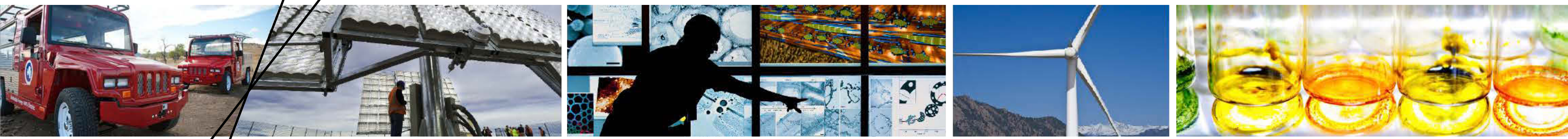
An Integrated Sustainability Evaluation of Indirect Liquefaction of Biomass to Liquid Fuels



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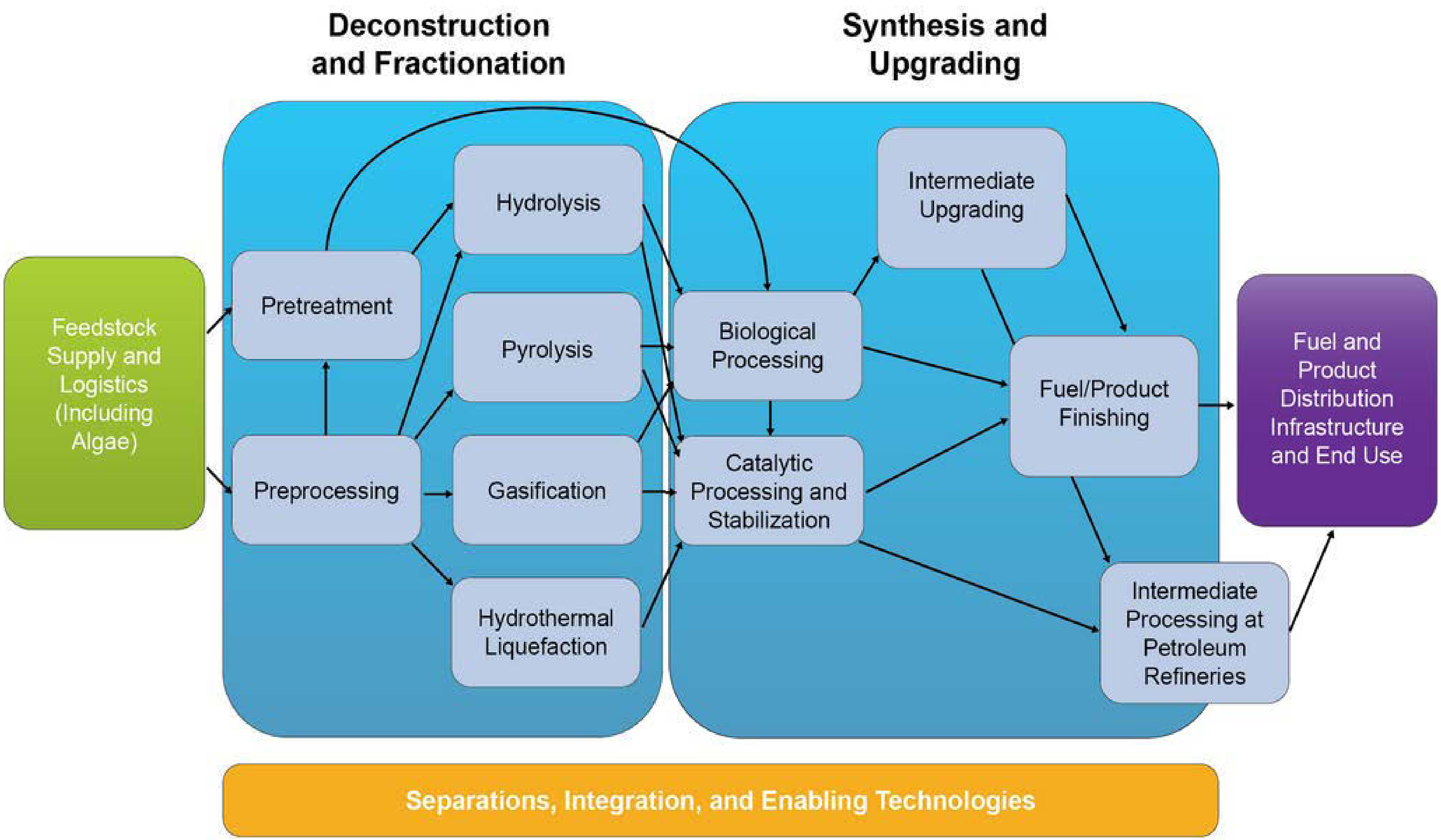
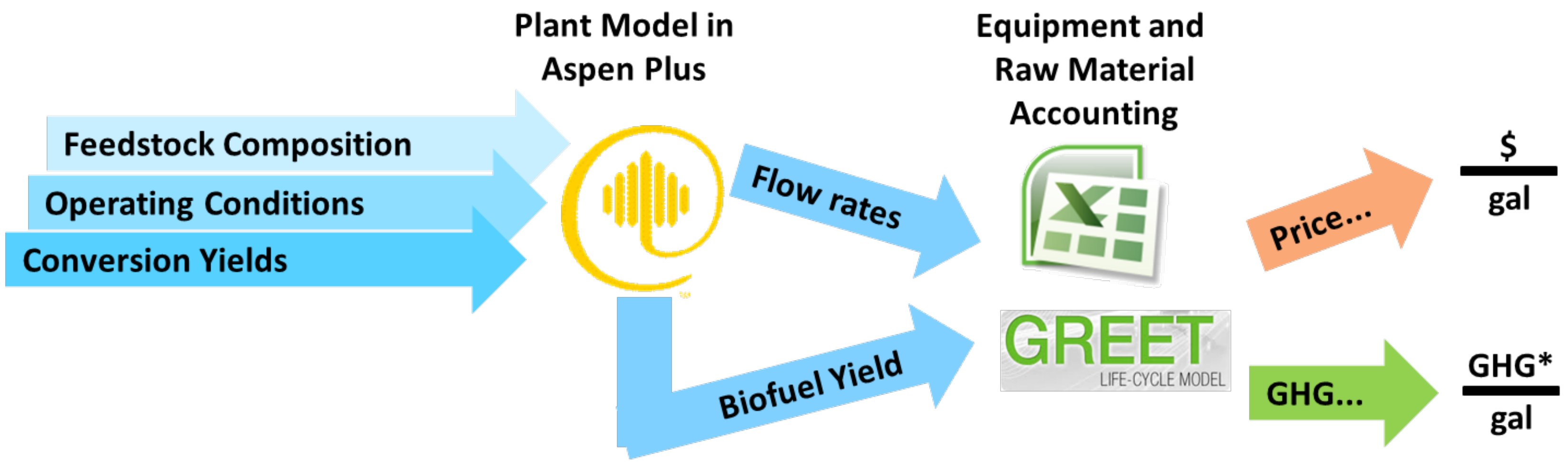
Biomass-to-fuels conversion pathways



