INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

Product Life Cycle Assessment

Case studies

Report on WP4 of the SYMOBIO 2.0 project: Consolidation of systemic monitoring and modeling of the bioeconomy

Horst Fehrenbach, Theresa Schlamp, Annika Wehrle, Susanne Köppen, Silvana Bürck, Viviann Bolte

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ifeu Wilckensstraße 3 69120 Heidelberg Phone +49 (0)6 221. 47 67 - 0 E-mail ifeu@ifeu.de www.ifeu.de

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Abbreviations

AP	Acidification Potential
CCU	Carbon Capture and Utilization
DNP	Distance to Nature Potential
EoL	End of Life
EP	Eutrophication Potential
eq	equivalents
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
IE	Inhabitant Equivalent
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
LCA	Life Cycle Assessment
LUC	Land Use Change
PE	Polyethylene
PET	Polyethylene terephtalate
PMF	Particulate Matter Formation
UBA	Umweltbundesamt

1 Background and goal

The aim and purpose of SYMOBIO is to provide a system for monitoring the sustainability of the bioeconomy in Germany. This system comprises a number of so-called footprints as indicators:

- Material footprint
- Forest footprint
- Agricultural footprint
- Water footprint
- Climate footprint
- Biodiversity footprint (new in SYMOBIO 2.0)
- Socio-economic footprint (new in SYMOBIO 2.0)

These footprints represent the resources used-or the emissions generated-as a result of domestic consumption of biomass-based products. For doing so, the production and supply chains are tracked, the exports are subtracted from the sum of domestic production and domestic production is added to imports. Imports are traced back to the countries of origin of raw materials using global multi-regional input-output datasets.

The SYMOBIO footprints therefore fundamentally follow the principle of the life cycle assessment (LCA), as established and standardized for product LCAs. The difference ultimately lies in the fact that the SYMOBIO footprints consider total material flows, whereas a life cycle assessment generally focuses on a product in terms of a specific functional unit. On the other hand, the results of the SYMOBIO footprints could also be understood as an aggregation of numerous product life cycle assessments.

The main difference lies in the granularity: for reasons of practicability alone, the SYMOBIO footprints cannot map ALL biomass products in ALL details. Generalized data sets are required here. An individual product LCA, on the other hand, can be designed in any level of detail, depending on the objective and framework. The approach of a macroeconomic material flow balance is therefore also referred to as "top-down" as opposed to the "bottom-up" approach of a product LCA.

A special difference between the SYMOBIO footprints and a LCA is that the system examined by SYMOBIO depicts a concrete actual situation of material flows in the bioeconomy. As a monitoring system, the footprints describe the development of resource expenditure or rather emissions derived from the bioeconomy over the years. However, they do not include a counterfactual scenario: what would it be like without the production of all these products? It would indeed be difficult to integrate such a scenario, as there are simply no real alternative products available for some products (e.g. staple foods). For other products, on the other hand, it is by no means clearly defined what exactly the alternative products would be. In most cases, this requires assumptions and case distinctions, which then leads to

ranges of results. A monitoring system would be overwhelmed by this, or at least overloaded.

Product LCAs, on the other hand, are specifically designed for such specialized cases and variant studies. For this reason, case studies on individual bioeconomy products are carried out as part of WP4 of SYMOBIO 2.0 using product LCAs.

The products considered are:

- (Beech) wood as a building material (glulam) to replace alternative building materials such as concrete and steel
- Bio-based ethylene from sugar/starch plants (maize) and lignocellulose (e.g. straw) as an alternative raw material for the chemical industry; since the processing passes via ethanol, this pre-cursor could be as well applied as a transport fuel.
- wood and bamboo fibers into textile fabrics to replace functionally identical polymer fabrics based on carbon capture and utilization (CCU), fossil fibers (polyester) and cotton.

2 Life cycle assessment method

2.1 Basic procedure

The LCA is a method described in ISO 14040 (2006) and ISO 14044 (2006) to assess the potential environmental impact of products. The term “products” covers material goods and services. The term “potential environmental impact” means that the impact cannot be predicted specifically for a place or time. Rather, it is a relative statement that relates to the functional unit (FU) of a product system. The method is therefore not suitable for analyzing specific interventions in the environment or ecological conditions in a region.

The LCAs carried out here follows the methodology of the ISO standards mentioned. The only difference to the normative specifications is that no critical review is carried out here in accordance with section 7 of ISO 14040, as the results are discussed by a broad, competent and purely knowledge-orientated body in the SYMOBIO project team.

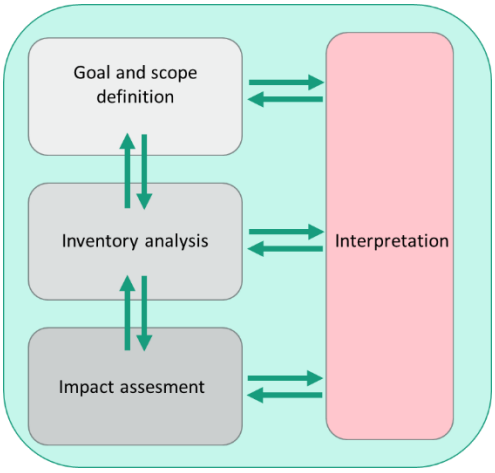


Figure 1: Life cycle assessment framework following ISO 14040 and ISO 14044

The results should provide a reliable overview of all environmental issues identified as relevant in the case studies under consideration. To this end, scenarios of complete life cycles are modeled for the individual biomass and product types. As the entire life cycle of a product is examined, the term "product systems" is used rather than "products"

Some key terms that are important for interpreting and assessing the relevance of impact assessment results in the LCA are explained below on the basis of the four phases "Goal definition and scope of investigation", "Life cycle inventory", "Impact assessment" and "Interpretation" and illustrated using examples of land use and land quality.

2.2 Step 1: Goal definition and scope of investigation

2.2.1 Basic rules for defining the goal and scope of the investigation

The goal definition is the fundamental step in an LCA, as it defines the questions to be answered by the study: What is the interest in knowledge? It also implies which questions will not be answered. This principle is often underestimated, as product systems can generally raise numerous questions that can be investigated due to their high level of complexity. It is therefore a question of limitation and focus.

The decisive step of limitation is carried out by defining the scope, the phase of the LCA in which the framework conditions are determined in consistency with the target definition. The FU and the reference flow are two central definitions here.

In ISO 14044 (2006) (section 3.20), the FU is defined as follows: *"quantified benefit of a product system for use as a reference unit".* This means that based on a defined benefit, those product variants that fulfill this benefit are defined.

Based on this FU, the quantities of materials contained in the product are calculated per unit of consumption, using these consumption units as the basis for material goods. As a reference flow, these masses form the basic framework for data collection in the Life Cycle Inventory. The areas used for the provision of raw materials and for the production, transportation and disposal during the life cycle of a material good must be taken into account.

Services are intangible goods for which a FU and the corresponding reference flow must also be defined. All areas that are occupied to provide the service must be taken into account.

Furthermore, in phase 1 of the LCA - starting from the defined product - the manufacturing processes (from raw materials to production and disposal) are analyzed. This defines the technical system boundary of the product system. In addition, temporal and geographical system boundaries, cut-off rules and the handling of allocation are defined.

2.2.2 Application in the case studies

The aim of the case studies is to obtain an overview of environmental behavior, based on selected specific product systems:

- that adequately addresses the complexity of these product systems,
- considers the different options of the systems,
- and in each case makes a comparison with functionally equivalent non-biobased products.

The framework definitions or rather system boundaries are listed at the beginning of the respective chapters on the case studies (see 3.1.2, 3.2.2, 3.3.1.).

2.3 Step 2: Life cycle inventory

2.3.1 Basic rules of the life cycle inventory

In the life cycle inventory, all production and disposal processes that play a role in the product system are quantitatively analyzed in terms of their inputs (resources) and outputs (emissions to water and air). The quantification is based on the reference flow, which generally reflects the FU. The inputs and outputs are first determined for all processes considered in the product system (usually with recourse to databases) and then added together.

In the case of emissions, the masses of emissions, i.e. acidic emissions (e.g. sulphur dioxide), toxic emissions (e.g. heavy metals) or emissions with global warming potential (e.g. carbon dioxide), from all analyzed processes of the product life cycle are quantified and added up. At the life cycle inventory level, these quantities are referred to as data categories and are presented in physical units (e.g. kg of carbon dioxide per unit of product). Inputs that come from outside the system and outputs that leave the system boundary should always correspond to elementary flows, i.e. they are taken from or enter the natural environment. Non-elementary material flows (e.g. secondary materials, by-products) that originate from or enter other technical systems require a system allocation. Figure 1 shows the exemplary flow diagram of a life cycle inventory taken from the ISO standard within the system boundary.

The processes in the life cycle of a product take place at different locations (global supply chains) and also at different times. The life cycle inventory result of emissions can therefore not be converted into a locally attributable emission. This results in the low spatial and temporal resolution mentioned above.

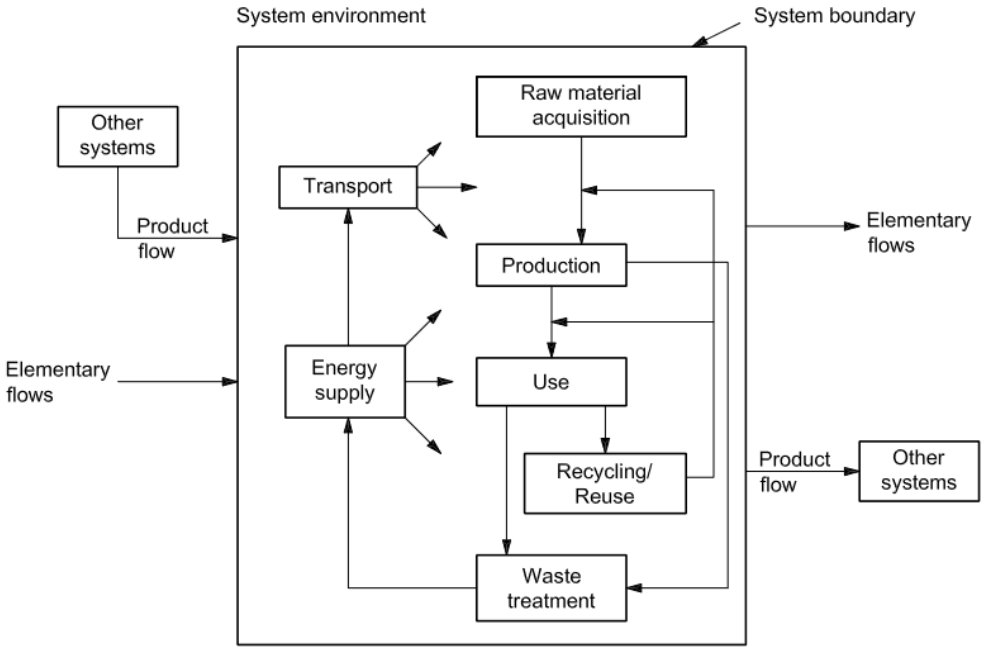


Figure 2: Example of a product system for a life cycle assessment at the life cycle inventory level (source: (ISO 14040 2006))

Depending on the data basis used, a life cycle inventory can be very extensive in terms of the number of data categories. In principle, the collection of data categories should be based

on the categories of the impact assessment that are to be considered (see next section). A key requirement here is the symmetry of the data categories. These can be very comprehensive for one process, while the number appears limited for other processes. Particularly in the case of toxic emission outputs, the data basis may not cover the various processes uniformly. This must be taken into account in the interpretation. It may be necessary to omit consideration of an impact category due to data asymmetry in the life cycle inventory.

2.3.2 Special topic allocation:

According to 14044 (2006) Section 4.3.4.2, allocation should be avoided wherever possible. In most cases, system space expansion is used as an avoidance measure - whereby it has become common practice to equate the so-called substitution method with system space expansion. However, there is no uniform position on this among experts (Weidema 2014). In cases where allocation cannot be avoided, physical relationships should be preferred according to the ISO standard. However, there may also be cases in which the economic value of the products is justified as the decisive factor.

The choice of allocation methods is of great importance for the result of an LCA and can even have a decisive influence on the result. Since there is no scientifically correct allocation method, conventions are required here. These conventions must be analyzed to determine whether their application violates basic scientific laws (especially the consistency of the mass and energy balance).

Process allocation is usually based on physical criteria (mass/energy). In these cases, the mass and energy balance of the processes is scientifically consistent. If an economically weighted mass- or energy-based allocation is carried out, the consistency is no longer readily apparent, but can be derived from the basic data if these are documented.

The system allocation for modeling the End-of-Life (EoL) flows (open-loop; material and energy recovery in product systems other than the one under investigation) usually has a significant influence on the result. For this reason, ISO 14040/44 stipulates that at least two methods must be examined and discussed as sensitivities (for publicly available comparative studies). As not all methods meet the requirement for consistent mass and energy balances across all product systems, careful evaluation is essential here.

The choice of allocation procedure for handling EoL flows (open loop) results in the rules for the credit and debit entries of the defined systems.

2.3.3 Application in the case studies

As for the applied **data bases**, a comprehensive amount of data is available to ifeu from various studies in its own data models. These include data and material flow master systems for electricity, fossil raw materials and refineries, a model for various forms of biomass use, and a model for PtX processes. In addition and where available, LCI data are taken from ecoinvent data sets are included as well as further process and LCA information from literature reviews.

With regard to **allocation**, a different variant can be applied to each of the three case studies:

- a **market price allocation** is used for the **construction beam** case study, but this is only relevant for the sawmill process (sawn timber versus sawmill by-products). The alternatives here would be: mass allocation would lead to equal treatment of sawn timber and sawmill by-products. The same applies to energy allocation, as the two co-products do not differ in terms of energy content. Or a cut-off that declares the by-products to be waste and allocates all costs to the main product.
- An **energy-based allocation** was carried out in the **ethylene** example. This is particularly relevant for crop-based variants, where the handling of by-products from ethanol production is important. The decision to use an energy-based allocation is based on aligning the approach for this example with the RED method.
- In the **textile** case study, on the other hand, a **mass-based allocation** approach was chosen, in particular with regard on the downstream processes from Ethylene towards PET production and PET fibre production; the same is true for hard wood viscose (wood completely used, no relevant co products).

2.4 Step 3: Impact assessment

2.4.1 Basic rules of impact assessment

In the third phase, the impact assessment, the life cycle inventory data is bundled with regard to the environmental impacts to be examined. The aim is to better understand the environmental relevance of the life cycle inventory results.

Which environmental impacts - called impact categories in LCA - are to be considered in a study must be determined in the first phase (goal and scope definition of the study). This is particularly important because the data to be collected in the life cycle inventory must be geared to the needs of the impact assessment.

Common impact categories include climate change, eutrophication, acidification and stratospheric ozone depletion. However, toxicity (human- and ecotoxicity) is also the subject of model developments in the context of LCA. Figure 1 shows the basic procedure for impact assessment based on characterization models. In the first step, the life cycle inventory data is qualitatively assigned to an impact category (classification). In the second step, characterization, the potential impact is quantified: on the basis of a cause-effect model used in the characterization model, the life cycle inventory data is converted into an impact indicator value using characterization factors specific to the model.

