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Concept for Solar Panel Recycling based on High-Temperature Density Separation

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ABSTRACT

The ever-growing application of solar panels for renewable energy has resulted in a significant increase in solar panel waste that is both difficult to recycle and hazardous to the environment. In order to provide a potential solution to this problem, a novel recycling concept employing high-temperature density separation was developed. This was accomplished by firstly completing a thorough literature review on current recycling methods and calculating results using previous experimental and theoretical data. From the results, it was determined that high-temperature density separation has significant potential for making recycling a profitable practice for up to $290/tonne of solar panels. Compared to current recycling methods, high-temperature density separation possesses many benefits such as higher efficiency, potential for energy recovery, and lower environmental impact. This solar panel recycling solution has the potential to greatly improve the sustainability of the solar energy industry while also finding potential applications in other industries that require specialized processing of materials.

Introduction

Problem Statement

The steep growth of the solar energy industry has outpaced the capabilities of current recycling technologies, causing end-of-life solar panels to enter landfills which poses a serious threat to the environment (Fasching & Ray, 2022) (US EPA, 2021). Important factors of an economical recycling method include processing time, energy consumption, environmental impact, and profitability. Currently no mechanical, chemical, or thermal technology has achieved these requirements at a reasonable cost.

Background

Effective recycling methods are essential to achieving truly sustainable solar energy systems. Solar energy is the fastest-growing dominant renewable energy source today, making it an essential component of the goal to phase out fossil fuels in the coming decades (Fasching & Ray, 2022). However, the apparent sustainability of solar panels only exists during their operation, not after they have been decommissioned and become hazardous waste (US EPA, 2021). Therefore, a suitable recycling method is required to manage the waste resulting from the fast growth of solar panel production as seen in Figure 1 (Peplow, 2022). Currently, mechanical and thermal recycling technologies can only economically recover low-value materials such as aluminum and impure glass, making the incentive for recycling solar panels incredibly low (Strachala et al., 2017). Similarly, chemical recycling is not feasible due to the impractical processing time and inhibitive operation costs (Strachala et al., 2017). Resolving the imbalance between the rate of solar panel production and recycling requires a simple yet precise recycling process.

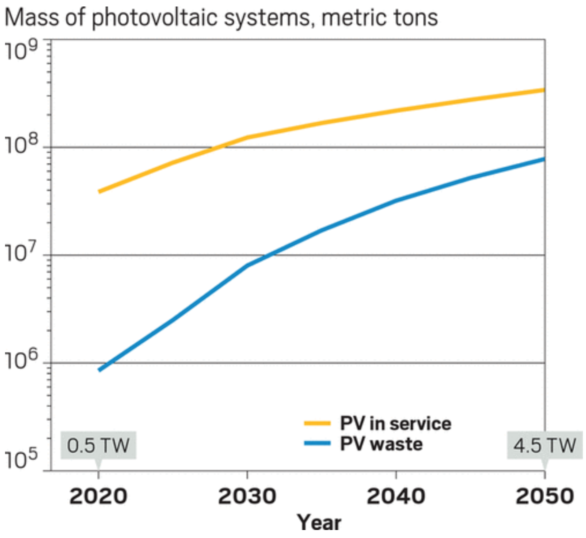

Figure 1. Mass of photovoltaic systems, metric tons (Peplow, 2022)

The difficulty of recycling solar panels is rooted in their manufacturing process. Solar panels are constructed to withstand physical and chemical threats of all weather conditions making traditional recycling tactics ineffective. The basic structure of solar panels is composed of layers of glass, solar cells, and ethylene vinyl acetate (EVA) polymer which are bound together by an aluminum frame (*How Are Solar Panels Made? | GreenMatch*, 2014). Materials such as glass and aluminum make up the majority of a solar panel but represent only a small percentage of the overall value (Deng et al., 2019). On the other hand, the small amount of silicon and silver in each solar cell makes up the majority of a solar panel's value (Deng et al., 2019). Therefore, the extraction of valuable materials is necessary for attaining a significant profit.

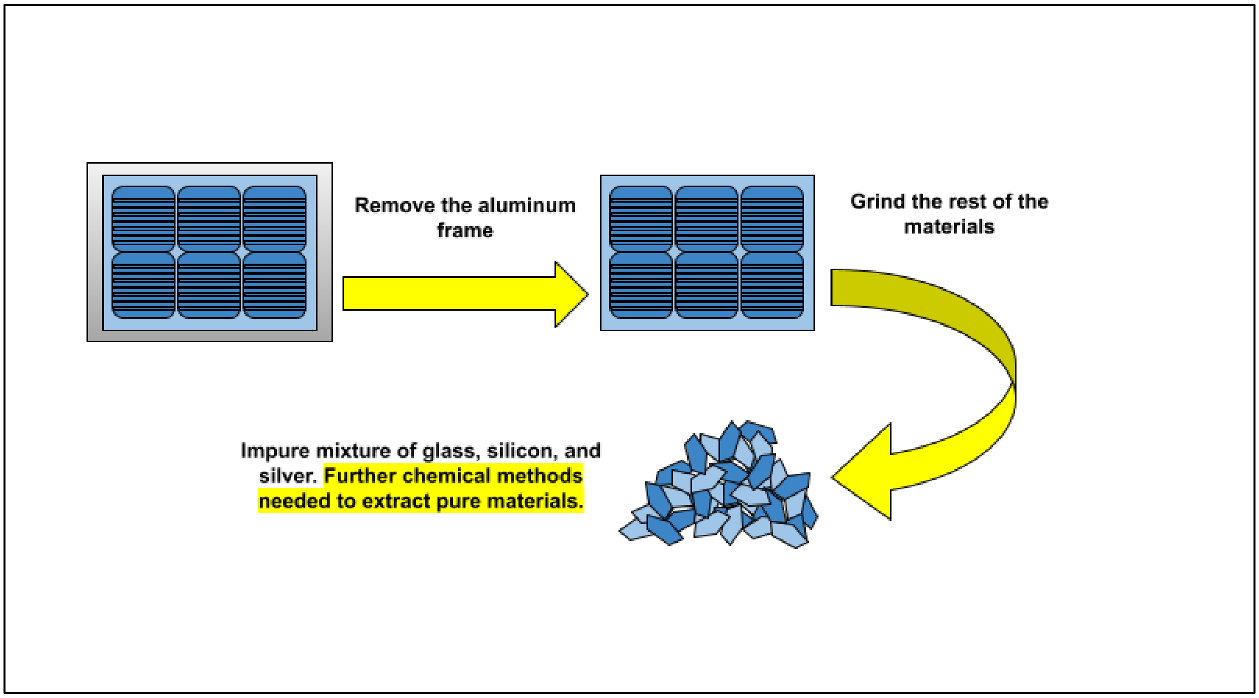

Figure 2. Diagram showing the steps of mechanical recycling.

