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KEY INSIGHT #3

THE CIRCULAR CARBON MERIT ORDER

What are the most sustainable circular value chains for carbon?

KEY MESSAGES

1 The circular carbon merit order provides insight into the effectiveness of processes that convert circular carbon feedstocks (from waste, biogenic residues and CO_2) into fuels and starting materials for the chemical industry.

2 This merit order can help industry and policymakers to decide on circular carbon based feedstocks and processes as they develop alternatives to fossil based value chains.

3 For the Netherlands, it will not be possible to replace all current fossil carbon use with locally available circular carbon from waste, biogenic residues and CO_2. This implies that circular carbon feedstocks will primarily have to be imported.

INTRODUCTION

Besides the energy transition, which is mainly focusing on renewable energy generation, there is a growing awareness about the importance of the materials transition. Carbon demand will change fundamentally for the energy, transport, chemicals & materials sectors. More specifically, the transition entails the replacement of fossil carbon feedstocks (coal, oil and natural gas) by circular carbon feedstocks (waste, biogenic residues and carbon dioxide) to produce fuels and starting materials for the chemical industry. This transition is essential for achieving a Net Zero and Circular Industry by 2050. **The objective of this study is to introduce the circular carbon merit order as a systemic framework to support strategic decision-making by both industry and regulators.**

DEFINITION OF THE CIRCULAR CARBON MERIT ORDER

The circular carbon merit order helps to identify the most effective process route to make circular carbon available as a feedstock for the production of chemicals and fuels. To quantify this merit order, three key performance indicators (KPIs) have been defined:

1. **Life cycle carbon dioxide emission:** This is defined as the emitted amount of CO_2 (in kg) per kg of carbon in the final product, over the complete product life cycle. The emissions of other greenhouse gases are included as CO_2 equivalents. For fuels applications (methanol and synthetic fuels) 100% combustion is assumed; for olefins (plastics) we have assumed 50% recycling and 50% incineration as an End of Life scenario.
2. **Specific energy consumption to convert the feedstock into the product:** This is defined as the amount of energy used (in MJ) per kg of carbon in the final product.
3. **Carbon dioxide emission reduction potential:** This refers to the emission reduction over the life cycle of the product, compared to the current fossil reference (expressed as a percentage).

The final circular carbon merit order results as a combination of these three KPIs.

SELECTED CARBON FEEDSTOCKS, PROCESSES AND PRODUCTS

For this study, we have selected feedstocks, conversion technologies and products that represent relevant value chains and major markets. Three circular carbon sources were selected: 1) fossil plastic waste, 2) residual biomass and 3) CO_2 from industrial emissions or direct air capture (DAC). Relevant industrial conversion processes and archetype products include methanol, olefins and synthetic fuels. Table 1 summarizes all value chains in the scope of this study.

Product → / ↓ Carbon Feedstock	Methanol	Olefins	Synthetic Fuel (gasoline or kerosene)
Plastic waste	Gasification → Methanol synthesis	Gasification → Methanol synthesis → Methanol-to-Olefins Pyrolysis → Hydro-treatment → Steam-cracking	Gasification → Methanol synthesis → Methanol-to-Gasoline
Biomass	Gasification → Methanol synthesis	Gasification → Methanol synthesis → Methanol-to-Olefins	Gasification → Methanol synthesis → Methanol-to-Gasoline Gasification → Fischer Tropsch
Carbon dioxide	CO_2 capture → Methanol synthesis; Electrolysis → Methanol synthesis	CO_2 capture → Methanol synthesis → Methanol-to-Olefins; Electrolysis → Methanol synthesis	CO_2 capture → Fischer Tropsch; Electrolysis → Fischer Tropsch CO_2 capture → Methanol synthesis → Methanol-to-Gasoline; Electrolysis → Methanol synthesis

Table 1: Selected feedstock-process-product combinations (circular carbon value chains).

RESULTS AND DISCUSSION

The feedstock-process-product combinations are shown in Figure 1. Please note that the three circular carbon KPIs are shown here as respectively the y-axis, x-axis and the ball size. Moreover, the circular feedstock types have been indicated for easy comparison.

The analysis reveals a clear order in the types of circular carbon feedstock when comparing the life cycle carbon dioxide emissions and the specific energy use. For products based on plastic waste, the value chain life cycle carbon dioxide emissions are highest (except for olefines production), followed by those from carbon dioxide feedstocks and biomass. Looking at the specific energy use of the end products, both plastic waste and biomass-based value chains score very low compared to those based on carbon dioxide. This can be explained by the thermodynamics of reducing CO_2 back to hydrocarbons ("reversed combustion") which requires a lot of low-emission electricity to obtain the green hydrogen that is needed for the reduction process. (In our study a carbon footprint of 15 kg CO_2/MWh for renewable electricity has been used, a conservative value for offshore wind in the Netherlands.) Finally, looking at the emission reduction potential represented by the ball size, it is clear that the non-fuel application (olefins for plastics) is generally the preferred option. There, part of the carbon will be stored in the product whereas the combustion of fuels results in carbon dioxide emissions.