Source: https://www.energy.gov/eere/bioenergy/conversion-technologies

Conversion Technology Assessment

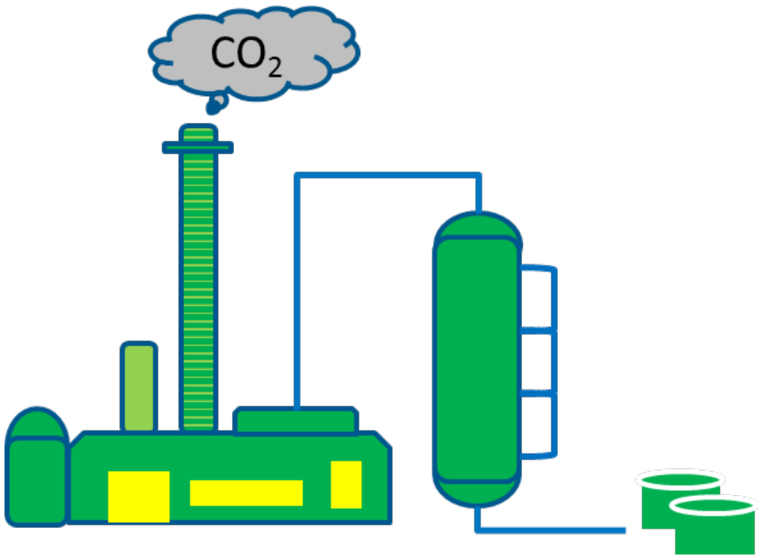
- Techno-economic analysis
  - Assess the technical and economic viability of new processes and technologies
  - Identify the potential for cost reduction
  - Assess cross-pathway and cross-technology progress, and
  - Provide input into portfolio development and technology validation
- Life-cycle analysis / Supply Chain Sustainability Analysis
  - Estimate the environmental impacts (e.g., GHGs, FEC)



*Biorefinery upstream and downstream processes not shown here.

Conversion Technology Sustainability Assessment

- Key Environmental Sustainability Metrics
  - ✓ Greenhouse gas emissions
  - ✓ Fossil energy consumption
  - ✓ Fuel yield
  - ✓ Biofuel carbon-to-fuel efficiency
  - ✓ Water consumption
  - ✓ Wastewater generation



- Not intended to be all-inclusive

- Work in progress to quantify additional metrics

Objectives and Motivation:

- Integration of sustainability in process design is core to the mission in developing renewable fuels and should be considered a best practice in biorefinery design.

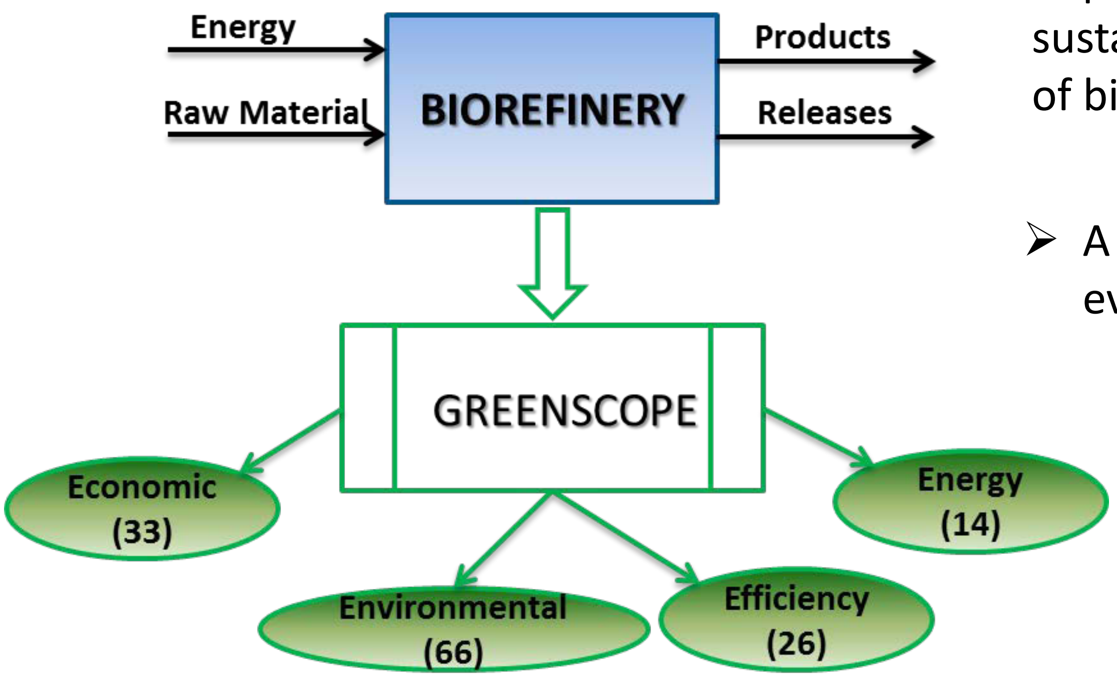
- Consider a wider range of sustainability metrics (beyond only costs, GHGs) that allow for more comprehensive direct comparison when evaluating design modifications and alternatives.

- Integrate a systematic framework in biorefinery process design
  - Understand impact of design variation
  - Evaluate alternative technologies
  - Track progress (vs baseline)

- Capture the multi-dimensional aspect of process design and operation

- Answer key questions like:
  - What process areas are in need of sustainability improvement?
  - What are the challenges and opportunities for achieving the best possible sustainability target?
  - Where to allocate the resources?