For all characterization factors used in the LCA, their justification logic is based on a characterization model. ISO 14044 (2006) Section 4.4.2.2.3 e) states that the characterization model for each impact indicator should be scientifically justified and technically valid. It should be based on a clearly identifiable environmental impact mechanism or a comparable empirical observation.

There are different models for describing cause-effect chains for most impact categories. The choice of characterization model depends on which areas of protection are being considered. Which model is used in an LCA study must be clearly described in the "goal and scope definition" phase.

Regional or local risks cannot be mapped with the impact indicator results. The reason for this is that real existing concentrations at a defined location under the geological and meteorological conditions prevailing there and the resulting exposures of protected goods (e.g. human health, aquatic ecosystems) must be known. The LCA does not provide this data. The term "potential environmental impacts" emphasizes the fact that the numerical results of the impact assessment are not actual effects in the environment that can be allocated in terms of location and time.

The temporal scope of the characterization model may differ from that of the life cycle inventory, as effects can also have a temporal dynamic. For example, to calculate the characterization factors of the IPCC GWP100, the greenhouse gas effect of the corresponding gases is modelled over a period of 100 years.

2.4.2 Application for the case studies

The selection of impact categories is primarily based on the list of SYMOBIO 2.0 footprints that need to be covered. In addition, categories that address other impacts are included in order to identify any potential gaps in the SYMOBIO 2.0 footprints, should such gaps be detected through this process.

Table 1: Assignment of different characterization approaches from LCAs to the SYMOBIO 2.0 footprints

SYMOBIO 2.0 footprints	Characterization approaches from LCAs
Material footprint (WP2.3)	• Abiotic depletion • Cumulated raw material expenses • Raw Material Index (RMI) • Total Material Requirement (TMR)
Agricultural land footprint (WP2.4)	• Land occupation (life cycle inventory figure) also differentiated according to corine land-use classes • Land rucksack (Fehrenbach et al. 2022)
Water footprint (WP2.5)	• Water as an inventory variable, partly differentiated according to "blue", "green", "gray" water • after water shortage according to AWARE
Climate footprint (WP2.6)	• GWP100 (GWP20) Dealing with C-memory and time dimension (previously only considered in LUC)
Biodiversity footprint (WP2.7)	• UNEP SETAC lifecycle initiative (Koellner et al. 2013) • Biodiversity Value Increment (Lindner et al. 2019) • Distance to nature potential (DNP) (Fehrenbach et al. 2022) • (Chaudhary and Brooks 2018)

The *forest footprint* from the list of SYMOBIO footprints describes the amount of primary wood raw material or raw wood that is felled for the production or consumption of wood-based products and is not listed as an impact category.

Table 2 shows the selection of impact categories and characterization models for the case studies. It also lists the impact indicator used in each case and, where applicable, the corresponding SYMOBIO 2.0 footprint.

Table 2: Selection of impact categories and characterization models for the case studies

Impact categories of the LCA	Indicator used	Corresponding SYMOBIO 2.0 footprint
• Resource utilization	• Water consumption	• Water footprint
• Use of natural space		• Agricultural land footprint approach, but only at life cycle inventory level
• Biodiversity loss	• Distance to nature potential	• Biodiversity footprint
• Climate change	• GWP100 in CO_2 equivalents (taking ISO 14067 into account)	• Climate footprint
• Acidification	• Acidification potential (AP) in SO_2 equivalents (CML v4.8 2016)	*No equivalent*
• Eutrophication	• Aquatic Eutrophication potential (EP) in PO_4^{3+} equivalents	*No equivalent*
• Toxic effects	• Respiratory inorganics (particulate matter, PM2.5 equivalents)	*No equivalent*
• Stratospheric ozone depletion	• Nitrous oxide (N_2O)	*No equivalent*

2.5 Step 4: Interpretation

2.5.1 Basic rules of interpretation

In the interpretation phase, conclusions are drawn from the results of the life cycle inventory and the impact assessment. Considering all limitations and the set boundary conditions, recommendations are made against the background of the objectives of the study. The interpretation therefore goes far beyond a simple comparison of the results of the impact assessment and selected life cycle inventory data (e.g. energy consumption).

According to ISO 14044, the interpretation phase of a LCA comprises the following components:

- Identification of significant parameters based on the results of the life cycle inventory and impact assessment,
- An assessment that takes into account the completeness, sensitivity and consistency checks,
- Conclusions, limitations and recommendations.

As optional components of the impact assessment, ISO 14044 (2006) contains normalization and ranking, which are well established as an aid for the interpretation. The UBA has already integrated both elements into its method for interpretation in LCAs (Schmitz et al. 1999). Joint Research Center (JRC) offers standardization factors on a global level (Sala et al. 2017).

ISO 14044 (2006) defines normalization as the calculation of the magnitude of the impact indicator values in relation to the reference information. As such, per capita loads are generally used, such as the average greenhouse gas (GHG) emissions (as GWP100) of a resident of Germany, Europe or the world. In this way, normalization is used to assess the relative significance of the indicator results (Schmitz et al. 1999).

With the ranking, the impact categories are classified according to a hierarchy such as high, medium and low priority. This is necessarily based on "values", on which the different significance of the individual impact categories is determined. The Federal Environment Agency, as also recommended in ISO 14044 (2006), determined this priority as an "organization" on the basis of its own "values" (Schmitz et al. 1999). Definable characteristics such as global, regional or local impact, reversibility/irreversibility can serve as criteria for ranking. The Federal Environment Agency initiated an internal process to update the rankings back in 2013. This process has not yet been completed.

2.5.2 Normalization

Normalization helps to better understand the relative magnitude of the results for the different environmental impact categories. To this end, the category indicator results are set into relation with reference information. Normalization transforms an indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected area. The reference information is the annual average resource demand and the average emissions of various substances per capita in Europe, the so-called inhabitant equivalent (IE) (Sala et al. 2017).

Table 3: Selection of impact categories and characterization models for the case studies

Impact categories of the LCA	Inhabitant equivalent (IE)	Unit per capita and year
GWP100	9159	kg CO_2 eq
Acidification, terrestrial	31.4	kg SO_2 eq
Eutrophication, freshwater	3.32	kg P-Eq
Particulate matter formation	23.1	kg PM2.5-Eq
N_2O emissions	1.73	kg N_2O
Land-use	4.33	m^2*a crop-Eq
Distance-to-nature potential (DNP)	1.13	m^2 aA-Eq*a
water use	61.2	m^3

Source: (Sala et al. 2017)

3 Selection of case studies

The following considerations were taken into account when selecting the case studies; The examples should

- be relevant to the bioeconomy in terms of quantity;
- demonstrate significant substitution potential; and
- be associated with progressive and forward-looking practices.

The case study on **construction timber** is particularly relevant in terms of quantity, as the construction sector is one of the most material-intensive sectors of all and timber has the highest volume and potential in the biomass sector (Hennenberg et al. 2023). Furthermore, the expansion of timber construction is a key strategy within the bioeconomy (Alfter et al. 2021).

For the chemical sector (especially the organic sector), moving away from fossil raw materials is a particularly big challenge because of its dependence on carbon. All three criteria also apply to the use of biomass for the production of basic chemicals (such as **ethylene**).

The same applies to the textile industry, which is largely dependent on the chemical industry as a processor of semi-finished products (keyword: dominance of synthetic fibres in the global market). However, the **textile fibre** market shows further possibilities for the use of biomass as a raw material.

This paper refers to these three case studies. They are described in more detail below.

3.1 Construction beam

3.1.1 Description of the options

In this case study, various options for a constructional load-bearing element (hall beam) with a span of 10 m are considered. The functional unit considered here is the support of an (equal) ceiling load and the spanning of a defined space.

The following versions of hall beams are considered:

1. Beam from glued laminated timber (Glulam) based on beech wood (hard wood),
2. Beam from sawn timber based on spruce wood (soft wood),
3. Steel,
4. Reinforced concrete.

To ensure that the (safety) technical aspects of these different load-bearing systems, which are typical for the construction of smaller industrial halls, are comparable, this case study refers to the detailed elaborations on this in Albrecht et al. (2008). Detailed information on the technical properties of the beams can therefore be found in Albrecht et al. (2008).

The dimensions and load are the same for all three systems: they have a span of 10 m and a load of 11.60 kN/m (without the dead weight of the beam).

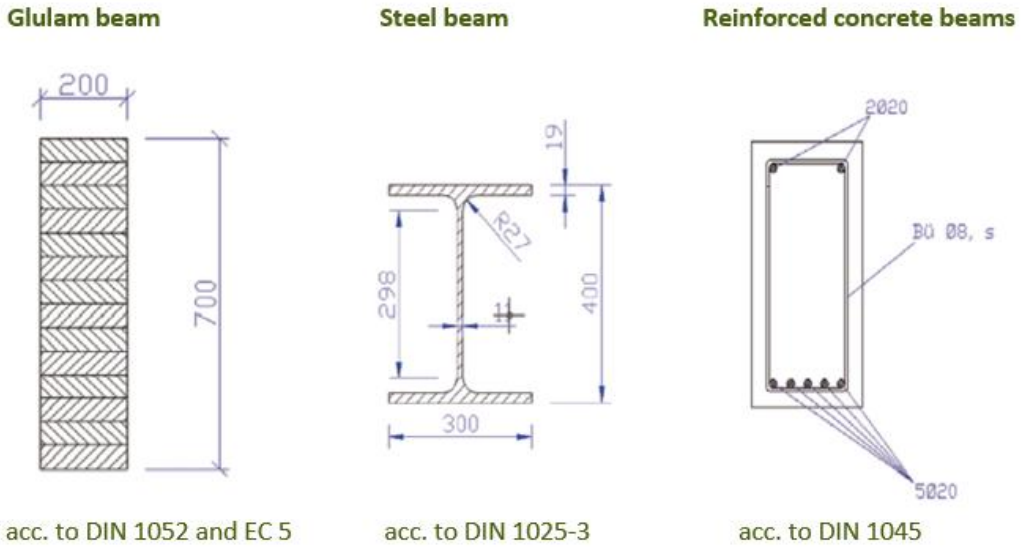


Figure 3: Structure of the three beams (side view): Source: (Albrecht et al. 2008), translated

3.1.1.1 Glulam beams (according to DIN 1052 /24/ and EC5)

On the basis of the values for glulam according to Albrecht et al. (2008) (w = 200 mm; h = 700 mm; l = 10.40 m), a required volume of **1.5 m³ of timber** was calculated.

The beam made from glued laminated timber lamellas (individual board thicknesses generally 33 mm, lamella width max. 220 mm) contains less than one percent polycondensation adhesive, which is not taken into account in this example.

According to Albrecht et al. (2008), spruce wood is most commonly used for glulam production, but other softwoods such as fir, pine, larch or Douglas fir are also used.[1] In this case study, a glulam beam manufactured from **beech wood (hard wood)**[2] or **spruce (soft wood)** are considered.

3.1.1.2 Steel beams (according to DIN 1025-3)

Based on the information on the dimensions of the hot-rolled I-steel girder (HEA profile; w = 300 mm; h = 400 mm; l = 10.40 m) in Albrecht et al. (2008) a required **steel quantity of approx. 1,206 kg** was calculated.

Steel is produced using the electric steel process or the oxygen steel process via the blast furnace route. It is important to briefly address this in this example, as the electric steel

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[1] https://www.brettschichtholz.de/brettschichtholz-bs-holz/holzarten/mn_42532

[2] Glulam made of beech wood has so far been approved for service class NKL 1, which applies to heated interiors in accordance with DIN EN 1995-1-1.

process is operated exclusively with steel scrap, whereas the blast furnace route only uses around 20% steel scrap on average and iron ore is required for the remaining 80%. The energy requirements of the two processes also differ greatly. The ratio of electric steel to oxygen steel in Germany is currently 30 : 70 (BDSV 2018). Across Germany in 2019, according to Szombathy (2020), the proportion of scrap in crude steel production across both processes averaged 44.6%.

According to Haidar et al. (2018), construction steel profiles from Germany are made from 100% scrap. The collection rates for reinforcing steel are not quite as high. Depending on the database, construction steel is produced entirely via the blast furnace route or entirely via the electric steel route. The production of blooms for hot rolling is possible via both routes.

In addition to other raw materials that are not relevant in terms of quantity, 1.1 tons of iron ore, 0.5 tons of steel scrap and 0.4 tons of coke were used per ton of steel product. These average figures are used in this example.

3.1.1.3 Reinforced concrete beams (according to DIN 1045)

The third type of beam presented is a reinforced concrete beam (w = 300 mm, h = 600 mm, l = 10.40 m) consisting of two construction materials: Concrete and steel for an incorporated reinforcement cage. Based on the information in (S. Albrecht et al. 2008), **a concrete quantity of 1.85 m³** and **a steel quantity of 203 kg** for the reinforcement grid (reinforcement cage) can be estimated for the reinforced concrete beam under consideration.

According to the information in Albrecht et al. (2008), a concrete of strength class C 25/30 was selected for the concrete in this example.

Derived according to (BET 2009; Biscoping and Kampen 2017) a normal concrete of strength class C25/30 contains approximately the following quantities per cubic meter: 285 kg of cement, 200 l of water and 1,900 kg of aggregates. In our example, this results in approx. 526 kg of cement and 3,508 kg of aggregates. A mixture of sand and gravel is assumed for the aggregates.

A CEM I (Portland cement) is selected as the cement type. Other types of cement with fly ash content, for example, could also be considered for production, but for conservative reasons a pure Portland cement clinker is assumed here. Limestone and clay or their natural mixture, limestone marl, are required for the production of Portland cement clinker. In this example, the extraction of limestone for the entire amount of cement is considered for simplification purposes.

According to the environmental data report of the German cement industry (VDZ 2022), an average of 2,807 MJ of fuel energy and 115 kWh of electrical energy were used to produce one ton of cement in Germany in 2019. Nowadays, alternative fuels (waste such as used tires, spent solvents, sewage sludge, plastic waste or sorting residues from packaging waste collection), are used to a large extent in the clinker process. In 2023, this accounted for 74% of the total fuel energy used in the German cement industry. The use of fossil fuels, such as hard coal and lignite in particular, now only accounts for around 26% of fuel energy input.

Since the alternative fuels are waste products of other systems that already carry this load, they are not assigned a load in this case.

In the case of fossil fuels, the proportion of lignite clearly outweighs the other fossil fuels and is used in this example as a simplification for the total amount of fossil fuels required to produce the cement.

For the production of the cement in the reinforced concrete beam considered in this case study, this results in **0.06 MWh of electricity** from the German electricity mix and **25 kg of lignite** (calorific value 15 GJ/ton of lignite) (Drosihn et al. 2017).

The same considerations apply to the production of the steel in the reinforced concrete beam as for the steel in the steel beam.

