

Sustainable Manufacturing: Application and Analysis of Circular Economy Strategies

AMO Strategic Analysis (StA) Team



Poster Presenter:

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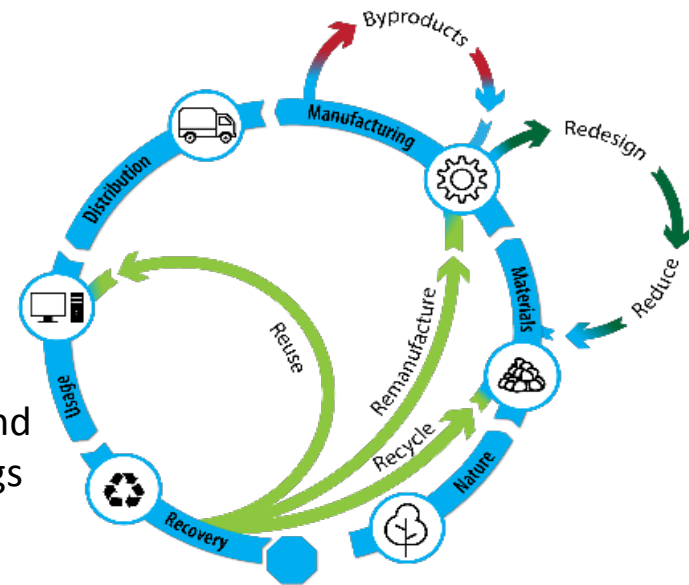
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Overview

- The multi-laboratory (Argonne National Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and Oak Ridge National Laboratory) AMO Strategic Analysis (StA) Team provides independent, objective, and credible information to inform decision-making.
- The StA team submitted 6 posters for this year's Program Review; the research topics are ongoing and do not follow the typical poster format
- This poster, **“Sustainable Manufacturing: Application and Analysis of Circular Economy Strategies”** includes information on five projects:
 1. U.S. Food Loss, Waste, and Byproducts Analysis
 2. Estimating the Potential Application of the NSF457 *Sustainability Leadership Standard for PV Modules* in Federal Government PV Procurement
 3. Battery Rare Earth Element (REE) Recycling
 4. Supply chain impact analysis of upcycling of recycling PET
 5. Design for recycling principles for some clean energy technologies

Project Objective(s) – Sustainable Manufacturing

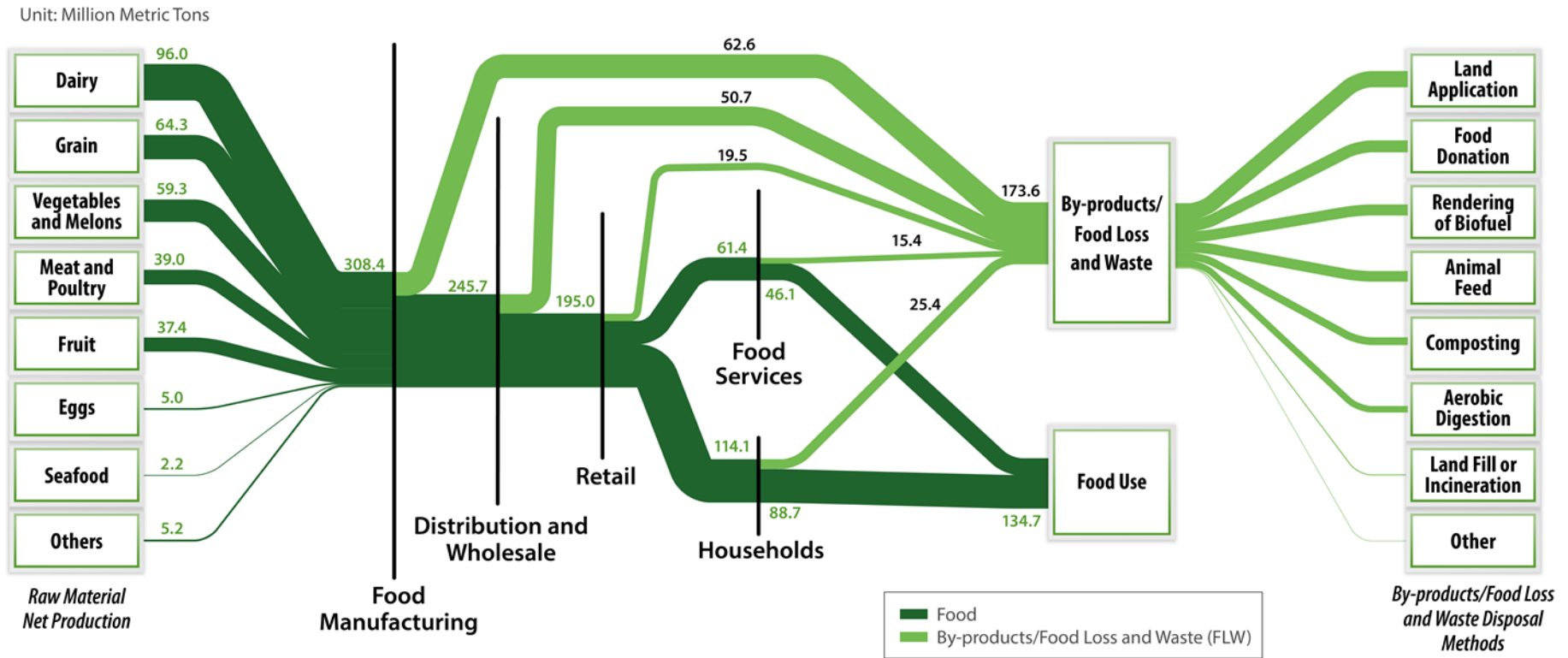
- **Sustainable manufacturing:** encompasses a widening range systems issues (e.g., energy intensity, carbon intensity, and use intensity) and solution can enable a more efficient and competitive advanced U.S. manufacturing future.
- **Challenge with many traditional manufacturing systems:** Develop an inefficient linear model, starting with raw materials extract (mining) and end disposal in a landfill at the end of the product's useful life.
- **Circular economy** (represented by the figure to the right) redirects the current approach by providing opportunities to re-manufacture and reuse end-of-life consumer products, leading to more efficient use of materials.
- **Analyzing the supply chain and material flows: throughout the product's entire lifecycle:** Can help to identify energy, material, and water savings opportunities for greater U.S. economy (including the production and delivery of energy and energy use within the industrial, transportation, and buildings sectors)



- The team's **past and current sustainable manufacturing activities** include: developing baseline knowledge, analyzing long-term trends, and assessing current opportunities. Methods, data, and results are vetted through conference presentations, workshop collaborations, and reports.
- A key in doing so is addressing the challenge of how to evaluate different strategies' potential by developing general evaluation approaches and establishing a baseline to use a reference point.

