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Solar photovoltaic tree and its end-of-life management using thermal and chemical treatments for material recovery

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\textbf{ABSTRACT}

Solar photovoltaic trees (SPVTs) are chosen as an alternative option for electricity generation due to numerous benefits (especially in land utilization, urban infrastructure, and landscaping). Currently, SPVTs are available in many designs, and one among them is the novel phyllotaxy pattern. Technically, SPVTs seem to be more reliable and cost-effective. The expected average lifetime of the photovoltaic (PV) modules used in SPVTs is around 25 years. Once, the lifetime is over, these SPVTs must undergo a waste management process, and the scope for recycling is very high. Even though the scope for PV waste recycling is very high, many recyclers face the problems especially in estimating material recovery potential. In this paper, thermal and chemical treatments based end-of-life (EOL) method is used to estimate the material recovery potential from the phyllotaxy pattern-based SPVT. Initial estimations on the total embodied materials of the SPVT system is evaluated based on the components material fraction. Next, under the applied EOL management method, material recovery potential is estimated as per the material (aluminum, copper, glass, silver, and steel). Lastly, a few limitations with this EOL method are highlighted, and presented results aim to serve as useful data for the recyclers to have decisions.

\section{1. Introduction}

The use of PV technology for electricity generation has turn out to be an attractive option in recent years. The technological advancements seen in the photovoltaics are tremendous, and mostly they are in line with the industrial, commercial, residential, and community's requirement [1]. Currently, there are many solar energy harnessing systems that include: conventional PV systems (ground and roof mounted) [2,3], building applied PV (roof and façade) [4,5], building integrated PV (sloped or pitched roof and façade) [4–7], submerged PV [8], floating PV [9], wavevoltaics [10], agrivoltaics [11], aquavoltaics [12] and solar PV tree (SPVT) [13,14]. Among these systems, SPVTs are becoming a popular option for electricity generation in recent years due to the benefits seen in terms of land footprints [13,14]. Electricity from the SPVT is an emerging clean source, especially in urban areas where the PV systems of large capacities are not possible to set up due to space constraints [14]. A unique blend of technology and art can be seen in the concept of SPVT [15]. An SPVT utilizes the technology of solar power, along with some artistic aesthetics. The components of an SPVT includes PV modules, electric wires or cables, inverters, batteries, steel structures, and charging points [13]. A typical SPVT

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structure consists of an edifice in which the solar PV panels are attached as leaves [16]. The main structure of the SPVT is made of steel or any other suitable material and on top of which solar PV panels are placed [16,17]. This structure can be used for charging the batteries of the street lights, and in some cases can be used for charging electric vehicles (EVs). One of the best features regarding the SPVT is its ability to generate electricity all over the day since the PV modules inclined at different angles [18]. Primary purposes behind the development of SPVT’s includes the promotion of awareness of sustainable energy, the energy efficiency improvement in a solar PV system using a structure that replicates a natural tree. SPVT’s are capable of harnessing energy more effectively and that too, with reduced land area [16]. From the above statements, the SPVT option seems to be more reliable, cost-effective, and sustainable in terms of electricity generation.

The promotion of this system is one of the sustainable initiatives, but what would happen to the SPVT’s sustainability if their waste is not handled correctly is a question. At present, the widely used PV technology is the crystalline silicon, and the average lifetime of a crystalline silicon PV module is usually considered as 25 years [19,20]. It is presumed that the first batch of PV modules installed in the 1980s has already retired [21]. There is a need for managing the retired PV modules, and in some cases, PV modules are removed before the retirement due to the reasons: mechanical damages caused to PV modules during the transportation, installation. In general, there are two levels at which PV wastes are generated. They are ‘in-plant generated PV manufacturing waste’ and ‘end-of-life PV modules waste’, and currently in this study, only ‘end-of-life PV modules waste’ is considered. It has been projected that PV waste generation by 2030 will be 1.7 million tonnes and 60 million tonnes by 2050. According to the study presented in Ref. [19], from a PV module weighing 20 kg, it is possible to recycle 19 kg of useful materials, and this signifies the enormous potential of PV waste recycling. However, a difficult task would be to engineer optimal recycling technology and combat high investment costs. The study presented in Ref. [22] shows that 97% of the materials used in the manufacturing of thin-film modules can be extracted and reused by the process of thermal recycling. On the other hand, recycling of silicon modules is much more complicated that requires disassembling of the modules which can be done either mechanically or manually. In a recent study, demanufacturing strategies for crystalline PV modules are discussed, where the method related to EOL management are highlighted focusing on the industrial perspective [23]. A recently published review on the PV waste recycling presents a detailed summary of the various process currently available concerning the PV technology. In addition to recycling methods, the review concentrated on global legislation related to PV recycling [24]. The study presented in Ref. [25] proposes a new procedure to recover the valuable resources available in PV waste. Their proposed method starts with the recovery of tempered glass materials by using organic solvents; following this, other essential materials are recovered. While the recovery of other materials in their maximum possible purest forms, they treated the residual waste using chemical etching process and this chemical etching solution allows them to remove the metal impurities from the solar cell surface.

