junction box from the PV panel. This stage is carried out with the help of automation from the Frame Removal Machine, which is integrated with the Internet of Things (IoT) feature as part of the innovation. The separation of the aluminium frame will use a system based on the principle of hydraulic dismantling with the application of Pascal's law, where high-pressure fluid flow will drive a mechanical system that presses the aluminium frame to detach it from the panel. The hydraulic fluid system has several advantages, such as greater precision in the release process, the ability to control fluid pressure, and minimal vibration, thereby minimising damage to the frame and junction box.

Furthermore, the Internet of Things (IoT) will play a role in facilitating the operation of machines in industrial and sustainable processes. There are several microcontrollers that can be used, such as ESP32, Arduino, or PLC in IoT applications. However, PLC (Programmable Logic Controller) is used as a sensor reader for several reasons, such as being more flexible for all types of machines, easy to repair and modify, having many relay contacts, being inexpensive, and being able to perform test programmes (Yuhendri, 2018). PLCs are also often used in large-scale industries with long and heavy workloads, as they are designed to operate 24/7. PLCs also use SCADA (Supervisory Control and Data Acquisition) in the data logging and monitoring process, allowing users to monitor machines remotely in real time. In terms of cyber security, PLCs are also more protected because they are equipped with built-in protection features, which include automatic threat detection and prevention, data security, and basic security settings. The MPX5700 pressure sensor can be used to measure the fluid pressure in the system, allowing operators to determine and adjust the required pressure. The GHT22 temperature sensor is used to

monitor hydraulic temperature. The higher the temperature, the greater the pressure that will be released. Furthermore, there are relays, MOFFSETs, and solid state relays that can be used to control the pump and solenoid valves that regulate the fluid flow rate. Finally, the dashboard displayed will contain all the sensor features and information contained in the machine, so that it can be monitored by the operator.

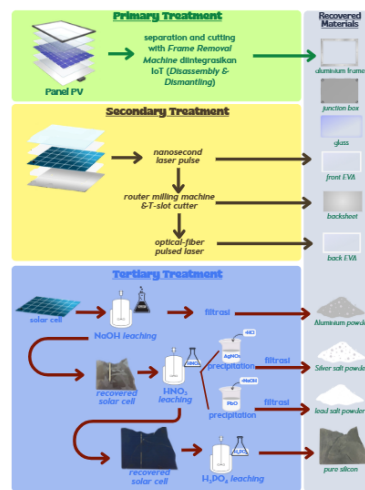


Fig. 3. Stages of PV panel recycling process

The implementation of the Internet of Things will result in the following scheme or steps: first, the PLC will activate the pump and solenoid valve that will regulate fluid pressure. Next, the MPX5700 pressure sensor will work to read the fluid pressure until it reaches the correct level, while the GHT22 temperature sensor will monitor the hydraulic temperature. Afterwards, the actuator will push the Frame Removal Machine separator, which will lift the aluminium frame until it is finally separated from the junction box. When the separation process is complete, the pump will automatically shut down.

2.2 Secondary treatment

After separating the aluminium frame and junction box, TeraCale will enter the secondary treatment stage, which consists of separating the front EVA, backsheet, and back EVA. First, the separation of the glass and front EVA from the solar cell is carried out using the laser irradiation method, specifically with a Q-switched Nd:YAG laser capable of emitting nanosecond pulses with a pulse width of 5 ns at a repetition rate of 10 Hz. This method utilises a nanosecond laser to induce selective transient melting at the EVA-solar cell interface. The energy from the laser is directly absorbed by the silicon solar cell, specifically at the rear aluminium (Al) and silver (Ag) electrodes. This absorption, combined with a very short pulse duration (5 ns), enables rapid and precise temperature increases, allowing the glass and EVA layers to be removed cleanly without leaving any residue on the solar cell surface (Anwar et al., 2024). From an environmental and economic perspective, this nanosecond laser pulse-based method can significantly reduce the risk of pollution while avoiding the harmful emissions often produced by recycling methods involving leaching or pyrolysis, thereby supporting sustainable development and the circular economy concept.

In this method, there are several parameters that need to be considered to achieve optimal melting and avoid component damage, including pulse fluence (laser pulse energy per area), wavelength, and scanning speed. Based on experiments conducted by Anwar et al. (2024), shorter wavelengths require lower pulse fluence for effective separation. Therefore, this process can utilize the MPX5700 pressure sensor system integrated with a network according to the wavelength. Wi-Fi wireless technology will be used as the network due to its high data speed, compatibility with many devices, and suitability for industrial

functions in real-time applications in factories and machine monitoring with large bandwidth.

