Cost-benefit Analysis: Solar Panel Recycling

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Executive Summary

This project compared the six delamination methods, which is a part of the solar panel recycling process, from financial and environmental perspectives. Our team gathered raw data and came up with our own algorithm in evaluating the efficiency of each method. In the report, we contained details in the algorithm design and showed our results at the end. We found that thermal treatment is the most economic and environmentally friendly delamination method based on our model. For an $1m^2$ solar panel, the cost of recycling for the delamination process using thermal treatment method is $0.047, which is a lost cost. However, the potential environment pollution problem is an important disadvantage that should be focused on. Apart from this result obtained from the financial-cost model, the carbon footprint model also helped us find the total amount of carbon footprint saved with each method. Based on the carbon footprint model, we found thermal treatment not only resulted in low cost, but also saved a great amount of carbon footprint. We combined these two models together and found thermal treatment brought about the lowest total cost in all six delamination methods. We think thermal treatment is the optimal way to deal with the delamination process for solar panel recycling, despite its disadvantages. The project is time-consuming because all raw data needs to be gathered from different resources. Sometimes, data can be confidential and could not be found online. Therefore, we only compared the delamination methods. In the future, comparisons of different methods for each individual element can also be made to give an overall best solar panel recycling method. The structure of the solar panel can also be re-designed in order to make the recycling process easier.

1 Introduction And Overview

As one of the most popular forms of clean energy, solar energy has been applied in a wide range, and has caused the high demand of solar panels. When people talk about photovoltaic (PV), it is always considered as a clean energy source. However, is PV really clean? The way solar panels produce energy: yes; solar panels themselves: no. Solar panels cannot last forever, and the average life-time for solar panels in the market is about 30 years (Deign, 2020). While PV systems are in high demand, it comes with high cumulative PV waste. If the panels are not collected and recycled properly, the metals in them might leach into the ground and cause damage to the environment (Shellenberger, 2019).

As Peplow has mentioned, “global photovoltaic capacity grew from 1.4 GW in 2000 to 760 GW in 2020.” (Peplow, 2022) We do have the methods to recycle solar panels nowadays, but they are not efficient and cost effective enough. We are sitting on a ticking bomb. By the end of 2030 it is estimated that the PV waste will increase to around 8 million metric ton and 80 million metric ton by the end of 2050 (Peplow, 2022). Figure 1.1 below shows this trend *(Peplow, 2022)*.

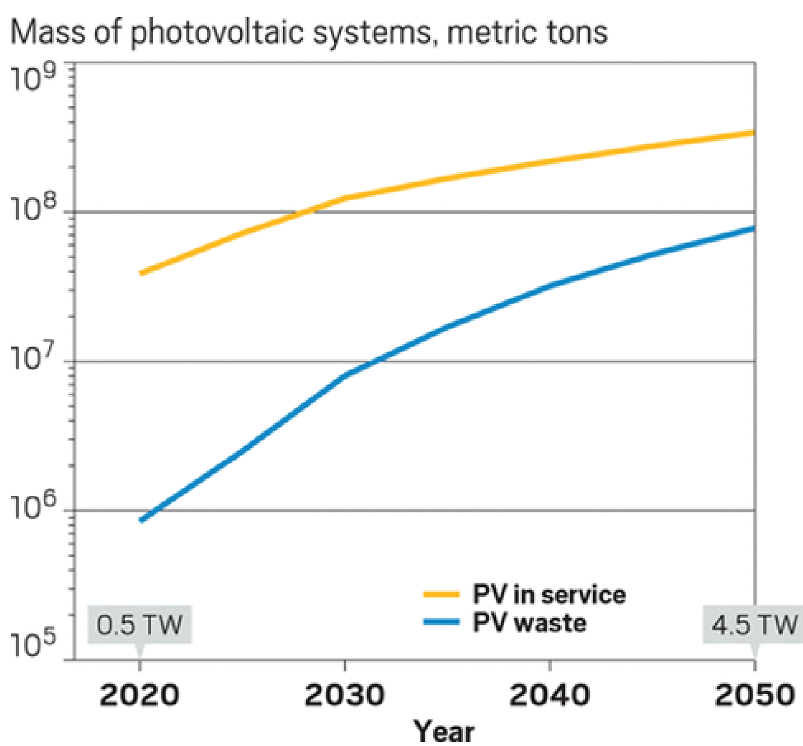

Figure 1.1: plot that shows the change of mass of photovoltaic systems in the future

Deign (2020) mentioned that about 90% of the after-life PV panels in the U.S. were being landfilled, instead of being recycled, by the time of 2018. Why were only 10% of the solar panels being recycled? One of the reasons is the lack of regulation policies. Even though California passed SB-489 in 2015, this policy only prevented wasted solar panels from being trashed or landfilled. No guidelines were given on the proper way to recycle solar panels (Pickerel, 2018).

Another reason for the low rate of solar panels recycling is that the action is not profitable. According to NREL it takes about \$15 - \$45 to recycle solar panels but it takes \$1 - \$5 to dump it (Peplow, 2022) There are different methods of recycling for one kind of PV panel, not to mention that there are several kinds of PV panels. It is difficult for factories to recycle all solar panels with the same process, especially because there are hazardous elements in these panels. In addition, because of the technical and environmental issues in the current recycling industry, not all materials in the solar panels can be reused afterwards. The recycling process itself might cost more than the value of reusable parts (Cucchiella, et al., 2015). Take the EU (European Union) for example, most facilities merely harvest the bulk materials which are aluminum and silicon which make up 80 percent of the weight of the solar panels. The remaining amount is incinerated.

Therefore, finding a balance between profitability and sustainability in solar panel recycling is essential in improving the recycling process. The aim of this paper is to analyze the economic impacts and the environmental impacts of different PV recycling techniques of c-Si and determine which technique is the best in terms of financial cost and carbon footprint dispense.

