Addressing Adoption Barriers and Accelerating Market Deployment of New Technologies – Supplemental Information

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The base case assumptions for the selected technology include:

- plant capacity of 50,000 MT/yr [150 metric tons per day (tpd)],
- 95% mechanical pre-treatment yield,
- 90% depolymerization of PET to rTPA and EG,
- 90% rTPA recovery,
- 50% EG recovery,
- 90% sorting yield,
- 93% bale-to-flake yield,
- 100% of TPA for rPET repolymerization comes from rTPA, but only 56% of EG comes from recovery due to its lower yield in the enzymatic process, and
- 0% collection losses.

S1 Air Emissions Modeling

Table S-1. Emission points associated with PET recycling process.

Plant Area	Initial Emission points	Potential Pollutants
Feedstock Pretreatment	Feedstock unloading, storage, and conveyance	PM, PM_{10}, $PM_{2.5}$
Depolymerization	Fermentation vent	VOC, HAP
	Leaking equipment	VOC, HAP
Clarifier	Ion exchange column	PM, PM_{10}, $PM_{2.5}$, VOC, HAP
	Activated carbon column	PM, PM_{10}, $PM_{2.5}$, VOC, HAP
	Leaking equipment	VOC, HAP
Crystallization	Dryers	PM, PM_{10}, $PM_{2.5}$, NO_x, SO_2, CO, CO_2, VOC, HAP
	Equipment leaks	VOC, HAP
Distillation column (recovery)	Reboiler	PM, PM_{10}, $PM_{2.5}$, NO_x, SO_2, CO, CO_2, VOC, HAP
	Leaking equipment	VOC, HAP
Storage tanks	Terephthalic acid tank	VOC, HAP
	Ethylene glycol tank	VOC, HAP
	Sulfuric acid tank	VOC, HAP, H_2SO_4
	Sodium hydroxide tank	VOC, HAP

Loading operations	Loading and unloading of chemicals	VOC, HAP
Truck traffic	Dust from roads of traffic of trucks hauling feedstock, other raw materials, and product	PM, PM_{10}, $PM_{2.5}$

Table S-2. Summary of emission factors for each emission point.

Plant Area	**Emission points**	**Emission factors**	**Data source**
Feedstock Pretreatment	Bale Shredder	PM: 0.039 lb/ton PM_{10}: 0.015 lb/ton $PM_{2.5}$: 0.015 lb/ton	EPA's AP-42 [1] https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s1902.pdf DAK Americas Air Permit: https://www.in.gov/idem/airquality/2356.htm
	Conveyor	PM: 0.003 lb/ton PM_{10}: 0.0011 lb/ton $PM_{2.5}$: 0.0011 lb/ton	EPA's AP-42 [1] https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s1902.pdf Permit Application: https://permits.air.idem.in.gov/33107f.pdf
Clarifier	Ion exchange and activated carbon column	Assume 0.1% of VOC and H_2SO_4 does not remain entrained in the mixed stream and emitted to atmosphere	Aspen Plus process modeling software [2]
Crystallizer	Dryers (purge)	Material balance from Aspen Plus	Aspen Plus process modeling software [2]
	Brine waste stream	Assume 0.1% of VOC does not remain entrained in the mixed stream and emitted to the atmosphere (engineering judgement). Assume 0.01% of H_2SO_4 input is emitted as mist	
Storage tanks	Ethylene glycol tank	Volume: 67,000 gallons and 26 turnovers/yr	TANKS 4.09D model [3]
	Sulfuric acid tank	Volume: 16,000 gallons and 224 turnovers/yr	
	Sodium hydroxide tank	Volume: 11,000 gallons and 224 turnovers/yr	
Loading operations	Loading and unloading of chemicals	Assume the facility will use splash loading for EG in clean cargo or dedicated normal service	EPA's AP-42[4]
Equipment leaks	Equipment leaks	Equipment component count scaled using Abengoa's air permit application	EPA's leak detection and repair (LDAR) program[5]
Truck traffic	Dust from road of trucks hauling feedstock, other raw materials,	PM: 4.6 lb/vehicle miles traveled (VMT) PM_{10}: 1.17 lb/VMT $PM_{2.5}$: 0.12 lb/VMT	EPA's Unpaved Roads Emissions[6] *DAK Americas air permit

	and product	Assume each truck holds 27.5 tons/truck of PET bales*	

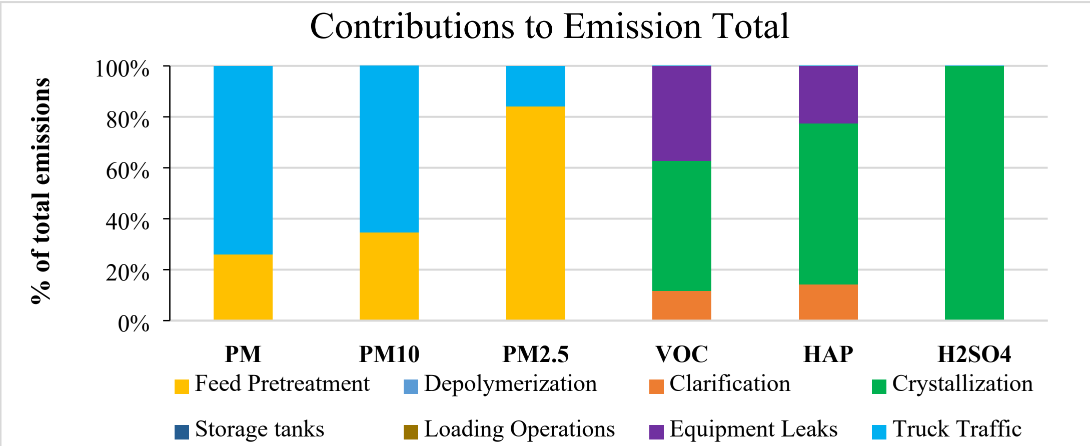

Figure S-1. Relative contribution of each process area to total emissions.

The contribution of the emission points to the overall emissions differs for each pollutant. For PM and PM_{10}, truck traffic contributes the most (65% for PM and 74% for PM_{10}) to overall emissions. In contrast, feed pretreatment is the largest contributor to $PM_{2.5}$, estimated to be 84% of emissions for this pollutant. For gaseous pollutants, the crystallization process area contributes the largest, up to 51%, 63%, and >99% of the overall VOC, HAP, and H_2SO_4 emissions respectively.

Table S-3. Permit modification thresholds under NSR classifications.

