Reducing product carbon footprint of lubricants by using biomass balanced basestocks: The importance of biogenic carbon modelling in LCA

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Introduction
While electricity production and mobility applications can and must be decarbonised, at least partially, chemical industry depends on carbon as a main building block for a variety of applications, including lubricants. Instead of "decarbonisation", chemical industry needs to focus on the defossilisation of the carbon feedstock. Fossil carbon resources, mainly natural gas and crude oil-based naphtha need to be replaced with renewable and recycled feedstocks, e.g., biomethane from organic waste, pyrolysis oil from plastic waste or the largescale application of carbon capture and utilisation [Berg 2022]. Life Cycle Assessment (LCA) is an appropriate tool to evaluate the environmental benefit of this transformation.

A B2B lubricants industry sustainability survey, commissioned by LUBE Magazine in collaboration with Kline & Company, has shown that measuring product carbon footprint and life cycle have been consistently mentioned as the most important metrics to measure sustainability improvements [Wilkinson 2021].

BASF created the BioMass Balance (BMB) methodology for the introduction of renewable feedstocks in existing production pathways and with it accelerating the reduction of product carbon footprint (PCF) of its products [Krüger 2018]. For the application of the BMB methodology, a better understanding of biogenic carbon modelling in LCA is indispensable. However, the modelling of biogenic carbon dioxide uptake and emissions in life cycle assessments is not harmonised yet [Wiloso 2012, Hijazi 2016, Bishop 2021]. Different approaches are established in the literature:

- "0/0"– biogenic uptake and emissions are excluded and considered to be neutral
- "-1/+1" – biogenic uptake and emission are included and characterised with "+/- 1 kg CO_2e)
- "dynamic" – surplus effects of carbon removal and temporal storage, depending on the product life time

This paper will showcase a study on "-1/+1" biogenic carbon modelling in a cradle-to-gate system on a commercially available product example. Additional end of life emissions based on the carbon content are included for a better comparability of the fossil and BMB products. It demonstrates that including biogenic carbon modelling on a cradle-to-gate perspective opens the path of showing the sustainability benefits of BMB materials towards their fossil counterparts transparently.

A polyalkylene glycol (PAG) basestock with significantly reduced carbon emissions is enabled by BMB methodology and offers the lubricant industry a novel drop-in solution for low-PCF lubricant solutions.

Biomass Balance Methodology

With the mass balance approach, sustainable (renewable/recycled) feedstock alternatives replace an equivalent amount of fossil feedstock at the beginning of the value chain (input) and is allocated to the product (out-put) in such a manner that the input and output match.

Both, fossil and renewable feedstocks are processed in the same Verbundsite (interlinked/integrated production plants, energy flows and infrastructure), therefore existing infrastructure can be used continuously. BMB products show the same quality and technical characteristics as their fossil counterparts. This approach is already established for electricity markets, where all types of electricity are submitted to and received from the same network. Furthermore, biomethane and natural gas share the same gas grid, which means that the biogenic carbon is not traceable via C14 method of carbon dating, which dates materials by analysing the longest living radioactive carbon isotope, when the feedstocks enter the BASF gate. Based on the purchased and certified volumes of biobased feedstocks, BASF can allocate the correlating amounts to certified BMB products. The attribution of the applied renewable feedstock volumes to an end-product in a fully transparent and auditable way is achieved by an independent certification according to the requirements of the REDcert2 scheme (a certification scheme for sustainable biomass production [RedCert 2022]). With the Biomass Balance approach BASF solely replaces fossil feedstocks used for material production purposes with renewable feedstocks [BASF 2022]. This means that fossil fuels, mainly natural gas, for steam and electricity generation, are excluded. Same accounts for inorganic intermediates like sodium hydroxide or chloric acid.

