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U.S. DEPARTMENT OF ENERGY

Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment

Techno-Economic Analysis and Life Cycle Assessment for Pyrolysis of Mixed Waste Plastics

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Pyrolysis of Mixed Plastic Waste

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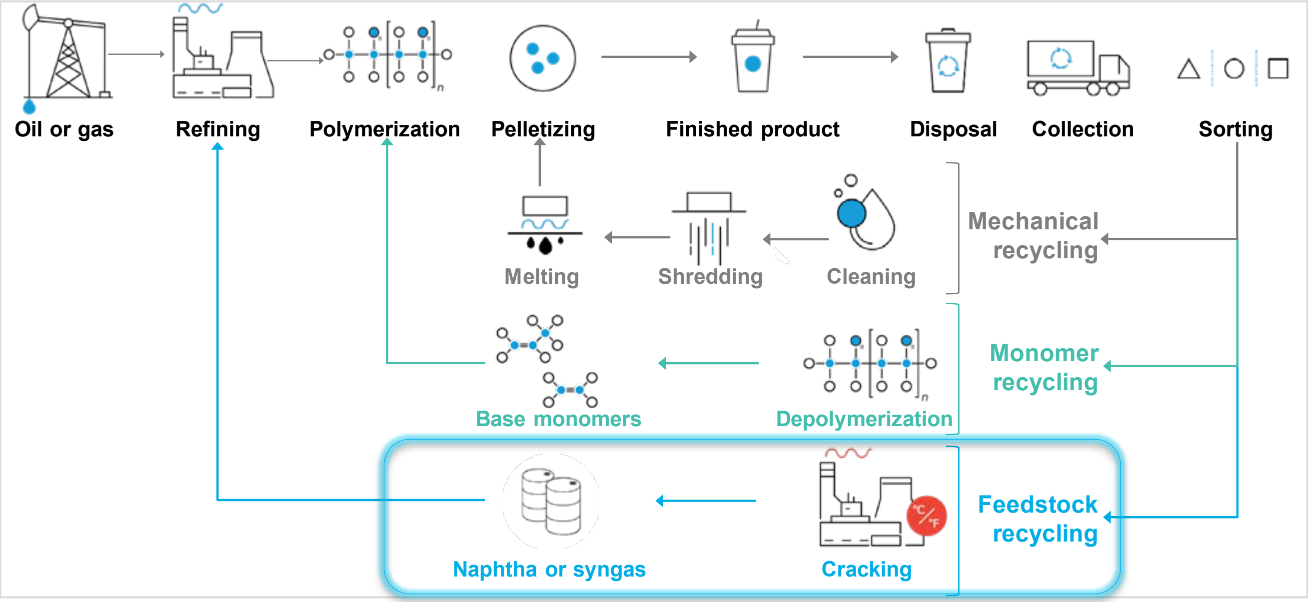
Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE™)

- Polymer recycling & upcycling technologies require accurate baselines.
  - Pyrolysis is thermochemical decomposition of materials at elevated temperature and **in the absence of O_2**
- Mixed plastic wastes[1]
  - Low-value, contaminated, expensive
- Pyrolysis is one of the most promising technologies
  - high feedstock flexibility
  - hard to recycle plastics (upto 20% contamination)
  - modular design

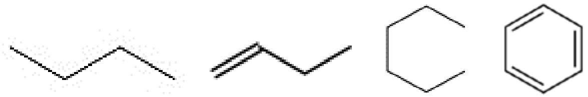


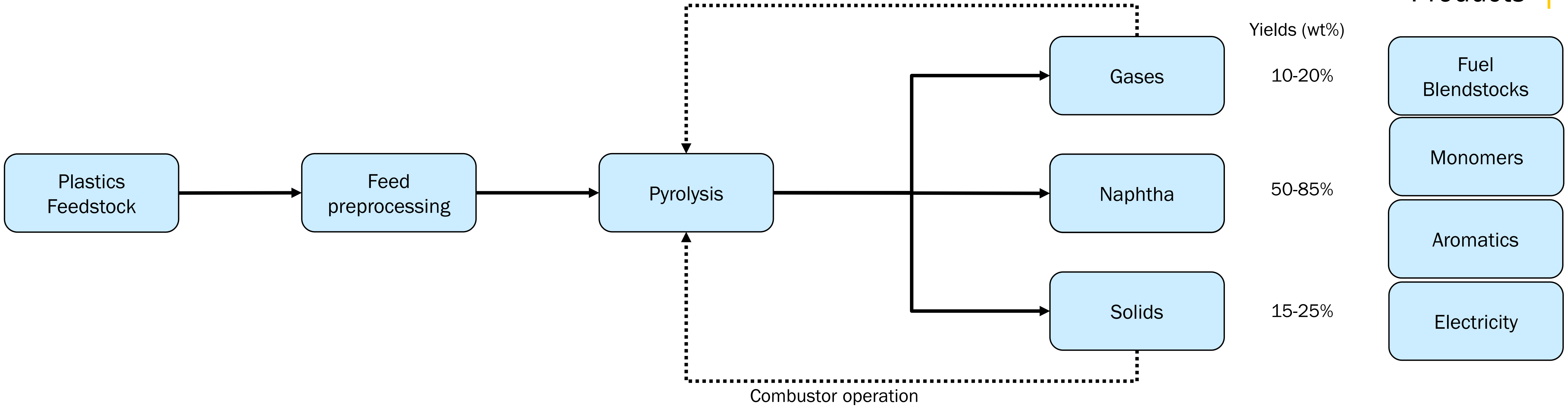
Major Industry Players

Source:
1. Bloomberg NEF (2019). Chemical Recycling (Figure)

Pyrolysis Naphtha

Global demand of light naphtha : 378 MMtpa



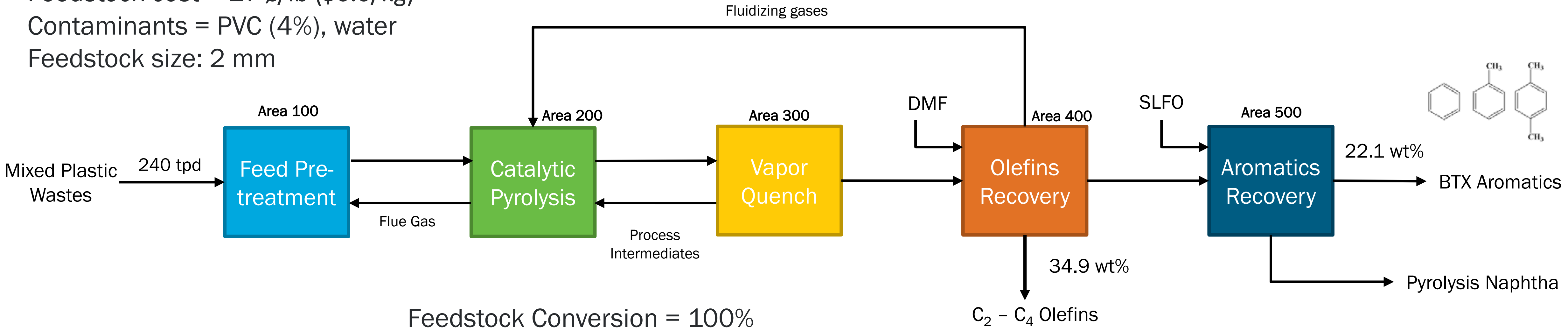


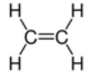
With the advancements in catalyst research and selection of appropriate reactor geometry, these yields can be tailored to produce desired products

Base Case Pyrolysis Model – Block Flow Diagram

Plant Size = 240 tpd*
Feedstock = Mixed Plastic Wastes
Composition = >75% polyolefins
Feedstock cost = 27 ¢/lb ($0.6/kg)
Contaminants = PVC (4%), water
Feedstock size: 2 mm

Low-Temperature separation
Overall Olefin's Recovery = 91%
Overall NGL's** Recovery = 85%