3.1.2 Assumptions and system boundaries

The assumptions made for each beam production route with regard to its raw material and, in some cases, its processing is listed below.

1. **Beam from hard wood (Beach)**
   a) Starting material
      Sawlog harvested in Germany and Sweden from hard wood

   b) Process
      Sawlog is processed in a sawmill to sawnwood and dried (air; oven) afterwards to produce a beam from hard wood using 1.5 m^3 of the sawnwood

   c) Transportation
      Raw material is collected and transported to sawmill via lorry, beam is transported from producers to consumers via lorry and train, Transport distance based on eurostat transport statistics

2. **Beam from soft wood (spruce)**
   a) Starting material
      Sawlog harvested in Germany and Sweden from soft wood

   b) Process
      (see beam from hard wood)
   c) Transportation
      (see beam from hard wood)

3. **Steel beams**
   a) Starting material
      1.1 tons of iron ore, 0.5 tons of steel scrap and 0.4 tons of coke were used per ton of steel product

   b) Process
      This activity describes the production of primary (carbon, unalloyed) steel using the basic oxygen furnace (BOF) process:
      I) Pretreatment of hot metal (pig iron) from the blast furnace (f.e. desulphurization and deslagging)

II) Oxidation in the BOF
III) Secondary metallurgical treatment in a ladle furnace
IV) Casting of the steel

c) Transportation
from producer to consumer is considered

4. **Reinforced concrete beams**

a) Starting material
concrete quantity of 1.85 m³ and a steel quantity of 203 kg for the reinforcement grid (reinforcement cage)

b) Process
For the production of the cement in the reinforced concrete beam considered in this case study, this results in 0.06 MWh of electricity from the German electricity mix and 25 kg of lignite (calorific value 15 GJ/ton of lignite) The same considerations apply to the production of the steel in the reinforced concrete beam as for the steel in the steel beam.

c) Transportation
from producer to consumer is considered

3.1.3 Results

In the following part, a comparison of the environmental impacts of the above mentioned conventional and bio-based products are displayed and will be plausibility checked and discussed in more detail. Subsequently the normalized impacts are presented in a comparable way.

3.1.3.1 Results per impact indicator

All impact categories discussed in table 2 are analyzed and the results displayed and discussed below.

3.1.3.1.1. Freshwater consumption

Figure 4 illustrates the freshwater consumption (measured in cubic meters, m³) associated with the life cycle of the analyzed beam types. It can be seen that steel beam has approx. three to ten times higher freshwater consumption compared to all other beams, deriving mainly from the “steel production” (approx. 90% - data not shown). Other beams, such as wood-based and reinforced concrete beams, exhibit much lower freshwater usage.

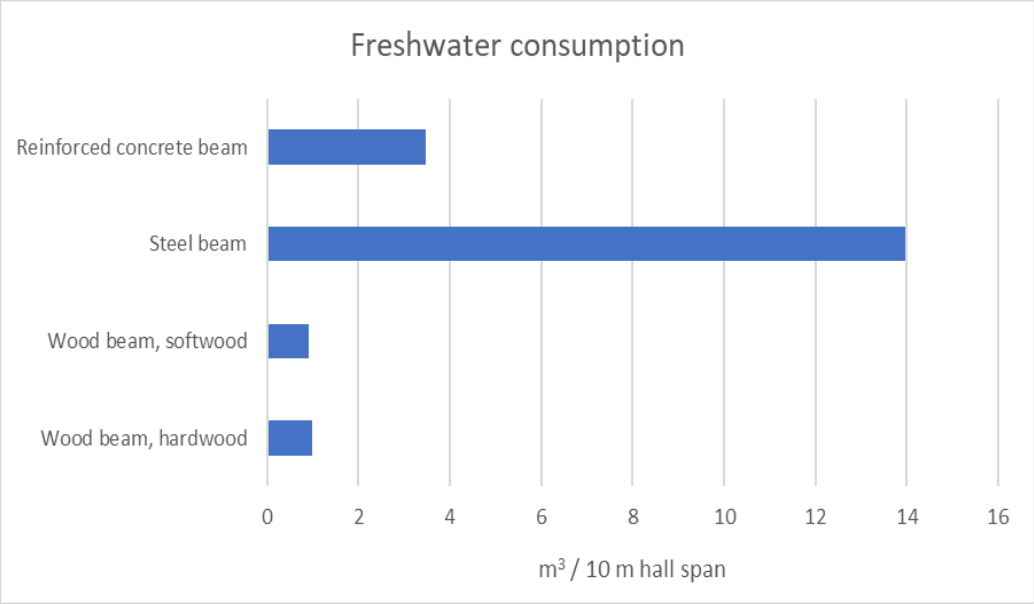


Figure 4: Results for beams from different materials for a 10 m hall span in the impact category "freshwater consumption"

3.1.3.1.2. Climate Change (GWP100)

Figure 5 presents the impact of the different beam types on climate change, measured in kg CO_2 equivalents. Among the beams, the steel beam exhibits the highest climate change impact (approx. 2100 kg CO_2-eq), followed by the reinforced concrete beam. Emissions are dominated by steel production (consumption of fossil energy and coke); reasoning more than 90 % of the CO_2-eq emitted. For the wood-based beams it is mainly the sawing (approx. 65%) and its transport (approx. 25%) that have an impact on climate change.

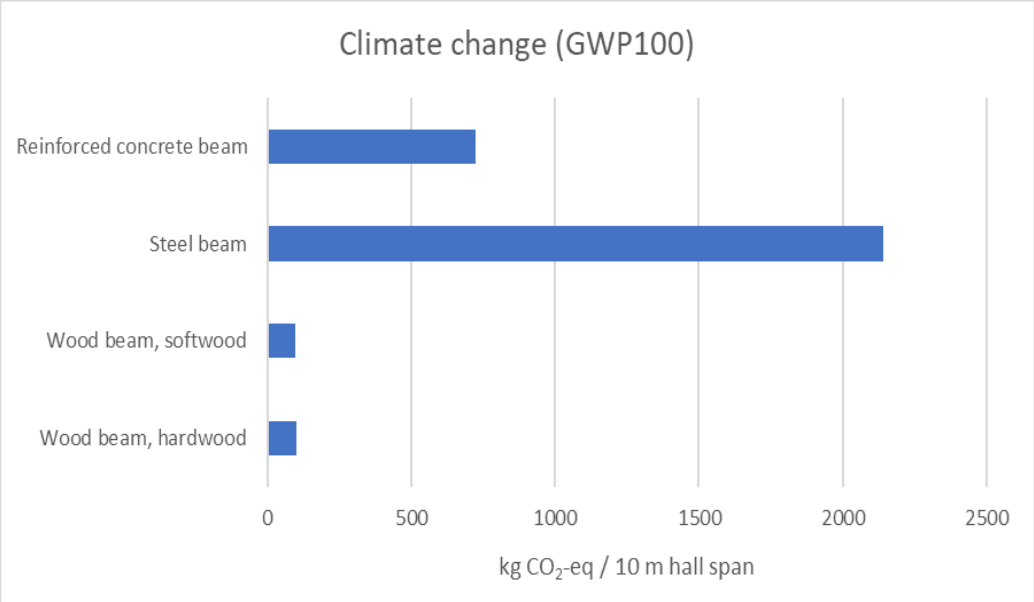


Figure 5: Results for beams from different materials for a 10 m hall span in the impact category "Climate change (GWP100)"

3.1.3.1.3. Terrestrial acidification

The following figure illustrates the different contributions to terrestrial acidification (in SO_2-eq) of beams from different materials, necessary for the construction of a 10 m span hall. Notably a beam from steel has a four to sixteen times higher impact on acidification compared to any other beam (in this study). The impact of a steel beam is mainly influenced by provision of the raw material (iron) and its processing (utilization of coke in the sinter process). For wood-based beams the impact in terrestrial acidification is mainly dominated from sawing and transport (comparable with GWP 100).

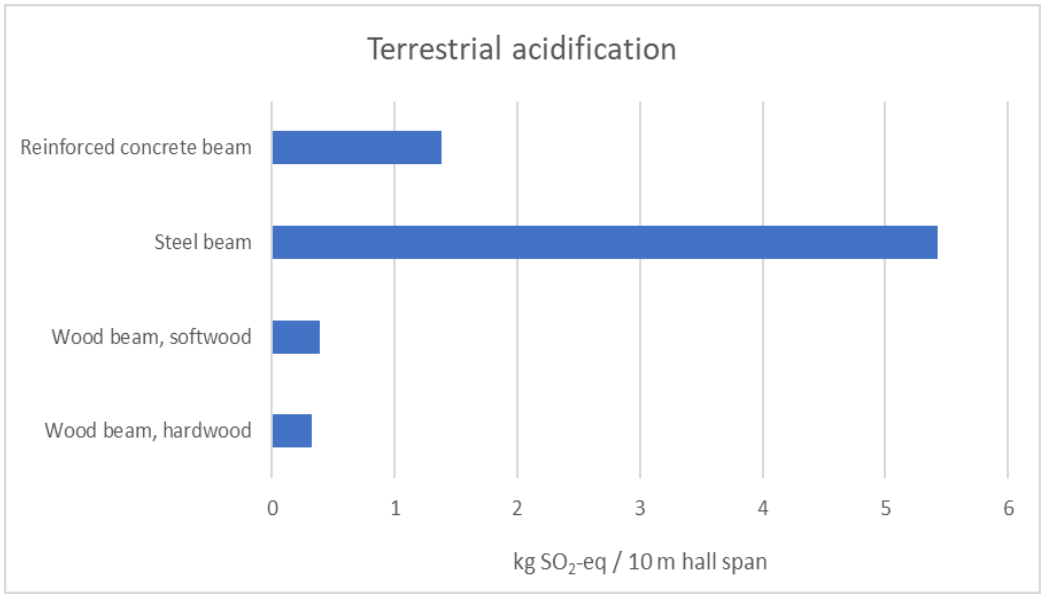


Figure 6: Results for beams from different materials for a 10 m hall span in the impact category “Terrestrial acidification”

3.1.3.1.4. Freshwater eutrophication

Figure 7 shows the impact of various beam types on freshwater eutrophication, measured in kilograms of PO_4 equivalents (kg PO_4-eq). The steel beam shows the highest impact on freshwater eutrophication, with emissions primarily resulting from steel production and the use of coke and hard coal. Reinforced concrete beams exhibit approximately a quarter the impact of steel beams and wood-based beams (soft- and hard-wood) display 5% of the impact of a steel beam in fresh water eutrophication.

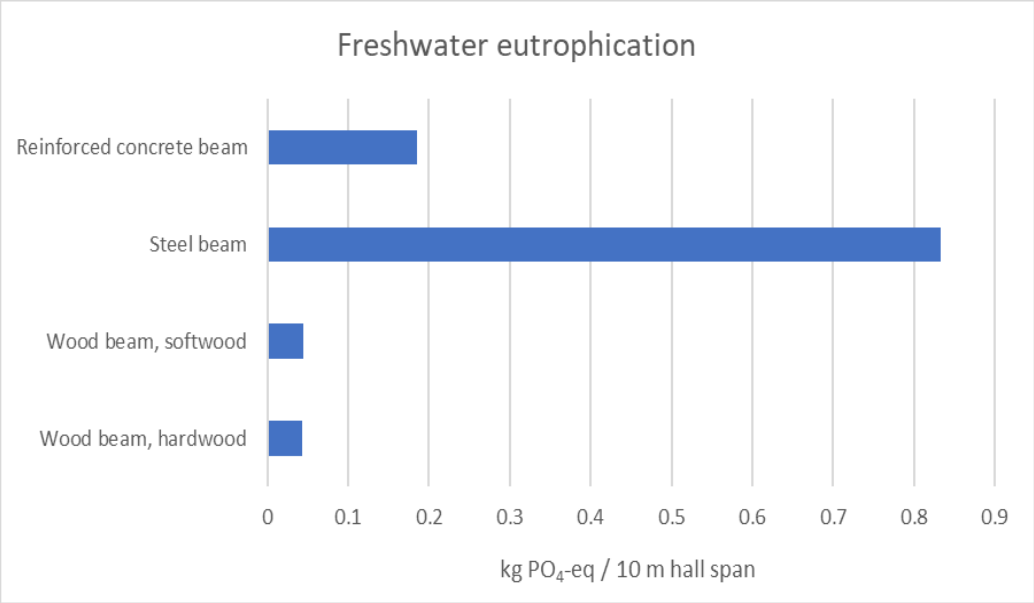


Figure 7: Results for beams from different materials for a 10 m hall span in the impact category “Freshwater eutrophication”

3.1.3.1.5. Toxic effects (particulate matter formation (PMF))

Figure 8 depicts the impact of various beam types on toxic effects related to particulate matter formation, measured in kilograms of PM2.5. Steel beams exhibit the highest total toxic effects, each approaching 3.1 kg PM2.5, with the majority of these emissions resulting from steel production and the use of coke and hard coal within this process step. Reinforced concrete beams show approx. 25% of the fine particulate matter formation and wood-based beams only 5% compared to the particulate matter formation associated with the steel beam.

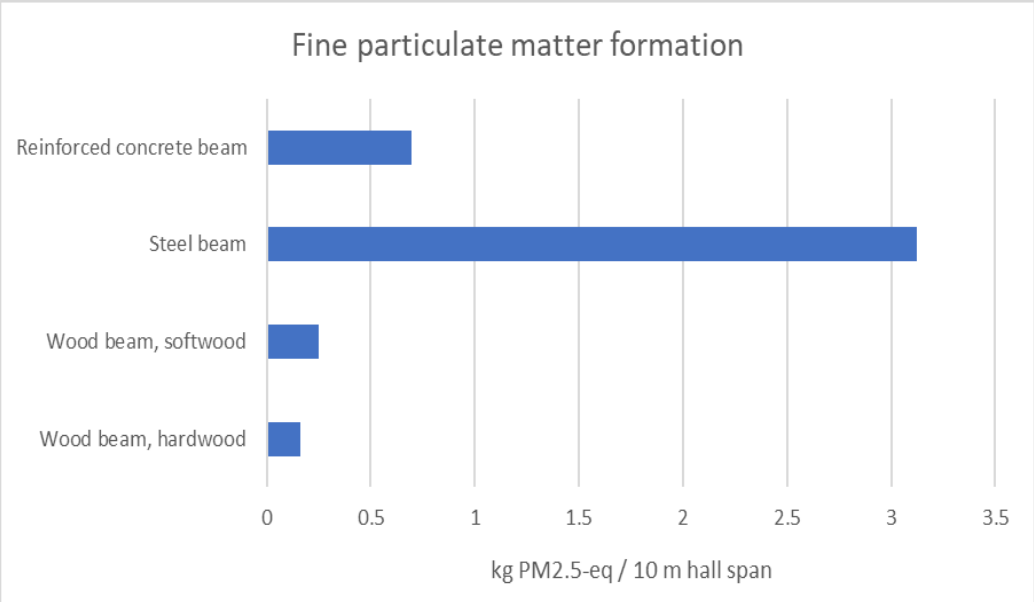


Figure 8: Results for beams from different materials for a 10 m hall span in the impact category “Fine particulate matter formation”

3.1.3.1.6. Stratospheric ozone depletion (nitrous oxide)

Figure 9 illustrates the impact of various beam types on stratospheric ozone depletion, measured in kilograms of N_2O equivalents (kg N_2O-eq).

