Michigan Technological University

Sustainable Futures Institute

Sustainability of Valorizing MSW

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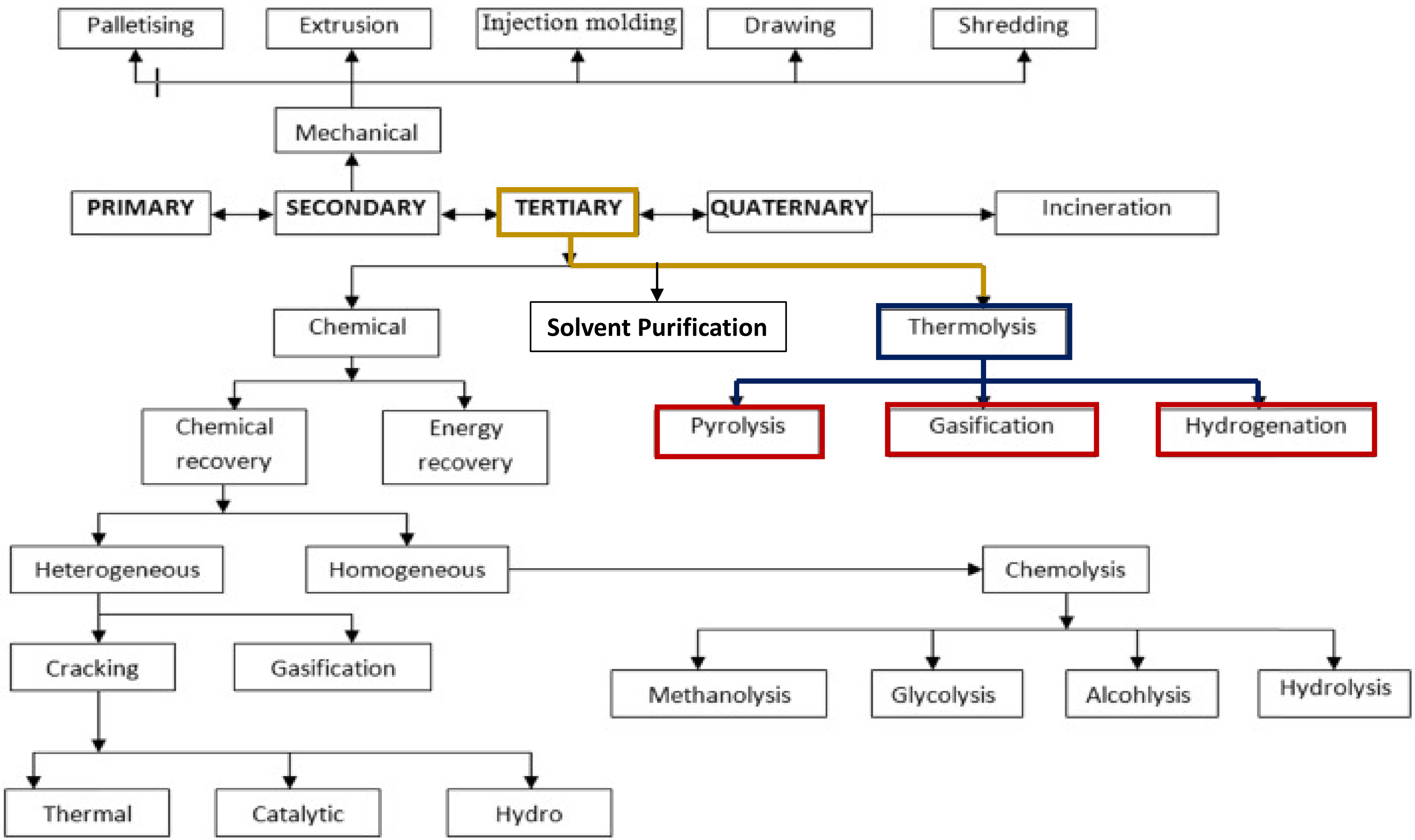
February 19, 2020

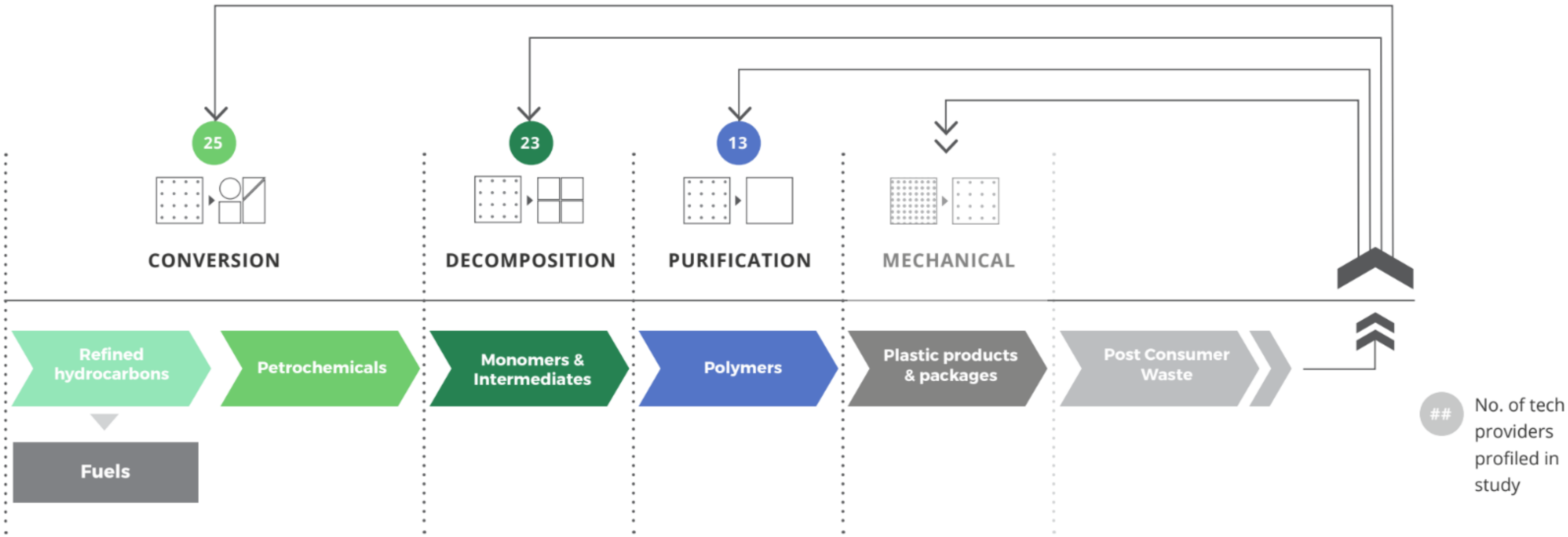
Introduction

- Recycling Alternatives for Municipal Plastic Waste



Singh N. et al. (2017) Composites part B, 115: 409-422

Chemical Recycling of Waste Plastic: Technologies



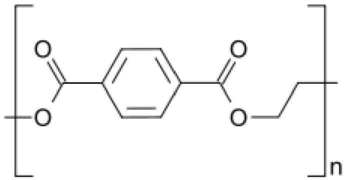
Conversion: a thermal process involving breaking bonds in the polymer to produce liquid and gaseous products such as fuels and petrochemicals.

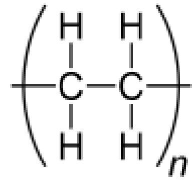
Decomposition: a biological, chemical, or thermal process involving selective breaking of bonds in the polymer to produce monomers.

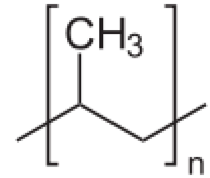
Purification: a process involving dissolving plastics in solvents to remove pigments and additives prior to separating pure resin.

Accelerating Circular Supply Chains for Plastics: A Landscape of Transformational Technologies. Closed Loop Partners, 2019

LCA Results for Mechanical Recycling: PET, HDPE, PP







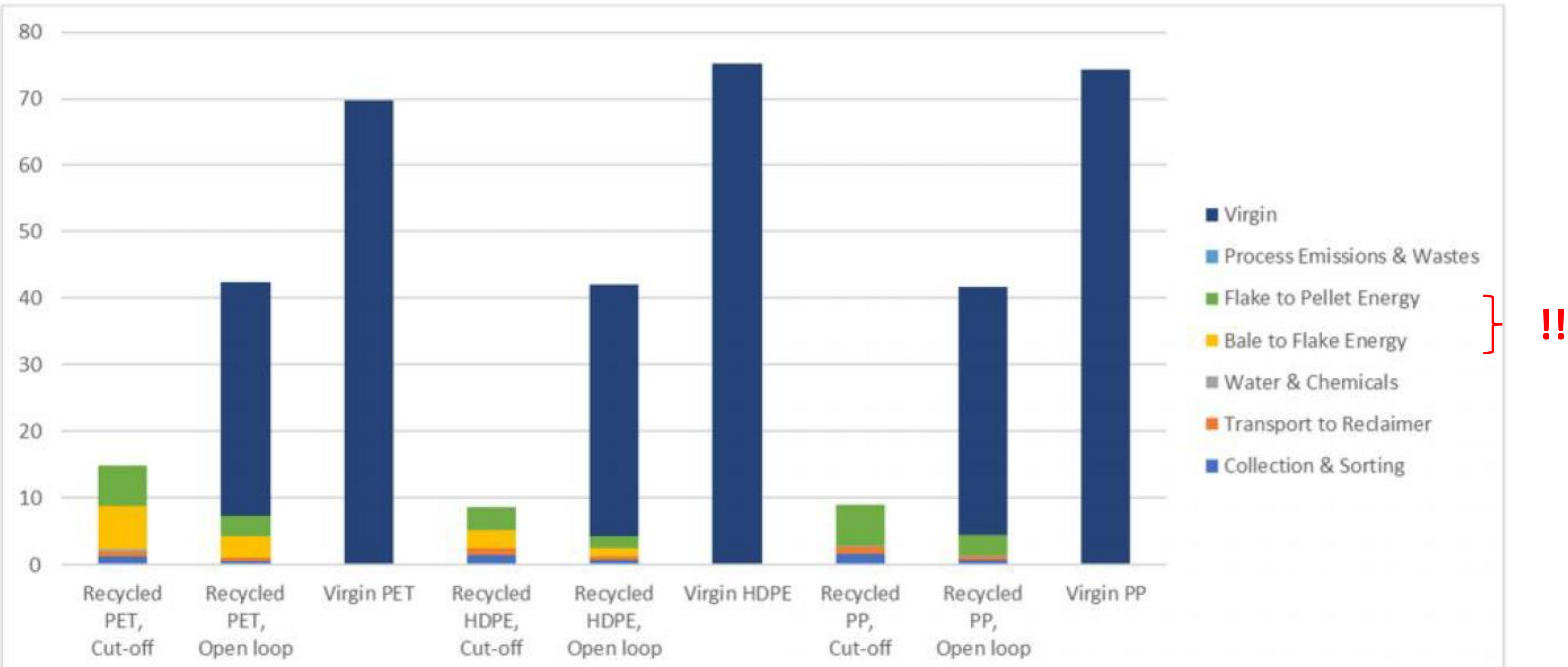
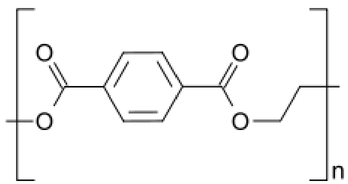
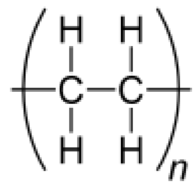