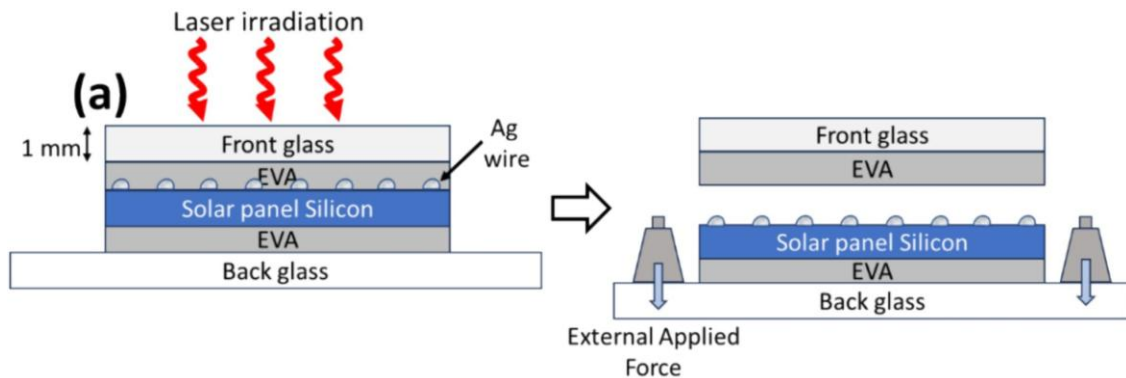


Fig. 4. Separation process of front glass and front EVA with nanosecond laser (Anwar et al., 2024)

Next, the remaining PV panels that have been separated from the front EVA will be turned over to enter the back sheet separation stage. Based on research conducted by Wahman et al., (2023), PV panels are placed on a flat surface. Then, the back sheet is separated using a 1200w router milling machine with a T-slot cutter set according to the thickness of the back sheet for mechanical peeling. This machine is equipped with a hose connected directly to a vacuum device so that the peeled material can be collected directly during the process. This method produces back sheet material with high purity (96.58%).

After removing the back sheet, the final step of secondary treatment is to separate the back EVA from the solar cell. This separation is carried out using laser irradiation, but with a 1064 nm pulsed optical fibre laser. This type of laser is capable of penetrating the back EVA, and, similar to a nanosecond laser, irradiates the EVA-solar cell interface. The aluminium (Al) and silver (Ag) electrodes on the back of the solar cell absorb the laser energy and induce a temperature increase across the interface, thereby weakening the adhesive strength of the back EVA. After that, the EVA can be peeled off mechanically using a machine equipped with a pressure sensor. With the sensor, the machine can detect the pressure of the EVA to be peeled off. The sensor will pull the EVA layer with a certain amount of pressure. With optical fibre lasers, the laser temperature can be controlled via temperature sensors with IoT on the machine. The parameters used in this IoT include the precise temperature used to detect and regulate the laser heat used in order to achieve the optimal temperature and an effective process.

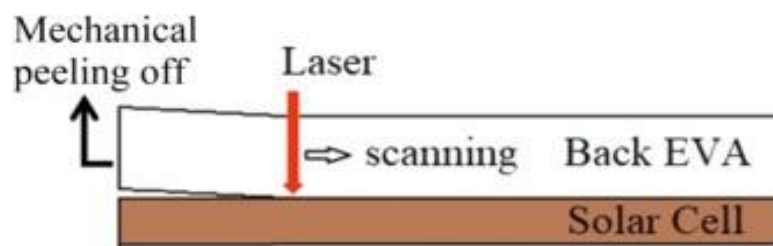


Fig. 5. Separation process of back EVA with optical-pulsed fibre laser (Li et al., 2022)

2.3 Tertiary treatment

PV panels that have undergone primary and secondary treatment will undergo tertiary treatment to recover valuable metals from previously processed solar cells. To improve the efficiency of the chemical etching process, an additional process is required to cut the solar cells into smaller pieces. This process is carried out by a solar cell cutting machine using a

156-230 solar cell laser scribing machine that can cut into various sizes ($\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{5}$, $\frac{1}{6}$, $\frac{1}{8}$). With a capacity of 2000 pcs/hour, power and air of 220V/50-60 Hz 0.6 MPa, and Full Auto working mode. Solar cells generally consist of three layers, namely the top, middle, and bottom layers. On the top layer, there is an antireflecting coating (Si₃N₄) with 1.56% silver electrodes and 0.04% lead. The middle layer consists of 91.59% silicon, while the bottom layer consists of 6.81% aluminium (Punathil et al., 2021).