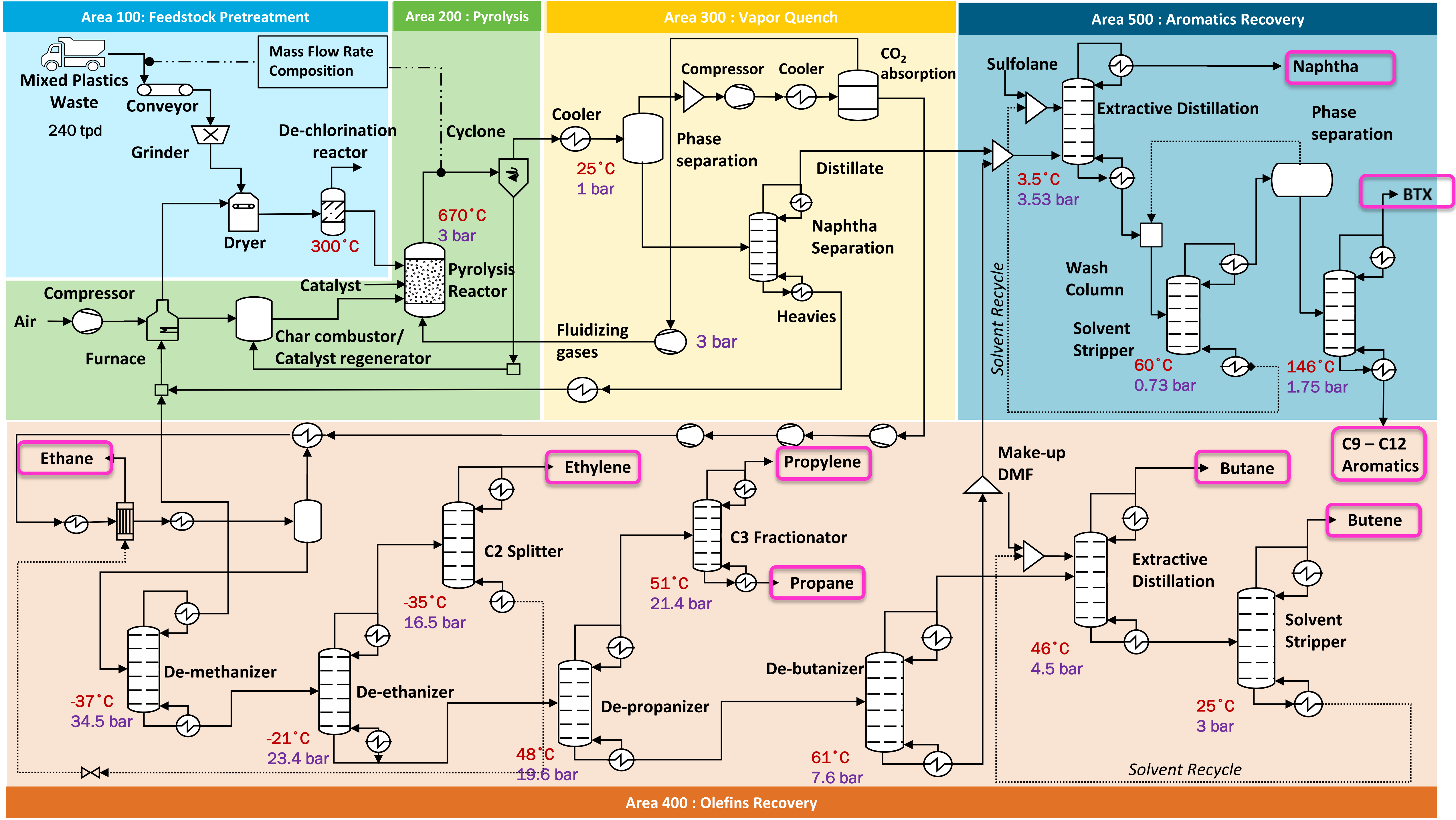




Feedstock Conversion = 100%
Temperature = 670˚C
Pressure = 3 bar
Residence time = 2 s
Catalyst to Feed ratio = 6
Catalyst Cost = $2.98/kg

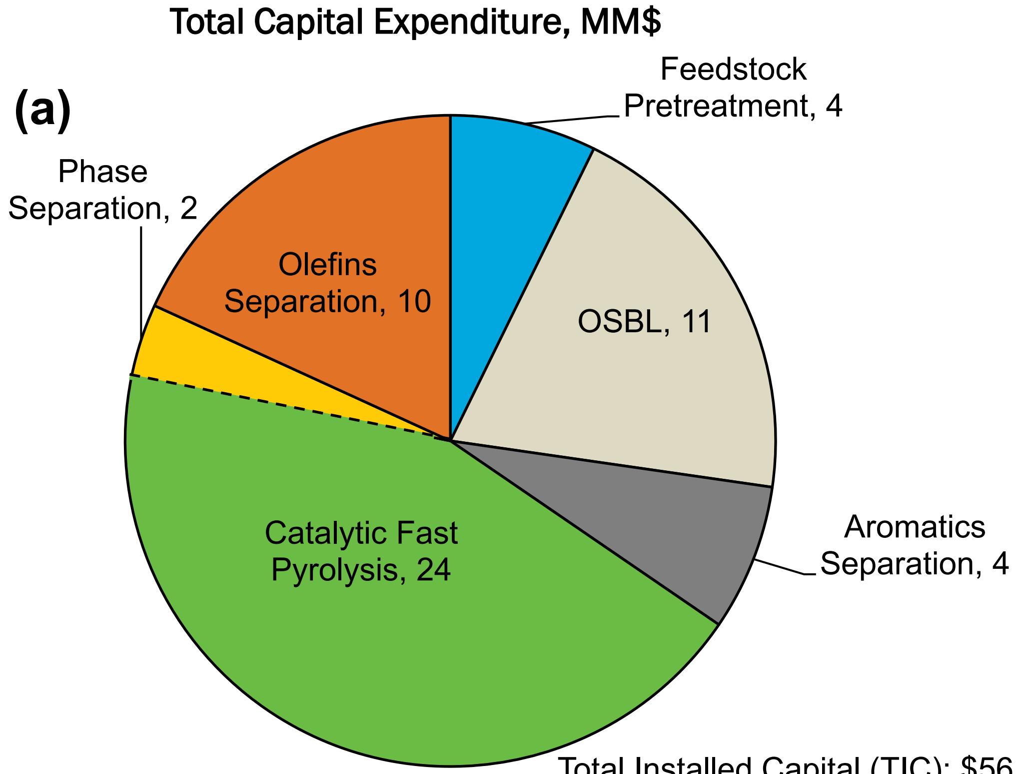
Overall Recovery, BTX = 90%
Olefins Co–Product Credit = 148 ¢/lb
NGL Co–Product Credit = 11 ¢/lb
C9 – C12 Co–Product Credit = 33 ¢/lb
Naphtha Co–Product Credit = 50 ¢/lb
Product: BTX Aromatics = 48 tpd