The objective of this study is to report the possible material recovery potential from the EOL management of SPVT’s. In this study, thermal and chemical treatment based EOL method is used to estimate the recovery potential of materials used for manufacturing the photovoltaic modules such as glass, aluminum, steel, copper, and silver. The article is organized in four different sections: the first section is the introduction briefing the background about the SPVT’s and EOL of PV. Section-2 briefs the 3/8 phyllotaxy pattern based novel SPVT design, and the thermal and chemical treatment based EOL method. In section-3, the estimated results are presented, and the discussion is carried out along with the limitations. Finally, in section-4, concluding points of this study are highlighted.

2. Materials and methods

The studied SPVT consists of several components, and these include crystalline solar PV modules, polyvinyl chloride (PVC) trunk structure, aluminum strips, wooden base, cable, and other accessories. These components are clearly shown in Fig. 1. The selected PV modules (specifications are given in Table 1) for the solar tree design are containing crystalline silicon solar cells. The overall dimensions of the PV panel are 185 mm × 185 mm × 175 mm (length, width, and thickness), see in Fig. 1. (a). The weight of the single PV module is 1150 g, and the total weight of 8 PV modules used in the SPVT system is around 9200 g. In general, the conversion efficiency of the crystalline PV is in the range of 13–18%. Exactly 72.4-inch length polyvinyl chloride (PVC) based pipe is used as the main trunk of the solar tree, see in Fig. 1. (b). The weight and the diameter of the PVC main trunk are 1000 g, and 4 inches respectively. On the main trunk, provisions are made to arrange PV leaf branches with the help aluminum strips shown in Fig. 1. (c).

![Fig. 1. Main components of the solar tree: a). Solar photovoltaic panel; b). Aluminum strips; c). Polyvinyl chloride (PVC) rod; d). Wooden base structure to hold the solar tree model.](image-url)
Here, the PV leaf branch arrangement is made by estimating the angle between each branch based on the design (refer to section 2.1 for this method). Eight aluminum strips having different lengths are used as branches, and they weigh approximately 960 g. To hold the weight of SPVT, a wooden block shown in Fig. 1. (d) weighing 1500 g is used.

2.1. Phyllotaxy pattern based SPVT

The concept of SPVT design is mostly bio-inspired. In most cases, SPVT’s are considered as the decorative means of solar power generators, primarily used as an attraction in the urban landscaping [13,14]. As discussed previously in SPVT, the solar PV modules are arranged in the form of leaves to an edifice. Phyllotaxy pattern is also one of such leaf arrangement in the plants, where all the leaves are arranged to a stem in a spiral manner [16,27,28]. The developed SPVT used in this study is based on the bio-inspired phyllotaxy design. There are three phyllotaxy patterns, namely, Opposite Phyllotaxy, Whorled Phyllotaxy, Alternate Phyllotaxy [16]. For more details about the three types of patterns, refer to the work mentioned in this [16]. Among the three, Alternate Phyllotaxy pattern is the most commonly seen one. Plant species such as Araucaria, potato, yucca, sunflower, rose, poplar tree, etc. comes under the Alternate Phyllotaxy pattern category. In this type of pattern from each node, only one leaf grows on the stem [27]. Inspiring from the Alternate Phyllotaxy pattern, a solar tree is designed in this paper. As we already knew that, in the Alternate Phyllotaxy pattern, only one leaf grows from each node, similar to this passion, only one solar panel is placed for each node [16]. With this, a 3/8 phyllotaxy pattern based SPVT is designed containing eight PV modules of each 3 W (the total peak capacity of the SPVT is 24 W) in three spiral arrangements. A PVC pipe is used as the central trunk for the SPVT. Different nodes are considered on this main trunk using a simple methodology (briefly mentioned in few steps below) to place solar panels onto the aluminum support structure used as the tree branches. The schematic of the developed SPVT experimental prototype is shown in Fig. 2.

The following methodology is used to optimally place the solar PV modules in the solar tree design [16].