As seen in Figure 2, current mechanical recycling of solar panels involves the disassembling of the aluminum frame and then crushing of the glass and solar cell layers into a granulated mix (Strachala et al., 2017). This process does not recover valuable materials and is therefore not economically viable. Furthermore, the glass and solar cell mixture is often considered a waste product due to its impurity and toxicity which does not resolve the issue of landfill pollution.

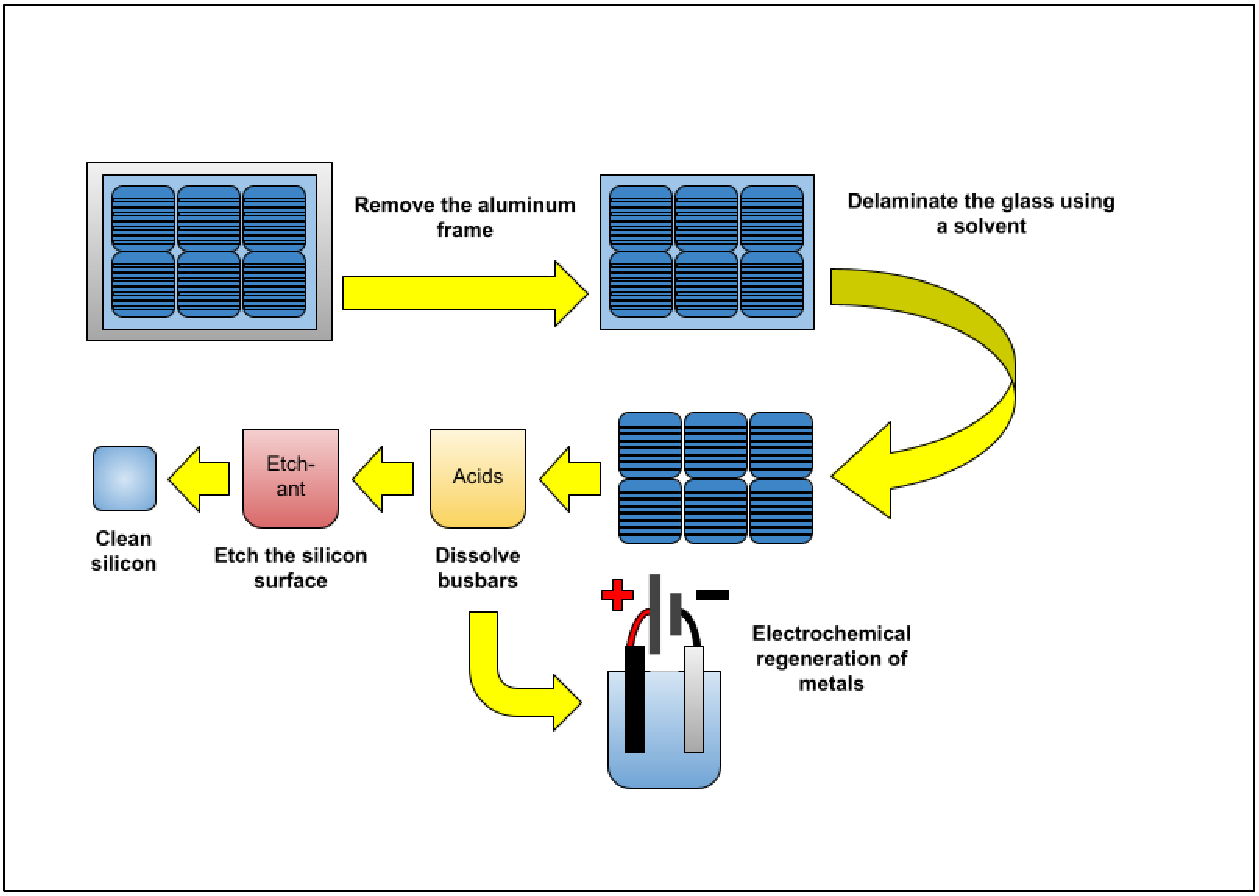

Figure 3. Diagram showing the steps of chemical recycling.

As seen in Figure 3, chemical recycling of solar panels allows the separation of the glass and solar cells by dissolving the encapsulating EVA in a solvent. The bus-bars on the solar cells are then removed in acid and the anti-reflection coating on the silicon is etched away (Strachala et al., 2017). The chemically dissolved silver busbars can be regenerated with high purity by electrochemical means. Although this process is capable of recovering high purity materials, the long treatment time and consumption of costly toxic etching chemicals do not make it an effective solution.

