Recycling of photovoltaic panels - A review of the current trends

K Macalova¹, V Vaclavik¹, T Dvorsky¹, J Svoboda¹, J Charvat¹ and L Gola¹
¹ VSB - Technical University of Ostrava, Faculty of Mining and Geology, Department of Environmental Engineering, Czech Republic

Abstract. Towards the end of the 20th century there was a huge boom in the development of solar energy, which led to an increase in the production of photovoltaic panels. The producers assume a lifetime of these panels of 30 years. Today, the life of this photovoltaic panels is ending and a large amount of waste is associated with it. This issue is also addressed by the Council of the European Union, which issued Directive 2012/19/EU on waste electrical and electronic equipment. Photovoltaic panels are included in IV. category “Consumer electronics and photovoltaic panels”. This Directive mandates that at least 70% of photovoltaic panel materials must be reused or recycled. This paper presents a review of the current trends in recycling of photovoltaic panels and the possibilities of reuse in cement matrix.

1. Introduction
There was a large boom in the field of photovoltaic panels in the early 1990s, when grant programs were launched to support renewable energy sources. Japan and Germany were among the first countries to take advantage of these grant programs. Over time, these grant programs have been implemented in other countries of the world. Photovoltaic energy is generally one of the renewable energy sources with a relatively long life span, which is estimated to be at least 30 years. We are gradually coming to the time of the expected end of life of the first photovoltaic panels and it is necessary to deal with the method of their disposal after the end of their life cycle. Together with the rapid increase in the use of photovoltaic panels, there will be a proportionately increasing production of waste from the area of solar energy production. So far, only panels with mechanical damage caused by poor handling during the installation and transport have been disposed of [1, 2].

The Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment states that at least 70% of photovoltaic panel materials must be reused or recycled [3]. By finding a suitable way of recycling materials from photovoltaic panels we can ensure sustainable production while minimizing the burden on the environment. At present, there are two most widespread methods of recycling photovoltaic cells, namely thermal and mechanical-chemical recycling. As research into the incorporation of waste materials from other industries into the cement matrix [4-7] shows, one of the new potential ways to recycle photovoltaic cells is to incorporate the resulting waste materials into cement composites, as suggested by the studies performed before [8-11].

2. Development of photovoltaic panels
The development of photovoltaic panels can be divided into several stages, when each stage brought a new generation of photovoltaic cells.
2.1. The first stage of development

The first generation photovoltaic cells were developed during this basic stage. The cells were made of a crystalline structure of silicon. The name “first generation” reveals that it is the oldest technology which is still very popular and commercially the most widespread. This technology is constantly evolving [12-14]. Silicon panels are made of monocrystalline or polycrystalline doped silicon. The structure of the photovoltaic panel is shown in figure 1. The individual cells are connected by means of soldered joints. The bottom solid Tedlar plate (a mixture of polyvinylidene fluoride and polyethylene terephthalate) contains a plastic film EVA (ethylene-vinyl acetate), on which the interconnected photovoltaic cells are placed. The cells are covered by a layer of EVA film and hardened glass [13, 15].

![Figure 1. Structure of a photovoltaic panel [15].](image)

2.2. The second stage of development

The second stage of development was focused on the material and manufacturing optimization, with an effort to reduce the production costs and to minimize the use of silicon. This effort resulted in the production of second generation photovoltaic cells, which are cells made from amorphous silicon, microcrystalline silicon and thin-layer technology. The examples of thin-layer technologies used in the production of photovoltaic cells are:

- Technology of Copper Indium Gallium Selenide (CIGS),
- Cadmium Telluride (CdTe),
- Amorphous Silicon (a-Si) [16].
2.3. The third stage of development
The third stage of development is focused on sustainable production and efficiency improvement using the latest production technologies. The third generation of photovoltaic cells is emerging now. The organic polymer-based prototypes are still in the research and development stage [18, 19].

3. Recyclable photovoltaic panel material
According to German company SolarWorld dealing with the recycling of photovoltaic panels and cells, it is possible to recover up to 84% of the module weight by recycling. Of these, 90% is glass and 95% is semiconductor material [20]. This issue needs to be addressed, because there were 250 000 tonnes of waste from the photovoltaic industry recorded by 2016. By 2050, when the lifetime of most panels will expire, this figure can go up to around 6 million tonnes of waste [2].

The recycled materials include:
- aluminium,
- glass,
- plastic components,
- photovoltaic cells,
- heavy metals (Cd, Pb, Se),
- silver, nickel, tellurium, indium, gallium, molybdenum, ...

The process of recovering crushed recycled material from the photovoltaic panels is shown in figure 3.
Figure 3. Diagram of obtaining pulp from photovoltaic panels A - photovoltaic panel before recycling, B - hammer crusher, C - recovered pulp - recycled material.

Table 1 shows the percentage of each type of material in photovoltaic panels and their percentage yield during recycling.

| Material       | Percentage share (%) | Yield (%) |
|----------------|-----------------------|-----------|
| glass          | 67                    | >95 %     |
| aluminium (Al) | 18                    | 100       |
| plastic materials | 11                | 0         |
| silicon (Si)   | 3                     | 85        |
| metals         | 1                     | 80        |

4. Methods of recycling materials from photovoltaic panels

The basic methods of recycling of photovoltaic panels include thermal recycling and mechanical-chemical recycling. In both methods, it is necessary to first remove the aluminium frame and subsequently recycle the cells [1].

5. Thermal recycling

This method is used to recycle crystalline silicon cells. A cleaned photovoltaic panel is completely placed in an oven heated to a temperature above 500 °C. In this step, the plastic parts (EVA) are evaporated and incinerated in a controlled manner in the following chamber. The remaining material is separated manually. If the recycled material is damaged, up to 85% of the cells can be reused for the repeated production of photovoltaic panels. This technology is considered to be the most advanced method of recycling photovoltaic panels. It is more cost-effective than mechanical-chemical recycling, which requires the use of costly and toxic agents [22].

5.1. Mechanical-chemical recycling

These are separation methods. In the first stage, it is necessary to remove the aluminium frame from the panel. Subsequently, the photovoltaic panels are crushed and the individual components of the panel are sorted according to size fractions. Metals (Cd, Cu, Pb, Ag) are obtained chemically and metallurgically from the separated material. The metals are obtained by leaching or electrolysis. The chemical recycling method is used to clean the first generation photovoltaic cells. The layers deposited on the cells are removed using a solvent. Acidic or basic solutions are used to dissolve the required material. Choosing the right solution with the right concentration and ideal operating temperature is very important with this method [23, 24]. For example, etching can be used to remove the metal coating present on the photovoltaic cell. Older photovoltaic cells contained silver in the back metal coating. In case of this procedure, silver is dissolved in acid and it can be recovered by means of acid electrolysis [25].
6. Conclusions
Nowadays, there has been pressure to reduce the environmental burden and to use primary raw materials in an economic way. This is the reason for the continuous development and search for new materials using mainly recycled secondary raw materials. The issue of recycling photovoltaic cells has so far been addressed only marginally due to the low production of such waste. However, the lifetime of the first types of photovoltaic cells is coming to an end, which will increase this type of waste and put its recycling in the centre of attention. This increase motivates research teams around the world to develop new and sustainable methods of using recycled photovoltaic cells as a secondary raw material.

7. References
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