![Fig. 2. 3/8 phyllotaxy pattern based solar photovoltaic tree (SPVT).](image)
Select one of the phyllotaxy patterns such 1/3, 2/5, 3/8, etc., (in this study 3/8 is selected) and evaluate the angle between each branch (say for example, if we selected the 3/8 pattern, the tree has 8 branches). Using Equation (1), we calculated the angle between each SPVT branch:

\[
\text{Branch angle} = \frac{3}{8} \times 360^\circ = 135^\circ
\]

Arrange the first branch and consider it as the reference point to arrange the rest of the branches (consider the first branch preferably from the top of the SPVT’s main trunk).

Arrange the second branch of the SPVT at an angle of 135° in clockwise or 225° in an anticlockwise direction to the first branch. In similar passion arrange other branches considering the branch angle.

Once, all the PV branches are arranged, we need to adjust the tilt angle of the PV module considering the geographical situation of the location. There are few ways to identify the tilt angle either by simulation, experimental, or the near to latitude angle. Here the tilt angle is chosen based on the PVsyst simulation studies.

2.2. EOL management using thermal and chemical treatments

End-of-life management of SPVT is done by using the thermal and chemical treatment scenario followed by the dismantling procedure. In the first step, the SPVT is dismantled as per the components (for example, dismantle the SPVT into PV modules, aluminum strips, PVC pipes, etc.). Once the dismantling process is finished, the PV modules are set to undergo thermal and chemical treatments. Here, the thermal and chemical treatments of PV modules are done separately, and the material recovery process is described in detail by Park et al. in Ref. [29], and Duflou et al. in Ref. [23] and shown in Fig. 3. Before the thermal treatment process, the frame is removed from which most of aluminum and steel material can be recovered. Once the frame is removed, the junction box and cables are also removed from which most of the copper material can be recovered. Now, the remainder of the PV modules is made to undergo the pyrolysis treatment at \( \sim 400^\circ \text{C} \), and this allows us to break down the polymers used in the PV module assembly. These polymers include ethylene-vinyl acetate (EVA) and back sheet, i.e., polyethylene terephthalate (PET). With the thermal treatment process, the release of PV cells and the glass layer becomes easy. The separated PV cells are subjected to undergo the chemical treatment by using the HNO\(_3\) (nitric acid). The chemical treatments of PV cells allow us to recover the silver and copper metals, and the glass material. The detail description of how this chemical treatment is done is depicted in the literature by Huang et al. [30].

3. Results and discussion

The material composition of various components used in 24 W SPVT and the available potential recovery has been estimated. The summary of components by weight in grams and the weight of the embodied material for each component in grams are given in Table 2. The 24 W SPVT, approximately weights 12660 g and it is the cumulative weight of PV modules (9200 g), aluminum strips (960 g), PVC main trunk (1000 g), and wooden base (1500 g). Among these components, the PV modules consist of many materials, based on its design. Based on the PV module design architecture, various layers exist, and these include the frame, junction box and cables, encapsulant, back sheet, front glass, and the solar PV cell. The material composition of the crystalline SPVT PV array is estimated based on the data given by Duflou et al. in Ref. [23]. The embodied materials in SPVT are shown in Fig. 4.

3.1. Material recovery potential

The material recovery potential results from the studied SPVT system under the thermal and chemical treatments are given in
Table 2
The material composition of various components used in 24 W SPVT.

<table>
<thead>
<tr>
<th>Components in SPVT and their weights</th>
<th>Total weight of SPVT (grams)</th>
<th>Weight (grams)</th>
<th>The material composition of crystalline photovoltaic modules (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline photovoltaics</td>
<td>12660</td>
<td>9200</td>
<td>Crystalline photovoltaics</td>
</tr>
<tr>
<td>Aluminum strips to hold photovoltaics</td>
<td>960</td>
<td>1000</td>
<td>Back sheet</td>
</tr>
<tr>
<td>Central pole with polyvinyl chloride (PVC)</td>
<td>1500</td>
<td></td>
<td>Encapsulant</td>
</tr>
<tr>
<td>Wooden block as the solar tree base</td>
<td>1352.4</td>
<td></td>
<td>Junction box and cable</td>
</tr>
<tr>
<td>Frame</td>
<td>795.8</td>
<td></td>
<td>Frame</td>
</tr>
<tr>
<td>Junction box and cable</td>
<td>174.8</td>
<td></td>
<td>Junction box and cable</td>
</tr>
<tr>
<td>Encapsulant</td>
<td>262.2</td>
<td></td>
<td>Encapsulant</td>
</tr>
<tr>
<td>Back sheet</td>
<td>176.64</td>
<td></td>
<td>Back sheet</td>
</tr>
<tr>
<td>Front glass</td>
<td>5474.92</td>
<td></td>
<td>Front glass</td>
</tr>
<tr>
<td>Solar cell</td>
<td>167.44</td>
<td></td>
<td>Solar cell</td>
</tr>
<tr>
<td>Aluminum</td>
<td>184.92</td>
<td></td>
<td>Silicon</td>
</tr>
<tr>
<td>Steel</td>
<td>183.08</td>
<td></td>
<td>Silicon</td>
</tr>
<tr>
<td>Copper</td>
<td>11.04</td>
<td></td>
<td>Aluminum</td>
</tr>
<tr>
<td>Plastic</td>
<td></td>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td>Ethylene-vinyl acetate (EVA)</td>
<td></td>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td></td>
<td></td>
<td>Silver</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td>Glass</td>
</tr>
</tbody>
</table>
In PV modules, the front glass is the dominant element, and it contributes to nearly 59.51% of the PV module weight. In this study, the weight of EOL PV modules is 9200 g, in which 5474.92 g is contributed by the glass. There is a possibility to recover around 98% of the glass material when these PV modules are subjected to recycle using the thermal and chemical treatments scenario [30]. The maximum possible glass material recovery potential from a 9200 g PV waste is 5365.42 g.