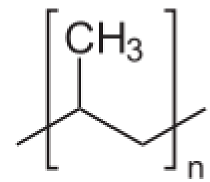
Figure 3-1. Total Energy Results for Recycled and Virgin Resins (MJ/kg)

LIFE CYCLE IMPACTS FOR POSTCONSUMER RECYCLED RESINS; PET, HDPE, PP, FRANKLIN AND ASSOCIATES DIVISION OF ERG, DEC 2018

LCA Results for Mechanical Recycling: PET, HDPE, PP







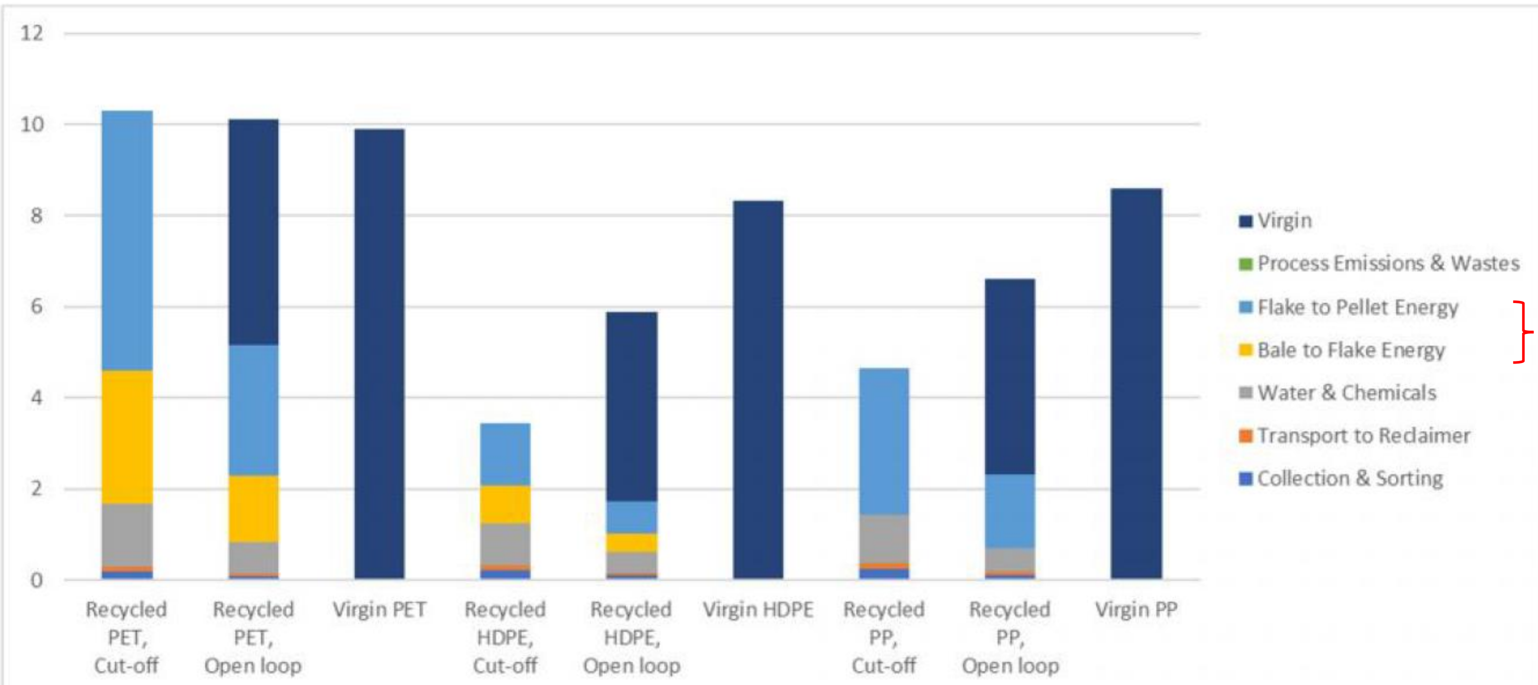


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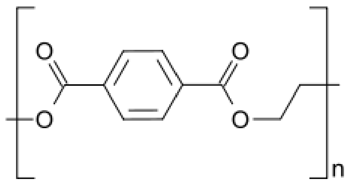
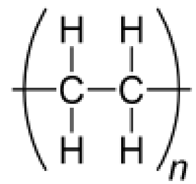
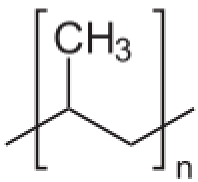
Figure 3-3. Water Consumption Results for Recycled and Virgin Resins (liters water/kg resin)

LIFE CYCLE IMPACTS FOR POSTCONSUMER RECYCLED RESINS; PET, HDPE, PP, FRANKLIN AND ASSOCIATES DIVISION OF ERG, DEC 2018

LCA Results for Mechanical Recycling: PET, HDPE, PP







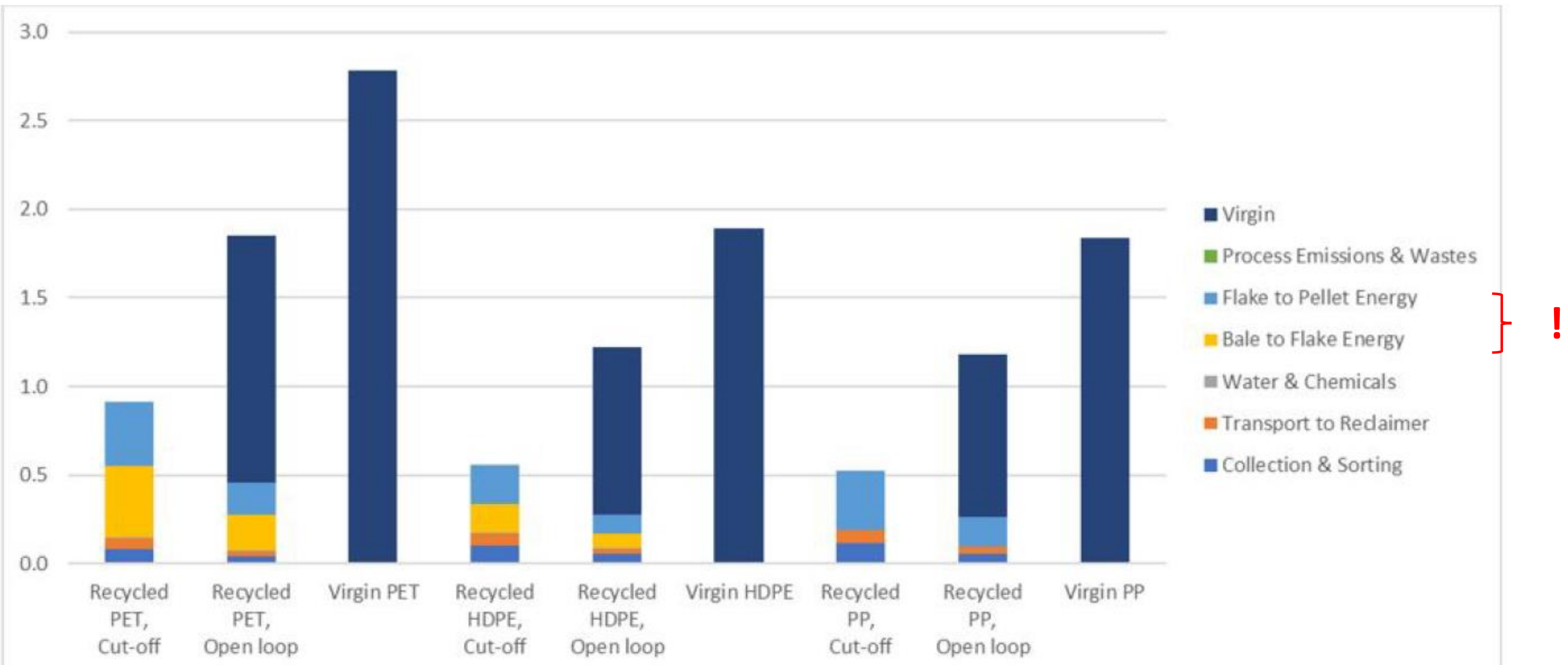
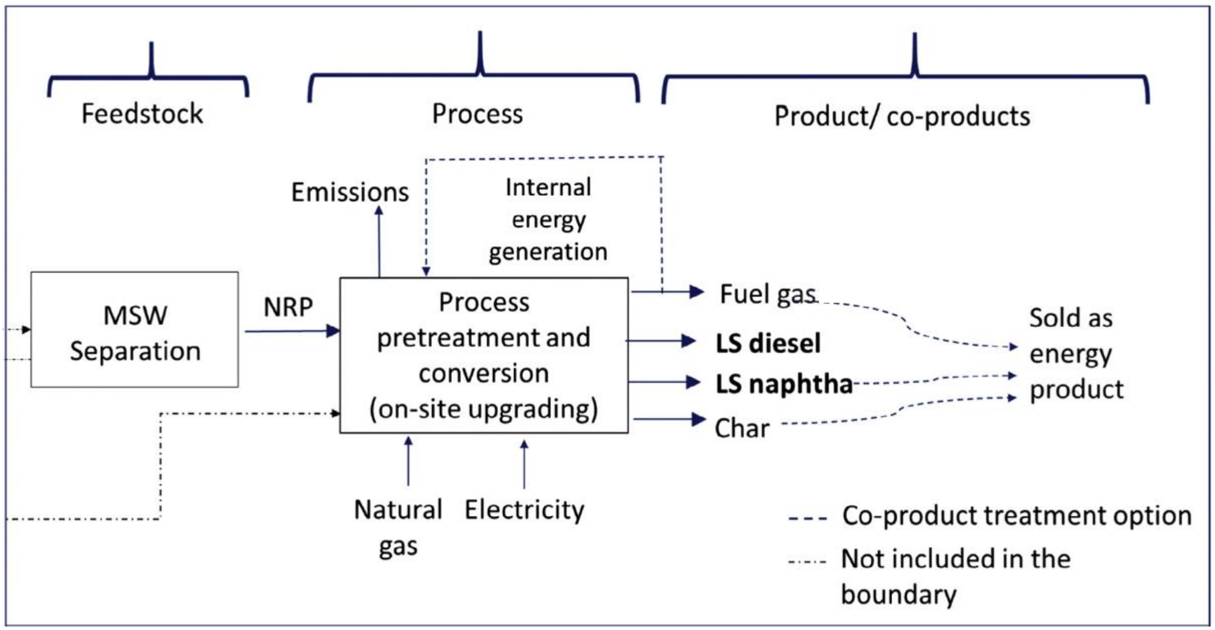
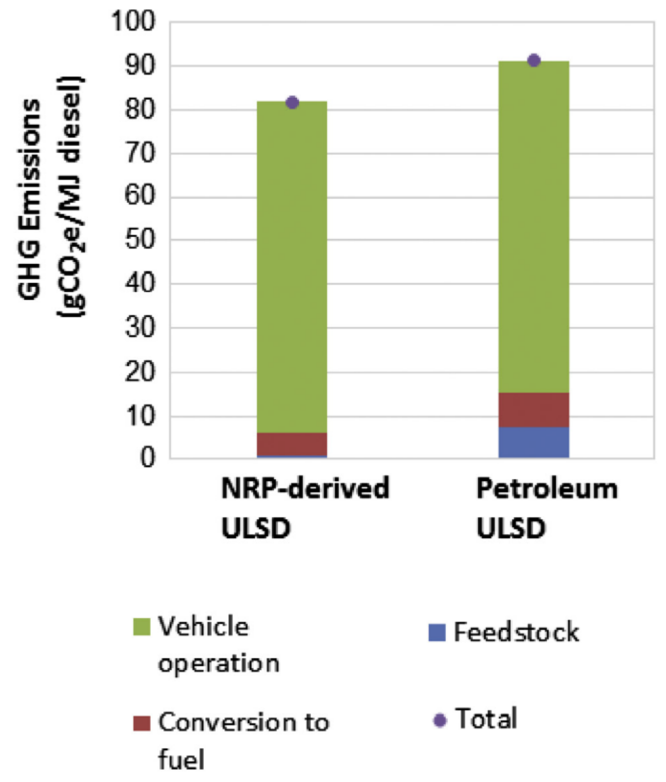