Steel beams demonstrate the highest level of ozone depletion, with an impact of approximately 2.2E-02 kg N_2O-eq., predominantly resulting from raw material extraction. Followed by reinforced concrete beam, which shows only 25% of the impact of a steel beam and wood-based beams showing only 20% of the impact of steel beam.

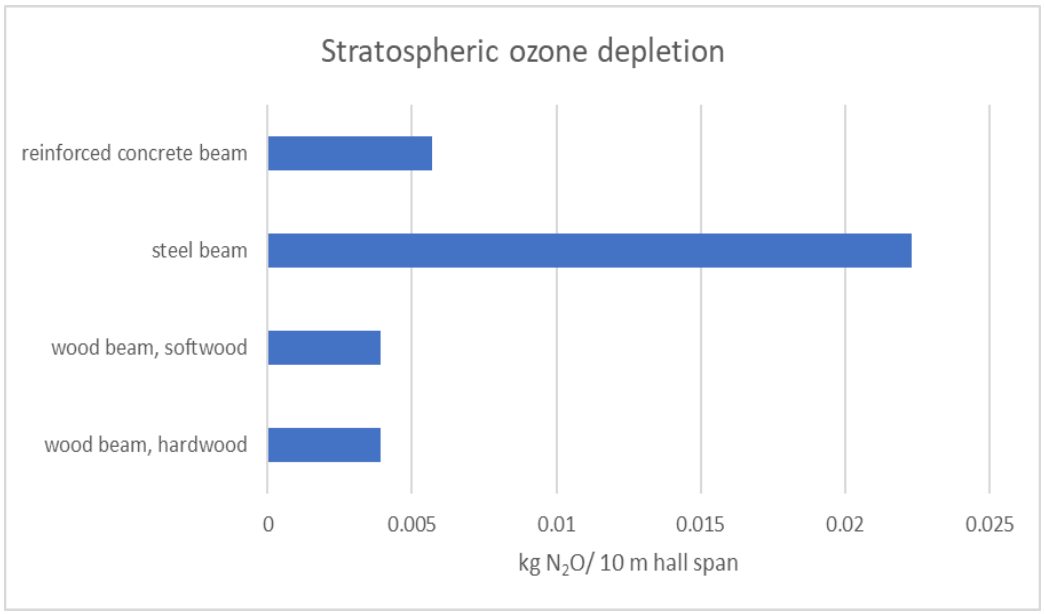


Figure 9: Results for beams from different materials for a 10 m hall span in the impact category “stratospheric ozone depletion (nitrous oxide)”

3.1.3.1.7. Biodiversity loss (distance to nature potential)

The following figure shows how the different beam types influence biodiversity; the characterization was made using the indicator *distance to nature potential* (DNP). Here the land use associated with the provision of the respected beam is multiplied by the factor that derived from the hemeroby classes of the raw materials used.

Wood beams made of softwood show the highest impact on biodiversity loss. Wood beams from hardwood (which means broadleaf wood, respectively beech, which is the tree species that occurs naturally in German forests) cause half of the effects. This is mainly reasoned by the higher hemeroby class of softwood (which means coniferous wood such as spruce or pine, growing predominantly in monoculture-type of forests) compared to hardwood (which grows mostly in mixed culture). The smallest influence is caused by reinforced concrete beams (11 m^2 aA-Eq*a per 10 m hall span).

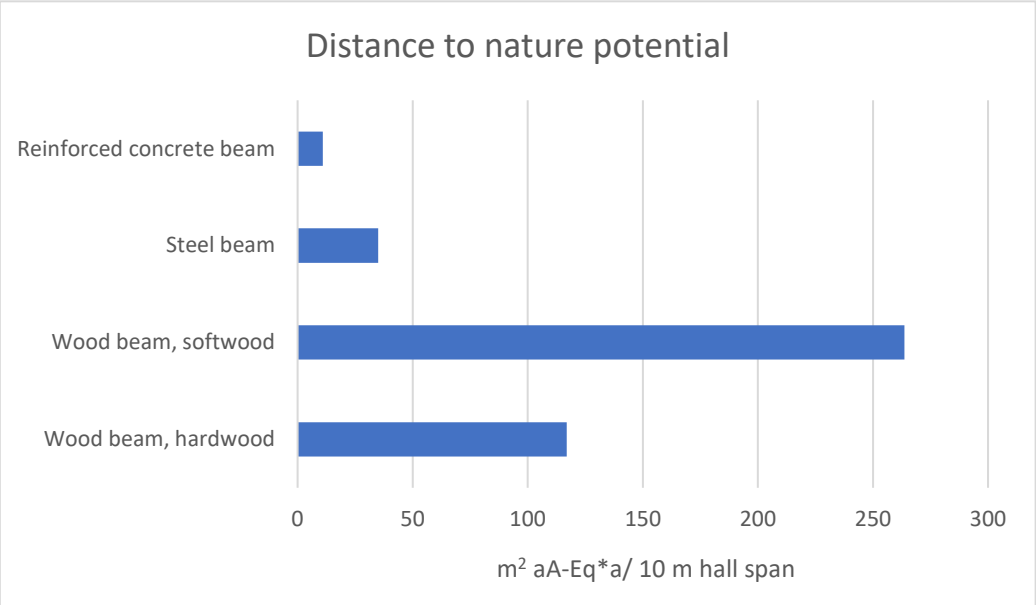


Figure 10: Results for beams from different materials for a 10 m hall span in the impact category "Distance to nature potential"

3.1.3.2 Normalization of impact indicator results

In Figure 11, normalized results for all studied cases in all environmental impact categories are displayed to enable a better comparability of results in different categories. Negative results can be interpreted as saving compared to the comparative while positive results come along with higher emissions compared to the comparative.

How to read Figure 11: The bars in the graph show the normalized emissions (see chapter 4.1.4) from the HIGFLY process in relevant environmental impact categories for all scenarios and variations. Positive values mean an increased impact of the HIGFLY process compared to fossil-based kerosene, while negative values can be interpreted as saving in this very impact category.

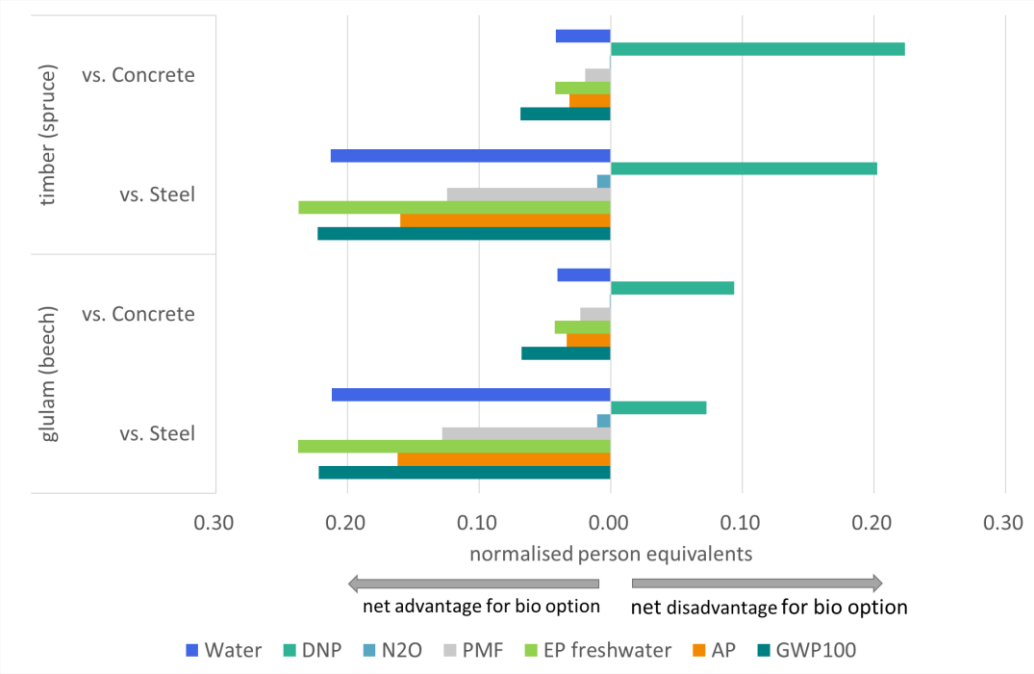


Figure 11: Comparison of normalized results for different beams (bio-options vs. non-bio-options)

The comparison of all impact categories shows a homogeneous picture of the environmental performance of the bio-based beams compared to steel or concrete beams, thereby it does not play a role, whether they are based on hard or softwood. Savings are especially high if wooden beams replace steel beams. Impact categories with the highest savings are climate change, eutrophication and water use. The only impact category with a clear increase of impact comparing wooden based beams against steel and or concrete beams is the distance to nature potential, which is driven mainly by the high land demand in this case.

3.1.4 Interpretation

A comparison of the impact of wood-based beams and of concrete or steel beams on the basis of their functionality in carrying a 10-metre span hall was made. The results of this comparison revealed that the substitution of steel and/or concrete beams by wood-based beams is beneficial in all analysed impact categories, except for distance to nature potential (DNP). The substitution of steel beams with wood-based alternatives can be interpreted as highly beneficial in terms of impact categories such as freshwater eutrophication, climate change and water scarcity. The advantages of replacing concrete beams with steel are less significant. The benefits are comparable across different types of wood. It is interesting to note that the choice of wood for the beam has a significant impact on burden as the analysis indicates a clear preference for beech over spruce in the impact on DNP.

Substitution of steel beams with wood-based beams made from beech wood has been shown to combine significant advantages with a reduced burden. This combination of benefits makes the substitution a favourable option.

3.2 Ethylene

3.2.1 Description of the options

This case study compares the base chemical ethylene made from various biomass-based raw materials with ethylene made from petroleum-based raw materials. In addition, a variant of ethylene is included which is manufactured via Pt-X – from renewable energy mix and CCU (carbon capture and utilization) CO_2 from the atmosphere (CCU). All manufacturing inventory data refer to one kilogram of the corresponding ethylene.

The following production routes for ethylene are considered:

1. Fossil-based Ethylene
2. Power-to-X Ethylene
3. Bio-based Ethylene from agricultural biomass (maize)
4. Bio-based Ethylene from agricultural residues (straw)

To ensure comparability, the inventory data is compiled in relation to one kilogram of ethylene as a functional unit.

3.2.2 Assumptions and system boundaries

The assumptions made for each ethylene production route (shown in Figure 12) with regard to its raw material and, in some cases, its processing is listed below.

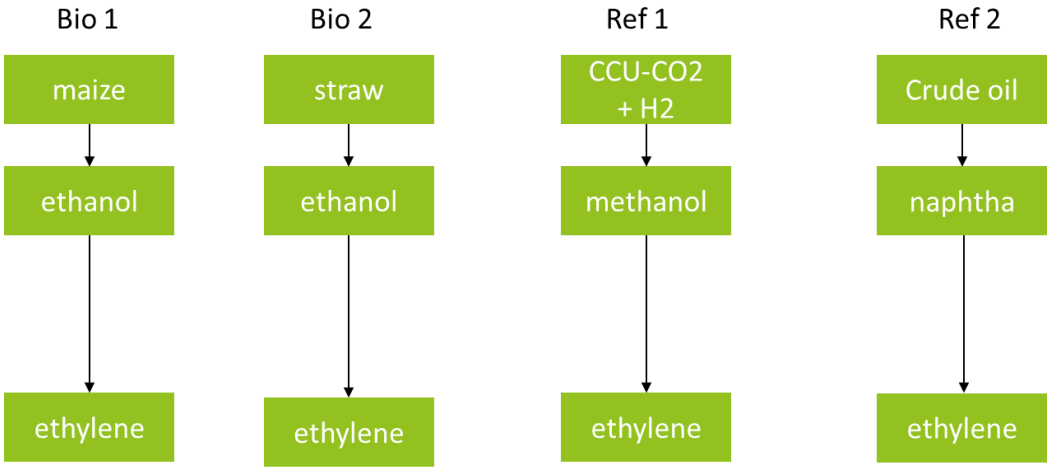


Figure 12: The four production routes considered for ethylene

1. **Bio-based Ethylene from agricultural biomass (maize) (Bio 1)**
   d) Starting material
   Maize is a primary source for the production of ethanol via fermentation

   e) Process
   Ethanol is converted to ethylene via catalytic dehydration

   f) Transportation
   Transportation of biomass is considered

2. **Bio-based Ethylene from agricultural residues (straw) (Bio 2)**
   Starting material
   Straw as a lignocellulose material is hydrolyzed and afterwards fermented to produce ethanol
   Process
   Ethanol is converted to ethylene via catalytic dehydration

   Transportation
   Transportation of biomass is considered

3. **Power-to-X Ethylene (Ref 1)**
   Starting material
   CO2 can be extracted from air via DAC, or from point-source using amine scrubbing. Hydrogen is provided by alkaline electrolysis.

   Process
   CCU products are synthesized and processed for purification.

   Transportation
   Is not considered

4. **Fossil-based Ethylene (Ref 2)**
   Starting material
   Petroleum-based ethylene is mainly produced from fossil naphtha.

   Process
   Naphtha is processed in the steam-cracker unit of a conventional refinery.

   Transportation
   This product is generally considered to be used at the production site. Therefore, the market does not contain any transport.

3.2.3 Results

In the following part, a comparison of the environmental impacts of the above mentioned conventional and bio-based products are displayed and will be plausibility checked and discussed in more detail. Subsequently the normalized impacts are presented, comparing bio-based beams to beams that are based on steel/ and concrete.

3.2.3.1 Results per impact indicator

All impact categories discussed in table 2 are analyzed and the results displayed and discussed below.

3.2.3.1.1. Freshwater consumption

The figure illustrates the freshwater consumption (measured in cubic meters, m^3) associated with the life cycle of Ethylene with different origins. Freshwater consumption is in a comparable range. Ethylene based on straw has the highest consumption of fresh water, since the special fermentation route for straw via ethanol is rather water consuming. Closely behind, Ethylene via PtX is following next, since the electrolysis for green hydrogen production requires water. The water consumption for fossil ethylene results from the number of high temperature processes (refining, steam cracking) which need high rates of cooling water. The lowest demand refers to the bio-ethylene based on maize and required and most of it required by the fermentation process.

