## Energie aus Abfall

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Lignite (namely brown coal) and carbonaceous waste are valuable primary and secondary carbon carriers which are generally combusted in Germany mainly for electricity generation. Such linear cradle to grave model is associated with significant CO₂ emissions and also represents a waste of precious domestic carbon resources. A coupling of the energy, chemical and waste management sectors, where lignite and waste are used as alternative feedstock to imported crude oil for chemical production, could facilitate a transformation from a linear to a circular carbon economy. In addition to promoting resource efficiency and conservation, such chemical utilization of lignite and waste via the interface technology gasification and the integration of renewably generated green hydrogen could also support closing the carbon cycle. In this article, we evaluate the role of chemical recycling in the waste hierarchy as well as the opportunities and challenges associated with achieving a closed carbon and circular economy for the waste management sector. To illustrate our concept, results from process models evaluations for olefin production in Germany are presented.
1. Introduction

Global warming, natural resource depletion and economic growth as well as the growing waste problem and associated environmental and human impacts are key challenges which the global community is facing in the 21st century. The transformation of energy systems from fossil fuels to renewable energies, the reduction in primary resource consumption and increase in utilization of secondary resources as well as the development from a linear to a circular economy are therefore central objectives for politics, industry and society in numerous countries. In Germany, an important focus – especially in view of its Energy Transition (Energiewende) and the continuous increase in the recycling quota for the waste sector – is thus the sustainable utilization of domestic primary and secondary carbon resources which is compatible with the goals of the Energiewende and the transition towards a circular economy.

Lignite and carbonaceous waste are valuable primary and secondary domestic carbon resources which are generally combusted in Germany mainly for electricity generation. Such linear cradle to grave model is not only associated with significant greenhouse gas (GHG) emissions as well as other trace components and fine dust, it also represents a waste of precious domestic carbon resources. The development of new and innovative value chains through the chemical utilization (that is chemische Verwertung or rohstoffliche Nutzung) of domestic carbon resources as alternative raw materials for the chemical industry – in contrast to their energetic utilization (that is energetische Verwertung or energetische Nutzung) for electricity and heat production – therefore offers a viable perspective for domestic carbon resources in contributing to closing the carbon cycle.

2. The future of coal utilization in Germany

Germany possesses significant amount of domestic lignite. Its geological resources are estimated at 72.7 billion t, out of which 36.2 billion t are deemed as economically minable [4]. Currently, coal is predominantly combusted in Germany for electricity generation. This represents a linear concept whereby the carbon inherent in this precious primary carbon resource is fully released as CO$_2$ into the atmosphere.

The focus of Germany’s Energiewende on transiting the country’s electricity production to renewables has led to the stepwise reduction of fossil generation capacity in the country. This has resulted in significant impacts for German lignite regions namely North Rhine-Westphalia, Saxony, Brandenburg and Saxony-Anhalt where coal mining, power generation and associated industries are major employers. While the release of domestic lignite from power generation poses significant structural challenges for these regions, it also offers a chance for an alternative utilization of coal (e.g. as feedstock for chemical production) whereby carbon is bonded into chemical products instead of being emitted into the atmosphere. Such chemical utilization of coal would not only offer a viable and sustainable perspective for coal regions in Germany, it could also contribute to the achievement of a circular carbon economy.
3. The waste management hierarchy

Currently, besides landfill and dumping, waste management globally still refer predominantly to waste incineration. The latter also represents a linear model whereby carbon in the waste are fully released as CO₂ into the atmosphere at the end of their lifespan. There is therefore a high potential for a transition in the waste management sector towards other forms of recycling whereby carbonaceous waste resources are channeled back into the economy as products.

In Germany’s circular economy law namely Kreislaufwirtschaftsgesetz - KrWG [2], the waste hierarchy is defined in terms of (1) reduce, (2) preparation for reuse, (3) recycling, (4) other utilization, in particularly energetic utilization and backfilling, and (5) disposal. In the case of recycling, while material recycling (werkstoffliche Verwertung bzw. Nutzung) is focused upon and carried out in certain industrialized societies, chemical recycling (that is chemische Verwertung or rohstoffliche Nutzung) continues to play an insignificant role on the global stage. For residue carbonaceous waste which are not suitable for material recycling, chemical recycling thus poses a feasible alternative to incineration and has the highest potential for closing the carbon cycle.

