Electrodynamic Eddy Current Separation of End-of-Life PV Materials

York R. Smith, James R. Nagel and Raj K. Rajamani

Abstract In this work, we examine the efficacy of Electrodynamic Eddy Current Separation (EECS) to recover valuable materials from end-of-life solar panels. Traditional rotary-based eddy current separators are capable of excitation frequencies of ≈1 kHz or less and struggle to economically separate particles smaller than ≈1 cm. A new design of eddy current separators has been developed at the University of Utah which has no mechanically moving parts. The design is capable of excitation frequencies up to 50 kHz, allowing sorting of particles as small as 1.0 mm. Recently, we have been successful in separating mixtures of Si/Al and CdTe/Al particles (1–3 mm) with recovery and grades greater than 85%, an energy demand of 68 kWh/short ton of sorted material, and throughput of roughly 10 kg/h. Current and future challenges utilizing this method for valuable material recovery from end-of-life solar panels are discussed.

Keywords Eddy current · Recycling · PV materials

Introduction

Photovoltaic materials have been the focus of recent work on resource scarcity and material criticality [1–3]. Overburden of end-of-life (EOL) solar panel materials is currently not an issue, as many of the panels in place have yet to reach their maturity (15–20 years). However, a large influx of EOL PV modules is anticipated in the next 10–15 years. The annual waste from the photovoltaic industry from EOL panels is expected to be ∼250,000 tons by 2016, and according to early-loss scenarios, this value could reach up to 78 Mt by 2050 [4].

Some EOL PV modules are considered hazardous waste and require special disposal methods with additional cost (e.g. CdTe and CIGS). Current recycling methods utilizing chemical treatment are more expensive than hazardous waste

Y.R. Smith (✉) · J.R. Nagel · R.K. Rajamani
Metallurgical Engineering Department, University of Utah, Salt Lake City, UT, USA
e-mail: york.smith@utah.edu

L. Zhang et al. (eds.), *Energy Technology 2017*,
The Minerals, Metals & Materials Series, DOI 10.1007/978-3-319-52192-3_37

disposal costs. A report by Bio Intelligence Services [5] highlighted the potential environmental problems related to the improper disposal of waste PV panels as: leaching of hazardous substances (i.e., Pb and Cd), losses of conventional material resources (i.e., Al and glass), and losses of precious and scarce metals (e.g., Ag, Ga, In, Ge). About 10–15% of the weight of a Si solar module consists of Al, Sn, Ag, and In. Recycling of such materials has relevance, not only from the point of waste management, but also from the recovery aspect of valuable materials. Several major benefits are achieved when recycled materials are used over virgin materials, namely natural resource preservation and energy conservation.

A first study on the technical and economic feasibility of the recycling crystalline silicon PV modules was presented in a photovoltaic technology conference in the 1990s [6]. However, the interest on PV recycling only started to rise around one decade later. For example, a study by Fthenakis [7] identified the challenges and the possible approaches for PV recycling in the USA. The study concluded that recycling was technologically and economically feasible, but not without careful forethought. The methods adopted so far for the recycling of silicon PV panels have been based on physical treatments, chemical treatments, or a combination of both. A description of these methods is reviewed [8]. However, a detailed analysis of the impacts related to such treatment in a lifecycle perspective is still missing from the literature.

To date, under most scenarios, the best option is landfill disposal [1] of EOL PV materials. However, this presents itself as only a short-term solution and is due to a lack of current innovative recycling methods/technical processes that are economically viable. The concept of recycling EOL PV materials is relatively new ($\sim$20 years), and only in the last few years have innovative commercial treatments been developed by *Deutsche Solar* for the recycling of crystal silicon panels, and by *First Solar* for the recycling of CdTe panels [5, 8].

As the market continues to expand and innovation cycles become even shorter, the replacement of equipment accelerates, making electrical and electronic equipment a quickly growing source of waste. One effective and established method of removing non-ferrous metals from such streams of industrial or municipal waste is by eddy current separation techniques [9]. The process is used to separate aluminum and copper from automobile scrap and to remove metals from recycled glass. The separation technique is based on the premise that conductive materials resist being moved in a magnetic field and, vice versa, will accelerate in a moving field [10]. The design and performance of rotating belted-drum type eddy current separators have been improved substantially in the last ten years, primarily due to advances in magnet materials and magnet configurations, as well as a better understanding of the separation mechanisms [11, 12]. Yet, problems associated with separation of small particles ($\leq \sim$5 mm), remains an arduous challenge to date.

