

Article

An Innovative Approach for Delamination of Solar Panels Using a Heated Metal Wire

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Abstract: Over the last two decades, the use of photovoltaic panels for the production of electricity has increased significantly, which leads to the need to solve the problems concerning the decommissioning and disposal of the panels and the development of appropriate technologies for their recycling. One of the key steps in this process is the separation of the tempered glass layer. Various technologies and devices are known for separating the glass of the solar panel by cutting it with a knife, as well as other instruments, with the different methods being based on mechanical, chemical, and thermal processes and accordingly having their own advantages and disadvantages. This article proposes an innovative approach for the mechanical delamination of solar panels using a metal wire heated by Joule heating, with the potential to become an energy-efficient, economical, and environmentally friendly method. This publication presents results from experiments using this type of tool to separate the layers of solar panels. Photos from a thermal camera are presented, showing the heat distribution in the panel and the reached operating temperature of the heated metal wire, necessary to soften the EVA bonding layer.

Keywords: solar panels; recycling; delamination; metal wire; Joule heating



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1. Introduction

Globally, the growing need for clean and renewable energy has led to the widespread use of photovoltaic technology [1], with solar cells becoming a powerful player in the renewable energy sector [2]. In recent years, photovoltaics (PVs) have become an established technology for generating electricity using solar radiation [3]. Among all types of photovoltaic panels, silicon panels are the most popular and represent 85–90% of photovoltaics on the market. The components of this type of solar panels are approximately 78% glass, 2% metal filaments, 7% solar cells, and 13% polymers [4].

As part of transformational development, solar power is expected to surpass natural gas by 2026 and coal by 2027, thus solidifying its position as the world's largest supplier of electricity [5]. Leading these changes are crystalline silicon photovoltaic modules, which are the main tools for harvesting solar energy in photovoltaic systems [6]. Due to the rapid growth of solar energy in many sectors, the number of photovoltaic systems is increasing. This is reflected in a significant rise in installed capacity, which has increased in the last decade to more than 1050 GW [7]. Although this rapid expansion has led to significant advances in solar power generation, it has also led to a critical environmental problem [8]. The disposal and recycling of solar panels become key aspects of sustainable energy management when their lifecycle ends [9]. These actions are driven by the need

to limit potential environmental damage, such as soil and water contamination from hazardous compounds used in solar panels, as well as to avoid resource depletion [10], as waste generated from end-of-life solar panels is likely to be one of the main challenges for the recycling industry in the future [11,12]. Due to the lack of sufficiently good regulations, only about 10% of solar panels are recycled worldwide [13]. By implementing effective recycling procedures, solar panel waste can be recycled, which would lead to a reduction in the negative impact on the environment, as well as the reuse of recovered valuable resources and less demand for new raw materials [14].

There are various approaches to recycling photovoltaic modules, most of which are based on thermal, chemical, and mechanical processes [15,16]. Thermal methods such as pyrolysis effectively degrade organic materials, but they require a large amount of energy. Chemical processes are suitable for extracting materials with high purity, but most of them are not environmentally friendly enough and have a high cost [17]. Another widely considered approach is the mechanical recycling of photovoltaic panels. In these technologies, the first step is usually the dismantling of the panels [18,19]. Then, separation of the main components, such as aluminum frames, solar cells, wiring, and laminated glass, is performed [20]. Prioritizing glass recycling is considered to be one of the key factors in maximizing mass recovery and ensuring the economic feasibility of the process [21]. Various techniques, ranging from manual methods to thermal treatments and automated systems, are used to facilitate separation [22–31].