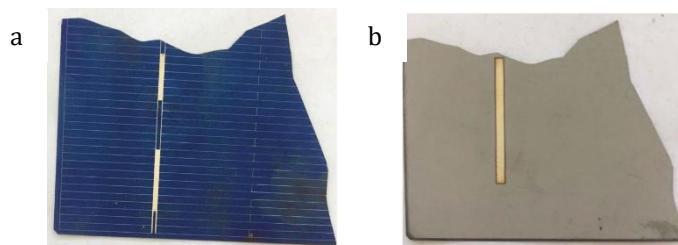
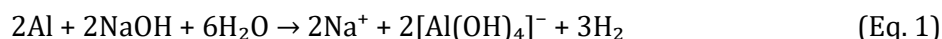
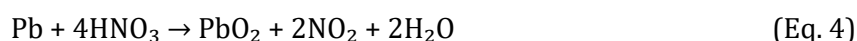
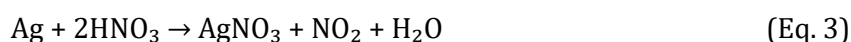


Fig. 6. Top layer (a) Blue antireflective coating and white silver electrode and bottom layer of the solar cell; (b) Aluminium layer (Punathil et al., 2021)

Punathil et al. (2021) conducted research related to the recovery of silicon and valuable metals from chemical etching-based solar cell waste using the main chemical solvents NaOH, HNO₃, and H₃PO₄. The aluminium layer was dissolved in NaOH, the silver and lead electrodes in HNO₃, and the antireflecting coating in H₃PO₄. H₃PO₄ was chosen to replace the toxic and corrosive HF solvent, while NaOH was preferred over KOH because it is more economical. The process began with the separation of the aluminium layer from the solar cell by treating the solar cell in 20 mL of 10 M NaOH solution for 5 minutes at 63°C. This reaction produces aluminium hydroxide (Al(OH)₃). The aluminium hydroxide is then separated from the leachate through filtration. The by-product hydrogen from reaction (Eq. 1) can be utilised as fuel.



Next, the silver and lead electrodes are separated from the solar cell by processing them in 20 mL of 6 M HNO₃ solution for 5 minutes at 70 °C. Reaction (Eq. 2) produces silver nitrate (AgNO₃), which is then precipitated with HCl in reaction (Eq. 3) to form silver chloride (AgCl). The silver chloride recovery process is carried out by filtration. The lead oxide (PbO) compound obtained from reaction (Eq. 4) can be precipitated with NaOH to separate the lead compound from the leachate and produce lead hydroxide (Pb(OH)₂). However, the precipitation of lead compounds was not carried out in this experiment due to the very low yield. The NO₂ compound can be utilised for the production of nitric acid.



Finally, the solar cells that have been separated from the metal layer will undergo a leaching process with H₃PO₄ to separate the antireflecting coating and p-n junction so that a pure silicon layer can be obtained, with a silicon yield of 99.9984% through ICP-MS analysis (Punathil et al., 2021). The remaining leachate that has been used will then be further treated in wastewater treatment before being disposed of. The recovered products, including pure silicon and various valuable metals (Ag, Al, Pb), will be distributed to the solar panel manufacturing industry as material supplies for producing new solar panels. To

optimise the work process, estimates of the appropriate treatment conditions are also made in accordance with the amount of solar cell feedstock using automation accompanied by several features. Weight sensors or RFID (Radio Frequency Identification) can track the amount of stock and the position of solar cells, and cameras equipped with CV (Computer Vision) can be visual sensors that can monitor the condition of solar cells in the room. Environmental conditions, such as temperature and humidity, can be controlled by the GHT22 sensor. The duration of solar cell storage can also be determined using the Timestamp in the IoT Gateway. The INA219 Voltage Sensor also plays a role in monitoring the quality of electricity in the cells. This is also done to estimate treatment conditions when scaling up to an industrial scale.

3. Results and Discussion

After het through some process of recycling, the metals obtained from recycling chemical etching are listed in the following table. The table shows that three types of metals obtained during the process and have prices that can be profit in the process of recycling. (Punathil et al., 2021).