FEEDSTOCK AVAILABILITY

Although the circular carbon merit order provides insight into how to prioritize the use of circular carbon sources, it is crucial to validate the local availability of plastic waste, residual biomass and CO_2. Moreover for Carbon Capture and Utilization (CCU) and using CO_2 as a feedstock, the availability of low-emission electricity can be a bottleneck. Figure 2 summarizes current fossil carbon flows and potential future circular carbon flows. It shows that the Netherlands will need to import substantial amounts of circular carbon feedstocks to sustain the current local production of chemicals and fuels.

CONCLUSIONS

The concept of the circular carbon merit order presented in this key Insight provides insights and assists in science-based decision-making on the basis of the most effective circular carbon value chains. From the perspective of energy efficiency and emission reduction, it can be concluded that when using circular carbon, priority should be given to the production of plastics (olefins) rather than fuels. The latter should not be produced from plastic waste, but preferably from sustainable biogenic residues or non-fossil carbon dioxide and green hydrogen, provided that there is a sufficient local supply of large amounts of low-emission electricity. Based on a concise supply-demand analysis, it can be concluded that the Netherlands will have to import substantial amounts of circular carbon-based feedstocks to meet current industrial demand for feedstock for fuels and olefins production.

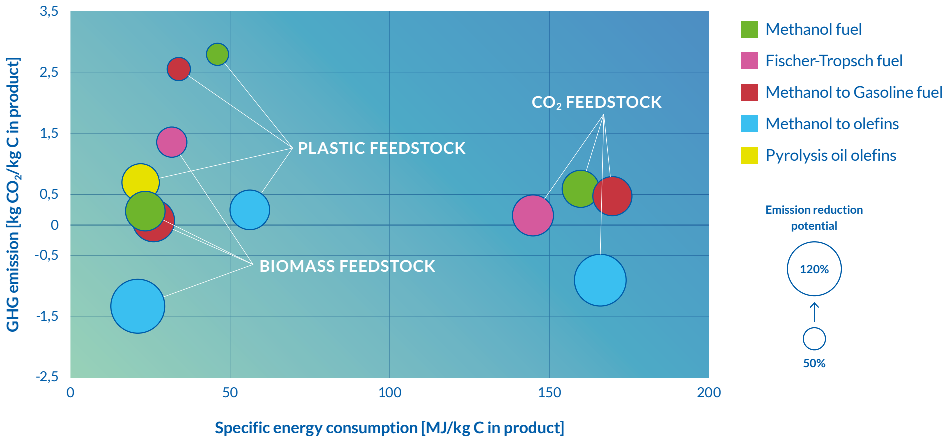

Figure 1: The circular carbon merit order impact matrix. Ball sizes represent the specific emission reduction potential per kg of product compared to the fossil-based reference product. The different types of circular carbon feedstocks have been indicated. Note that fuels like gasoline and kerosene release 50-55MJ heat per kg of carbon in the product when combusted.

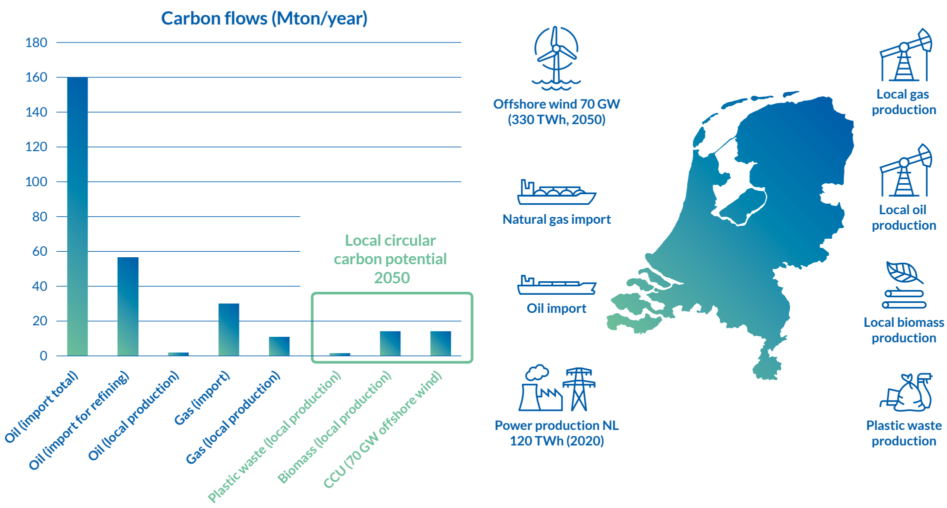

Figure 2: The current Dutch fossil carbon extraction and import via oil and gas (in 2020), and future local circular carbon potential (by 2050). The amount of CCU carbon is based on the assumption that all offshore wind electricity in 2050 is utilized for the conversion of CO_2 from point sources into circular hydrocarbons, including the production of required green hydrogen. Data derived from the EBN 2023 infographic (Energie Beheer Nederland) and TNO estimates for Biomass and CCU potential.

WANT TO KNOW MORE?

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