Environmental and Economic Benefits of Harvesting Machine for Magnet-to-Magnet Recycling

Jesús R. Pérez-Cardona, [1,*] *Nehika Marthur,* [2] *Sidi Deng,* [3] *Miha Zakotnik,* [4] *Catalina Oana Tudor,* [4] *and John W. Sutherland* [5]

[1]Department of Mechanical Engineering, University of Puerto Rico–Mayagüez Campus, Mayagüez, PR 00681–9000

[2]National Institute of Standards and Technology, Gaithersburg, MD 20899

[3]Department of Mechanical Engineering, University of Michigan, G.G. Brown Laboratory, 2350 Hayward St, Ann Arbor, MI 48109, USA

[4]Noveon Magnetics, 1550 Clovis Barker Rd., San Marcos, TX 78666, United States

[5]Environmental and Ecological Engineering, Purdue University, Potter Engineering Center, Rm 364, 500 Central Drive, West Lafayette, Indiana 47907, United States

ABSTRACT Closed-loop recycling streams are increasingly taking importance on the development of a sustainable future. Neodymium-Iron-Boron (Nd-Fe-B) permanent magnets are applied in a variety of applications, including direct-drive wind turbines, electric motors for electric vehicles, hard disk drives (HDDs) in laptops, and other electric devices. End-of-life HDDs are available in the United States to be collected and recycled for the production of Nd-Fe-B magnets for the exponentially increasing demand in electric vehicles and other industries. A comparative assessment of the environmental impact of HDD recycling pathways is conducted for the production of Nd-Fe-B magnets in the United States. The results show that the magnet-to-magnet recycling route has the lowest footprint. A techno-economic assessment is conducted to compare the added value of a harvesting process versus shredding HDDs. After conducting an uncertainty analysis with an optimization technique, multiple scenarios for a harvesting facility are economically feasible. Future work will be needed to reduce financial risks.

KEYWORDS: Hard Disk Drives, Harvesting Machine, Magnet-to-Magnet Recycling, Techno-Economic Assessment, Life-Cycle Assessment

SYNOPSIS: This study applies a comparative life cycle assessment and a techno-economic assessment to highlight the importance of a harvesting machine for magnet-to-magnet recycling over other recycling pathways.

*Corresponding author. E-mail address: jperezc@purdue.edu (J.R. Pérez-Cardona)

1. INTRODUCTION

Novel solutions for the value recovery of end-of-life products are increasingly taking importance in the development of a sustainable future. Rare earth elements (REEs) and other critical materials have distinctive physical and chemical properties that make possible the emergence of new technologies in power generation, transportation, communication, and other basic human activities (Yang et al., 2017; DOE, 2011). A common component for many technologies in different areas of innovation is the permanent magnet. Neodymium-Iron-Boron (Nd-Fe-B) permanent magnets can be found in direct-drive wind turbines, electric motors for electric vehicles, hard disk drives (HDDs) in laptops, and other electric devices. Due to the short lifespan of electric devices involving HDDs, they have become a research interest in building closing loop recycling streams in the actual economy.

In 2010, the available feedstock of HDDs in the U.S. was 17,700 metric tons, meaning that there are market opportunities to implement recycling streams (Nguyen et al., 2017). Since the supply of the electric vehicle industry is increasing rapidly, open-loop of HDD recycling routes can be used to produce Nd-Fe-B magnets for use in electric motors. Unfortunately, today's lack of infrastructure and logistics for collection and dismantling facilities leads to the uncertainty of investing in new recycling facilities for the value recovery of HDDs.

To decrease this uncertainty, this paper extends the work done by other researchers (Jin et al., 2018; Sprecher et al., 2014a; Maani et al., 2024) on the study of HDD recycling routes for the production of Nd-Fe-B magnets. Comparative cradle-to-gate life cycle assessments (LCAs) are conducted for the production of Nd-Fe-B magnets through the following pathways: by means of REEs imports coming from China (or primary production); by means of recovering HDDs from a hydrometallurgy recycling process, and by means of recovering HDDs from a magnet-to-magnet (M2M) recycling process. Besides conducting LCAs, a techno-economic assessment (TEA) is performed to observe the added value of acquiring a harvesting machine for the M2M recycling process.