* tpd = (metric) tonnes per day
**NGLs = Natural Gas Liquids

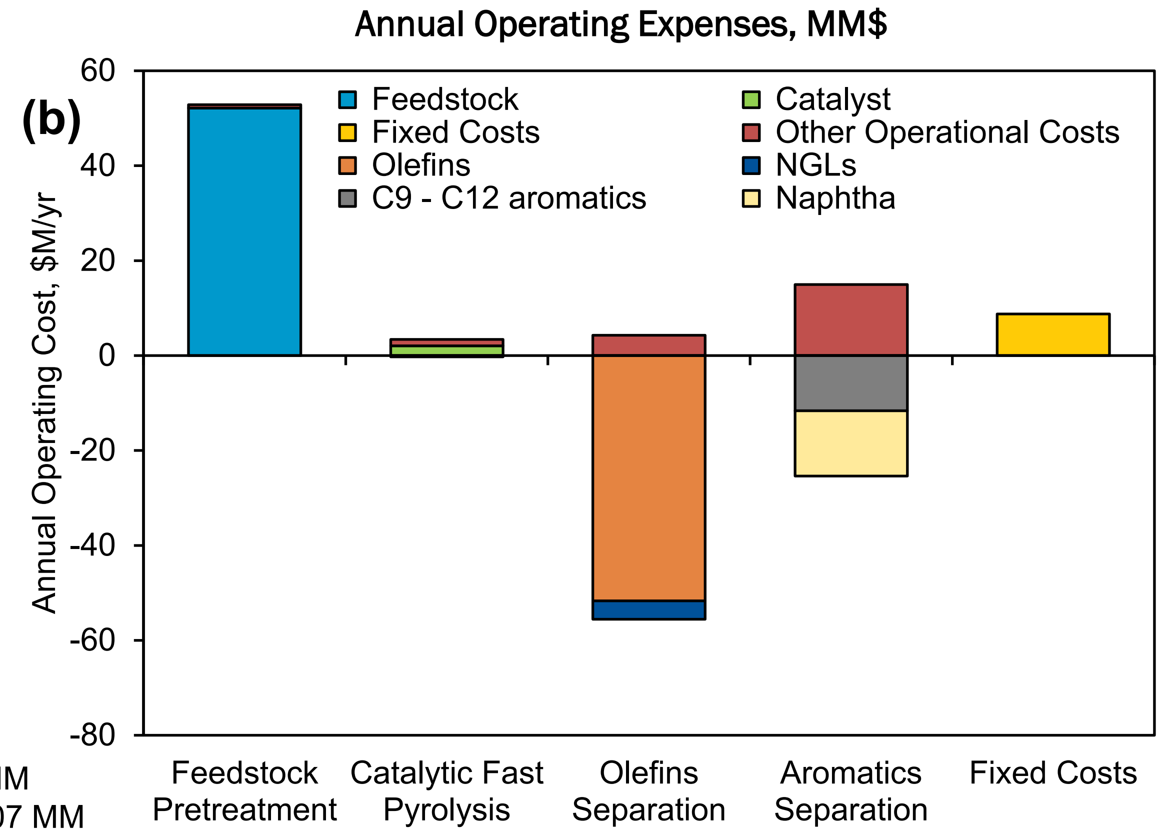


Area 100: Feedstock Pretreatment
Area 200 : Pyrolysis
Area 300 : Vapor Quench
Area 500 : Aromatics Recovery
Mixed Plastics Waste
240 tpd
Conveyor
Grinder
Mass Flow Rate Composition
De-chlorination reactor
Dryer
300˚C
Cyclone
670˚C
3 bar
Pyrolysis Reactor
Catalyst
Compressor
Air
Furnace
Char combustor/ Catalyst regenerator
Cooler
25˚C
1 bar
Compressor
Cooler
CO2 absorption
Phase separation
Distillate
Naphtha Separation
Heavies
Fluidizing gases
3 bar
Sulfolane
Naphtha
Extractive Distillation
Phase separation
3.5˚C
3.53 bar
BTX
Wash Column
Solvent Stripper
Solvent Recycle
60˚C
0.73 bar
146˚C
1.75 bar
C9 – C12 Aromatics
Ethane
Ethylene
Propylene
Make-up DMF
Butane
Butene
C2 Splitter
C3 Fractionator
Propane
-35˚C
16.5 bar
51˚C
21.4 bar
Extractive Distillation
De-methanizer
-37˚C
34.5 bar
De-ethanizer
-21˚C
23.4 bar
De-propanizer
48˚C
19.6 bar
De-butanizer
61˚C
7.6 bar
46˚C
4.5 bar
Solvent Stripper
25˚C
3 bar
Solvent Recycle
Area 400 : Olefins Recovery

Base Case Capital and Operating Expenses

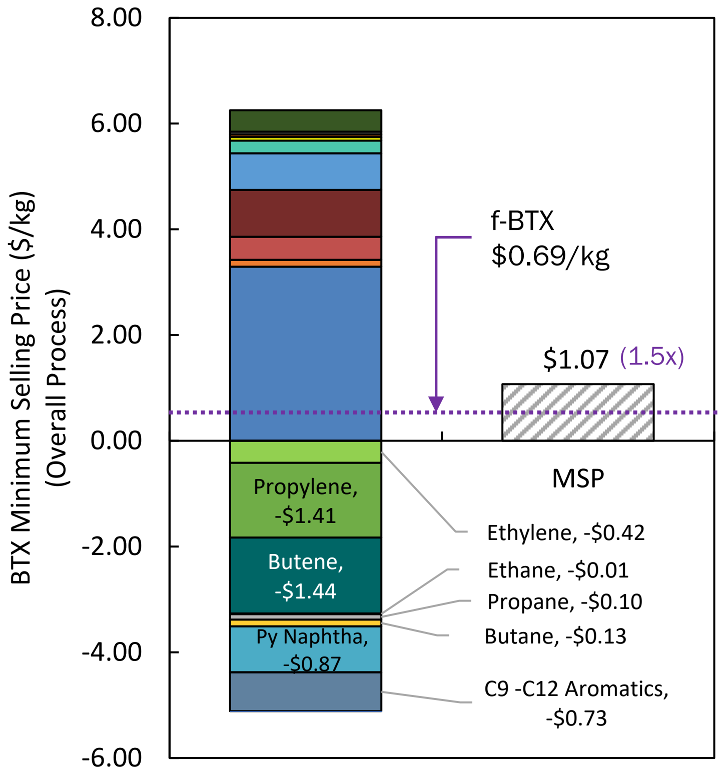


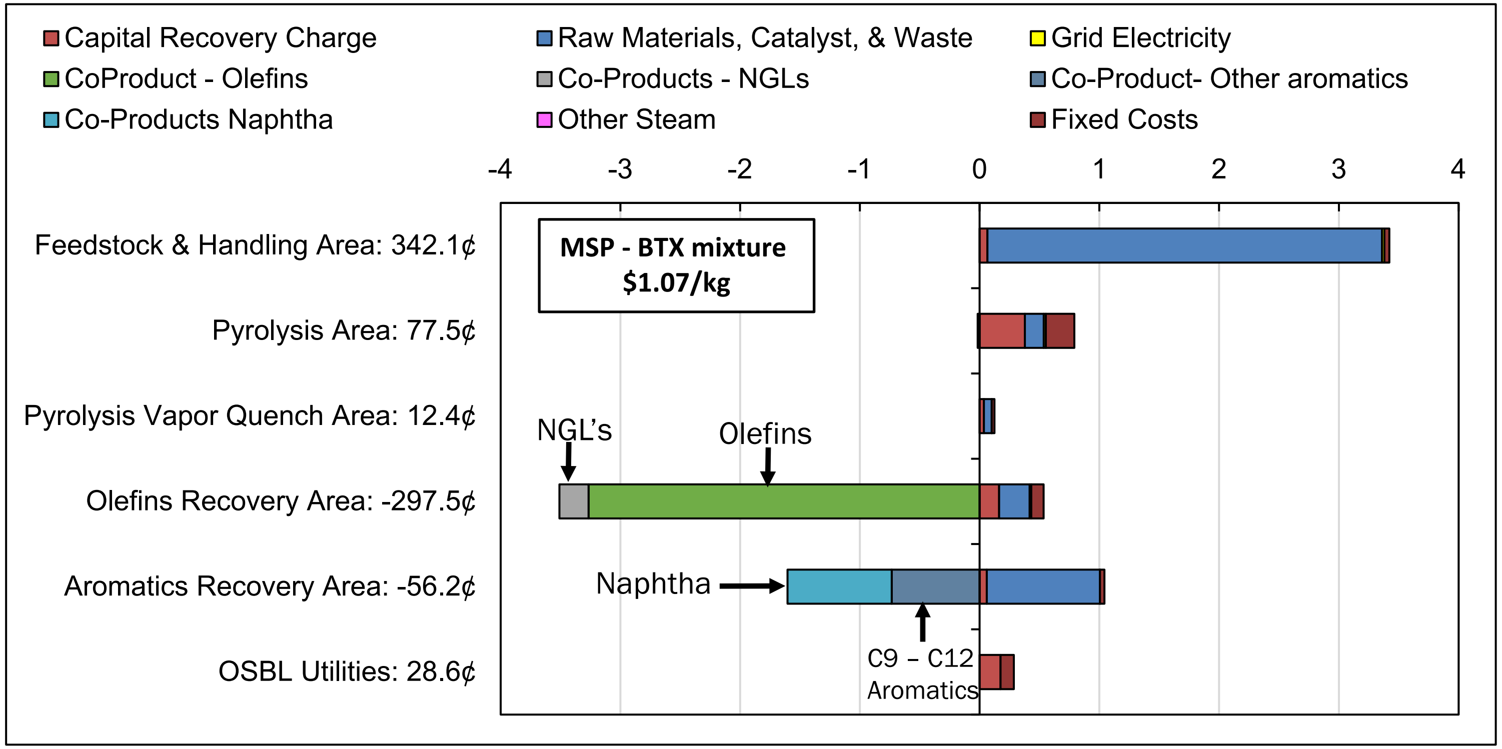
Total Installed Capital (TIC): $56 MM
Total Capital Investment (TCI): $107 MM



- Total base case capital expenditures of $56 MM
  - Catalytic Pyrolysis has the highest contribution with only reactors contributing $14 MM
  - Includes up to $10 MM in Olefins separation due to distillation columns costs operating at low temp & high pres.
- Annual operating cost of $89 MM/yr
  - Feedstock costs is the major cost driver