To increase the overall value we can obtain from our carbon waste resources, we propose the following extended hierarchy for the sustainable management of carbonaceous waste. Specifically, chemical recycling is recognized as a separate and equally important sector in the waste hierarchy (Figure 1).

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Objectives</th>
<th>Route</th>
<th>Applicable carbonaceous waste (Examples)</th>
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</thead>
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<tr>
<td>Reduce</td>
<td>Ultimate aim</td>
<td>From design to utilization</td>
<td></td>
</tr>
<tr>
<td>Reuse</td>
<td>As much as possible</td>
<td>Direct reutilization</td>
<td></td>
</tr>
<tr>
<td>Recycle (Material)</td>
<td>More sector targeted solutions</td>
<td>Material recycling not down cycling</td>
<td>Separated &amp; (pure) plastics</td>
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<tr>
<td>Recycle (Chemical)</td>
<td>Highest potential for closing the carbon cycle</td>
<td>Chemical recycling Via gasification, syngas production and synthesis</td>
<td>Mixed plastic waste, Sorting residues, Problematic waste (high Cl containing, shredder light fraction, carbon and glass fiber plastics, organic residues, PCB-containing, …, Municipal waste fractions</td>
</tr>
<tr>
<td>End of Life Utilization</td>
<td>As little as possible</td>
<td>1) Waste incineration 2) Substitute fuel (EBS) combustion</td>
<td>Municipal waste, Different waste fractions, Hazardous waste, Medical waste, …</td>
</tr>
<tr>
<td>Disposal</td>
<td>When no other options apply</td>
<td>Landfill</td>
<td></td>
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Figure 1: Extended waste management hierarchy for carbonaceous waste
Channeling carbonaceous waste back into the carbon cycle as feedstock for chemical production via chemical recycling is an alternative to using conventional feedstock such as oil and natural gas. Such chemical utilization of carbon waste not only increases resource efficiency, it also promotes fossil resource conservation and a circular carbon economy. Furthermore, it could contribute to significantly reducing a country’s dependency on fossil imports as well as carbon leakage along the upstream value chains lying beyond national borders (like oil and natural gas imports from third countries) for its chemical production.

4. Gasification as interface technology for closing the carbon cycle

Processes and technological routes for chemical utilization of carbon resources include depolymerization (thermische Spaltung), direct liquefaction (Hydrierung) and gasification (Partialoxidation bzw. Vergasung). However, depolymerization and direct liquefaction – with carbon-based fuels as their main targeted products – do not contribute to a transition from a linear to a circular carbon economy. This is because their products will eventually be emitted into the atmosphere as CO₂ following their utilization (namely combustion for electricity, heating or mobility). In contrast, gasification – which is the thermal conversion of carbon feedstock to obtain a synthesis gas (syngas) which mainly consists of H₂ and CO – is a key technology for closing the carbon cycle. Through synthesis, platform chemicals such as methanol can be produced from syngas and subsequently, derivates such as olefins which form the basis raw material for the production of a wide range of chemical products. Following their utilization, the spent products can be brought back into the carbon cycle where – via gasification and the subsequent synthesis – they are converted into new chemical products again, thus closing the carbon cycle.

An overview of different gasification technologies and the advantages of gasification for chemical recycling compared to other technologies such as depolymerization and direct liquefaction are presented in [8] and [10].

5. From linear to circular carbon economy

To facilitate closing the carbon cycle and a transformation of the waste sector from a linear economy to a circular carbon economy, a coupling of the waste management, chemical and energy sectors is necessary (Figure 2).