The work done by Jin et al. (2018) already showed that the environmental impacts of the M2M recycling route are lower than for primary production. In this study, the electricity consumption of the harvester is updated. Maani et al. (2024) showed a TEA for M2M recycling route for the recovery of magnets from end-of-life motors. Also, Sprecher et al. (2014a) completed a comparative LCA for a hydrometallurgy route through a shredding process that only recovers up to 10% of the magnet in the HDD versus a hand dismantling of HDD magnet route. This route was implemented in Great Britain. The results showed lower environmental impact for a hand dismantling of HDDs than for the hydrometallurgy route. These routes are now compared among them in a consistent location (United States) and with a uniform life cycle impact assessment. By assessing the environmental impact of these routes and the economic benefit of installing a harvesting machine, this study highlights the economic and environmental potential for implementing the M2M recycling route within the United States.

2. METHODS

LCAs are conducted to assess the environmental benefit of Nd-Fe-B magnet-to-magnet (M2M) recycling routes in comparison to 1) primary production (a.k.a., virgin production) and 2) hydrometallurgy recycling routes. The results of these two assessments are done for pessimistic, baseline, and optimistic scenarios. This paper extends the work done by Jin et al. (2018) on updating the electricity consumption of using the harvesting machine. Furthermore, two scenarios are considered for the M2M route. On the M2M route, Jin et al. (2018) assumed that a harvester is included to recover the Nd-Fe-B magnet. Then, this M2M route is compared to the scenario of manually recovering the magnet (i.e., without any harvester). The importance of this comparison is that, according to Sprecher et al. (2014b), the manual disassembly of HDDs can take up to 12 HDDs per hour and per operator while the harvester developed by Noveon Magnetic[1] (2024) processes up to 720 HDDs per hour. For this purpose, let M2M-Harvester denote that the M2M route includes the harvester, M2M-Manual if otherwise, and M2M if referred to contrast against the other main routes. The magnet composition for primary and secondary (i.e., recycling) production routes are assumed to be the same as of Jin et al. (2018) applied to motors in the electric vehicle industry.

2.1. Harvesting Machine. The harvesting machine is the capital equipment to separate HDDs into three main commodities: printed circuit board, magnetic assembly, and aluminum body (see Figure 1). Thus, this unit process is

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[1] Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST. Nor does it imply that the products identified are necessarily the best available for the purpose.

expected to raise the value recovery of the overall HDD recycling process in comparison to a shredding process that destroys the product, contaminates and mixes raw materials (Sprecher et al., 2014a). The weight composition of these three commodities are estimated by processing 4158 HDDs through a harvester.

This harvesting machine is operated to assist operators in achieving the separation process mentioned above, resulting in a processing rate of 180 HDDs per hour (i.e., cycle time of 20 seconds per HDD). Furthermore, as stated earlier the designers expect that this unit process can be automated in order to increase productivity by reaching a processing rate up to 720 HDDs per hour (i.e., cycle time of 5 seconds per HDD). Table 1 shows the machine specifications and the cycle time for both settings. In terms of cycle time, when comparing this harvester to other equipment used in the production of Nd-Fe-B magnets, if the setting is not automated, then this is the most critical (i.e., slowest) unit process to determine the processing rate of the whole route (Zakotnik et al., 2016). If the harvester is automated, then it can be potentially be far away from a critical unit process. The time needed to produce magnets for one year is based on the slowest unit process.

