Optimal methodologies for delaminating End-of-Life crystalline silicon solar photovoltaic panels

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ABSTRACT The increasing usage along with various programs introduced by the Malaysian government for solar energy will lead to a surge in the disposal of defective solar modules. Recycling of defective or End-of-Life (EoL) solar modules becoming the sustainable solution instead of direct disposal to the landfill. Layering structure of built-in solar module often hinders the recycling process. Efficient and cost-effective methodologies must be identified for delaminating the modules which include physical separation and thermal treatment. This is to assure each material comprised in the solar module such as glass, metal scrap, silicon, and plastic could be retrieved and processed for further usage. Besides layering structure, crystalline silicon solar module often encapsulated by ethyl vinyl acetate (EVA) for preventing degradation of performance. Identifying the optimal conditions specifically temperature and duration during thermal treatment are necessary to remove EVA encapsulation between each layer of solar module. Accordingly, applying heat from 150 – 200℃ within 30s - 2min are the optimal conditions for detaching adhesiveness of EVA encapsulation and delaminating the layering structure of solar module that is unachievable solely through the physical separation. Besides, the utility cost of the proposed thermal process remained minimum. This study indicates the proposed methodologies are capable of delaminating damaged or EoL solar module for recycling and retrieving valuable materials purposes.

KEYWORDS: Recycling, Silicon Solar Panel, Delamination, Physical Separation, Thermal Treatment

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INTRODUCTION

The increasing demand for electricity and transitioning towards renewable energy generation had led to upsurge in solar photovoltaic (PV) system installation. According to the International Renewable Energy Agency (IRENA, 2023) Malaysia's energy report, total installation from solar-based energy capacity in 2021 was twice the capacity installed in 2017. Self-Consumption (SELCO), Net Energy Metering (NEM), Large Scale Solar (LLS), and Feed-in Tariff with various financing scheme were the four main programs and schemes introduced by the Sustainable Energy Development Agency (SEDA), Malaysia that significantly escalated the usage of solar PV system.

Indirect connection of SELCO based solar PV system had gained interest among consumers in Sabah specifically when the power grid facing limitation due to sole dependency of ageing fleet natural gas (IRENA, 2023). Indirect connection of SELCO PV is connected to the electrical point instead of through internal distribution of common connections (Energy Commission, 2023). Meanwhile, Solar Street Light is often equipped with LED floodlight appliances as outdoor lighting solution for residential and industrial areas. Although the average life cycle of crystalline silicon PV module is within 20 – 30 years (Chowdhury *et al*., 2020), shorter lifetime is expected to occur when PV module is exposed to extreme weather conditions, less durable built-in system, and installation. Despite massive development and installation capacity of solar PV system all over the Asian countries, only Japan had promoted research and development for recycling the solar module (Palitzsch & Loser, 2012). Back in 2020, former Minister of Energy, Science, and Technology, Environment, and Climate Change of Malaysia had mentioned that the government was seeking for the establishment of recycling facility in Malaysia that fully operated by the next 10 years (Bernama, 2020).

Recycling process of silicon PV modules are categorized as delamination and material separation. Delamination was the most intricate process to separate the layering structure of solar module. Physical separation, thermal treatment, and acid-based dissolution were among the delamination and removal of EVA encapsulation processes practiced in the recycling process of solar module. However, organic-based acid dissolution for delaminating solar module took longer duration and required expensive equipment (Doi *et al*., 2001; Maurer & Schlummer, 2004). Ultrasonic irradiation paired with organic acid dissolution mainly to accelerate the process but, it steeply increased the operational cost (Kim & Lee, 2012). Meanwhile, practicing inorganic acid dissolution deteriorated the silicon cell and produced hazardous emissions (Bruton, 1994). In 2021, a new delamination technique by using diamond wire is developed by the French research institute CEA-Liten (Spaes, 2021). Although delamination process is conducted within shorter duration, usage of reel-fed diamond wire was often costly and continuous monitoring of tool wear became the main constraint of this technique. Henceforth, physical separation and thermal treatment were selected as the delamination techniques for the solar module investigated in this study. There was limited information of the optimal conditions and detailed procedure involved in both processes that must be thoroughly examined. This research mainly focused on determining the optimal parameters and procedure involved in both physical separation and thermal treatment for delaminating solar modules along with the assessment of the utility cost involved in the thermal treatment.