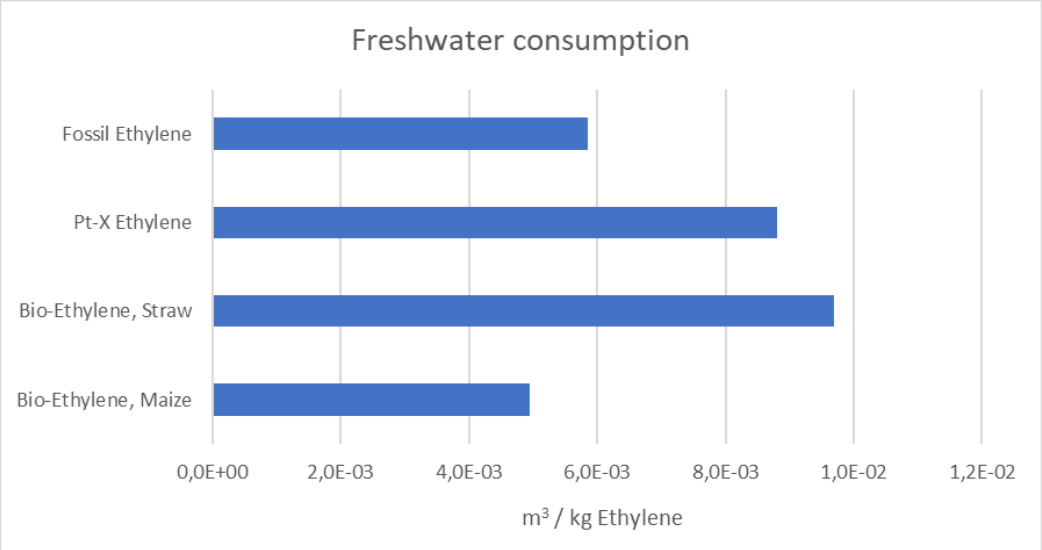


Figure 13: Results for 1 kg of ethylene produced from different raw materials in the impact category “freshwater consumption”

3.2.3.1.2. Climate Change (GWP100)

The figure presents the impact of Ethylene of the different origins on climate change, measured in kg CO_2-equivalents. Among the ethylene types, fossil-based ethylene exhibits the highest climate change impact (approx. 5.2 kg CO_2-eq.), of which two thirds result from end-of-life emission, when the respective product is combusted. Ethylene is based on renewable energy (PtX-based) has the lowest impact in climate change (1.3 kg CO_2-eq.).

The biomass-based ethylene from straw types results close to PtX-ethylene due (1.4 kg CO_2-eq.) while maize-based ethylene leads to clearly higher GHG (2.3 kg CO_2-eq.). This can be explained by the utilization of fossil-based chemicals and energy during its production while the raw material has minor (maize) to no impact (straw) on climate change. These values do not include emissions from land-use change. With the concept of attributional land-use change (aLUC) additional emissions from 0.093 kg CO_2-eq./kg ethylene have to be taken into account. (Fehrenbach et al. 2020)[1]

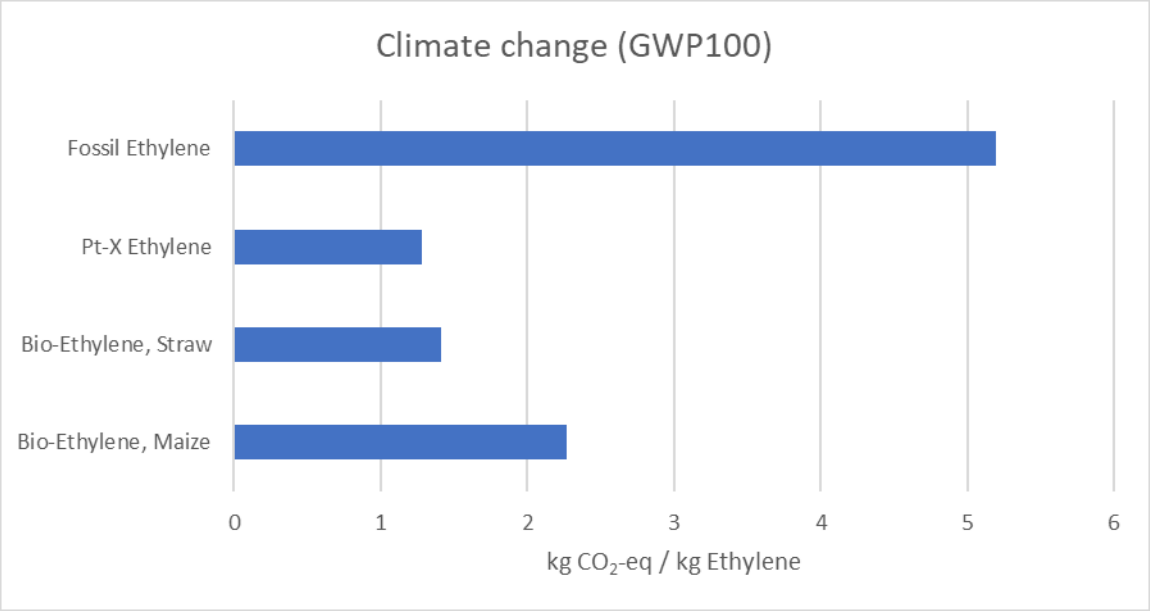


Figure 14: Results for 1 kg of ethylene produced from different raw materials in the impact category “climate change (GWP100)”

[1] The aLUC for annual crops in Germany is 0.21 t CO_2 per ha and year, similar values are stated for the USA as a relevant importer of maize for bioethanol. With land-use factor of 1.89 m^2 *1a per kg maize-based ethanol, the aLUC results in 0.04 kg CO_2eq/kg ethanol and with the conversion to ethylene: 0.092 kg CO_2/kg ethylene

3.2.3.1.3. Terrestrial acidification

The following figure illustrates the different contributions to terrestrial acidification (in SO_2-eq.) of ethylene from different raw material. Notably crop-based ethylene has the highest impact on terrestrial acidification. Agricultural processes lead to high emissions of ammonia, distributed by air to soils and ecosystems. The impact can be reasoned by two further processes: on the first hand, agricultural biomass is grown under the utilization of nitrogen-based fertilizers (mineral or/ and organic), which can lead to acidification of soil (through the formation of nitric acid in the soil). On the other hand, hydrolyzation of biomass often involves acids (acid hydrolysis) which impacts terrestrial acidification.

The impact is lower by using residual biomass, such as straw. PtX-based ethylene leads to comparable emissions. Rather low emissions are connected with the fossil pathways, although refineries are well-known for rather high SO_2 emissions at stack.

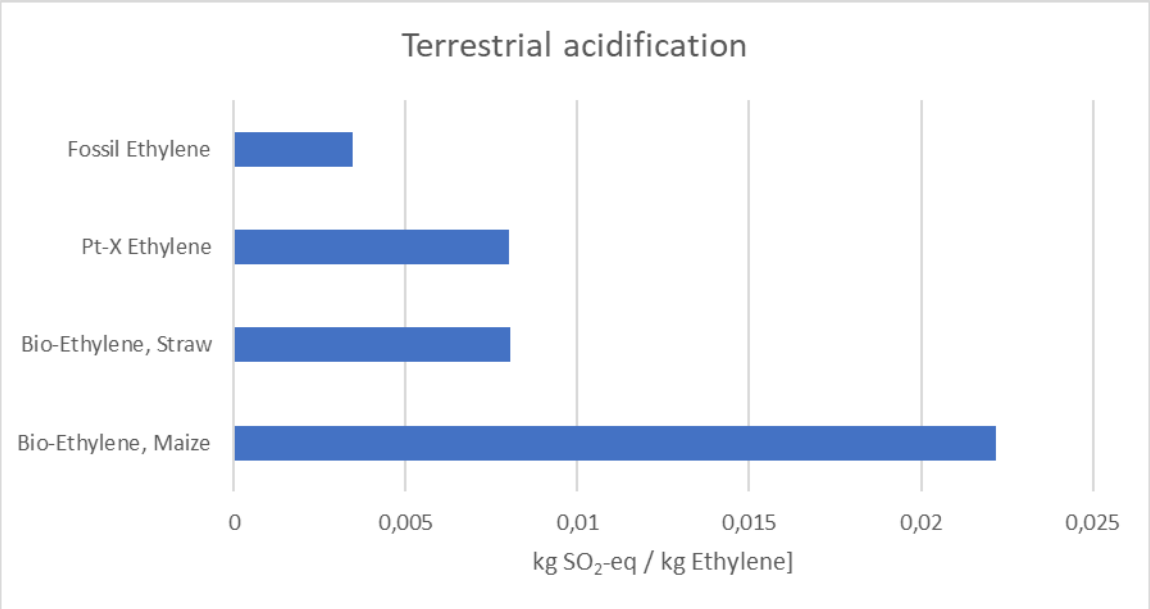


Figure 15: Results for 1 kg of ethylene produced from different raw materials in the impact category “terrestrial acidification”

3.2.3.1.4. Toxic effects (particulate matter formation)

The figure depicts the impact of various ethylene types on toxic effects related to particulate matter formation, measured in kilograms of PM2.5. Maize-based ethylene shows the highest impact in particulate matter formation which can be explained by the emission of precursors as ammonia as a side-effect of fertilizing. Its impact is two times higher compared to the impact of straw-based ethylene. PtX-ethylene ranks in-between the two bio-options, while fossil ethylene has the lowest emissions. The picture somehow resembled the one for acidification, since ammonia is a key pollutant in both pathways.

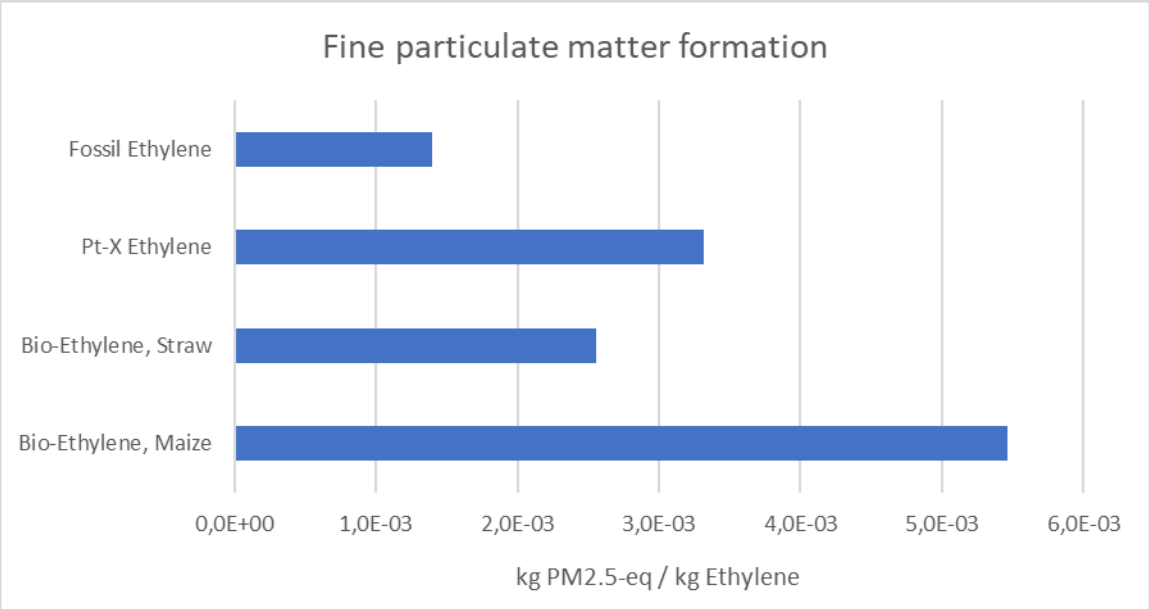


Figure 16: Results for 1 kg of ethylene produced from different raw materials in the impact category “fine particulate matter formation”

3.2.3.1.5. Stratospheric ozone depletion (nitrous oxide)

The figure illustrates the impact of various ethylene types on stratospheric ozone depletion, measured in kilograms of N_2O-equivalents.

Maize-based ethylene demonstrate the highest level of ozone depletion, with an impact of approximately 0.23 g N_2O-eq./ kg ethylene, predominantly resulting from field emissions due to nitrogen fertilizer application. In contrast, the production of ethylene from straw has the lowest N_2O emissions, as the agricultural emissions are not attributed to the residue straw and the hydro-chemical process for producing ethanol involves comparatively low combustion emissions.

PtX and fossil-based ethylene show an intermediate impact on stratospheric ozone depletion.

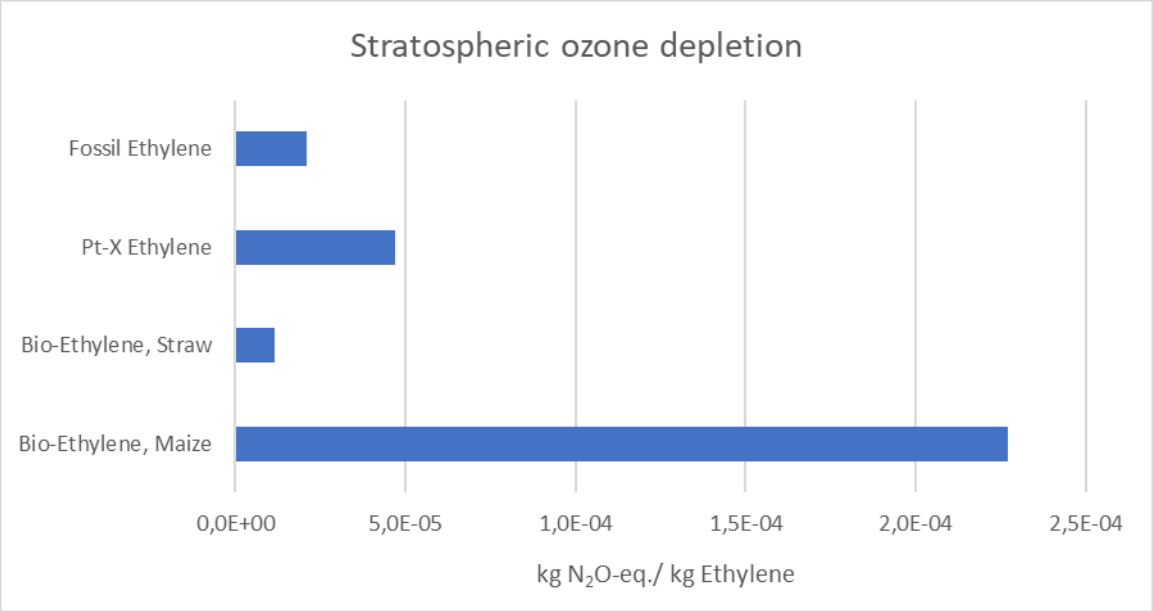


Figure 17: Results for 1 kg of ethylene produced from different raw materials in the impact category “stratospheric ozone depletion (nitrous oxide)”

3.2.3.1.6. Biodiversity loss (distance to nature potential)

The following figure shows how the different beam types influence biodiversity; the characterization was made using the approach “distance to nature potential” (DNP). Here, the land use associated with the provision of the respected type of ethylene is multiplied by the factor that derived from the hemeroby classes of the raw materials used.