Table 1. Harvesting machine specifications

Category	Specifications
Throughput	3-12 HDDs processed into 3 commodities per minute
Utility Requirement	12kW, 460/480V, 3 Phase
Space Requirements	8 ft x 10 ft Floor Space
Options for Installation	HDD indexing for traceability; shredding process for Al body; Al interface for modularity
Cycle Time	Manual operation: 12.3–13.55 Nd-Fe-B kg/hr Automated operation: 49.0–54.2 kg of Nd-Fe-B/hr

Each setting has different electricity consumption per magnet unit mass due to the mechanism and the cycle time. A queuing-system-based simulation was developed to estimate the electricity consumption during the operation of the harvesting machine. The simulation of the operation process in the harvester was done in a laboratory environment, where the settings of statistical parameters strictly followed the laboratory data provided by Noveon Magnetic (2024), including the total unit of HDDs processed, and the expected average processing time per HDD. As for the manual operation case, the human factors, including fatigue, have been appropriately modeled by penalizing the processing speed over operating time. The robustness of the simulation design has been rigorously investigated to ensure the reliability of the simulation results. Thus, for a manual setting of the harvester, the electricity consumption is estimated to be 283.13–287.24 kWh per HDD, whereas, for an automated setting, the electricity consumption is 187.96–188.65 kWh per HDD. These values are used in the LCA and TEA of the M2M-Harvester route. For more details about the harvester, refer to the Supplementary Information (SI), Tables S1–S4.

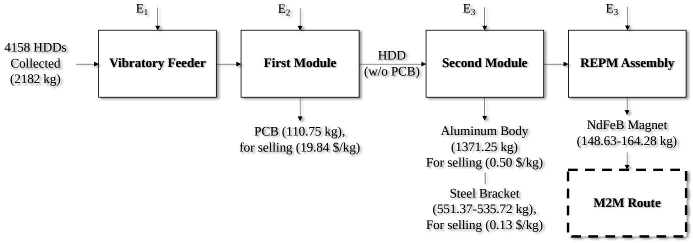

Figure 1. Harvesting Machine Block Diagram

2.2. Life Cycle Assessment. *2.2.1. Goal and Scope.* The goal of this LCA is to compare different alternatives for producing 1 kg of Nd-Fe-B magnets within the United States. The three pathways considered are primary production, hydrometallurgy, and M2M recycling.

2.2.2. Life Cycle Inventory. Most of the life cycle inventories (LCIs) are coming from Jin et al. (2018) and Sprecher et al. (2014a), except for harvesting machine data which is collected by Noveon Magnetic (2024). Jin et al. (2018)

provided in their supplementary information the LCIs for the primary and M2M routes. The primary production route was unmodified. For the M2M route, only the harvester electricity consumption was modified based on the model simulation results. For the hydrometallurgy recycling route, the LCI for the recycling of neodymium metal from the recycling of HDDs was collected from Sprecher (2014a); and the LCI for the production of Nd-Fe-B magnet using recycled neodymium and adding fresh REEs was completed with the magnet weight composition and other inventories obtained from Jin et al. (2018). The resulting LCI can be found in SI, Table S5. It is important to remark that the LCIs from Sprecher et al (2014a) were redone for the United States, to maintain consistency on the same location. Also, the software used to conduct the LCAs was on Simapro 9.0, the LCIs database was on Ecoinvent 3.0, with exception of electricity consumption, that was on Ecoinvent 2.2 and applied to Texas, U.S (selected location for harvesting facility).

2.2.3. Life Cycle Impact Assessment. Since these LCAs are focused on the implementation of Nd-Fe-B magnet production in the United States, the life cycle impact assessment tool used to base the results is "Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts" (TRACI 2.6), developed by the U.S. Environmental Protection Agency.

According to Jin et al. (2018), the contributions of REEs (i.e., Nd, Dy, and Pr) to the life cycle impacts of virgin production are 61–95% for their baseline scenario. Their results are obtained from other LCIs on REE production in China (Sprecher et al., 2014a; Vahidi et al., 2016; Vahidi and Zhao, 2017; Arshi et al., 2018). In order to keep consistency to their compilation of results, an economic allocation was used to split this contribution to Nd, Dy, and Pr, so they can be applied to account for the contribution of REEs to the other routes under study.

2.3. Techno-Economic Assessment. *2.3.1 Added Value of HDDs Separation Process.* The value added of separating the HDDs to recover the magnets and send them to M2M recycling versus shredding the whole HDDs is assessed by collecting the selling prices of each separated commodity versus selling the shredded HDDs. Revisit Section 2.1 and Figure 1 for more details about the commodities.