Pollutants	Threshold for Attainment Area (tpy)	Nonattainment Area Classification	Threshold for Nonattainment areas (tpy)
PM	25	Not applicable	
PM_{10}	15	Serious, Moderate	15
$PM_{2.5}$	10	Serious, Moderate	10
Ozone (regulated through VOC and NO_X precursors)	40 (VOC or NO_X)	Moderate, Marginal	40
		Severe, Serious	25
		Extreme	Any emissions increase
CO	100	Serious	50
SO_2	40	Nonattainment	40
Pb	0.6	Nonattainment	0.6
H_2SO_4	7	Not applicable	

S2 TEA Assumptions

Operation and maintenance (O&M) costs for conventional TPA were based on Nexant ChemSystems [7] for a typical 350,000 metric tons/yr facility using the Amoco process with para-xylene feedstock. Crude

TPA is produced via oxidation of para-xylene with air and purified via hydrogenation. The main inputs for the process are para-xylene, acetic acid and hydrogen. In 2017, U.S. domestic production of terephthalic acid amounted to 2.3 million metric tons, mostly consumed by PET manufacturing (97%)[8]. TPA sales were allocated exclusively to the *Plastic Resins Manufacturing* industry (TPA is the sole output of this industry). The environmental profile for conventional TPA production was estimated using 2017 point source data from the National Emissions Inventory, Toxics Release Inventory, Discharge Monitoring Report, and Greenhouse Gas Reporting Program (Subsection C) for four major U.S. TPA plants that represented 89% of TPA production in 2018.[i]

Table S-4. Key assumptions for techno-economic analysis

Parameter	**Basis**
Discount rate (internal rate of return)	10%
Plant economic life	30 years
Debt/Equity	60%/40%
Loan term	10 years
Loan interest	8%
Construction years	3 years
Cost year	2016
Direct Costs	
Site development	9% of ISBL
Warehouse	4% of ISBL
Additional piping	4.5% of ISBL
Indirect Costs: % of total direct costs	
Expenses (pro-rated)	10%
Project contingency	10%
Field Expenses	10%
Home Office and Construction Fees	20%
Other costs (start-up and permitting)	10%
Land purchase	$140,000
Working capital	5% of FCI
Fixed Operating Costs	
Labor burden	90% of total salaries
Maintenance	3% of ISBL
Property insurance and taxes	0.7% of FCI

ISBL = inside battery limits of the plant; Direct Costs = Installed Capital Costs + Site Development + Warehouse + Additional Piping; FCI = fixed capital investment = total direct costs + total indirect costs

O&M costs for recycled TPA were based on NREL's design case for both a 31.1 and 56.8 million metric tons/yr facilities using enzymatic depolymerization of PET flakes. This feedstock is supplied by MRF plants. We followed the same process as Lamers *et al*. [9] to convert a typical design case into a new industry in the input-output model. A single recycled TPA plant of each capacity was assumed in the analysis, producing TPA, ethylene glycol and sodium sulfate. Similar to the conventional TPA commodity, recycled TPA is allocated exclusively to the *Plastic Resins Manufacturing* industry. Ethylene glycol and sodium sulfate sales were distributed to different sectors according to their respective domestic consumption shares based on IHS Markit data[10,11]. For the recycle TPA process, we rely on the ASPEN model to identify the type of pollutants from unit operations or equipment, and then use EPA's AP-42 emission factors or equations, EPA's TANKS model and mass balance approach to estimate emissions of

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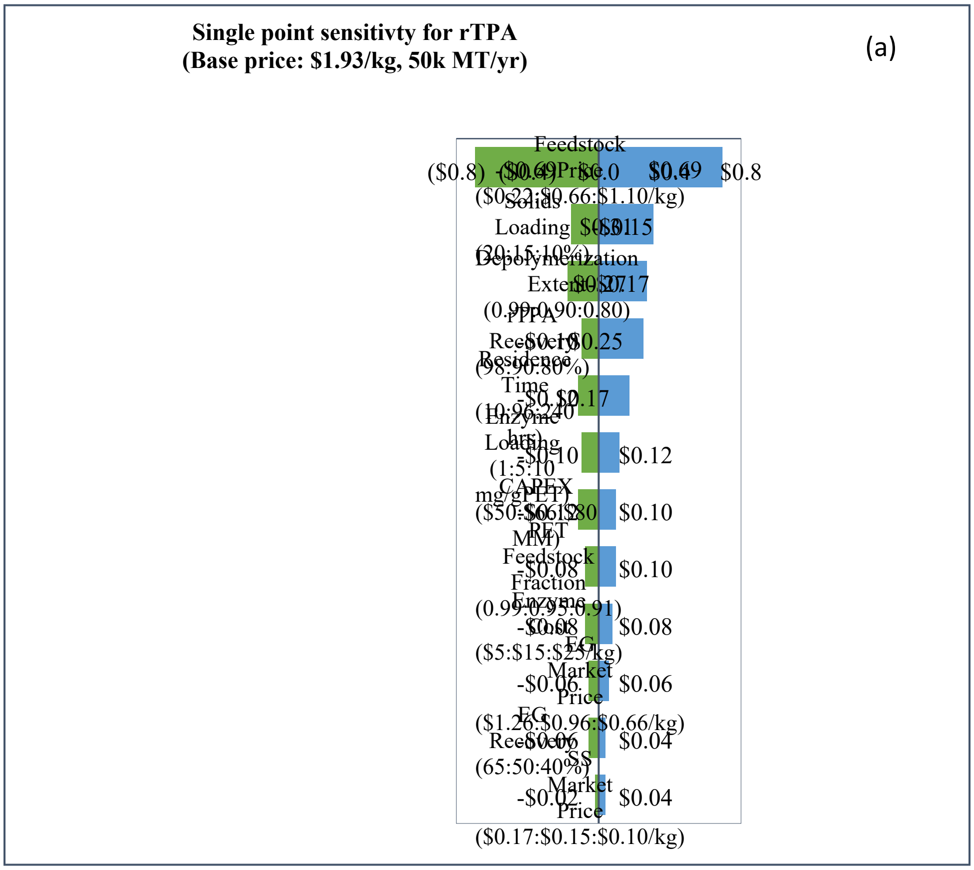
[i] BP - Cooper River, SC; DAK Americas - Columbia, SC; Eastman - Kingsport, TN; and PCL - Decatur, AL.

regulated pollutants (e.g., criteria air pollutants, hazardous air pollutant). To err on the conservative side, we assume that the facility producing recycled TPA operates at the design capacity (which is a required criterion in estimating potential emissions for air permits).