Devices for separating the glass of a solar panel by cutting with a knife, as well as other instruments, are known. An invention [32] relates to separating the tempered glass (transparent layer) without breaking it using two consecutive knives. The proposed method focuses on keeping the glass intact, although most panels, subject to recycling, have broken glass, and in most cases preserving the glass intact is not economically feasible from the point of view of its subsequent transport and utilization. There is another technical solution [33], which relates to separating the glass and other components mechanically using two blades, transverse and longitudinal, both of which have the ability to recycle double-sided panels. The panel passes through a spring-loaded heated roller to melt the bonding material (EVA), which allows for the processing of different panel thicknesses, after which the layers are separated depending on the configuration of the solar panel. There is also an invention [34], which relates to the preliminary thermal treatment of the solar panel and subsequent mechanical treatment to separate the glass by attaching it to the worktable by vacuum and separating the lower part. The subject of another design involves the mechanical separation of the glass by using several knives at a certain distance and pulling the separated material, gripped in jaws [35]. There are other patents related to the mechanical separation of elements from solar panels. The Korea Institute of Energy Research proposes a method for the recycling of solar panels by crushing the glass with the maximum amount of material separated from the remaining layers without the adhesion of adhesive materials and additional chemical action. Various crushing rollers and tips have been considered [36]. The Hebei Phoenix Valley Zero Carbon Development Research Institute and Yingli Energy China Co Ltd. hold a patent for a promising method for recycling solar panels by crushing the panel and the subsequent separation of the fractions by various mechanical methods using conventional technologies [37]. A patent filed by Yingli Group Co Ltd. in 2012 relates to the separation of glass from the solar panel and subsequent crushing and sorting of the remaining layers without chemical action [38]. Another patent proposes a technology for the thermal treatment of the EVA layer in order to separate the glass from the solar panel [39]. A technology for crushing solar panel glass, its subsequent removal using a knife, and sorting the fractions is patented by Showa Shell Sekiyu KK [40].

This article proposes an innovative approach for the mechanical delamination of solar panels by using a metal wire heated by Joule heating. This publication presents the results from experiments using this type of tool to separate the layers of solar panels. Photos from a thermal camera are presented, showing the heat distribution in the panel and the reached operating temperature of the heated metal wire, necessary to soften the EVA bonding layer. The proposed method for mechanically separating the glass of the panel proves promising, combining a simple cutting tool, energy efficiency, and an inexpensive device design, for which an application for the registration of a Utility Model has been filed.

2. Results

2.1. Test Results with Kanthal Round Wire

Experiments are conducted to separate the glass layer using a heated Kanthal wire with a circular cross-section and a diameter of 0.2 mm without additional heating of the test specimen. The required wire temperature, sufficient to soften the EVA layer, is expected to be in the range of 100–180 °C and is achieved with a voltage supplied from the external power supply of 9.5 V and an electric current of 3.6 A.

Figure 1a shows a photo from the thermal camera after threading the round heated wire into the bonding layer between the glass and the PV cells. A portion of the crushed separated glass is shown in Figure 1b. This experiment is conducted with the insulating back sheet pointing towards the table.

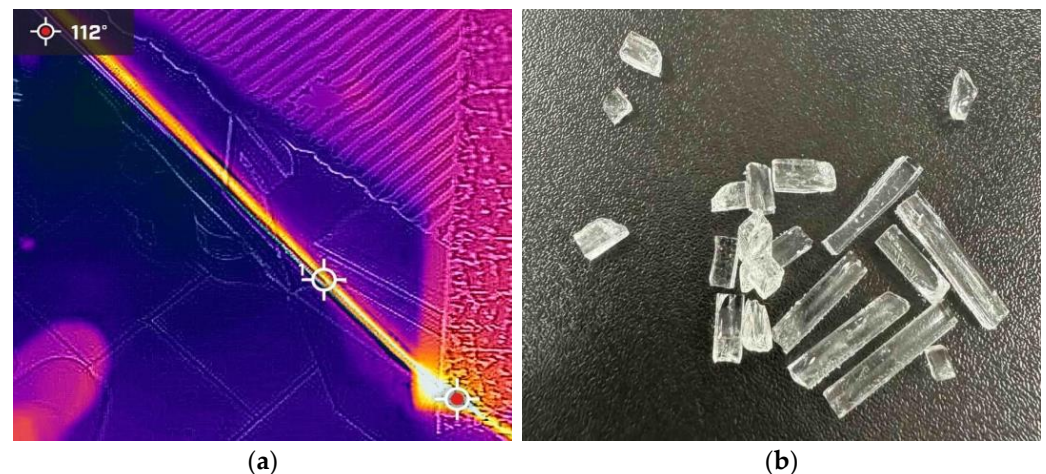


Figure 1. Test results of glass separation using a round wire and a specimen placed with the glass layer facing the table: (a) photo from the thermal camera after threading the round heated wire into the bonding layer between the glass and the PV cells; (b) portion of the crushed separated glass.