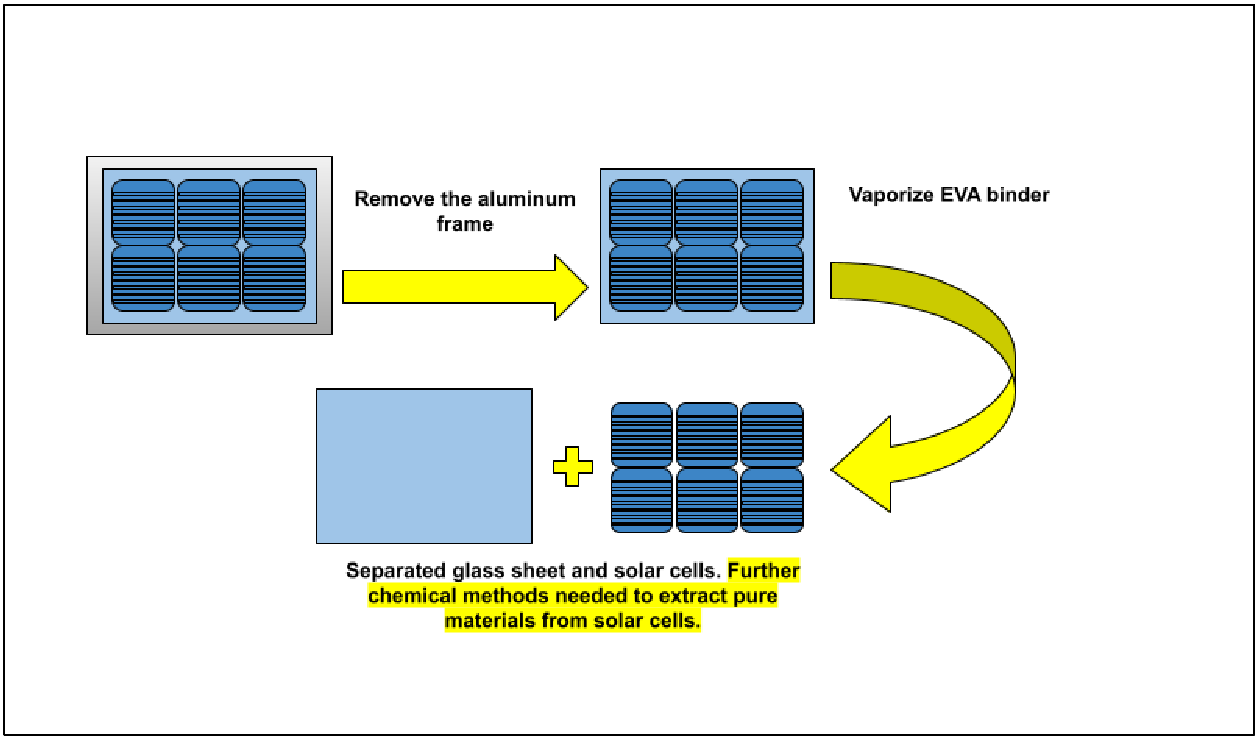

Figure 4. Diagram showing the steps of thermal recycling.

As seen in Figure 4, thermal delamination separates the glass from the solar cell array by evaporating the EVA encapsulant at high temperatures (Strachala et al., 2017). However, it is unable to further separate the solar cells into silicon and silver. Damaged solar cells must be further separated into raw materials, but functional solar cells can be reused without additional processing. The low complexity and high efficiency make traditional thermal recycling a feasible method even though it cannot extract high-value materials. One disadvantage however is that evaporation of EVA produces emissions that require additional steps to prevent damage to the environment.

The key processes implemented in this proposed solution include density separation, induction heating, and steam energy recovery. Density separation is the process by which materials can be organized due to differences in their densities. The process is commonly implemented in the coffee bean industry in the form of density tables which use air and small vibrations to sort beans by size (SEPARATION EXPERTS, n.d.). Also, the process can be observed when immiscible fluids such as water and oil are mixed but quickly form distinct layers. Induction heating is used to melt metals and glass by inducing strong electric currents inside the materials which become thermal energy. Once the desired result is attained, it is possible to recover energy during the cooling process by generating steam which can spin a turbine to produce electricity. The process of energy recovery essentially decreases the total amount of energy required to melt the initial materials thereby lowering energy consumption.

Literature review

Although the previously mentioned recycling processes are the most promising for commercial application, there are other novel solutions that are being researched. These include hot-wire cutting and laser irradiation (Lunardi et al., 2018). A new method that has already been adopted commercially for separating the glass sheet from a solar panel is hot-wire cutting. Hot-wire cutting separates the glass from the solar panel array by softening and cutting the EVA encapsulant. This allows for minimal energy consumption while separating the glass but requires further processing to remove the EVA residue after cutting.

A process being researched for removal of the glass and antireflection coating without damaging the silicon wafers of solar cells is laser irradiation. Laser irradiation separates the glass from the solar panel array by burning out the EVA encapsulant. It can be used to remove metallization and antireflection coatings on solar cells (Strachala et al., 2017). However, it is an extremely slow process and requires inhibitive expensive equipment.

Current commercial recycling processes often implement a combination of mechanical, chemical, or thermal treatments to fully disassemble a solar panel (Lunardi et al., 2018). This increased complexity translates to higher costs. For reference, the cost of landfilling solar panels is $64/tonne or $1.16/panel (Deng et al., 2019). The typical operation cost for mechanical recycling is approximately $399/tonne or $7.24/panel. Accounting for the value of recovered materials, the net cost for mechanical recycling is $76/tonne or $1.38/panel (Deng et al., 2019). The operation cost for solely chemical recycling is about $922/tonne or $16.73/panel but varies depending on the types and amounts of chemicals used. Accounting for the value of recovered materials, the net cost for chemical recycling is $269/tonne or $4.88/panel (Deng et al., 2019). The operation cost of a combination of thermal delamination and chemical recycling is around $1200/tonne or $21.77/panel. Accounting for the value of recovered materials, the net cost for thermal/chemical recycling is $235/tonne or $4.26/panel (Deng et al., 2019).

Although there is significant research on the active separation of solar panel materials, there is limited work being done on passive separation. The high complexity of active separation and sorting has made it difficult to drive down operating costs without sacrificing material quality. The passive recycling process proposed here has the potential to make solar panel recycling a worthwhile industrial practice.

Methods

Firstly, to design the solar panel recycling process, it was necessary to research the overall problem of solar panel recycling and the operation of current solutions. This was done to pinpoint the main obstacles preventing facile recycling from being accomplished. Developing a solution to current problems in solar panel recycling required an understanding of the material properties of each component. Specifically, in high-temperature density separation, the melting point, boiling point, miscibility, and density of each material were essential. Ensuring that the characteristics of each material were compatible with the others was necessary for evaluating the feasibility of such a recycling process.

The concept of using high-temperature density separation to recycle solar panels was inspired by other industries such as the coffee bean industry which sorts bean sizes on a density table. The separation of immiscible fluids was based on the interaction between polar and non-polar liquids such as water and oil.

Attaining the high temperature required for melting the materials in a solar panel required a heating method such as a gas, induction, or electric arc furnace. Firstly, the characteristics of each method were researched. Since each heating method had its own benefits and drawbacks, the one that matched best with the requirements of the recycling process was chosen. For a recycling process to be economical, the main aspects were processing time, energy consumption, environmental impact, and profitability (Strachala et al., 2017). The method that performed best in all categories was chosen.