Base Case Minimum Selling Price (MSP)

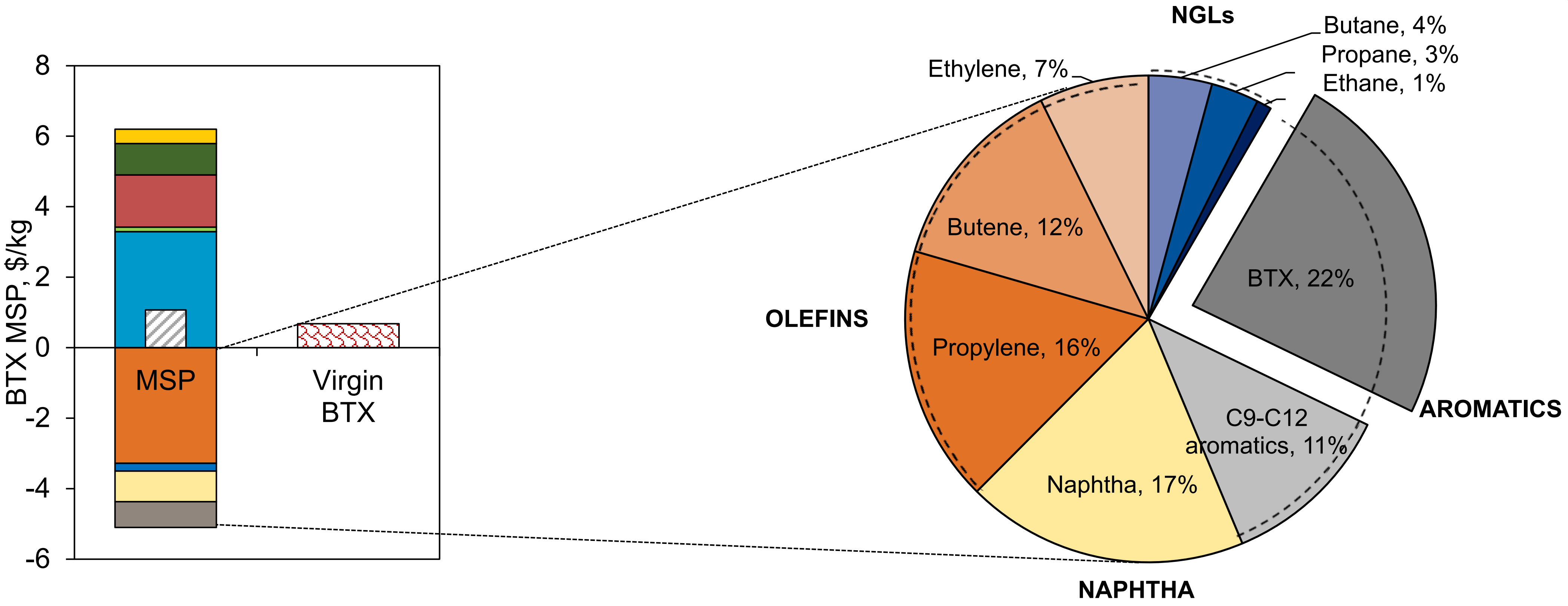




- Overall MSP of $1.07/kg of BTX aromatics.
  - Current market price of fossil-BTX price range from $0.69/kg[1].
- Higher feedstock costs of the mixed plastic waste is offset by coproduct credits.
- Higher cost in Aromatics recovery area is due to the cost of sulfolane solvent.

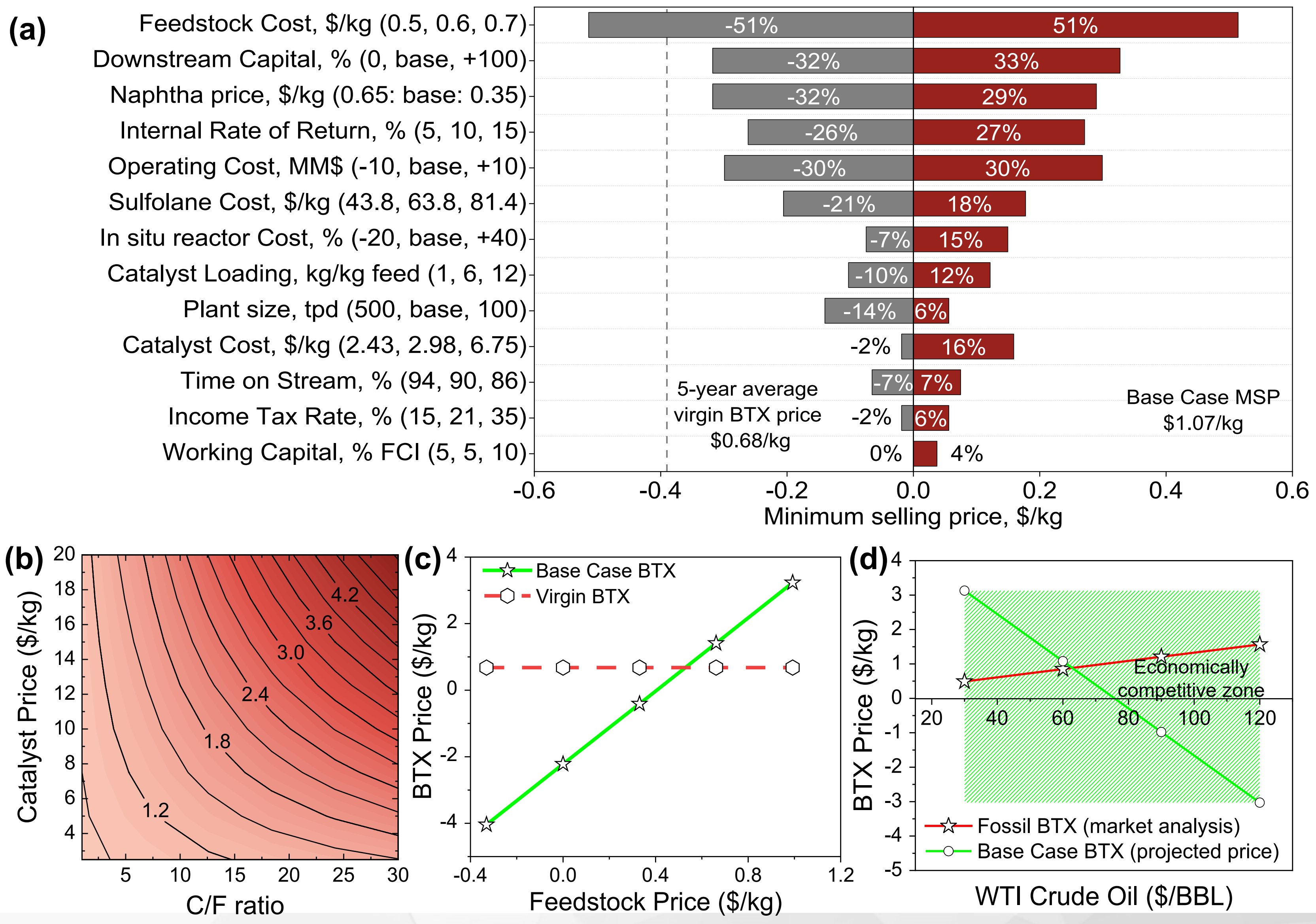
Source:
1. Internal Industry Database (5-year average price).

