Tampere University of Applied Sciences

Applying LCA in Product Development and Design

Sustainable design in bio-based plastic-glass fibre composite for durable applications

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Risk Management in Circular Economy

ABSTRACT

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Risk Management in Circular Economy

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The aim of this thesis was to find a suitable tool and develop a life-cycle assessment procedure for the company Arctic Biomaterials Oy (ABM), as sustainability aspects are highly prioritized in the company values and policy. The company is a provider of raw materials for other manufacturers and it is vital to have a LCA tool that can be applied in the early stages of the product development. In the past, ABM has relied on declarations by its raw material suppliers on environmental declarations. These peer-reviewed environmental claims are only sufficient to a certain point. ABM purchases bio-based polymers from renewable sources and increases their environmental impact during its own manufacturing process, which produces bioplastics composite by adding bio-glass fibers based on ABM's own technology.

Through the manufacturing process, ABM increases the environmental impact of a product by using energy and using global raw material supply chains. In addition to the choice of raw material, these effects have to be computationally added to the carbon footprint estimate to avoid possible unintentional green washing. Green washing is perceived as a business risk. The search for a tool and its evaluation was conducted in accordance with internationally recognized standards, to the extent possible. A comparison between different LCA-tools was conducted based on literature reports.

The GaBi Envision computing software provided by ThinkStep was chosen as the most suitable tool. ThinkStep is one of the market leading database aggregators. Databases, known as GaBi, are accredited values based on primary data, that is, data collected from industries. Stoichiometrically modelled data is also used as part of the LCA to fill the missing information. The selected tool was found efficient due to the shadow calculation and streamlined what if-scenario building features.

After conducting what if scenario –type LCA for selected imaginary composite materials the performed life cycle assessment found that the greatest environmental impact of all products comes from the production of the polymeric raw material itself, before it enters the ABM gate. Finally, it was concluded that ABM produces environmentally friendly plastic alternatives. The future EoL options and their challenges were acknowledged and discussed during LCA result interpretation phase. Standardisation for downstream processes for bio-based materials need to be further developed.

Incorporating a life-cycle assessment tool into research and development was proven to be a valuable method throughout the project, as customers have a strong need to have proof about the sustainability value of the material they purchase and use this information in their own marketing efforts. Proper evaluation and, in particular, rigorous communication will allow for a transparent discussion of the implications of material choices in the future.

Key words: LCA, bio-based plastics, glass fibre, composites

CONTENTS

ABBREVIATIONS AND TERMS

1,4,BDO	1,4-butanediol
ABM	Arctic Biomaterials Oy
ABS	Acrylonitrile butadiene styrene
ASTM	ASTM international, American Society for Testing and Materials
B2B	Business-to-business
B2C	Business-to-consumer
BST	Black surface temperature
CA	Cellulose acetate
CAD	Computer aided design
CED	Cumulative energy demand
CF	Carbon footprint
CFGF	Continuous filament glass fibre
CWM	Corn wet mill
DIN	German Institute for Standardization
DNA	Deoxyribonucleic acid
EE	Eco efficiency
EF	Environmental footprint
E-glass	Glass type (electrical)
ELCD	European Reference Life Cycle Database
ENTSO E	European Network of Transmission System Operators for Electricity
EOL	End of life
EPD	Environmental product declarations
FU	Functional unit (product)
GHG	Green house gas
GWP	Global warming potential
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life cycle assesment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LFT	Long fibre reinforced termoplastic
MCI	Material circularity indicator
NMVOC	Non-Methane Volatile Organic Compounds
OEM	Original equipment manufacturer
PA	Polyamide
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PCL	Polycaprolactone
PCR	Product gategory rule(s)
PE	Polyethylene

PED	Primary energy demand
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate
PLA	Poly lactic acid
PP	Polypropylene, polypropene
PTT	Polytrimethylene terephthalate
PUR	Polyurethane
PVC	Polyvinyl chloride
RBS	Risk breakdown structure
S&P 500	US stock market index
SCC	Stress corrosion cracking
SETAC	Society of Environmental Toxicology and Chemistry
SFS EN	European standard in Finland
SME	Small and medium-sized enterprises
SUP	Singe use plastic
TPS	Termoplastic starch
UNFCCC	United Nations Framework Convention on Climate Change
USBCSD	Unites states Business Council for Sustainable Development
UV	Ultra violet light
WBCSD	World Business Council for Sustainable Development