An attempt with a round wire to separate the insulating back sheet of the solar panel from the PV layer is also conducted. The result of a partially separated insulation layer is shown in Figure 2. The experiment is conducted with the glass layer pointing towards the table and with additional heating using a hot air gun.

2.2. Test Results with Kanthal Wire with a Rectangular Cross-Section

Tests using a rectangular wire are performed with additional heating of the test specimen using a hot air gun. A wire heating temperature of over 160 °C is achieved at a voltage of 5.6 V and an electric current of 5.2 A. A thermal image of the rectangular heated wire is shown in Figure 3a. Figure 3b shows a thermal image of the rectangular wire being threaded between the glass layer and the PV layer with the insulating back sheet facing the table.



Figure 2. Partially separated insulating back sheet.

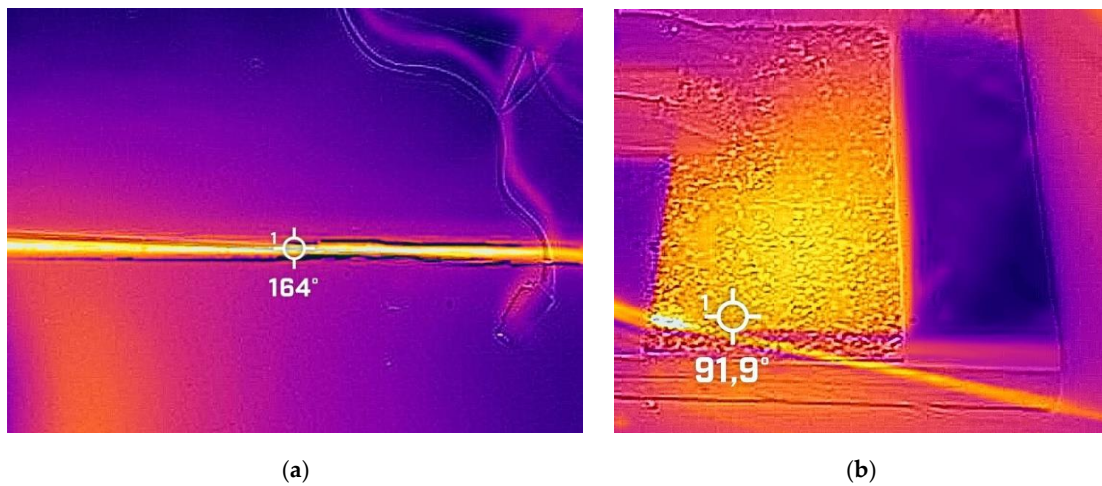


Figure 3. Thermal images (a) of the rectangular heated wire; (b) of the rectangular wire being threaded between the glass layer and the PV layer with the insulating back sheet facing the table.

A thermal image of an attempt to thread the rectangular wire between the glass and the PV cells during an experimental setup of the test specimen with the glass layer pointing towards the table is shown in Figure 4.

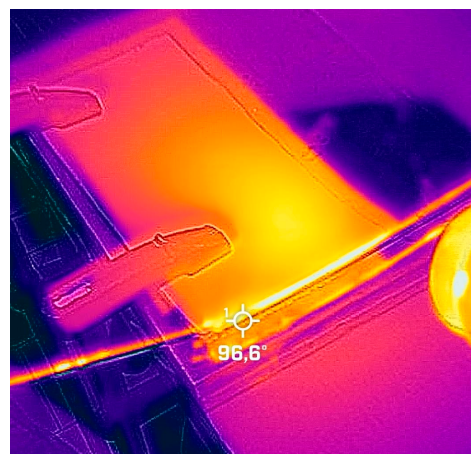


Figure 4. Thermal image of an attempt to thread the rectangular wire with the glass layer pointing towards the table.

3. Discussion

When performing the tests with a round wire, it is found that movement between the layers is difficult due to the shape of the wire and the lack of a guiding surface. Therefore, further experiments are performed with a Kanthal heating wire with a rectangular cross-section.