Ethylene made from maize show the highest impact on biodiversity loss. This can be explained by the fact, that the land demand for the agricultural biomass maize is the highest under all ethylene types. The factor connected to the hemeroby class of agricultural maize is 0.5 as the hemeroby class of maize is VI, but plays here a minor role. The DNP for 1 kg maize-based ethylene is 2.2 m^2 artificial area-equivalents (aa-eq.) per kg ethylene

PtX-based ethylene is bound to green hydrogen, which – in this setting – is based on solar power. The areas required for photovoltaic systems or concentrated solar power (e.g. produced in sun-rich regions from which hydrogen or PtX is imported to Germany) result in a DNP of around 0.5 m^2 aa-eq. per kg ethylene.

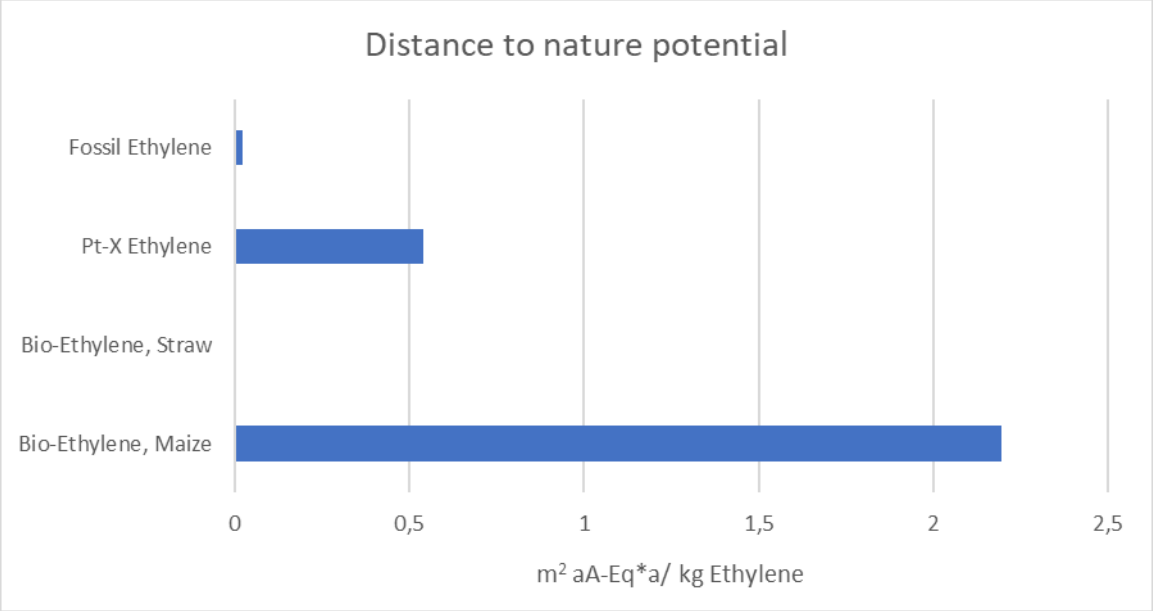


Figure 18: Results for 1 kg of ethylene produced from different raw materials in the impact category “distance to nature potential”

3.2.3.2 Normalization of impact indicator results

The comparison of all impact categories shows a homogeneous picture of the environmental performance of the bio-based ethylene compared to ethylene from fossil or PtX source.

Savings of the crop-based ethylene are especially high compared to the PtX-based ethylene in the impact category water, while it shows advantages against fossil-based ethylene regarding climate change. Crop-based ethylene performs worse than PtX-and fossil-based ethylene in the impact categories: distance to nature potential and acidification.

Savings of the residual-based ethylene are especially high compared to the PtX-based ethylene in the impact category distance to nature, while it shows advantages against fossil-based ethylene regarding climate change. Residue-based ethylene performs worse than PtX-and fossil-based ethylene in the impact categories: particulate matter formation, acidification and fresh water eutrophication.

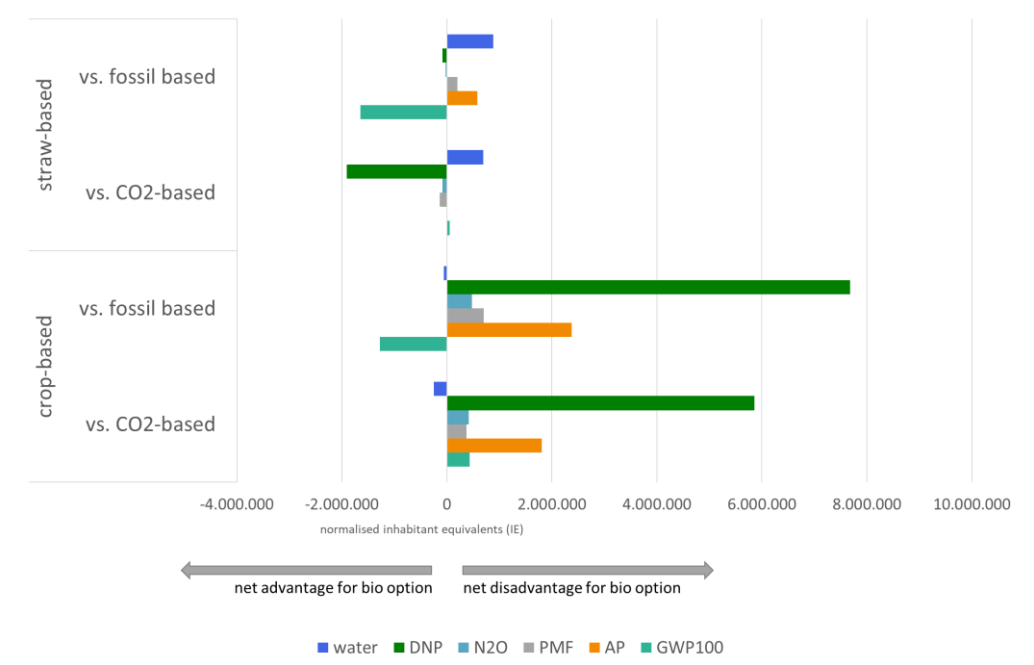


Figure 19: Comparison of normalized results for bio-based ethylene vs. results for CO_2-based and fossil-based ethylene

3.2.4 Interpretation

The production of the basic chemical ethylene, which is the basic building block for the vast proportion of petrochemical products (especially polymers), was analysed here using four different product pathways. The two bio-based pathways differ only in terms of the raw material used, namely cultivated corn on the one hand and agricultural waste straw on the other. Apart from specific details relating to the breakdown of the lignocellulose in the straw, the process sequence is largely comparable, with the final conversion of ethanol to ethylene (EtE process) being the same. Completely different processes underlie PtX-based ethylene (methanol from CO2 and green hydrogen and via methanol to ethylene (MtE process)), ethylene and, of course, fossil ethylene (steam cracking of naphtha).

We therefore consider two bio-options in comparison with two references: the conventional reference of today's fossil product and the non-biogenic renewable competitor product of the future. At first glance, the presentation in Figure 19 also allows a direct comparison of the two bio-based options. As can be seen from the diagram, the relevant disadvantages of maize-based ethylene are not apparent for the straw-based option. One exception is water consumption, which is slightly higher for the straw option than for the conventional corn option due to the process involved. Otherwise, all the advantages speak in favour of the

straw option, in particular acidification and the natural effect on land use (DNP) show a clear picture in favour of straw ethylene – when compared with maize-based ethylene.

Overall, the maize-based variant presents a virtually clear picture, with almost consistent disadvantages over all other options – with the following exception: in the climate change (GWP) category, maize ethylene has a clear advantage over the fossil fuel reference. Since climate change plays a leading role in the environmental debate, this is a real balancing act, as all other impact categories point in exactly the opposite direction. Land-use change via aLUC is taken into account here. However, if an iLUC factor were to be included, the GWP advantage of maize-ethylene would also melt away. The result can therefore be interpreted as follows: the climate benefits of maize-ethylene come at a high price in terms of numerous other significant environmental disadvantages.

But how does the 'future reference' PtX-based ethylene fare? Compared to corn-based ethylene, the ranking is quite clear, as described above. However, the results are close when compared to straw-based ethylene. The only major differences due to standardisation are, on the one hand, the DNP due to the land required for solar power for hydrogen and, on the other hand, the slightly higher water requirement for the straw option – which would not necessarily be expected given the substantial water requirement for electrolysis. In this respect, however, the data for the straw option is much more uncertain and the process may require greater optimisation. It can therefore be concluded that, at least in terms of trends, the straw-based process has a greater advantage.

3.3 Textiles

3.3.1 Description of the options

This case study compares fibers made from various biomass-based raw materials with fibers made from petroleum-based raw materials. In addition, a variant of the petroleum-based fiber is included whose manufacturing process obtains the carbon via CCU. All manufacturing inventory data refer to one kilogram of the corresponding fiber.

The following fibers are considered:

1. Cotton fiber
2. Viscose fiber made of hardwood (birch)
3. Viscose fiber made of bamboo
4. Polyethylene terephthalate fiber (PET fiber) – from crude oil
5. PET -fiber - ethylene production via CCU

To ensure comparability, the inventory data is compiled in relation to one kilogram of fibers as a functional unit.

3.3.2 Assumptions and system boundaries

The assumptions made for each fiber with regard to its raw material and, in some cases, its processing are listed below.

1. Cotton fiber

a) Starting material
Conventionally grown cotton for the global market (taking into account the use of pesticides and fertilizers).
b) Process
The cotton ginning corresponds to the average global process, i.e. the electrical energy for the process, for example, comes from certain (cotton processing) countries. The heat required in the process is provided by natural gas.
c) Transportation
Global transportation by truck (local technical specifications (e.g. emission standards) are stored according to the transport composition.

2. Viscose fiber from hardwood

a) Starting material
It is a birch wood (hardwood) from sustainable cultivation in Sweden (as the majority of wood pulp producing wood mills are located in Northern Europe). In order to convert the data set used from Ecoinvent ("sulfate pulp production from hardwood, bleached (RER)"), a moisture content of 81% and a density of 866 kg/m^3 [1] were assumed.

[1] https://extension.psu.edu/calculating-the-green-weight-of-wood-species

b) Process

First, pulp is produced from the wood in wood mills, then it is converted into viscose fibers using chemicals. The production of the pulp corresponds to a European average, whereas the process for producing the fiber corresponds to a global average, as there is no European process in the database.

c) Transportation

The transportation of the pulp is purely European and consists of transport by rail, road and waterways; corresponding specifications (such as emission standards) have been created. No assumptions have been made regarding the transportation of the pulp to the fiber production site.

3. Viscose fiber made from bamboo

a) Starting material

Bamboo cane from sustainable cultivation is used as a raw material. The market is made up of the Brazilian, Chinese, Colombian and Philippine markets.

b) Process

The process corresponds to that used in the production of viscose fiber from hardwood; no adjustments were made with regard to the quantity used or the use of chemicals and energy.

c) Transportation

Corresponds to the transport of viscose fiber from hardwood.

4. Polyethylene terephthalate fiber (PET fiber) made from crude oil

a) Raw materials

Two raw materials are obtained from crude oil and used in the polyester fiber production process. These are xylene produced in Europe, which is later converted to terephthalic acid, and ethylene produced globally, which is converted to ethylene glycol.

b) Process

A global average process is assumed for the conversion of ethylene to ethylene glycol, whereas a European process is used for xylene. The conversion of the two chemicals to polyethylene terephthalate is based on a European average.

c) Transportation

The transportation of the xylene is purely European and consists of transport by rail, road and waterways, with corresponding specifications (such as emission standards). No assumptions have been made regarding the transport of ethylene to the fiber production site.

5. Polyester fiber - ethylene from CCU

a) Starting material

Ethylene is synthesized from methanol (2.64 kg methanol per 1 kg ethylene). The methanol loads are allocated to main and by-products. The methanol is supplied via CCU (0.2 kg hydrogen to 1.4 kg CO2 per 1 kg methanol). An electrical energy requirement of around 1000 kJ/kg ethylene and 1620 J/kg methanol is assumed for the facilities.

b) Process

Corresponds to the production process of PET fiber from crude oil.

c) Transportation

Corresponds to the transport of PET fiber from crude oil.

3.3.3 Results

3.3.3.1 Results per impact indicator

All impact categories discussed in table 2 are analyzed and the results displayed and discussed below.

3.3.3.1.1. Fresh water consumption

The figure illustrates the freshwater consumption (measured in cubic meters, m^3) associated with the life cycle of the analyzed fiber types. It can be seen that cotton fiber has approx. ten times higher freshwater consumption compared to all other fibers, deriving from the "raw material" phase. Other fibers, such as bamboo-based viscose and wood-based viscose fibers, exhibit much lower freshwater usage. For these fibers, the largest contribution comes from the production of the fibers. The PET fibers, both fossil and non-fossil based, show the lowest total freshwater consumption.

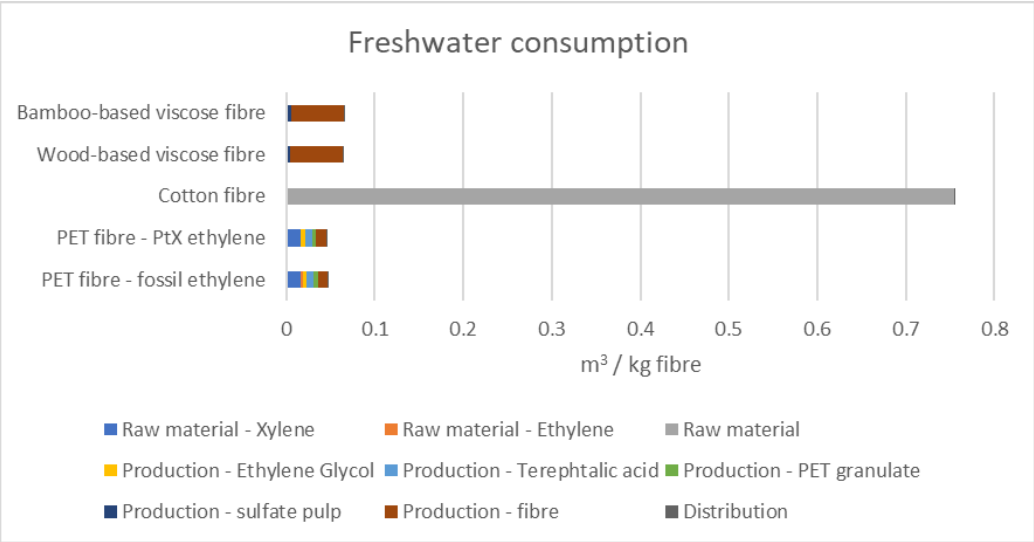


Figure 20: Results for 1 kg of fiber from different raw materials in the impact category “freshwater consumption”

3.3.3.1.2. Climate change (GWP100)

The figure presents the impact of the different fiber types on climate change, measured in kg CO_2 equivalents. Each color in the bars represents a specific stage or component in the fiber's life cycle, detailing the contributions of different materials and processes to the overall carbon footprint.