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1 INTRODUCTION

Life cycle assessment offers an efficient tool for research purposes for Arctic Biomaterials Oy (ABM), a composite material manufacturer. LCA as methodology will enable systematic evaluation of material sustainability for ABM products and their development and helps during sustainability communication with stakeholders when LCA is used as transparent process. ABM technical materials can be divided into three platforms: Bio glass reinforced composites, unreinforced compounds partially bio-based composites and compounds. Composite technology is based on proprietary bio glass fiber and thermoplastic long fiber pultrusion technology (LFT). Matrix polymer is bio-based and biodegradable or partially bio-based. These grades can be processed with standard injection molding machines and tools. ABM Products are under trademark *ArcBiox*. LCA implementation to product design in case where the product is a raw material to the final product creates a responsibility towards the end of the product life cycle. During building of the LCA itself, the implementation of LCA in the product design phase is studied. The system thinking behind planning materials with multiple end-of-life options and simultaneously the missing technology for EoL options are recognized for future consideration. If materials are designed in the framework of current technology, continuing business as usual, can cause transitioning towards circularity out from visions and strategy. Scenario LCA is built to consider future alternatives for material life cycle. Raw material carbon cycle is studied, as the material is formed from renewable source up taking atmospheric carbon during feedstock production. Implementing LCA to product development will enable proofing of sustainable business and work simultaneously as risk management method in prevention of unintended greenwashing in B2B communication.

1.1 Objectives

The specific objectives of this study are to quantify the potential life cycle environmental impacts associated with the production of the novel glass fiber containing bio derived polymeric composite materials. And to assessment the performance of the novel glass fiber material in the end life functionality of the polymer composite trough it’s added functionality of decomposition together during composites polymer part biodegradation process. During this project aim is establishing a LCA process that can be used together with R&D and with sales and marketing activities as preliminary and final product environmental declarations. Another aim is to compare the environmental performance of the composite made using the novel glass fiber and ABM-glass fiber, and examining the role of the bio-based composition in the material. To map areas of potential lack of information and technologies for improving the environmental life-cycle profile of the composite.

The novel bio-glass composite sustainability assessment is done to evaluate the future and end-life options for degradable glass fiber composite. The global warming potential and energy consumption are studied for the entire life cycle of product using selected data and LCA tool. Different case scenarios of transportation are analyzed and use phase, life span is assessment in order to demonstrate the potential use of the composite materials and the performance of the LCA process itself will evaluated: The competence of simplified LCA scenario tool usage during product development process is studied. Material manufacturer can only offer a limited LCA since use phase for ABM products starts early on, when B2B customer is producing their products from ABM composite and more weigh to environmental impact is loaded outside material manufacturers reach. This aspect is considered in sustainable material product design.

1.1.1 Goal and Scope

The Goals focused on during and after LCA implementation in product development are:

-To study the selected GaBi based LCA tool performance during LCA conduction with imaginary products and,

-To gain LCA data to support B2B decision-making and marketing by using LCA is to compare the effect of material selection, manufacture location and transportation route to the build-up of the carbon footprint for the ABM product: glass fibre reinforced polymer pellet.

Polymeric Raw material selection is evaluated in relation to each other’s and group of raw material scenarios is assessment in variation for location and transportation scenarios. End-of-life options effects are evaluated in scenarios: Composting (when possible)/ Incineration and recycling. Land fill as end of life option is excluded due to its nature being opposable to current situation and development goals (EU waste management)

LCA phase focuses composites with glass fiber reinforcing and Bio-based polymer options: Bio-based PLA (Polylactic acid derived from corn), PBS (Polybutylene Succinate) and PA 1010 (Polyamide 1010 from castor oil) and petroleum based polymers ABS (Acrylonitrile butadiene styrene), PP (Polypropylene). Since ABM Bio glass fiber is novel technology the data needed for further LCA evaluation is collected during and after this project as continuum. PBS is assumed to be bio-feedstock based. Notable is that data in this LCA is for optimal situation. In current supply status PBS is approx. 50% biobased. (PBS feed stock are Succinic acid from bio based fermentation and 1,4-BDO from fossil based source) PBS polymer provider has DIN-certified bio based content 50-80%.

The need behind LCA project

The motivation initiating the project comes from the climate change caused by imbalanced carbon cycle and consumption sustainability issues that have finally reached most of the humans taking part in the economy as individual consumers or as representatives of business. As the latter one the project outcome will help in drafting the true environmental impacts via building different scenarios of different manufacture process inputs and outputs and impacts derived from the assessment. Natural Resources Institute Finland operating under The Finnish Ministry of Environment has recently build a roadmap for promoting the use of bio-based material as plastic materials. ”*Muovitiekartta*” *-roadmap for plastics* promoting new material applications and research for increasing the usage of bio sourced raw materials and applications, mainly focused on disposables and packaging applications. Since the focus is on promoting the sustainability of non-durable consumer goods, there is a need for additional research for durable goods which could also be replaced with bio-based and biodegradable options. Extending the lifetime of bio-based products is a target and considered as good practice according to the European Environment Agency. Novel ABM composite glass fiber technology enabling glass fiber composite being compostable emerges application ranges that can benefit from new composite material. Growing market for bio-based fiber composites have application gaps that could be fulfilled with usage of glass fiber.

