Washington, D.C.
June 10–12, 2019
NREL/PO-6A20-74053

Sustainable Manufacturing – Recycling

Opportunities, Trends, and Technoeconomic Analysis

Birdie Carpenter

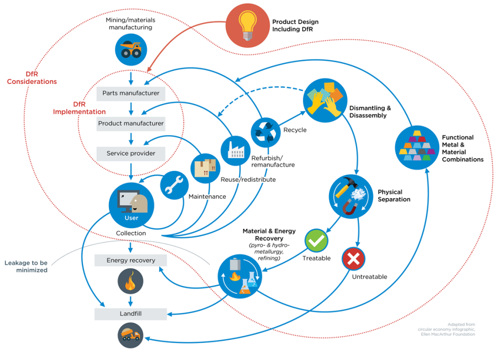
2019 PROGRAM PEER REVIEW
U.S. DEPARTMENT OF ENERGY
ADVANCED MANUFACTURING OFFICE

Design for Recycling (DfR)

NREL Transforming ENERGY

Motivation

- In pursuit of a circular economy, the proverbial last line of defense when a product reaches its End-of-Life (EOL) is recycling.
- Fundamentally, there are only two ways to improve recyclability; design a better recycling process, and/or implement Design for Recycling (DfR) strategies during product development.
- Recycling itself often consists of multiple stages. For example, a metallic output from a shredding recycler will likely undergo various degrees of smelting and refining before a product manufacturer can make use of the material.
- The relationship between a circular economy, recycling stages, implementation, and considerations necessary for effective DfR are illustrated in the figure below.



Adapted from circular economy infographic, Ellen MacArthur Foundation

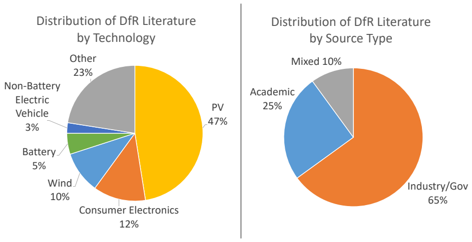
- In some cases, as shown by the dotted line, DfR may enable the direct recovery of intact components for immediate reuse, thus bypassing significant intermediate energy expenditures and potential materials losses.
- Specific DfR strategies are a function of both the product in question, as well as the nature of available recycling processes. Additional factors, such as legislation and business realities, must also be considered.

Methodology

- A literature review was performed to compile a preliminary list of DfR best practices.
- The results of the literature review were socialized iteratively with 20 domestic and international experts across PV, wind, and batteries within NREL, DOE, academia, and industry.

Results

- Out of 95 sources reviewed, 40 were deemed to have some degree of direct relevance to DfR.
- Breakdowns by subject matter and origin are shown in the charts below:


Distribution of DfR Literature by Technology

Distribution of DfR Literature by Source Type

- Industry feedback was generally positive, and often consisted of suggestions for alternative wording to improve the clarity of the guidelines. In one instance, an expert proposed two additional guidelines deemed appropriate for inclusion in later iterations.
- Two examples of a DfR strategies resulting from industry feedback is as follows:

"Ensure circularity, minimize the use of or substitute hazardous materials. This will impact not only the safety of recycling efforts, but potentially also avoids contamination of recycling outputs and characterization as hazardous waste."

"Minimize the use of additional materials other than the resin and fibers to ease recycling of blades. This includes eliminating adhesives where possible."

- At present, this list consists of 10 overarching DfR guidelines, and 4 to 8 RE tech specific DfR guidelines & observations each for PV, wind, and batteries.

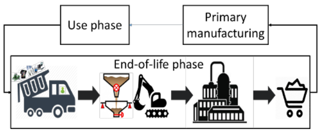
Battery Rare Earth Element (REE) Recycling

Argonne NATIONAL LABORATORY

Motivation

As emerging electronics and clean energy technologies drive up demand for rare earths, value recovery from end-of-life recycling provides an option for closing the material loop, conserving natural capital and enhancing resource security.

Yet, the economic feasibility of recycling depends on product recovery and purity targets, as well as uncertain inputs like feed compositions and volumes.



Robust, first-principles models that propagate and quantify these uncertainties are needed to determine their effect on the economic viability of recycling.

Method

The modeling strategy integrates the extraction physics into techno-economic optimization framework to provide robust technology assessment.

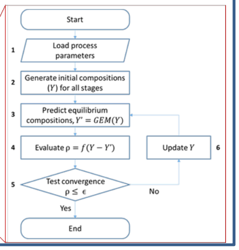
$\min f(x_i, y_i)$
☐Yield
☐Cost/Revenue
☐Energy use
☐Ecologic impact

$s.t$

$h(x_i, y_i) = 0$
☐$\min(Gibbs(x_i, y_i))$
☐Mass, species & charge balance

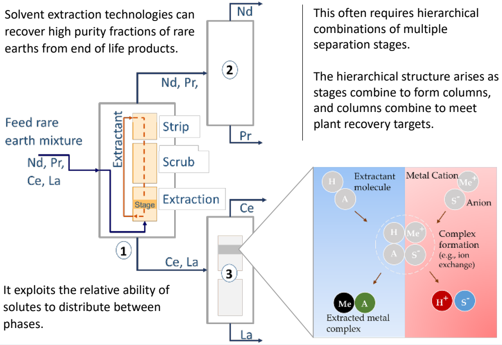
$g(x_i, y_i) \leq 0$
☐Yield, process and/or economic constraints

$x_{min} \leq x_i \leq x_{max}$



Technology: Solvent Extraction

Solvent extraction technologies can recover high purity fractions of rare earths from end of life products.