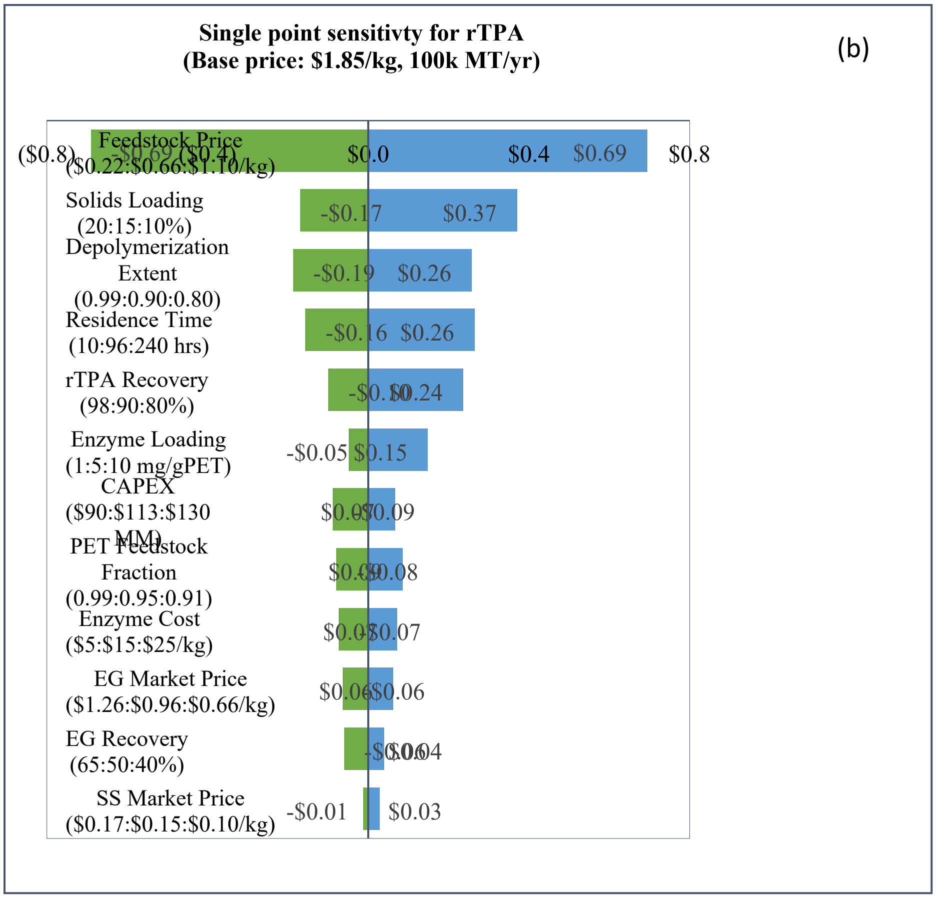


Figure S-2. Single point sensitivity for rTPA on plant scales of 50,000 MT/yr (a) and 100,000 MT/yr of PET (b)

The sensitivity results show that the top cost drivers impacting the MSP of rTPA include feedstock price, solids loading associated with depolymerization, extent of depolymerization conversion, rTPA recovery, and residence time. While changing the feedstock price has the largest effect on MSP by (36% or $0.69/kg) based on the selected parameter range for each plant scale, the other four cost parameters can increase MSP up to 16% ($0.31/kg) and 20% ($0.37/kg) using the maxima value, while MSP can be reduced to up to 9% (or $0.17/kg) and 10% ($0.19/kg) using the minima bound, for 50,000 and 100,000 MT/yr plant scale, respectively. Other sensitivity parameters (e.g., enzyme loading, capital cost, enzyme cost, co-product costs, etc.) are shown to have low impact on MSP value.

S3 Local Economic Impacts and Jobs Added

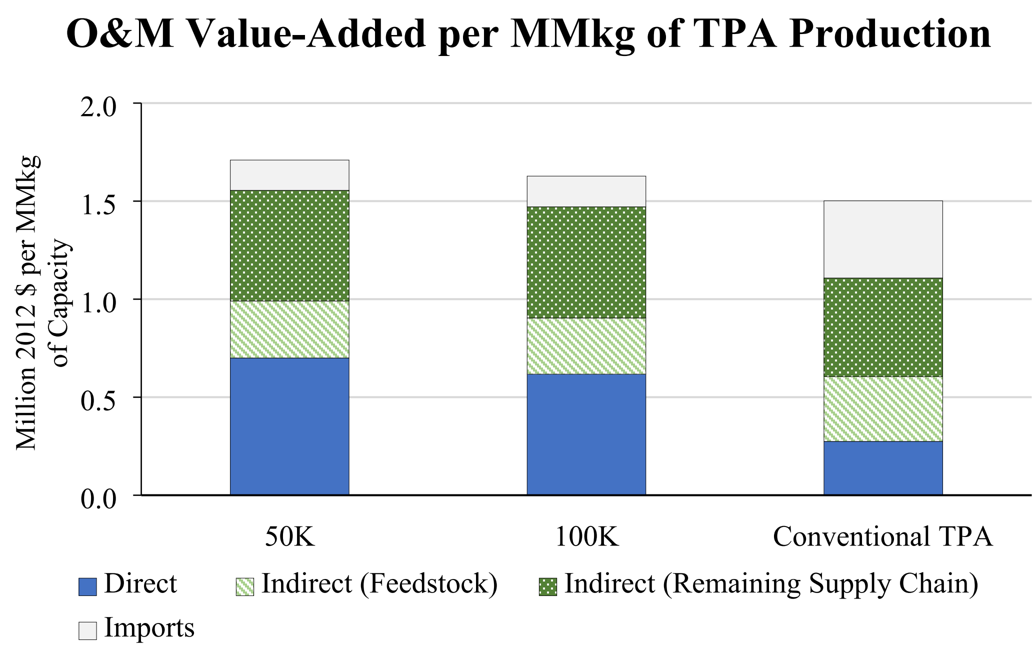


Figure S-3. Value added for 50K, 100K, and existing TPA production methods per MM kg of TPA product. Value added is shown for operational inputs.

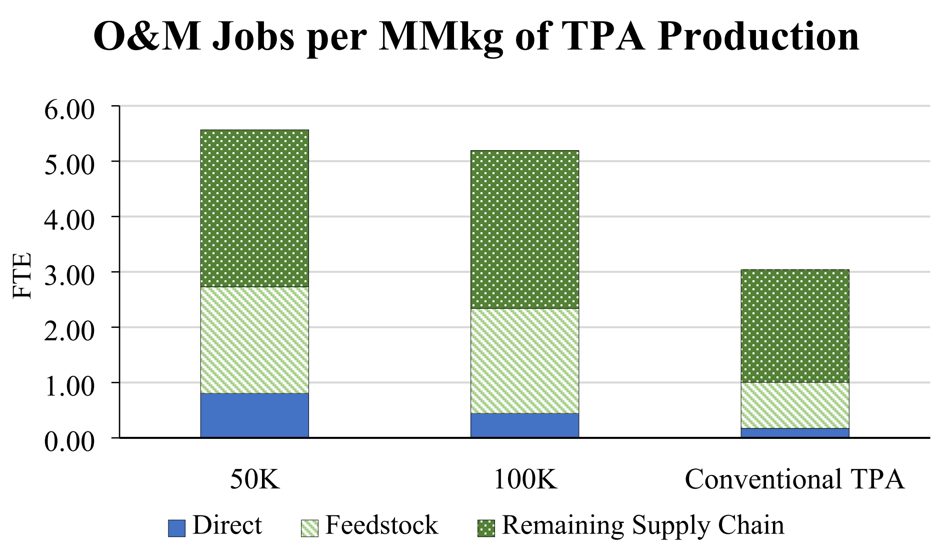


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Figure S-4. Jobs added for 50K, 100K, and existing TPA production methods per MM kg of TPA product. Jobs are shown for operational inputs.