Approach: GREENSCOPE Sustainability Framework

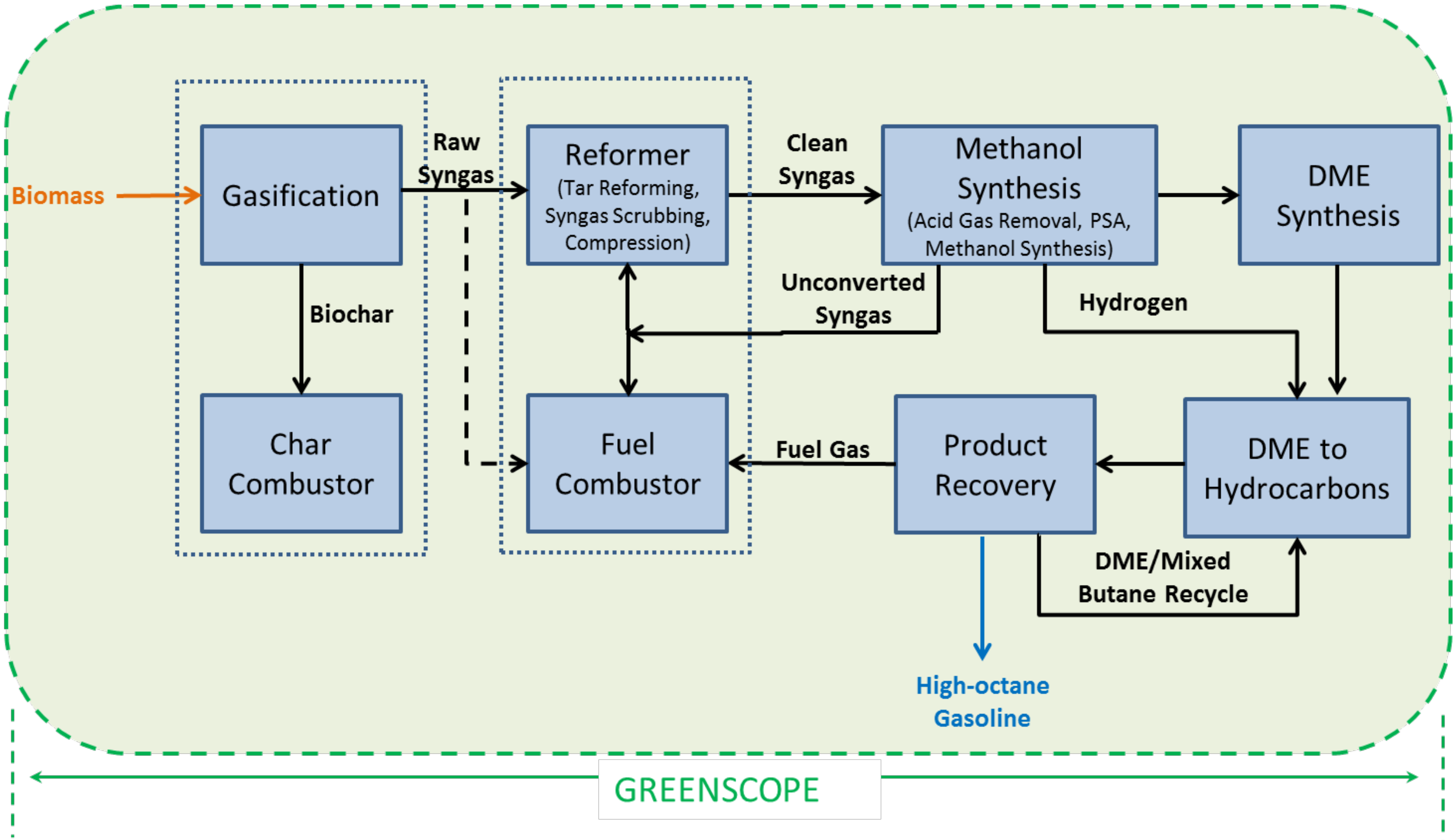


$$\text{Percent Score} = \frac{(\text{Actual-Worst})}{(\text{Best-Worst})} \times 100\%$$

100% sustainability   0% sustainability

- Implementing GREENSCOPE for sustainability performance assessment of biomass-to-fuel pathways
- A sustainability tool for process evaluation and design
  - Ruiz-Mercado, et al., Ind. & Eng. Chem. Res. (2013) 52:6747-6760.
  - Ruiz-Mercado, et al., Clean Techn Environ Policy (2014) 16:703-717.
- Sustainability assessed by employing a set of indicators, categorized in 4 areas (4 E's)
- The strength/uniqueness of the method was demonstrated through the definition of **best-target** and **worst-case** limits for each of the indicators (**dimensionless** scale)

Case Study: Conversion of biomass to high-octane gasoline blendstock via indirect liquefaction and methanol / dimethyl ether intermediates



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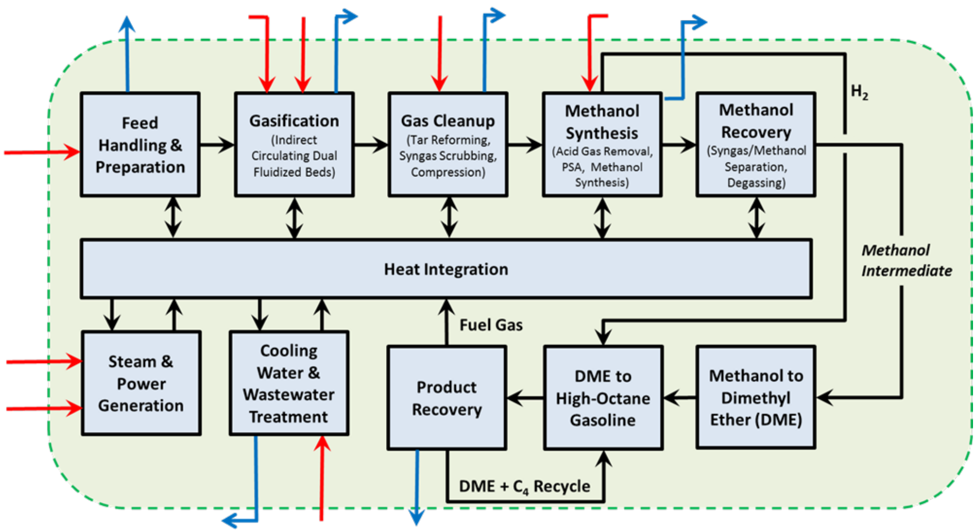
Material and Energy Flows (per annum)