Products & Co-Products Yields



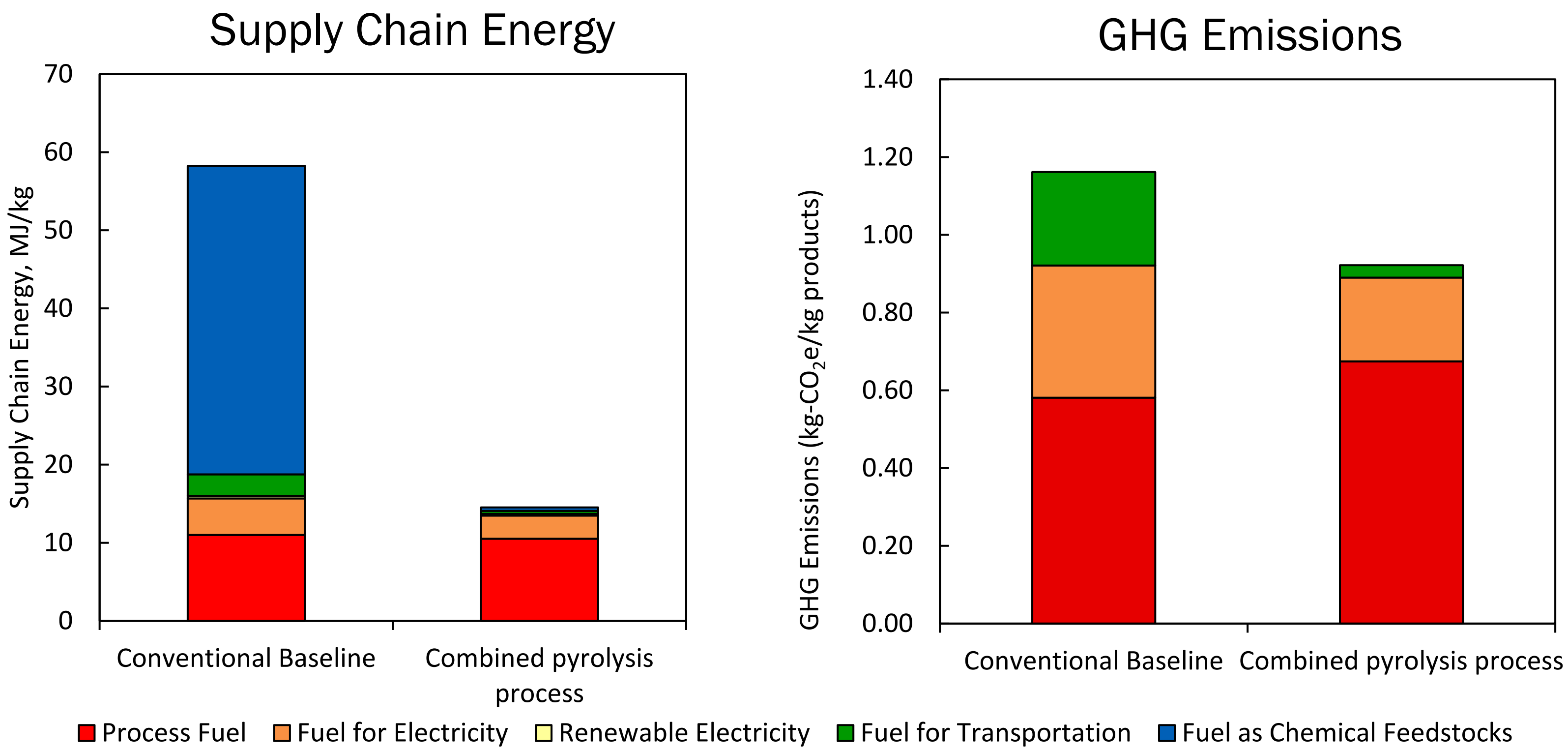
- With a 90% overall recovery BTX aromatics, the process also co-produces olefins, NGLs, naphtha and other aromatics.
- Process intermediates – Coke (~3%) and heavies (bp > 270˚C), are utilized within the pyrolysis plant.

Sensitivity Analysis



*Values in the middle represents conditions assumed in the base case scenario

LCA Results: Materials Flows through Industry (MFI)



- Base case shows a 75% reduction in supply chain energy and 21% reduction in GHG emissions due to the use of waste plastics as feedstock compared to the conventional baseline.
- The base case process fuel requirement is comparable to the conventional baseline.
- Also, fuel for electricity is lower in the base case due to efficient process heat integration, especially in the pyrolysis and olefins recovery section.

Process results generated by Scott Nicholson with NREL's Material Flows through Industry (MFI) tool available at https://mfitool.nrel.gov/

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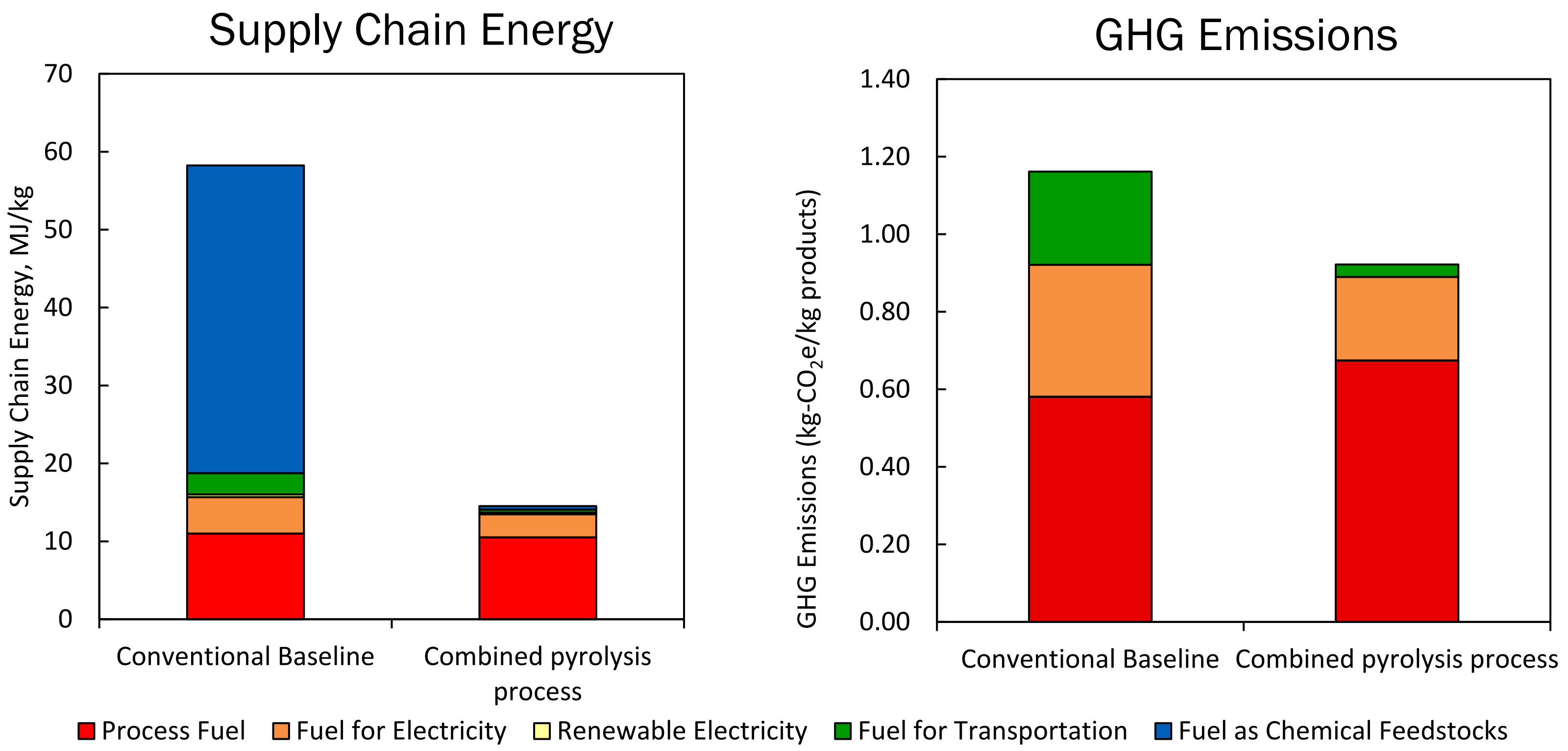

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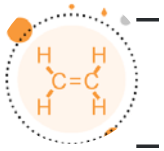
Case Studies

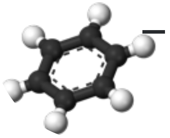
Two scenarios were evaluated

- High Olefins[1]



  - Olefins were increased to 64 wt% (tradeoff with aromatics)
  - Catalyst to Feed ratio of 28

- High Aromatics[2]



  - Aromatics were increased to 60 wt% (trade-off with olefins)
  - Catalyst to Feed ratio of 4

Percent composition	Scenarios		
	Base Case	High Olefins	High Aromatics
Total Olefins Yield	34.9%	64%	16%
Total Aromatics Yield	32.7%	11%	60%

Depending on the severity of operations in the pyrolysis reactor as well as choice of catalyst, the yields of light olefins and aromatics are tunable

Source:

1. SABIC Global Technologies B.V. (2020) US Patent 10,975,313.
2. Anellotech, Inc. US Patent (2020) 10,822,562.

Case Studies – High Olefins

Case - 1

Percent composition	Scenarios		
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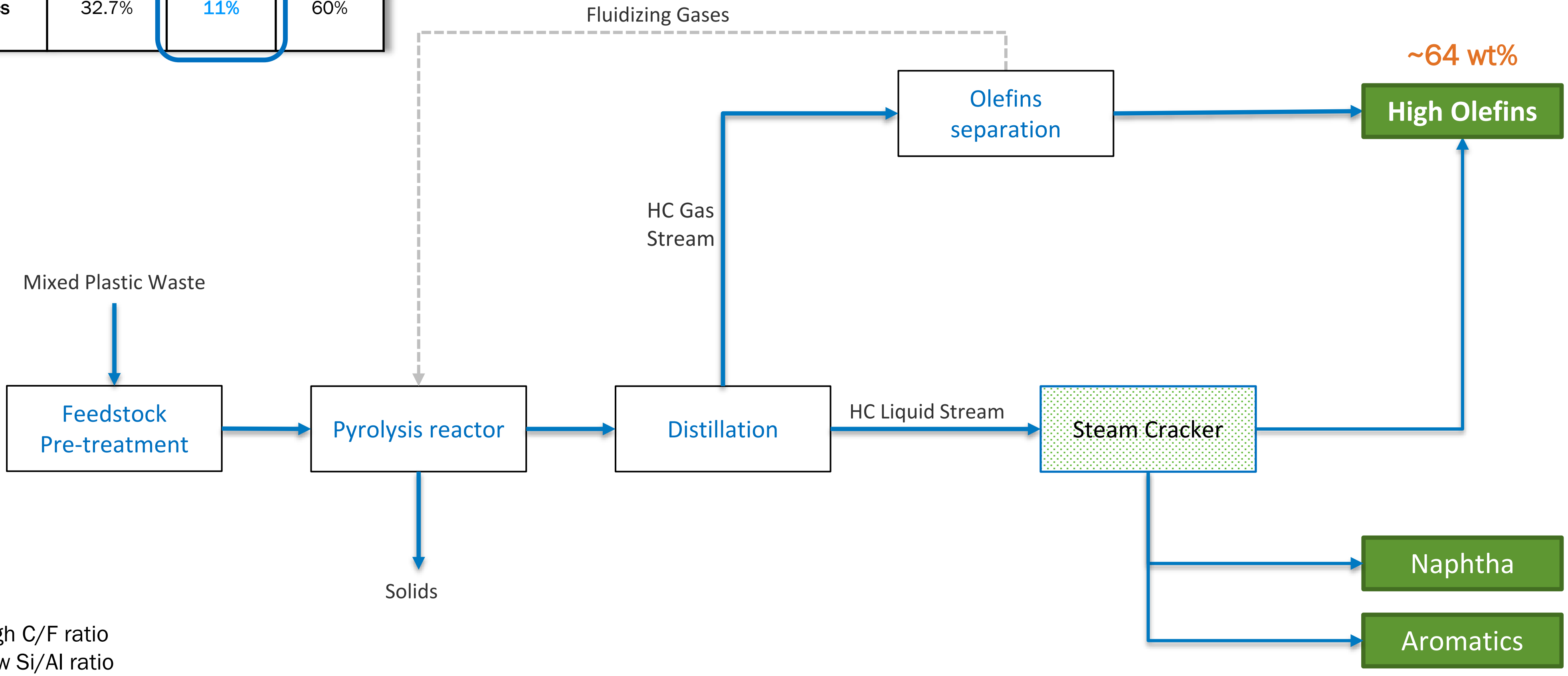
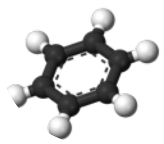
Total Aromatics Yield	32.7%	11%	60%



- High C/F ratio
- Low Si/Al ratio
- High mass norm. space vel. = 10 per hr.

Case Studies – High Aromatics

Case - 2



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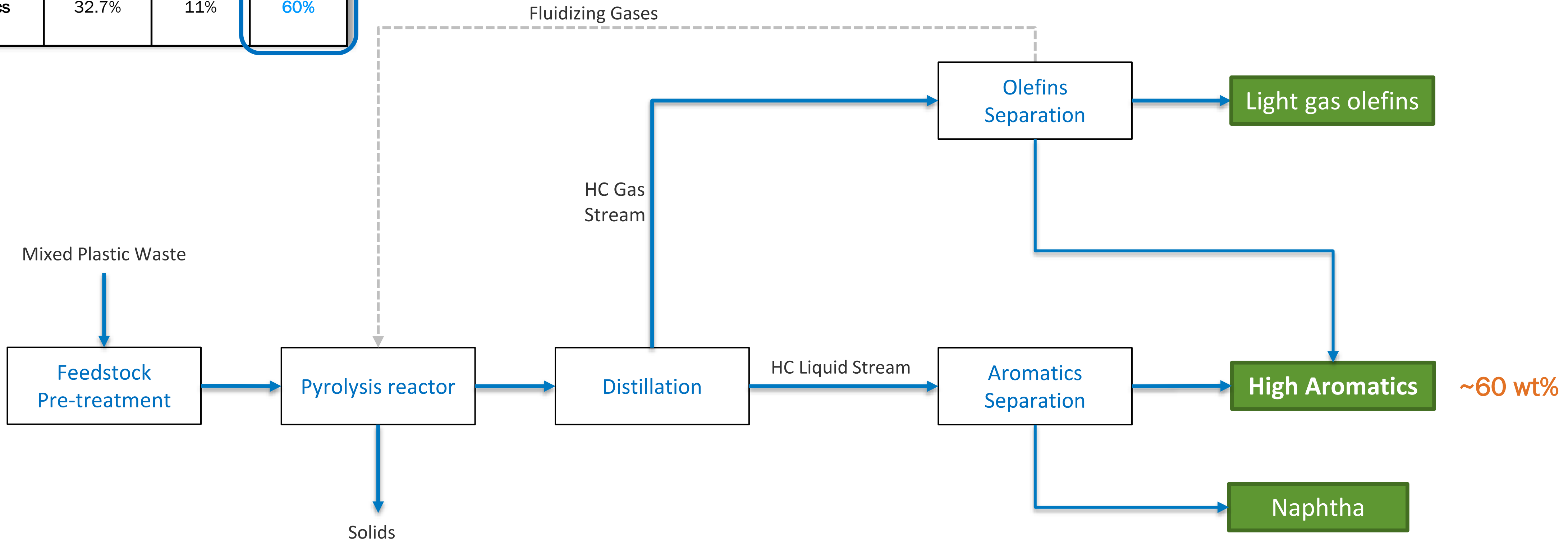
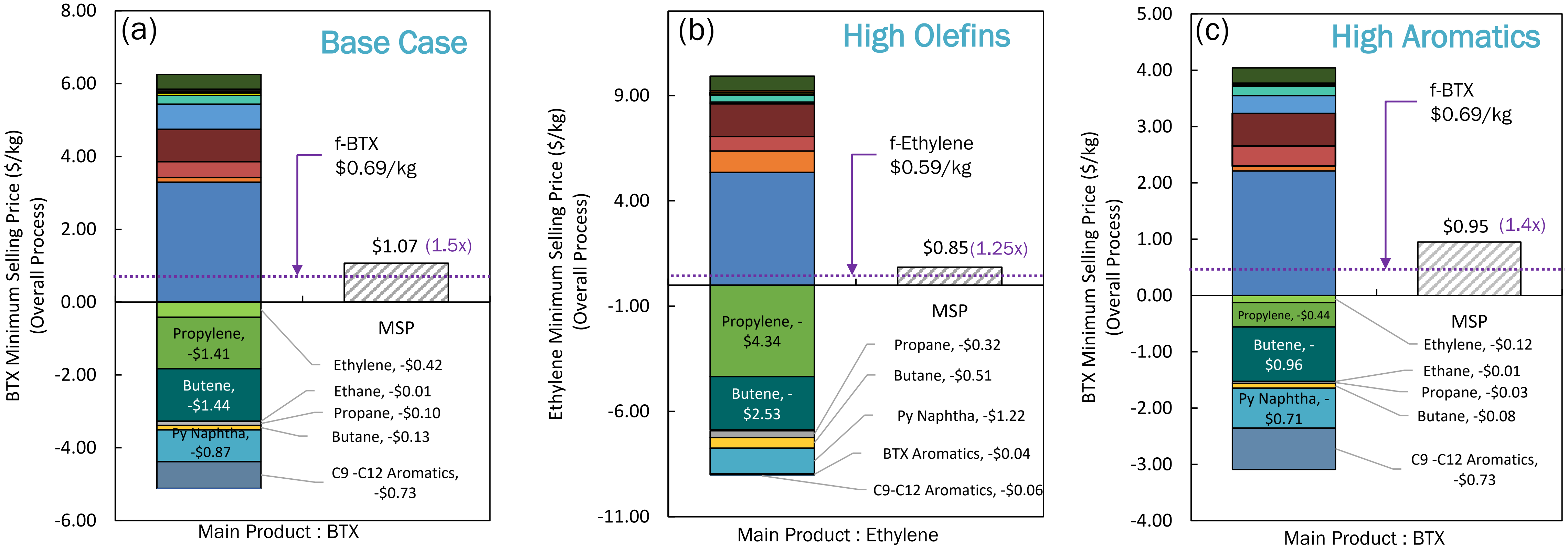