Table 1. Metals recovered from chemical etching

Recovered metal	Recovered metal mass (kg)	Metal price (USD/kg)	Profit (USD/kg solar cell)
Si	0.9158	2	6.4106
Al(OH) ₃	0.1946	1.21	0.2355144
AgCl	0.02064	12000	247.68

(Punathil et al., 2021)

The recovered metal masses demonstrate that even from just 1 kg of end-of-life solar cells, valuable materials can be extracted with high economic potential. However, these gross revenues must be weighed against the operational costs of the chemical etching process to determine true economic viability. To evaluate this, we adopt the recycling cost (RC) benchmark of 68.9 USD/kg of solar cells as reported by Punathil et al. (2021), which includes chemical reagents, energy consumption, and waste treatment. According to Punathil et al. (2021), the recycling cost (RC) of solar cells is 68.9 USD/kg of solar cells. Thus, the total recycling profit for 1 kg of solar cells can be calculated as follows.

$$\begin{aligned}
 P_T &= P_{Si} + P_{Al} + P_{Ag} - RC \\
 &= (6.4106 + 0.2355144 + 247.680 - 68.9) \text{ USD/kg} \\
 &= 185.4261 \text{ USD/kg of solar cells}
 \end{aligned}
 \tag{Eq. 6}$$

The overall calculation of the PV panel recycling process has been projected previously by other studies. Assuming that improved recycling processes can recover 85% (by weight) of solar-grade silicon, silver, aluminium, glass and copper with high purity for reuse in the PV industry, revenues of more than USD 15-16 per module could be achieved at 2021 market prices, with silicon and silver contributing the majority. This could enable the development of a profitable c-Si module recycling business without additional financial support (Huang et al., 2017). The potential application of TeraCale on an industrial scale could be a comprehensive solution to address the issue of PV panel waste processing, which has yet to be properly handled. There are several internal and external aspects in the process of creating this innovation, which are presented in the form of a SWOT analysis.

For the first analysis, Strength, TeraCale can overcome the limitations of existing methods and reduce manual labour by human resources. With the chemical etching process, TeraCale also enables the recovery of high-purity materials and increases the economic value of waste. In addition, this innovation can also reduce environmental impacts such as the risk of forming hazardous emissions. There are also several weaknesses, such as the need for substantial initial capital investment and specialised expertise to implement it, as

well as the chemical etching process, which still requires careful management of liquid waste. There are opportunities to be found in the expected increase in the volume of PV panel waste in the future, which could create a huge market for recycling solutions, innovations that apply the principles of the circular economy that are increasingly emphasised globally, and the ability to recover high-value materials, thereby creating significant economic opportunities through the sale of recycled raw materials. Finally, there are threats in the form of competition from existing recycling methods or new technologies that may emerge in the future, changes in regulations and PV waste management standards that may affect the economic feasibility of innovation, and instability in the market price of recovered materials, which may affect the profitability of the recycling process.



Fig. 7. TeraCale SWOT analysis

The potential application of TeraCale on an industrial scale could be a comprehensive solution to address the issue of PV panel waste processing, which has yet to be properly handled. There are several internal and external aspects in the process of creating this innovation, which are presented in the form of a SWOT analysis. A PESTLE analysis was also conducted to review external factors that could affect TeraCale's innovation in the future. PESTLE analysis is a method used to determine various external factors that could potentially affect the business. PESTLE analysis assists in decision-making and strategic planning for the implementation of TeraCale in the future.



Fig. 8. TeraCale PESTLE analysis

Political factors such as the global government's commitment to Net Zero Emission (NZE) 2060 can encourage the use of PV panels, thereby increasing the need for sustainable recycling solutions through TeraCale in the future. In addition, subsidies and licensing facilities in the renewable energy sector and related industries from the government can also support faster technology acceleration. In the long term, stability and support from the government are essential to determine the implementation of TeraCale on a large scale. Sudden policy changes related to the renewable energy sector can hinder long-term planning. Economic factors such as increases in the price of recovered metals (raw materials), such as Si, Ag, Al, etc., can increase the economic value of TeraCale's recycled products and improve profitability. In addition, external investment support is also needed to achieve reasonable economic growth. Energy efficiency in the overall process can also have a significant impact on production costs. Therefore, optimising the overall process is essential to increase profits.