S4 Water and Waste Regulations

Appendix A to South Carolina Regulation 61-9 lists NPDES Primary Industry Categories, which states that:

> *Any permit issued after June 30, 1981, to dischargers in the following categories shall include effluent limitations and a compliance schedule to meet the requirements of section 301(b)(2)(A), (C), (D), (E) and (F) of CWA, whether or not applicable effluent limitations guidelines have been promulgated.*

Both “Plastics processing” and “Plastic and synthetic materials manufacturing” are categories listed in Appendix A, which means that the requirements of CWA Section 301(b) apply. The requirements of the CWA are spread throughout 40 CFR Parts 402 – 699, according to 40 CFR 401.10 General Provisions. The general provisions state that any specific categories in Appendix A (such as plastics processers) must meet the discharge criteria from that specific subpart (such as 40 CFR Subchapter N Part 414), which was discussed earlier.

The standards listed for applicable dischargers are for pH of the discharge stream, total suspended solids (TSS) content, and biological oxygen demand measured over a five-day period (standard is 20 days) (BOD_5). TSS can affect human health depending on what solids are dissolved in the water, such as bacteria, pollution, or sediment, and BOD_5 signals organic pollution that can decrease the dissolved oxygen level in water that organic life depends on to survive[12]. Each standard is measured in mg/L. Limits for each polymer type are listed in Table S-5.

Table S-5. Operational standards from 40 CFR Subchapter N, Part 414 – Organic Chemicals, Plastics, and Synthetic Fibers. Standards apply to both polymer fibers and polymer resin.

	Subpart C – Other Fibers [non-Rayon]		**Subpart D - Thermoplastic Resins**	
Measurement	**Daily maximum**	**Max for month avg**	**Daily maximum**	**Max for month avg**
BOD_5	48	18	64	24
TSS	115	36	130	40
pH	Range 6 - 9		Range 6 - 9	

These limits apply to both new and existing dischargers, which in turn refer to wastewater streams that existed after or before implementation of Section 306 of the Clean Water Act (CWA) in 1972. There are also limits for hazardous and toxic chemicals that are discharged to a wastewater treatment facility (known as indirect discharge), none of which are present in Table 1 in the main text.

New dischargers represent a new wastewater stream built after the CWA was put into effect, which would be represented by a new and separate PET facility. An existing discharger would be part of a facility that was in operation before the CWA. Direct dischargers discharge directly to a water body, while indirect dischargers discharge to a wastewater treatment plant (WWTP), which then discharges to a water body. New direct dischargers are subject to NSPS, which are the most stringent and up-to-date regulations and have less of a cost consideration compared to standards for existing dischargers. Fewer locations are existing dischargers due to the age requirement, and existing dischargers may already have updated control technology in place. The same requirements also apply to indirect dischargers, with sets of standards for new and existing standards that discharge to WWTP instead of directly to a water body.

- Primary treatment includes the treatment at WWTP and facilities with the sole purpose of wastewater pollutant removal. This level of treatment does not apply to dischargers since manufacturers are not expected to apply the same level of treatment as specialized facilities.
- Secondary treatment refers to biological processes that remove organic matter and pollutants from wastewater, which can also include nitrogen, phosphorus, or toxic materials. This level of treatment is required for any discharge to fishable, swimmable, or drinkable waters.
- ‘Equivalent to secondary treatment’ applies for facilities that are not able to consistently achieve the standards of secondary treatment, and where a trickling filter or waste stabilization pond is the primary method of treatment.

Table S-6. Requirements of wastewater discharge streams for all manufacturers in South Carolina.

Water Standard	**Trout**	**Fresh**	**Shellfish Harvesting**	**Tidal Saltwater**
Garbage, oils, sludge, refuse	None	None	None	None
Treated/toxic waste not listed above	None	None	None	None
Specific toxic pollutants	Must stay below concentration limits listed in Appendix of regulation = none in this process			
Stormwater, nonpoint source runoff	Allowed if water quality maintained			
Dissolved O_2	6 mg/mL	5 mg/mL	5 mg/mL	4 mg/mL
pH	6.0 – 8	6.0 – 8.5	6.5 – 8.5	6.5 – 8.5
Temperature	Not to vary from natural conditions			
Turbidity	10% above natural conditions	50% above natural conditions, 25% for lakes	25% above natural conditions	25% above natural conditions

Table S-7. Wastewater standards for outgoing streams for all facilities in South Carolina.

Averaging Period	**BOD_5**	**TSS**	**pH**	**$CBOD_5$**
Secondary treatment				
30-day average less than	30 mg/L	30 mg/L		25 mg/L
7-day average less than	45 mg/L	45 mg/L		40 mg/L
30-day average removal at least	85%	85%		85%
Must be within range			6 - 9	
Equivalent to secondary treatment				
30-day average less than	45 mg/L	45 mg/L		40 mg/L
7-day average less than	65 mg/L	65 mg/L		60 mg/L
30-day average removal at least	65%	65%		65%
Must be within range			6 - 9	

Waste generators have different regulations depending on which level of hazardous waste facility they are classified as, as shown in Table S-8.