Once the recycling process was finalized, the preliminary layout of a recycling plant could be designed. Since the first few steps were identical to current recycling methods, they were left untouched. The layout was made as compact as possible to take advantage of the simplicity of high-temperature density separation while also giving ease of access to the recovered materials.

In order to compare high-temperature density separation to current recycling methods, it was important to analyze environmental impact as well as calculate the energy consumption and operation cost. Utilizing data about material properties, it was possible to determine a theoretical amount of energy required to melt the components of a solar panel. This was converted into cost using the average US electricity price per kWh. The general equations used to calculate the energy consumption for melting the materials at 1415ºC were:

Equation 1: General formula for calculating thermal energy consumption of melting glass.

$$Q = mc\Delta T$$

Equation 2: General formula for calculating thermal energy consumption of melting silicon.

$$Q = mc\Delta T + m\Delta H_f$$

Equation 3: General formula for calculating thermal energy consumption of melting silver.

$$Q = mc\Delta T_1 + m\Delta H_f + mc\Delta T_2$$

The approximate 85% efficiency of induction heating was used to estimate the practical efficiency of the heating process (Ministry of Micro, Small & Medium Enterprises Govt. of India et al., 2015). The energy recovery process using steam was assumed to be from 65% to 90% efficient depending on the unit size (Darrow et al., 2015). To calculate the overall cost of the recycling process, the cost of high-temperature density separation was added to the cost of basic mechanical recycling. With the operation cost calculated, it was possible to estimate the profitability of the process by referencing values from other literature. Specifically, the profits from recovered materials were added to the operation and module collection costs. Once all significant results were obtained, the process was then compared to current technologies in terms of time, energy consumption, environmental impact, and profitability. The graphs for each data set were created in Google Sheets. Word values (Low, Moderate, High, etc.) were converted to integers between one and nine which enabled them to be represented in graphs. The sum of these integer values was used to determine the "process score" of each recycling process.

Results

Table 1. Table of material properties.

	Density (g cm^{-3})	**Melting temp. (°C)**	**Boiling temp. (°C)**	**Miscibility with other components**
Glass (soda-lime) (Karazi et al., 2017)	2.5	1000	3427	None
Silicon (Royal Society of Chemistry, 2011a)	2.3	1414	3265	1ppm silver in silicon (Weber, 2002)
Silver (Royal Society of Chemistry, 2011b)	10.5	962	2162	
EVA (*Overview of Materials for Ethylene Vinyl Acetate Copolymer (EVA), Adhesive/Sealant Grade*, n.d.)	0.95	80	Decomposes	N/A

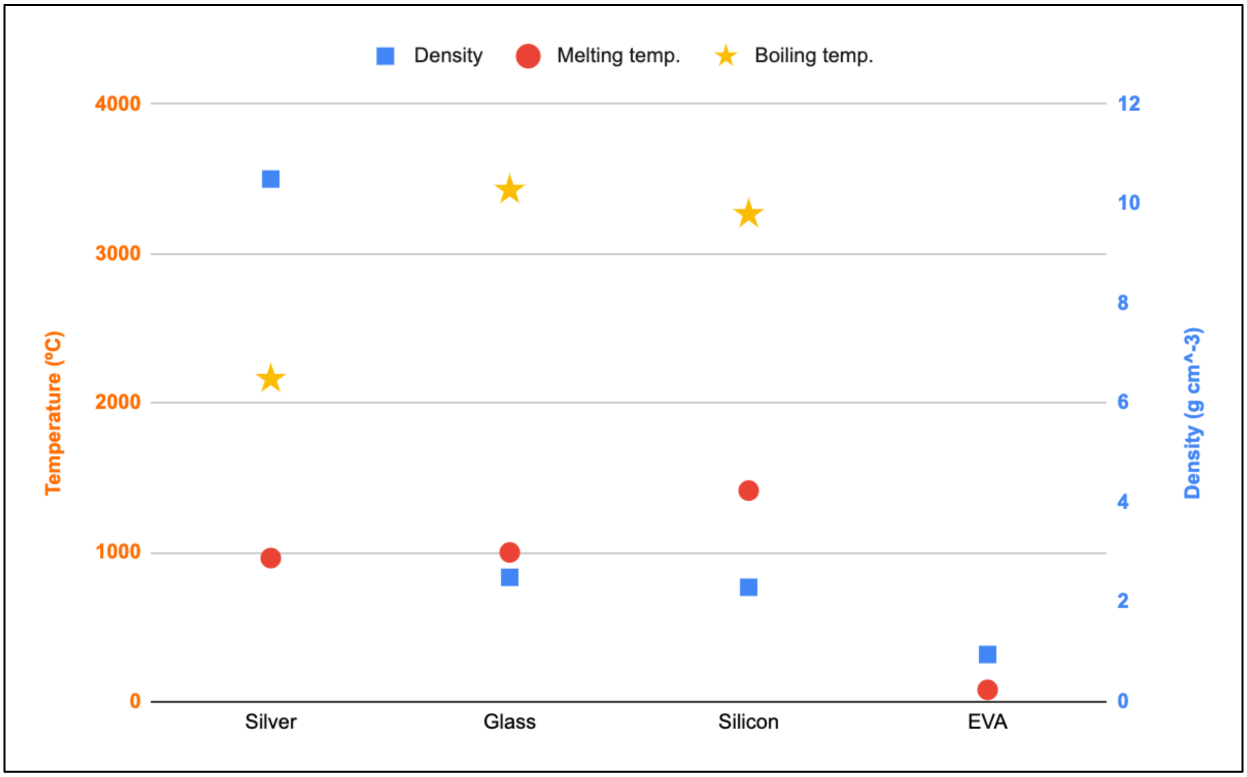

Figure 5. Graph of material properties.

Table 2. Table of heating methods.