U.S. Food Loss, Waste, and Byproducts Analysis

Estimated U.S. Food Use, Loss, Waste, and By-products in 2016



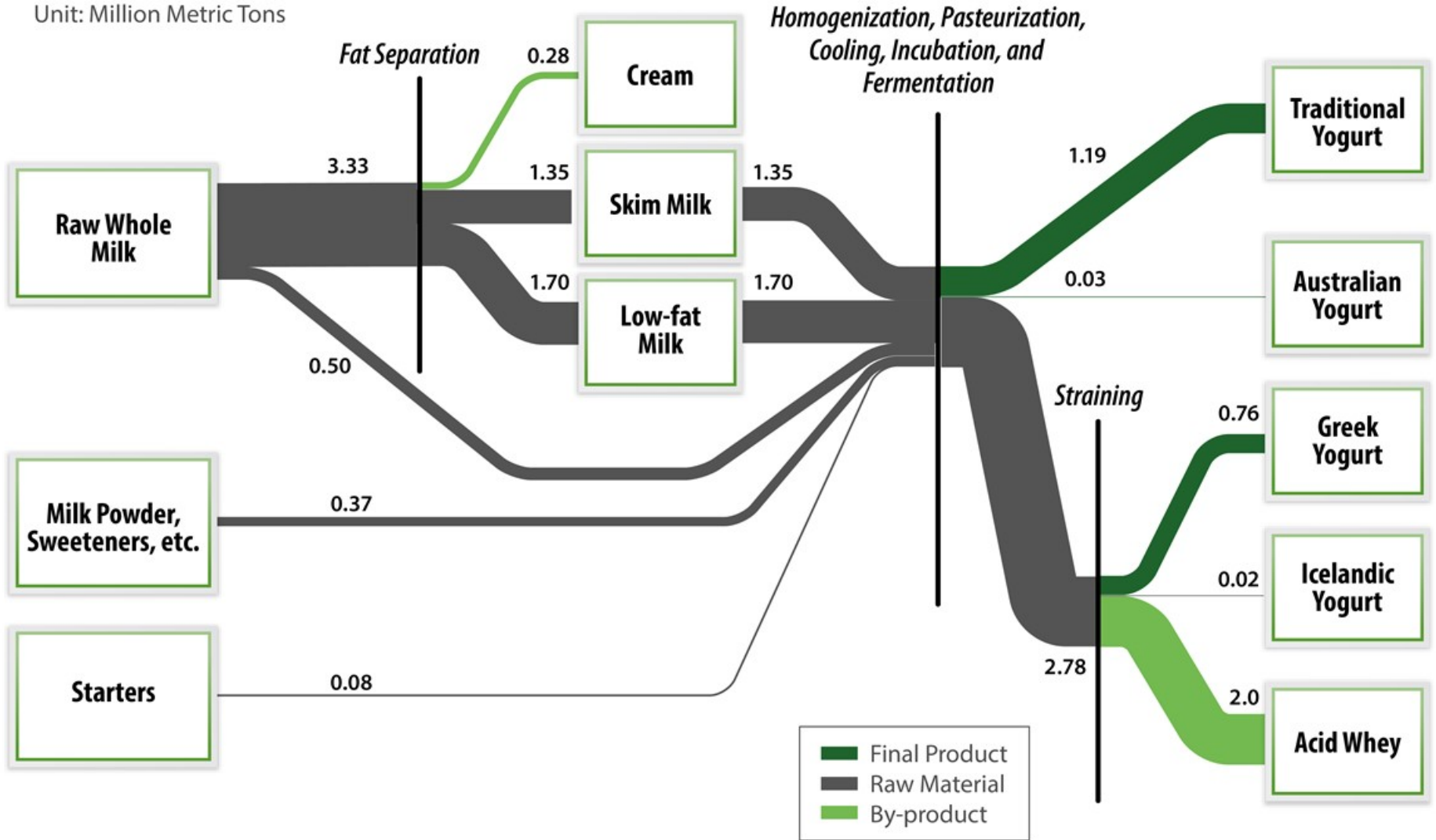
- All of the food products are based on **farm weight**
- Raw materials** used for **non-human-foods** and **alcohol products** are **excluded**
- Waste quantities for each disposal method will be determined**

U.S. Food Loss, Waste, and Byproducts Analysis

- Billion tons of waste is generated in U.S. every year and food industry is one of the major waste sources (**173.6 million metric tons** of wastes/byproducts in the **whole food supply chain**)
- More than **7 methods** can be found to **dispose** wastes/by-products from U.S. food sector
- Each method will be analyzed to **identify the technical and economical barriers** for implementation
- Some **optimal combinations of disposal methods** will be proposed to improve the energy and greenhouse gas emission savings
- A **R&D road map** will be developed to guide the research on food waste reduce, reuse and recycle
- **Similar studies will be conducted** for **other industries** (iron and steel, aluminum, pulp and paper, etc.)

U.S. Yogurt Industry Material Flow (2017)

Unit: Million Metric Tons



Sources: USDA, DMI, McElhatton, White, and Others

U.S. Food Loss, Waste, and Byproducts Analysis

- **2.0 million metric tons** of yogurt was **consumed** in the United States in 2017
- Market shares for 4 major yogurt product in U.S.: **traditional (60%), Greek (38%), Australian (1.3%) and Icelandic (0.9%) yogurt**
- **3.83 million metric tons of raw milk** was **consumed** for producing yogurt with **0.28 million metric tons of cream** and **2.0 Million metric tons of acid whey** generated as byproducts
- Producing **Greek yogurt accounts for 97% of total acid whey**, and **Icelandic yogurt** accounts for **3%**
- Acid whey can usually be disposed through **landfill, land application, animal feeding and bio-digestion**

Sustainability of PV Modules

- **Solar PV panels benefits:** Yield significant environmental benefits during use phase by reducing the emissions-intensity of the electric grid
- **Environmental Impacts:** Before and after the use phase from materials mining, manufacturing, and disposal
- **Other Concerns:** Possible issues associated with sourcing materials from areas with poor labor or governance conditions

“The PV industry’s continued growth makes it critical to take action now to reduce the use of toxic chemicals, develop responsible recycling systems, and protect workers throughout global PV supply chains.”

- *Silicon Valley Toxics Coalition*

Solar PV Sustainability Standards

NSF457 (Sustainability Leadership Standard for Photovoltaic Modules): addresses a growing need for PV sustainability standards.