According to The European Environment Agency the establishment of a circular economy can support the transition to decarbonisation of Europe by 2050 and allows to bridge the gap between national climate mitigation measures on paper and climate action by citizens and companies. The bio-economy is not circular/sustainable by definition. Lack of systems perspective can prevent circularity from coming into realisation. Processed bio based polymers are not always biodegradable, and mixing them with technical materials can hamper recycling. (De Schoenmakere, 2018)

During LCA implementation the gained awareness on the environmental declarations and communication of sustainability that will help break barriers between stakeholders; the business-to business communication and also a bit forgotten internal value based increase in information delivery, the company internal sustainability know how. The purpose of this project is to implement LCA in the research and development phase of new composite compositions. Together with a growing demand for new materials derived from bio-based feedstock and need for increasing mechanical performance of those materials developed, relevance of sustainability evaluation also emerges. During this project information on LCA tool is gathered to support non-LCA experts' usage of the LCA tool. Internal instructions and guidelines for following ISO 14040, 14020 principles during environmental assessment and communication will be a part for the project.

1.2 Life Cycle Assessment according ISO 14040 and 14044

The figure 1 draws the most familiar principles and framework for life cycle assessment in ISO 14040. Requirements and guidelines in ISO 14044 describes LCA process in its introduction of LCA's dimensions and usage as follows. LCA can be used: To Identify opportunities to improve the environmental performance of products at various stages in their life cycle, informing decision-makers in industry; government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign), the selection of relevant indicators of environmental performance, including measurement techniques, and marketing (e.g. implementing an eco-labelling scheme, making an environmental claim, or producing an environmental product declaration).

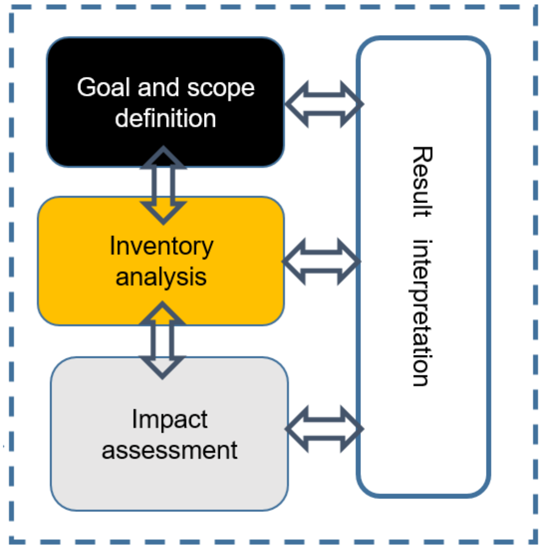


FIGURE 1 Stages of LCA framework redrawn according ISO 14040:2006

System boundaries in the scope definition can be categorized as:
Gate to Gate: All company or site-related activities from material acquisition or pro-curement, beginning at entrance gate through all the production steps on site, until final commissioning steps before leaving the site gates again.
Cradle to Gate: All activities from resource mining through all energy and pre-cursor production steps and on site production, until final commissioning steps before leaving the site gates.
Cradle to Grave: Cradle-to-Gate extended through the use, maintenance and the end of life (disposal, recycling, and reuse) of a product.
(Kupfer, Baitz et al 2018, GaBi)

According ISO 14044 the resulting LCA data and comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent. Therefore this International Standard contains several requirements and recommendations to ensure transparency on these issues.