Capacity: 2,000 dry tonne/day

Releases	
Sand and ash purge	9593 ton
Tar reformer catalyst	35 ton
Scrubber solids	37 ton
Wastewater	44677 ton
Flue gas	1206071 ton

Raw Materials	
Blended woody biomass (dry)	724218 ton
Magnesium oxide (MgO)	27 ton
Fresh olivine	2141 ton
Tar reformer catalyst	35 ton
Methanol synthesis catalyst	21 ton
DME catalyst	26 ton
Beta zeolite catalyst	124 ton
Zinc oxide catalyst	10 ton
Cooling tower water makeup	7812 ton
Boiler feed water makeup	322214 ton
Dimethyl Disulfide (DMDS)	8 ton
Amine (MDEA) makeup	15 ton
LO-CAT chemicals	467 ton
Boiler feed water chemicals	11 ton
Cooling tower chemicals	2 ton
No. 2 diesel fuel	273 ton

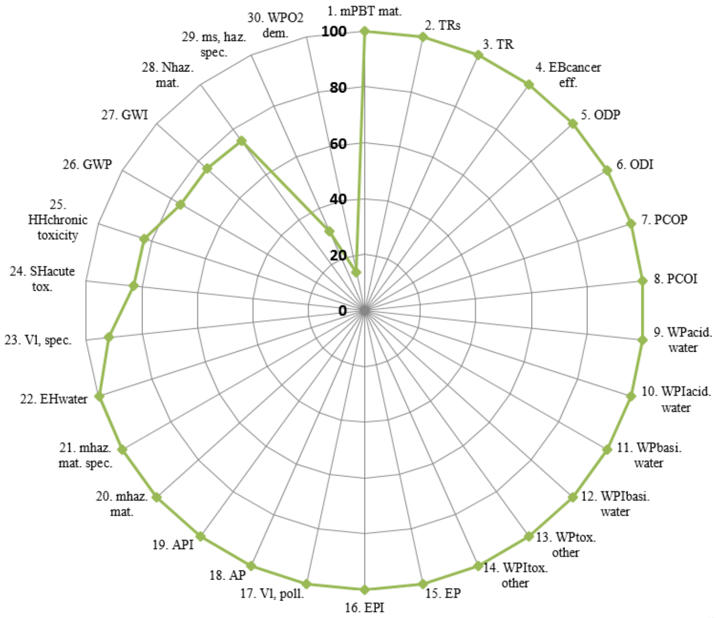


Products	
High octane gasoline	129700 ton
Sulfur	469 ton

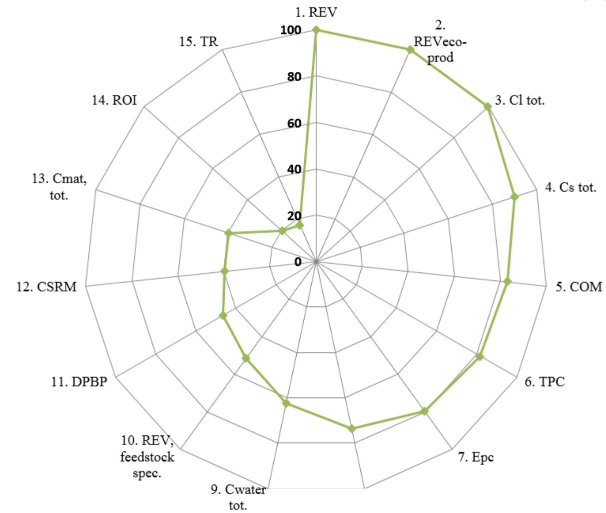
Economic	
Cost year / on-stream factor	2014 / 90%
Total Installed Equipment Cost (TIC)	$247.1 MM
Total Capital Investment (TCI)	$430.4 MM
Total Annual Sales	$155.8 MM
Annual Manufacturing Cost (Average)	$95.4 MM

GREENSCOPE Results (4 E's)