Figure 1.2 below shows the material distribution in solar panels *(Peplow, 2022)*. Solar panels are a sandwich structure with silicon cells between the glass. The layers are tight together to protect the silicon cells from weathering. The tough challenge is to separate them. Most recycling companies rather shred the PV-module after removing the Aluminum frame and sell the impure glass for a lower price. The whole business model of recycling just does not work.

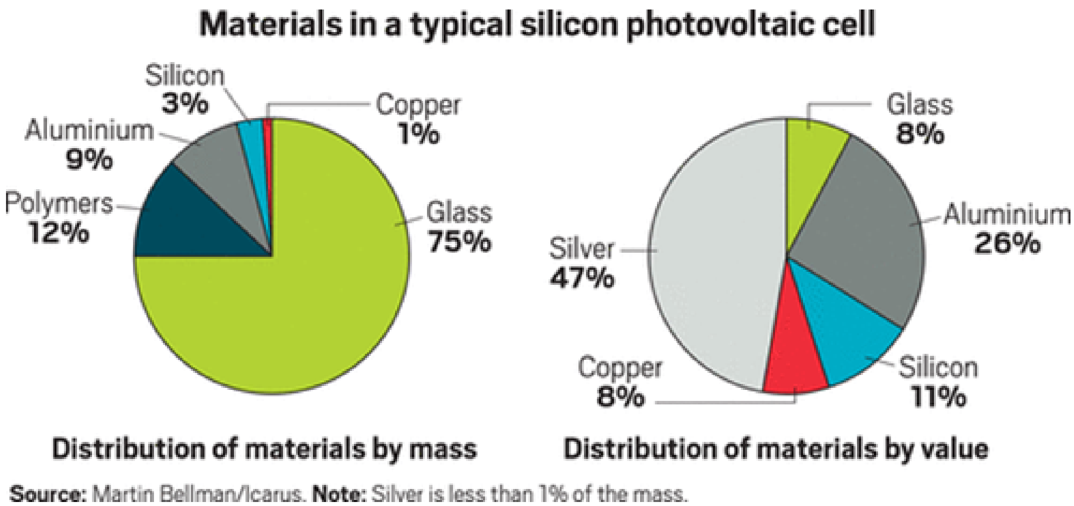

Figure 1.2: plot that shows the distribution of materials in the solar panel

In this project, the recycling process of crystalline silicon (c-Si) solar panels is researched. As mentioned in the introduction part, in order to find the optimal recycling process, the financial-cost model and carbon footprint model were created. In this project, five different elements, which are aluminum, silicon, glass, ethylene-vinyl acetate (EVA) and silver, of the solar panel are analyzed. They either occupy a high percentage in the composition of solar panels or have high unit prices. After determining these target elements, the overall procedure for recycling end-of-life solar panels is researched. Figure 1.3 below shows the flow chart for this recycling process.

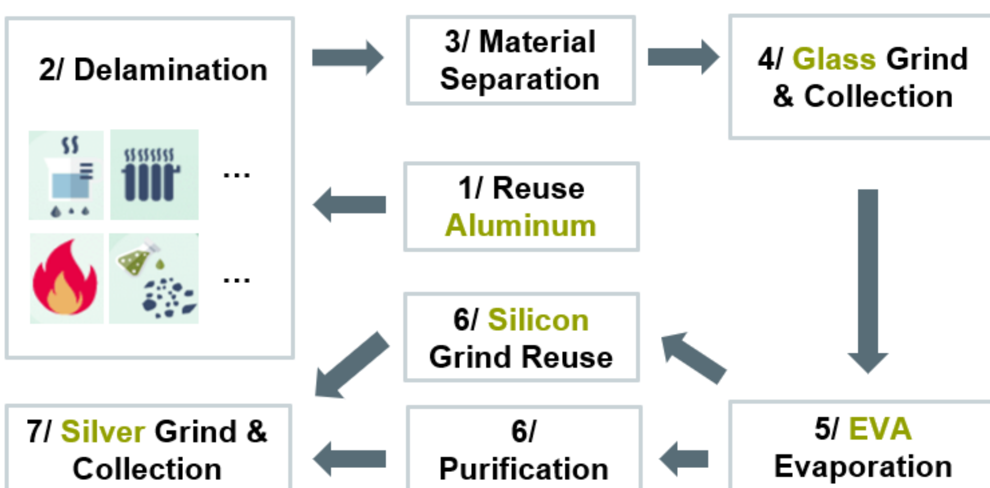

Figure 1.3 flow chart that illustrates the entire recycling process for solar panels

Based on this figure, it is clear that the first step is determining materials that can be directly reused without recycling. Since most of the aluminum in solar panels would be used to create the frame, which can be removed from the entire structure easily without damaging other elements, it should be dealt with at the beginning of the entire recycling process. The mechanical properties of the aluminum frame should be tested to ensure it could be used in new solar panels. After that, the delamination and material separation process are focused on. As Jiang has mentioned, “delamination occurs when laminated solar panel components are detached from each other.” (Jiang, 2020) It is not good for regular solar panels since that would influence the efficiency of the solar panels and reflect the cheap manufacturing. However, this process is really important for recycling solar panels. Without this step, materials inside the structure could not be separated from each other. Six different delamination methods were analyzed and compared in this paper with financial-cost model and carbon footprint model to get the optimal one. The material separation process always comes after delamination in order to complete final steps to separate materials. After delamination and material separation, materials inside the solar panel structure are separated and the recycling choices for themselves are researched. Most of them would be grinded or evaporated, but some purification steps could also be considered in order to get higher benefit.