	Heating time (Juxinde, 2022) (Win, 2020)	**Energy efficiency**
Induction	Very low	85% (Ministry of Micro, Small & Medium Enterprises Govt. of India et al., 2015)
Electric Arc	Low	60% (Kirschen et al., 2009)
Gas	Moderate	10% (Donskov et al., 2015)

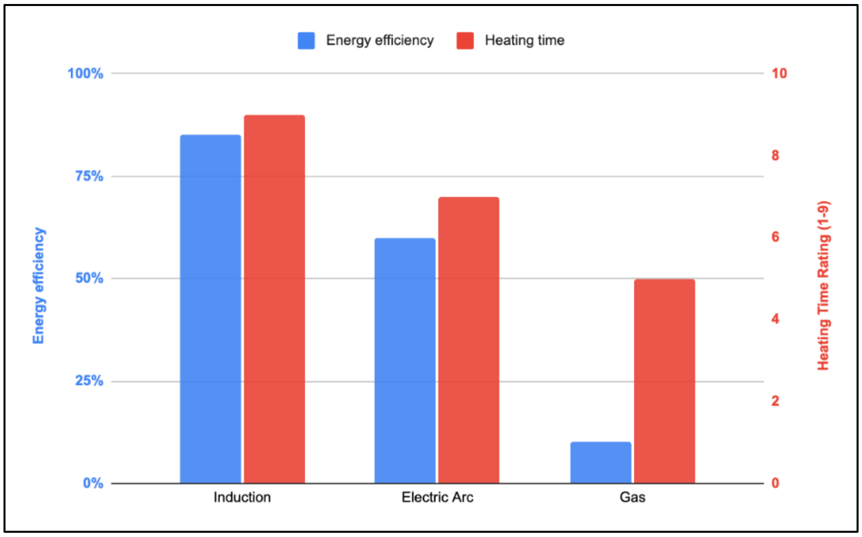

Figure 6. Graph of different heating method characteristics (Very low=9, Low=7, Moderate=5).

Gas heating is used in many applications because of its simplicity and compatibility with many materials, however, it has low efficiency and is harmful to the environment. On the other hand, induction and electric arc heating methods are more complex but significantly more efficient than gas. Furthermore, induction heating is capable of fast heating time. In metal industries, induction furnaces are the preferred method for melting raw materials (Ministry of Micro, Small & Medium Enterprises Govt. of India et al., 2015). The benefits of induction furnaces over other technologies are visualized in Figure 6. Induction heating was chosen for use in high-temperature density separation because it was fast, efficient, and environmentally friendly.

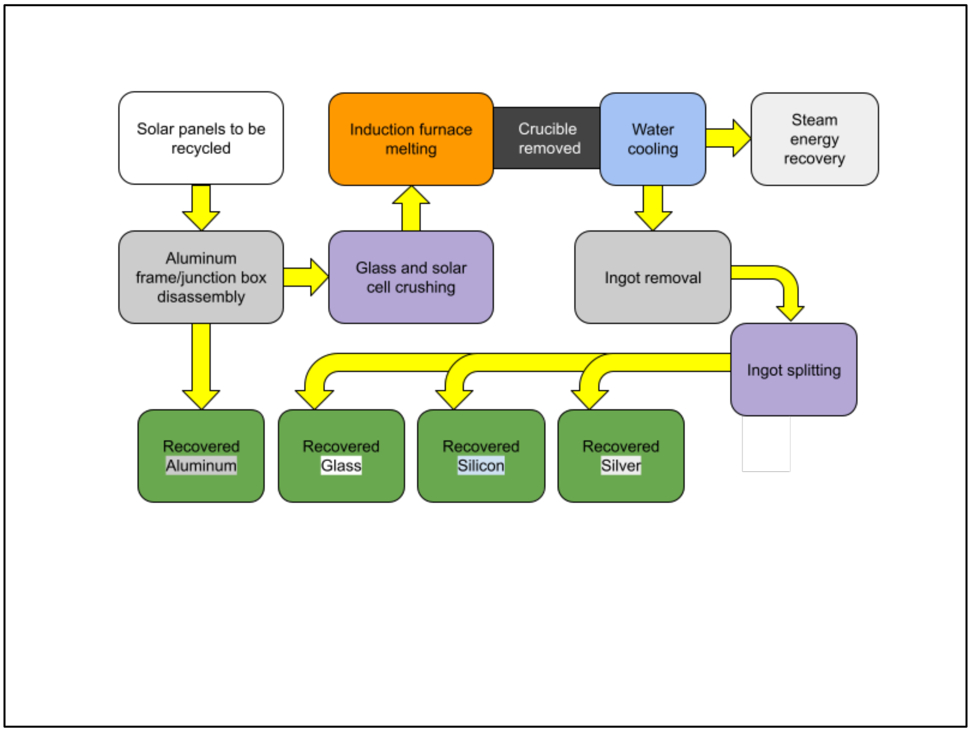

Figure 7. Preliminary layout design of a solar panel recycling plant.

