Energy and CO_2 Calculations for REMADE Project Proposals

Updated October 15, 2019 with further guidance covering chemical recycling and solvent-based recycling

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Energy and CO_2 Calculations for REMADE Project Proposals

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Definition of Embodied Energy and CO_2 Emissions

- Embodied Energy is the energy required by all processing associated with converting a material into a manufactured product – from mining to final product delivery. When a material is landfilled, the raw material and the energy related to the material are lost.
- The unit "CO2e" (CO2 equivalent) represents an amount of a GHG whose atmospheric impact has been standardized to that of one unit mass of carbon dioxide (CO_2), based on the global warming potential (GWP) of the gas.

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Purpose of Calculator

- Simple ***scoping*** method to calculate potential energy and CO2e savings arising from successfully developed and implemented technologies studied in each project
- Consistent estimates across REMADE projects on the material-specific embodied energy and CO2e emissions.
- Consistent units across REMADE projects to allow quick evaluation ("scoping") of their potential impact.

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Components of Calculator

"Calculator" tab includes inputs and outputs for "current" and "potential future" scenarios.

Calculator (Beta Version) to estimate embodied emissions and CO2e emissions of materials and processes

Instructions or Explanation (read comment)	*Current Status*	*Material 1*	*Material 2*	*Material 3*	*Material 4*	*Total*	*Units*
	Material Type	Material 1	Material 2	Material 3	Material 4		
	% Recycle content	0%	0%	0%	0%		
	% yield	100%	100%	100%	100%		
	EE of primary material	0.0					MJ/kg
	EE of secondary material						MJ/kg
	CO2e of primary material						kgCO_2/kg
	CO2e of secondary material						kgCO_2/kg
	Embodied Energy per kg of product	0.0	0.0	0.0	0.0		MJ/kg
	CO2e emissions per kg of product	0.00	0.00	0.00	0.00		kgCO_2/kg of product
	Mass of material in product			0	0		metric tons
	Total EE impacted	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	MJ
	Total CO2 emissions impacted	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	metric tons CO_2
	Potential Future Status	*Material 1*	*Material 2*	*Material 3*	*Material 4*		
	Material Type	Material 1	Material 2	Material 3	Material 4		
	% Recycle content	0%	0%	0%	0%		
	% yield	100%	100%	100%	100%		
	EE of primary material						MJ/kg
	EE of secondary material						MJ/kg
	CO2e of primary material						kgCO_2/kg
	CO2e of secondary material						kgCO_2/kg
	Embodied Energy per kg of product	0.0	0.0	0.0	0.0		MJ/kg
	CO2 emissions per kg of product	0.00	0.00	0.00	0.00		kg CO2/kg
	Mass of material in product			0	0		metric tons
	Total EE of improved products	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	MJ
	Total CO2 emissions of improved pr	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	metric tons CO_2
	Impact of Change						
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	MJ
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	PJ
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	TBtu
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Quad
	Reduction in CO2e emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	metric tons CO_2
	Relative decrease in EE	#DIV/0!				#DIV/0!	
	Relative decrease in CO2 emissions	#DIV/0!				#DIV/0!	

"EE and CO2e" tab

Suggested Embodied Energy (EE) and CO2 equivalent (CE) Data for Calculator

Material	Emb. Energy (MJ/kg)		CO2e (kg/kg)	
	Primary (virgin)	Secondary (mechanically recycled)	Primary (virgin)	Secondary (mechanically recycled)
Low Carbon steel	26.5	7.3	1.80	0.44
Low alloy steel (cranskshafts and tools)	32.5	8.6	2.00	0.52
Stainless_Steel	84.5	12.0	4.95	0.73
Aluminum	210.0	26.0	12.00	2.10
Copper alloys	59.0	13.5	3.70	0.83
Nickel-Chromium alloy	181.5	33.0	11.50	2.00
Zinc (die cast)	60.0	11.0	4.10	0.67
Lead	27.0	7.5	2.00	0.45
Magnesium alloys	315.0	36.0	24.50	2.90
Gold	252500.0	684.5	26500.00	43.00
Platinum	271000.0	12561.0	14750.00	367.00
Silver	1475.0	155.0	100.00	9.30
Titanium alloy	685.0	87.0	46.50	5.20
Paper_Cardboard	51.5	19.5	1.15	0.76
Eglass_Fiber	65.5		3.52	
Cotton	46.0		2.55	
PP	79.0	50.0	3.05	2.10
PE (HDPE, LDPE, LLDP	81.0	50.0	2.75	2.85
PVC	59.0	36.0	2.50	2.15
PS	97.0	47.5	3.80	2.85
PET	85.0	39.0	3.90	2.35
PUR foam	109.0		4.50	
Polyamide_Nylon	122.5	42.5	7.95	2.56
Ethylene Vinyl Acetate (EVA)	79.0	46.0	2.10	2.80
Nat_Rubber	67.5		2.10	
Butyl_Rubber_Synthetic	118.0		6.60	
ABS	94.5	46.5	3.80	2.80
Polycarbonate	108.5	42.5	6.00	2.55