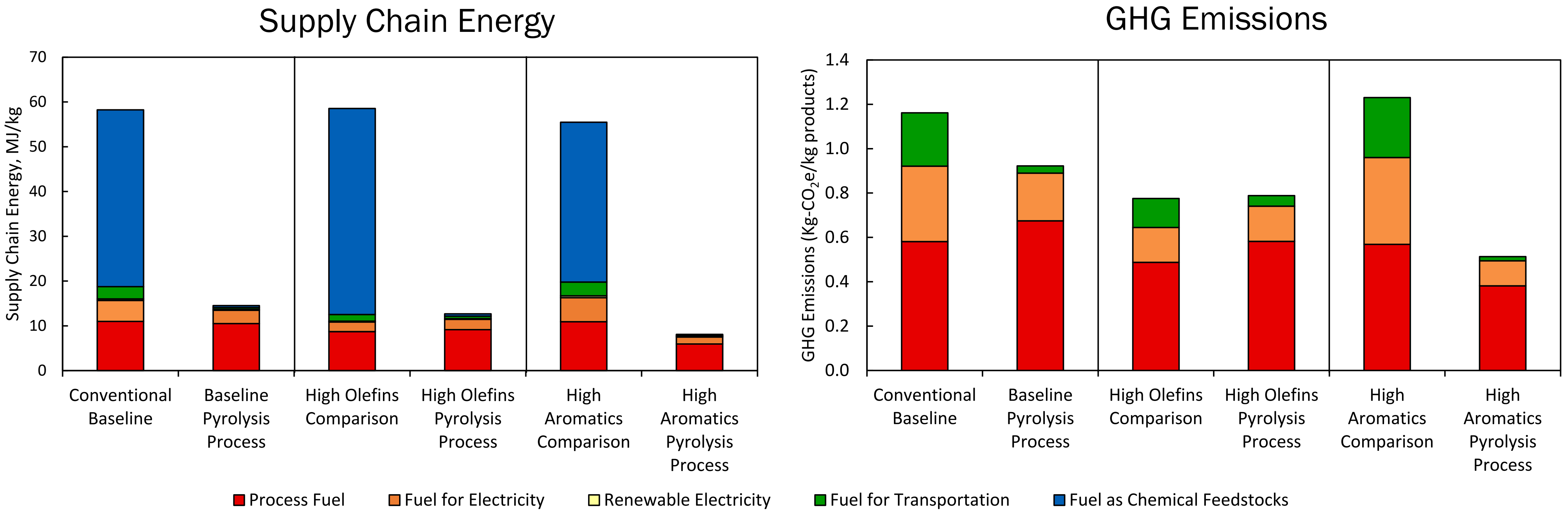
- Low C/F ratio
- High residence time
- High Si/Al ratio
- Low mass norm. space vel. = 1 per hr.

Case studies – MSP Results



	Base Case	High Olefins	High Aromatics
Olefins (wt %)	34.9%	64%	16%
Aromatics (wt %)	32.7%	11%	60%
Co-Product revenue (MM$)	81	88	73
Product (MM kg/yr)	16	10	23

MFI: Base Case vs. High Olefins and High Aromatics



- Supply chain energy in the case of High Olefins and High aromatics case shows a 79% and 85% reduction, respectively.
- GHG emissions in the case of High olefins shows an increment of 2% whereas it is a 58% reduction in High Aromatics case.
- Use of waste plastics as feedstock greatly helps in minimizing the environmental impacts associated with supply chain and GHG emissions due to the avoided emissions from extraction.

Process results generated by Scott Nicholson with NREL's Material Flows through Industry (MFI) tool available at https://mfitool.nrel.gov/

Discussion

- A process was developed to treat 240 tpd of mixed plastics waste
  - Annual production of 15.5 MM kg/yr of BTX aromatics
- Minimum selling price (MSP) of BTX was $1.07/kg, which is 1.5x higher than its fossil-derived counterpart
  - Feedstock costs, co-products costs, and downstream capital are the major cost drivers.
- The process benefits from the sale of multiple co-products
- Advancements in the areas of reactor design and catalysis can drive the necessary change for large-scale implementation

Future scope

- Opportunities for process optimization
  - Heat integration to minimize overall plant costs.
  - Employment of green chemicals and renewable electricity for minimizing environmental impacts.
  - Development of a robust BTX separation scheme

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Thank you!