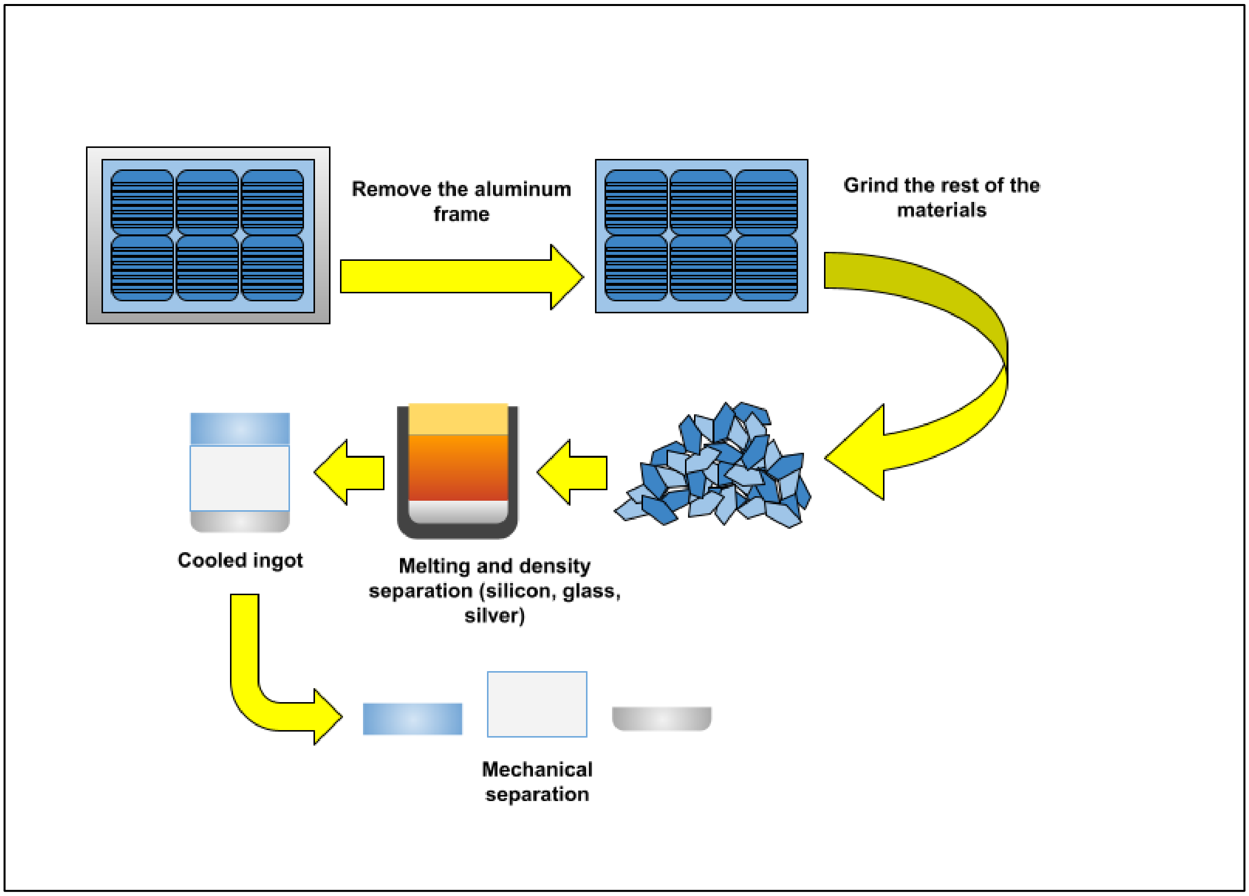

Figure 8. Diagram showing the steps of high-temperature density separation.

As seen in Figure 7, integrating high-temperature density separation into solar panel recycling was accomplished by designing a preliminary layout for a recycling plant. As seen in Figures 2, 3, 4, and 8, the initial processing steps such as removal of the aluminum frame and crushing of the remaining glass and solar cells are essentially standard across most recycling methods so they were untouched during the design process (Lunardi et al., 2018). The most basic form of mechanical solar panel recycling is solely composed of these two initial steps which meant that its operation cost could be used to calculate the operating cost of high-temperature density separation (Deng et al., 2019).

First solar panels are sent to the aluminum frame disassembly machine which recovers virtually 100% of the aluminum, about 3.6kg per solar panel (Joint Research Centre (European Commission) et al., 2016). Then the rest of the solar panel (glass and solar cells) is crushed into a granulated mixture that will be further refined. These first steps are generally standard in all recycling methods. Next, the mixture is loaded into an induction furnace which melts the glass, silicon, and silver. Once the materials have become molten and have separated into distinct density layers, the crucible in which they are contained is transferred to a water cooler. The steam resulting from this step is used for energy recovery. When the crucible has cooled, each material can be removed from the ingot by splitting apart each layer. For each solar panel, about 14kg of glass, 0.712kg of silicon, and 0.0106kg of silver can be recovered in ideal conditions (Joint Research Centre (European Commission) et al., 2016).

Table 3. Energy consumption and recovery per solar panel results.

	$m\ (kg)$	$c\ \left(\frac{J}{kg°C}\right)$	$\Delta H_f\ \left(\frac{kJ}{kg}\right)$(Engineering ToolBox, 2008)	ΔT_1 (°C)	ΔT_2 (°C)	kJ
Energy consumption for melting glass	14	870	-	1390	-	**16930.2**
Energy consumption for melting silicon	0.712	712	1787	1390	-	**1989.7**
Energy consumption for melting silver	0.0106	235	105	937	453	**2.5**
Total theoretical energy consumption	-	-	-	-	-	**18922.3**
Total practical energy consumption (85% efficiency)	-	-	-	-	-	**22261.6**
Minimum energy recovery (65%)	-	-	-	-	-	**12299.5**
Maximum energy recovery (90%)	-	-	-	-	-	**17030.1**

Table 4. High-temperature density separation operation cost and profitability per tonne results (approximately 55 solar panels per tonne).

	Average electricity cost ($/kWh)	**Average energy in kWh (kJ/3600)**	**Monetary value ($)**
Net operation cost per tonne	0.15	7596.8	**- 17.41**
Net profit per tonne	-	-	**+ 289.53**

Table 5. Comparison of major recycling methods to the proposed solution.

	Throughput capacity	Energy consumption	Energy recovery	Environmental impact	Profitability ($/tonne)
Mechanical (Deng et al., 2019)	High	Low	No	Hazardous contaminated glass	-76
Thermal (Deng et al., 2019)	Low	High	Yes	Emissions from EVA vaporization	-235
Chemical (Deng et al., 2019)	Very low	Very high	No	Hazardous waste chemicals	-269
High- temperature density separation (HTDS)	Moderate	High	Yes	Emissions from EVA vaporization	+290