There are six different ways for the delamination process that are studied: Nitric acid dissolution, solvent and ultrasonic irradiation, solvent dissolution, thermal treatment, electrothermal heating and pyrolysis. These methods require different amounts of electricity input and chemical products. These data are collected in order to calculate the final cost of financial and carbon footprint for each of them. For the material separation process, only one method named chemical etching is considered. For each separate element, our group focused on the initial state and final state. We used appropriate assumptions to study the amount of materials required at first and materials left for end-of-life solar panels. By doing the subtraction, we got the difference between these two states. Then we convert these data into total financial-cost and carbon footprint for these separated recycling processes of different elements. In this project, the carbon footprint is calculated based on the amount of released carbon dioxide. In order to get the final conclusion, we combine these two models together with an influence coefficient λ. This coefficient helps us convert the amount of carbon dioxide into corresponding financial-cost. Due to that, we can just use one equation to calculate the final result. This equation is shown below.

$$M = Cost + \lambda * Carbon\,Footprint \tag{1.1}$$

Where:

- $Cost$: the result (cost) from the financial cost model;
- $Carbon\,Footprint$: the cost from the carbon dioxide emission obtained from the carbon footprint model;
- λ: an influence parameter indicating the importance of the carbon cost. If setting λ to be large, more importance is attached to the environmental influence.

2 Methodology

2.1 Financial-cost Model

In the financial-cost model, the price for the delamination process and materials separation process are calculated. As mentioned before, the cost for these two processes would be calculated based on the amount of required chemical products and electricity. Due to that, the this part cost could be expressed as:

$$Cost(D + ME) = AE \times electricity\,price + ACP \times chemical\,product\,price \tag{2.1}$$

AE and ACP in this equation represent the amount of electricity and amount of chemical products, respectively. The recycling cost of five elements should also be included in the final model, and for elements that have more than one way for recycling, the equation would change based on the specific method that is selected. To illustrate it, for aluminum, if the company decides to reuse the frame directly, then the equation would be:

$$\Delta P(Al) = R(Al) \tag{2.2}$$

R(Al) here represents the recycling cost, which includes the cost for labor, machine and transportation. However, if the company choose to grind the aluminum and recreate the frame with recycled aluminum, then the equation would be:

$$\Delta P(Al) = R + TP_f(Al) - TP_i(Al) \tag{2.3}$$

Here $TP_f(Al)$ and $TP_i(Al)$ represent the material value for the final state and initial state, respectively. It means $TP_f(Al) = RR(Al) \times \%(Al) \times W \times P_f(Al)$, where RR(Al), %(Al), W and $P_f(Al)$ represent recycling rate for aluminum, weight percentage of aluminum in the solar panel, total weight of the solar panel and final price of aluminum per unit weight. Besides, $TP_i(Al) = \%(Al) \times W \times P_f(Al)$. $P_i(Al)$ here means the initial price of aluminum per unit weight. When we create this model we stand on the position for solar panel recycling companies or organizations, which means they need to pay the material cost for end-of-life solar panels, which is the final state. They also need to spend money for the recycling or purification process. Finally, after recycling, they can sell these initial state materials to other companies for benefit.

With the similar idea, the basic expression for the other four elements could be completed. They are shown below:

$$\Delta P(Si) = R(Si) + TP_f(Si) - TP_i(Si) \tag{2.4}$$

$$\Delta P(Glass) = R(Glass) + TP_f(Glass) - TP_i(Glass) \tag{2.5}$$

$$\Delta P(EVA) = R(EVA) + TP_f(EVA) - TP_i(EVA) \tag{2.6}$$

$$\Delta P(Ag) = R(Ag) + TP_f(Ag) - TP_i(Ag) \tag{2.7}$$

These four equations represent the recycling cost for silicon, glass, EVA and silver, respectively if they are grinded or evaporated. Among all of these five elements, apart from aluminum, silicon is another element that could be recycled in different ways. Based on the research of Heath, instead of reusing the grinded silicon directly, it could give companies higher economic benefit by purifying the recycled silicon in order to increase the quality of the recycled silicon to solar-grade silicon, whose purification level is at least 99.999% (Heath, et al., 2020). For this recycling choice, the equation for silicon would be:

$$\Delta P(Si) = R(Si) + TP_f(Si) - TP_i(Si) + C(purify) \tag{2.8}$$

C(purify) here represents the purification cost to increase the grade of silicon. Figure 2.1 - figure 2.5 below shows the calculation and model for aluminum recycling, silicon recycling, glass recycling, EVA recycling and silver recycling in detail.

Aluminum

Two major ways for recycling:

1. 100% recycle rate, grind the aluminum frame and get aluminum scrap
2. Test mechanical properties of the aluminum frames after 25 years. If they meet the requirement, then continue to use them for new solar panel

- $R_1(Al)$: Recycling cost for method 1
- $R_2(Al)$: Recycling cost for method 2

Initial State:

- W: Total weight of all panels in kg
- $P_i(Al)$: Initial price of aluminum per kg
- $TP_i(Al)$: Total price for initial aluminum
- %(Al): Weight percentage of Al in solar panel
- $TP_i(Al) = \%(Al) \times W \times P_i(Al)$

Final State:

- $P_f(Al)$: Final price of aluminum per kg
- $TP_f(Al)$: Total price for final aluminum
- $TP_f(Al) = \%(Al) \times W \times P_f(Al)$
- $\Delta P_1(Al)$: Cost for aluminum with method 1
- $\Delta P_2(Al)$: Cost for aluminum with method 2
- $\Delta P_1(Al) = TP_f(Al) + R_1(Al) - TP_i(Al)$
- $\Delta P_2(Al) = R_2(Al)$

Figure 2.1 illustration for the financial-cost model of aluminum element

Silicon

Two major ways for recycling:

1. 100% recycle rate, sell directly
2. 100% recycle rate, increase the purity to solar-grade silicon and reuse them

- R(Si): Recycling cost for method 1 and 2
- C(purify): Purify cost for method 2

Initial State:

- W: Total weight of all panels in kg
- $P_i(Si)$: Initial price of silicon per kg
- $TP_i(Si)$: Total price for initial silicon
- %(Si): Weight percentage of Si in solar panel
- $TP_i(Si) = \%(Si) \times W \times P_i(Si)$

Final State:

- $P_f(Si)$: Final price of silicon per kg
- $TP_{f1}(Si)$: Total price for final silicon with method 1
- $TP_{f2}(Si)$: Total price for final silicon with method 1
- $TP_{f1(2)}(Si) = \%(Si) \times W \times P_{f1(2)}(Si)$
- $\Delta P_1(Si)$: Cost for silicon with method 1
- $\Delta P_2(Si)$: Cost for silicon with method 2
- $\Delta P_1(Si) = TP_{f1}(Si) + R(Si) - TP_i(Si)$
- $\Delta P_2(Si) = TP_{f2}(Si) + R(Si) + C(purify) - TP_i(Si)$

Figure 2.2 illustration for the financial-cost model of silicon element

Glass

One major way for recycling:

1. 100% recycle rate, grind and get the scrap

- $R(G)$: Recycling cost for glass
- C_D: Delamination cost
- C_M: Material separation cost
- $R(Si)+R(G)= C_D+ C_M$

Initial State:

- W: Total weight of all panels in kg
- $P_i(G)$: Initial price of glass per kg
- $TP_i(G)$: Total price for initial glass
- $\%(G)$: Weight percentage of glass in solar panel
- $TP_i(G) = \%(G) \times W \times P_i(G)$

Final State:

- $P_f(G)$: Final price of glass per kg
- $TP_f(G)$: Total price for final glass
- $TP_f(G) = \%(G) \times W \times P_f(G)$
- $\Delta P(G)$: Cost for glass
- $\Delta P(G) = TP_f(G) + R(G) - TP_i(G)$

Figure 2.3 illustration for the financial-cost model of glass element

EVA

One major way for recycling:

1. 100% recycle rate, evaporating and collecting, but the recycled product has worse properties

- $R(EVA)$: Recycling cost for glass

Initial State:

- W: Total weight of all panels in kg
- $P_i(EVA)$: Initial price of EVA per kg
- $TP_i(EVA)$: Total price for initial EVA
- $\%(EVA)$: Weight percentage of EVA in solar panel
- $TP_i(EVA) = \%(EVA) \times W \times P_i(EVA)$

Final State:

- $P_f(EVA)$: Final price of EVA per kg
- $TP_f(EVA)$: Total price for final EVA
- $TP_f(EVA) = \%(EVA) \times W \times P_f(EVA)$
- $\Delta P(EVA)$: Cost for EVA
- $\Delta P(EVA) = TP_f(EVA) + R(EVA) - TP_i(EVA)$

Figure 2.4 illustration for the financial-cost model of EVA element

Silver

One major way for recycling:

1. 95% recycle rate, grind and get the scrap

- R(Ag): Recycling cost for silver

Initial State:

- W: Total weight of all panels in kg
- P_i(Ag): Initial price of silver per kg
- TP_i(Ag): Total price for initial silver
- %(Ag): Weight percentage of silver in solar panel
- TP_i(Ag) = $\%(Ag) \times W \times P_i(Ag)$

Final State:

- P_f(Ag): Final price of glass per kg
- TP_f(Ag): Total price for final glass
- TP_f(Ag) = $\%(Ag) \times W \times P_f(Ag)$
- ΔP(Ag): Cost for silver
- $\Delta P(Ag) = TP_f(Ag) + R(Ag) - TP_i(Ag)$

Figure 2.5 illustration for the financial-cost model of silver element

By combining all of these equations, we can get the total recycling cost for these five elements as:

$$P(elements) = \Delta P(Al) + \Delta P(Si) + \Delta P(G) + \Delta P(Ag) + \Delta P(EVA) \qquad (2.9)$$

The final financial-cost model could be created by combining this equation with the cost of delamination and material separation process. It means the final financial-cost model equation is:

$$P = \Delta P(Al) + \Delta P(Si) + \Delta P(G) + \Delta P(Ag) + \Delta P(EVA) + Cost(D + ME) \qquad (2.10)$$

Since the recycling price for each element would change hugely for different companies since they use different amounts of production lines and each of them have different labor cost and transportation cost, only the optimal delamination process for solar panel recycling was determined based on our model via the calculation with specific data obtained from references. We provide the model and equation to calculate the cost for recycling each element here, and the estimation for optimal recycling process for each element would be left as the future work.

2.2 Carbon footprint Model

2.2.1. Model Construction

When considering the environmental effect of the recycling process, it's natural to use the carbon footprint as the metrics. In this model, to be more specific, the carbon dioxide emission (CO2e) is used.

While it's natural to compare the CO2e from the industrial process, in this project it's better to compare the ***saved*** carbon instead of the produced carbon, since the whole project is about recycling, which is supposed to reduce the carbon footprint compared to none-recycling process. The model is constructed as below:

$$C_i = C_{new,\,i} - C_{R,\,i} \tag{2.11}$$

Where

- $i = 1, \ldots 6$, representing the six different solar panel recycling methods analyzed, same as in the cost model;
- C_i : ***saved*** carbon from recycling via method i (comparing to without recycle) (kg CO2);
- $C_{new,\,i}$: ***saved*** carbon from recycling using method i, because less new material is produced (kg CO2);
- $C_{R,\,i}$: ***produced*** carbon from the recycling process itself, using method i (kg CO2).

Let's take a closer look at the two metrics on the right hand side.

2.2.2. Carbon saved from new production: $C_{new,\,i}$

This part is rooted in the comparison of recycling process versus non-recycling process.

As shown in the left part of *Figure 2.1*, when the solar panels are not being recycled, 100% of the solar panel will go to the waste disposal and to compensate for it, a new solar panel will be produced, which means 100% of the new material will be used. When the recycling is conducted, as shown in the right part of *figure 2.6*, with r being the recycle rate, less new material will be produced since we are recycling r% of the panel.