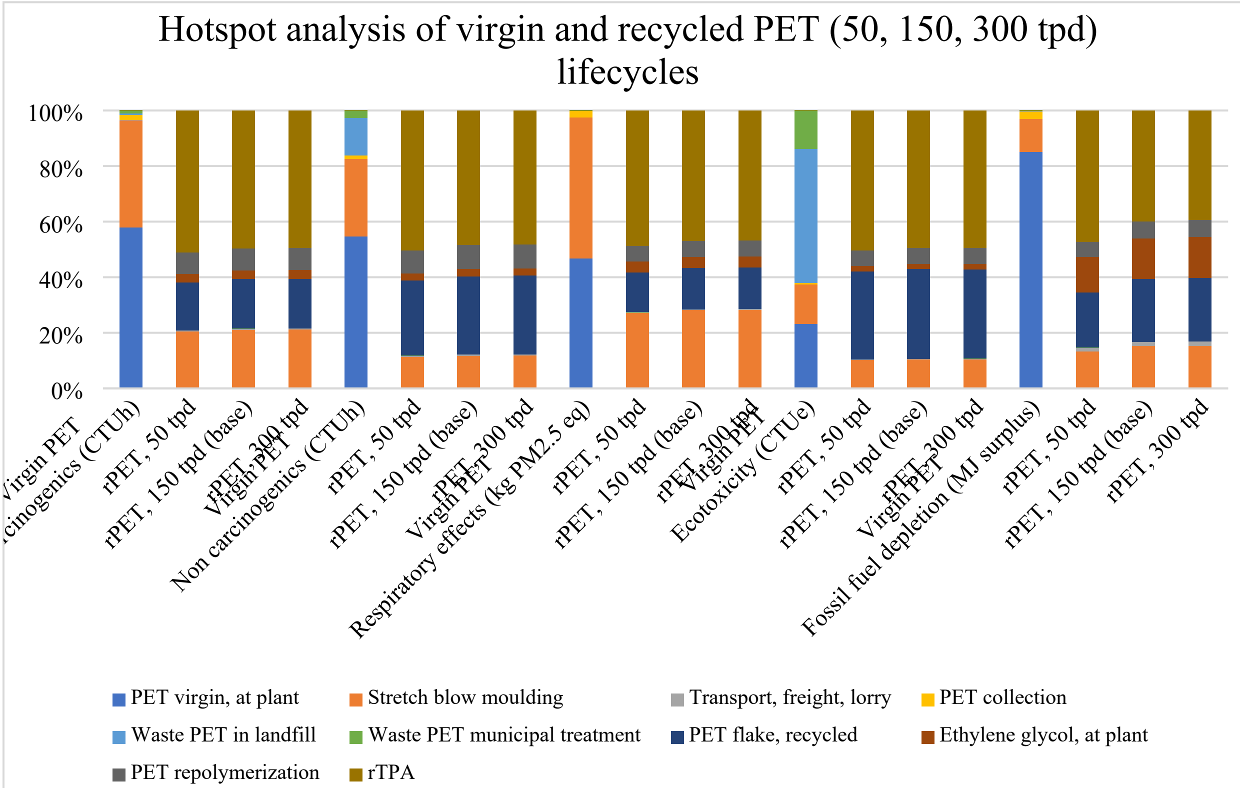
Table S-8. Categorization of hazardous waste generators based on the amount and type of waste stored onsite in a calendar month.

Quantity of acute hazardous waste	Quantity of non-acute hazardous waste	Quantity of residues from acute hazardous waste cleanup	Generator category
> 1 kg	Any amount	Any amount	Large quantity generator
Any amount	≥ 1,000 kg	Any amount	Large quantity generator
Any amount	Any amount	> 100 kg	Large quantity generator
≤ 1 kg	>100 kg and <1,000 kg	≤ 100 kg	Small quantity generator
≤ 1 kg	≤ 100 kg	≤ 100 kg	Very small quantity generator

S5 Federal Air Regulations

- NESHAP Subpart JJJ states that: *"For the purposes of these standards, the polymerization reaction section begins with the equipment used to transfer the materials from the raw materials preparation section and ends with the last vessel in which polymerization occurs."* Therefore, wastewater streams from chemical processes are covered under a separate regulation compared to those for polymer processes alone and must follow those requirements instead. NESHAP Subpart G is referred to in NESHAP Subpart JJJ to determine applicability for unit operations such as transfer racks, storage vessels, wastewater, leak inspections, and process vents.
- Either NSPS Subpart IIII or JJJJ would apply depending on whether the combustion units are compression ignition or spark ignition, respectively, as well as NESHAP Subpart ZZZZ for all stationary internal combustion engines.
    - Emergency engines must meet Tier 2 or Tier 1 emission standards, depending on the model year. These standards will either be certified by the manufacturer (typical), or emission controls must be installed to meet the standards for the engine size/model year. The fire pump must meet emission standards of Table 4 to Subpart IIII or JJJJ. A continuous emission monitoring system (CEMS) may be required to ensure that each unit is meeting its emission standards, as well as a non-resettable hour meter to count the annual hours of operation. There are no NESHAP requirements that would apply for emergency engines only.
- NESHAP Subpart Q applies to the onsite cooling tower and requires that <0.5 ppm Chromium VI is present in the cooling water recirculation.
- NSPS Subpart VVa applies to equipment leaks of VOC in the synthetic organic chemical manufacturing industry and is referred to in NSPS Subpart DD for equipment leak standards as well. NESHAP Subpart H applies to HAP emissions from equipment leaks.
    - The standard mandates more frequent monitoring of all potential leak sites, which yields a higher estimated control effectiveness and lower VOC and HAP emissions. There are no direct limits or emission factors that would apply, just the more frequent monitoring and subsequent reports or actions that may result from the monitoring schedule.

S6 Detail LCA results



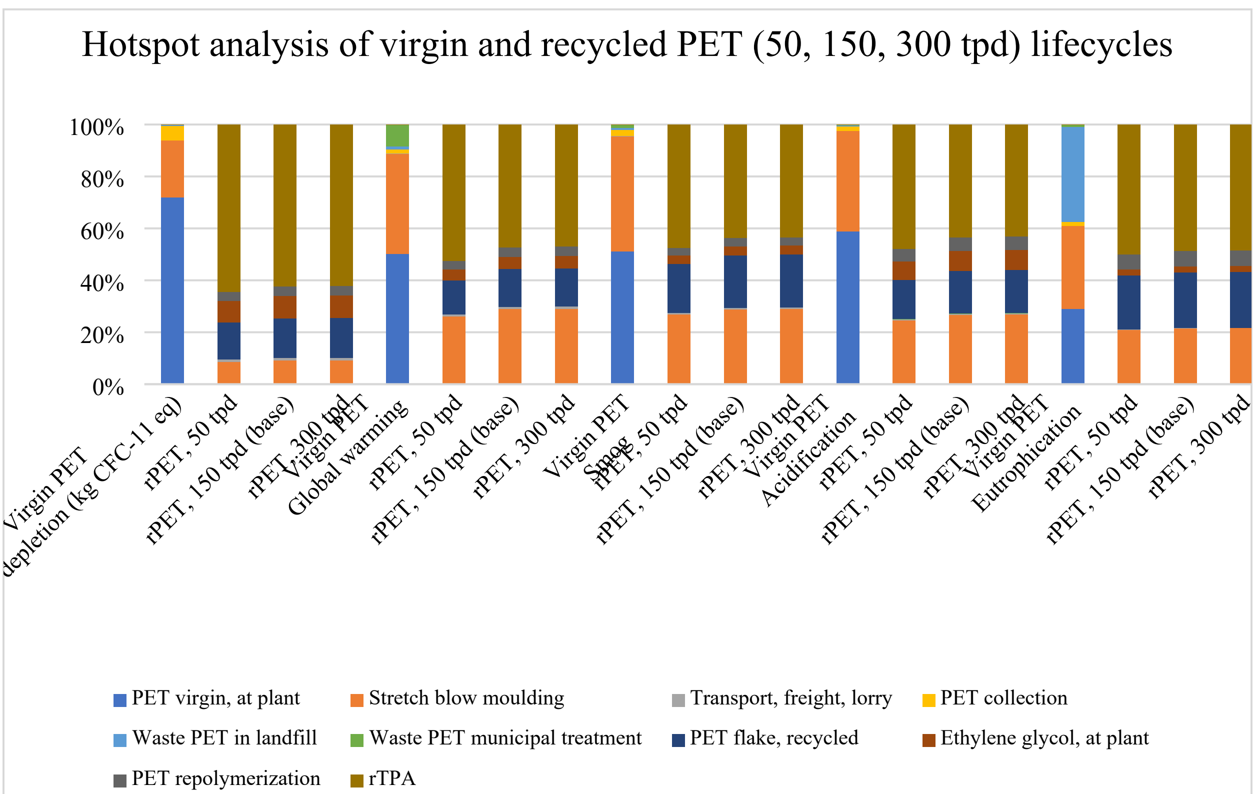


Figure S-5. Hotspot analysis of LCA results for each category and scenario in the analysis.