2.3.1 Preliminary TEA. After observing the benefits of separating the HDDs over shredding, a preliminary TEA is modeled for assessing profitability of having a stand-alone facility to process the collected HDDs and sell the commodities. All the material and energy balances for collection and process of the HDDs are from the LCI established in the LCA. As a base scenario, 1,000 metric tons of HDDs are collected from within the U.S. internal economy, which represents 5.6% of 2010 available end-of-life HDDs. This relatively small amount of feedstock is assumed due to the inefficiencies of HDD collection in the U.S. The capital investment is estimated based on the cost of the harvester to include other capital expenses such as depreciable and non-depreciable expenses. Data of raw material prices, capital equipment prices, and other assumptions can be found in SI, Tables from S7 and S8.

First, to determine the net annual profit of a project, the production cost and revenue are estimated based on Silla (2003). Direct, indirect, general, and annualized capital costs are the categorized components used to estimate the production cost for one year. The annualized capital refers to the total capital investment at year 0 (i.e., at beginning of first year having revenue source) divided by the total life plant. This is just one interpretation for considering the operating and capital costs for one year. Once the production cost is estimated and the revenue for an industrial scale, the net profit is estimated. With this information, the cash-on-cash return (CoC) and breakeven point (BEP) can be used as preliminary economic indicators.

2.3.2 Comprehensive TEA. After the annual net profit is estimated, a net cash flow for a 20-year lifespan plant is assumed. Table 2 lists the assumptions for the terms of financing the project, startup conditions, among other. Due to a lack of data, this comprehensive TEA does not consider the dynamics of prices, capital expenses, and inflation variance, among others. The economic indicators used on this TEA are based on the net cash flow for every year in plant life. These are the following: net present value (NPV), internal rate of return (IRR), and payback period.

Table 2. Comprehensive (static) TEA Assumptions

Category	Assumption
Debt/Equity ratio	1.5
Term of debt financing, years	10
Interest for debt financing, %	6
Compounds per year	1
Plant Life, years	20

Depreciation period, years	7
Depreciation Rate, %	14.29, 24.49, 17.49, 12.49, 8.93, 8.92, 8.93, 4.46
Income tax rate, %	35
Startup time, years	0.5
Revenue and costs during startup, %	50
Operational cost during startup, %	50
Administrative cost during startup, %	100
Operating time, days/year	330
Plant salvage value, years	0
Static Inflation, %	1.56

2.4. Sensitivity Analysis. The results of the LCAs are further investigated by conducting sensitivity analyses. The sensitivity analysis consists of observing the effects of varying between the best and worst scenarios to the LCIA environmental impact categories for all Nd-Fe-B production routes. In addition, further analysis is done with tornado plots for each life cycle TRACI impact category in the M2M-Harvester route.

2.5. Uncertainty Analysis. The result of the TEA is further investigated by conducting uncertainty analysis using a multi-objective optimization technique. This multi-objective optimization technique is used to find profitable optimal solutions and to show the likelihood of getting profit based on the defined ranges of uncertain parameters. A genetic algorithm, i.e., the Genetic Optimization Systems Engineering Tool (GOSET) – version 2.6, is applied (Sudhoff, 2014). Besides maximizing for profit, it is desired to maximize for operating labor wage and HDD acquisition cost, and to minimize for HDD annual feedstock. Maximizing for operating labor wage (i.e., hourly pay rate) may be desired to observe how competitive the facility can become in the labor market while getting a profit. Maximizing for HDD acquisition cost is important to see how much the facility can pay per unit of mass ($/kg) while getting a profit. And finally, the economy of scale has an important effect on the profit. When a process is profitable, if more HDDs are processed, then more profit is obtained. The opposite is also true (i.e., if less HDDs are processed, then less profit is obtained). Therefore, it is desired to know the minimum annual metric tons of HDDs requiring processing while getting a profit. The decision/uncertain parameters for this portion of the analysis are the facility uptime (0% – 90%), annual feedstock (290 – 3,000 metric tons per year), feedstock acquisition cost ($0 – $0.75 per kg), and operator wage ($21.15 - $150.00 per hour, where $21.15 is the median wage in Texas-2023) (BLS, 2023).