Figure 3-6. Global Warming Potential Results for Recycled and Virgin Resins ($kg\ CO_2$ eq/kg resin)

LIFE CYCLE IMPACTS FOR POSTCONSUMER RECYCLED RESINS; PET, HDPE, PP, FRANKLIN AND ASSOCIATES DIVISION OF ERG, DEC 2018

LCA Results for Chemical Recycling: HDPE





Benavides et al., 2017, Life-cycle analysis of fuels from post-use non-recycled plastics, *Fuel* **203**, 11–22

Case Study: Sustainability Assessment - Thermal Conversion of Waste HDPE

Research Objectives

- Design and simulation a multi-product refinery process for conversion of waste High Density Polyethylene using pyrolysis.
- Evaluate the energy requirements of the refinery (Energy returned over energy invested).
- Evaluate the environmental performance of the refinery products (kg CO_2 eq./kg of product).
- Evaluate the economic feasibility of the project (Net present value).

Materials and Methods

1. **Laboratory experiments** — Pyrolysis experiments performed at 650 °C and 2.8 s of residence time, in a two-stage micropyrolysis reactor (Gracida-Alvarez et al., 2018).

2. **Conceptual design** — Modeled with aid of the software Aspen Plus v.8.8. Operating conditions obtained from literature from similar petrochemical processes.

3. **Energetic evaluation** — Calculation of the Energy Returned over Energy Invested (EROI) indicator.

4. **Environmental evaluation** — Use of Life Cycle Assessment (LCA) with aid of the software Simapro v.8.5.0. Inventory of inputs obtained from the process simulation.

5. **Economic evaluation** — Calculation of the Net Present Value (NPV) considering five products. Costs and prices obtained from Aspen Plus and literature.

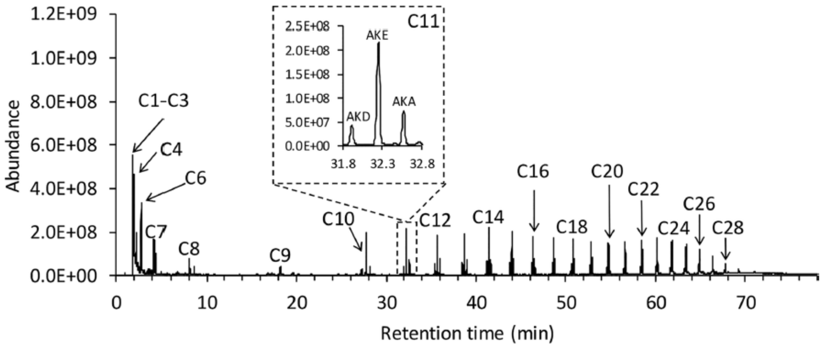
Gracida-Alvarez U. et al. (2018) *Industrial & Engineering Chemistry Research*, 57: 1912-1923

Results – Micro-pyrolysis experiments

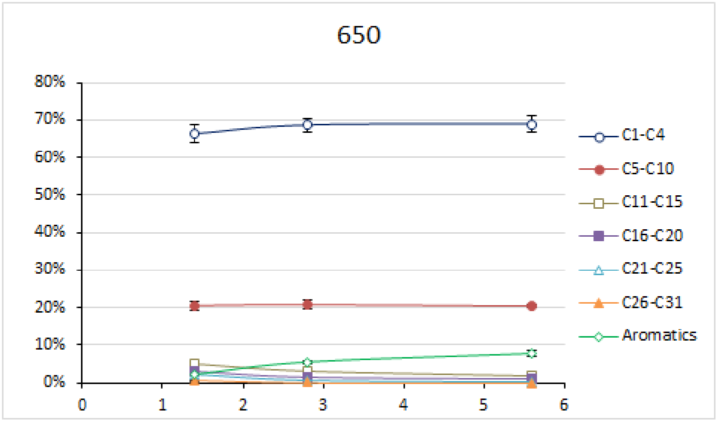
- Composition of the two-stage micro-pyrolysis reactor outlet

(650 °C & 2.8s vapor residence time)

Chemical class	Mass percentage
Hydrocarbon gases (C1-C4)	68.63
Gasoline range hydrocarbons (C5-C10)	20.68
Diesel range hydrocarbons (C11-C15)	3.14
Light waxes (C16-C20)	1.34
Heavy waxes (C21-C29)	0.75
Aromatics	5.46



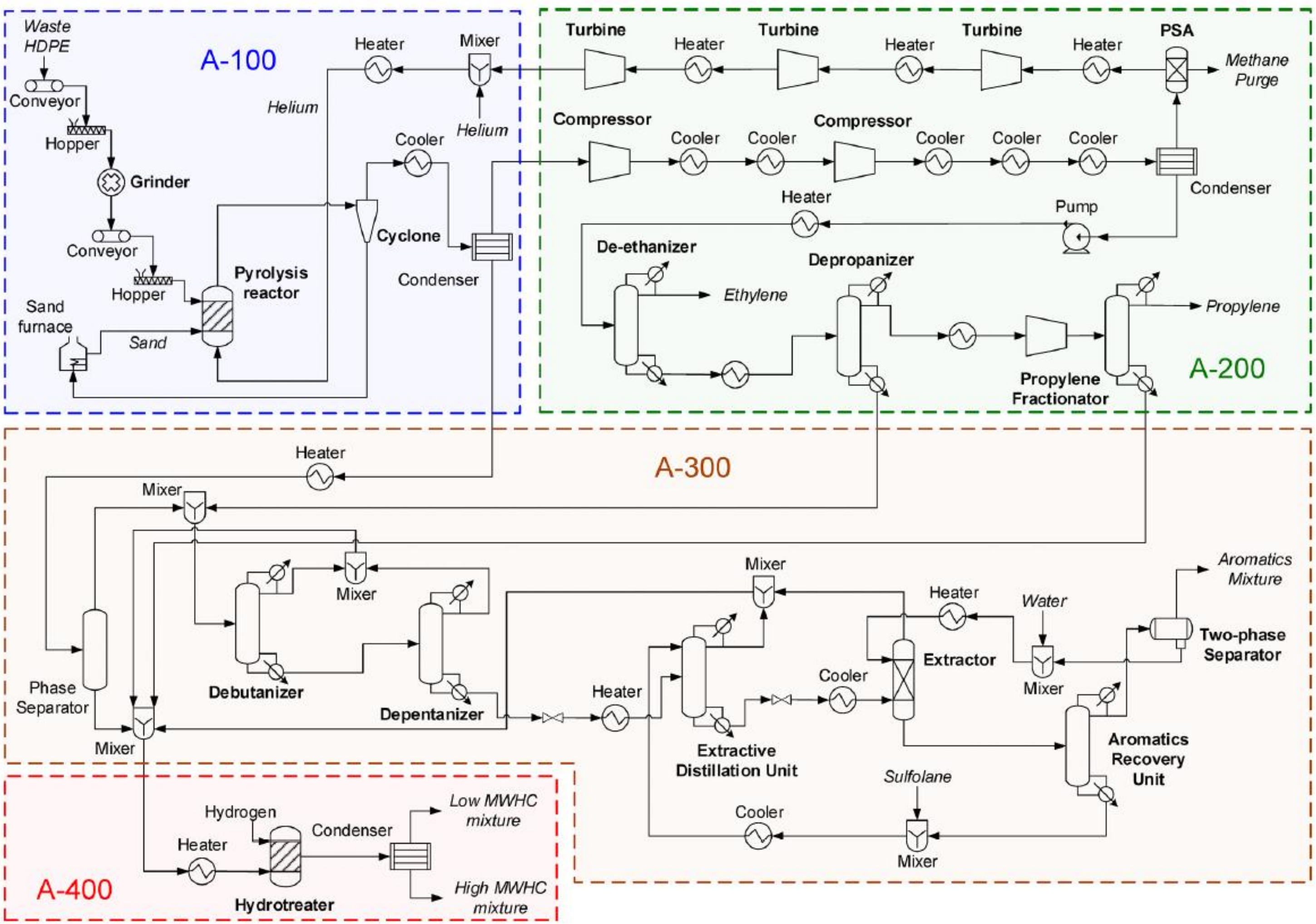
A total of 86 compounds were used in the simulation



Process Temperature range: -140 °C to 1200 °C
Process Pressure range: 0.5 to 25 bar
Processing Capacity: 500 tonnes/day (20.83 tonnes/hr)

Results – Conceptual design

- Process Flow Diagram (PFD)