S7 Technology adoption rate modeling

The Bass diffusion model provides a mathematical representation of the adoption of a new technology or product through time within a population. In other words, the model defines a relationship between the fraction of a population that has adopted a technology, and the rate of change for the remaining adopting fraction[13]. The model is also a quantitative application of Everett Rogers qualitative description of diffusion of innovations[14]. According to the model, the adoption rate $F(T)$ is:

$$F(T) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}} \#(1)$$

Where p is the coefficient of innovation (parameter characterizing change in adoption due to external effects such as advertising) and q is the coefficient of imitation (parameter characterizing change in adoption due to internal effects such as word-of-mouth). The parameters p and q can be determined by fitting the model to empirical data using the nonlinear least squares method. When such empirical data are missing, one can use published values as a first approximation. A better method, however, is to estimate the likelihood of adoption (or adoption score s) using the attributes of a technology (Hanes et al., 2019). The adoption score is defined according to Equation 2:

$$s = \sum_c w_c Score_c \#(2)$$

With w_c and $Score_c$ the strength and value of the attribute c in shaping the adoption process of a technology. Then based on a dataset of published p and q parameters, we use the median q/p value of the dataset as a fixed parameter, choose the q value in the dataset according to the s score (with higher s scores leading to higher q values in the dataset), and determine p based on the q/p median and the q value[13].

Table S-9: Expert answers from the survey estimating which technological barriers could be more impactful on the adoption of enzymatic recycling technology.

Question	Respondent 1	Respondent 2	Average score	Weight
A low profitability is a strong barrier to new technology adoption	Strongly agree	Strongly agree	5	0.12
A long payback period is a strong barrier to new technology adoption	Strongly agree	Agree	4.5	0.10
The disruption caused by a new technology is a strong barrier to its adoption	Neutral	Agree	3.5	0.08
A long lifetime is a strong barrier to new technology adoption	Strongly agree	Neutral	4	0.09
High indirect costs (e.g., to train labor) is a strong barrier to new technology adoption	Agree	Disagree	3	0.07
Weak operational demonstration is a strong barrier to new technology adoption	Agree	Strongly agree	4.5	0.10
Low cross-cutting potential is a strong barrier to new technology adoption	Neutral	Disagree	2.5	0.06
Securing air emission permits is a strong barrier to new technology adoption	Neutral	Neutral	3	0.07

Regulatory compliance costs are a strong barrier to new technology adoption	Strongly agree	Disagree	3.5	0.08
Securing hazardous waste management permits is a strong barrier to new technology adoption	Agree	Disagree	3	0.07
A high carbon footprint is a strong barrier to new technology adoption	Agree	Disagree	3	0.07
A low social acceptance is a strong barrier to new technology adoption	Neutral	Agree	3.5	0.08

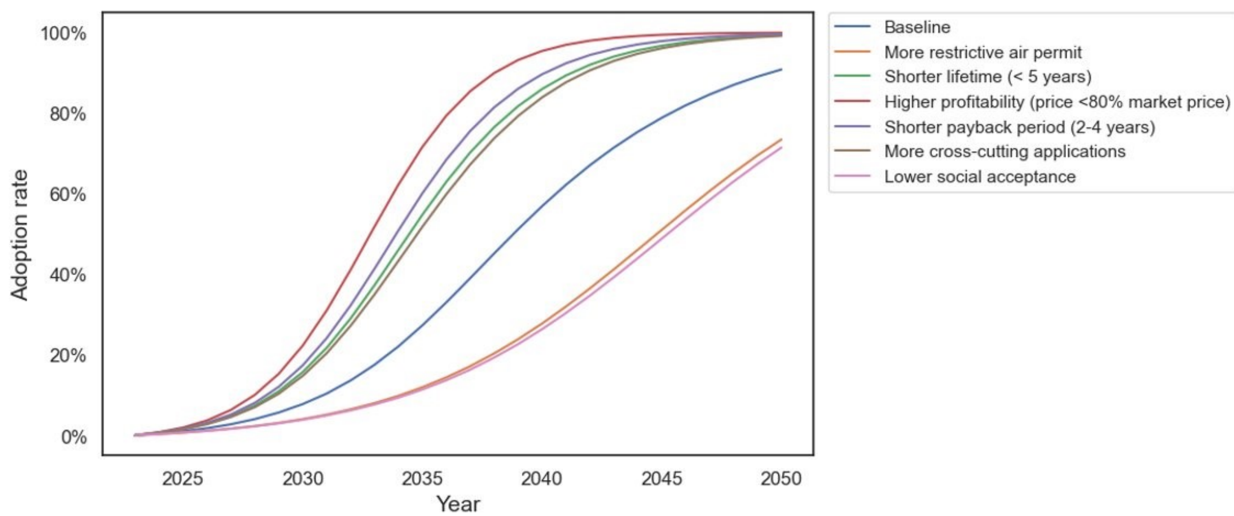


Figure S-6: Adoption curves for the enzymatic recycling process with expert defined weights (w_c) and accounting for answers' ($Score_c$) uncertainty.

Table S-10: Scores given to each attribute and justification.