Updated 11/12/19

Inputs and Outputs of Calculator

Instructions or Explanation (read comment)	Current Status	Material 1	Material 2	Material 3	Material 4	Total	Units
	Material Type	Material 1	Material 2	Material 3	Material 4		
	% Recycle content	0%	0%	0%	0%		
	% yield	100%	100%	100%	100%		
	EE of primary material	0.0					MJ/kg
	EE of secondary material						MJ/kg
	CO2e of primary material						$kgCO_2/kg$
	CO2e of secondary material						$kgCO_2/kg$
	Embodied Energy per kg of product	0.0	0.0	0.0	0.0		MJ/kg
	CO2e emissions per kg of product	0.00	0.00	0.00	0.00		$kgCO_2/kg$ of product
	Mass of material in product			0	0		metric tons
	Total EE impacted	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	MJ
	Total CO2 emissions impacted	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	metric tons CO_2
	Potential Future Status	***Material 1***	***Material 2***	***Material 3***	***Material 4***		
	Material Type	Material 1	Material 2	Material 3	Material 4		
	% Recycle content	0%	0%	0%	0%		
	% yield	100%	100%	100%	100%		
	EE of primary material						MJ/kg
	EE of secondary material						MJ/kg
	CO2e of primary material						$kgCO_2/kg$
	CO2e of secondary material						$kgCO_2/kg$
	Embodied Energy per kg of product	0.0	0.0	0.0	0.0		MJ/kg
	CO2 emissions per kg of product	0.00	0.00	0.00	0.00		kg CO2/kg
	Mass of material in product			0	0		metric tons
	Total EE of improved products	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	MJ
	Total CO2 emissions of improved pr	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**	metric tons CO_2
	Impact of Change						
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	MJ
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	PJ
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	TBtu
	Reduction in Embodied Energy	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Quad
	Reduction in CO2e emissions	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	metric tons CO_2
	Relative decrease in EE	#DIV/0!				#DIV/0!	
	Relative decrease in CO2 emissions	#DIV/0!				#DIV/0!	

- Inputs (for both “Current Status” and “Potential Future Status”) are the cells highlighted in bright blue.
  - Material type(s)
  - % Recycle content
  - % yield
  - Mass of material in product
- Embodied Energy (EE)and CO_2 equivalent emissions (CO2e) from the “EE CO2e” tab in the spreadsheet or from other referenced sources
- Outputs are the cells highlighted in bright green.
  - Reduction in Embodied Energy (EE reduction reported in TBtu)
  - Reduction in CO2e (in metric tons)
  - Relative decreases in Embodied Energy and CO2e

Example 1: Increase recycled content (RC) in PET bottles from 10% to 50%

Current Process: RC in clear bottles is limited by rPET availability (economic/policy reasons)

- 3,000,000 metric tons PET used in clear bottles
- 10% RC* in clear bottles (i.e. 300,000 metric tons)

Potential Future Process: Technical improvements (e.g. more efficient process) lead to greater RC

- 3,000,000 metric tons PET used in clear bottles
- 50% RC in bottles (i.e. 1,500,000 metric tons)

Tabulated values of Embodied Energy (EE) and CO2 Emissions (CE) for primary (virgin) PET and rPET (mechanical)

$EE_{virgin\ PET} = 85.0\ MJ/kg$ | $EE_{rPET} = 39.0\ MJ/kg$

$CO2e_{virgin\ PET} = 3.9\ kg\ CO_2/kg\ PET$ | $CO2e_{rPET} = 2.4 kg\ CO_2/kg\ PET$

EE and CE for PET containing 10% rPET

$$EE_{current} = 0.9 EE_{virgin\ PET} + 0.1 EE_{rPET} = 80.4\ MJ/kg$$

$$CO2e_{current} = 0.9 CO2e_{virgin\ PET} + 0.1 CO2e_{rPET} = 3.75\ kgCO_2/kgPET$$

The total EE and CE for the 3,000,000 metric tons of PET in clear bottles

$$EE_{total} = 3 \times 10^9 kg \times 80.4 \frac{MJ}{kg} = 2.41 \times 10^{11} MJ$$

$$CO2e_{total} = 3 \times 10^9 kg \times 3.75 \frac{kgCO_2}{kgPET} = 1.1 \times 10^{10} kgCO_2$$
$$= 1.125 \times 10^7 metric\ tons\ CO_2$$

EE and CE for PET containing 50% rPET

$$EE_{current} = 0.5 EE_{virgin\ PET} + 0.5 EE_{rPET} = 62.0\ MJ/kg$$

$$CO2e_{current} = 0.5 CO2e_{virgin\ PET} + 0.5 CO2e_{rPET} = 3.15\ kgCO_2/kgPET$$

The total EE and CE for the 3,000,000 metric tons of PET in clear bottles

$$EE_{total} = 3 \times 10^9 kg \times 62.0 \frac{MJ}{kg} = 1.86 \times 10^{11} MJ$$

$$CO2e_{total} = 3 \times 10^9 kg \times 3.75 \frac{kgCO_2}{kgPET} = 9.45 \times 10^9 kgCO_2$$
$$= 9.45 \times 10^6 metric\ tons\ CO_2$$

Benefits of Future Process

$$\Delta EE_{total} = 2.4 \times 10^{11} MJ - 1.9 \times 10^{11} MJ = 5.5 \times 10^{10} MJ = 55\ PJ$$

$$\Delta CE_{total} = (11.25 - 9.45) \times 10^6 metric\ tons\ CO_2 = 1.8 \times 10^6 metric\ tons\ CO_2$$

* 10% rPET content for demonstration purposes only.

Example 1: Increase recycled content (RC) in PET bottles from 10% to 50%

Example 1: Increase recycled content (RCC) in PET bottles from 10% to 50%

Instructions or Explanation (read comment)