In Electrodynamic Eddy Current Separation (EECS), particles are allowed to fall freely through an alternating magnetic field with adjustable frequency. This applied

magnetic field induces eddy currents but only in the electrically conductive particles. The movement of the eddy currents generated in the conducting particles leads to produce a Lorentz forces on the nonferrous metallic particles. The generated Lorentz forces results in expelling them out of the main stream. The use of EECS for recycling EOL solar panels represents a potential low-cost and low-environmental impact technology.

Theory of Eddy Current Separation

Eddy current separation is a developed technology with many practical applications in the recycling industry. The basic principle is derived from the fact that when a permanent magnet passes over a conductive metal object, electric charges within the metal tend to experience a net magnetic force [13]. This causes distinct swirling flow patterns of charges, commonly referred to as eddy currents or Foucault currents. With a strong enough magnetic field with relative quick motion, enough force can be generated to significantly accelerate the entire metal particle. Modern eddy current separators are generally a large, rotary drum implanted with a series of permanent magnets. When the drum is rotated at a high velocity, nearby metal particles tend to deflect along distinct kinematic trajectories away from nonmetallic particles/material. Two distinct material streams are then isolated by a physical barrier placed between their respective trajectories.

For our case of electrodynamic sorting design, spinning permanent magnets are replaced with a single fixed electromagnet excited by an alternating electric current. This significantly changes the mathematical nature of the physics involved. In such a configuration, the relative velocity between magnet and particle is no longer a significant factor. We may therefore begin with Faraday's law of electromagnetic induction, which states that a time-varying magnetic field **B** will give rise to an electric field **E** in accordance with [14]

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}. \tag{1}$$

If we next assume sinusoidal steady-state operation at angular frequency

ω, all time derivatives can be replaced with $\partial/\partial t = -j\omega$. The phasor form of Faraday's law is therefore written as

$$\nabla \times \mathbf{E} = j\omega \mathbf{B}. \tag{2}$$

Now let us now consider a metal particle placed somewhere in the magnetic field **B**. Because of the induced electric field **E**, electric charges within the metal are accelerated accordingly, thus giving rise to an eddy current density **J**. The relation between **E** and **J** is given by the point form of Ohm's law, written as

$$\mathbf{J} = \sigma \mathbf{E}, \tag{3}$$

where σ is the electrical conductivity of the metal. Changing magnetic fields therefore give rise to electric fields, which in turn give rise to eddy currents in metallic objects.

Next, we note that electrical currents also give rise to magnetic fields of their own in accordance with Ampere's law,

$$\nabla \times \mathbf{B}_e = \mu_0 \mathbf{J}, \tag{4}$$

where $\boldsymbol{B}_e$ indicates the magnetic fields produced just by the eddy current density **J**. This implies more changing magnetic fields that must be accounted for in Eq. (1), which in turn cause changes in the resultant eddy current **J**. Thus, a complete solution for **J**, **E**, and **B** requires us to solve Eqs. (1)–(4) simultaneously. While such a process extends well beyond the scope of this article, we can at least note that once a solution for **J** is finally obtained, it becomes possible to calculate the net Lorentz force **F** acting on the metal particle. This is given by the magnetic force law,

$$\mathbf{F} = \iiint \mathbf{J} \times \mathbf{B} \, dV, \tag{5}$$

where the integral is carried out over the volume defined by the space within the particle. Thus, if the excitation field **B** is strong enough and the frequency ω great enough, the net force **F** will be great enough to significantly deflect arbitrarily large particles of metal.

Description of Experimental Setup

The eddy current separator designed and used in this study overcomes some of the limitations of belted-drum type eddy current separators. One advantage is there are minimal mechanically moving parts, which enables the system to operate at higher excitation frequencies. The principle of this design was originally pioneered by Saveliev to extract gold particles from ore [15], but the original design has remained relatively unrefined. Previously, Dholu et al. [16] demonstrated the sorting of 6.0 mm sphere mixtures of Al/Cu, Cu/Brass, Al/Brass with nearly perfect recovery and grade. The same configuration also demonstrated promising sorting of Al alloys from Al alloys. For example, the separation of Al-110/Al-2024, Al-110/Al-6061, and Al6061/Al-2024 series alloy mixtures using 12 mm size spheres, recoveries and grades of 85–95% can be realized. Operating at a higher frequency improves separation of smaller conducting particles. In this experimental campaign, 1–3 mm particles of Si, CdTe, and Al where examined.