3. RESULTS & DISCUSSION

3.1. Life Cycle Assessment. *3.1.1. TRACI Impact Assessment.* Table 3 shows the life cycle impact assessment of producing 1 kg of Nd-Fe-B magnets through primary, hydrometallurgy recycling, and M2M recycling routes for the baseline scenario. The results show that the primary route has the highest environmental impact for all impact categories. When normalizing the data with respect to the virgin route, the environmental footprint for the hydrometallurgy and M2M routes are 42–62% and 4–38% for the baseline scenario, respectively. Also, the environmental footprint for the M2M routes is 11–61% for the baseline scenario with respect to the hydrometallurgy route. Note that the M2M-Manual route only has 95.33–98.97% of the M2M-Harvester route environmental footprint because of the low electricity consumption of the harvester. The results show that either M2M-Manual or M2M-Harvester routes are more environmentally beneficial for every impact category, as shown by a previous study (Jin et al., 2018). The normalization results can be found in Table S6 of the SI.

Table 3. TRACI Life Cycle Impacts of Producing 1 kg of Nd-Fe-B Magnet through all Three Routes Under Study

Impact Category	Unit	Virgin (A)	Hydro (B)	M2M-Manual (C)	M2M-Harvester (D)
Ozone Depletion	kg CFC-11 eq	1.80E-05	7.57E-06	8.11E-07	8.12E-07
Global Warming	kg CO2 eq	1.27E+02	6.78E+01	2.44E+01	2.45E+01
Smog	kg O3 eq	1.17E+01	5.25E+00	1.07E+00	1.08E+00
Acidification	kg SO2 eq	9.86E-01	6.16E-01	3.75E-01	3.75E-01
Eutrophication	kg N eq	1.39E+00	5.92E-01	1.09E-01	1.09E-01
Carcinogenics	CTUh	6.50E-06	3.29E-06	1.24E-06	1.24E-06
Non Carcinogenics	CTUh	3.51E-05	1.93E-05	8.77E-06	8.77E-06
Respiratory Effects	kg PM2.5 eq	2.08E-01	9.64E-02	2.47E-02	2.47E-02
Ecotoxicity	CTUe	8.81E+02	4.84E+02	2.25E+02	2.25E+02
Fossil Fuel Depletion	MJ surplus	1.69E+02	9.00E+01	2.63E+01	2.63E+01

Besides these results on the life cycle impact assessment for all ten categories, characterization of the footprint for each route is found in Figure S2–S4. The dominant material input (in terms of footprint) for the primary production route and hydrometallurgical route are the use of fresh REEs coming from mining (i.e., 62–95% and 39–88%, respectively). For the M2M route, depending on the impact category, the dominant material input could be either the use of nickel as magnet coating and the electricity consumption on the decoating and pressing processes (i.e., 4–75% and 13–76%, respectively). It makes sense that fresh REEs additions are not the dominant input for the M2M route because only 1% of the REEs used in the production of Nd-Fe-B magnets is not coming from the recovery of HDDs. On the other hand, the hydrometallurgical recycling route has low recovery of REEs from HDDs in the shredding process (i.e., up to 10%) (Maani et al., 2024), leading to a reliance of REEs coming from mining.

3.1.2. Sensitivity Analysis. According to the TRACI impact assessment, the M2M routes have the lowest footprint on the baseline scenario. If the worst and best scenarios are considered for each route, a sensitivity analysis can be conducted. Figure 2 includes the contribution of environmental impacts for all routes with respect to the baseline scenario of Nd-Fe-B production. This figure confirms that M2M routes are certainly more beneficial to the environment than the other ones because the error bars do not overlap. However, the error bars for primary and hydrometallurgy routes overlap between them. Nonetheless, the hydrometallurgy route shows an improvement for each impact category, even for the worst scenario, in comparison to the base scenario of the primary production route. If the best scenario of the primary production route can be guaranteed, then it is hard to say which of these two routes is better from an environmental perspective. On the other hand, both M2M-Manual and M2M-Harvester routes have relatively the same environmental performance; however, from a lifecycle perspective, the latter would have a higher environmental impact than reported if the manufacturing of the harvester were included.