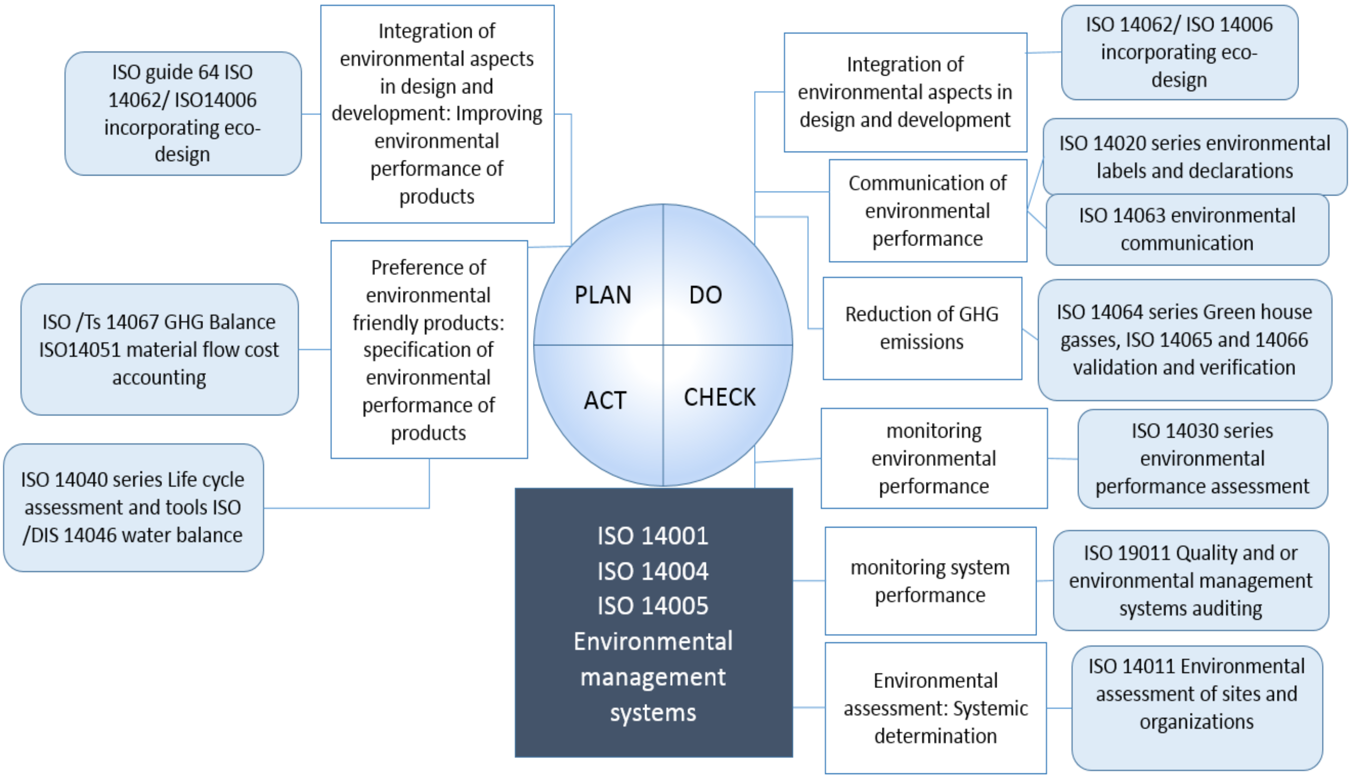


FIGURE 2 ISO 14000 model (picture adapted from Köpffler at al. 2014)

1.2.1 CO_2 equivalent GWP

Carbon footprint analogy and time frame of carbon as carbon being temporarily storaged…

Global warming potentials (GWPs) are widely applied for assessing the contribution of GHGs to the climate change: they are used in LCA, and have also been adopted for national inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and accounting under the Kyoto Protocol. GWPs indicate the climatic impact of a GHG emission as a function of the GHG's radiative efficiency and its lifetime in the atmosphere. The GWP index for a given GHG is calculated as the cumulative radiative forcing caused by a unit mass emission of that GHG integrated over a given time horizon, as compared with the cumulative radiative forcing due to emission of a unit mass of carbon dioxide (CO2) over that same time horizon. As each GHG has a different atmospheric lifetime, the choice of a time horizon is critical, with shorter time horizons shifting

the relative importance toward the shorter-lived GHGs (i.e. methane) whereas longer time horizons increase the relative importance of the long-lived
GHGs (i.e. CO2, N2O, CFCs). The most common time horizon used for GWP in LCA and CF, and in reporting to the UNFCCC, is currently 100 years. (Brandao et al, 2013, 232)