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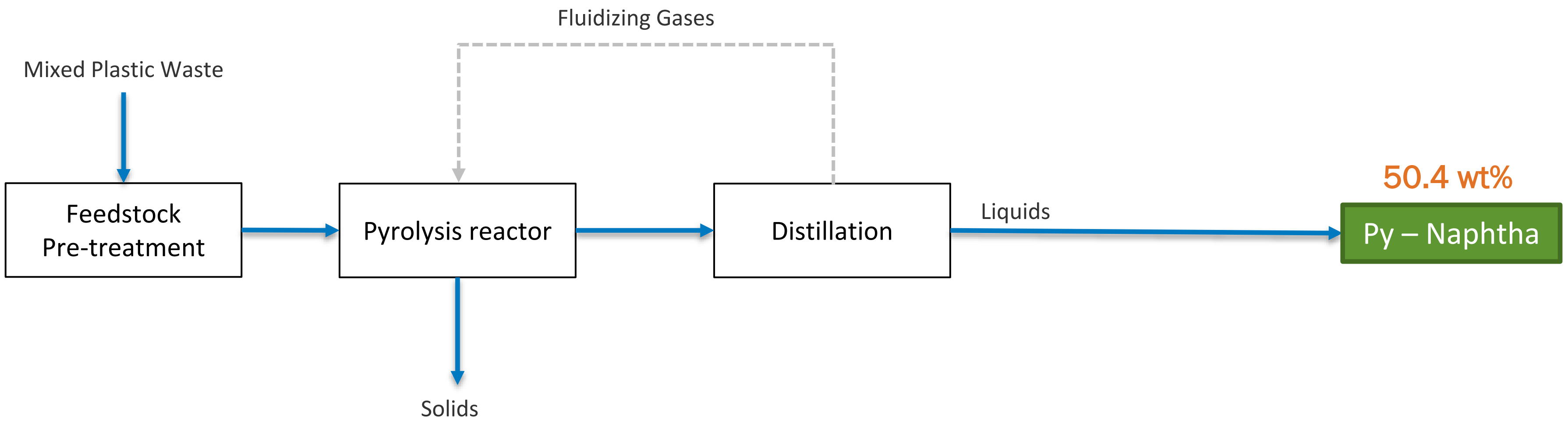
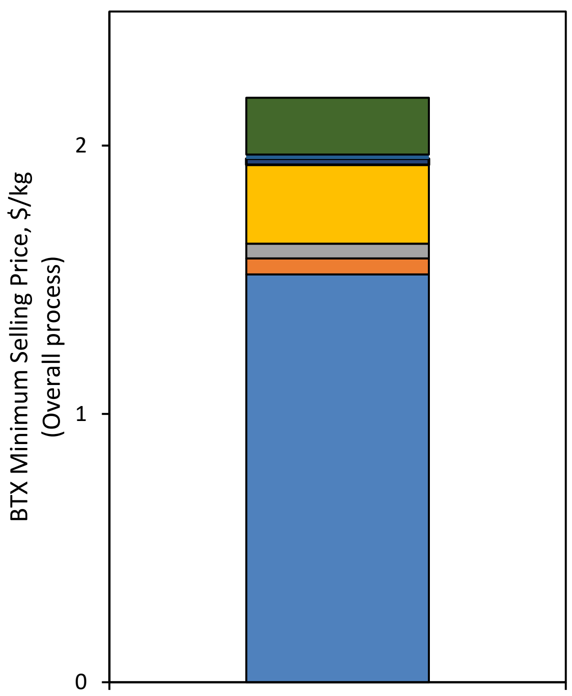
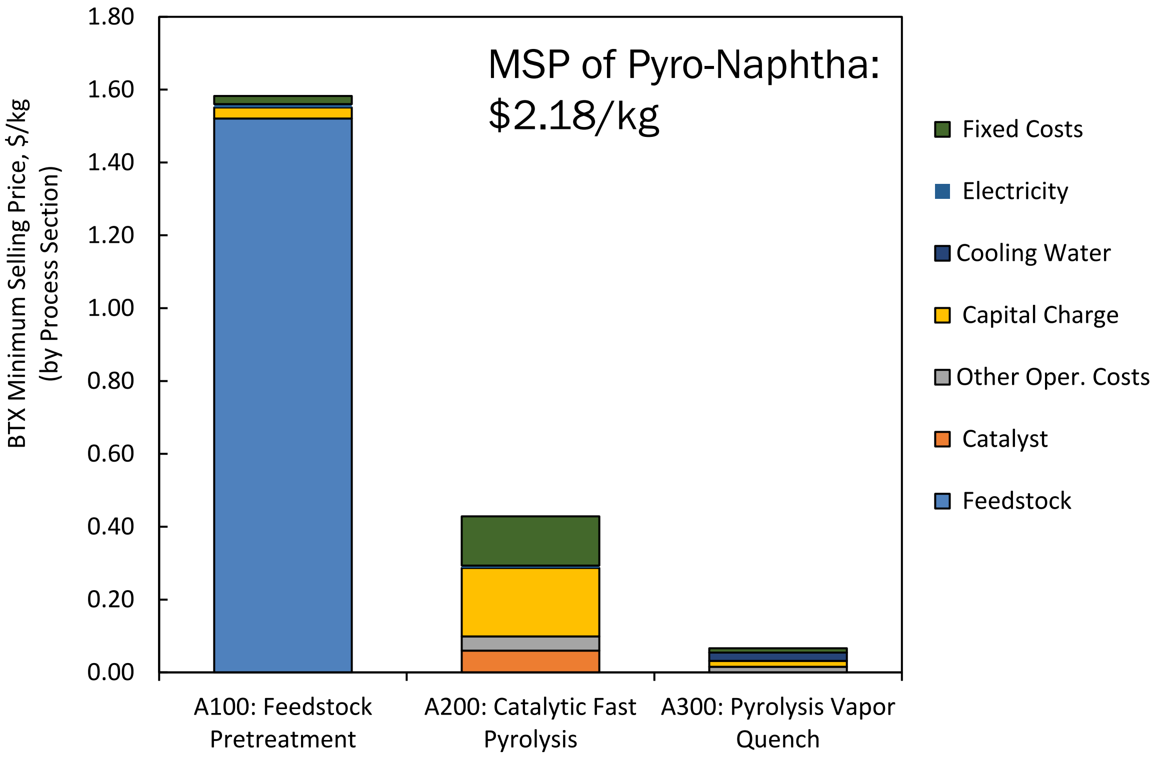
Case Study – Naphtha Only



Naphtha Only

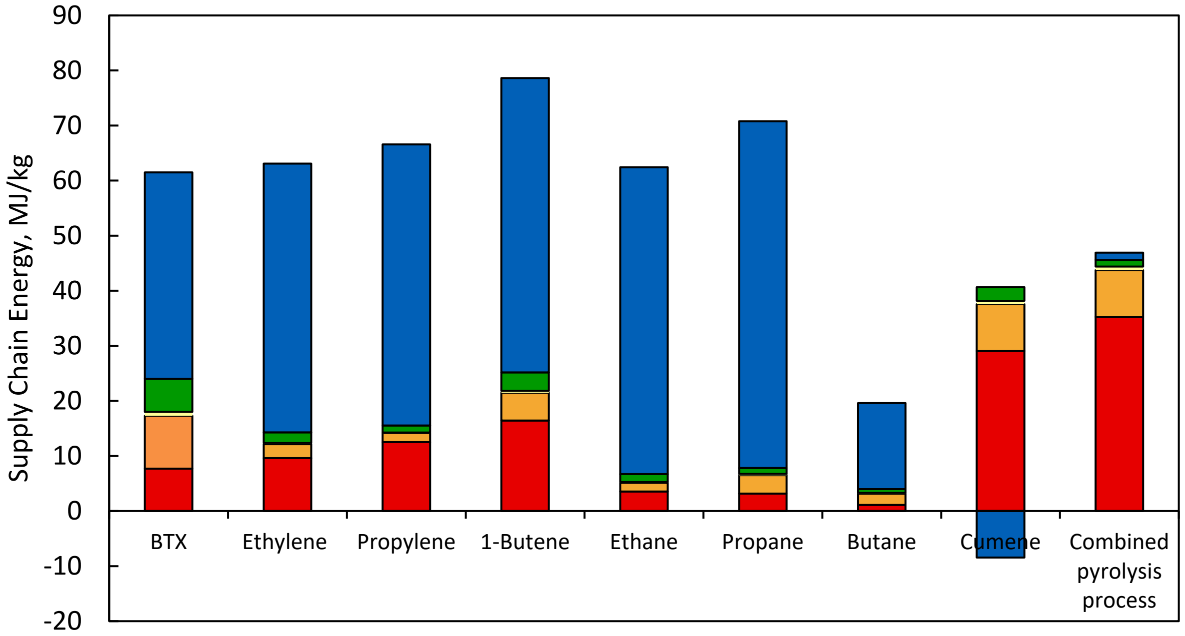


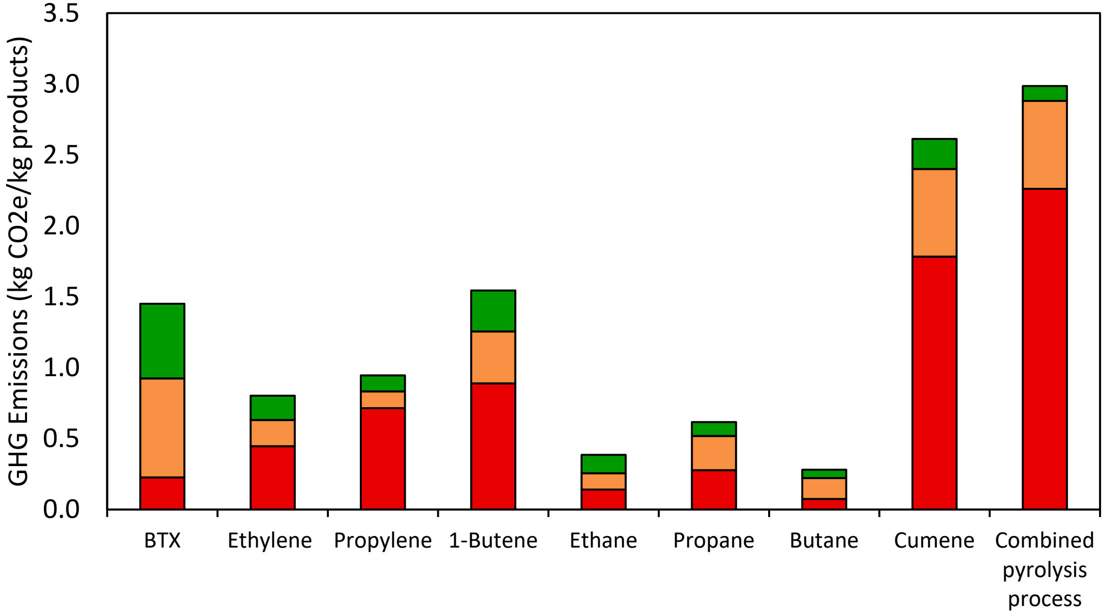


- Fossil Naphtha Selling Price[1] = $0.50/kg.
- High feedstock costs is the major economic driver and brings the MSP of pyro-naphtha 4.3 times higher that of fossil naphtha.

1. IHS Markit. PEP Year Handbook 2020.

MFI Results – Products wise





Process Fuel
Fuel for Electricity
Renewable Electricity
Fuel for Transportation
Fuel as Chemical Feedstocks

WTI Crude oil price vs.