	Material 1	Material 2	Material 3	Material 4	Total	Units
Current Status						
Material Type	PET	Material 2	Material 3	Material 4		
% Recycle content	10%	0%	0%	0%		
% yield	100%	100%	100%	100%		
EE of primary material	85.0					MJ/kg
EE of secondary material	39.0					MJ/kg
CO2e of primary material	3.9					$kgCO_2/kg$
CO2e of secondary material	2.4					$kgCO_2/kg$
Embodied Energy per kg of product	80.4	0.0	0.0	0.0		MJ/kg
CO2e emissions per kg of product	3.75	0.00	0.00	0.00		$kgCO_2/kg$ of product
Mass of material in product	3,000,000		0	0		metric tons
Total EE impacted	2.41E+11	0.00E+00	0.00E+00	0.00E+00	**2.41E+11**	MJ
Total CO2 emissions impacted	1.13E+07	0.00E+00	0.00E+00	0.00E+00	**1.13E+07**	metric tons CO_2
Potential Future Status						
Material Type	PET	Material 2	Material 3	Material 4		
% Recycle content	50%	0%	0%	0%		
% yield	100%	100%	100%	100%		
EE of primary material	85.0					MJ/kg
EE of secondary material	39.0					MJ/kg
CO2e of primary material	3.9					$kgCO_2/kg$
CO2e of secondary material	2.4					$kgCO_2/kg$
Embodied Energy per kg of product	62.0	0.0	0.0	0.0		MJ/kg
CO2 emissions per kg of product	3.15	0.00	0.00	0.00		kg CO2/kg
Mass of material in product	3,000,000		0	0		metric tons
Total EE of improved products	1.86E+11	0.00E+00	0.00E+00	0.00E+00	**1.86E+11**	MJ
Total CO2 emissions of improved pr	9.45E+06	0.00E+00	0.00E+00	0.00E+00	**9.45E+06**	metric tons CO_2
Impact of Change						
Reduction in Embodied Energy	5.52E+10	0.00E+00	0.00E+00	0.00E+00	5.52E+10	MJ
Reduction in Embodied Energy	5.52E+01	0.00E+00	0.00E+00	0.00E+00	5.52E+01	PJ
Reduction in Embodied Energy	5.23E+01	0.00E+00	0.00E+00	0.00E+00	5.23E+01	TBtu
Reduction in Embodied Energy	5.23E-02	0.00E+00	0.00E+00	0.00E+00	5.23E-02	Quad
Reduction in CO2e emissions	1.80E+06	0.00E+00	0.00E+00	0.00E+00	1.80E+06	metric tons CO_2
Relative decrease in EE	23%				23%	
Relative decrease in CO2 emissions	16%				16%	

- Read Instructions (comments in column A" for explanations)
- 10% rPET currently in clear bottles
- Assume 100% yield since no yield change expected
- Embodied Energy (EE) and CO2e of virgin PET and rPET found in the "EE CO2e" tab (future versions to link automatically)
- Enter amount of clear bottle PET affected (in metric tons)
- Only one material involved, so enter "0" as mass for Materials 2-4
- Calculated EE and CO2e for "Current Status"

- Enter similar data for "Potential" Future Status, with only change to 50% for "% recycle content" in this example.
- Calculated EE and CO2e for "Potential Future Status"

- Calculated "Impact of Change" highlighted in bright green.

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Example 2: Process Improvement Reduces Production of Scrap from 2% to 1%

Current Process: Current scrap rate (losses) of injection molded of PP in a type of product is 2% (98% yield)

- 100,000 metric tons of PP (all virgin) in affected product
- Assume all scrap is discarded to landfill

Potential Future Process: Technical improvements to injection molding process reduce losses (scrap rate) to 1% (99% yield)

- Same amount (100,000 metric tons of virgin PP) in the affected product
- Scrap still goes to landfill

Tabulated values of Embodied Energy (EE) and CO2 Emissions (CE) for primary (virgin) PP and secondary PP (mechanical)

$EE_{virgin\ PP} = 79.0\ MJ/kg$ $EE_{rPP} = 50.0\ MJ/kg$

$CE_{virgin\ PP} = 3.1\ kg\ CO_2/kg\ PET$ $CE_{rPP} = 2.1 kg\ CO_2/kg\ PET$

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Example 2: Process Improvement Reduces Production of Scrap from 2% to 1%

Current Status	Material 1	Material 2	Material 3	Material 4	Total	Units
Material Type	PP	Material 2	Material 3	Material 4		
% Recycle content	0%	0%	0%	0%		
% yield	98%	100%	100%	100%		
EE of primary material	79.0					MJ/kg
EE of secondary material	50.0					MJ/kg
CO2e of primary material	3.1					$kgCO_2/kg$
CO2e of secondary material	2.1					$kgCO_2/kg$
Embodied Energy per kg of product	80.6	0.0	0.0	0.0		MJ/kg
CO2e emissions per kg of product	3.16	0.00	0.00	0.00		$kgCO_2/kg$ of product
Mass of material in product	100,000		0	0		metric tons
Total EE impacted	8.06E+09	0.00E+00	0.00E+00	0.00E+00	**8.06E+09**	MJ
Total CO2 emissions impacted	3.16E+05	0.00E+00	0.00E+00	0.00E+00	**3.16E+05**	metric tons CO_2

Potential Future Status	Material 1	Material 2	Material 3	Material 4	Total	Units
Material Type	PP	Material 2	Material 3	Material 4		
% Recycle content	0%	0%	0%	0%		
% yield	99%	100%	100%	100%		
EE of primary material	79.0					MJ/kg
EE of secondary material	50.0					MJ/kg
CO2e of primary material	3.1					$kgCO_2/kg$
CO2e of secondary material	2.1					$kgCO_2/kg$
Embodied Energy per kg of product	79.8	0.0	0.0	0.0		MJ/kg
CO2 emissions per kg of product	3.13	0.00	0.00	0.00		kg CO2/kg
Mass of material in product	100,000		0	0		metric tons
Total EE of improved products	7.98E+09	0.00E+00	0.00E+00	0.00E+00	**7.98E+09**	MJ
Total CO2 emissions of improved pr	3.13E+05	0.00E+00	0.00E+00	0.00E+00	**3.13E+05**	metric tons CO_2

Impact of Change	Material 1	Material 2	Material 3	Material 4	Total	Units
Reduction in Embodied Energy	8.14E+07	0.00E+00	0.00E+00	0.00E+00	8.14E+07	MJ
Reduction in Embodied Energy	8.14E-02	0.00E+00	0.00E+00	0.00E+00	8.14E-02	PJ
Reduction in Embodied Energy	7.71E-02	0.00E+00	0.00E+00	0.00E+00	7.71E-02	TBtu
Reduction in Embodied Energy	7.71E-05	0.00E+00	0.00E+00	0.00E+00	7.71E-05	Quad
Reduction in CO2e emissions	3.20E+03	0.00E+00	0.00E+00	0.00E+00	3.20E+03	metric tons CO_2
Relative decrease in EE	1%				1%	
Relative decrease in CO2 emissions	1%				1%	

- **"Current" and "Potential Future" yields entered**
- **100,000 metric tons of product (before and after)**

Material	EE_{virgin} (MJ/kg)	$EE_{recycled}$ (MJ/kg)	CE_{virgin} ($kgCO_2/kg$)	$CE_{recycled}$ ($kgCO_2/kg$)
PP	79.0	50.0	3.1	2.1

