Economic performance of thermochemical recycling of mixed plastic waste: Open-loop vs closed loop

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**Objective:**

Compare the **economic performance** of closed-loop versus open-loop recycling of polyolefin waste.
PYROLYSIS

- Break the polymer molecules into smaller hydrocarbon chains
- Product distribution depends on the pressure:
  - Higher pressure → smaller molecules
  - Higher temperature → smaller molecules

Polyolefin molecule (from 10000 to 100000 monomers)

![Diagram showing product distribution under different conditions.]

- Gas
- Naphtha
- Waxes

Product distribution (%)

Chain length

- Atmospheric pressure
- High pressure
METHODOLOGY

**Mass and Energy Balance**
- Process flow diagram

**Market study**
- Product prices

**Economic Assessment**
- Net present value per ton of plastic treated
- Probability distribution function of the NPV

**Sensitivity analysis**
- Variables with a higher influence on the results
- Global sensitivity analysis
- Parametric sensitivity analysis

**Uncertainty Analysis**
- Probabilistic distribution of most important variables

- 1\textsuperscript{st}: deterministic analysis
- 2\textsuperscript{nd}: Stochastic analysis
PROCESS FLOW DIAGRAM – CASE 2: ONLY NAPHTHA

Mixed polyolefins → Extrusion → Cracking and condensation → Energy generation → Energy

Energy generation → Gas → Energy

Energy generation → Naphtha → Post-treatment

Energy generation → Consumables

Energy generation → Residues (gas, water and solids)
MARKET STUDY: PRODUCT PRICE

- Normal distribution for every year price.
- Variance according to observed projection errors of past world energy outlook estimations. More future → higher uncertainty, higher error.
ECONOMIC ASSESSMENT: CAPITAL EXPENDITURE

- Mid (most likely) value:
  - Project design
  - +10% project
  - +15% of contingency

- Uncertainty analysis:
  - Negatively skewed pert distribution with uncertainty range for TRL 6:
    - Low -22.5%
    - High +35%

- Working capital: 15% of capex on year 1 and -15% of capex on year 20.
RESULTS — COMBINED MONTE-CARLO SIMULATION:

- **General assumptions:** Discount rate: 15%, Tax rate: 25%, evaluation period: 20 years.
- **Probabilistic variables:** wax price, CAPEX, naphtha price, hydrogen price and feedstock price.

Main message: open loop outranks closed loop recycling.
## Sensitivity Analysis: One-at-the-Time

### Case 1: Naphtha-Wax

- Feedstock availability
- Slack wax price
- CAPEX
- Wax yield
- Naphtha price
- Naphtha yield
- Plant size
- Tax rate
- Maintenance expenses
- Feedstock price
- General plant overhead
- Low heating value gas
- Electric energy...
- Hydrogen price
- Cost of labour

### Case 2: Only Naphtha

- Naptha price
- Naphtha yield
- Feedstock availability
- CAPEX
- Plant size
- Tax rate
- Maintenance expenses
- Feedstock price
- Hydrogen price
- Hydrogen/product ratio
- General plant overhead
- Cost of labour
- Electric engine efficiency
- Low heating value gas
- Electric energy...

- Probabilistic variables: Prices and CAPEX
- Parametric sensitivity analysis: Discount rate, plant size, feedstock availability and tax rate.
SENSITIVITY ANALYSIS: GLOBAL

- How the variance of each variable is related to the variance of the results.

- Spearman's rank coefficient: correlation of the ranking of the variable to the ranking of the results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Case 1: naphtha-wax</th>
<th>Case 2: only naphtha</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>49.3%</td>
<td>37.8%</td>
</tr>
<tr>
<td>Hydrogen price</td>
<td>3.4%</td>
<td>5%</td>
</tr>
<tr>
<td>Feedstock price</td>
<td>6.1%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Naphtha price</td>
<td>52.6%</td>
<td>90.1%</td>
</tr>
<tr>
<td>Wax price</td>
<td>73.9%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Main message: Result uncertainty depend mainly on the uncertainty of CAPEX and product prices.
SCENARIO ANALYSIS: PRODUCT PRICE SCENARIOS

Expected value and probability of negative results of net present value per ton of plastic treated (EUR/t)

<table>
<thead>
<tr>
<th></th>
<th>Coupled</th>
<th>Decoupled</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1: naphtha and wax</td>
<td>21 (0%)</td>
<td>10 (14%)</td>
</tr>
<tr>
<td>Case 2: only naphtha</td>
<td>3 (35%)</td>
<td></td>
</tr>
<tr>
<td><strong>Sustainable Development</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1: naphtha and wax</td>
<td>1 (47%)</td>
<td>-2 (60%)</td>
</tr>
<tr>
<td>Case 2: only naphtha</td>
<td></td>
<td>-12 (93%)</td>
</tr>
</tbody>
</table>

Negative results observed in sustainable development scenario
Worse results in case wax prices are decoupled from oil prices
SCENARIO ANALYSIS: SMALLER PLANT SIZE

Main message: Min size 68 kton/year for open loop and 106 kton/year for closed loop.
SCENARIO ANALYSIS: FEEDSTOCK SHORTAGE

Main message: Min availability is is 78% for open loop and 94% for open loop.
CONCLUSIONS

- Open-loop recycling outranks closed loop recycling under a range of possible scenarios.
- Main drivers: feedstock availability, product price and investment cost.
- To ensure the economics benefits from chemical recycling it is important:
  - Ensure the provision of plastic waste feedstock to chemical recycling (at least 70,000 ton/year).
  - Enable a decoupling of plastics value chain from oil values.

- Future research:
  - Environmental assessment of both cases and comparison with other recycling and end-of-life treatments.

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Thank you

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