Among the fibers, PE fiber - fossil ethylene exhibits the highest climate change impact (nearly 7.1 kg CO_2-eq.), followed by PE fiber - PtX ethylene (with 6.2 kg CO_2-eq.), which is influenced to a big extend by the EOL emission (that account for the fossil CO_2). For the bio-based fibres the breakdown indicates that fiber production are the largest contributors to emissions for bamboo- and wood-based viscose fibers. Cotton fibers show with nearly 3.1 kg CO_2-eq. the lowest impact on climate change compared to the others. For cotton fibers, the extraction of raw materials makes the highest contribution to climate change.

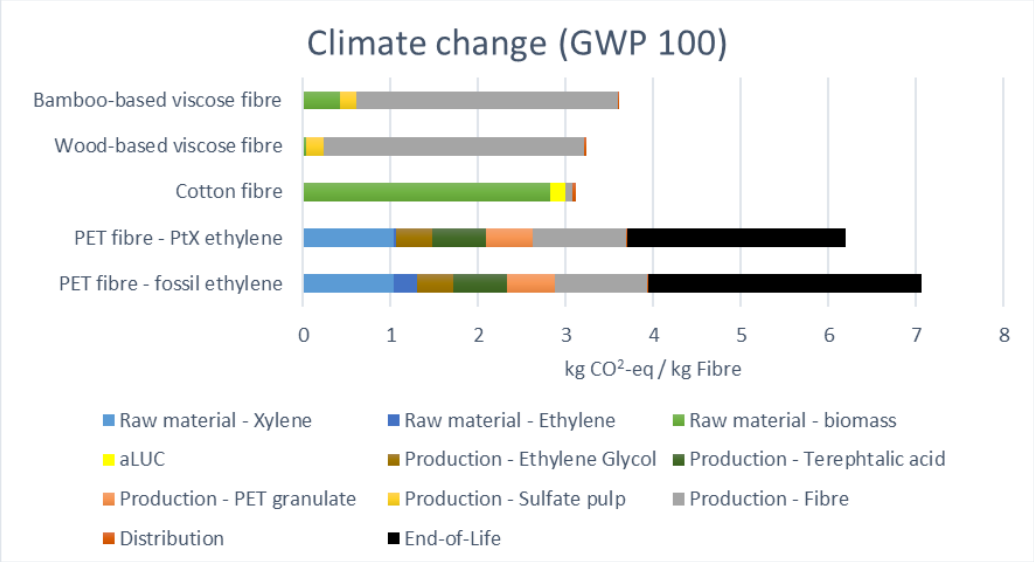


Figure 21: Results for 1 kg of fiber from different raw materials in the impact category “climate change (GWP100)”

3.3.3.1.3. Terrestrial acidification

The following figure illustrates the different contributions to terrestrial acidification across various life cycle stages, emphasizing the significant impact of raw material extraction for cotton and the production processes for viscose fibers. Furthermore, it can be seen that cotton fibers exhibit the highest level of terrestrial acidification, with approximately 0.03 kg SO_2-eq, as already mentioned primarily due to raw material extraction. Bamboo-based and wood-based viscose fibers follow closely, each contributing around 0.025 kg SO_2-eq, with the majority of their impact stemming from fiber production. PE fibers (both non-fossil and fossil ethylene) demonstrate the lowest levels of acidification, with emissions significantly lower than the other fibers (nearly 0.01 kg SO_2-eq).

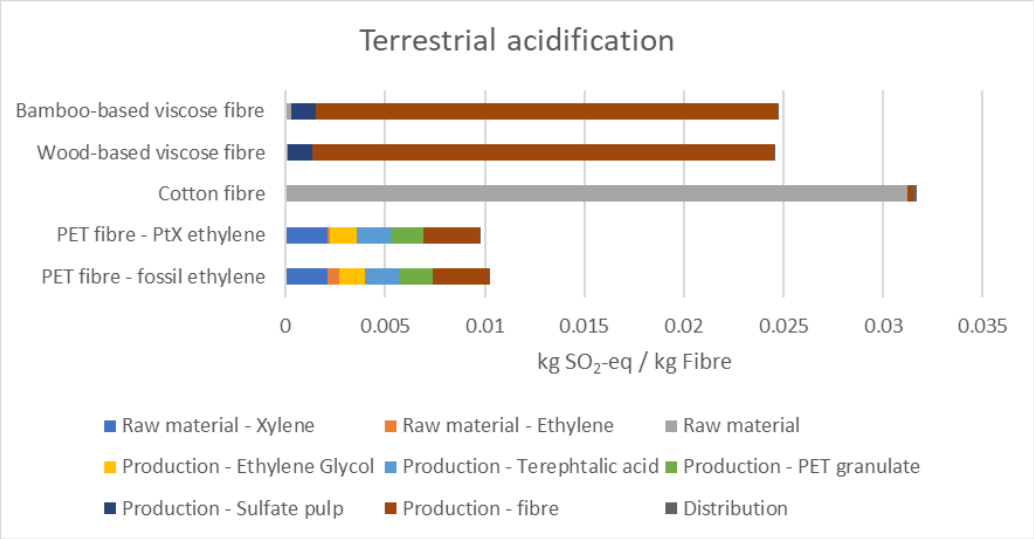


Figure 22: Results for 1 kg of fiber from different raw materials in the impact category “terrestrial acidification”

3.3.3.1.4. Freshwater eutrophication

The figure shows the impact of various fiber types on freshwater eutrophication, measured in kilograms of PO_4-equivalents (kg PO_4-eq). Cotton fibers have the highest impact on freshwater eutrophication, with emissions primarily resulting from raw material extraction. All other fiber types exhibit approximately half the impact of cotton, contributing significantly lower levels of eutrophication. For these alternative fibers, the percentual contribution from raw material extraction to total eutrophication is notably less than that for cotton fibers.

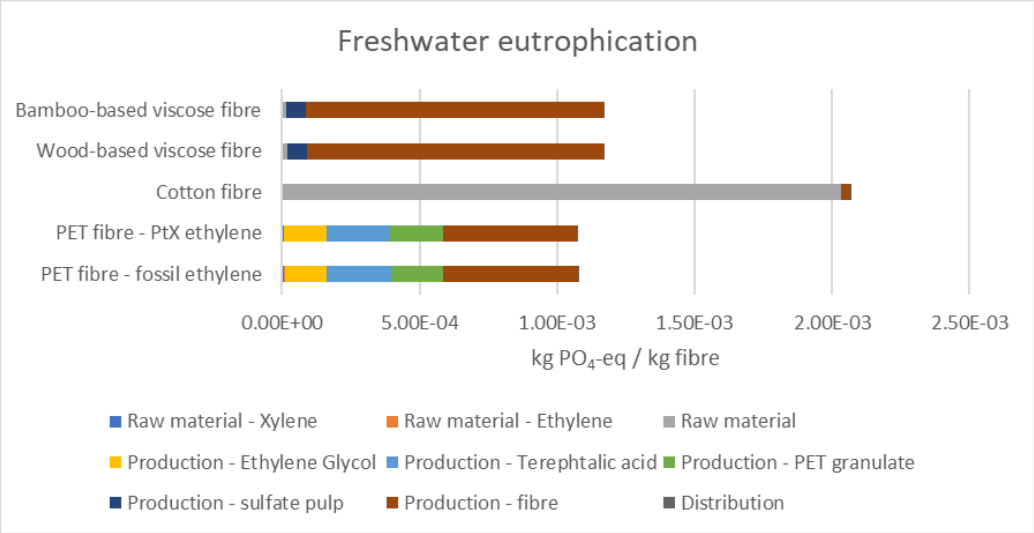


Figure 23: Results for 1 kg of fiber from different raw materials in the impact category “freshwater eutrophication

3.3.3.1.5. Toxic effects (particulate matter formation)

The figure depicts the impact of various fiber types on toxic effects related to particulate matter formation, measured in kilograms of PM2.5. Bamboo-based and wood-based viscose fibers exhibit the highest total toxic effects, each approaching 0.01 kg PM2.5, with the majority of these emissions resulting from fiber production. Following these, cotton fiber resulting in nearly 0.007 kg PM2.5, with the largest portion of its toxic effects arising from raw material extraction. In contrast, PE fibers show the lowest formation of fine particulate matter, with their total toxic effects being distributed relatively evenly across the various life cycle stages.

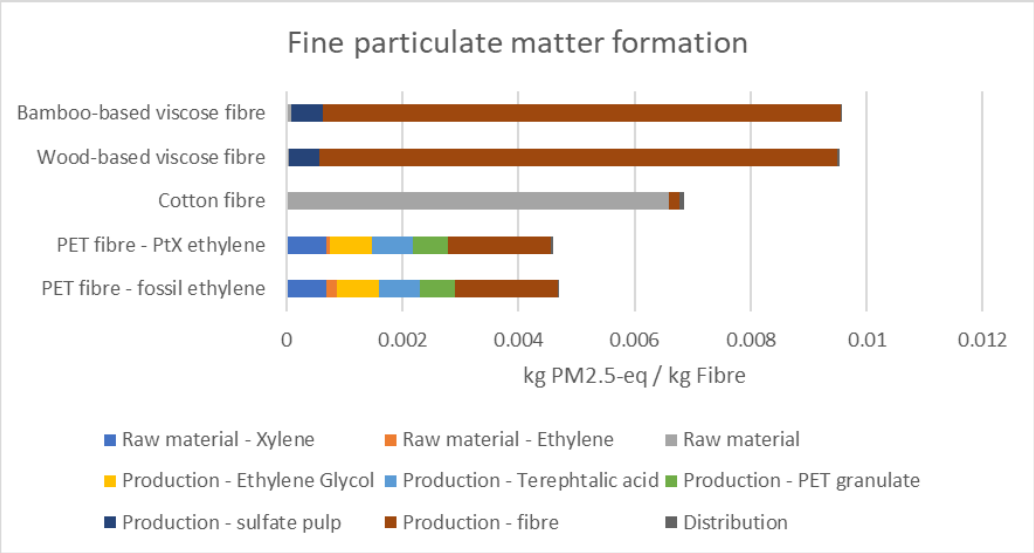


Figure 24: Results for 1 kg of fiber from different raw materials in the impact category “fine particulate matter formation”

3.3.3.1.6. Stratospheric ozone depletion (nitrous oxide)

The figure illustrates the impact of various fiber types on stratospheric ozone depletion, measured in kilograms of N_2O equivalents (kg N_2O-eq.). Fibers based on PTX ethylene and fibers based on cotton demonstrate the highest level of ozone depletion, with 12.6 g N_2O-eq./kg fiber and 12.5 g N_2O-eq./kg fiber. The impact of PtX-based fiber is dominated by the production of the fiber, while with cotton-based fibers it's the provision of the raw material that has the highest impact. Viscose based on wood or bamboo has a lower impact in stratospheric ozone depletion than fossil-based PE fibers.

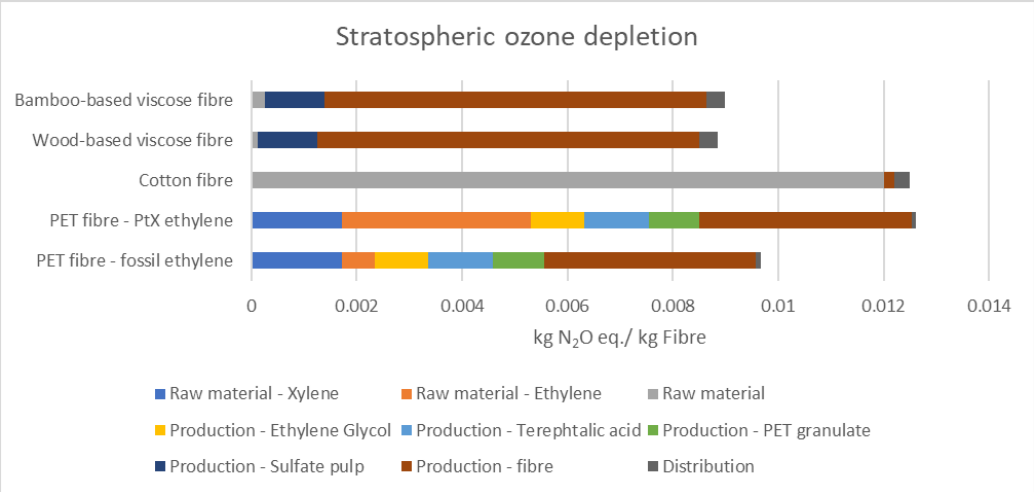


Figure 25: Results for 1 kg of fiber from different raw materials in the impact category "stratospheric ozone depletion (N_20)"

3.3.3.1.7. Biodiversity loss (distance to nature potential)

Figure 26 shows how the different types of fibers influence biodiversity, the characterization was made using the approach “distance to nature potential”. Here the land use associated with the provision of the respected type of fiber is multiplied by the factor that derived from the hemeroby classes of the raw materials used.

Fibers based on biomass show a higher impact on biodiversity loss than fibers based on fossil sources or PtX. The highest impact on biodiversity loss is shown by cotton fiber, mainly influenced by the provision of the raw material, the hemeroby class of cotton is supposed to be V – VI (depending on the intensification), simultaneously cotton-based fibers have a high land-demand per kg fibers. Wood- and bamboo-based fibers have not only a lower land-demand per kg fiber but result also in a lower hemeroby class and therby a lower factor.

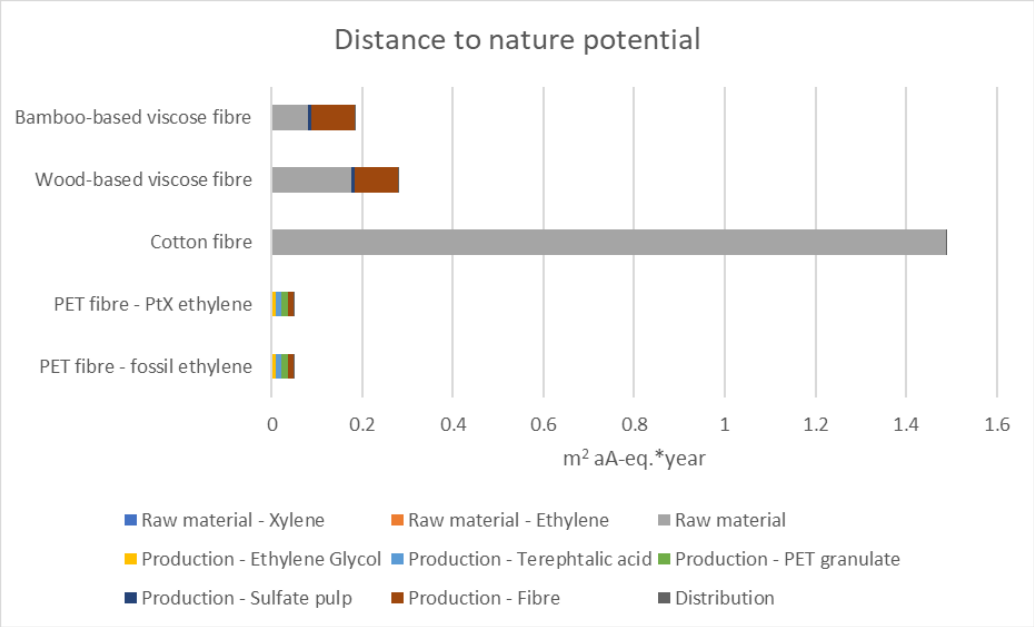


Figure 26: Results for 1 kg of fiber from different raw materials in the impact category “distance to nature potential”

3.3.3.2 Normalization of impact indicator results

In Figure 27 normalized results for all studied cases in all environmental impact categories are displayed to enable a better comparability of results in different categories. Negative results can be interpreted as saving using bio-based fibers compared to the fossil- or partial fossil – based (PtX Ethylene + fossil terephthalic acid) comparative while positive results come along with higher emissions can be interpreted as burden occurring as a result of substitution.