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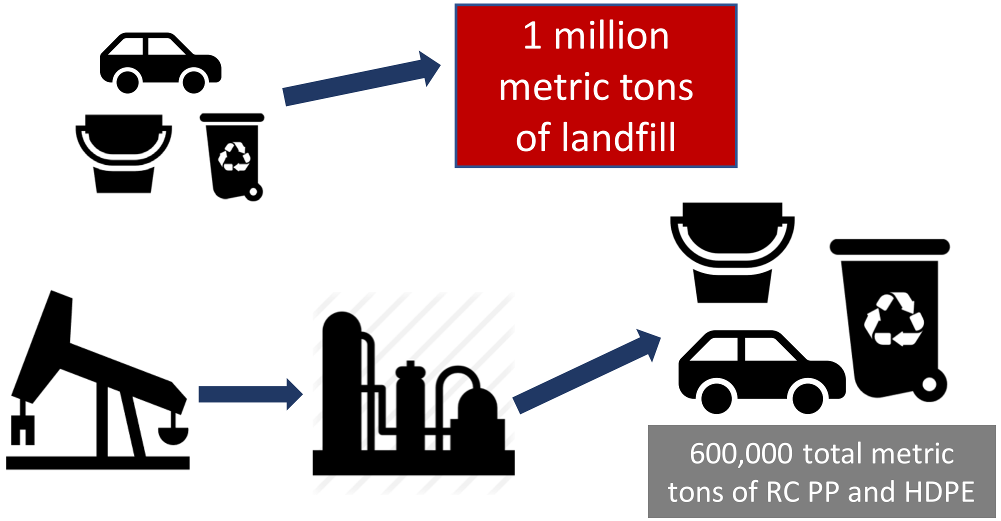
Example 3: Improvements enable replacement of 600,000 metric tons of virgin plastics with RC plastics

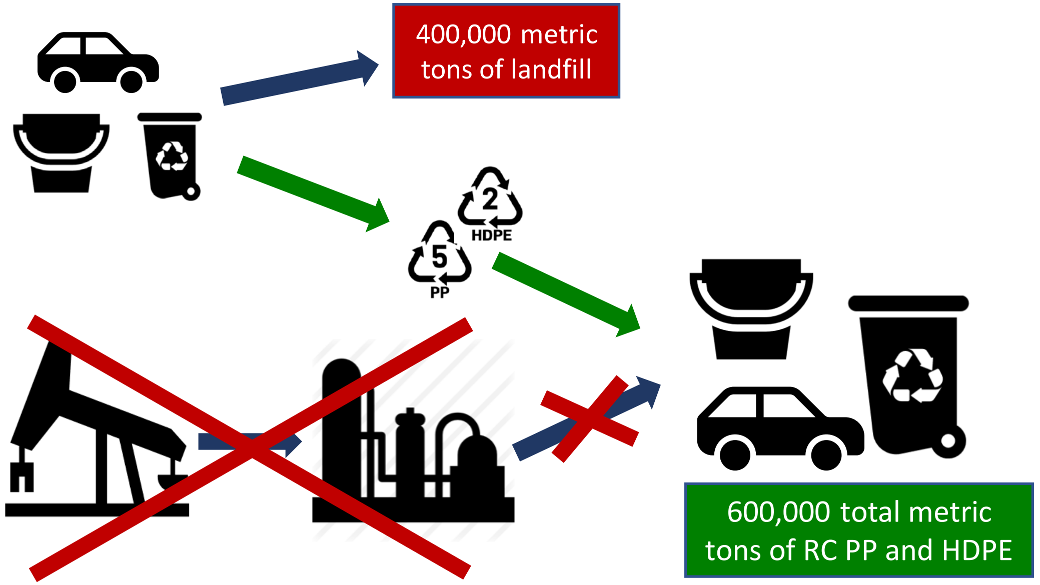
Current Process: A mix of PP (40%), HDPE (40%) and PVC (20%) cannot be adequately separated

- 1 million metric tons per year are landfilled (i.e. 400,000 metric tons PP; 400,000 metric tons HDPE; 200 thousand metric tons PVC)
- New PP and HDPE products are made using virgin PP and HDPE pellets

Potential Future Process: Technical improvements to separation enable recovery of RC PP and HDPE pellets

- 300,000 metric tons each of RC PP and HDPE used in new products instead of virgin PP and HDPE
- 400,000 metric tons of mixed byproduct landfilled





Tabulated values of Embodied Energy (EE) and CO2 Emissions (CE) for primary (virgin) and mechanically recycled plastics

Material	EE_{virgin} (MJ/kg)	$EE_{recycled}$ (MJ/kg)	CE_{virgin} ($kgCO_2$/kg)	$CE_{recycled}$ ($kgCO_2$/kg)
PP	79.0	50.0	3.1	2.1
HDPE	80.0	40.0	3.3	2.3

Example 3: Improvements enable replacement of 600,000 metric tons of virgin plastics with RC plastics