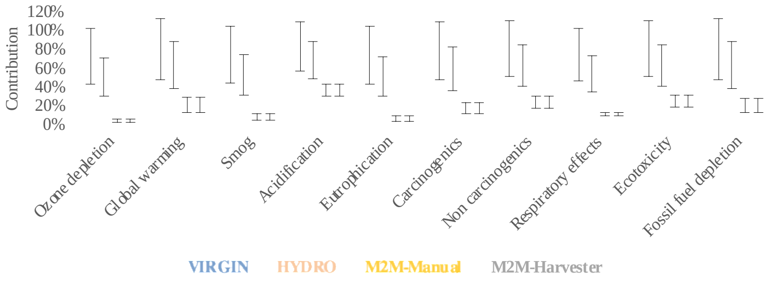

Figure 2. Comparative contribution of life cycle impact assessment on the production of 1 kg of Nd-Fe-B magnet for all routes studied and all impact categories.

In the SI, Figures S5–S14 are tornado plots for each life cycle TRACI impact category in the M2M-Harvester route. The most sensitive input or process is the electricity consumption on decoating and pressing processes in terms of ozone depletion (-13.5–29.2% change of environmental impact from baseline scenario), global warming (-18.5–40.3%), smog (-13.7–29.9%), carcinogenics (-12.1–26.4%), non-carcinogenics (-5.6–12.3%), ecotoxicity (-5.2–11.3%), and fossil fuel depletion (-19.8–43.0%) categories. On the other categories, nickel is the most sensitive on acidification (-7.7–7.7%) and respiratory effects (-8.0–8.0%) while sludge due to slicing and dicing is the most sensitive on eutrophication (-6.6–19.2%). It is important to note that the sum of the footprint of all inputs and processes for the worst and best scenarios are plotted in the error bars of Figure 2. Hence, the results shown in this figure are enough to conclude that the M2M routes are significantly better for the environment.

3.2 Techno-Economic Assessment. *3.2.1. Added Value of HDDs Separation Process.* Table 4 shows the data used for assessing the value added of separating the HDDs versus shredding the whole HDDs. It is calculated that the value for separating HDD materials is \$1.35 per kg whereas the value for shredding the whole HDD is \$0.40 per kg. The added value based on separated materials is \$0.95 per kg (237.5% of increase in value).

Table 4. TRACI Life Cycle Impacts of Producing 1 kg of Nd-Fe-B Magnet through all Three Routes Under Study

Commodity	Weight (%)	Value ($/kg)
Recovery Based on Separated Materials		
Printed Circuit Board (PCB)	5%	$19.84
Magnetic Assembly	32%	$0.13
HDD Aluminum Body	63%	$0.50
Total Value Separated Value Recovery		$1.35
Recovery Based on Whole Scrap HDD		
Cut HDD	100%	$0.40
Total Whole HDD Value Recovery		$0.40
Increase in value: 237.5%		
Added Value: $0.95 / kg of HDD		

3.2.2. Preliminary Economic Indicators. From the preliminary TEA, operating and annualized capital expenses and expected revenue were estimated for M2M and shredding processes. Figure 3 shows the revenue and cost contribution between shredding and harvesting HDDs for the baseline scenario. It is seen that the processing cost is similar in harvesting (\$1,107k/yr, \$1.11/kg) than in shredding (\$1,112k/yr, \$1.11/kg). Regarding revenue, since harvesting adds higher value to HDDs than shredding, harvesting has more potential to operate profitably as a stand-alone facility than shredding. In general, since the harvester throughput can be higher than the shredder (12 versus 3.3 HDDs per minute), one can save direct operating labor cost and other indirect expenses and offset the initial investment cost of the harvesting machine. At lower HDD demand, this cost savings decreases giving a higher processing cost for the harvesting scenario. Of course, this capital cost is still preferred in exchange of higher added value commodities and higher throughput.