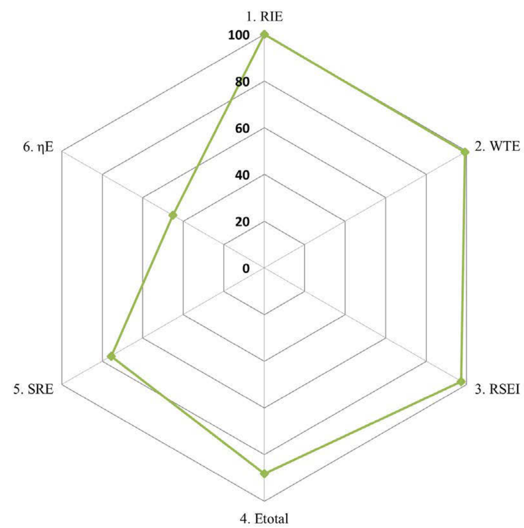
Environmental



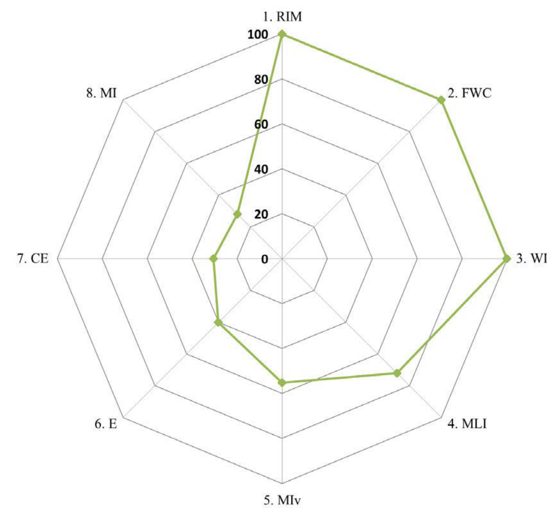
Economic



Energy

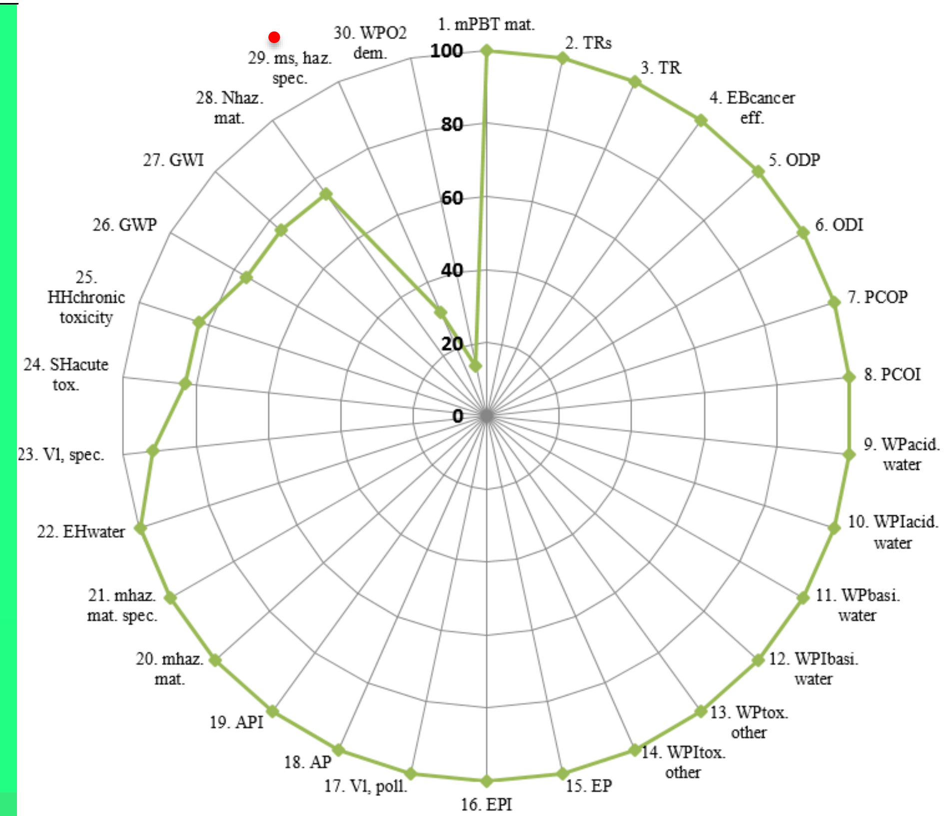


Efficiency



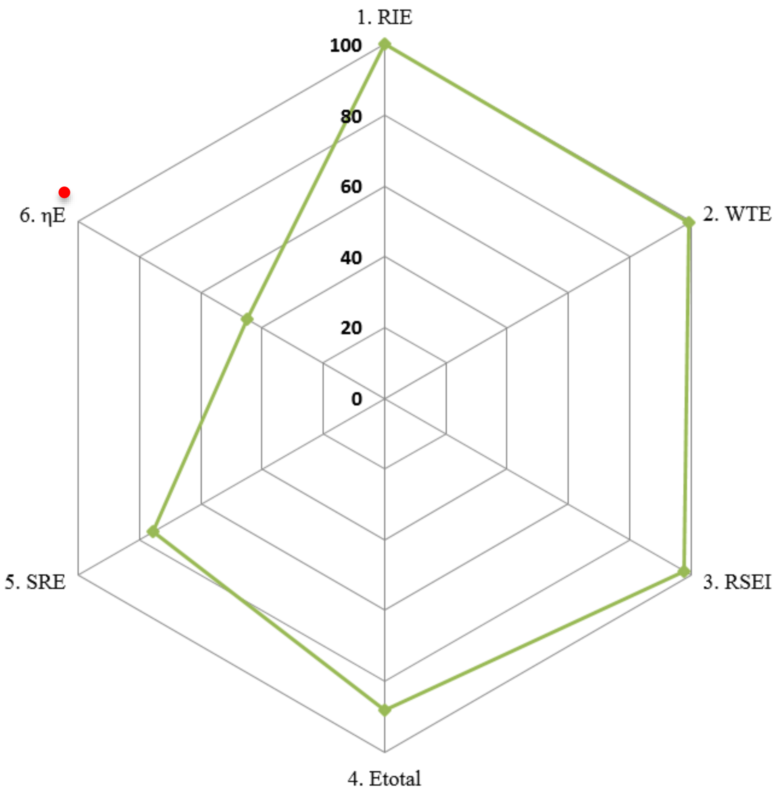
GREENSCOPE Environmental Indicators

Indicator	Description	Sustainability % Score
1. $m_{\text{PBT mat.}}$	Total mass of persistent, bio-accumulative and toxic chemicals used	100
2. TR_s	Specific toxic release	100
3. TR	Toxic release intensity	100
4. $EB_{\text{cancer eff.}}$	Human health burden, cancer effects	100
5. ODP	Stratospheric ozone-depletion potential	100
6. ODI	Stratospheric ozone-depletion intensity	100
7. PCOP	Photochemical oxidation (smog) potential	100
8. PCOI	Photochemical oxidation (smog) intensity	100
9. $WP_{\text{acid. water}}$	Aquatic acidification potential	100
10. $WPI_{\text{acid. water}}$	Aquatic acidification intensity	100
11. $WP_{\text{basi. water}}$	Aquatic basification potential	100
12. $WPI_{\text{basi. water}}$	Aquatic basification intensity	100
13. $WP_{\text{tox. other}}$	Ecotoxicity to aquatic life potential	100
14. $WPI_{\text{tox. other}}$	Ecotoxicity to aquatic life intensity	100
15. EP	Eutrophication potential	100
16. EPI	Eutrophication potential intensity	100
17. $V_{\text{l, poll.}}$	Polluted liquid waste volume	100
18. AP	Atmospheric acidification potential	99.98
19. API	Atmospheric acidification intensity	99.98
20. $m_{\text{haz. mat.}}$	Mass of hazardous materials input	99.96
21. $m_{\text{haz. mat. spec.}}$	Specific hazardous raw materials input	99.96
22. EH_{water}	Environmental hazard, water hazard	99.8
23. $V_{\text{l, spec.}}$	Specific liquid waste volume	91.8
24. $SH_{\text{acute tox.}}$	Safety hazard, acute toxicity	83.1
25. $HH_{\text{chronic toxicity}}$	Health hazard, chronic toxicity factor	82.9
26. GWP	Global warming potential	75.8
27. GWI	Global warming intensity	75.8
28. $N_{\text{haz. mat.}}$	Number of hazardous materials input	75.0
29. $m_{\text{s, haz. spec.}}$	Specific hazardous solid waste	31.07
30. $WP_{\text{O2 dem.}}$	Aquatic oxygen demand potential	13.92