Characteristics		Score	Justification
Economic context	*Minimum selling price*	>120% of market price [0]	$1.93/kg versus $1.015/kg
	Payback period	>8 years [0]	Payback period is 15.8 years
Technical context	*Scope of impact*	Local [1]	Existing infrastructure (collection, sorting, etc.)
	Lifetime	>20 years [0]	Lifetime of 30 years
Information context	*Transaction costs*	10-50% of initial expenditure [1]	Project contingency + other costs
	TRL	7 or lower [0]	No demonstration in operational environment
	Sectoral applicability	Single process [0]	Only applies to the chemical sector
Regulatory context	*Air permitting*	Minor source permit [2]	In most cases, not expected to trigger major permitting requirements
	Regulatory compliance costs	10-25% of initial expenditure [1]	Other costs
	Waste regulations	Not a hazardous waste generator [3]	No materials in this process qualify as hazardous

Social and environmental impacts context	*Carbon footprint*	>120% of market footprint [0]	GHG emissions of 90% versus 67% (compared to max GHG emissions)
	Social acceptance	No significant documented contention [1]	No specific cases of social acceptance issues for plastic recycling facilities

Table S-11: Possible technology ratings for each adoption barrier (or attribute)

Characteristics		**Technology attributes [Technology Attribute Ratings]**			
Economic context	*Minimum selling price*	>120% of market price [0]	80-120% of market price [1]	<80% of market price [2]	
	Payback period	>8 years [0]	5-8 years [1]	2-4 years [2]	<2 years [3]
Technical context	*Scope of impact*	System [0]	Local [1]		
	Lifetime	>20 years [0]	5-20 years [1]	<5 years [2]	Not relevant [3]
Information context	*Transaction costs*	>50% of initial expenditure [0]	10-50% of initial expenditure [1]	<10% of initial expenditure [2]	
	TRL	7 or lower [0]	8 [1]	9 [2]	
	Sectoral applicability	Single process [0]	Cross-cutting [1]		
Regulatory context	*Air permitting*	Prevention of Significant Deterioration [0]	Nonattainment new source review (NNSR) permit [1]	Minor source permit [2]	
	Regulatory compliance costs	>25% of initial expenditure [0]	10-25% of initial expenditure [1]	<10% of initial expenditure [2]	
	Waste regulations	Large quantity generator [0]	Small quantity generator [1]	Very small quantity generator [2]	Not a hazardous waste generator [3]
Social and environmental impacts context	*Carbon footprint*	>120% of market footprint [0]	80-120% of market footprint [1]	<80% of market footprint [2]	
	Social acceptance	Significant documented contention [0]	No significant documented contention [1]		

S8 Supply chain risk assessment

Table S-12: Annual production (thousands of metric tons), consumption (thousands of metric tons), scarcity (calculated) and price (thousands of dollars per metric ton), and flowrate (kg/hr) of key raw materials.

Chemical	**Annual Production (thousands of metric tons)**	**Annual Consumption (thousands of metric tons)**	**Scarcity**	**Price (thousand dollar per metric ton)**	**Flowrate (kg/hr)**
Activated Carbon	277	294	0.9422	6.401	2,000
Sodium Hydroxide	14,251	11,256	1.2661	0.230	2,184

Sulfuric Acid	36,220	30,527	1.1865	0.146	2,702
Terephthalic Acid (TPA)	3,050	3,015	1.0116	1.015	2,769
Poly(ethylene terephalate (PET)	4,700	3,751	1.2530	0.725	6,250
Ethylene Glycol (EG)	5,039	1,894	2.6605	0.559	8,199

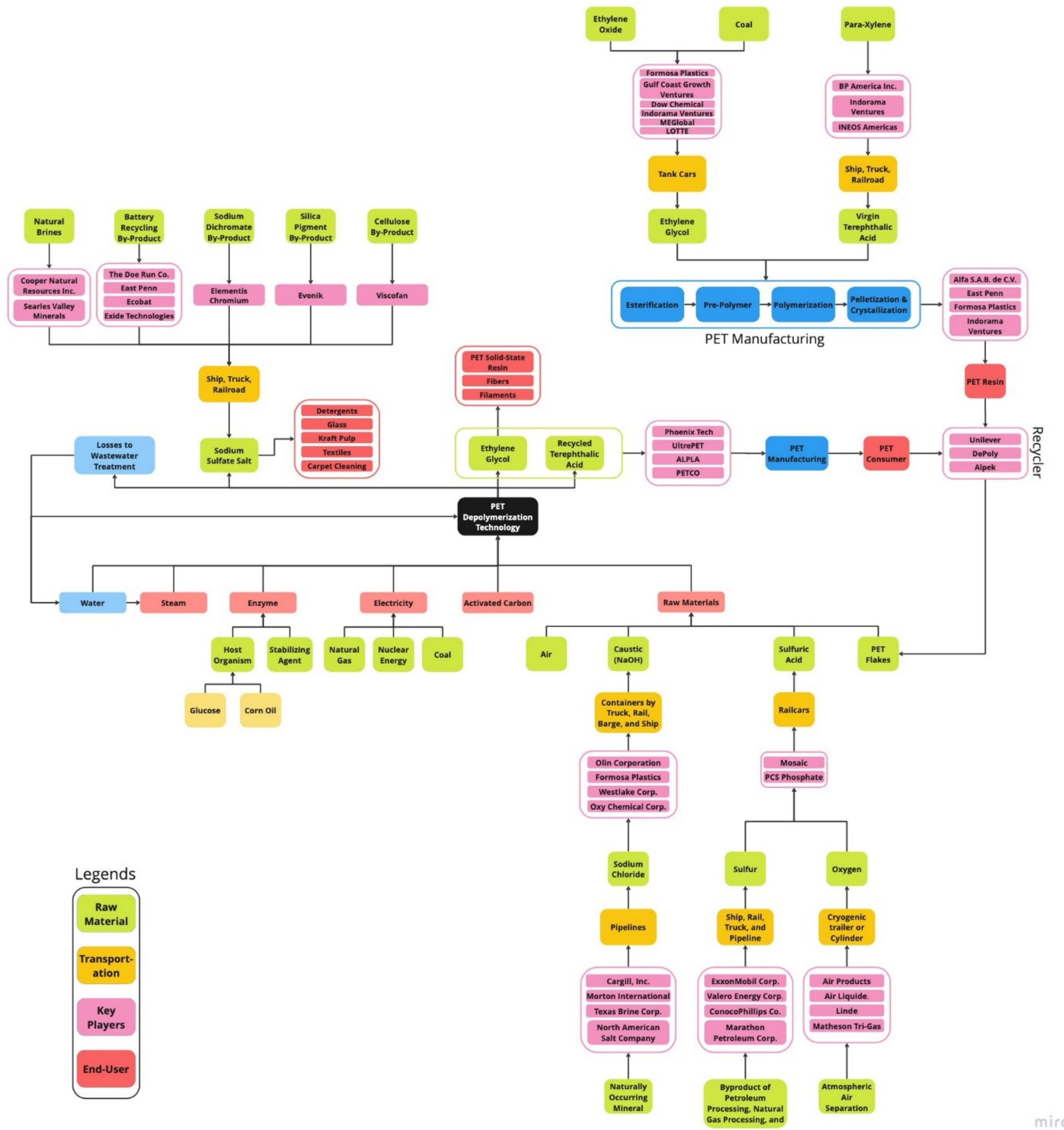


Figure S-7: Mapping exercise showing the key raw materials, producers/ suppliers of raw materials, and end users along each stage of the vPET and rPET supply chains.

The reasoning behind the numbered scoring is as follows:

- 0 = information unknown or not applicable,
- 1 = low supply chain risks or no risk factors exist,
- 2 = some risks exist but risks are well known and manageable,
- 3 = moderate risks currently exist, and some risks might be unknown,
- 4 = high risks exist and/ or no knowledge of potential risks is prevalent,
- 5 = very high risks exist for this material.