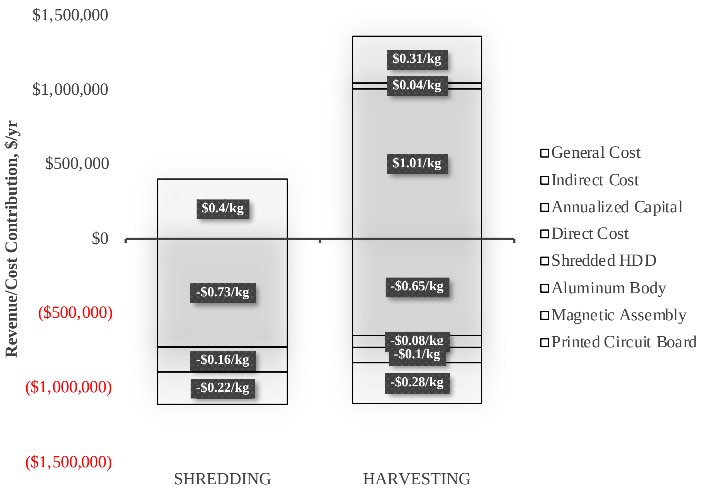

Figure 3. Revenue (green) and cost (red) contribution of shredding versus harvesting HDDs

Based on this baseline scenario, the profit margin and cash-on-cash return (CoC) are estimated. The results for separating HDDs with the harvester are as follows: the annual profit is $256k/yr, so the profit margin is 18.8% and the CoC is 22%. As of these preliminary economic indicators and annual net profit, the baseline scenario turns out to be profitable.

3.2.2. Comprehensive Economic Indicators. In order to know more specific information about how beneficial it is to invest in the harvesting machine, a comprehensive TEA is conducted. Based on the assumptions presented in Table 2, the NPV is $2.3M, the IRR is 30%, and the payback period is 3-4 years. These baseline results confirm that processing the HDDs with the harvester in a stand-alone facility can be profitable.

3.2.3. Uncertainty Analysis. An optimization technique is performed to find profitable optimal solutions and to show the likelihood of getting profit based on the defined ranges of uncertain parameters, as explained in Section 2.5. Figure 4 shows an output of 1,141 optimal solutions of the last generation of the genetic algorithm (2,000 generations and 2,000 population size). Based on the defined ranges for the uncertain/decision parameters, the values of the economic metrics (i.e., NPV, IRR, and payback period), the objectives to be optimized (i.e., annual profit, operator wage, HDD acquisition cost, and feedstock), and the parameters (i.e., uptime and throughput) are plotted in ascending order of NPV. It is observed that as NPV increases, IRR, annual profit, feedstock, and uptime tend to increase, whereas payback period, operator wage, HDD acquisition cost tend to decrease, as expected. The throughput tends to range between 11 and 12 HDDs/min to maximize feedstock processing at low uptime, and to satisfy with the required demand as feedstock processing increases.

Green data points represent those solutions such that NPV is greater than or equal to zero. In addition to the solutions, the corresponding probability distributions for each plotted metric, objective, and parameters are plotted. The green bars represent the portion of solutions of each corresponding range such that NPV is greater than or equal to zero. Based on the defined ranges for the uncertain/decision parameters, one may interpret these green bars against the corresponding gray bars as a likelihood of profitability in terms of NPV. For example, it is more likely that the plant will be profitable (i.e., less risk) as the operator wage and HDD acquisition cost tend to be minimal (i.e., $21.15 per hour and $0 per kg of HDD, respectively). On the other hand, it is less likely that the plant will be profitable (i.e., more risk) as the annual feedstock and plant uptime tend to be minimal (i.e., 290 metric tons per year and 8.78%, respectively).