Current Status	***Material 1***	***Material 2***	***Material 3***	***Material 4***	***Total***	***Units***
Material Type	PP	HDPE	Material 3	Material 4		
% Recycle content	0%	0%	0%	0%		
% yield	100%	100%	100%	100%		
EE of primary material	79.0	80.0				MJ/kg
EE of secondary material	50.0	40.0				MJ/kg
CO2e of primary material	3.1	3.3				$kgCO_2/kg$
CO2e of secondary material	2.1	2.3				$kgCO_2/kg$
Embodied Energy per kg of product	79.0	80.0	0.0	0.0		MJ/kg
CO2e emissions per kg of product	3.10	3.30	0.00	0.00		$kgCO_2/kg$ of product
Mass of material in product	300,000	300,000	0	0		metric tons
Total EE impacted	2.37E+10	2.40E+10	0.00E+00	0.00E+00	**4.77E+10**	MJ
Total CO2 emissions impacted	9.30E+05	9.90E+05	0.00E+00	0.00E+00	**1.92E+06**	metric tons CO_2
Potential Future Status	***Material 1***	***Material 2***	***Material 3***	***Material 4***		
Material Type	PP	HDPE	Material 3	Material 4		
% Recycle content	100%	100%	0%	0%		
% yield	100%	100%	100%	100%		
EE of primary material	79.0	80.0				MJ/kg
EE of secondary material	50.0	40.0				MJ/kg
CO2e of primary material	3.1	3.3				$kgCO_2/kg$
CO2e of secondary material	2.1	2.3				$kgCO_2/kg$
Embodied Energy per kg of product	50.0	40.0	0.0	0.0		MJ/kg
CO2 emissions per kg of product	2.10	2.30	0.00	0.00		kg CO2/kg
Mass of material in product	300,000	300,000	0	0		metric tons
Total EE of improved products	1.50E+10	1.20E+10	0.00E+00	0.00E+00	**2.70E+10**	MJ
Total CO2 emissions of improved pr	6.30E+05	6.90E+05	0.00E+00	0.00E+00	**1.32E+06**	metric tons CO_2
Impact of Change						
Reduction in Embodied Energy	8.70E+09	1.20E+10	0.00E+00	0.00E+00	2.07E+10	MJ
Reduction in Embodied Energy	8.70E+00	1.20E+01	0.00E+00	0.00E+00	2.07E+01	PJ
Reduction in Embodied Energy	8.24E+00	1.14E+01	0.00E+00	0.00E+00	1.96E+01	TBtu
Reduction in Embodied Energy	8.24E-03	1.14E-02	0.00E+00	0.00E+00	1.96E-02	Quad
Reduction in CO2e emissions	3.00E+05	3.00E+05	0.00E+00	0.00E+00	6.00E+05	metric tons CO_2
Relative decrease in EE	37%				43%	
Relative decrease in CO2 emissions	32%				31%	

Material	EE_{virgin} (MJ/kg)	$EE_{recycled}$ (MJ/kg)	CE_{virgin} ($kgCO_2/kg$)	$CE_{recycled}$ ($kgCO_2/kg$)
PP	79.0	50.0	3.1	2.1
HDPE	80.0	40.0	3.3	2.3

- **300,000 metric tons each of rPP and rHDPE used in new products instead of virgin PP and HDPE**

 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

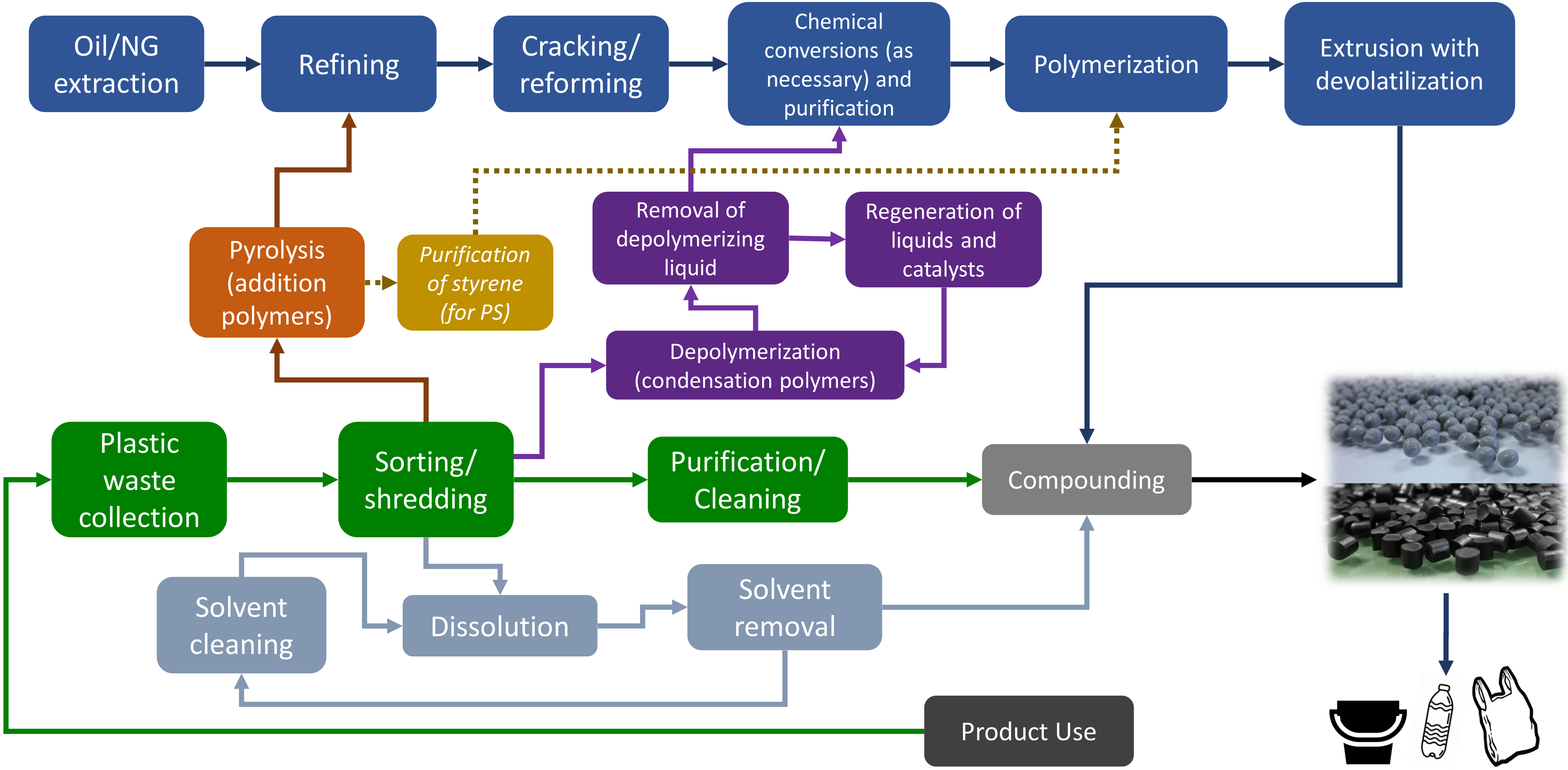
Updated 11/12/19

Guidance for Chemical and Solvent-based Recycling Processes

- Embodied energy and CO2e data are not available for plastic recycling processes involving solvent dissolution or for chemical depolymerization or degradation processes (e.g. pyrolysis), so these values must be estimated based on calculations of an expected process.
- These should be "back of the envelope" calculations in their level of detail, though they should consider the major energetic steps in the processes and the significant material streams.
- The basis for the calculations are converting an existing waste stream into polymer pellets. This means that mechanical recycling steps and extrusion should be included in the calculations (along with the special steps for the new process and any auxiliary processes to recover solvents or reagents)
- The "Plastics recycling calculator" tab guides the user through these calculations
- Calculated values for embodied energy and CO2e for chemical or solvent-based recycling processes can be entered into the "Calculator" tab for these secondary materials