Biomethane produced from waste via anaerobic digestion, according to BASF responsible procurement policies, is considered as main feedstock, which does not compete with food production. Life cycle inventory (LCI) data for biomethane have been sourced from the world's largest LCA database; the GaBi database [Sphera 2022]. In this model, biowaste is considered as burden-free on the environment due to its recycled content. If the bio-feedstocks have the same chemical properties as their fossil counterparts, hence being totally interchangeable, the life cycle environmental burdens of natural gas are subtracted from the total burdens of the fossil-based product and the burdens of biogas are added to the model. However, some bio-feedstocks may have different carbon content, energetic value, or other chemical properties from the fossil feedstocks to be replaced. In such situations, it is necessary to consider the chemical value or the equivalent quantities of bio-feedstocks. For these purposes, it is suggested to use an equivalent factor, based on the lower heating value (LHV) of fossil and bio-feedstocks as an approximation of the chemical properties [Jeswani 2019].

Biogenic Carbon Modelling

Product carbon footprints (PCF) can be calculated in two different ways: including and excluding biogenic carbon [Pawelzik 2013]. The dynamic approach is not suitable for Cradle-to-Gate assessment. So far, the Product Environmental Footprint (PEF) methodology developed by the European Commission's Joint Research Centre (JRC) still recommends the first approach "excluding biogenic carbon" [Manfredi 2012]. Both carbon uptake and biogenic carbon dioxide emissions are considered as climate neutral. This approach is often used for cradle-to-grave assessment of biobased fuels. The specific characteristic of these product systems is that the combustion of the fuel, and therefore the CO_2 released to the atmosphere, is inside system boundaries. The system boundary represents the scope of the unit processes, which are included in the Life Cycle Assessment (LCA) study and contribute to final impact results. From this perspective, the biogenic carbon flows can be cancelled out, without effecting the results.

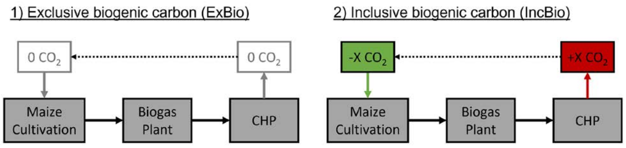

Figure 1: *biogenic carbon modelling*

But this paradigm is not suitable for a cradle-to-gate assessment of biobased, carbonic products, as shown in the next chapter. Approach 2 "including biogenic carbon" is targeted by ISO 14067 (the international standard for measuring the carbon footprint of products) and other guidelines:

"Removals of CO_2 into biomass shall be characterised in the LCIA as –1 kg CO_2e/kg CO_2 in the calculation of the CFP when entering the product system. Emis-sions of biogenic CO_2 shall be characterised as +1 kg CO_2e/kg CO_2 of biogenic carbon in the calculation of the CFP[1]." [ISO 14067]

Effects of temporal carbon storage as proposed by Levasseur are not considered in this study [Levasseur 2012]. For a detailed discussion on biogenic carbon modelling, we refer to the paper "Biogenic Carbon Modelling in CCU (Carbon Capture and Utilisation) Systems: A Case Study on Methanol and Hydrogen Production from Biogas" from Rauch and Hartmann, which will be published soon.

If no Product Category Rules (PCR) are available, BASF uses mass allocation for products with similar value. If the difference of the economic value is higher than factor 5, economic allocation is applied. Carbon dioxide is cut-off and carries no environmental burden for further product system like CCU-process.

Applied PCRs are:
- Chlorine [EuroChlor 2013]
- Steam cracker products [PlasticsEurope 2017]
- Toluene diisocyanate and methylenediphenyl diisocyanate [ISOPA 2021]

PCF calculation with focus on biogenic carbon

Cradle-to-gate PCF assessments cover part of a product life cycle, from material acquisition ("cradle") to the factory gate (i.e., before it is transported to the customer). Subsequent production steps at the customer and the use phase are not considered. For the sake of com-parability of biobased and fossil products, we add end-of-life (EoL) emissions, assuming a full oxidation of the carbon in the product to carbon dioxide. Additional functions of waste incineration, like heat and electricity generation, are neglected. We cannot guarantee that the costumer produces and emits methane from the contained carbon.