During experiments with rectangular wire, it is found that better threading is obtained when the insulating back sheet is placed facing the table. In this way, the glass layer provides greater stiffness to the test specimen and allows for stable wire guidance between the layers (Figure 5a,b). The wire guidance is not adequate when the glass layer is facing the table.

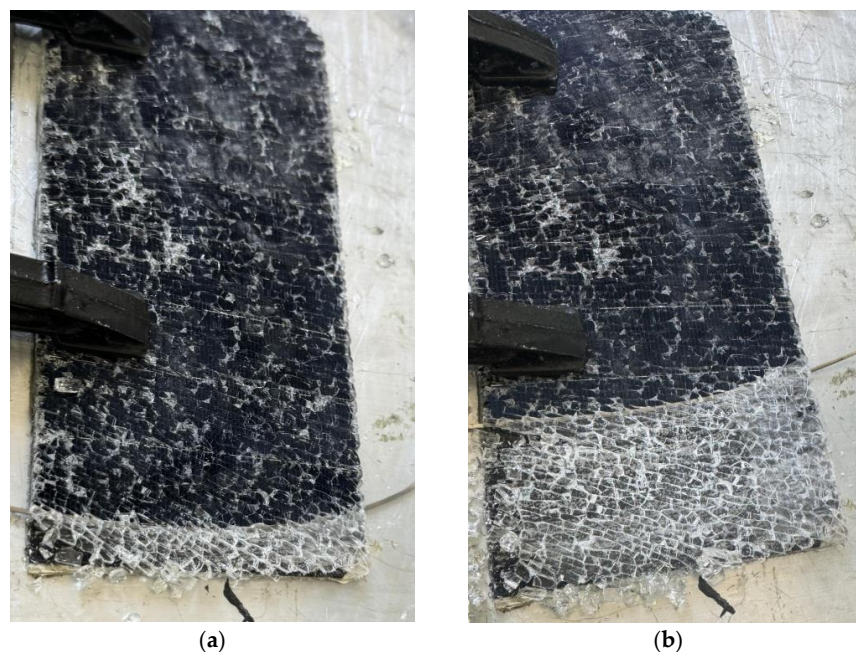


Figure 5. Heated wire movement: (a) in the beginning of the cutting process; (b) during the cutting process.

Based on the test results, it is also found that the angle of attack is important for good separation of the glass layer, and it is appropriate to be in the range of 0–45°. It is confirmed that a wire heating temperature between 120 and 170 °C is sufficient to soften the EVA bonding layer, with additional heating of the test specimens with a hot air gun allowing for faster separation and easier wire guidance. It is found that the main part of the EVA binder remains on the PV cell layer and not on the glass, as seen in Figure 6a,b.

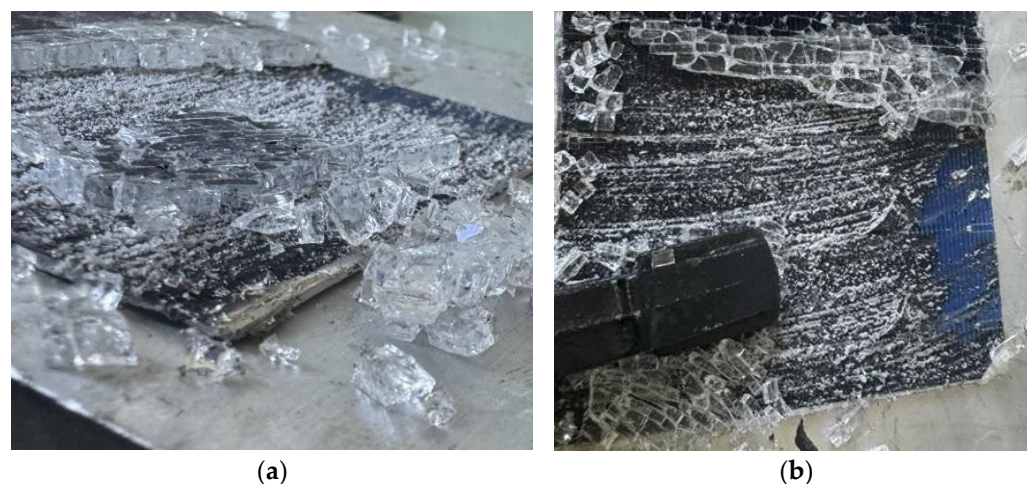


Figure 6. (a) Separated glass; (b) PV cell layer with the remaining EVA on top of it.