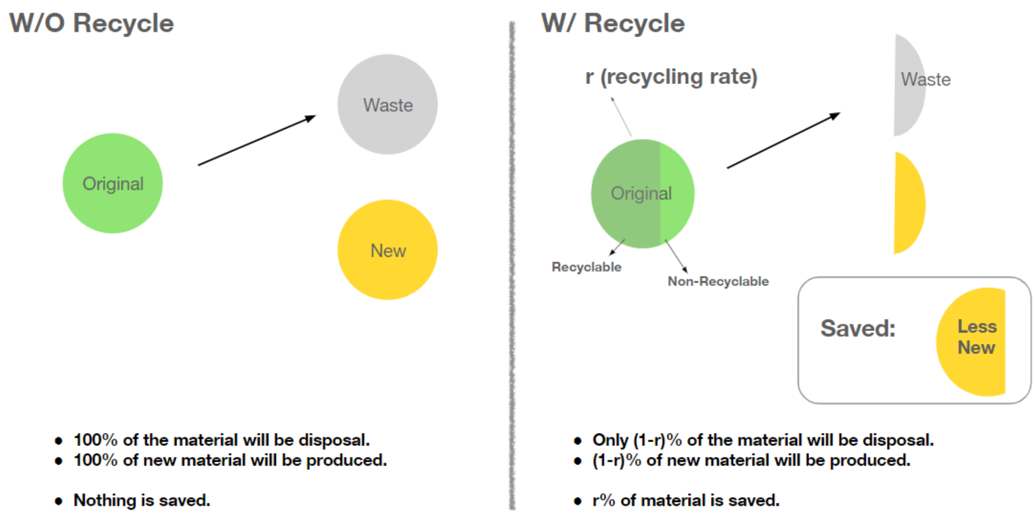

Figure 2.6 with recycling solar panel, less new material will be produced

Thus, $C_{new,\,i}$ is calculated as below:

$$C_{new,\,i} = \sum_{j}(r_j * w_j * TW) * CO2e_j \tag{2.12}$$

Where:

- j = 1, …3 represents the four major components of solar panel: glass, aluminum , and silicon;
- r_j : the recycling rate of component j (%);
- w_j : the weight percentage of component j;
- TW : the total weight of one unit of solar panel (kg).

- $CO2e_j$: carbon dioxide emission from producing one unit of new material j (kg CO_2 / kg material j).

Note that $C_{new,\,i}$ is the same for every method i, since in all six methods the recycling rate for each material is roughly the same, as well as the weight percentage. This part serves like a "base" of the equation: it saves carbon from the recycling process in contrast to non-recycling processes.

There's also some carbon saved in the waste disposal part, but the amount is tiny compared to the new material part, which can be ignored in this model.

2.2.3. Carbon produced during recycling: $C_{R,\,i}$

The carbon produced during the recycling process itself consists of two parts: the carbon from electricity usage and the carbon from burning EVA. Note that in all six methods, the EVA can be removed completely through thermal burning or dissolution. So the produced carbon from EVA is the same for all six methods.

$C_{R,\,i}$ is calculated as below:

$$C_{R,\,i} = E_i * ce + C_{EVA} \tag{2.13}$$

Where:

- E_i : the electricity used during the recycling process i (kWh);
- ce : carbon produced by one unit usage of electricity (kg CO2 per kWh electricity);
- C_{EVA} : carbon produced by burning EVA (kg CO2).

2.3 Final Metrics

In order to compare the methods and select the "best", the two models will be combined into one. To conduct this, we first transform the carbon into financial cost, using the social cost of carbon, which, as the Biden administration has announced in 2021, is estimated to be \$51 per ton (0.051 per kg) carbon dioxide (Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA), 2022).

To satisfy different needs, we assign the "importance" to the cost and the carbon footprint in the final metrics, shown as λ_1 and λ_2 in (2.15). They indicate how important the cost (carbon emission) is to the model user. If the user consider the environmental effect to be the priority in the recycling process, then λ_2 should be bigger in the model.

The final metrics is calculated as below:

$$TC = \lambda_1 Cost - \lambda_2 Carbon * 0.051$$

$$subject\ to: \lambda_1 + \lambda_2 = 1 \tag{2.14}$$

Where:

- TC : total "cost" of the recycling method (\$);
- $Cost$: financial cost of the recycling method (\$), calculated from the financial cost model;
- $Carbon$: saved carbon from the recycling (kg CO2), calculated from the carbon footprint model.
- λ_1: importance weight of the financial cost, default to 0.5;
- λ_2: importance weight of the carbon footprint, default to 0.5;

Note the negative sign before the carbon footprint part. This is because the carbon calculated represents the saved carbon from recycling, which can be considered as a "good" metric. On the other hand, financial cost is considered as a "bad" metric.

3. Result and Discussion

3.1 Data input

To compute the two metrics, the following data is gathered or calculated:

A. The weight of solar panel per m^2

In all the data and calculation below, the unit of solar panel is in 1 m^2. So first determine the corresponding unit weight of it. One industrial used solar panel is about 42 pounds, 66 inches long and 40 inches width (Solar panel size and weight explained - EnergySave, 2022), so the weight of solar panel per m^2 is:

$$\frac{42\ pounds \times 0.4536\ kg/pound}{(66\ inches \times 0.0254\ m/inch) * (\ 44\ inches \times 0.0254\ m/inch)} = 11.19\ kg/m^2 \qquad (3.1)$$

B. The weight percentages and recycling rates of solar panel components

The solar panels consist of five major components: glass, aluminum, silicon, EVA and silver. The weight percentages and the average recycling rates of each component is summarized in *Table 3.1*(Maani et al., 2020).

	Silicon	Glass	EVA	Silver	Aluminum
Recycling Rate (%)	100	100	100	95	100
Weight Percentage (%)	6.27	67.8	6.73	<1	16.9

Table 3.1 recycling rate and weight percentage of the five major components of solar panel

C. The required input for each delamination process

Table 3.2 ((Maani et al., 2020) shows the required input of the six major delamination processes we are analyzing, the data is in one-unit m^2 of solar panel.