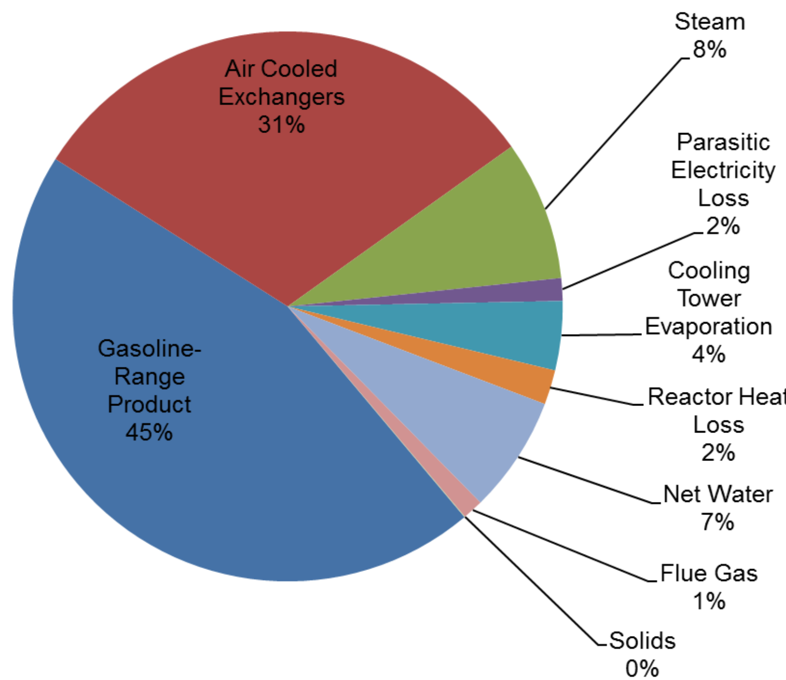
Specific hazardous solid waste:
Produced hazardous solid waste per unit mass of product
Best target = 0
Worst-case = All solid waste are considered hazardous
Ash = hazardous solid waste
Using lower ash content feedstock for achieving improved process sustainability

GREENSCOPE Energy Indicators



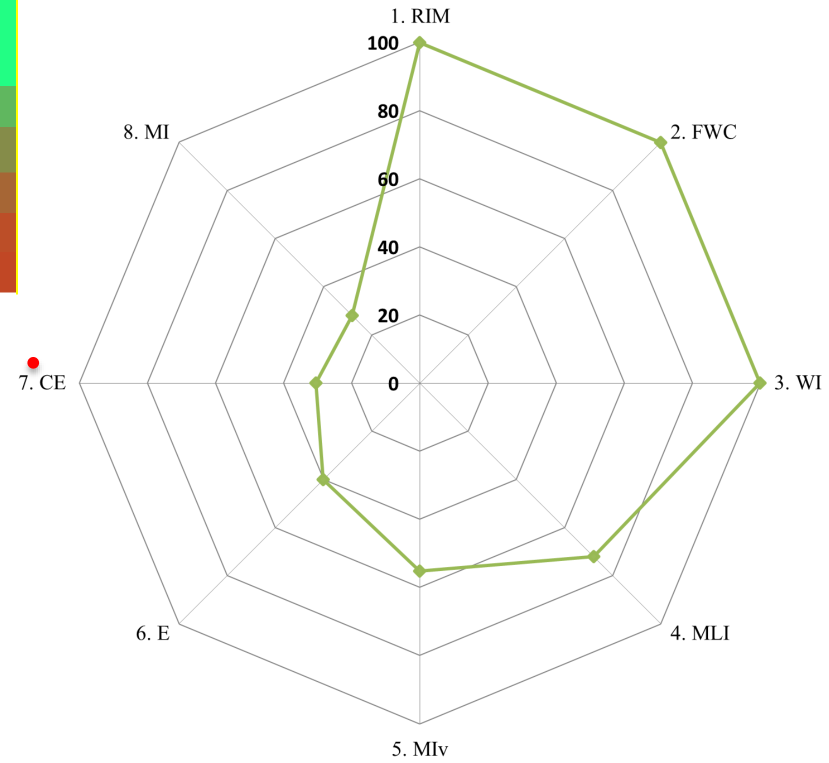
Indicator	Description	Sustainability % Score
1. RIE	Renewability-energy index	100
2. WTE	Waste treatment energy	99.2
3. RSEI	Specific energy intensity	97.9
4. Etotal	Total energy consumption	88.1
5. SRE	Solvent recovery energy	75.6
6. ηE	Resource-energy efficiency	45.0

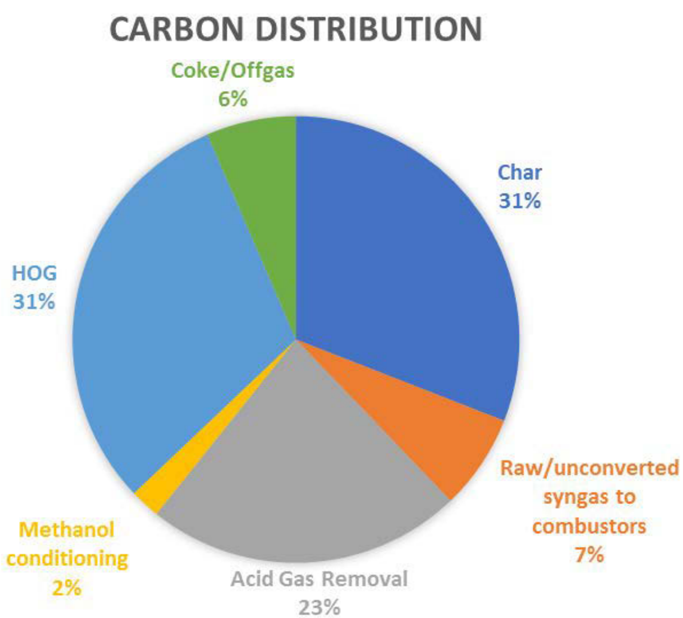
Resource-energy efficiency :
The ratio between the energy content of the products to the total energy content of the feedstocks
Best target = 1
Worst-case = 0
Increasing HOG yield and better heat integration for achieving improved process sustainability