BACKGROUND THEORY

Crystalline Silicon Solar Panel Structure

Crystalline ribbon and module comprised of layering structure of glass, EVA, silicon cell with metal tabbing ribbon, and backing sheet that were sealed by metal frame. A junction box was attached to the backing sheet of solar module as the output interface of solar PV module.

Utility Cost of Thermal Treatment

The utility cost involved in the thermal treatment was the electrical power consumption to operate hot air gun during delamination process and removing adhesiveness of EVA encapsulation between glass and silicon cells. The power consumption, P was calculated according to the Equation (1) given as

$$P = P_o t \tag{1}$$

where P_o is the power output of the appliance (2000 W) and t is the duration in hour of utilizing the hot air gun. The computational utility cost involved during thermal treatment is obtained through the Tariff bill calculator based on domestic, low voltage commercial, and low voltage industrial tariffs provided by Sabah Electricity Sdn. Bhd. (SESB, 2023) based on the calculated P. This was due to various rates introduced by SESB according to the tariff category and consumption rates per month. The minimum monthly charge for domestic tariff and low voltage commercial and industrial tariffs were equivalent to RM 5.00 and RM15.00, respectively.

METHODOLOGY

Solar Module Collection

Defective or End-of-Life (EoL) solar module is retrieved from the residential area and landfill because the electrical waste management centre (e-Waste) in Kota Kinabalu, Sabah was not yet initiated the collection of solar panel waste. Most of the retrieved solar panel was either had shattered glass or detaching of junction box causing failure of operation.

Physical Separation

The junction box was first detached from the solar module followed by removal of metal frames. Insulating layers of wires connected to the junction box were further striped to retrieve valuable metal, copper. Next, the backing sheet was manually peeled off from the solar cell, metal tabbing ribbon, and glass layers. The solar cells and metal tabbing ribbon were strongly adhered to the glass due to EVA encapsulation. Thus, thermal treatment is required to delaminate these layers and remove adhesiveness of EVA encapsulation.

Thermal Treatment

The main parameters that must be controlled throughout the thermal treatment process were applied temperature, working distance, and duration. The working distance was the distance between hot air gun nozzle to the surface of solar module. Identifying optimal parameters applied during thermal treatment was crucial to avoid high utility cost, deterioration of silicon cells, and shattered glass that will lead to hazard during operation. Safety goggles and gloves were utilized during this process as a safety precaution.

RESULT AND DISCUSSION

Junction box along with wire and metal frame were successfully dissembled from the solar module through the physical separation process as shown in Figure 1. Copper was retrieved after stripping the insulating layer of wire. The backing sheet of solar module was delaminated manually from the glass and silicon cell. The investigated solar module had lesser EVA encapsulation at the backing sheet compared with the encapsulation between silicon cell and glass. Thus, backing sheet of the solar module was able to be removed manually without the needs of thermal treatment. Besides, solar cell possessed brittle characteristics and thermal treatment is required to perform delamination process.