	Nitric acid dissolution	Solvent and ultrasonic irradiation	Solvent dissolution	Thermal treatment	Electrothermal heating	Pyrolysis
Electricity (kWh)	0.45	7.14	/	0.45	4.17	25
Chemical input	HNO_3 46.2 kg	$C_6H_4Cl_2$ 46.2 kg	C_2HCl_3 46.2 kg	/	/	/

Table 3.2 required input for delamination processes

3.2 financial-cost model results

As mentioned in the methodology, the cost for transportation, labor and equipment would be quite different for different companies, as they have different locations and numbers of production lines. Therefore, we calculated the recycling cost for each element separately. Based on the recycling rate shown in table 3.1 above, the cost difference for materials in initial state and final state could be obtained by inputting the value of materials before recycling and after recycling. Then the R value could be obtained by combining the cost for labor, equipment and transportation based on the real situation of the company. After that, these data could be input in our model to help these companies get the recycling cost directly. In this project, we use the delamination and material separation part of the financial-cost model to get the optimal delamination process successfully. Based on the data in table 3.2, the amount of chemical products and electricity for each delamination method could be obtained with the electricity price and price for each chemical product. The result is shown in table 3.3 below:

Method	Electricity Input（kWh）	Cost from the delamination process ($)
Nitric Acid Dissolution	0.45	2633.05
Solvent and Ultrasonic Irradiation	7.14	1478.47
Thermal Treatment	0.45	0.05
Electrothermal Heating	4.17	0.43
Solvent dissolution	0.00	41.58
Pyrolysi	25.00	2.60

Table 3.3 recycling cost for each delamination method

The material separation cost could be calculated in the same way, and it is obtained as $605. All data is for the 1m^2 solar panel.

In order to get a clear comparison, these data are shown in figure 3.1 below.

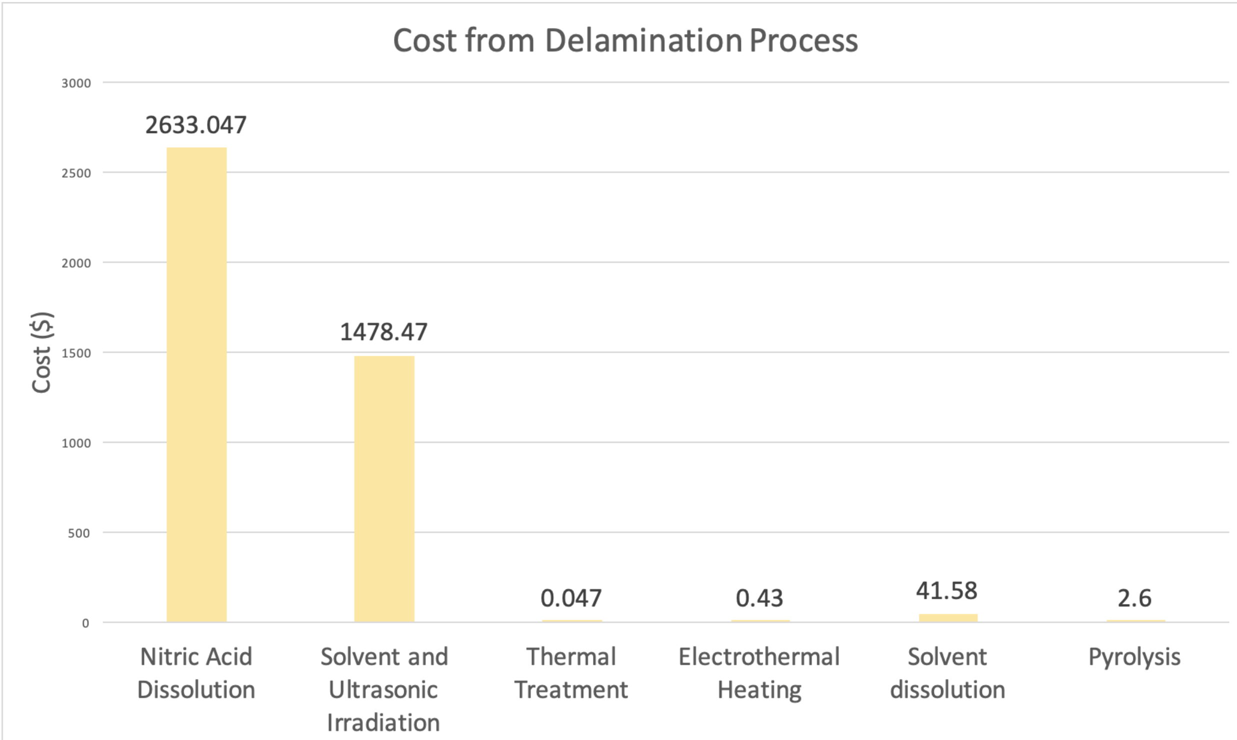

Figure 3.1 financial cost of using different delamination methods

Based on this plot, it is clear that thermal treatment and electrothermal heating have much lower costs. Among them, thermal treatment cost the least.

3.3 Carbon footprint model results

3.3.1 $C_{new,i}$

Recall that the saved carbon emission from less new material production is given by equation 2.13

$$C_{new,i} = \sum_j (r_j * w_j * TW) * CO2e_j$$

From table 3.1, it's shown that the three major components—glass, aluminum, and silicon— consist of more than 90% weight of the solar panel. They are also the most heavily carbon polluted in production compared to the other two components (EVA and silver). So these three elements will be the main focus of this part.