The comparison of all impact categories shows a homogeneous picture of the environmental performance of the bio-based fibers compared to fossil or partial fossil-based fibers, they show higher burden in all impact categories except for global warming potential, where they have a clear advantage against fossil-based fibers. The impact of cotton fibers is in all comparison most disadvantageous and have especially high impact on water utilization.

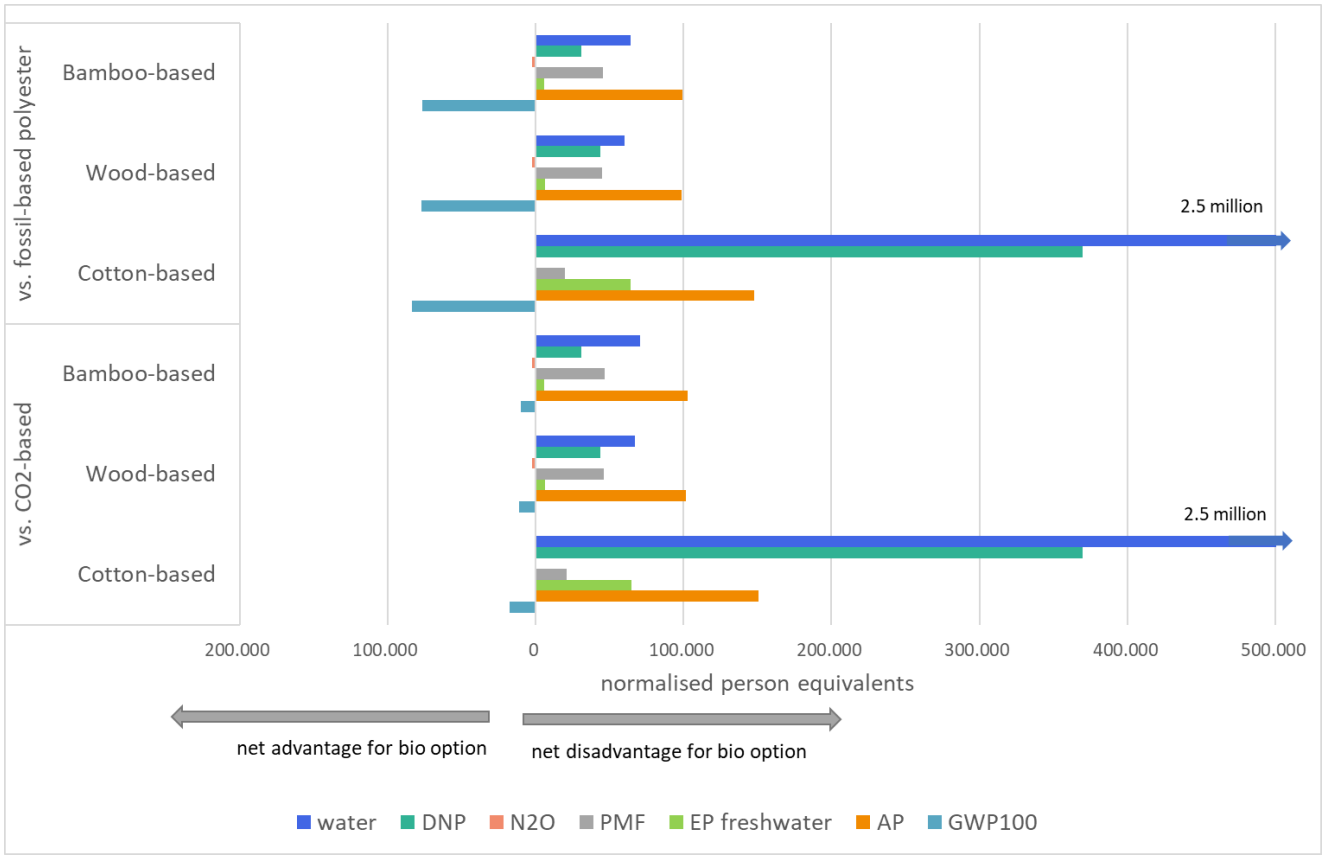


Figure 27: Comparison of normalized results for bio-based fibers vs. results for CO_2-based and fossil-based fibers

3.3.4 Interpretation

The impact of biomass-based fibres (wood, bamboo and cotton) and fossil-based fibres was compared on the basis of their functionality. The results revealed that substituting fossil-based fibres with biomass-based fibres results in an additional burden in all impact categories except climate change and ozone depletion. Substituting fossil-based fibres with bio-based fibres is disadvantageous in most impact categories, showing no differences in burden between complete or partial fossil-based fibres. This result is independent of the raw material used for the bio-based fibre. It can generally be said that cotton fibres display the highest burden and the fewest advantages when substituting fossil-based fibres.

When substituting fossil-based fibres with bio-based fibres, it is important to choose the raw material accordingly. It is recommended to substitute fossil-based fibres with wood- or bamboo-based viscose fibres, as these have a lower environmental impact and offer clear advantages in terms of GWP and ozone depletion.

4 Conclusions

4.1 With regard on the case studies' results

Comparative LCAs rarely yield clear-cut results. Production systems are generally far too complex for this. That is precisely where the advantage of LCA lies: it breaks down the conflicting aspects of alternative courses of action according to their specific advantages and disadvantages. On this basis, it is then possible to weigh up the pros and cons.

In the case of **constructions beams**, the results are relatively clear. In this comparison, wood has a consistent advantage over steel and reinforced concrete, with the exception of land occupation and the associated impact on biodiversity (*distance to nature*). In this respect, the more natural use of beech wood over spruce also has a clear advantage.

The **ethylene case** is much less clear-cut. Production based on maize, which is largely applicable to other starch- or sugar-producing crops, is less favourable than the reference cases in all categories. These are fossil ethylene (which has an advantage over maize ethylene in terms of climate change, but not in any other respect) and ethylene from PtX (which has a slight advantage over maize ethylene in terms of water consumption). This example gives us an indicative ranking: straw-based ethylene has the most advantages and fewest disadvantages overall, ahead of CO_2-based PtX ethylene, ahead of – and here it gets unclear: ethylene from maize or fossil sources – depending on how strongly one weighs the one advantage of corn – climate change – against all the other disadvantages.

The **textile example**, in turn, reveals the following general findings: bio-based fibres consistently outperform the reference products in terms of climate change – and only in this impact category. The advantages over fossil-based fibres are relatively clear, while the advantage over CO_2-based fibres is not very significant. This clearly shows that CO2-based fibres have a relatively clear overall advantage. Among the bio-based fibres, cotton proves to be the most disadvantageous option overall, with some very significant disadvantages (especially in terms of water and land use) (conventional cotton was considered here; organic cotton was not analysed). Wood- and bamboo-based fibres are in the middle of the field. Here, the conflict between the clear advantage in terms of climate change and disadvantages in all other categories compared to fossil fibres becomes apparent again.

Overall, bio-based products cannot be assessed uniformly. It depends very much on the individual case. Biomass produced by agriculture as a raw material is generally connected with various ecological disadvantages. Biogenic residues (such as straw in this case), on the other hand, can eliminate many of these disadvantages. The renewable competition from alternative products produced using CO_2-based PtX technology has many advantages. Whether it will prevail is not yet clear. However, it will offer a partially better alternative to bio-based solutions from an ecological perspective, at least beyond biogenic residues. It, and not fossil reference products, should therefore continue to be the standard for comparisons in the future.

4.2 With regard on the overarching question of this Work package

In the life cycle assessment approach, the analysis is invariably based on functional equivalence, a principle which facilitates the interpretation of results according to their effect upon substitution. A thorough investigation into the consequences of replacing conventional, fossil-based products with innovative bio-based products across all the analysed impact categories is indeed feasible. The findings of this high level of refinement allow for the provision of counsel for action and the calculation of the consequences of decisions.

The selection of case studies alone demonstrates how precise the definition of the subject matter is, because this also determines the question of what exactly the objective of the study is. This, in turn, is linked to the question of how the system boundary should be drawn in each case. The example of the wood beam alone clearly shows the simplifications that are necessary in order to develop a robust LCA with manageable effort in the context of an overview study such as this one. This is because the questions of the investigation options and the **system boundary** make the task extremely broad in some cases:

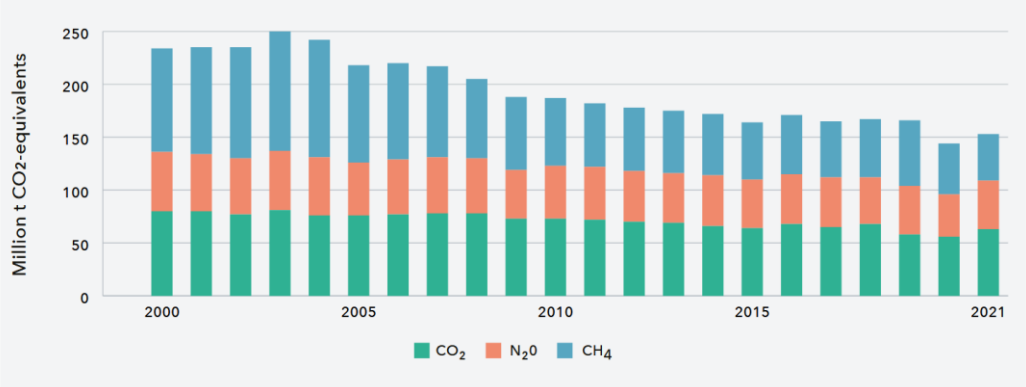
1. The selection of wood and the technical processing of wood alone offer countless possible variants, all of which would be worth including in the study, depending on the question being asked.
2. The difficulty of the system boundaries becomes apparent when defining the functional unit for comparison with alternatives. In the present case, an attempt was made to limit the functionality to the static load-bearing capacity of the beam. In building construction, however, decisions in favour of wood or concrete entail a cascade of further structural requirements. In case of doubt, the entire structure would always have to be assessed, which would involve an immense amount of LCA effort.

The second point played a rather minor role in the other two case studies, as the functionalities here are relatively clear. The example of ethylene shows that an LCA can only go as far as a semi-finished product if all variants of the same material are used for comparison. This is referred to as a *cradle-to-gate* approach or a partial footprint. However, it must then be clear how, in the case of a comparison between a non-fossil and a fossil intermediate product, the issue of CO_2 emissions at the end of the life of the product produced from it will be dealt with. In this case, the end-of-life (EOL) emissions were included in the balance sheet without including the EOL itself (i.e. specific recycling). This means a CO_2 burden for the C content in fossil ethylene, but no burden for the renewable variants.

This raises the question of how to deal with **biogenic CO_2**. As explained in the first report on WP4, experts generally calculate this with a GWP factor of 0. If the source biomass is of agricultural origin, this biogenic CO_2 balance would be covered by land use change. In a counterfactual scenario that takes into account the C storage lost through the preservation of low-C agricultural land due to the continued production of non-food crops, this leads to a significantly higher CO_2 penalty. This would also result in consistent disadvantages for the anaerobic biomass options considered here compared to the non-biogenic options in terms of GWP results. However, such penalty values are not included in the case studies here.

As noted in deliverable 1 (“Footprints and LCA concepts”), LCA offers the possibility of in-depth and well-carved comparisons with alternative options. This also opens up the possibility of bringing up the concept of **substitution**. By balancing reference cases – which in turn can be defined in a differentiated and variable manner (as shown in all three case

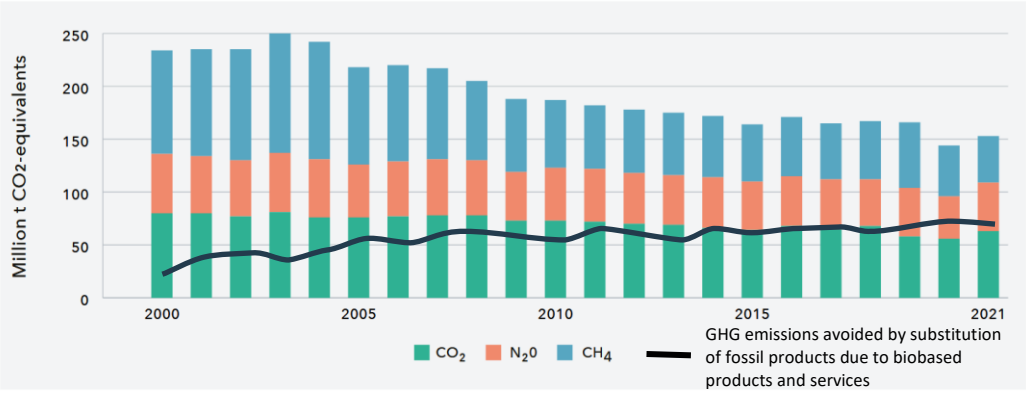
studies) – it is possible to quantify the change (positive as savings or negative as an increase in pollution) caused by, for example, a technical option in the bioeconomy. This can thus be determined precisely on a case-by-case basis. This is the main difference to the footprint results of bioeconomy monitoring, which ultimately differs clearly in terms of the task and scope of the LCA. On contrast, here is the macroeconomic level on focus. A visualisation such as the one in Figure 28 therefore ideally illustrates the development of the bioeconomy's contribution in Germany. However, what is not apparent from this is the extent to which the substitution of existing production methods with biomass-based products is contributing to this development. This would also be unfeasible in this form due to the immense amount of data involved.



Source: GWS, based on calculation with GLORIA database from 2000 to 2021.

Figure 28: Climate footprint of the German bioeconomy in million tonnes of CO_2 equivalents from 2000 to 2021; from (Beck-O´Brien et al. 2024)).

However, it would be advisable not to completely disregard the idea of the substitution effect when monitoring the bioeconomy. For example, an accompanying analysis of which processes in the overall economy are being replaced by the use of biomass could be a meaningful addition to the standard footprints. This could be realized, for example, as shown in Figure 29, which adopts the values of Figure 28 and adds the emissions, prevented by substitution by purely fictitious values. This would require a survey or model-based determination of the products and services effectively displaced by biomass products. However, this should be possible with the available models of the economy.



Source: GWS, based on calculation with GLORIA database from 2000 to 2021.

Figure 29: Climate footprint of the German bioeconomy in million tonnes of CO_2 equivalents from 2000 to 2021; from (Beck-O´Brien et al. 2024)); modified by the addition of the fictitious line of emissions avoided by substitution of fossile products.

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