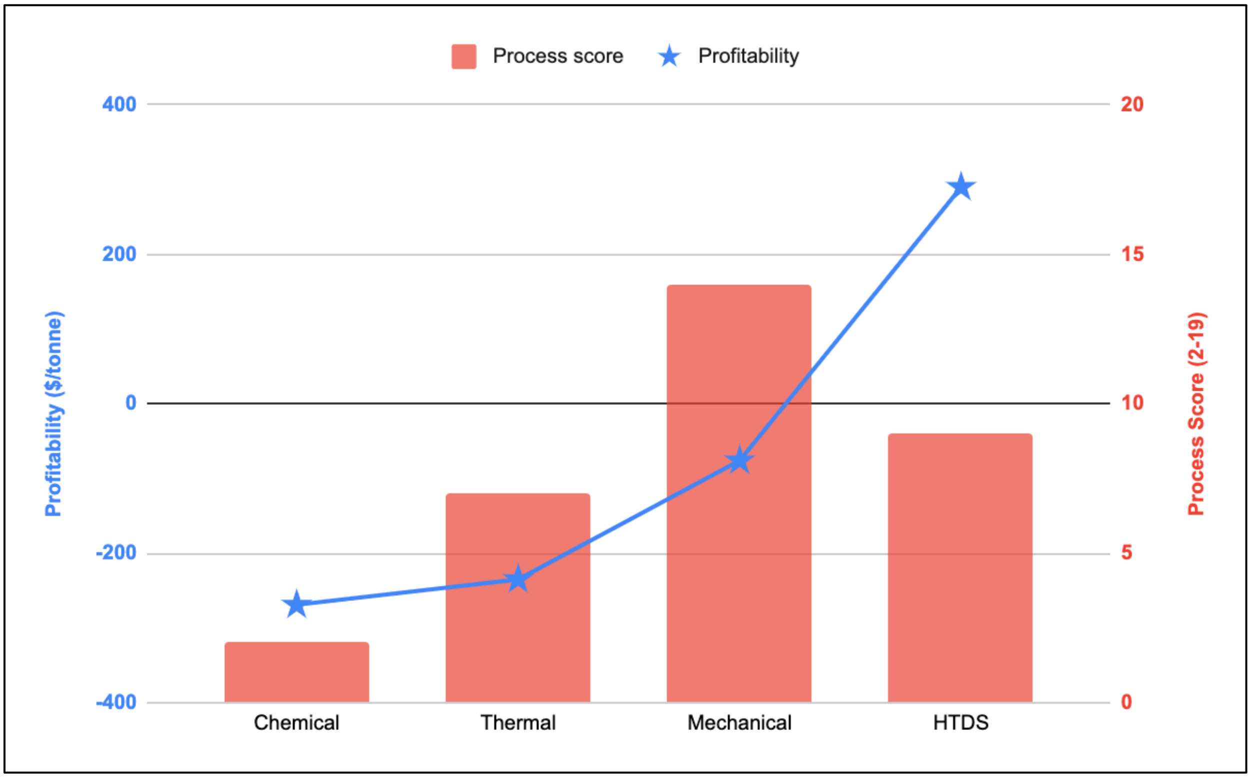

Figure 9. Graph comparing proposed solution to current recycling methods (Throughput: High=7, Moderate=5, Low=3, Very low=1; Energy consumption: Low=7, High=3, Very high=1; Energy recovery: Yes=1, No=0).

Discussion

In determining the economic viability of high-temperature density separation, the most significant results to analyze were individual and net operation costs, profitability, process score, and environmental impact. While analyzing the energy cost required for melting each component of a solar panel, the main focus was on identifying the highest energy-consuming material as well as possible ways to reduce the cost. Table 3 shows the component that consumed by far the most energy during the melting process was glass due to its high melting point and making up the majority of solar panels by mass as seen in Table 1 and Figure 5. Compared to the second most energy-consuming material in solar panels with the aluminum frame removed, melting glass required nearly ten times the energy as melting silicon. Therefore, if glass could be removed before the step of high-temperature density separation using a lower energy-consuming technology such as hot-wire cutting, a significant reduction in net operation cost could be realized.

However, even without this potential improvement, the currently estimated net operation cost of high-temperature density separation shown in Table 4 is already quite impressive. As seen in Figure 9, due to the minimal operation cost and other liabilities, high-temperature density separation displays a significantly greater profit margin than other recycling processes which should outweigh the uncertainties due to slight inaccuracies in theoretical calculations. Therefore, the theoretical positive profit will likely still apply in real-world conditions meaning that high-temperature density separation will increase the incentive for recycling solar panels over the landfill alternative.

In addition to profitability, the process score gives insight into how practical high-temperature density separation might be to scale up to meet future demands for solar panel recycling. Figure 9 demonstrates the strong direct correlation between process score and profitability. However, the reason the process score of high-temperature density separation does not perfectly follow the trend may be due to inaccurate assumptions of its real-world performance. As seen in Table 5, the three main components of the process score were throughput capacity, energy consumption, and the availability of energy recovery. The throughput capacity is the most important component when determining how easily the recycling process might be scaled. A high throughput capacity would allow for a smaller recycling plant size which would greatly reduce initial startup costs. Specifically for high-temperature density separation, the throughput capacity was only rated as “moderate” due to the need of melting solar panels in batches instead of a continuous process. However, with further research, it may be possible to use a continuous furnace to increase the throughput capacity. A continuous furnace is a type of furnace that allows materials to be constantly fed into and removed from the heating area similar to an assembly line (AG, n.d.). Although the energy consumption of high-temperature density separation is high, it can be largely offset by energy recovery which means that the net energy consumption is not inhibitive to scaling the process. Additionally, as discussed above, by removing the glass sheet on solar panels before melting, it is possible to drastically reduce energy consumption.

Lastly, the environmental impact of a recycling process is important for maintaining the overall sustainability of solar panels. Although no recycling process analyzed in this study was flawless in terms of environmental impact, some are less problematic than others. Specifically, in high-temperature density separation, the only waste created is EVA-related emissions as seen in Table 5. Compared to mechanical and chemical processes which produce highly toxic hazardous waste, EVA-related emissions do not pose direct health threats to humans and are much simpler to eliminate. The complete combustion of EVA produces water and carbon dioxide. Water poses no threat to humans or the environment, but carbon dioxide does contribute to warming the global climate. Currently, there exist technologies that can remove carbon dioxide from factory emissions and the atmosphere which can easily be implemented in a solar panel recycling plant (Climeworks, 2022). Although this extra step will increase net operation costs, it will allow the recycling process to maintain the sustainable image of solar energy.

Conclusion

The problem of creating an economically viable recycling process for decommissioned solar panels must be addressed in order for solar energy to be truly sustainable. The high costs associated with current recycling processes have inhibited their success in real-world applications. The high-temperature density separation process discussed in this study aims to reduce recycling costs by simplifying the process. This was done by analyzing the material properties of solar panel components, identifying the optimal heating method for carrying out the separation process, designing a preliminary recycling plant layout, and calculating the operating costs and profitability. With the obtained results, high-temperature density separation was compared with other recycling methods and evaluated on economic viability. After analyzing the benefits and drawbacks of high-temperature density separation, potential areas for improvement were described.

In conclusion, this research identified some key aspects of the concept of high-temperature density separation. These include choosing a proper heating temperature, method of heating, and designing an effective recycling plant layout. The most optimal heating temperature for completing the density separation of solar panel components was 1415℃. This temperature matches the component with the highest melting point which is silicon which minimizes unnecessary energy consumption. The most effective heating method determined was induction heating, as seen in Table 2 and Figure 6, because of its high efficiency. Important features of the recycling plant layout included the compact organization of each step and ease of access to all pure recovered materials. Providing unobstructed access to the recovered materials limits the complexity within the recycling plant and the transportation needed to deliver and export goods.