Brandao et al.(2013) discuss the timeframe for CF (Carbon footprint) accounting: Relative GWPs are a metric developed by the IPCC to allow GHGs of different radiative efficiencies and atmospheric lifetimes to be compared, so that CO2 as well as non-CO2 GHGs can be included in GHG inventories for reporting and accounting under UNFCCC and the Kyoto Protocol. Use of GWPs enables net emissions/removals for a product or project, in t CO2-eq., to be calculated. The application of GWPs constitutes is an interesting and unusual way of dealing with time preference in that it applies no discount for the radiative forcing within the chosen time. Hence, all radiative forcing across the time horizon is assigned the same importance. Subsequent radiative forcing is abruptly assigned a value of 0 beyond the end of the chosen time horizon. For example, in using 100-year GWP, the radiative forcing in both year 1 and year 100 after emission (e.g. that in year 99) is accounted fully, but any radiative forcing after year 100 (e.g. that in year 101) is excluded. (Brandao et al. 2013) Carbon sequestration during biomass growth can be accounted for as a negative emission in LCA, but the duration of carbon storage is usually not taken into account. The European Commission's ILCD Handbook (European Commission 2010), also proposes a way to account for the timing of GHG emissions in LCA. According to the ILCD Handbook, temporary carbon storage and delayed emissions shall not be considered in LCA, unless the goal of the study clearly warrants it (e.g. the study aims to assess the effect that delayed emissions have on the overall results of an LCA study).
The study by Brandao et al. (2013) consideration for any delayed GHG emission is to be treated on the same basis as temporary carbon storage was made. In this approach, to account for a delayed emission, a credit is given by multiplying kg CO2-eq. of the emission by the number of years the emission is delayed by, up to 100 years, and by a factor of −0.01. Emissions occurring beyond 100 years from the time of the study are inventoried separately as “long-term emissions”, and are not included into the general LCIA results calculation and aggregation. (Brandao et al, 2013, 236)

Biogenic/ fossil carbon

Biospheric carbon management differs from fossil-fuel carbon management in that carbon can be both sequestered to and emitted from the biosphere. An initial carbon release can be balanced by subsequent biomass regrowth, or conversely an initial carbon sequestration balanced by subsequent release. Although the net exchange in these examples may be the same, their different timing with respect to the order of uptake and release of carbon will lead to different trajectories of atmospheric CO_2 concentrations and thus different cumulative radiative forcing, because the atmospheric concentration is determined by the interactions between anthropogenic CO_2 flows (both emissions and sequestration), on one hand, and the CO_2 exchange between the atmosphere and the world's natural carbon reservoirs (terrestrial biosphere and oceans), on the other hand. (Brandao et al, 2013, 236)

1.2.2 Blue water consumption

Blue water is clean water drawn from rivers, or ground water. Grey water is reused blue water. Pfister et al. wrote an manuscript "Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA" In the publication water scarcity by water types was discussed: "What should recognized is the concept of "green water" originates from Falkenmark (1995) and was used to partition the water used for plant growth between naturally available water from precipitation (green water) and irrigation water withdrawn from rivers and aquifers(blue water). It is typically defined as soil water that is later consumed by plant growth. One of the confusing messages in Hoekstra (2016) is that he criticizes LCA for neglecting green water use while later stating that he agrees that in LCA green water impacts are best considered in the context of the land use impact category. LCA and ISO compliant water footprints do not neglect green water, as all inputs and outputs of the system being studied are explicitly included in the water footprint inventory analysis (ISO 14046; Pfister et al., 2015) and green water use and its effects have been explicitly addressed in LCA literature. However, in the absence of human interventions, natural vegetation would have also consumed green water. Indeed, it has been shown that land, and thereby green water, use by humans has led to reduced green water consumption compared to natural vegetation. Although green water might be depleted by human intervention, it is only the net change compared to a baseline condition that can be compared to blue water consumption.” (Pfiser et al, 2016)

Accounting for total green water consumption might lead to double-counting of impacts with land use impacts in LCA or with the ecological footprint, which should be avoided for transparent information to stakeholders. The inclusion of the net change in green water consumption compared to natural vegetation is nevertheless meaningful and part of LCA and ISO water footprint (Núñez et al., 2013, Pfister et al., 2015; ISO/AWI TR 14073). In this way the relevance of efficient green water use and management, which can reduce blue water consumption and resulting impacts, is considered in ISO based water footprints. (Pfiser et al 2016)

“Therefore, the LCA method focuses on environmental impacts rather than on global water use. The question emerges whether or not it is possible to compare the consequences of water use in water rich and water poor regions. The answer given by the LCA community is ‘yes’, and scarcity weighted water use is such a metric. However, while this approach is very relevant when the goal is assessing potential impacts in a complex supply chain, it is definitely less robust from an epistemic viewpoint than simple accounting for water consumption, as the latter doesn’t imply a number of value choices which are instead inherently defined in non-physical metrics such as scarcity equivalents. This is a common problem of footprint metrics.” (Pfiser et al, 2016)

1.3 EF 2.0 Indicators described

The Environmental footprint indicators are listed and described here for supporting the LCA communication within the ABM Company. For example Sales and Marketing representatives offering sustainable materials can use LCA reports during presentations and discussions with customers whose level of substance knowledge can vary enormously. There are many methodologies and models for the indicators and the models, EF 2.0 for resource use and photochemical ozone formation are presented more detailed in appendix 3.