A-100: Pyrolysis

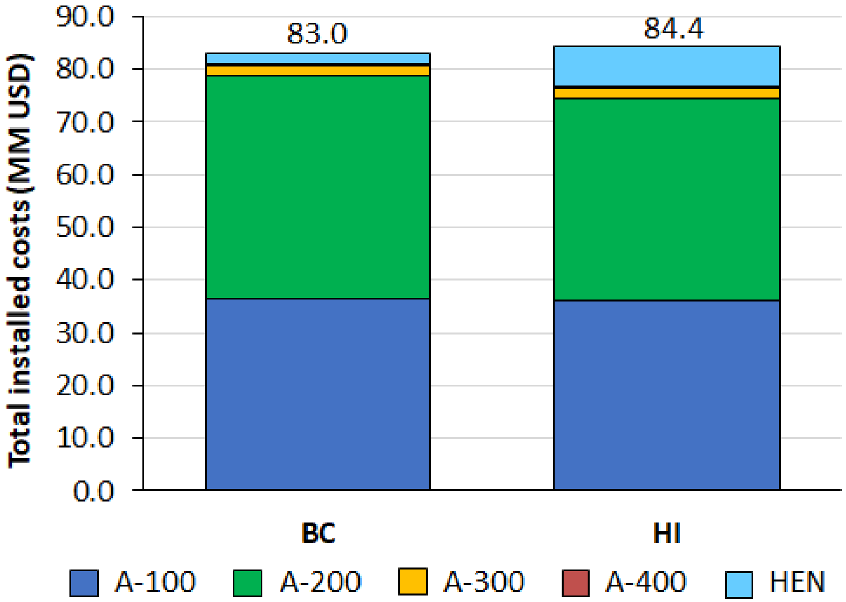
A-200: Monomer Separation

A-300: Aromatics Separation

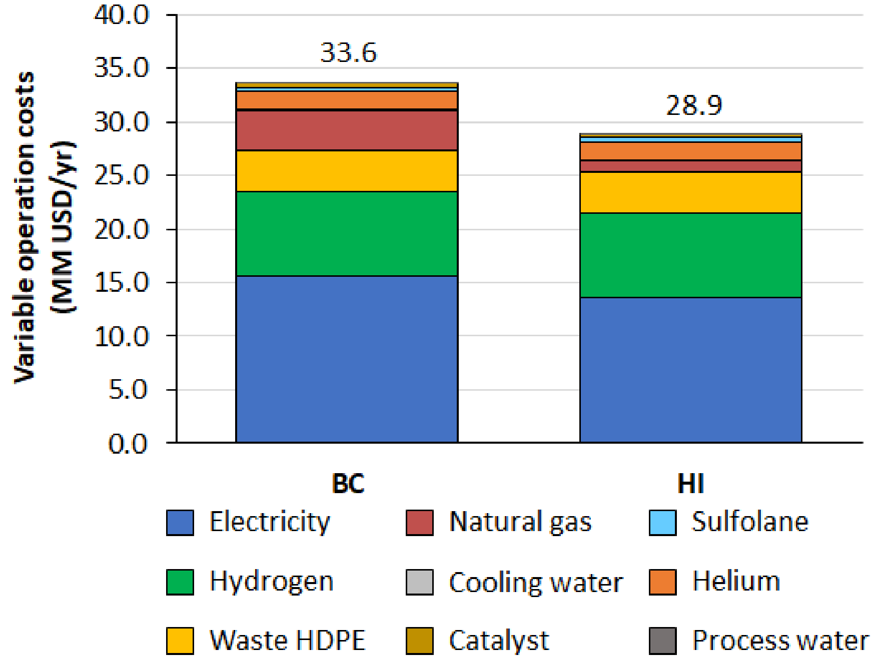
A-400: Hydrotreatment

TEA Results

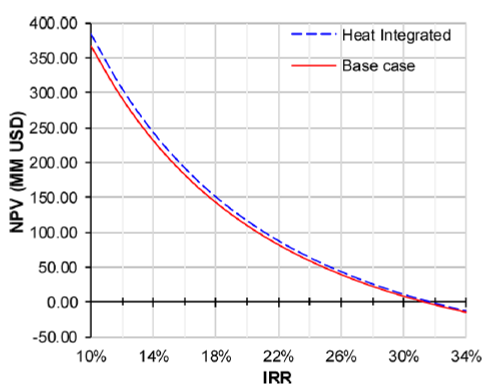
Total Installed Costs (MM USD)

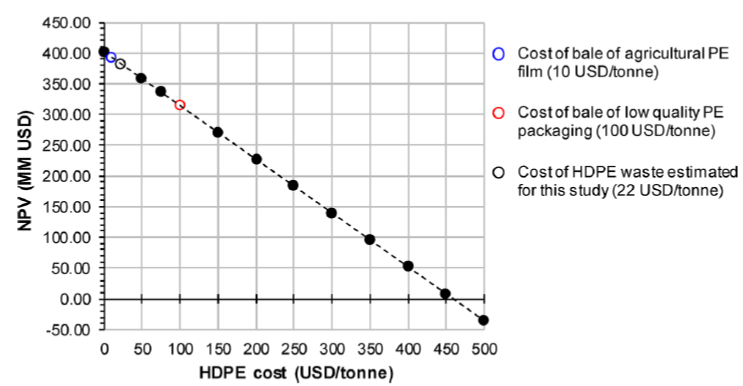


Variable Operating Costs (MM USD/yr)



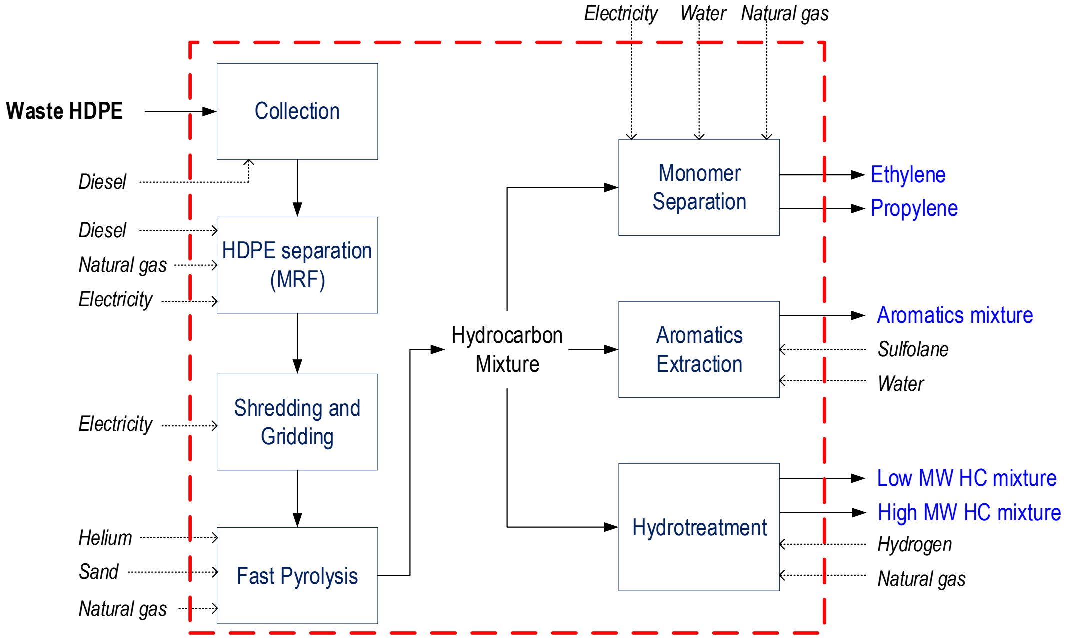
Gracida-Alvarez, U.R., et al., *ACS Sustainable Chemistry and Engineering*, DOI: 10.1021/acssuschemeng.9b04763





Results – Environmental evaluation

- Functional unit: 1 kg of product
- Scope: Cradle to gate
- Allocation: Mass allocation
- US grid electricity



MRF: Materials Recovery Facility

- Heat from Flue gas is utilized internally
- Electricity generated in turbines is utilized internally

- General inventory

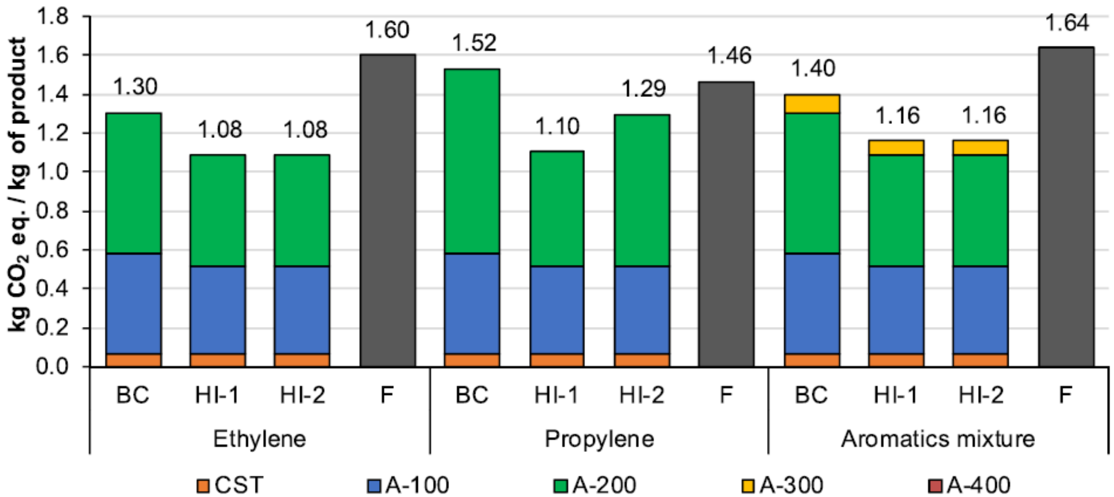
Basis: Processing of 20.83 tonnes of HDPE (Plant capacity for 1 hr of operation)

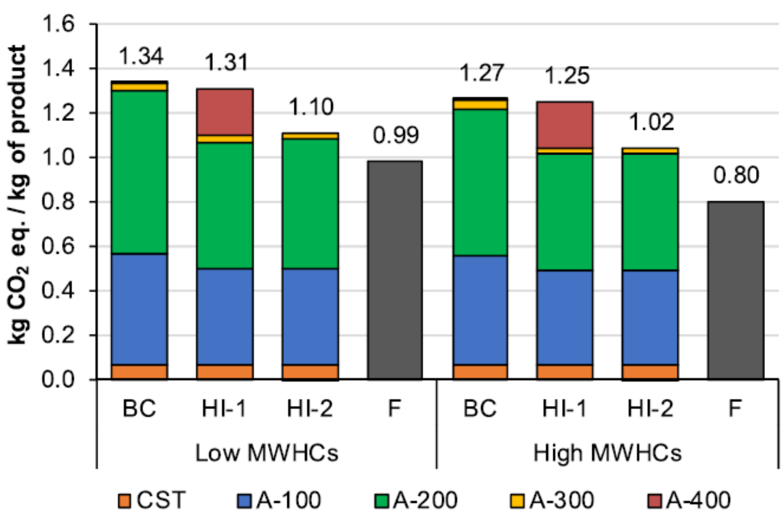
area	input	BC	HI-1	HI-2
A-100	electricity (kWh)	333.54	330.70	330.70
	natural gas (GJ)	2.20	0.50	0.50
	purge combustion (GJ)	3.10	3.10	3.10
	cooling water (m^3)	3.95	1.44	1.44
	helium (kg)	0.04	0.04	0.04
A-200	electricity (kWh)	954.55	791.57	791.57
	natural gas (GJ)	2.42	0.59	1.49
	cooling water (m^3)	7.37	5.75	5.75
A-300	natural gas (GJ)	0.60	0.51	0.51
	cooling water (m^3)	0.79	0.63	0.63
	sulfolane (kg)	0.27	0.27	0.27
	process water (kg)	0.17	0.17	0.17
A-400	natural gas (GJ)	0.25	0.00	0.00
	cooling water (m^3)	0.09	0.09	0.09
	hydrogen (kg)	15.82	15.82	15.82

Note: Recycled inputs (Helium, sand, and refrigerants) were not considered in the inventory.