 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

“Chemical Recycling” includes most Mechanical Recycling Steps



 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

Updated 11/12/19

Calculations for "Chemical Recycling"

Steps include:

- Collection
- Material preparation (size reduction, sorting, etc.) – This step could include many processes typical of mechanical recycling
- The Chemical Recycling process, which may include steps such as dissolution, depolymerization, recovery and purification of process liquids and catalysts, drying of recovered polymer or monomer, chemical conversions back to monomer, and polymerization of the monomer(s) back to the polymer.
- Extrusion back to pellets for use in conversion processes (including solid-stating for PET to get to bottle grade PET)

The "Plastics recycling calculator" tab of "REMADE Energy and CO2e calculator V4.0" leads the user through the above steps.

 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

Example 4: Solvent-based Recycling of HDPE

- Assume we can recover an additional 1 million metric tons of HDPE by using a solvent-based process.
- We start our calculations using the “Plastics recycling calculator” tab as shown below and continuing on the next slides.

***DRAFT* Plastic Recycling Calculator Worksheet**

Instructions: Please feel free to use the worksheet below to estimate the energy requirements for various processes including both "mechanical recycling" and the broad category of "chemical recycling" (including processes involving solvents, depolymerization to monomers, or pyrolysis). As you go through the form, please read each step carefully and enter data to the best of your knowledge in cells highlighted in bright blue. We realize that some information about your proposed process may be missing at this early stage, but please use your best realistic estimates for each step. The results highlighted in bright green cells in Line 9-9 and 9-10 may be used as inputs for secondary polymers in Rows 10,12, 24 and 26 of the "Calculator" tab. Please use the "Notes" column (column G) after each entry to provide a BRIEF explanation to help us better understand the logic and uncertainties of the calculation. We may ask for this completed sheet and the completed "Calculator" worksheet during the review process or after your project is selected for award. If you have any questions about the calculations, please reach out to Brian Riise (briise@remadeinstitute.org) or Ed Daniels (edaniels@remadeinstitute.org).

Section	Line	Question for consideration or *Result*	Entry	Result (MJ/kg of product)	Notes
1: Collection	1-1	How many kg of waste material must be collected to ultimately recover 1 kg of the product polymer? If the product is one of several products recovered from the mixture (including by other means), you can estimate an overall product yield of the mix and calculate this entry based on that yield (i.e. the inverse of the yield). The number must be greater than 1, and should most likely between 1.2 and 1.5. After entering the number, proceed to Section 2.	1.5		
	1-2	***Collection energy***		***0.75***	

 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

Example 4: Solvent-based Recycling of HDPE (continued)

2: Sorting and Material Preparation	2-1	Does the collected material need processing such as size reduction, sorting, removal of contamination to prepare it for downstream processes? If "Yes", enter "1" at right and proceed to Line 2-2. If "No", enter "0" and proceed to the relevant section below for the next processing step (e.g. Section 3 for solvent-based recycling).	1		
	2-2	How many mechanical conveying steps are involved to prepare the material for chemical processing or extrusion (in the case of mechanical recycling)? The number should be at least 2 greater than the sum of entries in Lines 2-4, 2-6, 2-8, 2-10 and 2-12. Enter the number at right, which is the multiplier for number of conveyors. Proceed to Line 2-4.	9		
	2-3	*Energy for material conveying*		2.7	
	2-4	How many size reduction steps? The number is typically 2 if reducing from large objects to flakes, but can be 1 if feed to the chemical process is larger than about 20 mm. Proceed to Line 2-6.	2		
	2-5	*Energy for Size Reduction*		1.65	
	2-6	How many total steps involve screening, magnets or eddy current separators to prepare the material for chemical recycling? After entering the number, proceed to Line 2-8.	1		
	2-7	*Energy for screening, magnets or eddy current separators*		0.3	
	2-8	How many total steps involve air separations or dry cleaning? After entering the number, proceed to Line 2-10.	1		
	2-9	*Energy for air separations or dry cleaning*		0.3	
	2-10	How many total steps involve wet density separations or cleaning followed by drying? After entering the number, proceed to Line 2-12.	1		
	2-11	*Energy for wet density separations or cleaning followed by drying*		0.45	
	2-12	How many total steps involve optical sorting? After entering the number, proceed to Line 2-14.	2		
	2-13	*Energy for optical sorting steps*		0.6	
	2-14	Enter energy (MJ per kg of final secondary polymer) for any additional transportation, mechanical recycling or sorting processes not captured thus far in Section 2. Proceed to the relevant section below for the next processing step (e.g. Section 3 for solvent-based recycling).			
	2-15	*Energy of other processes*		0	
	2-16	***Total Energy for Sorting and Material Preparation***		**6**	

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Example 4: Solvent-based Recycling of HDPE (continued)