In 2013, the Environmental Footprint methodology has been established with a specific Recommendation (2013/179/EU), within the framework of the “Single Market for Green Products” communication (COM/2013/0196). The International Life Cycle Data system, developed since 2007, released in 2010 and continuously maintained by JRC, has been adopted in the EF framework. ILCD format and nomenclature were adopted as requirements for EF. Given the different needs and goals of the EF, some methods for the Life Cycle Impact Assessment have been changed compared to ILCD (and therefore the elementary flows have been adapted accordingly, and to some extent, the format has been expanded). The LCIA methods are developed within the database as ILCD-formatted xml files to allow electronic import into LCA software. The LCIA methods are implemented as separate data sets which contain all the descriptive metadata documentation and the characterisation factors assigned to different elementary flows. The effects of near term climate forcers are uncertain and therefore excluded (following the UNEP/SETAC recommendations of the Pellston Workshop, UNEP 2016). The GWP presented here represents only the effects from degradation of CO into CO_2 (stoichiometric calculation). (Fazio et al, JCR, 2018)

EF 2.0 Climate Change, fossil and Biogenic [kg CO2 eq.]

Indicator Global Warming Potential (GWP), Model: IPPC, 2013 + adaptations.
The Global Warming Potential (GWP) data reported in the IPPC (2013) have only one emission compartment ("to air"). Therefore, the values were assigned to the different emission compartments in the ILCD and EF(i.e. "emissions to lower stratosphere and upper troposphere", "emissions to non-urban air or from high stacks", "emissions to urban air close to ground", "emissions to air, unspecified (long term)", and "emissions to air, unspecified"). As the IPCC report does not report GWP values smaller than 1 (but lists these as <1), such values were calculated by using the Absolute Global Warming Potential (AGWP)(Fazio et al, JCR, 2018)

EF 2.0 Water scarcity [m³ world equiv.] Scarcity-adjusted water use

The AWARE, *Available WAter Remaining,* model is taking into account different resolution levels, however, for the EF recommendation, only the country scale is adopted. In this LCA tool world equivalent is used. AWARE is the result of a two-year consensus building process developed by WULCA, a working group of the UNEP SETAC Life Cycle Initiative. AWARE complies with ISO 14046 and represents the state-of-the-art of current water LCIA methods. AWARE is used for instance within the Environmental Footprint Initiative of the European Commission for Product Environmental Footprints (PEF) Besides world water data generilazed in AWARE, other regionalised LCIA methods would allow more accurate impact . LCA tool used in this study offers more streamlined comparison excluding regional effects. Another methodology to further evaluate the regionality for water scarcity comes from Classification of scarcity levels, based on the ration between water consumption and water availability, as in Frischknecht et al 2008. Table 1 below adapted from Frischknecht et al.

TABLE 1 Water scarcity example regions

Scarcity classification	Water scarcity ratio (water consumption /available resource)	Typical countries
Low	<0.1	Argentina, Austria, Estonia, Iceland, Ireland, Madagascar, Russia, Switzerland, Venezuela, Zambia
Moderate	0.1 to <0.2	Czech Republic, Greece, France, Mexico, Turkey, **USA***
Medium	0.2 to <0.4	China, Cyprus, Germany, Italy, Japan, Spain, **Thailand***
High	0.4 to <0.6	Algeria, Bulgaria, Morocco, Sudan, Tunisia
Very High	0.6 to <1.0	Pakistan, Syria, Tadzhikistan, Turkmenistan
Extreme	≥1	Israel, Kuwait, Oman, Qatar, Saudi Arabia, Yemen

*countries for biomass origin in polymer materials used in ABM (2019) for materials in this LCA

EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]

Acidification is mainly caused by air emissions of NH_3, NO_2 and SO_X. In the data set, the elementary flow “sulphur oxides” (SO_X) was assigned the characterization factor for SO_2. Other compounds are of lower importance and are not considered in the recommended LCIA model. Few exceptions exist however for NO, SO_3, for which CFs were derived from those of NO_2 and SO_2 respectively. CFs for acidification are expressed in moles of charge (molc.) per unit of mass emitted (Posch et al 2008). As NO and SO_3 lead to the same respective molecular ions released (nitrate and sulphate) as NO_2 and SO_2, their charges are still z=1 and z=2, respectively. Using conversion factors established as z/M (M: molecular weight), the CFs for NO and SO_3 have been derived as shown in following Table,
CFs for specific flows, not available in the original model, but contained in the elementary flow list, both for ILCD and have been calculated. For the most relevant flows in the specific category, country-specific CFs have been calculated. method from Seppälä et al 2006, Posch et al 2008: Accumulated Exceedance (AE):