The scoring method and associated color were determined as follows: Score of 0 for cases where the risk is not applicable, 1 for cases where the risk is low or where no risk factors exist, 2 for cases where some risks exist but risks are well known and manageable, 3 for cases where moderate amounts of risks currently exist and some risks might be unknown, 4 for cases where high risks exist and/or no knowledge of potential risks exists, and 5 for cases where very high risks exist.

Definitions of supply chain risk criteria and their overarching core risk areas as adopted from the CARAT tool are as follows:

Market Acceptance (*Core Risk Area)*: This risk area captures the target market demand characteristics and risks posed by existing players, including competitors, customers, and other contributors to the value chain. Under this risk area we considered two risk criteria:
a) Market Size (*Risk Criterion)*: This criterion captures risk associated with the overall size of the market that can be served by the technology, and the level of uncertainty with which it will materialize.
b) Downstream Value Chain (*Risk Criterion)*: Risk associated with the projected path to get the product from a producer to a customer along the value chain (e.g., considering split incentives, technology acceptance, business model changes).

Resource Maturity (*Core Risk Area)*: This risk area determines risks standing in the way of inputs that are needed to produce the technology solution. Under this risk area we considered three risk criteria:
c) Capital Flow (*Risk Criterion)*: This criterion captures risks associated with the availability of capital needed to move the technology solution from its current state to production at scale, including total investment required, availability of willing investors, availability of associated financial and insurance products, and the speed of capital flow.
d) Manufacturing and Supply Chain (*Risk Criterion)*: This criterion captures risks associated with all the entities and processes that will produce the end-product, including integrators, component and sub-component manufacturers, and providers.
e) Materials Sourcing (*Risk Criterion)*: This criterion captures risks associated with the availability of critical and scarce materials required by the technology (e.g., rare earth and other limited availability materials).

License to Operate (*Core Risk Area)*: This risk area identifies the societal (national, state, and local) and non-economic risks that can hinder the deployment of technology. Under this risk area we considered a single risk criterion:
f) Policy Environment (*Risk Criterion*): This criterion captures risks associated with local, state, and federal government policy actions that support or hinder the adoption of the technology at scale.

Table S-13. Summary of existing and potential future barriers for each main section of this report.

Barrier to entry	**Hard barrier for case study?**	**Potential issues for this technology**
Air permitting	No	Only if located in extreme ozone non-attainment area, either stand-alone or with existing vPET facility, a major modification permit would be needed
Water or waste	No	Only if wastewater testing yielded high solids or oxygen depletion levels, or if hazardous chemicals added to process
Economic analysis	No	Feedstock handling is the largest contributor to overall production costs, fewer incentives materialize, or payback time is unfavorable compared to existing methods
LCA	No	Only if higher impacts of rPET compared to vPET become an important factor and can't be reduced
Local jobs and economic impact	No	Jobs added and economic impacts are larger than existing PET production, much larger plants may have less of an advantage
Air regulations	No	Variation of process could have higher emissions in a regulated section of plastics manufacture, which would then require additional emissions reduction
Risk and return analysis	No	Only if identified supply chain risk factors become dominant and the market does not identify alternatives to source and produce raw materials at risk, which would mean that the rPET technology could suffer from possible supply chain disruptions.

S9 CARAT tool results

(Double click on the image below to open the Adobe file)

U.S. DEPARTMENT OF ENERGY

Commercial Adoption Readiness Assessment Tool (CARAT)

Version: June 2023[1]

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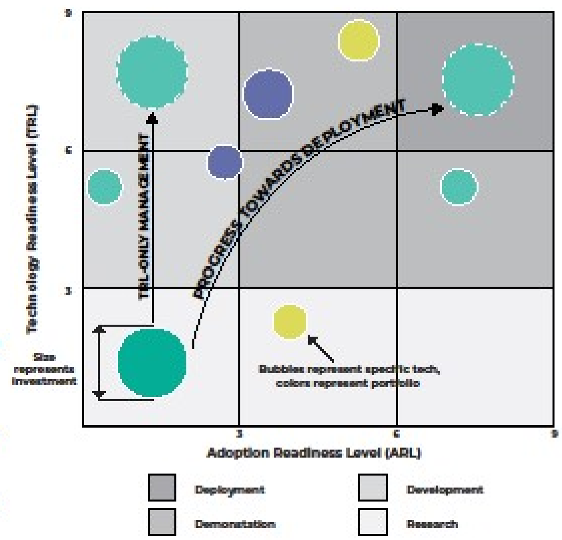

INTRODUCTION TO ADOPTION READINESS LEVELS (ARLS) AND CARAT

Commercialization is the progression of a technology from an idea in a lab to full-scale adoption in the market. This requires actively moving technologies across the research, development, demonstration, and deployment (RDD&D) continuum through close coordination and partnership among public sector organizations, private sector entities, and community stakeholders. To do this effectively, research and development, whether conducted in labs, universities, or corporations, must be done with the end-market in mind. This means that managing a technology portfolio solely through the well-understood and widely used Technology Readiness Levels (TRL) stage-gates is not enough.

To describe adoption risks, the Department of Energy's (DOE) Office of Technology Transitions has developed the Adoption Readiness Level (ARL) framework to complement TRL, in partnership with other DOE and industry stakeholders. ARL represents important factors for private sector uptake beyond technology readiness, and can be determined by performing a qualitative, but fact-based, risk assessment across 17 dimensions of adoption risk spanning four core risk areas –

- ***Value Proposition***
  Assesses the ability for a new technology to meet the functionality required by the market at a price point that customers are willing to pay, to meet the market demand (a broadened definition of "product-market fit").
- ***Market Acceptance***
  Captures the target market(s) demand characteristics and risks posed by existing players -- including competitors, customers, and other value chain players.
- ***Resource Maturity***
  Determines risks standing in the way of inputs that are needed to produce the technology solution.
- ***License to Operate***
  Identifies the societal (national, state, and local), non-economic risks that can hinder the deployment of a technology.

This Commercial Adoption Readiness Assessment Tool (CARAT) provides a rubric for assessing the Adoption Readiness Level (ARL) of a technology solution. The tool can be used to surface critical barriers to technology commercialization, to facilitate and structure discussions between stakeholders in the commercialization process, and to compare the relative commercialization challenges across technology solutions in a portfolio. This document provides instructions for using the assessment, as well as the rubric itself.

For more information about the ARL framework and tool, visit energy.gov/technologytransitions/arl.

[1] THE INFORMATION IN THIS DOCUMENT WILL BE UPDATED ON A ROLLING BASIS SUBJECT TO FUTURE DEVELOPMENT AND FEEDBACK; INPUT AND FEEDBACK ARE ENCOURAGED AND CAN BE SENT TO OTT@HQ.DOE.GOV.

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