Fitzgerald G. et al. (2012) Resources, Conservation, and Recycling, 69: 50-56

LCA Results – Carbon Footprint of Products





Gracida-Alvarez, U.R., et al., *ACS Sustainable Chemistry and Engineering*, DOI: 10.1021/acssuschemeng.9b04764

GHG Savings

HI-2 vs Fossil (F):

Ethylene:	**32.5%**
Propylene:	**11.6%**
Aromatics:	**29.3%**
Low MWHCs:	**-11.1%**
High MWHCs:	**-27.5%**

LCA Results – Regional Electricity Grid Effects

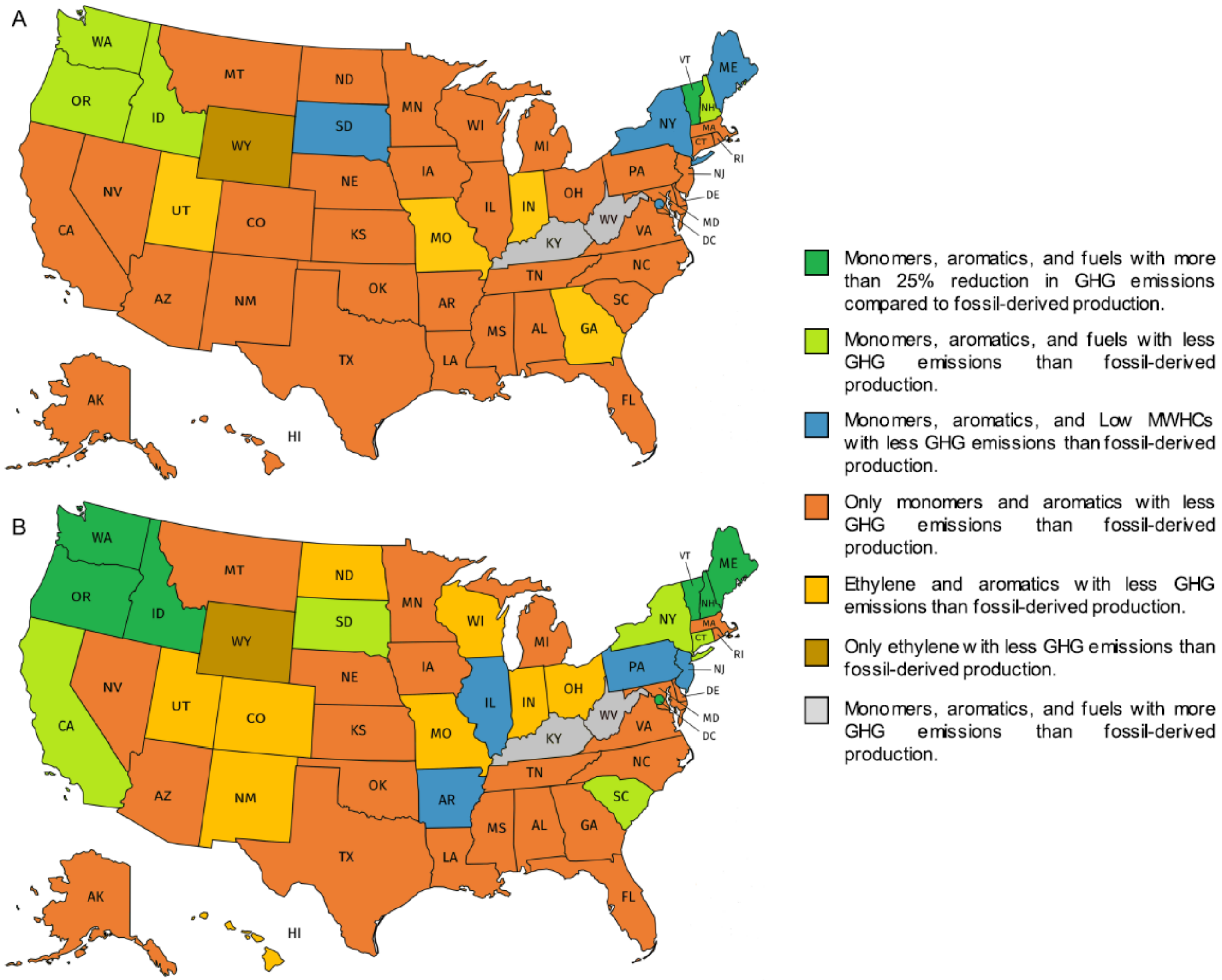


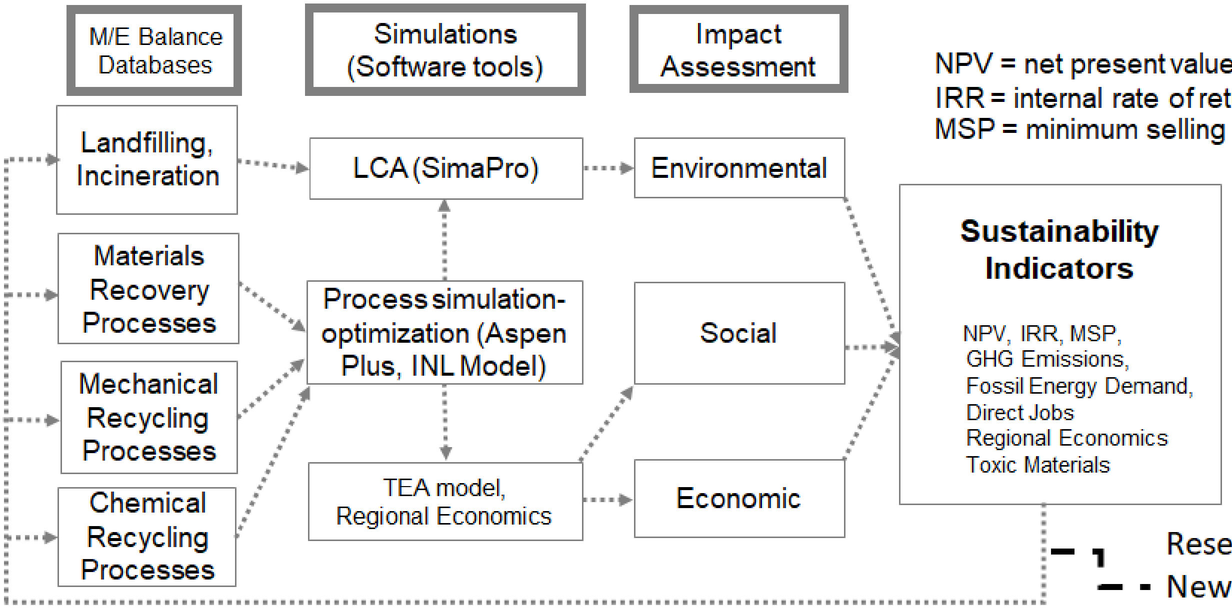
Figure 9. Effect of state mixture composition on the GHG emissions of the refinery products. (A) Scenario HI-1 and (B) scenario HI-2.

Systems Analysis Framework

Sustainability Assessments of Plastics in a Global Circular Economy

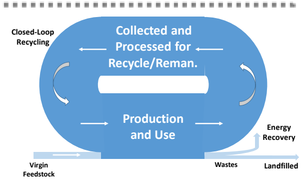
Model-based approach

- Materials flow analyses
- Process simulation
- TEA models
- LCA
- Social LCA
- Sustainability Indicators
- Policy-driven analyses



NPV = net present value.
IRR = internal rate of return
MSP = minimum selling price

Research questions, New policies, trigger new analyses



Shonnard, et al., 2019, Systems analysis for PET and olefin polymers in a circular economy, *Procedia CIRP*, 80, 602-606, 26th CIRP Life Cycle Engineering (LCE) Conference.

REMADE Project 18-01-SA-04

Research issues and questions

- Will a plastics *circular economy* improve performance compared to the current plastics *linear economy*
  - environmental, economic, and societal impacts?
- How would the prevalence of chemical versus mechanical recycling versus incineration for energy affect system performance?
- If renewable (i.e. plant-derived) feedstocks increase vs fossil, what affect would this have on system performance?
- What could be the impacts of biodegradable plastics on system performance?
  - Including ocean debris effects
- External effects beyond the plastics pathways
  - Indirect economic multipliers
  - Impacts to the petroleum, gas, and petrochemical industries

Acknowledgements

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- Graduate School of Michigan Technological University.
- Richard and Bonnie Robbins Endowment.
- REMADE Institute (Manufacturing USA Institute Advanced Manufacturing Office Award Number DE-EE0007897)