TABLE 2 Acidification conversion factors to CF’s

	Conversion factors		CF's	
SO_2	3.12E-02	eq/g	1.31	eq/kg
NO_2	2.17E-02	eq/g	0.74	eq/kg
NH_3	5.88E-02	eq/g	3.02	eq/kg
NO	3.33E-02	eq/g	1.13	eq/kg
SO_3	2.50E-02	eq/g	1.05	eq/kg

(Fazio et al, JCR, 2018)

EF 2.0 Eutrophication freshwater [kg P eq.] and Marine water (kg N eq.) and terrestrial [Mole of N eq.]

Only main contributors to the impact were reported in the current documentation of factors However, if other relevant N- or P-compounds are inventoried, the LCA practitioners can calculate their inventories in total N or total P – depending on the impact to assess – via stoichiometric balance and use the CFs provided for “total nitrogen” or “total phosphorus”. Additional elementary flows were generated for “nitrogen, total” and “phosphorus, total” in that purpose. Double-counting is of course to be avoided in the inventories, and - given that the reporting of individual substances is preferred - the "nitrogen, total" and "phosphorus, total" flows should only be used if more detailed elementary flow data is unavailable

- Freshwater: Phosphate, phosphoric acid, phosphorus total *
- Marine: Ammonia, ammonium ion, nitrate, nitrite**, nitrogen dioxide, nitrogen monoxide**, nitrogen total

** Phosphorus pentoxide, which has a factor in the original paper, is not implemented in the ILCD flow list due to its high reactivity and hence its low probability to be emitted as such. Inventories where phosphorus pentoxide is indicated should therefore be adapted/scaled and be inventoried e.g. as "phosphorus, total", based on stoichiometric consideration (P content).*
*** CFs not listed in ReCiPe data set; these were derived using stoichiometry balance calculations.*

With respect to terrestrial eutrophication, only the concentration of nitrogen is the limiting factor and hence important, therefore, original data sets include CFs for NH_3, NO_2 emitted to air. The CF for NO was derived using stoichiometry, based on the molecular weight of the considered compounds. Likewise, the ions NH_{4+} and NO_{3-} were also characterized since life cycle inventories often refer to their releases to air. Site-independent CFs are available for ammonia, ammonium, nitrate, nitrite, nitrogen dioxide, and nitrogen monoxide. Note that country-specific characterisation factors for ammonia and nitrogen dioxide are provided for a number of countries (in the LCIA model data sets for terrestrial midpoint).
As for acidification and terrestrial eutrophication, CFs for “emissions to air, unspecified”, available in ReCiPe2008, were used for mapping CFs for all emissions to air, emissions to “air, unspecified (long term)”. This omission needs to be further evaluated for its relevance and may need to be corrected. In freshwater environments, phosphorus is considered the limiting factor. Therefore, only P-compounds are provided for assessment of freshwater eutrophication. In marine water environments, nitrogen is the limiting factor, hence the recommended model’s inclusion of only N compounds in the characterization of marine eutrophication. The characterisation of impact of N-compound emitted into rivers that subsequently may reach the sea has to be further investigated. At midpoint, marine eutrophication CFs were calculated for the flow compartment “emissions to water,

unspecified". These factors have been added as approximation for the compartments "emissions to water, unspecified (long-term)", "emissions to sea water", and "emissions to fresh water". No impact assessment models, which were reviewed, included iron as a relevant nutrient to be characterized. Therefore, no CFs for iron is available. (Fazio et al, JCR, 2018,21)

1.4 Methodology and data

A LCA study requires a large scale of data collection to construct a proper life cycle inventory (LCI). LCI is considered to be the most labour-and time- intensive step. Literature values and LCI databases are widely used to develop LCIs for (sub-) processes. Many national and/or regional LCI datasets have been released over the past few years, including the Swedish CPM database, the Japanese JEMAI database, the US NREL database, the Swiss Ecoinvent database, and the European Reference Life Cycle Database (ELCD). (Yelin Deng, 2014, p5)

During this project following LCA softwares were examined as options.: Sustainable minds ® (easy-to-use, cloud-delivered Eco-concept + Life Cycle Assessment software) OpenLCA (supports Gabi and Eco invent datasets) and Think-Step Gabi

During the project start LCA software were investigated and evaluated based on available information from experts and suppliers. Accuracy, relevance, availability and volume are important factors when choosing LCA software package including the data. According to comparative study for LCA software by Bach et al, (2019) Gabi, Simapro, Umberto, and Legep require a high level of user proficiency, there are still software programs like CAALA and 360 Optimi that do not require much user knowledge of LCA, but still provide a good range of other opportunities. According the study software BEES is considered to be a program that requires no prior knowledge, it has fewer editable options and therefore provides less accurate statements. Similarly, eLCA is a tool that provides more editable options, which makes it an easy-to-use tool for designing simple systems.