- **Problem:** PV panels yield significant environmental benefits during use phase, but there are environmental impacts before and after the use phase from materials mining, manufacturing, and disposal.
 - Before 2018, there was no clear, objective, verifiable, consensus-based criteria for sustainability attributes of PV modules.
- **Challenge:** Remains difficult for purchasers to learn about PV modules' sustainability attributes & identify sustainability-leading modules in the marketplace.
- **Progress:** Green Electronics Council developed the *Sustainability Leadership Standard for PV Modules* (NSF457) standard to fill the need for verifiable, objective sustainability standards for PV modules and identify leaders in sustainability performance.

Solar PV Sustainability Standards

Opportunity: Federal government can lead by example by becoming an early adopter of sustainability-certified solar PV panels.

Current collaboration:

- To address growing need for PV sustainability standards, the Green Electronics Council¹ initiated a process following American National Standards Institute rules to develop an objective, verifiable standard to define high sustainability performance for PV module manufacture and disposal—the NSF457 standard.
- NSF457 enables large PV modules purchasers to easily identify highly sustainable modules in the marketplace and easily specify high sustainable performance PV modules in their procurement documents.
- Reduces arduous and complex task for individual purchasers of defining sustainability performance and collecting information from individual manufacturers to assess, verify, compare, prioritize, and monitor.

¹ managers of the well-known EPEAT registry for sustainability-leading IT products

Sustainability Leadership Standard for PV Modules (NSF457) Scope

• Sustainability Performance Categories

(product-specific and corporate-specific criteria, *see figure right*)

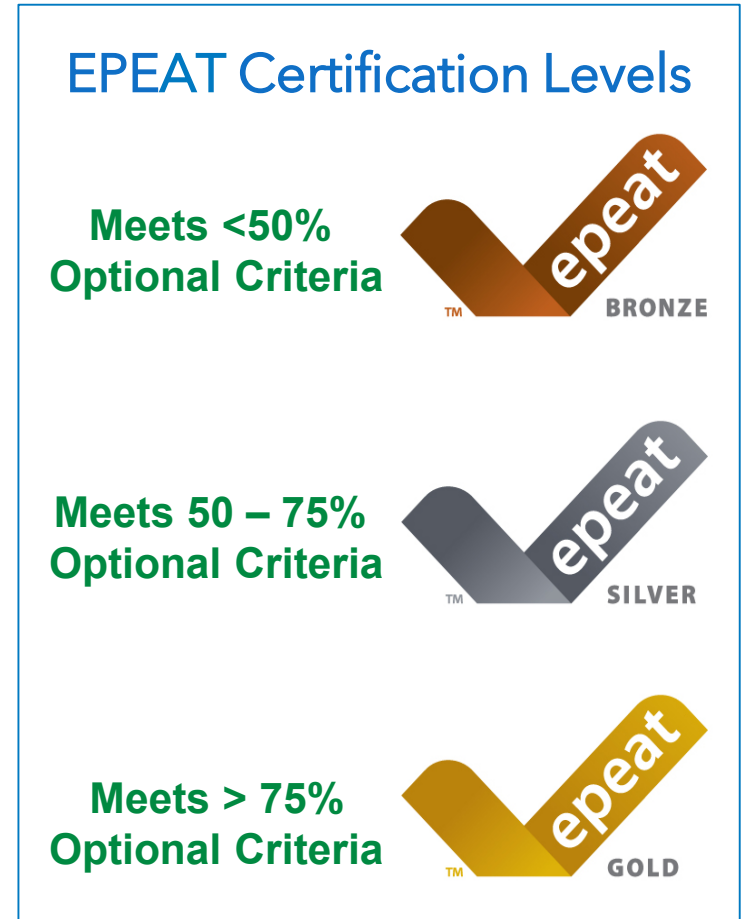
- Management of substances
- Preferable materials use
- Life cycle assessment
- Energy efficiency and water use
- End-of-life management and design for r
- Product packaging
- Corporate responsibility.



Source: GEC, 2018

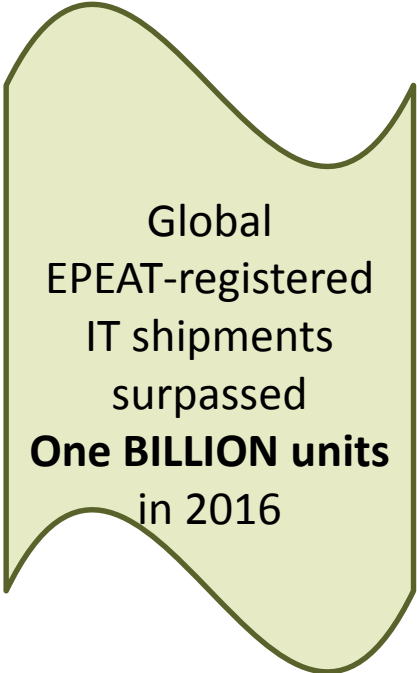
Design as an Eco-Label (EPEAT certification)

- NSF457 will become part of the trusted EPEAT program with a registry where certified modules can be easily found and where certification is maintained over time
- NSF457 is designed to identify leaders:
 - Only the top 1/3 of the market should qualify for an EPEAT label (all levels)
- Under EPEAT, modules can be certified according to three levels—bronze, silver, and gold—according to the percentage of criteria which are satisfied.



Who Uses EPEAT?

- Entities that specify EPEAT: Thousands of **public jurisdictions**, dozens of **national governments**, 300+ **colleges and universities**, and hundreds of **private sector** organizations in hospitality, finance, healthcare
 - EPEAT is used by large buyers such as the U.S. federal government and many corporations. <https://greenelectronicscouncil.org/epeat/epeat-overview/>
- EPEAT highlighted in countless laws, directives, policies, best-practices, and guidance documents
- Widespread adoption and repeated endorsement for over a decade based on:
 - Trust
 - Credibility
 - Ease of use in procurements
 - Product availability: Broad range of brands available via EPEAT.



Global
EPEAT-registered
IT shipments
surpassed
One BILLION units
in 2016

NSF457 Points System

NSF457 Points System

PV manufacturers must earn all required points and can earn extra optional points to achieve higher levels of certification

Reduction of substances of concern	●	●	○	○	○	
List and assessment of substances	●	●	○	○	○	○
Recycled content	●	○	○	○	○	
Reduction in LCA impacts	○	○	○			
PV module LCA	●	○	○	○		
Water use metrics	●	○	○	○		
Energy management system	○	○	○	○	○	○
Design for recycling	○					
End-of-life management	●	○	○	○		
Recycled content in packaging	○	○				
Recyclability of packaging	●					
Eliminate substances of concern	●	●				
Conflict mineral sourcing	●	○	○			
Corporate social performance	●	○	○			
Corporate reporting	●	○	○	○	○	
Environmental, health, and safety management	●	●				

● Required point
○ Optional point

Status of the NSF457 Standard

The NSF457 standard has been finalized and at least three PV manufacturers are actively pursuing certification.