The CO_2 emissions are characterised regarding their origin: fossil or biogenic. Biogenic methane emissions contribute to the fossil PCF as well as carbon dioxide emissions from land use change (Table 1). BASF calculates the PCFs in alignment with the GHG Protocol Product Standard and based on the global warming potential for a 100-year evaluation period (GWP100) using characterisation factors from the 2013 IPCC (Intergovernmental Panel on Climate Change) Assessment Report (AR5) including land use change and climate carbon cycle feedback [Stocker 2013].[2]

	IPCC excluding biogenic carbon	**IPCC including biogenic carbon**
CO_2 uptake	0	-1
CO_2 biotic	0	1
CO_2 fossil	1	1
CO_2 LUC	1	1
CH_4 fossil	36	36
CH_4 biotic	34	36

Table 1: *Characterization factors according to IPCC AR5 [unit: kg CO_2-eq./kg]*

The carbon content of a typical PAG basestocks is 57 weight percent carbon per kilogram of final product [kg C / kg]. This value is divided by 12 [g/mol], the molar mass of carbon, and multiplied with 44 [g/mol], the molar mass of carbon dioxide.

0.57 [kg C/kg] / 12 [g/mol] * 44 [g/mol] = 2.09 [kg CO_2 / kg] (equ. 1)

Based on this result, we assume end-of-life emissions of 2.09 kg CO_2 per kilogram of product. For the fossil product, these emissions are modelled with GaBi-flow "Carbon dioxide – inorganic emissions to air". For the Biomass-based product we use the elementary flow "Carbon dioxide (biotic)", because of the attributed renewable origin via mass-balance. Furthermore, we consider CO_2 uptake as renewable resource from atmosphere as part of biomethane production.

A negative cradle-to-gate PCF, including both fossil and biogenic carbon, is possible, if more carbon diox-ide is taken up during plant growth and stored in the product, than fossil carbon dioxide is released during the production.

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[1] *CFP = Carbon Footprint*

[2] *Impact Assessment methods will be updated to AR6*

For a cradle-to-grave analysis, end-of-life emissions from incineration usually compensate the CO_2 uptake, which means that the total cradle-to-grave PCF is positive. An exception might be the production of hydrogen from biomethane pyrolysis using renewable electricity and with final deposition of the coal byproduct [Kreysa 2009]. In this way, the hydrogen has a negative cradle-to-grave PCF below zero since carbon dioxide is removed from the atmosphere for a long time [Timmerberg 2020].

However, at the moment this is hypothetical, because of economic and cultural constraints. Instead, we should focus on small steps, beginning with a BASF BMB product.

Life cycle impact assessment results for PAG basestocks

The BMB calculation must be carried out for specific products and starts with the PCF of the conventional product containing fossil feedstocks based on the SCOTT tool. SCOTT is the Strategic CO_2 Transparency Tool, developed by BASF. Based on actual and primary production data, which is linked with GaBi datassets for background processes, the PCF of almost all conventional products can be derived automatically.

For the example chosen for this showcase, the typical fossil PCF of representative PAG basestock from SCOTT is 3.0 kg CO_2eq./kg product. Additional 2.1 kg CO_2 product are added, representing potential end-of-life emission (Figure 2).

From the PCF of the conventional product, the environmental impacts of displaced fossil feedstocks are subtracted, while the burden of the equivalent amount biomethane is added.

Usually, the cradle-to-gate PCF excluding biogenic carbon (ExBio) of biomethane is higher, compared to natural gas, since the processing of biowaste to bio-methane requires more energy than exploration and transport of natural gas. Biowaste must be collected, fermented and the biogas be purified to biomethane. Leakage of methane from the plant must be considered, too. But in the ExBio paradigm biomethane can be combusted climate neutral, while additional fossil emissions must be considered for natural gas.

Results for the representative polyalkylene glycol (PAG) product are shown in Figure 2. The PCF ExBio (without CO_2 uptake) of BMBcert™ PAG is 2.8 kg CO_2eq./kg, which is 0.2 kg smaller than the PCF of the fossil-based product.

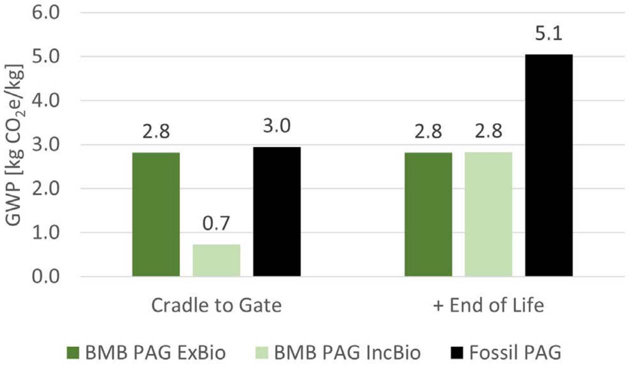

Figure 2: *Global Warming Potential (GWP) of fossil and BMB PAG, including (IncBio) and excluding biogenic carbon (ExBio)*