A. Glass

From 2018 to 2020, the average total production of glass in the United States is 12.3×10[6] tons(EPA, 2016), and the total CO2e from glass production is 15×10[6] tons(EPA, 2016). Using formula 2.13, the carbon saved from less new glass production in recycling 1m[2] of solar panel is:

$$100\% \times 67.8\% \times 11.19\, kg/m^2 \times \frac{15 \times 10^9\, kg\ CO2e}{12 \times 10^9\, kg\ glass} = 9.25\, kg\ CO_2/m^2 \quad (3.2)$$

B. Aluminum

In the industrial production process, producing 1kg of Al requires 2 kg of Al2O3, 0.46 kg C, and 16 kWh of electricity(Saevarsdottir, Magnusson and Kvande, 2021). In California, the carbon emission from 1 kWh of electricity is 0.85 pound CO2, which is equivalent to 0.3856 kg CO_2 / kWh electricity. So the total carbon dioxide emission from the production of 1 kg Al is:

$$(0.46\, kg\ C \times \frac{44\, kg\ CO2e}{12\, kg\ C}) + (16\, kWh \times 0.3856\, \frac{kg\ CO2e}{kWh}) = 7.86\, kg\ CO_2/\, kg\ Al \quad (3.3)$$

Using formula 2.13, the carbon saved from less new aluminum production in recycling 1m[2] of solar panel is:

$$100\% \times 16.9\% \times 11.19\, kg/m^2 \times 7.86\, \frac{kg\ CO2e}{kg\ Al} = 14.86\, kg\ CO_2/m^2 \quad (3.4)$$

C. Silicon

In the industrial production, the silicon is produced through the following chemical process:

$$SiO_2(s) + 2C(s) \Leftrightarrow Si(l) + 2CO(g) \quad (3.5)$$

So when 1mole of silicon is obtained, 2 moles of carbon dioxide will be produced. Thus, the CO2e companying 1 kg silicon production is:

$$(1kg\ silicon \times 1/14) \times 2 \times 44 = 6.29\ kg\ CO_2 \tag{3.6}$$

Using formula 2.13, the carbon saved from less new silicon production in recycling 1m^2 of solar panel is:

$$100\% \times 6.27\% \times 11.19\ kg/m^2 \times 6.29\ \frac{kg\ CO2e}{kg\ Si} = 4.41\ kg\ CO_2 \tag{3.7}$$

The total carbon saved from less new material production in recycling 1m^2 of solar panel is:

$$C_{new,i} = 9.25 + 7.86 + 4.41 = 28.52\ kgCO_2 \tag{3.8}$$

3.3.2 $C_{R,i}$

Recall that the CO2e in the recycling process is calculated using formula 2.14:

$$C_{R,i} = E_i * ce + C_{EVA}$$

A. $E_i * ce$

The electricity input for each delamination process is given in table 3.2. In California, the carbon emission from 1 kWh of electricity is 0.85 pound CO_2, which is equivalent to 0.3856 kg CO_2 / kWh electricity, So:

$$ce = 0.3856\ kg\ CO2e\ /\ kWh \tag{3.9}$$

B. C_{EVA}

EVA, or Ethylene-vinyl acetate, has a chemical formula $(C_2H_4)_n(C_4H_6O_2)_m$. The EVA used in solar panels is "low VA" type, meaning that the "VA ($C_4H_6O_2$)" only counts for 4% of the total molecular chain — n:m ratio is approximately 96:4. This simplify the chemical formula into $C_{46}H_{102}O_2$.

When burning EVA, all C in it will finally be stable in the carbon dioxide state. So the CO2e from burning 1kg of EVA is given by:

$$1kg\ EVA \times \frac{46\ C}{46\ C \times 12 + 102\ H \times 1 + 16\ O \times 2} \times 44 = 2.95\ kgCO_2 \tag{3.10}$$

In all six delamination methods, the EVA will be completely removed, so C_{EVA} is the same for all methods. The total carbon emission from burning EVA when recycling $1m^2$ of solar panel is:

$$C_{EVA} = 100\% \times 6.73\% \times 11.19\ kg/m^2 \times 2.95\ \frac{kg\ CO2e}{kg\ EVA} = 2.22\ kg\ CO_2 \tag{3.11}$$

The $C_{R,i}$ is summarized in table 3.4.

	Nitric acid dissolution	Solvent and ultrasonic irradiation	Solvent dissolution	Thermal treatment	Electrothermal heating	Pyrolysis
Electricity (E_i) (kWh)	0.45	7.14	/	0.45	4.17	25
ce (kg CO_2 / kWh)	0.3856	0.3856	0.3856	0.3856	0.3856	0.3856

CO2e from electricity usage (kg)	0.1732	2.7532	/	0.1732	1.6080	9.64
C_{EVA} (kg)	2.22	2.22	2.22	2.22	2.22	2.22
$C_{R,i}$ (kg)	2.3935	4.9732	2.22	2.3935	3.8280	11.86

Table 3.4 CO2e from recycling process, decomposition

3.3.3 Final result: C_i

The total saved carbon footprint using method i to recycle the solar panel is given by :

$$C_i = C_{new,i} - C_{R,i}$$

The two parts in the RHS have been calculated in section 3.3.1 and 3.3.2. The final results (C_i) is summarized in table 3.5 below.

	Nitric acid dissolution	Solvent and ultrasonic irradiation	Solvent dissolution	Thermal treatment	Electrothermal heating	Pyrolysis

$C_{new,i}$ (kg)	28.52	28.52	28.52	28.52	28.52	28.52
$C_{R,i}$ (kg)	2.3935	4.9732	2.22	2.3935	3.8280	11.86
C_i (kg)	26.12648	23.5468	26.3000	26.1265	24.6920	16.6600

Table 3.5 total saved CO2e using method i to recycle

Using the data from table 3.4, the total carbon saved from different recycling methods is shown in figure 3.2.