Acknowledgements and Disclaimers

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Extra Slides

Plastics Challenge

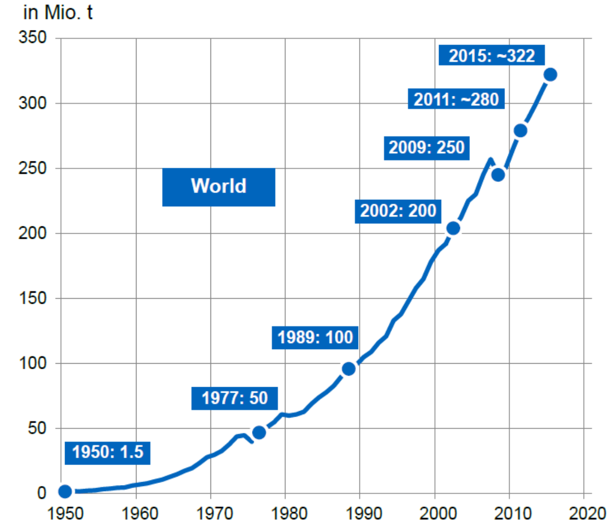
- Global Situation of Plastics

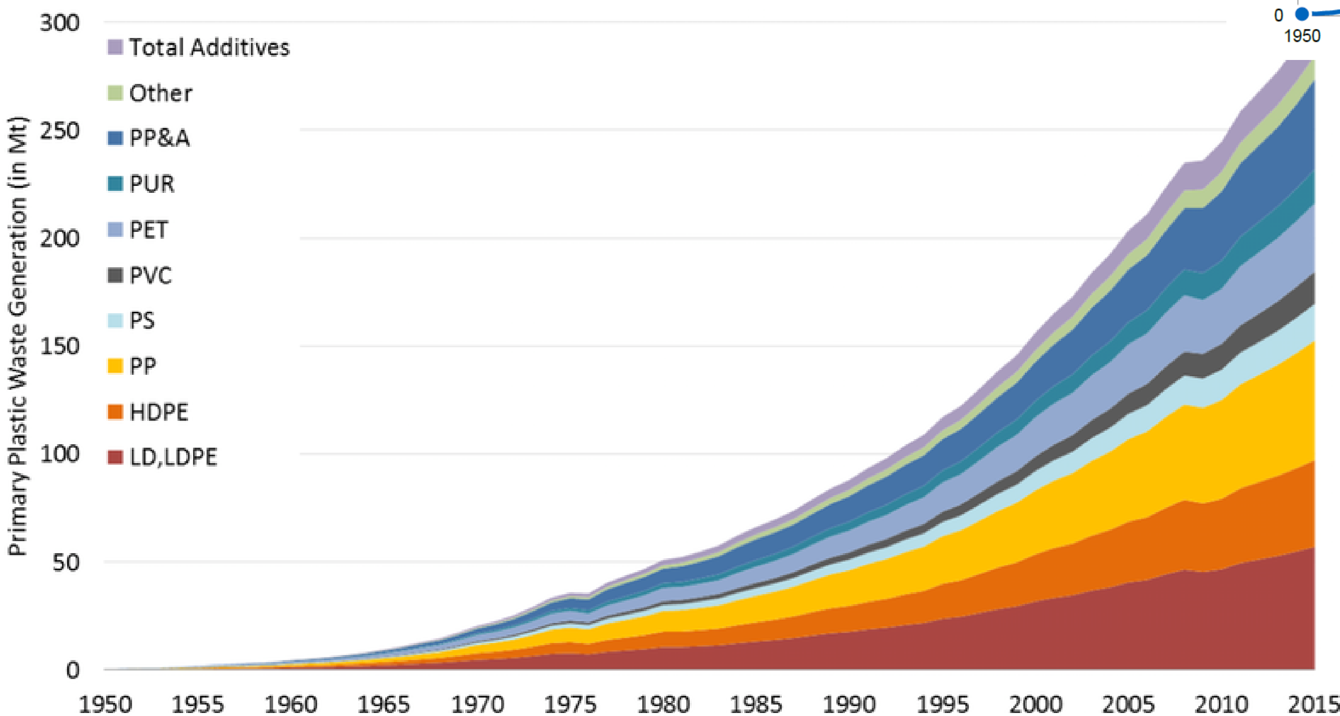
PRODUCTION: 322 million tonnes /year (2015)

WASTE GENERATION: 300 million tonnes /year (2015)

RECYCLING RATE: 9 % (2015)

World
Plastics Production 1950 – 2015





Plastics Europe (2018) Plastics – the Facts 2017

Geyer R. et al. (2017) Science Advances, 3: e1700782

Cumulative Plastic Production/Use Data

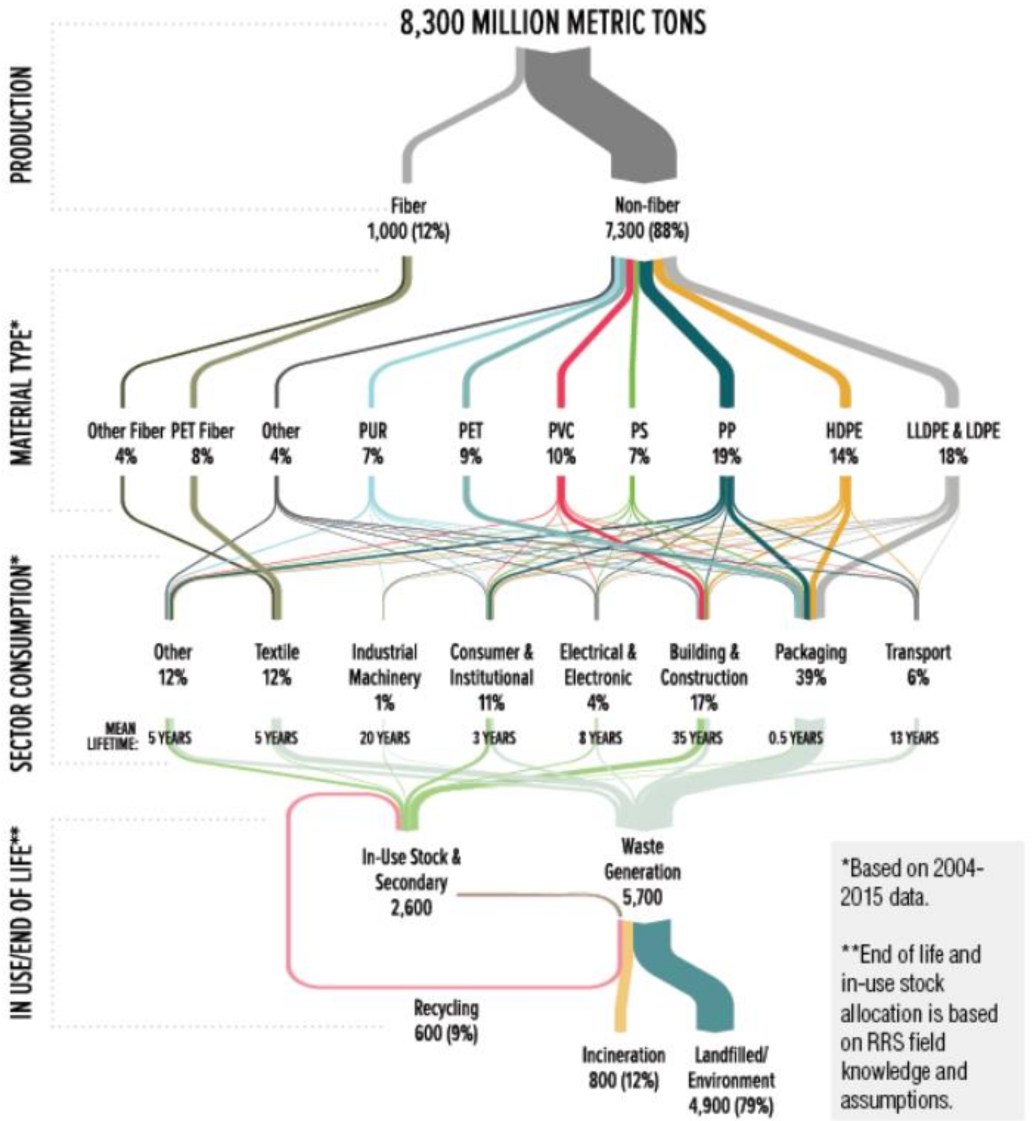
Production/Use

- 4% of petroleum (feedstocks)
- 4% of petroleum (process energy)
- Additional inputs in Natural Gas
- Non-fiber plastics (88%)
- Packaging (39%) is largest consumption sector (PE, PP, PET) with the shortest in-use lifetime (<1 yr)

End of Life

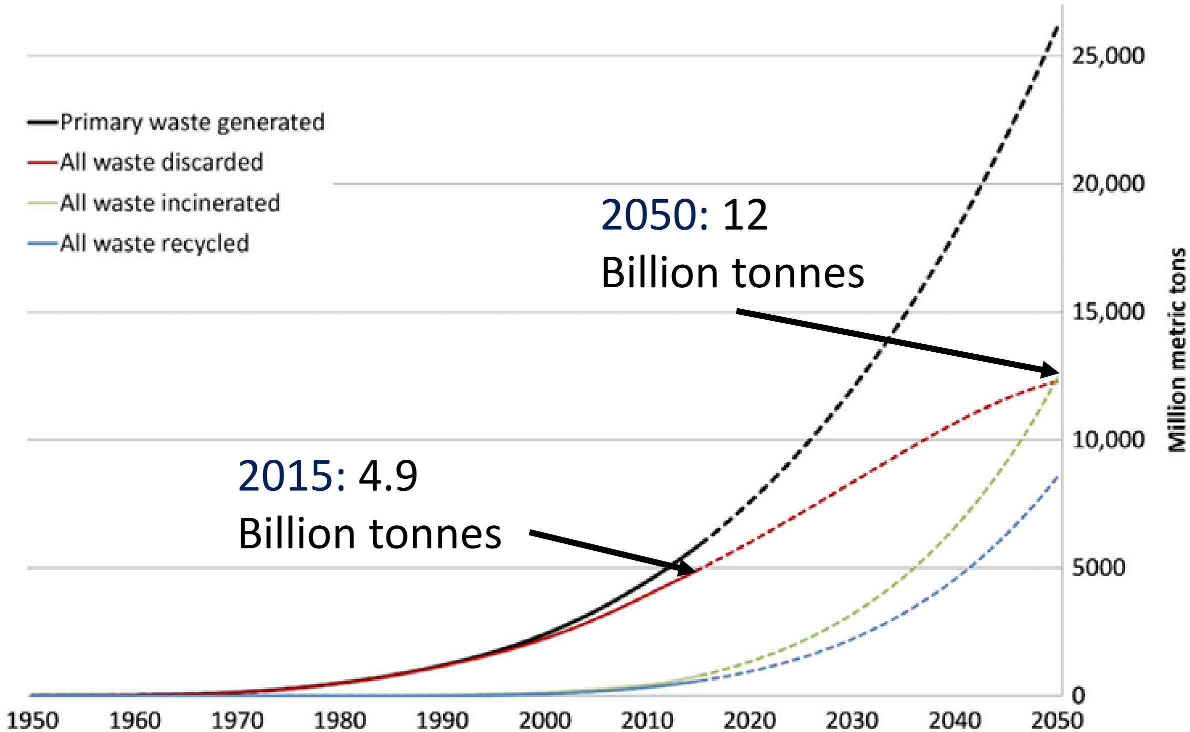
- Landfilling (79%)
- Incineration (12%)
- Recycled (9%)