From a thermodynamic perspective, not all of the carbon in the waste feedstock can be bonded in the chemical products. Moreover, not all chemical products will re-enter the carbon cycle as waste materials following their utilization. To illustrate, consider the case of plastics in Germany. In 2015, while 10.1 million tons of plastics are consumed, only 5.9 million tonnes came back into the system as waste for recycling [3]. This represents a gap which has to be topped up by feeding new primary carbon resources into the system for chemical production. Furthermore, plastics undergo rapid volatilization upon heating during the gasification process. As gasification
technology requires a certain amount of coke to guarantee a stable process, the co-gasification of carbon waste with a feedstock having a higher fixed carbon content is therefore technologically required. Last but not least, there is considerable competition on the market for carbon waste as feedstock e.g. by incinerators and as substitute fuel (*Ersatzbrennstoff*) for electricity and heat production. In view of these considerations and the projected release of lignite from Germany’s energy system, domestic lignite thus represents a potential and attractive partner to fulfill this role as partner for carbon waste (Figure 3).

Figure 2: Closing the carbon cycle through sector coupling


Figure 3: Domestic coal as partner for waste in transforming from a linear to a circular carbon economy
Additionally, to close the carbon cycle, a coupling of the waste management and chemical sectors needs to be complemented with the energy sector not only for the coal input, but also for the green hydrogen. An integration of green H₂ – produced via electrolysis powered by renewable energy – into the syngas could facilitate an achievement of not just zero CO₂ emissions but also net zero emissions i.e. all other emissions such as heavy metals, organic and inorganic traces, fine and ultrafine particulates. Moreover, it is also possible to achieve zero liquid discharge¹ along the process through waste water evaporation to obtain a concentrate.

6. Comparison of CO₂ emissions

Figures 4a-c provide a simplified overview of CO₂ emissions associated with the linear carbon economy where coal and carbon waste are combusted for electricity and heat in comparison to a circular carbon economy whereby they are gasified for chemical production, with and without integration of green H₂.

During combustion, 100 percent of the carbon in such primary and secondary carbon carriers are emitted into the atmosphere as CO₂ (Figure 4a). In Germany, under the current EU Emissions Trading System (ETS), CO₂ emissions by fossil power plants face an ETS penalty whereas those emitted from waste incineration enjoy ETS allowances (that means, they face no penalty payment). Despite this differentiation in ETS penalties between CO₂ emissions from different sources, the combustion of 100 units C (carbon atoms) of lignite and 100 C of waste in Germany for electricity and heat will nevertheless result in 200 C being released as CO₂.

In the mid-term (that is 2025), a coupling of the energy with waste and chemical sectors in the form of conventional chemical utilization already supports the transition from a linear to circular carbon economy. As can be seen in Figure 4b, even with the utilization of lignite as a co-feedstock for gasification, the majority of the carbon in the primary and secondary carbon carriers are bonded in the chemical products (104 C), resulting in reduced CO₂ emissions (96 C) compared to the combustion of waste and lignite as illustrated above (200 C).

¹ Zero Liquid Discharge (ZLD) is defined under strict conditions as a complete reduction of the water volume, with water leaving the system only in the form of steam and solids are recycled or separated in dry form. Under restricted conditions, no waste water leaves the system but sludge, brine, aerosols or water by leaching [5]
In the long term (that is 2050+), with an integration of green H₂ – a probable scenario considering the projected surplus of renewable electricity resulting from Germany’s Energiewende – it is possible to achieve net zero emissions via the interface technology gasification (Figure 4c). This will represent a milestone in efforts to achieve a closed carbon cycle whereby 100 percent of carbon in waste feedstock can be bonded into the chemical products, thus resolving the problem of feedstock carbon losses. Additionally, technological innovations and further developments could potentially support the mono-gasification of waste, thus eliminating the technological requirement for a coke delivering partner. Furthermore, in focusing on specific waste segments which are challenging for combustion such as high calorific as well as problematic waste (for example high Cl containing, shredder light fractions, carbon and glass fiber plastics, composites), chemical recycling could be a valuable partner for waste incinerators, thus addressing the market competition problem.