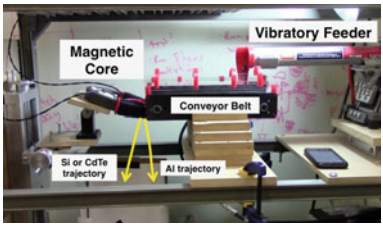

Fig. 1 A picture of the experimental setup utilized for separating Si/Al and CdTe/Al 1–3 mm particles

Table 1 Summary of experimental results for sorting 1–3 mm particles mixtures of Si/Al and CdTe/Al

	Si	Al	CdTe	Al
Recovery, %	97.5	98.2	95.1	98.8
Grade, %	99.5	98.3	85.7	99.5
	Si/Al		CdTe/Al	
Feed rate, kg/h	5.6		12.4	
Energy consumption, kWh/short ton	68.0		68.0	

Particles 1–3 mm in diameter of Si (American Elements, 99.9%) and Al (American Elements, 99.9%) was carried out using an experimental setup depicted Fig. 1 and described in further detail elsewhere [16]. The ferrite core (CMD5005 NiZn ferrite) has an outer diameter of 160 mm and an inner diameter of 120 mm. A specialized gap of approximately 1.1 cm in width was cut on the ferrite core, which is used to funnel flux into a tight volume of space. The core is wound (N = 173) with two windings in parallel on either side of the gap. The magnet was powered by a 400 W power supply, operating at 52.8 V and 6.60 Å with at a resonance frequency of 21.4 kHz. Under these operating conditions a $\boldsymbol{A}$ field of 60–80 mT is achieved in the gap. In each of the experiments, approximately 200 g of each sorting material was used for a total of ∼400 g sorted per each experimental run. An equivalent circuit model for the drive electronics is detailed in a previous publication [16].

Results of Sorting Demonstration

The results from this experimental campaign demonstrate the capability of this technology to separate Si/Al and CdTe/Al particle mixtures of 1–3 mm with recoveries and grades >85% under the given conditions. The results for Si/Al and CdTe/Al mixtures after one pass are given in Table 1. To define quality metrics of the separation, such as recovery (R) and grade (G), we consider two initial masses, m_0 and M_0, of differing materials mixed together before the sort. The collection bins consist of two bins, labeled bin 'A' and bin 'B'. The desired outcome of the experiment is for all of the mass m_0 to collect in bin 'A' and all of mass M_0 to collect in bin 'B'. We can define M_A and M_B as the total masses from M_0 that fall

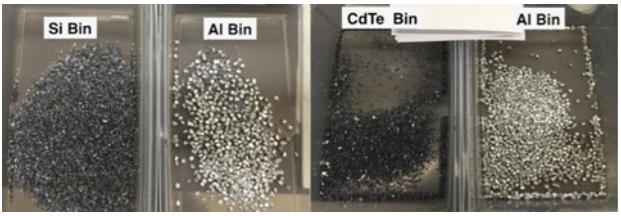

Fig. 2 An example of a sorting result separating 1–3 mm particle mixtures of Si/Al or CdTe/Al

into their respective bins. Common industry terms for these bins are "throw" and "drop." For our case, bin 'A' represents the "drop" bin (Si or CdTe particles) and the "throw" bin is bin 'B' (Al particles).

The recovery of bin 'A' and 'B' as the fraction of the initial material can be defined as:

$$R_A = \frac{m_A}{m_0} \tag{6}$$

$$R_B = \frac{M_A}{M_0} \tag{7}$$

The grade of the separation is then defined by the following:

$$G_A = \frac{m_A}{(m_A + M_A)} \tag{8}$$

$$G_B = \frac{m_B}{(m_B + M_B)} \tag{9}$$

The feed rate was determined by dividing the total mass sorted over the time duration of the sort. The energy consumption was determined using a P3 International Kill A Watt® real-time power monitoring device, which monitored the energy consumption of the whole operating unit. A typical sorting outcome is depicted in Fig. 2, which shows particle mixtures after one sorting pass.

Discussion and Concluding Remarks

Under the given conditions, the application of EECS to separate simple mixtures of semiconductor/metal particle mixtures is demonstrated. The particles used in this demonstration were not spherical, but rather granular chunks of material. Using such particles contributes to deviation of a perfect separation. Perfect spherical

particles would yield higher consistency due to symmetry of the particle. For example, the majority of Al particles that were found in the Si or CdTe bin were thin sheet-like particles. The particle experiences a torque as well as a net force. Due to the geometry, (i.e. sheet-like particles) the torque tries to orientate the particle along a direction that minimizes the cross-sectional area exposed to the magnetic field. Since these thin particles have small cross-sectional area, they are exposed to less magnetic flux and thus do not kick as strong out of the stream.