GREENSCOPE Material Efficiency Indicators

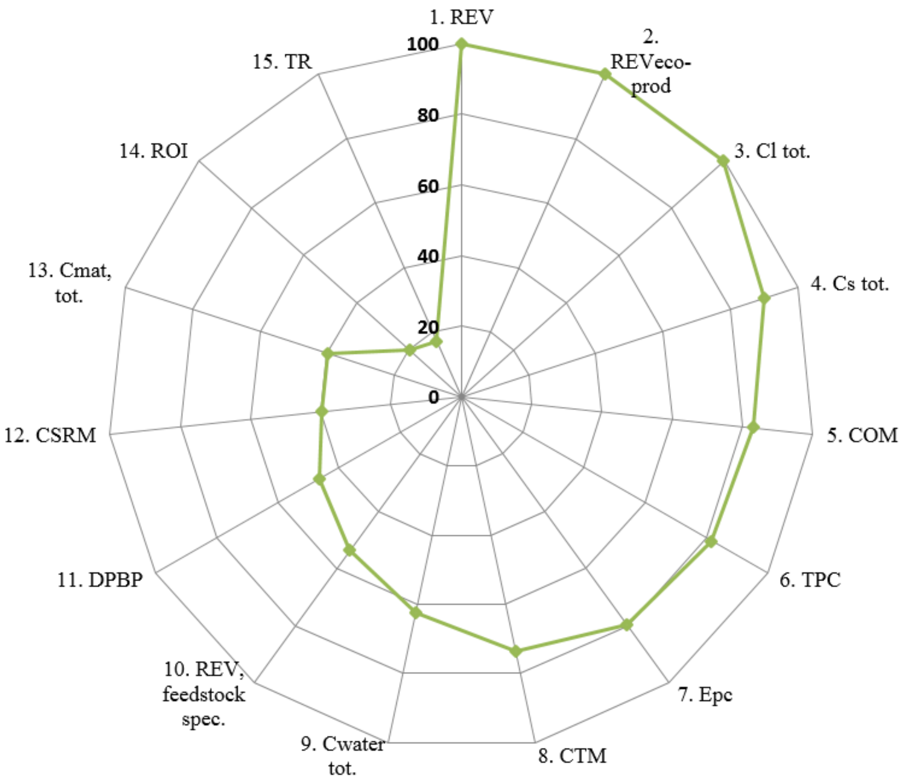
Indicator	Description	Sustainability % Score
1. RI_M	Renewability-Material Index	99.9
2. FWC	Fractional water consumption	99.9
3. WI	Water intensity	99.8
4. MLI	Mass Loss Index	72.1
5. MI_v	Value mass intensity	55.3
6. *E*	Environmental Factor	40.2
7. CE	Carbon Efficiency	30.6
8. MI	Mass intensity	28.1





Carbon efficiency :
Percentage of carbon in the reactants remaining in the final product.
Best target = 1
Worst-case = 0
Recycle CO2 from AGR to reformer for dry reforming
Reactivate CO2 from AGR in HC synthesis reactor

GREENSCOPE Economic Indicators



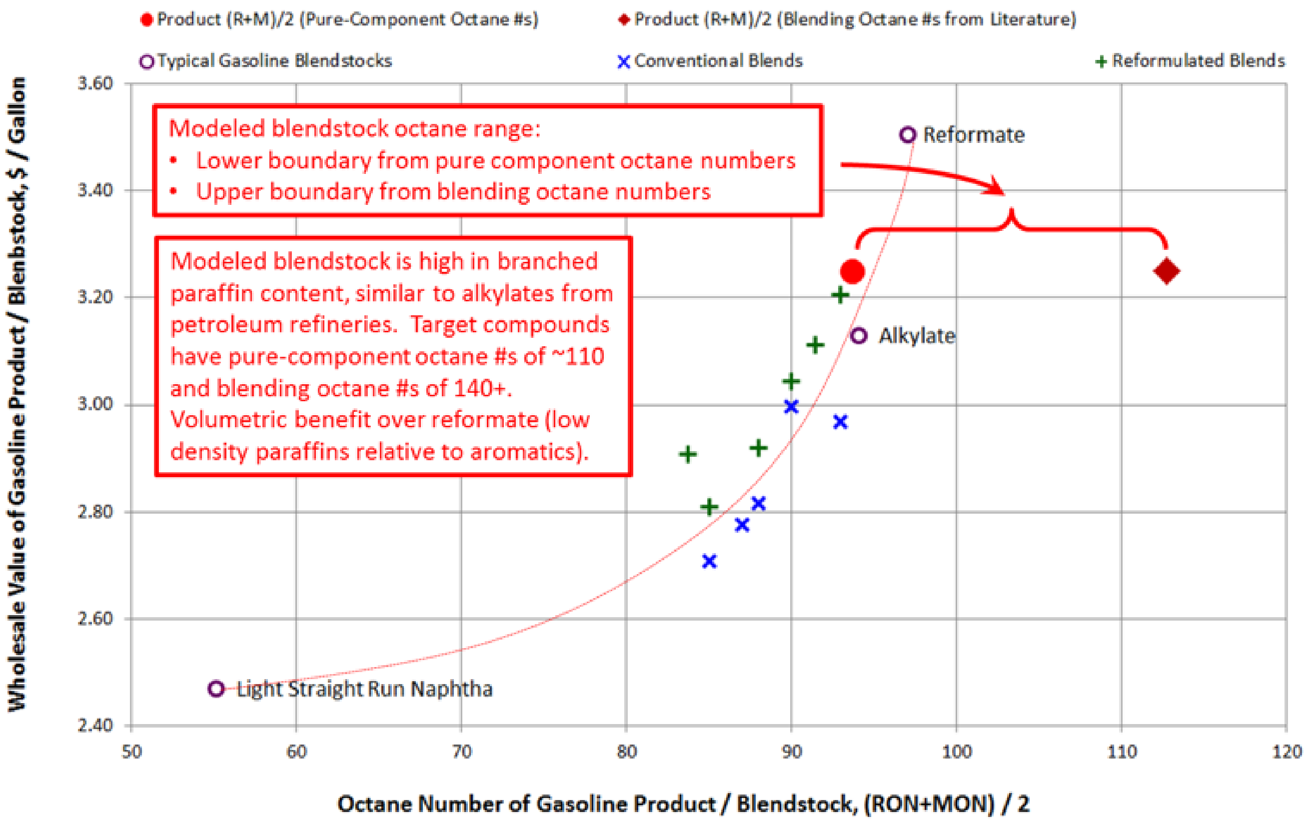
Indicator	Description	Sustainability % Score
1. REV	Revenues from eco-products	100
2. REVeco-prod	Revenue fraction of eco-products	100
3. Cl tot.	Total liquid waste cost	99.7
4. Cs tot.	Total solid waste cost	90.2
5. COM	Manufacturing cost	83.2
6. TPC	Total product cost	81.8
7. Epc	Production cost	79.6
8. CTM	Capital cost	73.7
9. Cwater tot.	Total water cost	62.6
10. REV, feedstock spec.	Specific feedstock revenue	53.8
11. DPBP	Discounted payback period	46.5
12. CSRM	Specific raw material cost	39.7
13. Cmat, tot.	Total material cost	39.7
14. ROI	Rate of return on investment	19.9
15. TR	Turnover ratio	17.3