7. Case analysis – emissions free olefin production with domestic carbon feedstock

In the long term perspective (that is Scenario 2050+), all carbonaceous waste streams (CO₂ emissions, carbon components in purge gases and others) must be recycled. Sufficient amount of green H₂ thus need to be produced so as to bond all waste carbon atoms into the chemical products. A central criterion for technology development and implementation would thus be the minimal demand for green H₂ to produce emissions free chemical products.
To illustrate the demand on renewable electricity in order to achieve zero CO₂ emissions, our case analysis focuses on olefin production in Germany. Olefins, especially ethylene and propylene, form the largest group of chemical intermediates (especially for plastic production). Up till now, imported crude oil plays a predominant role as carbon feedstock for Germany’s production of organic basic chemicals such as olefins. In view of current developments and the potential presented by a coupling of the energy, chemical and waste sectors, we evaluate two alternative technological routes for replacing imported crude oil with domestic carbon resources for the production of 10 million t/a of olefins (which roughly amounts to Germany’s annual production in 2015). The two technological routes are namely:

- **Carbon Capture and Utilization (CCU)** – In this scenario, we assume that all carbon waste streams from the incineration of plastic waste in Germany are captured and bonded into chemical products through the integration of green H₂. In this scenario, we assume that there is enough plastic waste available to support the production of 10 million t/a of olefins.

- **Gasification** – To illustrate the renewable electricity demand to achieve zero CO₂ emissions via the interface technology gasification, we base our evaluations on the COORVED² (CO₂ reduction by innovative gasifier design) gasifier technology. The amount of renewable electricity required to produce sufficient green H₂ to ensure zero CO₂ emissions is determined for different combinations of waste and lignite for olefin production.

A detailed description of methods, evaluation parameters and assumptions for the evaluation of alternative technological routes is described in [9]. Selected results are presented here.

Table 1 presents a description of where renewable energy is required (and produced in the case of waste incineration) in the production process, both for general operation as well as for producing green hydrogen for integration in the syngas (CO₂ and CO) and exhausted gases (so-called diffuse CO₂) so as to bond all waste carbon into the chemical products.

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<th>Description of demand for renewable energy</th>
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<td><strong>Power plant</strong></td>
<td>Power production from waste incineration</td>
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<tr>
<td><strong>Steam demand</strong></td>
<td>Excess steam: utilization in steam turbine</td>
</tr>
<tr>
<td><strong>Auxiliary</strong></td>
<td>Direct power demand in process chain e.g. for CO₂ compression</td>
</tr>
<tr>
<td>e-H₂ for diffuse CO₂</td>
<td>Renewably generated green hydrogen for CO₂ conversion from exhaust gases into methanol</td>
</tr>
<tr>
<td>e-H₂ for syngas CO₂</td>
<td>Renewably generated green hydrogen for CO₂ conversion from syngas into methanol</td>
</tr>
<tr>
<td>e-H₂ for syngas CO</td>
<td>Renewably generated green hydrogen for CO conversion from syngas into methanol</td>
</tr>
</tbody>
</table>

² For an overview of the COORVED gasification technology, please refer to [12, 15]
Figure 5 illustrates the model evaluation results for the quantity of renewable energy required to achieve zero CO\textsubscript{2} emissions. In our evaluations, we assume a 70 percent efficiency for the water electrolysis to produce green hydrogen.

![Diagram](image)

We observed that the electricity demand is significantly dominated by the supply of green hydrogen. Compared to gasification, the demand for renewable electricity in the CCU scenario is significantly higher in order to achieve zero CO\textsubscript{2} emissions. Specifically, the amount of renewable electricity required to close the carbon cycle for producing 10 million t/a of olefins via CCU is higher than Germany’s current renewable generation of 188 TWh in 2016 [1]. Strikingly, the amount of electricity which is generated via waste incineration (i.e. power plant) is only a small proportion compared to the amount of renewable electricity which is needed to close the carbon cycle with the CCU alternative. Moreover, efforts which are required to address other emissions from the incineration process (e.g. heavy metals, fine particulate etc.) so as to achieve net zero emissions still need to be considered.

In the case of sector coupling via gasification for the production of 10 million t/a of olefins, the innovative COORVED gasification technology requires considerably less green H\textsubscript{2} to achieve zero CO\textsubscript{2} emission compared to CCU. Furthermore, gasification technology has the advantage that it could achieve net zero emission for chemical
production. By increasing the plastic waste content for gasification, the hydrogen content in the syngas increases due to the higher H/C ratio, thus lowering the demand for green hydrogen via electrolysis.