RRS, Ann Arbor, MI, 2017

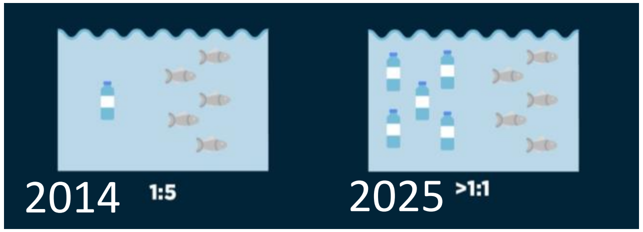


Projections to 2050

- Cumulative plastic waste generation and disposal

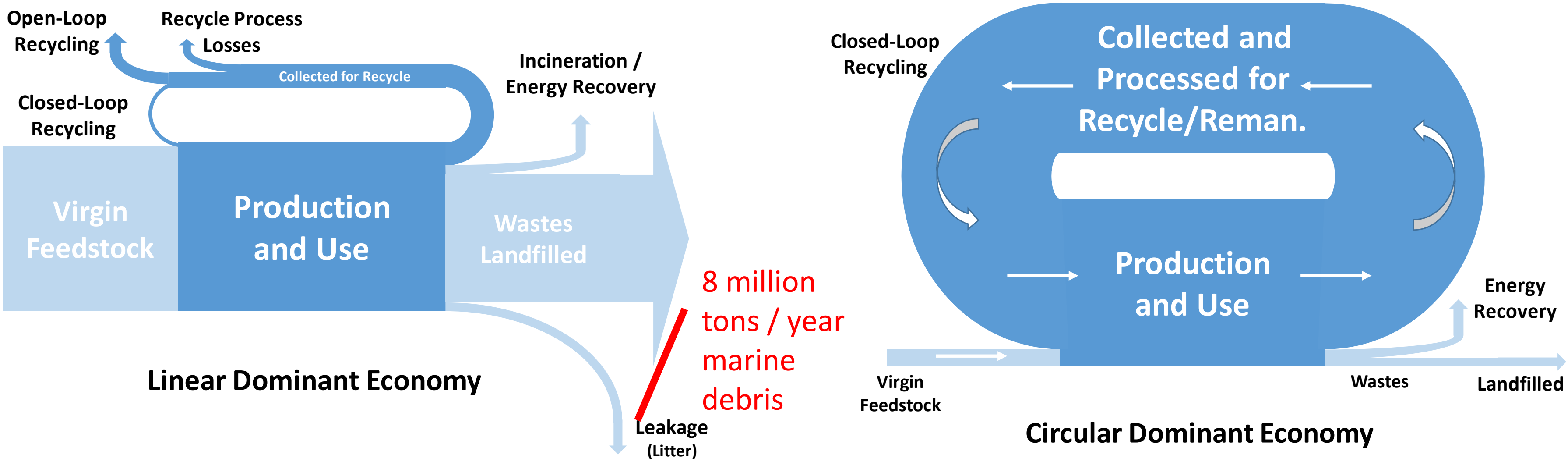


- Health risk to aquatic and terrestrial life.
- Displacing primary plastic production.
- Use of emerging technologies.



Plastics Europe (2018) Plastics – the Facts 2017
Geyer R. et al. (2017) Science Advances, 3: e1700782
World Economic Forum et al. (2016) The New Plastics Economy. Rethinking the future of plastics.

Linear vs Circular Economy for Plastics



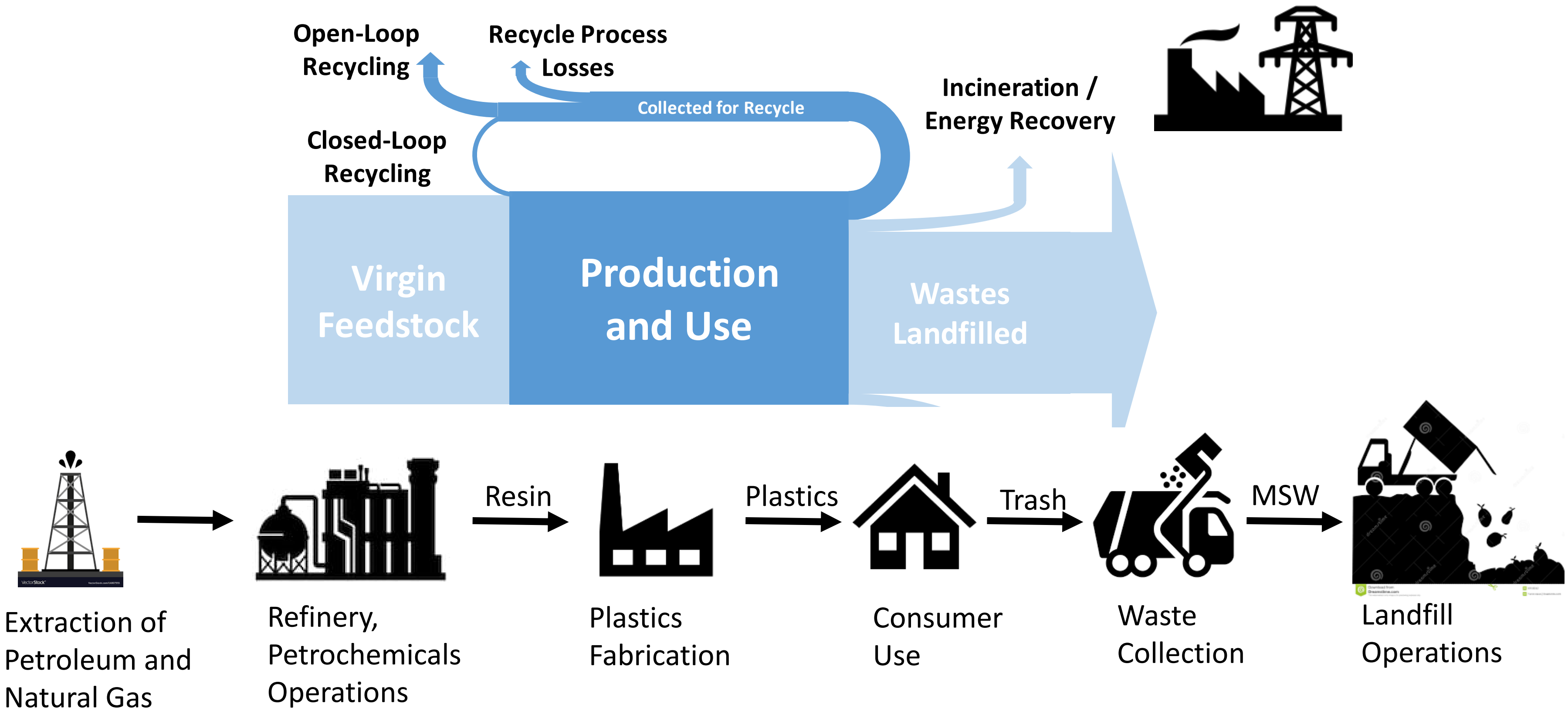
- 80% of plastics is landfilled or lost to the environment.
- Economic losses between 80 to 120 billion USD/year.
- Consumption of virgin fossil resources.

- Reduce the use of virgin materials.
- Eliminate mismanagement and leakage.
- Build up recycling infrastructure.

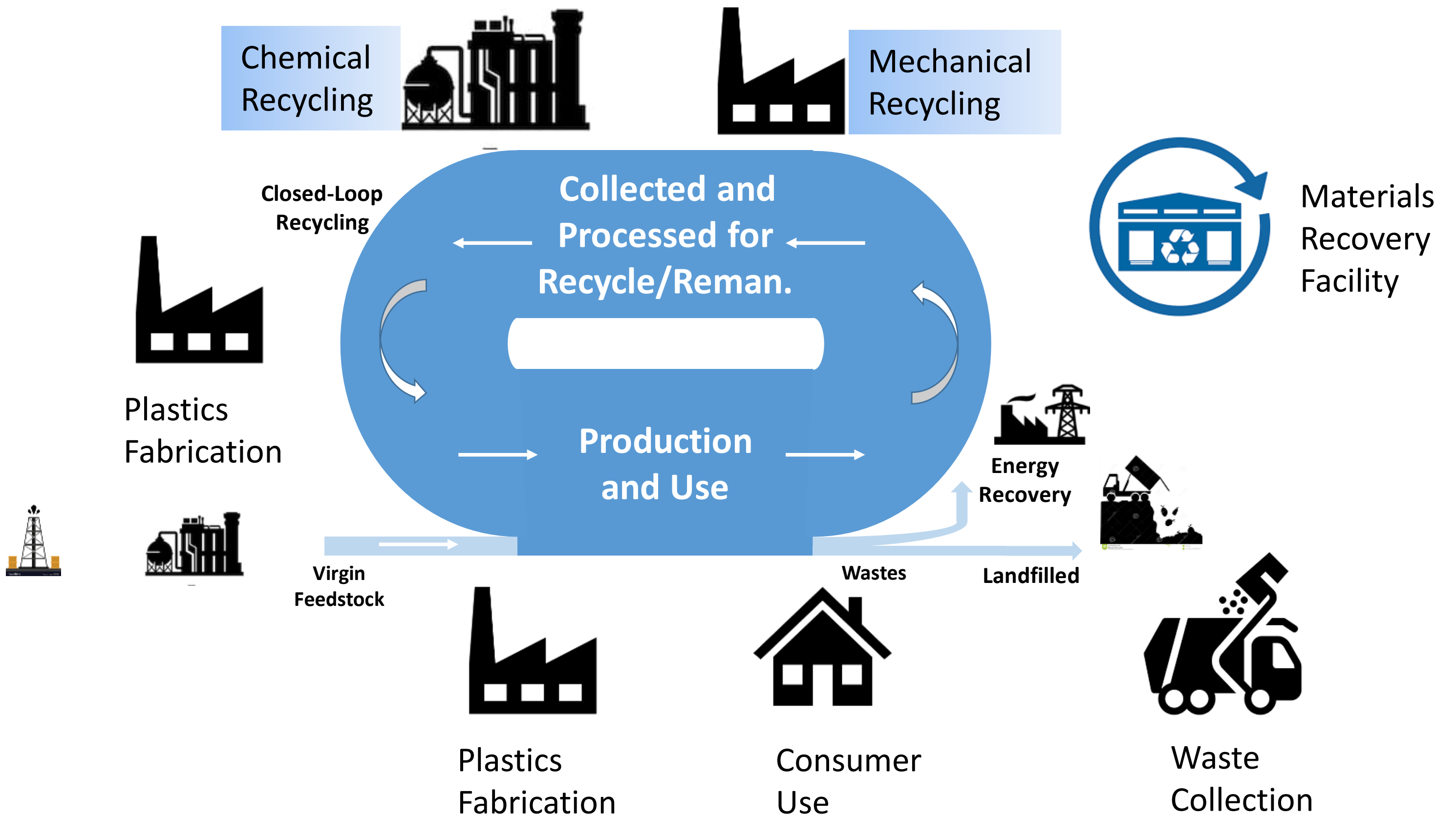
World Economic Forum et al. (2016) The New Plastics Economy. Rethinking the future of plastics.
Arena U. et al. (2011) Waste Management, 31, 1494-1504.
European Commission (2016) A European Strategy for Plastics in a Circular Economy.

Shonnard, D.R., Tipaldo, E., Thompson, V., Pearce, J., Caneba, G., Handler, R.M., 2019, Systems analysis for PET and olefin polymers in a circular economy, *Procedia CIRP*, 26th CIRP Life Cycle Engineering (LCE) Conference.