Increased public awareness of the importance of PV waste recycling can strengthen TeraCale's image and facilitate market acceptance among the public. When this innovation is implemented, TeraCale will require a workforce with high technical skills, which will

indirectly create new jobs. Rapid technological developments related to PV waste recycling systems can improve the overall optimisation of the TeraCale process, thereby increasing work productivity. The availability of more energy-efficient and high-precision tools (such as sensors, computer vision, lasers, and PLCs) at more affordable prices can also reduce CAPEX and OPEX, thereby minimising production costs.

Regulations related to the disposal of hazardous waste (B3), particularly e-waste such as solar panels, can assist TeraCale in obtaining PV panel waste feedstock. Regulations related to Extended Producer Responsibility (ESR), which require PV panel manufacturers to be responsible for managing their products until the end of their useful life, can also indirectly guarantee a stable supply of PV waste feedstock, resulting from cooperation between TeraCale and relevant manufacturers. Patent protection and intellectual property rights are also necessary to legally protect TeraCale's innovations in the future. TeraCale has a chemical etching stage that has the potential to produce hazardous waste in the form of dangerous acids. For this reason, a comprehensive neutralisation system and Water Treatment Plant (WTP) are needed to treat this waste in order to prevent water pollution and meet environmental standards. The use of recyclable solvents can also save energy during the chemical etching process, making it more efficient.

Essentially, TeraCale is a recycling system designed to process PV panels so that recovered metals can be obtained for use as components in solar panels without mining new raw materials. TeraCale is expected to be a green technology solution that contributes directly to reducing carbon footprints and conserving rare minerals. Therefore, a Life Cycle Assessment (LCA) is needed to review the sustainability of the TeraCale innovation if it is implemented directly in the community. LCA is a comprehensive method for quantifying the environmental impact of an innovation/product (Mao et al., 2024). LCA consists of four processes, namely goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. In c-Si PV panel materials, PV panel recycling is divided into upcycling and downcycling. Downcycling includes recycling aluminium frames, glass, junction boxes, and cables. Upcycling includes recycling all materials from PV panels. The upcycling process includes the dismantling of the PV panel, aluminium frame, junction box, and cables; separation of the glass (furnace heat treatment, medium- and short-wave infrared heating), cutting, incineration, or pyrolysis; hydrometallurgical processing for bottom ash or cell scrap to recover various metals (Mao et al., 2024). Several studies related to LCA for upcycling processes. In terms of climate change, Ardente et al. (2019) reported the lowest observed EOL value of 361.3 kg CO₂ eq/t. Latunussa et al. (2016), Ardente et al. (2019), Mahmoudi et al. (2020), Lisperguer et al. (2020), and Ansanelli et al. (2021) reported EOL values of 446, 461, 1035, 1380, and 1021.25 kg CO₂ eq/t, respectively.

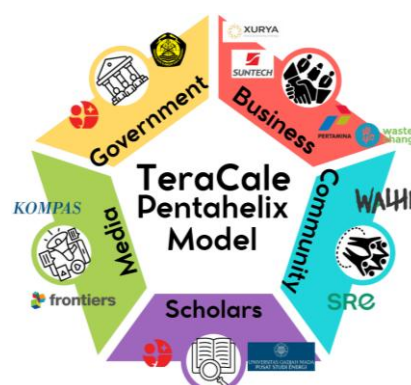


Fig. 9. Pentahelix model of TeraCale

To realise this, TeraCale certainly needs support from various stakeholders who play an important role in the sustainability of this innovation process. From the academic community, support can come from academics in related fields and Energy Study Centres

that can refine core technologies such as lasers and chemical etching, conduct pilot studies, validate the efficiency and purity of recovered materials to ensure sustainability, and share research findings to advance this field. Furthermore, from the business sector, support can come from waste management and recycling companies, material processors or manufacturers, and equipment manufacturers. The business sector will provide a supply of EoL PV panels for recycling, utilise recovered materials in the manufacture of new panels, and assist in managing material flows to maintain efficiency. Moreover, the Community sector consisting of local communities near PV recycling facilities, communities supporting energy transition, and environmental NGOs (Non-Governmental Organisations), will receive and grant social permission to operate, advocate for strong recycling policies and monitor environmental impacts, encourage transparency in the solar panel life cycle, and promote the use of recycled content in new products.