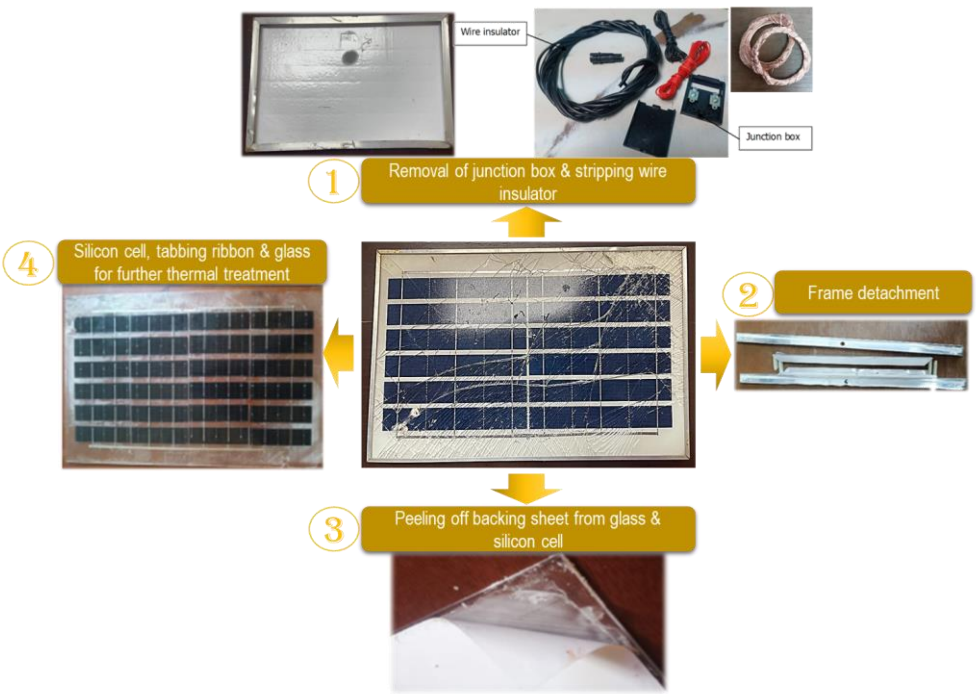

Figure 1. Disassembly of crystalline silicon solar module through the physical separation process.

Table 1. Parameters assigned during thermal treatment for delaminating silicon cells and metal ribbon tabbing with glass along with the computed electrical power consumption.

Parameters	Temperature (°C)	Heating Duration (s)	Working Distance (cm)	Power Consumption, *P* (kWh)
Range Value	150 - 250	600	5 - 15	0.3334

Thermal treatment was further carried out to eliminate EVA encapsulation between silicon cell and metal tabbing ribbon with the glass. After experimenting with various parameters involved during the thermal treatment, Table 1 depicted the most preferable conditions for delaminating the silicon cell with glass. Based on Table 1, the total duration of heat supplied on the solar module was 600s whereby the heating process was not conducted continuously. Half part of the solar module was heated within 300s to remove adhesiveness of EVA encapsulation followed by immediate scrapping of solar cell and metal tabbing ribbon using a cutter knife as presented in Figure 2. The procedure is repeated on another part of the solar module within the next 300s. Although the temperature of hot air gun could be maximized up to 600°C, the glass was easily shattered, and the silicon cells will turn yellow-brownish coloured indicating cell deterioration.