- NSF457 for PV modules was approved and published December 2017.
- It is referenced in a new *Solar Technology and Project Developers Sustainability Accounting Standard* published by the Sustainable Accounting Standards Board (SASB).
- An [EPEAT](#) registry is planned for PV modules to identify those certified to meet NSF457 – to be completed by end of 2019.
- European Commission has stated it will adopt NSF457 as basis for its expected Ecolabel for PV electricity.
 - Scope of NSF457 is being increased to include inverters by October 2019 based on EC need
- Several manufacturers are in the process of certifying modules to the standard.

Channels For NSF457 Adoption in Federal Sector

Product Registries

Procurement Influencers

Candidates for Early Deployment

DOE

EPA

USGBC

Federal Energy Management Program (FEMP)

GreenBuy Awards Program

Environmentally Preferable Purchasing Program

Procurement Specifications
Templates for On-Site Solar Photovoltaic

Priority Products List (PPL)

Recommendations of Specifications, Standards, and Ecolabels

LEED (v4)

Policies

Registries

Influencers

Early Movers

NSF457 Standard: Wedge Analysis

- The following slides identify four pathways for NSF457 uptake and the potential deployment through each pathway
- The pathways are independent, such that multiple pathways could be pursued to increase overall NSF457 uptake
- Each pathway therefore represents a “wedge” of a broader suite of strategies to increase NSF457 uptake:

Wedge 1

NSF457 in new federal buildings

Wedge 2

NSF457 on GSA-owned buildings

Wedge 3

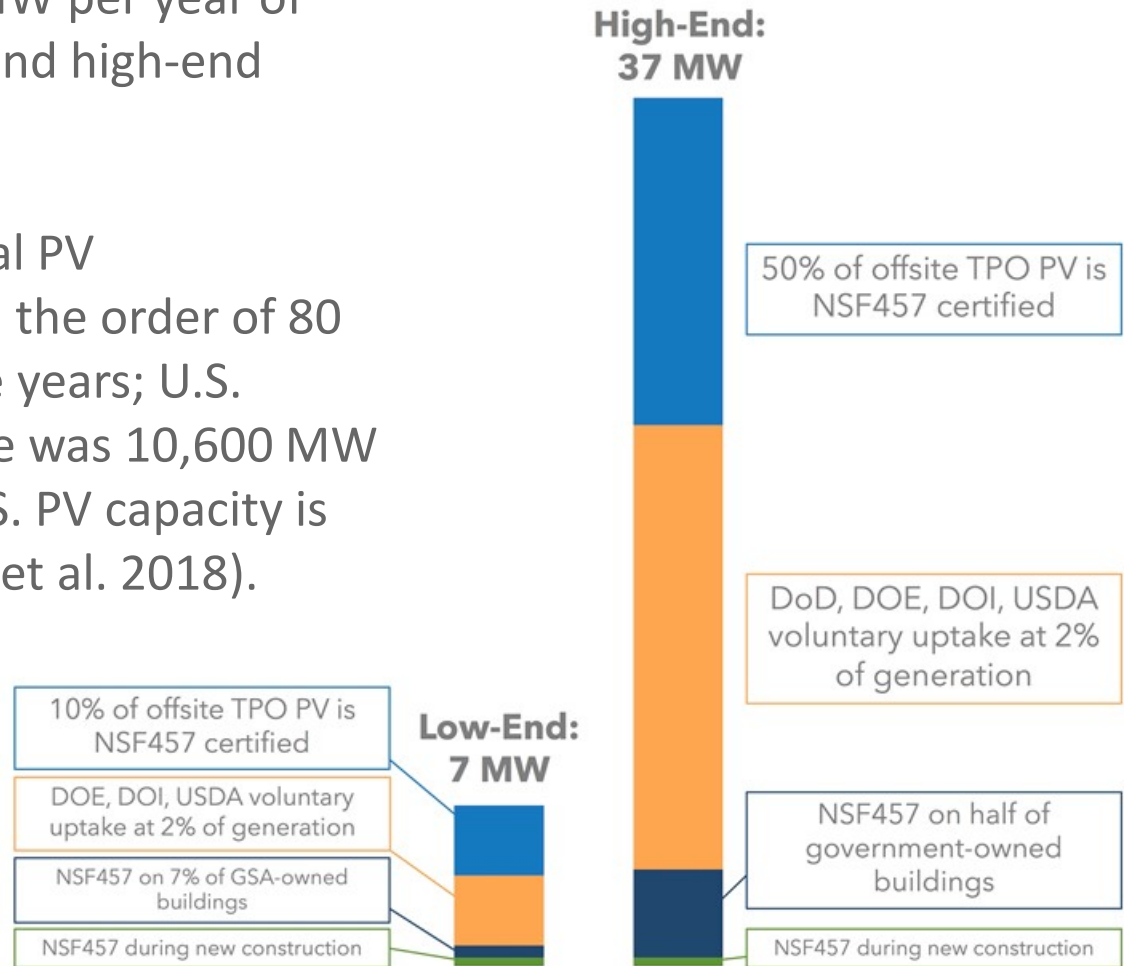
Voluntary agency-level initiatives

Wedge 4

NSF457 in off-site third-party owned PV

NSF457 Standard: Wedge Analysis

- Wedges (figure on right) collectively amount to 7 MW to 37 MW per year of NSF457 demand as low- and high-end estimates
- For context, annual federal PV procurement has been on the order of 80 MW/year for the past five years; U.S. annual installation volume was 10,600 MW in 2017; total installed U.S. PV capacity is about 57,000 MW (Perea et al. 2018).



Battery Rare Earth Element (REE) Recycling

- **Context:** As emerging electronics and clean energy technologies drive up demand for rare earths, value recovery from recycling end-of-life products provides an option for closing the material loop, conserving natural capital and enhancing resource security.
- **Challenge:** The techno-economic feasibility of recycling depends on product recovery and purity targets, as well as a host of other uncertainties, including variable feed compositions and volumes.
- **Opportunity:** Assessment tools that integrate the physics and techno-economics of the recycling technology can provide a more realistic assessment, and give a clearer understanding of the impacts of uncertain parameters.
- **Action:** The Strategic Analysis team is developing robust, first-principles models and frameworks that capture, propagate and quantify these impacts to determine their effect on the economic viability of recycling.