Aluminum is used in the solar tree branches and the PV modules. Aluminum contributes to nearly 16.71% of the total PV module weight (out of which nearly 14.7% in the frame and nearly 2.01% in the solar cell). The weight of EOL PV modules is 9200 g, in which 1352.4 g and 184.92 g of aluminum are used in the frame and solar cell, respectively. Apart from this, while arranging the solar modules to the main trunk, nearly 960 g of aluminum is used. With this, the cumulative of aluminum used in SPVT becomes 2497.32 g. PV modules and branch strips, when subjected to recycling using the thermal and chemical treatments scenario, nearly 86% of the aluminum, can recover [30]. The maximum possible aluminum material recovery potential from 2497.32 g of SPVT waste is 2147.7 g.

Steel is another material mostly used in the PV modules frame. The material fraction of steel in the frame is 8.65% in the total weight of the PV module. Here, EOL PV modules weight 9200 g, and it contains 795.8 g of steel. Under the thermal and chemical treatments recycling scenario, nearly 98% of steel material can be recovered [30]. The maximum possible steel material recovery potential from a 9200 g PV waste is 779.88 g.

Copper material is used in the junction box, electrical cables, and the solar cell. Copper contributes to nearly 3.89% of the total PV module weight (out of which nearly 1.90% in the junction box and cables and nearly 1.99% in the solar cell). The weight of EOL PV modules is 9200 g, in which 174.8 g and 183.08 g of copper is used in the junction box and cables and solar cell. With this, the
cumulative of copper used in SPVT becomes 357.88 g. Under the thermal and chemical treatments scenario, nearly 85% of copper material can be recovered [30]. The maximum possible copper material recovery potential from 357.88 g of SPVT waste is 304.2 g.

Among the various materials present in the solar cell, silver is the one. The material fraction of silver in a solar cell is 0.12% in the total weight of the PV module. Here, the EOL PV modules weight 9200 g, and it contains 11.04 g of silver. Nearly 74% of silver material can be recovered from the solar cells under the thermal and chemical treatments scenario [30]. The maximum possible silver material recovery potential from a 9200 g PV waste is 8.17 g.

3.2. Limitations

The current study has not focused on recovering certain materials due to lack of data, and these are shown as limitations:

- The recovery potential of silicon and EVA materials from the solar cells are not provided here due to the lack of data. The removal of EVA is possible when the PV waste is treated by a few methods such as thermal decomposition and dissolution by using nitric acid. However, this process has a few disadvantages such as cell defects, and the release of harmful emissions [24]. Hence, the recovery of EVA is not possible entirely. On the other side, there is a chance for metal impurities on the surface of solar cells, and this limits the recovery of silicon.

- We used electrical cables to collect the power outputs of the SPVT system, and these cables consist of copper material which is not considered in the study.

- In the design of SPVT, a wooden block is used as a base supporting structure. In general, the wood material may deform over the lifetime and later can be served as a useful material in many applications (for example, as a fuel in heating applications). However, here the quantity of wood material used in the SPVT experimental prototype is very less, hence the recovery of it is considered as negligible.

4. Conclusions

This article provides a preliminary study on the possibility of EOL management of solar photovoltaic tree. While EOL management, the scope for material recovery from the SPVT’s system is identified. Also, the total embodied materials based on the material fraction of various components is presented. Once the embodied material quantity is identified, the possible recovery potentials are estimated by using thermal and chemical treatment scenarios. We believe this article serves as a suitable material for the PV waste managers to have decisions related to material recovery from any PV system. It is strongly advised to use EOL management methods in managing the PV waste and contribute to reducing the environmental impacts.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2019.100474.

References