It is also concluded that it is necessary to have an additional separating element to prevent the layers from re-adhering after the heated wire passes through, as well as that it is necessary to provide greater tension on the wire.

Based on the analysis of the results obtained from the tests performed, an exemplary scheme for separating the glass layer from the PV solar cells layer in the solar panels is proposed, as shown in Figure 7.

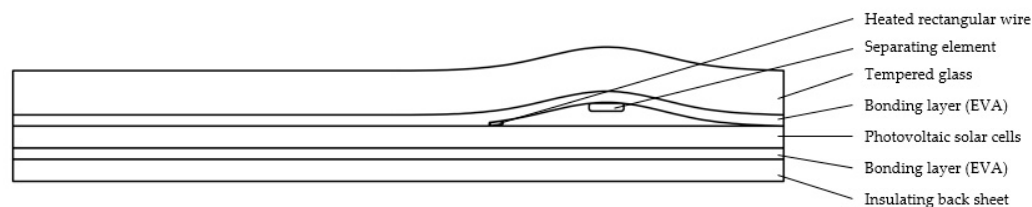


Figure 7. Exemplary scheme for separating the glass layer from the PV cell layer in solar panels.

The presented research is part of the development of a device for separating the glass of a solar panel, for which an application for the registration of a Utility Model has been filed with the Patent Office of the Republic of Bulgaria.

4. Materials and Methods

4.1. Test Samples

For the purposes of this study, pre-cut pieces of an obsolete single-sided PV panel with cracked glass with approximate dimensions of 150×300 mm are used. A test sample is shown in Figure 8a. The entire thickness of the test panel is about 4.5 mm, distributed as follows: 3 mm for the tempered glass, 1 mm for the insulating back sheet, 0.4 mm for the photovoltaic solar cell layer, and less than 0.1 mm for each of the bonding layers. The cross-sectional structure of the panel is shown schematically, not to scale, in Figure 8b.



(a)

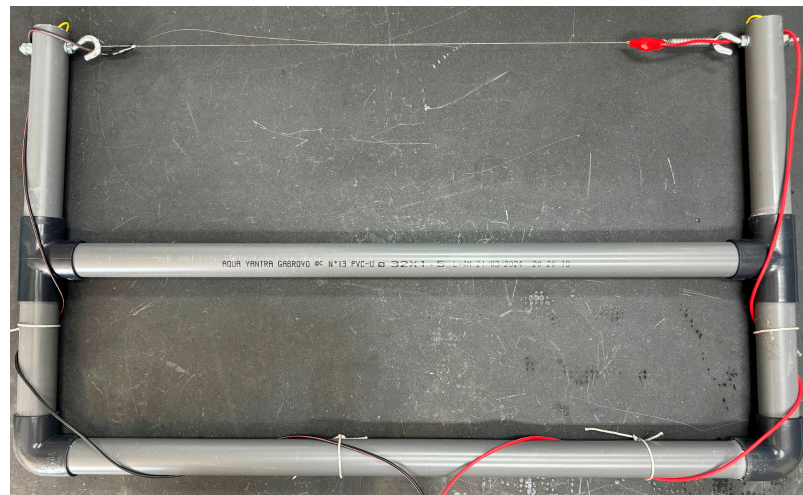


(b)

Figure 8. (a) Test sample from an obsolete single-sided PV panel; (b) scheme of the cross-sectional structure of the panel used for the tests.

4.2. Proof-of-Concept Test Device and Other Tools

For testing purposes, a simple manual proof-of-concept device is constructed, consisting of a plastic frame and a place to attach a metal wire. A spring is also added to provide additional tension when heating the wire. Two cables with cable clamps at the end are added to allow for an electrical current to be applied to the wire via an external power supply so that it could be resistive-heated. Experiments are performed with two types of ferritic iron–chromium–aluminum alloy wires suitable for Joule heating: Kanthal round wire with a diameter of 0.2 mm and Kanthal with a rectangular cross-section and dimensions of 1.250×0.150 mm. The length of the working area of the cutting wire is about 500 mm. The device is shown in Figure 9a. A DC Power Supply HY3005D (Mastech, Taipei City, Taiwan) is used for the tests, as shown in Figure 9b.