From the Government sector, there are stakeholders in the form of the Ministry of Energy and Mineral Resources (ESDM), the National Research and Innovation Agency (BRIN), and Local Governments that play a role in formulating energy policies, setting renewable energy targets, integrating PV waste management into a broader energy framework, providing and supporting the development of innovative technologies, and granting permits for PV panel waste management infrastructure facilities. The media sector, which includes specialised publications on renewable energy innovation, online news portals, and social media, will play a role in raising public awareness of the urgency of sustainable solutions for e-waste recycling, particularly PV panels, and enabling the rapid and widespread dissemination of information so that innovations can reach the general public and policymakers. To ensure the project runs smoothly, TeraCale also has an implementation strategy spanning a minimum of 5.5 years, consisting of the following seven stages.



Fig. 10. TeraCale implementation strategy

Technical and environmental analysis during the first six months, the author will conduct a needs and environmental analysis through literature studies and consultations with local researchers. This stage involves determining technical requirements, such as machinery, IoT devices, various chemicals, etc. In addition, a proper environmental analysis is also necessary to support an optimal recycling process. The analysis covers the location of operations, temperature, and accessibility of infrastructure in the surrounding area. Prototype making during months 7–24, over the course of 1.5 years, the author will then begin designing and developing prototypes in collaboration with researchers from the Gadjah Mada University Energy Study Centre to conduct further research. Prototype development will be limited to a small scale, starting with the mechanical construction of the device, electronic components, program writing, and laboratory-scale testing. In developing the prototype, unused solar panels from Waste4Change's solar panel waste management collaboration will be utilised. Once the prototype is complete, an evaluation will be conducted to review the success of the device in accordance with the initial innovation concept.

Innovation development during months 24–48, the next stage involves scaling up the previously developed prototype. This stage involves constructing the innovation on a larger scale, namely an industrial scale. This stage is carried out gradually over two years in collaboration with various companies, research institutions, and relevant stakeholders. Once the innovation has been scaled up, an evaluation is conducted to optimise the overall process. Innovation feasibility assesment during months 48–60, once the innovation has been constructed, an innovation feasibility test will be conducted to assess its effectiveness and environmental and economic feasibility. This stage is expected to last for a full year in collaboration with BRIN and the Ministry of Energy and Mineral Resources (ESDM).

Launching and marketing during months 60-66, after passing the feasibility test certification, the innovation will be launched to the public in collaboration with relevant media outlets, such as Kompas and Frontiers. In addition, there will be collaboration with the solar panel manufacturing industry as further stakeholders who will process recycled metals to be re-produced into complete solar panels. Evaluation and scalability during month 66 onwards, after the innovation has been successfully operated and implemented, periodic evaluations will be conducted, both in terms of the overall recycling process and its environmental impact. To review social responses, evaluations will also be conducted based on user and community feedback. Furthermore, collaboration with NGOs was also carried out, both at the university level (SRE) and community level (WALHI) to expand the reach of the community so that the benefits could be felt more widely.

4. Conclusions

Photovoltaic (PV) technology is becoming increasingly well known to the general public as fossil fuels become scarcer. Although civilisation has found a solution through this technology, a new problem has arisen in the form of waste from PV panels that have reached the end of their useful life. Various solutions have been found, but they also seem to cause other environmental problems. For this reason, TeraCale has emerged as an innovative solution for recycling PV panels using Integrated Laser Irradiation and Chemical Etching. Equipped with various features as part of the implementation of the Internet of Things, TeraCale offers a solution so that the sorting process can be carried out effectively over a long period of time and on a large scale. Based on the literature review and analysis conducted, it can be concluded that TeraCale deserves to be further developed and implemented. TeraCale can also be a solution that supports the achievement of SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) by 2050. Recommendations for the future development of TeraCale include further research and testing to optimise processes, reduce operational costs, and ensure the sustainability of the recycling cycle. In addition, collaboration between various parties is needed to realise TeraCale's innovation from concept to real solution as presented in the pentahelix diagram. Furthermore, further research is needed to better understand the trade-offs between module recycling and durability (equipment lifespan), performance, costs, and potential revenue from recycled materials. With TeraCale, researchers hope to create a solution that can solve the main problem of PV panel waste with an environmentally friendly recycling process.

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Author Contribution

The authors were collectively involved in formulating the idea of the innovation, designing the study, collecting and analyzing the data, and preparing the manuscript. All authors took equal parts in writing, revising, and giving final approval for the overall manuscript to be published.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Declaration of Generative AI Use

During the preparation of this work, the author used ChatGPT to assist in improving and summarizing the difference for types of IoT so that the author acknowledges the best tools to use in this system. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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