	3-1	How much solvent is used (on a weight ratio to the final amount of polymer product) to dissolve the polymer? The ratio should typically be between 5 and 15 to ensure rapid dissolution and to keep energy use reasonable. Proceed to Line 3-2.	9		
	3-2	Enter the specific heat capacity of the slurry containing polymer and solvent (in units if kJ/kg/K). You can estimate the slurry specific heat capacity based on the solvent heat capacity. Several solvents are listed in the "EE CO2 solvents+processes" tab, or you can look up elsewhere or estimate. Proceed to Line 3-3.	1.72		Using Xylene as the solvent
	3-3	Enter the latent heat of vaporization of the solvent (in units if kJ/kg). Several solvents are listed in the "EE CO2 solvents+processes" tab, or you can look up elsewhere or estimate. Proceed to Line 3-4.	206		Value for Xylene
	3-4	What is the expected dissolution temperature in degrees C? Proceed to Line 3-5.	120		Assume the process is at 120°C
	3-5	What fraction of the targeted polymer will be recovered after dissolution and reprecipitation? Proceed to Line 3-6.	1		Here we assume full dissolution and recovery.
	3-6	If the heating source for boiling off solvents is using natural gas, enter "1" at right. If heating uses electricity, enter "0.3". Proceed to Line 3-8.	0.3		
	3-7	*Energy input to heat up slurry (from 20° C) for dissolution*		*5.7*	
	3-8	Enter the energy to convey material, slurry and solution, including filtration of insolubles. Number should be approximately 1 MJ/kg, but enter alternative if available. Proceed to Line 3-10.	1		
	3-9	*Enter the energy to convey material, slurry and solution, including filtration of insolubles*		*1*	
	3-10	How much anti-solvent (in kg per kg of final product) is used to precitatate the polymer? Number should be much less than the value entered in Line 3-1, but should be non-zero. Procees to Line 3-11.	1		Assume we add 1 part of ethylene glycol to precipitate the HDPE polymer
	3-11	Enter the latent heat of vaporization of the anti-solvent (in units if kJ/kg). Several solvents are listed in the "EE CO2 solvents+processes" tab, or you can look up elsewhere or estimate. Proceed to Line 3-12.	372		Value for Ethylene Glycol
	3-12	What is the boiling point of the solvent in degrees C? See "EE CO2e solvents+processes" or a suitable reference. Proceed to Line 3-13.	140		Value for Xylene
3: Solvent-based recycling	3-13	What is the boiling point of the anti-solvent in degrees C? See "EE CO2e solvents+processes" or a suitable reference. Proceed to Line 3-19.	197		Value for Ethylene Glycol
	3-14	*This is the lower of the two boiling points of the solvent and anti-solvent?*	*140*		
	3-15	*Energy to heat liquid mixture up to the lower boining point (per kg of polymer product)*		*6.9*	
	3-16	*Energy to boil off solvent (when it is lower boiling) per kg of polymer end product*		*6.180*	
	3-17	*Energy to boil off anti-solvent (when it is lower boiling) per kg of polymer end product*		*0.000*	
	3-18	*Energy to remove liquid from precipitated polymer. This assumes 1 part liquid per part solid, heating the solid/liquid from 20° C to the boiling point of the solvent, and vaporizing the solvent.*		*0.62*	
	3-19	How much energy is required (per kg of solvent) to clean up and purify the solvent after separation from the polymer and the anti-solvent? Proceed to Line 3-20.	1		
	3-20	How much energy is required (per kg of ant-solvent) to clean up and purify the anti-solvent after separation from the polymer and the asolvent? Proceed to Line 3-22.	1		
	3-21	*Energy to treat solvent and anti-solvent (per kg of polymer end product)*		*10.00*	
	3-22	What % of the solvent is lost in each batch run? Use 1% as a default unless there are better numbers. Proceed to Line 3-23.	1%		
	3-23	What is the embodied energy of the solvent? See "EE CO2e solvents+processes" or suitable reference. Proceed to Line 3-24.	47		Estimate for Xylene from the "EE CO2e solvents+processes" tab.
	3-24	How much energy is required to treat the solvent (per kg of solvent that is lost)? Proceed to Line 3-26.	1		
	3-25	*Embodied energy consumption due to solvent use*		*4.32*	
	3-26	What % of the anti-solvent is lost in each batch run? Use 1% as a default unless there are better numbers. Proceed to Line 3-27.	1%		
	3-27	What is the embodied energy of the anti-solvent? See "EE CO2e solvents+processes" or suitable reference. Proceed to Line 3-28.	60		Estimate for EG from the "EE CO2e solvents+processes" tab.
	3-28	How much energy is required to treat the anti-solvent (per kg of solvent that is lost)? Proceed to Line 3-30	1		
	3-29	*Embodied energy consumption due to solvent use*		*0.61*	
	3-30	Enter energy (MJ per kg of final secondary polymer) for any additional processes related to Section 3. Proceed to Section 8.			
	3-31	*Energy of other processes in solvent-based recycling*		*0*	
	3-32	***Total Energy for Solvent-based Recycling Processes***		***24.7***	

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Example 4: Solvent-based Recycling of HDPE (continued)

- Sections 4-7 are left blank as they apply to other processes

8: Extrusion and Compounding	*8-1*	*Conveying energy assuming feed and take-away.*		*0.4*	
	8-2	A 100% yield is assumed for the extrusion step. Proceed to Line 8-4.			
	8-3	*Extrusion energy per kg of polymer*		*6*	
	8-4	Is the process with PET so that solid-stating is used to convert to bottle grade PET? Is "Yes" enter "1" at right. Proceed to Line 8-6.			
	8-5	*Energy for PET solid-stating*		*0*	
	8-6	Enter energy (MJ per kg of final secondary polymer) for any additional processes related to Section 8. Examples could include additional compounding stages, post-drying, etc. beyond the normal processes for extrusion compounding. Proceed to Section 9.			
	8-7	*Additional Energy*		0	
	8-8	***Total Energy for Extrusion and Compounding to produce pellets***		**6.4**	
9: Results Summary	9-1	Collection energy (from Line 1-3)		0.75	
	9-2	Total Energy for Sorting and Material Preparation (from Line 2-17)		6	
	9-3	Total Energy for Solvent-based Recycling Processes (from Line 3-23)		24.7	
	9-4	Total Energy for Depolymerization and Repolymerization of PET (from Line 4-9)		0	
	9-5	Total Energy for Depolymerization and Repolymerization of PS (from Line 5-7)		0	
	9-6	Energy of pyrolysis of polyolefins and repolymerization (from Line 6-6)		0	
	9-7	Calculated energy to convert waste polymer to new polymer (other chemical recycling process) (from Line 7-1)		0	
	9-8	Total Energy for Extrusion and Compounding to produce pellets (from Line 8-8)		6.4	
	9-9	***Total Process Energy to Produce Pellets from Waste Stream***		***37.9***	Use this in the "Calculator" tab.
	9-10	***Calculated CO2e (divide Energy by 20 for an estimate)***		***1.89***	Use this in the "Calculator" tab.