(a)



(b)

Figure 9. (a) Manual proof-of-concept test device with a metal wire; (b) DC Power Supply HY3005D during testing.

Due to the large energy dissipation of the heated wire when cutting the panel, a Steinel HL 2020 E hot air gun is also used for part of the experiments to maintain stable temperature in the area of the passage of the cutting tool.

A FLIR ONE EDGE–Wireless Thermal Imaging Camera is used to track the heating of the panel and to monitor the temperature in the area where the cutting heated wire passes.

4.3. Experimental Setup

A piece of the solar panel is attached to a fixed table using clamps. Experiments are conducted with two orientations of the piece, with glass facing the table (Figure 10a) and with an insulating back sheet facing the table (Figure 10b). An electric current is passed along the length of the wire to heat it and then it is threaded into the EVA layer between the glass and the photovoltaic solar cells. By alternating the longitudinal and transverse movements of the wire, the layers are separated, as shown in Figure 10c.

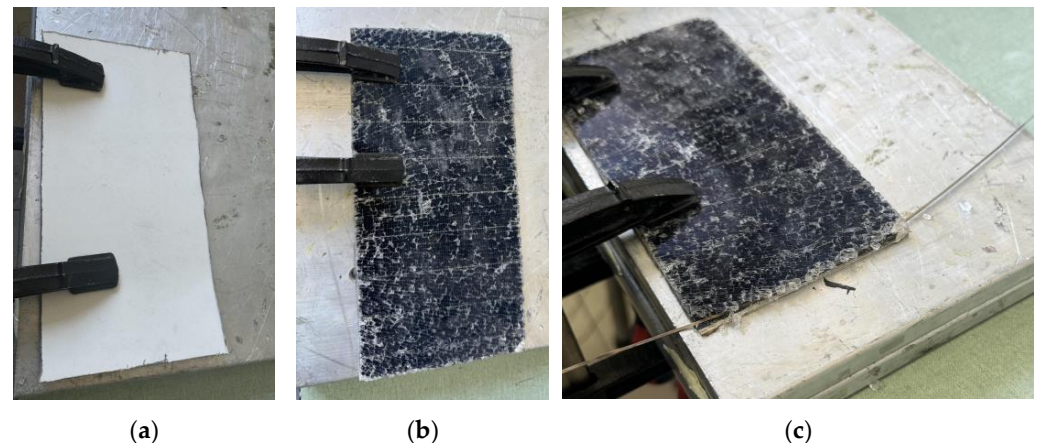


Figure 10. Different orientations of the pieces: (a) with glass facing the table; (b) with insulating back sheet facing the table; (c) the wire threaded into the EVA layer between the glass and the photovoltaic solar cells.

5. Conclusions

Since the separation of glass and its subsequent recycling is one of the main aspects in the solar panel recycling process, the proposed solution seems to be a promising method for achieving this goal. The described approach offers satisfactory results in the tests conducted. The innovativeness of this method lies in the lack of the necessity to manufacture a special profiled cutting tool; the Kanthal wire is a standardized mass-produced product at a low cost. The use of Joule heating is also justified as a feasible method for heating the cutting tool. Due to the above, it can be concluded that the proposed method has the potential to be energy-efficient, economical, and environmentally friendly.

However, a delamination test device must be constructed and produced, beyond proof of concept, in order to make a correct energy and economic assessment of the proposed technology, which is also the next step in these studies.

6. Patents

Application for registration of a Utility Model № BG/U/2025/6400 with the Patent Office of Republic of Bulgaria.

Author Contributions: Conceptualization, methodology, writing—original draft preparation, M.Z.; software, resources, visualization, K.D.; validation, V.K., A.N. and K.S.; investigation, K.S. and A.N.; writing—review and editing, V.K.; supervision, V.K.; project administration, Y.S.; funding acquisition, Y.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data will be available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EVA	Ethylene-vinyl acetate
PV	Photovoltaic
GW	Gigawatts

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