While mono-gasification using only plastic waste as feedstock is highly desirable in terms of increasing carbon resource efficiency and fossil resource conservation, such technology is currently not yet mature for widespread and large-scale applications. Examples of pilot scale applications for near atmospheric waste gasification exist in Japan [14] and Canada [11]. In Germany, industrial application of large-scale pressurized gasification of carbonaceous waste together with coal has been successfully carried out in Berrenrath (till 1997) and Schwarze Pumpe (till 2007), both for the production of methanol – an important basic chemical used for the production of other value-added chemical products. However, diverse reasons ranging from the significant costs associated with running and maintaining such plants, the low prices acquired by methanol on the market, to the recognition of energetic waste utilization as a form of accepted recycling in the late 1990s have resulted in the cease of operations of these gasification plants as they were unable to compete economically under the existing regulatory and market conditions [13].

8. Limitations & directions for future research

In this article, we have presented evaluations based on the assumptions that chemical (olefin) production from conventional oil imports in Germany is completely replaced by domestic carbon sources (that is CO₂ from waste incineration in the CCU scenario, and waste and coal in the gasification scenario), and that there is enough plastic waste available to support the production of 10 million t/a of olefins. However, the availability of plastic waste – 5.9 million tonnes are currently available for recycling [3] but over 10 million tonnes would be required to fully replace conventional feedstock for olefin production in Germany – is a bottleneck which makes the use of plastic as a chemical feedstock highly challenging. Moreover, plastic waste, in particular separated and pure plastics, are highly suitable for material recycling. Hence, in the waste hierarchy (refer to Figure 1), such alternative utilization of plastics would be favored to its chemical utilization.

In the next steps, we aim to assess the actual potential of plastic waste – in terms of availability as well as market competition for alternative utilization – as feedstock for the chemical industry. Furthermore, other types of waste (in terms of quantities, carbon content, current form of utilization/recycling and others) will also be evaluated to determine the potential for chemical recycling in Germany. Last but not least, location-specific requirements and parameters for a commercial-scale facility at one million t/a of olefins will be analyzed to support the assessment of the feasibility of using domestic carbon resources for chemical production in Germany.
9. Conclusion

To conclude, through a coupling of the energy, chemical and waste management sectors via the interface technology gasification, it would be possible to achieve:

(1) net zero emissions (that means not only for GHG emissions but also for rest emissions such as heavy metals, organic and inorganic traces, fine particulates) via gasification and integration of renewably generated hydrogen,

(2) resource efficiency through chemical recycling instead of incineration (namely transformation from linear to circular carbon economy), and

(3) resource conversation whereby carbon waste is used as a feedstock for chemical production instead of oil or natural gas.

Besides contributing to reducing Germany’s total CO₂ emissions, resolving global waste problem as well as conserving natural resources, other advantages and motivation for using domestic primary (namely lignite) and secondary (namely waste) carbon resources as alternative feedstock for the chemical industry in Germany include reducing import dependency for chemical production, reducing carbon leakage along upstream international carbon value chains, supporting sustainable structural change in lignite mining regions in Germany, and promoting technological leadership in the field of chemical waste recycling among others.

However, although there are various advantages for closing the carbon cycle via sector coupling, in the past, unfavorable regulatory and market conditions as well as high costs have contributed to the demise of industrial applications (like Berrenrath and Schwarze Pumpe) in Germany. In the meantime, political pressure – especially the increasing focus on achieving a circular economy in addition to the energy transition – is setting new demands on carbon intensive industries to take steps to achieve lower emissions, higher resource efficiency and conservation of natural resources. However, regulatory and legal frameworks in their current forms do not sufficiently support efforts to meet these challenging objectives. As such, regulations and incentives will have to be adapted and/or developed so that such efforts at closing the carbon cycle via sector coupling will be competitive to existing routes of energetic waste utilization and import dependent fossil-based chemicals production [8]. In addition, widespread acceptance in the society (for example by the politics, local communities as well as by market players) is also necessary to support a successful and sustainable transformation from a linear to a circular carbon economy [6, 7].

10. Literature