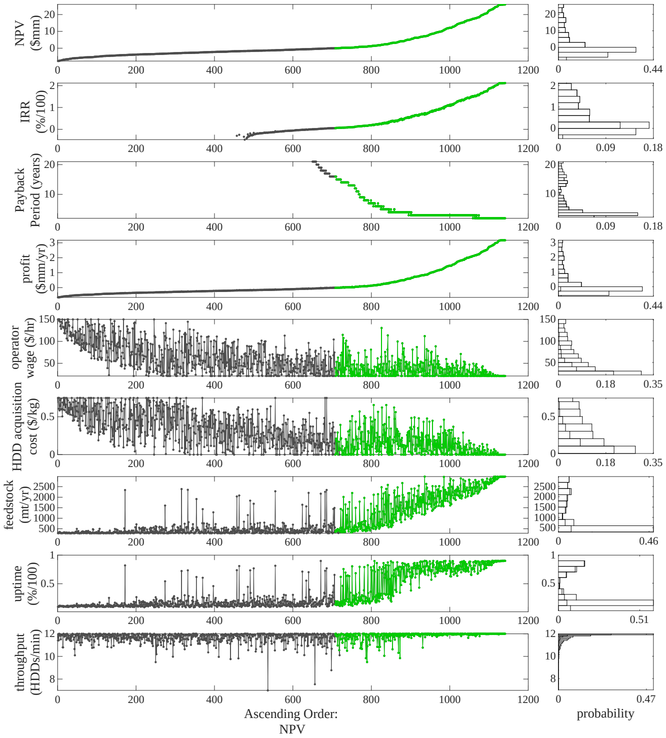

Figure 4. Economic metrics (NPV, IRR, payback period), optimized objectives (profit, operator wage, HDD acquisition cost, and feedstock), and parameters (uptime and throughput). The green datapoints represent profitable solutions in terms of NPV and the green horizontal bars represent the corresponding portion of solutions which are profitable.

The ranges giving at least one profitable solution (i.e., NPV ≥ 0) for each economic metric, objective, and parameter are as follow: NPV ($0 – $26M), IRR (6% – 212%), payback period (2 – 15 years), annual profit (-$0.01M – $3.17M per year), operating labor wage ($21.15 – $130.42 per hour), HDD acquisition cost ($0.00 – $0.66 per kg), feedstock (299 – 2,979 metric tons per year), uptime (8.8% – 90.0%), and throughput (7 – 12 HDD per minute). However, as seen in Figure 4, some scenarios may be riskier than others in terms of profitability. Based on these results, future work may involve the assessment of integrating downstream processes as part of a same Nd-Fe-B production facility to further reduce the risks shown in this study, especially at lower feedstock processing rates.

4. SUMMARY & CONCLUSIONS

LCAs were conducted to compare the production of Nd-Fe-B permanent magnets in the following routes: (1) primary production, (2) hydrometallurgy recycling, (3) magnet-to-magnet recycling with manual labor, and (4) magnet-to-magnet recycling with a harvesting machine. From the environmental perspective, the M2M routes for the production of 1 kg of Nd-Fe-B have the lowest impacts among all the routes under study, obtaining 4–38% in comparison to primary production footprint and 11–61% in comparison to hydrometallurgy recycling footprint of all ten TRACI impact categories for the base scenario. The results for the comparison between M2M-Manual and M2M-Harvester showed that the difference in environmental impacts changed insignificantly. Also, the most sensitive input in almost all the impact categories is found to be "Electricity, medium voltage, at grid, Texas/US US-EI U" on decoating and pressing processes. In contrast to other routes, the addition of fresh REEs is not the most sensitive input on the environmental footprint for each category due to the high recovery of REEs coming from HDDs recycling.

From techno-economic perspective, we investigated the added value of harvesting HDDs over shredding due to the recovery of more commodities and higher processing rate. A TEA was conducted to recover 1,000 HDD metric tons per year, obtaining an annual profit of $256k, a profit margin of 18.8% and a CoC of 22%. Further financial analysis showed that a NPV of $2.3M, an IRR of 30%, and a payback period of 3-4 years is obtained in the baseline scenario. An uncertainty analysis using an optimization technique showed the ranges and likelihoods by which the plant may be profitable in terms of NPV. Each investor would have different parameters to identify what are the "risks" for profitability and determine whether to invest in a harvesting facility. In conclusion, these assessments show a promising investing alternative to achieve better environmental and economic performance and a safer Nd-Fe-B magnet supply for the U.S. economy.

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