Linear Economy: Production Inputs



Circular economy: production inputs



Conceptual Design –Mass and Energy Balances

Refinery Mass Balances

Streams	Product	Amount (tonnes/hr)
INLET	Waste HDPE	20.83
	Helium	0.001
	Sulfolane	0.006
	Water	0.004
	Hydrogen	0.33
	TOTAL	**21.17**
OUTLET	Flue gas purge	1.32
	Ethylene	3.91
	Propylene	2.80
	Aromatic mixture	0.77
	Low MW HC (C4-C12)	11.25
	High MW HC (C12-C29)	1.12
	TOTAL	**21.17**

Refinery Energy Balances

Streams	Energy Source	Amount (GJ/hr)
INLET	Process Energy	223.03
	Materials Energy	931.31
	TOTAL	**1154.35**
OUTLET	Process Energy	180.78
	Products Energy	966.43
	TOTAL	**1147.20**

Conceptual Design - Results

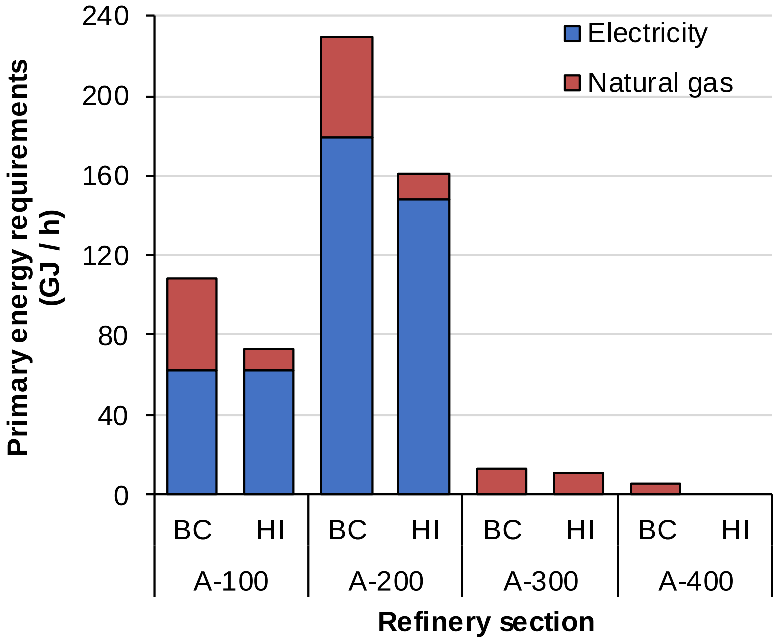
Refinery Products Specifications

Product	Recovery (%)	Purity (%)
Ethylene	89.51	97.22
Propylene	99.70	97.85
Aromatics mixture	57.15	84.27
Low MWHCs	56.10	97.74
High MWHCs	76.43	83.33

Energy Returned over Invested (EROI)

Base Case (BC): 2.2
Heat Integrated (HI): 3.0
Petroleum Refining: 9

Primary Energy Requirements



Primary Energy Savings

HI vs BC: 35% reduction

TEA Methods

Parameters for Discounted Cash Flow Analysis

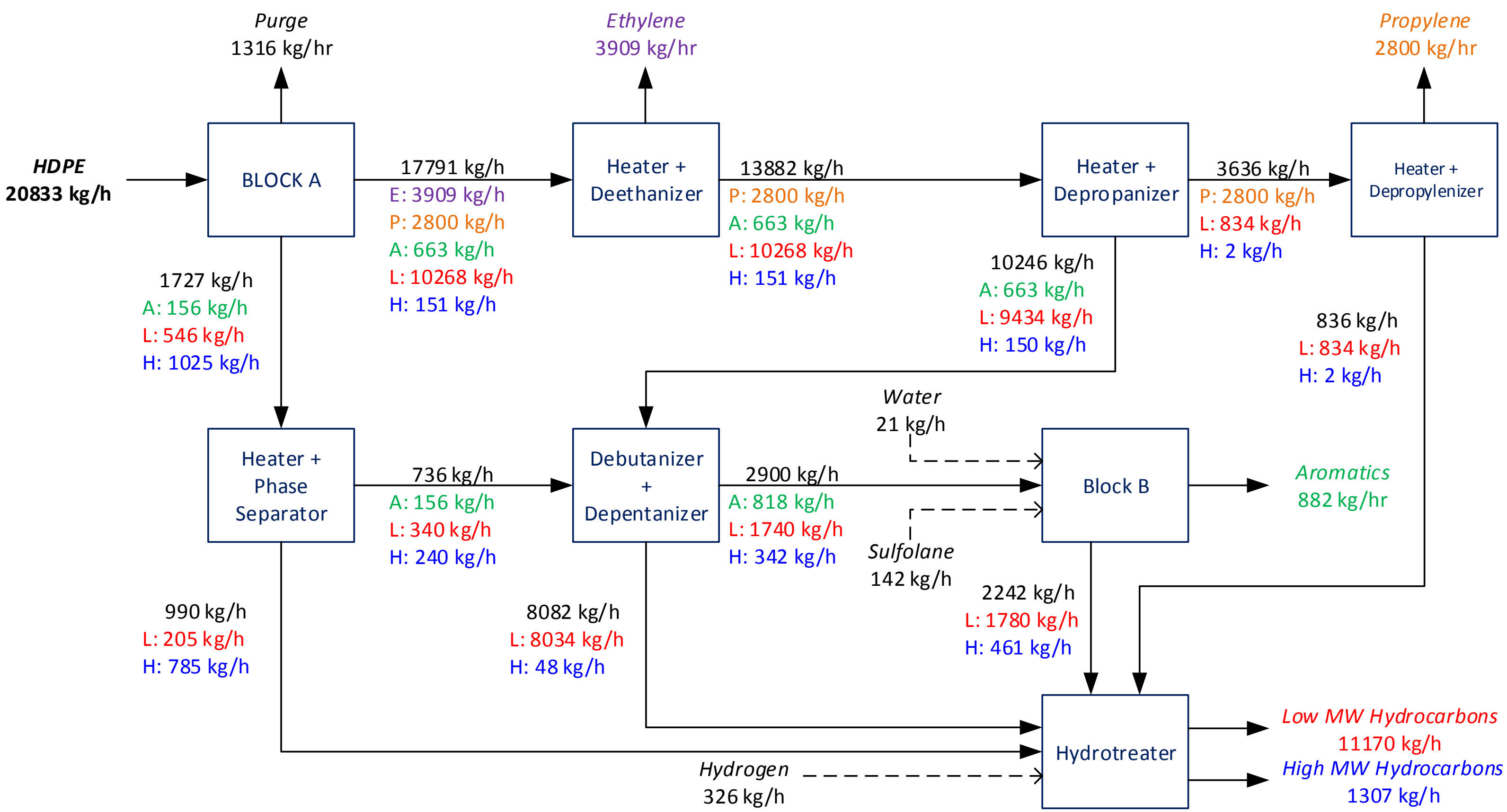
Parameter	Value
Internal rate of return (%)	10
Project economic life (years)	20
Depreciation method	7-year MACRS
Tax rate (%)	21
Working capital (WC)	15% FCI
Base year	2017
Operating days per year	350
Investment year 1	30% FCI
Investment year 2	50% FCI
Investment year 3	20% FCI + WC + FOC + 50% VOC
Investment year 4	FOC + 90% VOC
Investment year 5	FOC + VOC

Prices for Discounted Cash Flow Analysis

Product	**Price**
Waste HDPE (USD/tonne)	22.0
Electricity (USD/kWh)	0.069
Natural gas (USD/GJ)	3.95
Cooling water (USD/m^3)	0.053
Hydrogen (USD/kg)	2.83
Helium (USD/kg)	42.81
Ethylene (USD/kg)	0.61
Propylene (USD/kg)	0.97
Aromatics mixture (USD/kg)	1.02
Low MWHC mixture (USD/kg)	0.86
High MWHC mixture (USD/kg)	0.84
LP steam (USD/kg)	0.021

Results – Environmental evaluation

- Multi-product mass allocation

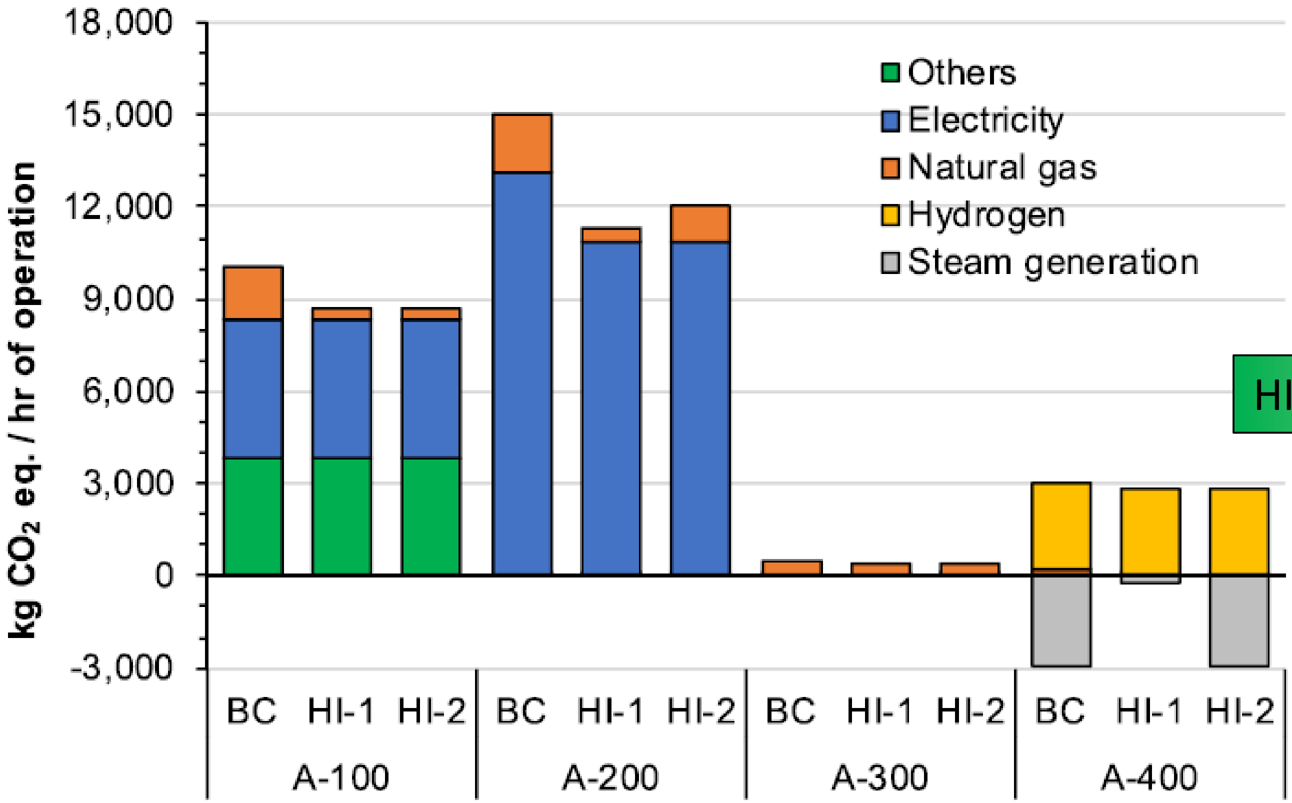


E: Ethylene product, **P**: Propylene product, **A**: Aromatics mixture product, **L**: Low MW HC mixture product, **H**: High MW HC mixture product

- Allocation was product-based, therefore, trace amounts of different chemical species included in a particular product were also included on its allocation factors.

Results – Environmental evaluation

- Carbon Footprint: Process Sections



GHG Savings

HI-2 vs BC: **18% reduction**