- Embodied energy and CO2e highlighted in bright green are entered in the appropriate cells in the "Calculator" tab (see next slide)

Example 4: Solvent-based Recycling of HDPE (continued)

Current Status	***Material 1***	***Material 2***	***Material 3***	***Material 4***	***Total***	***Units***
Material Type	HDPE	Material 2	Material 3	Material 4		
% Recycle content	0%		0%	0%		
% yield	100%	100%	100%	100%		
EE of primary material	81.0					MJ/kg
EE of secondary material	37.9					MJ/kg
CO2e of primary material	2.8					$kgCO_2/kg$
CO2e of secondary material	1.9					$kgCO_2/kg$
Embodied Energy per kg of produc	81.0	0.0	0.0	0.0		MJ/kg
CO2e emissions per kg of product	2.75	0.00	0.00	0.00		$kgCO_2$/kg of product
Mass of material in product	1.00E+09		0	0		metric tons
Total EE impacted	8.10E+13	0.00E+00	0.00E+00	0.00E+00	**8.10E+13**	MJ
Total CO2 emissions impacted	2.75E+09	0.00E+00	0.00E+00	0.00E+00	**2.75E+09**	metric tons CO_2
Potential Future Status	***Material 1***	***Material 2***	***Material 3***	***Material 4***		
Material Type	HDPE	Material 2	Material 3	Material 4		
% Recycle content	100%		0%	0%		
% yield	100%	100%	100%	100%		
EE of primary material	81.0					MJ/kg
EE of secondary material	37.9					MJ/kg
CO2e of primary material	2.8					$kgCO_2/kg$
CO2e of secondary material	1.9					$kgCO_2/kg$
Embodied Energy per kg of produc	37.9	0.0	0.0	0.0		MJ/kg
CO2 emissions per kg of product	1.90	0.00	0.00	0.00		kg CO2/kg
Mass of material in product	1.00E+09		0	0		metric tons
Total EE of improved products	3.79E+13	0.00E+00	0.00E+00	0.00E+00	**3.79E+13**	MJ
Total CO2 emissions of improved p	1.90E+09	0.00E+00	0.00E+00	0.00E+00	**1.90E+09**	metric tons CO_2
Impact of Change						
Reduction in Embodied Energy	4.31E+13	0.00E+00	0.00E+00	0.00E+00	4.31E+13	MJ
Reduction in Embodied Energy	4.31E+04	0.00E+00	0.00E+00	0.00E+00	4.31E+04	PJ
Reduction in Embodied Energy	4.08E+04	0.00E+00	0.00E+00	0.00E+00	4.08E+04	TBtu
Reduction in Embodied Energy	4.08E+01	0.00E+00	0.00E+00	0.00E+00	4.08E+01	Quad
Reduction in CO2e emissions	8.50E+08	0.00E+00	0.00E+00	0.00E+00	8.50E+08	metric tons CO_2
Relative decrease in EE	53%				53%	
Relative decrease in CO2 emissior	31%				31%	

Guidance on Total Relevant Material Mass Affected

- The energy and CO_2e impacts of your project will depend directly on the amount of material assumed to be impacted by implementation of the technology
- The amount should be estimated based on
  - How much of the material type(s) is available in the end-of-life stream of interest? The proposer should provide references with the estimated amount while showing a grasp of the waste stream's current and expected future potential for recycling the material(s).
  - What fraction of the material could potentially be affected by implementation of the technology? This should provide an optimistic long-term estimate assuming the new technology is successful, while also being realistic about the likelihood of competitive technologies limiting market share and logistical or regulatory limitations that prevent full adoption for the entire amount. We suggest using something like 50% or less for this fraction.

 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

Additional References

Embodied Energy Data (incudes data on production processes such as casting, injection molding)

M. F. Ashby, *Materials and the Environment (2nd Edition)*: Chapter 6 - Eco-data: values, sources, precision, 2013, pages 119-174. Available at https://www.sciencedirect.com/science/article/pii/B9780123859716000063

M. F. Ashby, *Materials and the Environment (2nd Edition)*: Chapter 15 - Material Profiles, 2013, pages 459-595. Available at https://www.sciencedirect.com/science/article/pii/B9780123859716000154

Benoit Cushman-Roisin and Bruna Tanaka Cremonini, *Useful Numbers for Environmental Studies and Meaningful Comparisons*, looking for a publisher, 2019.

Energy and Emissions Data for Plastics (includes data for intermediate chemicals)

Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors, prepared for the Plastics Division the American Chemistry Council by Franklin Associates, August 2011. Available at https://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-Rpt-Only/ plus further details at https://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-APPS-Only/

https://www.plasticseurope.org/en/resources/eco-profiles

Recycling and Recovery

Energy Impacts of Production and Recycling of Materials (EPA)

Updated 11/12/19

What to include in your proposal

- Assumptions used in the calculation (e.g. increase in recycle content, yield improvement, amount of additional secondary material use, energy savings in process)
- Reference the source of data used for the calculation (e.g. data in REMADE calculator tool)
- Method of Calculation (e.g. REMADE calculator tool)
- Results of Calculation
  - Potential embodied energy savings (in PJ and TBtu)
  - Potential savings in CO_2 equivalent (in metric tons)
- Comparison of expected improvements with TPMs stated in the RFP
- Save your calculations, as REMADE will want to review the calculations

 Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Advanced Manufacturing Office Award Number DE-EE0007897.

Questions

For questions about use of the tool or assumptions, or suggestions for improvements, please contact:

REMADE_RFP@remadeinstitute.org

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