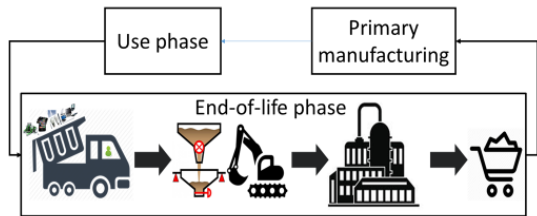
Battery Rare Earth Element (REE) Recycling

- Illustrate modeling framework and present initial analysis focused on a case study for separating rare earth mixtures from coming from nickel metal hydride batteries via solvent extraction.
- Results: show how these integrated models can capture and provide insight on the relationship between uncertain or variable inputs and target outputs. Result highlights include:
 - **Impact of design recovery targets:** Additional separation requirements translate to a significant increase in equipment size, hence capital equipment cost. The marginal benefit must justify the additional capital outlay for meeting target design specifications.
 - **Impact of feed compositional uncertainty:** Variations in feedstock composition translates to a spread in the number of theoretical separation stages required for the same target recovery and purity specifications. This also provides an estimate of the redundant capacity that needs to be built into the plant design.

Battery Rare Earth Element (REE) Recycling

Context

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

$$s. t$$

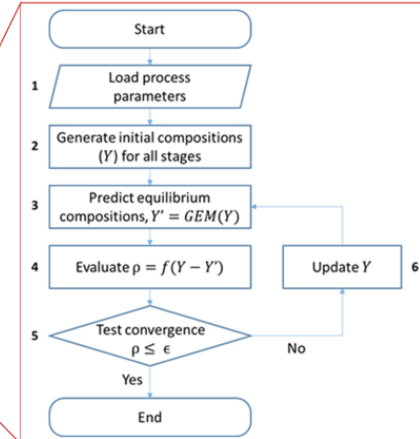
$$h(x_i, y_i) = 0$$

$\min(\text{Gibbs}(x_i, y_i))$
 Mass, species & charge balance

$$g(x_i, y_i) \leq 0$$

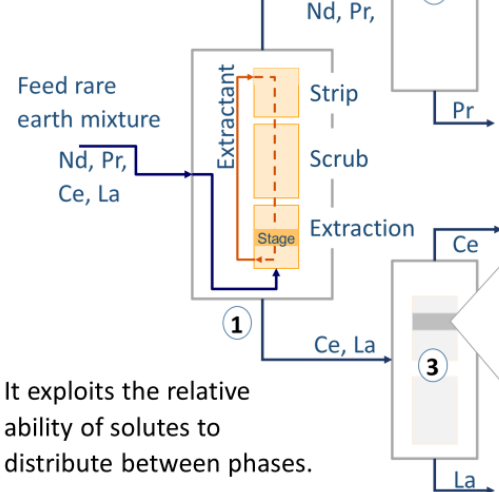
Yield, process and/or economic constraints

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



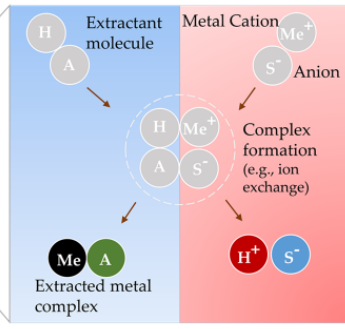
Technology: solvent extraction

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



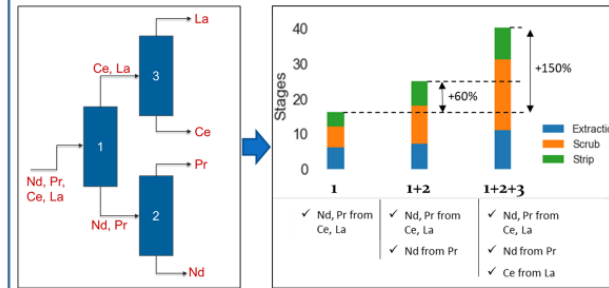
This often requires hierarchical combinations of multiple separation stages.

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

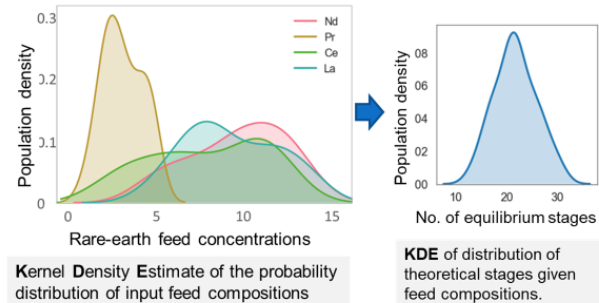


It exploits the relative ability of solutes to distribute between phases.

Preliminary Analysis



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



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.

Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling

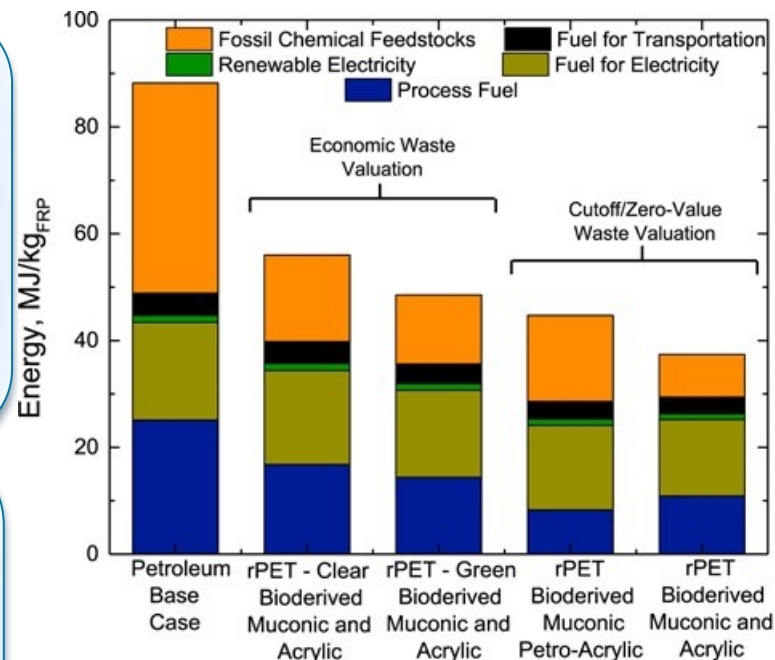
Abstract:

- Upcycling: ability to produce **higher-value products** from reclaimed material.
- Upcycling with bioderived monomers results in composites with **superior properties**.
- These upcycled materials can result in **reduced energy requirements and lower GHG emissions**.