Considering that the recycling process discussed in this study is a theoretical concept, future validation of its function must be acquired through more research. As covered in the discussion, some current potential areas for improvement include reducing heating energy consumption, increasing throughput capacity, and eliminating EVA-related emissions. Future research on integrating hot-wire cutting into the recycling process would minimize energy consumption. The feasibility of using continuous furnaces to complete high-temperature density separation must be tested in the future. Additionally, research on lowering the cost of carbon emission capture systems will allow for a more sustainable recycling process.

Limitations

This research was limited by a lack of resources and equipment to construct or simulate an experimental recycling process. As a result, much of the research is based on theoretical values that are approximate estimates of real values.

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References

AG, A. (n.d.). *Continuous furnaces*. Www.andritz.com. https://www.andritz.com/products-en/group/metals/furnaces/carbon-steel/continuous-furnaces#:~:text=In%20continuously%20operating%20furnaces%2C%20the

Climeworks. (2022). *Climeworks offers a technology to reverse climate change*. Climeworks.com. https://climeworks.com/

Darrow, K., Tidball, R., Wang, J., & Hampson, A. (2015). *Section 4. Technology Characterization -Steam Turbines*. https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies_section_4._technology_characterization_-_steam_turbines.pdf

Deng, R., Chang, N. L., Ouyang, Z., & Chong, C. M. (2019). A techno-economic review of silicon photovoltaic module recycling. *Renewable and Sustainable Energy Reviews*, *109*, 532–550. https://doi.org/10.1016/j.rser.2019.04.020

Donskov, E. G., Lyalyuk, V. P., & Donskov, A. D. (2015). The energy efficiency of blast furnaces. *Steel in Translation*, *45*(2), 130–132. https://doi.org/10.3103/s0967091215020047

Engineering ToolBox. (2008). *Metals - Latent Heat of Fusion*. Www.engineeringtoolbox.com. https://www.engineeringtoolbox.com/fusion-heat-metals-d_1266.html

Fasching, E., & Ray, S. (2022, January 10). *Solar power will account for nearly half of new U.S. electric generating capacity in 2022 - Today in Energy - U.S. Energy Information Administration (EIA)*. Www.eia.gov. https://www.eia.gov/todayinenergy/detail.php?id=50818

How are Solar Panels Made? | GreenMatch. (2014). Greenmatch.co.uk. https://www.greenmatch.co.uk/blog/2014/12/how-are-solar-panels-made

Joint Research Centre (European Commission), Ardente, F., Blengini, G. A., Mancini, L., Latunussa, C. E. L., & Pennington, D. (2016). Analysis of material recovery from photovoltaic panels. In *Publications Office of the European Union*. Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/3b3d0582-0c3a-11e6-ba9a-01aa75ed71a1/language-en

Juxinde. (2022, March 23). *Induction furnace's characteristics - Juxinde*. Www.used-Equipments.com. https://www.used-equipments.com/induction-furnace-s-characteristics.html

Karazi, S. M., Ahad, I. U., & Benyounis, K. Y. (2017, January 1). *Laser Micromachining for Transparent Materials*. ScienceDirect; Elsevier. https://www.sciencedirect.com/science/article/pii/B9780128035818041497

Kirschen, M., Risonarta, V., & Pfeifer, H. (2009). Energy efficiency and the influence of gas burners to the energy related carbon dioxide emissions of electric arc furnaces in steel industry. *Energy*, *34*(9), 1065–1072. https://doi.org/10.1016/j.energy.2009.04.015

Lunardi, M. M., Alvarez-Gaitan, J. P., & Corkish, J. I. B. and R. (2018). A Review of Recycling Processes for Photovoltaic Modules. In *www.intechopen.com*. IntechOpen. https://www.intechopen.com/chapters/59381

Ministry of Micro, Small & Medium Enterprises Govt. of India, United Nations Industrial Development Organization, Global Environment Facility, Bureau of Energy Effi ciency A statutory body under Ministry of Power, Government of India, & Ministry of New and Renewable Energy. (2015). *Energy Efficiency Best Operating Practices Guide for Foundries*. http://sameeeksha.org/brouchres/BOP-Guide-Oct2015.pdf

Overview of materials for Ethylene Vinyl Acetate Copolymer (EVA), Adhesive/Sealant Grade. (n.d.). Www.matweb.com. https://www.matweb.com/search/datasheet_print.aspx?matguid=0eeb0c7bf44349e39580d1d1ff302764

Peplow, M. (2022). Solar Panels Face Recycling Challenge. *ACS Central Science*, *8*(3), 299–302. https://doi.org/10.1021/acscentsci.2c00214

Royal Society of Chemistry. (2011a). *Silicon - Element information, Properties and Uses | Periodic Table*. Rsc.org. https://www.rsc.org/periodic-table/element/14/silicon

Royal Society of Chemistry. (2011b). *Silver - Element information, Properties and Uses | Periodic Table*. Rsc.org. https://www.rsc.org/periodic-table/element/47/silver

SEPARATION EXPERTS. (n.d.). *Densimetric Table Separators – SEPARATION EXPERTS*. SEPARATION EXPERTS. Retrieved August 27, 2022, from http://separationexperts.com/densimetric-table-separators/

Strachala, D., Hylský, J., Vaněk, J., Fafilek, G., & Jandová, K. (2017). Methods for recycling photovoltaic modules and their impact on environment and raw material extraction. *Acta Montanistica Slovaca*, *22*(3), 257–269. https://publik.tuwien.ac.at/files/publik_267021.pdf

US EPA, O. (2021, August 23). *Solar Panel Recycling*. Www.epa.gov. https://www.epa.gov/hw/solar-panel-recycling

Weber, L. (2002, April). *Equilibrium solid solubility of silicon in silver - ProQuest*. Www.proquest.com. https://www.proquest.com/openview/f704070bffdda9be58a65d94c6940697/1?pq-origsite=gscholar&cbl=49316

Win. (2020, October 28). *What is the difference between electric arc furnace and induction furnace? - DanCrabon*. Www.dancarbon.com. https://www.dancarbon.com/q/eaf/what-is-difference-between-electric-arc-furnace-induction-furnace-216.html