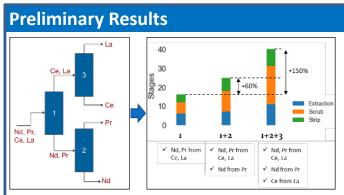


It exploits the relative ability of solutes to distribute between phases.

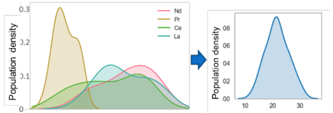
This often requires hierarchical combinations of multiple separation stages.

The hierarchical structure arises as stages combine to form columns, and columns combine to meet plant recovery targets.

Preliminary Results



Impact of design targets: Additional separation requirements translate to a significant increase in equipment size. The marginal benefit must justify the additional capital outlay.



Kernel **D**ensity **E**stimate of the probability distribution of input feed compositions

KDE of distribution of theoretical stages given feed compositions.

Impact of uncertainty in feed composition: Variation in feedstock composition translates to a spread number of theoretical stages for the same recovery and purity target.

Supply Chain Analysis of rPET Upcycling

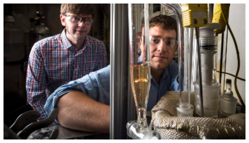
NREL Transforming ENERGY

Motivation

- Most commercial PET plastic recycling is mechanical
- Mechanical recycling leads to lower-grade plastic with fewer applications (carpet fiber, etc.)
- Chemical recycling of PET bottles back to monomers is energetically and economically expensive
- What if we could make higher value glass fiber reinforced plastic (GFRP) with chemically-recycled PET and bio-based additives?
- **Key analysis question:** Are there energy/emissions savings associated with rPET–based GFRP production?

Methodology

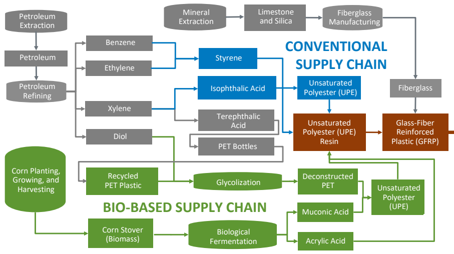
- The Materials Flows through Industry (MFI) tool is a supply chain modeling tool created at NREL to identify and analyze opportunities to reduce the energy and carbon intensities of the U.S. industrial sector.
- We model the lab-scale rPET upcycling process developed by other NREL researchers to determine the requisite energy and material inputs, then connect this lab-scale unit process to existing MFI unit processes
- Energy requirements and combustion-related greenhouse gas (GHG) emissions were calculated for the full bio-based supply chain models and compared to results from conventional GFRP manufacturing
- Scenarios 2-4 below represent different methods of handling the impacts attributed to the "first life" of the upcycled PET plastic bottle.



NREL researchers Nic Rorrer (front) and Gregg Beckham (back) working on their lab-scale rPET upcycling process. Photo by Dennis Schroeder, NREL 47350

Key Findings

- Supply chain fossil energy reductions range from **37% to 58%**.
- Supply chain fossil *feedstock* energy reductions range from **58% to 79%**
- Supply chain GHG emissions reductions range from **30% to 40%**
- If all conventional GFRP were replaced: we estimate 0.7 – 1.0 MMT-CO_2e annual offsets; Roughly equivalent to taking **150,000 to 200,000 cars** off the road



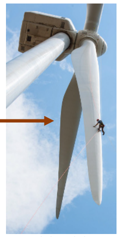


Photo by Dennis Schroeder, NREL 27204

Future Work

Future applications of this broader MFI methodology which are either currently underway or being considered include:

- Bio-based nylons
- Bio-based polyesters and polyaramids
- Biodegradable PET

Acknowledgments

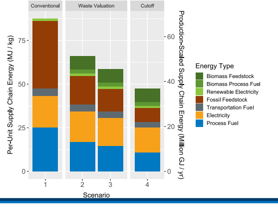
The MFI analysis portion of this work was funded by the Dept. of Energy's Advanced Manufacturing Office.

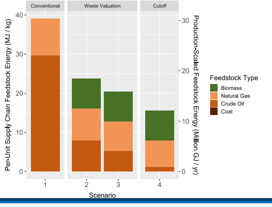
Results Figures

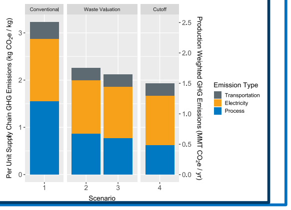
Scenario	Name	PET Bottle (First Life) Impacts Allocation
1	Conventional GFRP production	*N/A* *(No rPET Used)*
2	Waste Valuation; Reclaimed Clear rPET	$\frac{\frac{45¢}{lb}\,Clear\ rPET\ Flake^*}{\frac{83.5¢}{lb}\,Virgin\ PET\ Resin^*} \approx$ 54% (Economic)
3	Waste Valuation; Reclaimed Green rPET	$\frac{\frac{27¢}{lb}\,Green\ rPET\ Flake^*}{\frac{83.5¢}{lb}\,Virgin\ PET\ Resin^*} \approx$ 32% (Economic)
4	Reclaimed rPET - Cutoff	*0%* *(First Life Ignored)*

** Commodity market prices as of July 2018*

Publication: Rorrer et al. 2019. "Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling". *Joule.* DOI: 10.1016/j.joule.2019.01.018







This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Advanced Manufacturing Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.