Significance & Impact:

- Potential supply chain **energy savings of 57%** and **GHG savings of 40%** over the conventional method of composite production
- Applications include **wind turbine blades** and automotive parts
- Collaborative effort with **National Bioenergy Center** at NREL

Journal: Joule (Cell Press), Publication Date: **February 27, 2019** NREL authors: Nic Rorrer, **Scott Nicholson**, Birdie Carpenter, Mary Bidy, Nick Grundl, Gregg Beckham (**Bold** denotes AMO StA team member)



*(See figure above) Supply chain energy requirements, as calculated with NREL's **Materials Flows through Industry (MFI) tool**, are significantly reduced in all bio-based composite manufacturing scenarios.*

Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling: Background and Motivation

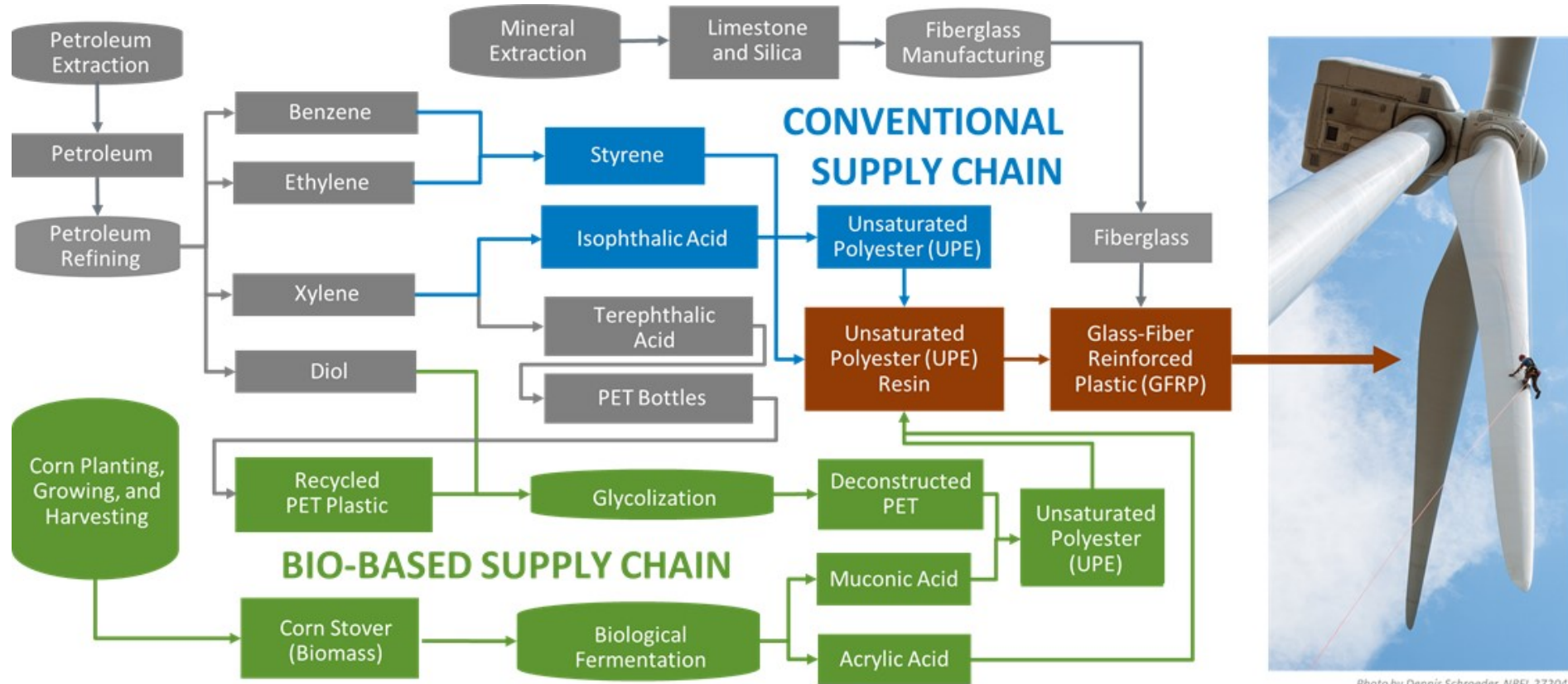
Motivation

- Most commercial polyethylene terephthalate (PET) recycling is mechanical
- Mechanical recycling leads to lower-grade plastic with fewer applications (carpet fiber, etc.)
- Chemical recycling of PET bottles back to its monomers is expensive
- What if we could make higher value glass fiber reinforced plastic with recycled PET?
- **Key research question:** Are there energy savings associated with rPET-based GFRP production?

Methodology



1. 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.
2. We model the lab-scale rPET upcycling process developed by other NREL researchers to determine the requisite energy and material inputs
3. We develop full supply chain models by connecting this lab-scale unit process to existing MFI unit processes, including PET recycling
4. 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

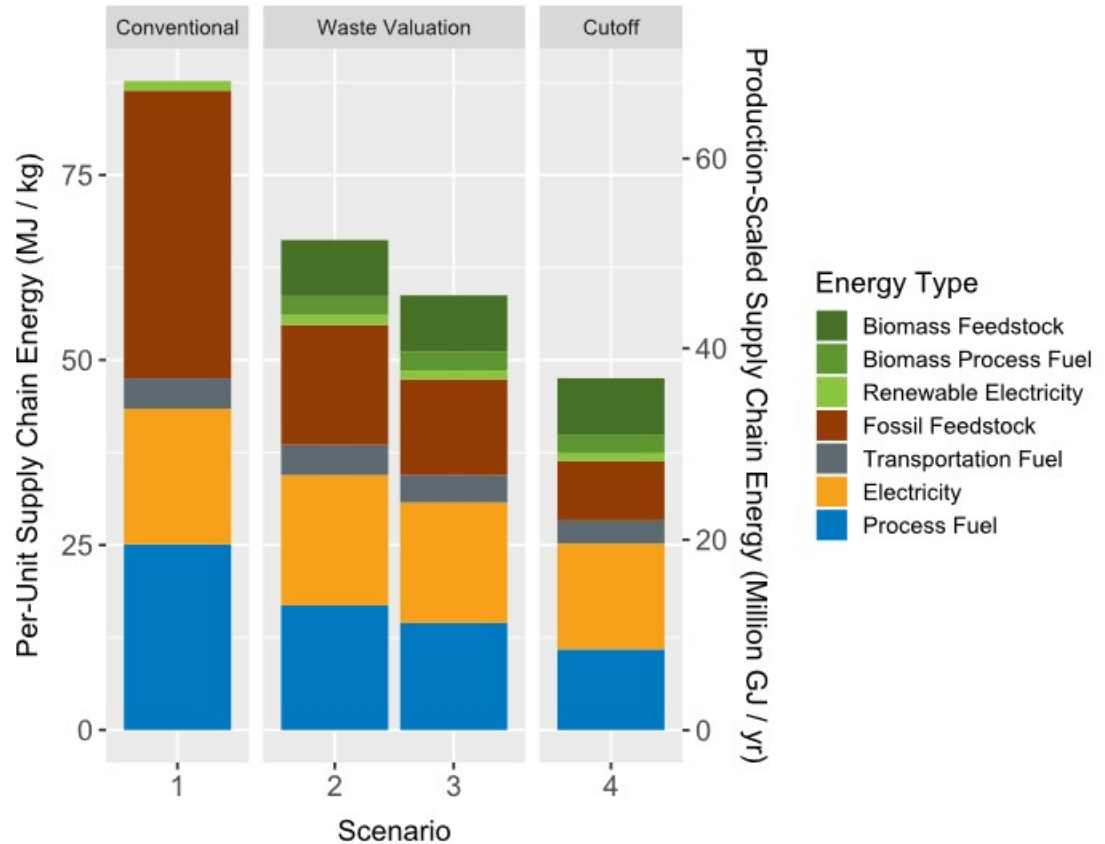
Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling: Supply Chain Comparisons



Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling: Supply Chain Energy



Depending on the allocation method, supply chain fossil energy reductions range from **37% to 58%**.

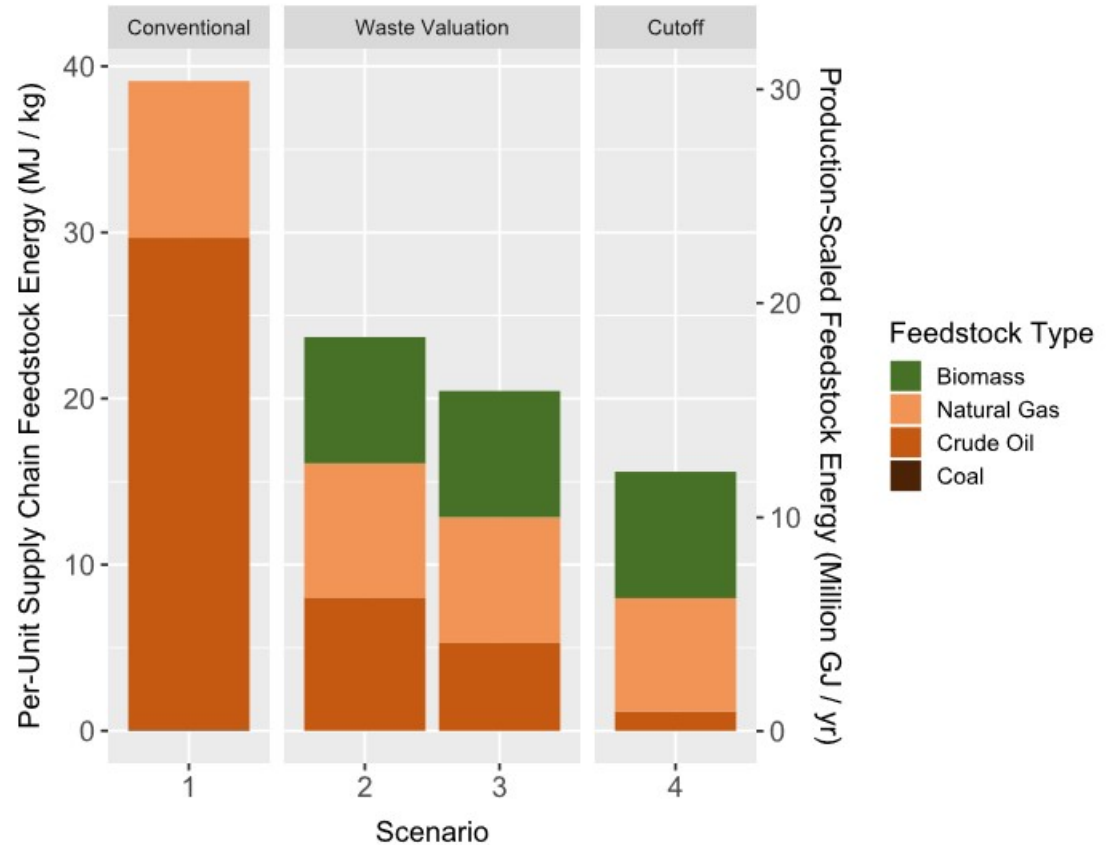
Scenario	Name	PET Bottle (First Life) Allocation
1	Conventional GFRP	N/A (No rPET Used)
2	Waste Valuation; Reclaimed Clear rPET 	≈54% (Economic)
3	Waste Valuation; Reclaimed Green rPET 	≈32% (Economic)
4	Reclaimed rPET - Cutoff	0%



Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling: Supply Chain Feedstock Energy



Overall, supply chain fossil feedstock energy reductions range from **58% to 79%**

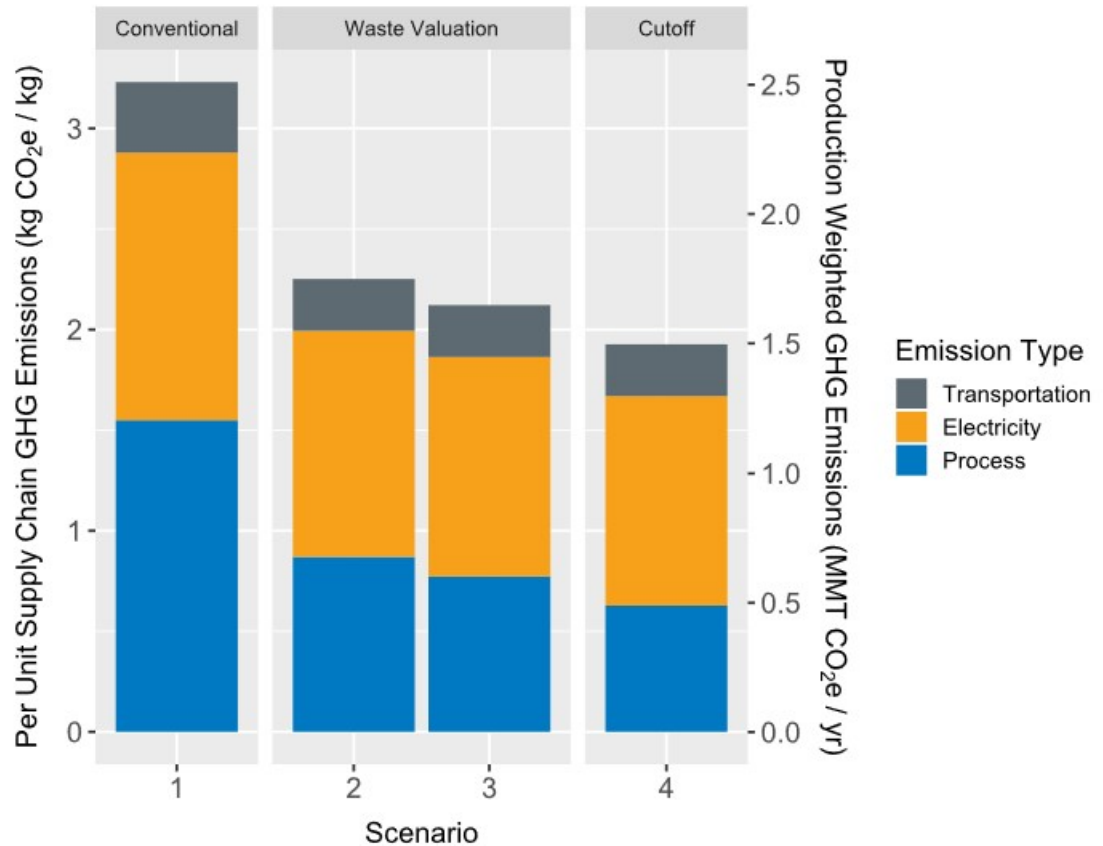
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Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling: Supply Chain GHG Emissions