Another cause for error in the sort has to do with how the particles are fed to the magnetic core gap, which has its limitation of throughput. Particle trajectories can become altered or screened by too much of material. For example, as a material is ejected from the gap, its trajectory is altered by a collision with another particle and ends up in the wrong bin. For our configuration, the particle mixtures are fed to a conveyor belt by a vibratory feeder. By using a relatively fast enough belt velocity and channels above the conveyor belt, the particles are fed to the core gap in such a way as to not fill the gap with too much material. Techniques and methods to deliver material to the gap for optimal separation remain an area of active investigation.

The current configuration is only able to effectively sort $\sim$10 kg/h of material while maintaining high selectivity and grade. Increasing the throughput by an order of magnitude while maintaining high selectivity and grade (>95%) is necessary if commercial application is to be realized. Although the system configuration has a low throughput, the energy consumption for one unit is rather low. It should be noted this does not take into account any active cooling of the system. Since the energy demand is relatively low, several unit configurations of parallel and series can be utilized to achieve desired throughput while maintaining high enough selectivity and grade.

Since particle size plays a large role in application of this technology, detailed characterization on the comminution of PV panels and materials is of great necessity. Moreover, how various parts of the panel break up under milling conditions will be valuable information. This technology demonstrates an ability to effectively separate particles of 1–3 mm under these set conditions, whereas in real-world applications the particles will likely be of much smaller size. Separation of particles smaller in size has yet to be realized and warrants further investigation. These are currently active areas of investigation.

Separation based on materials that have relatively large differences in conductivity appears to be easily achievable with this technique. On the other hand, separation of materials with relatively close conductivities presents a challenge. Moreover, it is not just also the differences in conductivity, but the absolute magnitude of the conductivity. A higher excitation frequency of the magnet will be required to achieve effective separation of less conducting particles (i.e., Si, CdTe), which faces physical limitations of the system. One approach to potentially increase the conductivity of Si and CdTe particles during separation is exposure to light irradiation, thereby increasing the conductivity of the semiconductor particles.

Acknowledgements YRS would like to acknowledge support provided though the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Sunshot Initiative Postdoctoral Research Award. RKR and JRN acknowledge support through the United States, Advanced Research Project Agency-Energy (ARPA-E) METALS Program under cooperative agreement grant DE-AR0000411. The authors would also like to acknowledge technical contributions by Dave Cohrs and Jacob Salgado.

References

1. M. Goe, G. Gaustad, Estimating direct climate impacts of end-of-life solar photovoltaic recovery. Sol. Energy Mater. Sol. Cells **156**, 27–36 (2016)
2. M. Goe, G. Gaustad, Identifying critical materials for photovoltaics in the US: a multi-metric approach. Appl. Energy **123**, 387–396 (2014)
3. N.T. Nassar et al., Criticality of the geological copper family. Environ. Sci. Technol. **46**, 1071–1078 (2012)
4. S. Weckend, A. Wade, G. Heath, End-of-life management: solar photovoltaic panels. Int. Renew. Energy Agency, 100 (2016)
5. V. Monier, M. Hestin, Study on photovoltaic panels supplementing the impact assesment for a Recasr of the WEEE directive, Bio Intelligence Service, 2011, pp. 86
6. T. Doi et al., Experimental study on PV module recycling with organic solvent method. Sol. Energy Mater. Sol. Cells **67**, 397–403 (2001)
7. V.M. Fthenakis, End-of-life management and recycling of PV modules. Energy Policy **28**, 1051–1058 (2000)
8. C.E.L. Latunussa et al., Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol. Energy Mater. Sol. Cells **156**, 101–111 (2016)
9. W.L. Dalmijn, Practical applications of eddy current separators in the scrap recycling industry, 2nd international symposium recycling of metals and engineered materials, 1990, pp. 303–314
10. T.A. Edison, Ore Separator, U.S. Patent 400,317, in: U.S. Patent (Ed.) USA, 1889
11. S. Zhang, P.C. Rem, E. Forssberg, The investigation of separability of particles smaller than 5 mm by eddy current separation technology. Part I: rotating type eddy current separators. Magn. Electr. Sep. **9**, 233–251 (1999)
12. S. Zhang, P.C. Rem, E. Forssberg, Particle trajectory simulation of two-drum eddy current separators. Resour. Conserv. Recycl. **26**, 71–90 (1999)
13. P.C. Rem, P.A. Leest, A.J.V.D. Akker, A model for eddy current separation. Int. J. Min. Process. **49,** 193–200 (1997)
14. J.D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1999)
15. V. Saveliev, System and method for separating electrically conductive particles, in: U.S. Patent (Ed.)USA, 1998
16. N. Dholu et al., Eddy current separation of nonferrous metals using a variable-frequency electromagnet. KONA Powder Part. J. 1–7 (2016). http://doi.org/10.14356/kona.2017012