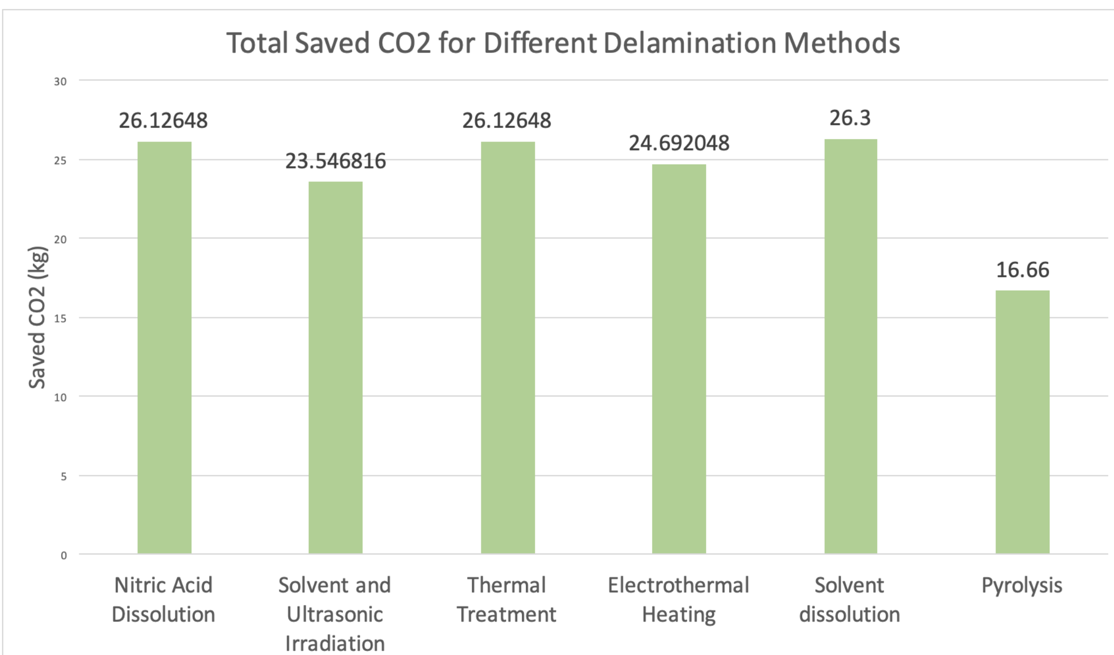

Figure 3.2 total saved CO2 of using different delamination methods

There are several take away from the result above:

- All six delamination have positive total saved CO2e, meaning more carbon is saved than being produced during the recycling process itself. So recycling solar panels can indeed reduce the carbon footprint compared to non-recycle processes.

- While there's no obvious difference between the saved amount of carbon for the first five methods, it's clear that Pyrolysis is the least environmentally friendly recycling method, mainly because it uses too much electricity.
- The Solvent Dissolution is the "greenest" with respect to the carbon dioxide emission, but its harmful bi-products which had not been taken into account in the model should not be ignored.

3.4 Overall Comparison

To combine the financial model and the carbon footprint model, both models need to have the same unit. The amount of saved carbon footprint was transformed into an amount of finance by using the social cost of carbon, 0.05 $/kg. After the transformation, the cost of carbon footprint was subtracted from the financial cost, and gave the total cost shown in the figure 3.3. As in the graph, thermal treatment is the "best" delamination method.

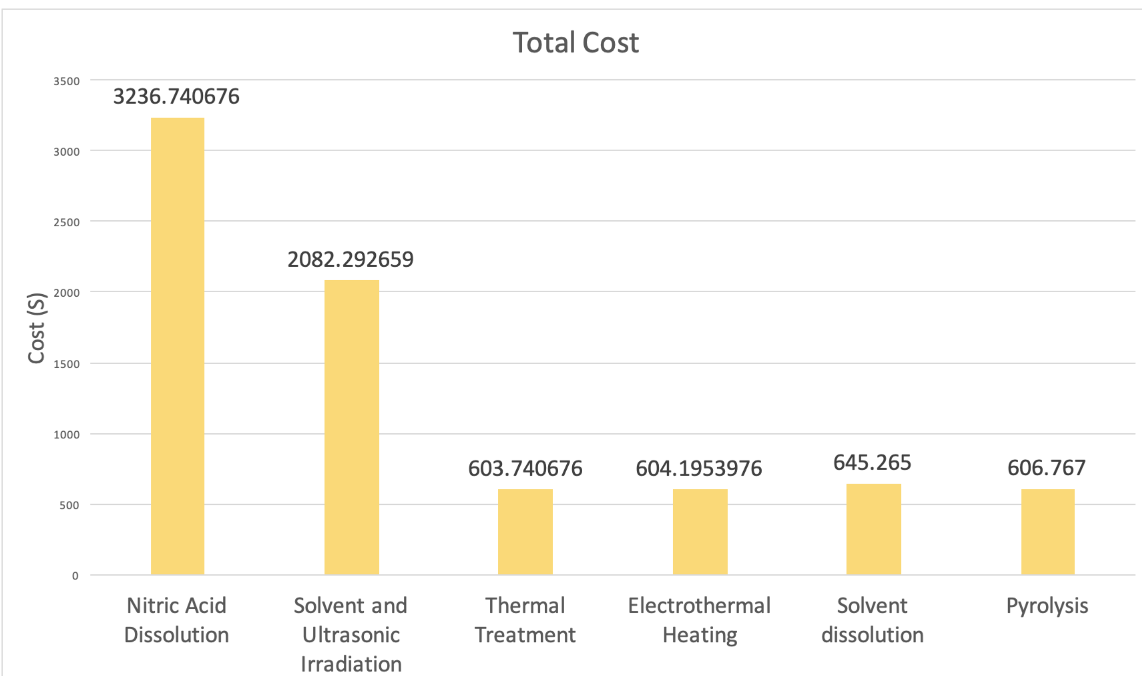

Figure 3.3 total cost of using different delamination methods

4. Conclusion And Future Work

The overall model can give a balanced estimation of the economic impact and environmental impact for each delamination method. Based on our model, thermal treatment has the lowest financial cost among the six delamination methods. On the other hand, solvent dissolution saved the most amount of carbon footprint, followed closely by nitric acid dissolution and thermal treatment. Overall, thermal treatment is the “best” delamination method.

As the recycling organizations might use different delamination methods nowadays, it is important for them to know the “best” delamination method so that they can start saving carbon footprint as well as making more profit. For future solar panel recycling projects, research can be done on the other steps in the recycling process, but not only focus on delamination. The in-depth research for each element could be done with a real solar panel. Besides, the structure of the solar panel could be re-designed in order to make the overall recycling process easier.

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