The reason for this is that the biogenic feedstock is not converted completely - yields never reach 100%. Since biogenic carbon dioxide emissions are not considered in the ExBio impact assessment, the incineration does contribute to GWP but is climate neutral. In contrast to the BMB product, additional 2.1 kg CO_2 must be added to the conventional product if end-of-life emissions are considered (57 wt.-% C; equ. 1).

In total, the PCF of the BMB certified PAG is 2.3 kg CO_2e/kg and those around 77% lower compared to the conventional PAG.

This reduction can be shown on a cradle-to-gate level, if biogenic carbon dioxide uptake during plant growth is included, which reduces the PCF to 0.7 kg CO_2e/kg. The CO_2 uptake is derived from the carbon content of the product and is therefore directly linked to the end-of-life emissions. This shows that both approaches are two sides of one coin.

The harmonisation is achieved by biogenic carbon correction, which closes the biogenic carbon balance. This approach is introduced by Sphera and ecoinvent [Jungbluth 2007, Sphera 2022], but rarely applied in scientific literature.

Please be aware that this is not covering a cradle-to-grave assessment since emissions from downstream processing and usage are not known nor included.

Transparency and comprehensibility are requirement for robust decision making. Since biomethane is more expensive than natural gas, the price of BMB products is higher, under current economic dogmata. Since the lower PCF is selling point of BMB products, clear and transparent communication is crucial.

Campaigning for low PCF products against economic constrains, we want to remark that in the case of in-cluding external costs, the price of the fossil products would be significantly higher. External cost will arise through damage from climate change induced environmental disasters, like floods, storms, or droughts [Stern 2006].

Conclusion

Biomass balanced basestocks reduce the product carbon footprint of lubricants and including biogenic carbon is necessary to communicate the benefit. Excluding biogenic carbon is not recommendable for the comparison of fossil and a BMB product on a cradle-to-gate perspective if they contain biogenic carbon. In such a case, the scope must be expanded to cradle-to-grave, or at least include expected end of life emissions. Including biogenic carbon modelling opens the path of showing the benefit of BMB materials towards their fossil counterparts on a cradle-to-gate perspective.

With carbon content as the core variable, which can be precisely defined, allocation of biogenic carbon uptake with biogenic carbon correction fulfils the requirements of ISO 14040 and 14044 for evironmental management and life cycle assessment and life cycle inventory. The first choice for dealing with multifunctionality, after substitution and system expansion is physical allocation. Since the carbon balance is closed by definition, also the requirements of ISO 14067 on biogenic carbon modelling are accomplished.

The general BMB approach can be applied to many BASF products, also specifically for various lubricants components such as PAG basestocks (Breox® BMBcert™), but also ester basestocks and lubricant oil additives. With the BMB methodology BASF provides customers with a sustainable option for decarbonisation and use of waste-based feedstocks, without compromising proven performance. Beside the benefit of lower PCF BMB methodology enable product benefits and claims such as "100% based on renewable feedstocks" or "100% based on recycled feedstocks".

A holistic approach from cradle-to-grave, or better cradle-to-cradle, is necessary for guiding a sustainable transition rationally. Academy and politics are responsible for a wider scope, while industry delivers data for cradle-to-gate product systems since downstream appli-cations are not known.

Based on an established and independently certified method, the biomass balanced products enable transparency for sustainable purchasing decisions and a faster transition to a carbon-neutral circular economy. Providing the benefits of sustainably sourced renewable feedstock, flexible scale-up and identical product quality, the new biomass balanced product range BMBcert™ provide basestocks and lubricant oil additives that help save fossil resources and reduce overall greenhouse gas emissions, while maintaining the same performance.
The biomass balance approach creates unique solutions for the lubricant industry, enabling customers to differentiate their lubricant solutions from competition and helps towards achieving industry sustainability goals.

LINKS:
www.basf.com/sustainability
www.basf.com/circular-economy

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