Specific feedstock revenue :
The ratio of the sales revenue over the feedstock fed ($/dry ton). A good bioeconomy indicator.
Best target = 400
Worst-case = 0

Rate of return on investment:
Ratio of average annual net profit (no time value) to fixed capital investment.
Best target = 0.4
Worst-case = 0

Turnover ratio:
The ratio of gross annual sales to fixed capital investment. This a faster evaluation method suitable for order of magnitude estimates.
Best target = 1.25
Worst-case = 0.2

"Premium" product value can improve sales/revenue/income



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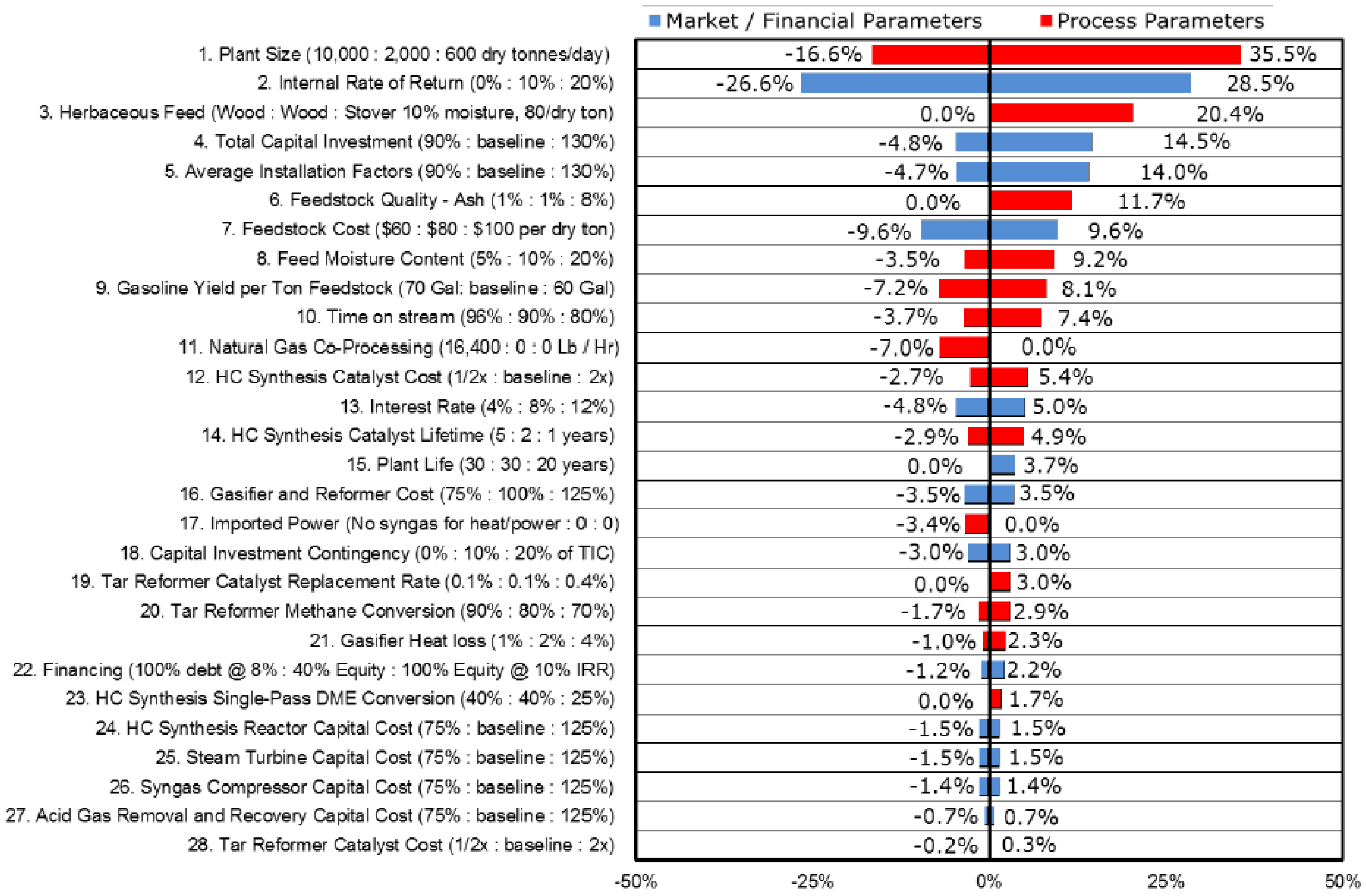
Key parameters that can impact economic indicators



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Summary

- Integrating sustainability in process design should be considered a worthy practice in biorefinery design. It should also be done in early stages of development and not something to wait to do until the end.
- Considering multiple metrics for evaluation when comparing technologies and design modifications can help make more informed decisions by looking at the design more holistically.
- GREENSCOPE can be an effective tool for biomass-to-fuels/chemicals process sustainability evaluation and design.
- The successful implementation and use of GREENSCOPE for a sustainability performance assessment for the production of high-octane gasoline from biomass has been demonstrated.
- Results from the current sustainability evaluation help answer the following questions:
  - What process areas are in need of sustainability improvement?
  - What are the challenges and opportunities for achieving the best possible sustainability targets?
  - Where to allocate the resources?

Acknowledgements

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