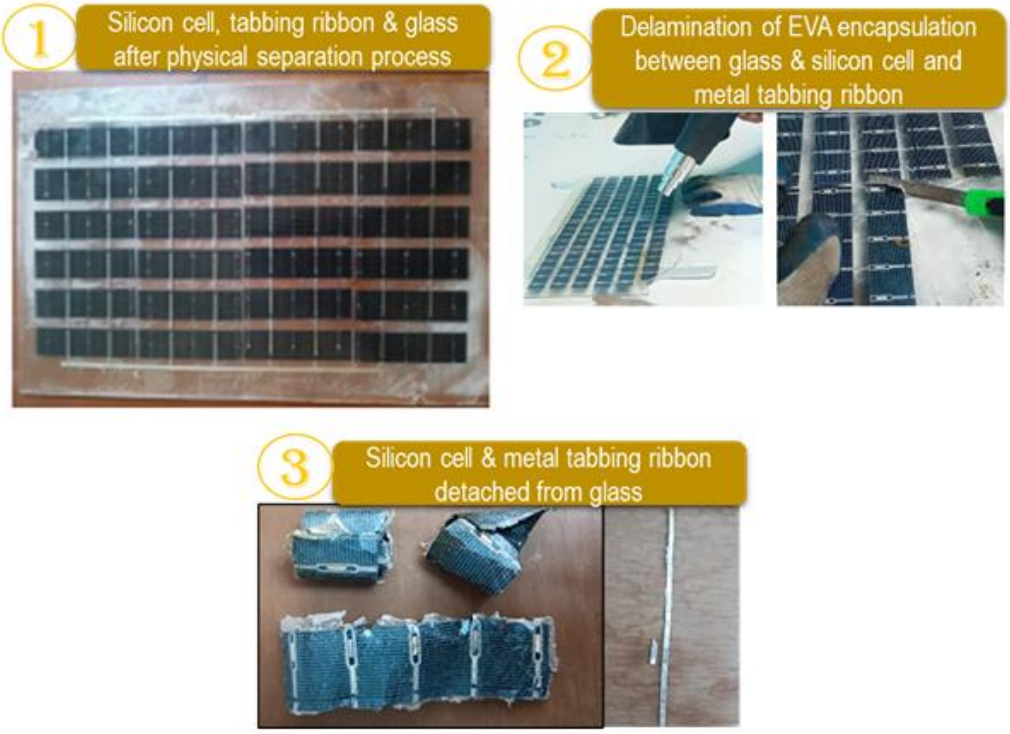

Figure 2. Delamination of EVA encapsulation between silicon cell and metal tabbing ribbon with the glass through thermal treatment process.

The heating duration remained acceptable specifically the calculated power consumption was equivalent to 0.3334 kWh. Since the electrical power consumption was lesser than 100 kWh, only rates for the first 100 kWh specified by SESB are included in Table 2. The computed utility cost per bill category remained minimal as depicted in Table 2. Nonetheless, the total bill enforced by SESB is still considered the minimum monthly charge as stated in their policy. Furthermore, the total bill presented in this study is excluded from the "Pemulih electricity discount". There was potential for the increased of heating duration during thermal treatment process if the solar module had larger dimension compared to the investigated solar module. The dimension of the solar module utilized in this study was equivalent to 320 mm × 245 mm. Besides, different arrangement and metal ribbon tabbing connection than the investigated solar module would involve diverse heating duration specified in this research study.

Table 2. Utility cost based on bill category for the thermal treatment process.

Tariff Bill Category	Power Consumption, *P* (kWh)	Rate for The First 100kWh	Computed Utility Cost (RM)	Total Bill (RM)
Domestic	0.3334	17.50 cents/kWh	0.0583	5.00
Low voltage commercial	0.3334	38.50 cents /kWh	0.1284	15.00
Low voltage industrial	0.3334	37.60 cents /kWh	0.1254	15.00

Prolonging the heating duration during thermal treatment is significantly increased the utility cost. Hence, determining the optimal condition applied during the thermal treatment was vital to minimize the utility cost upon operation. Moreover, the computed tariff bills were only based on domestic, low voltage commercial, and low voltage industrial tariffs specified by SESB. Different tariff bills are imposed for medium voltage commercial and industrial. The utility cost was also depending on the location because Malaysia had three main utility energy supply companies: Tenaga Nasional Berhad (TNB), SESB, and Sarawak Energy. Each utility energy supply company implied different tariff for their designated location and category of bill. Minimizing the operational cost while maintaining the efficiency of delamination process for the solar module was significant to assure the proposed methods were applicable in both research and industrial applications.

Despite the ability of the proposed methods for delaminating EoL or damaged solar panel, there was limitation for retrieving pure silicon from the silicon cell. The solar cell still consists of various materials such as silicon, metal, and anti-reflection coating which required to be separated. Developing further material separation process was necessary to assure retrieval of each material from the solar panel. An optimal separation process was vital to assure minimum operational cost while maintaining the efficacy of retrieving valuable material. Thus, providing circular economy and encouraging the recycling endeavour of solar PV industry.

CONCLUSION

The delamination process for recycling damaged or EoL crystalline silicon solar module was investigated through the physical separation and thermal treatment processes. The proposed physical separation process was able to dissemble the junction box, wire, metal frame, and removal of backing sheet from the solar module. Moreover, valuable materials including copper and metal frame were retrieved throughout the process. Delamination of EVA encapsulation between silicon cell and metal tabbing ribbon with the glass is achieved through the thermal treatment process conducted between 150 to 250 ℃ within 600 s of the total heating duration. The calculated electrical power consumption utilized during the thermal treatment process was equivalent to 0.3334 kWh resulting in minimum utility cost throughout the operation. The detailed findings throughout this research provided insightful information specifically procedure, optimal parameters, and utility cost for recycling solar module which required delamination process.

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