- Overall, supply chain GHG emissions reductions range from **30% to 40%**
- 0.7 – 1.0 MMT-CO₂e offsets; Equivalent to taking **150,000 - 200,000 cars** off the road

Scenario	Name	PET Bottle (First Life) Allocation
1	Conventional GFRP	N/A (No rPET Used)
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4	Reclaimed rPET - Cutoff	0%



Design for recycling (DfR) principles for some clean energy technologies

- In pursuit of a circular economy, the proverbial last line of defense when a product reaches its End-of-Life (EOL) is recycling.
- Two ways to improve recyclability
 1. design a better recycling process, and/or
 2. Implement Design for Recycling (DfR) strategies prior to the product manufacturing stage.
- DfR strategies: function of both the product in question & the nature of available recycling processes. Additional factors, such as legislation and business realities, must also be considered.

Design for recycling (DfR) principles for some clean energy technologies

- Literature review: performed to compile a preliminary list of DfR best practices. The results of which were socialized with experts within NREL, DOE, and industry in order to obtain feedback for further inclusion.
 - List currently consists of 10 overarching DfR guidelines, and 4 to 8 renewable energy (RE) tech specific DfR guidelines & observations each for PV, wind, and batteries.
- Example of one such DfR strategy after industry feedback:
 - “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.”

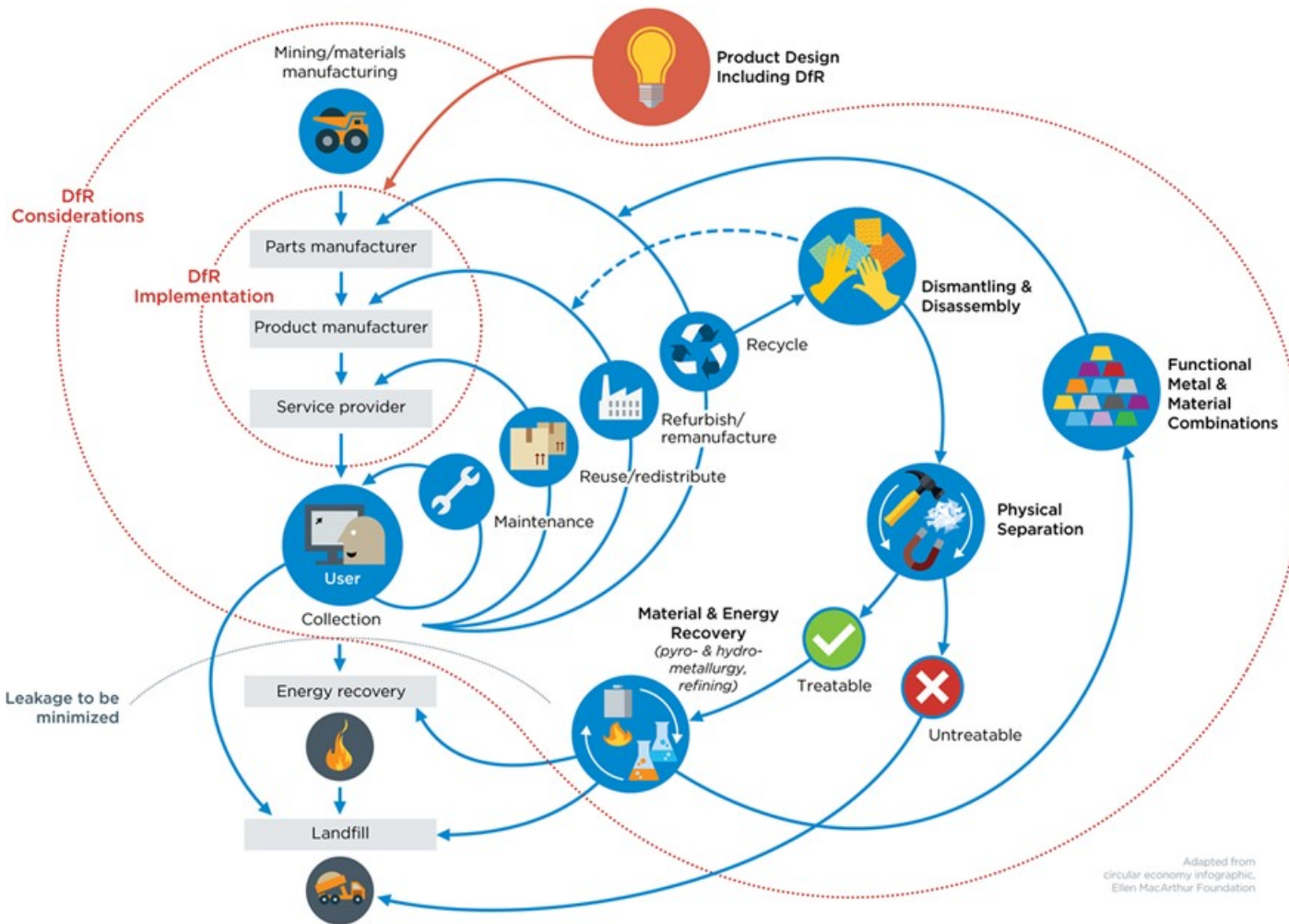
Design for recycling principles for some clean energy technologies

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, the implementation of, and considerations necessary for effective DfR are illustrated in the figure below.

(See Figure on next slide)

Design for recycling principles for some clean energy technologies



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.

Circular Economy Butterfly Diagram
(Modified from the Ellen McArthur Foundation)