The paper from Bach et al. (2019) showed different existing LCA software products, which are suitable for different levels of user knowledge. It was demonstrated that a number of software are available for simpler design, such as eLCA or CAALA. Whereas Gabi, Simapro, Umberto, and Legep require high levels of user proficiency. If material innovation requires the LCA for a specific material, GaBi, Legep, or Umberto are suitable. In this regard, an (external) person with expert knowledge on LCA is required due to the complexity of the programs (highly editable)

Two major LCI databases exist on the market: The Ecoinvent Database which is developed by the Swiss Center of Life Cycle Inventories and GaBi which is developed by PE International, now Sphera company. Many other LCA software providers use the same data bases; GaBi or Ecoinvent. The Ecoinvent is a not-for-profit association providing over 14 700 LCI datasets in many areas such as energy supply, agriculture, transport, biofuels and biomaterials, bulk and specialty chemicals, construction materials, wood, and waste treatment, According to themselves ecoinvent version 3 is the most comprehensive, transparent, international LCI database. ThinkStep, GaBi database contains over 14,000 inventories from 20 + industrial sectors that are available for customers and ThinkStep consultants, responsible for building Bioplastic tool, have over 60,000 proprietary inventories, according to their marketing material

ThinkSteps's GaBi Envision and Bioplastic tool

Selected tool: GaBi Envision is a tool that enables streamlined LCA calculation. Original LCA is modelled in the GaBi TS Software, then imported as file into GaBi Envision, where then is possible to build scenarios with predefined and selected variables in product system frame enabling building what-if scenarios. Data used is from the 2019 GaBi databases (Thinkstep, 2019).GaBi tool provided the principle data source for LCI development. The GaBi database contains large amount of data from which a customization for tool was done according to the implementation project needs. The database possesses good transparency and reproducibility. GaBi Envision tool for bioplastics was selected due to the light weight computing; the fixed shadow calculation is enabling the “behind the scene” calculations and therefore other professionals than just LCA experts can benefit from the tool. There were positive reviews from earlier customers using selected tool. Gabi Envision can use other calculation tools, for example the Material Circularity Indicator can be implemented as calculation tool in Envision software.

GaBi Envision based ABM Bioplastic tool v. 2019 is using several methods which are combined and applied in the EF 2.0 methodology (European Commission). Complete methodologies, basis of all GaBi databases, the professional database and the extension databases, as well as all data-on-demand datasets:

- CML 2001, ver. 2016 (CML 2001), additionally ver. 2001-2013
- ReCiPe 2016 v1.1, Mid- and Endpoints (I+H+E) (RECIPE 2012), additionally ver.1.05 ver.1.07 (H) and1.08 (H)
- TRACI 2.1 (TRACI 2012), additionally TRACI 1 and TRACI 2.0
- UBP 2013 (UBP 2013), additionally UBP 1998 and UBP 2006
- EDIP 2003 (HAUSCHILD 2003), additionally EDIP 1997
- Ecoindicator 99 (ECO-INDICATOR 99 2000) and 95 (ECO-INDICATOR 95 2000)
- Impact 2002+ (IMPACT 2002)
- Environmental Footprint 2.0 (ILCD/EF 2.0): Combined using IPCC 2013 (IPCC 2013), World Meteorological Organisation (WMO 2014), ReCiPe (RECIPE 2016), USETox 2010 (USETOX 2010), Soil quality index based on LANCA (BOS ET AL. 2016), Ac-cumulated Exceedance (SEPPALA 2006), UN Environment (FANTKE 2016 and UNEP/SETAC 2016), Ionizing Radiation (PFISTER ET AL. 2009), Resource use (CML) (ultimate reserve and MJ fossil energy (CML 2001), and AWARE (AWARE)
  (Kupfer, Baitz et al 2019, GaBi, 71-72)

1.4.1 Life cycle inventory data: Quality and credibility

Data, which is generated in con-junction with industry or associations for distribution with GaBi databases to the professional LCA user community undergo an additional quality check by the respective data providers or by selected neutral third party organisations, as an independent third party review.
(Kupfer, Baitz et al 2019, GaBi, 3)

Additional External review activities: The different elements of the GaBi databases were independently reviewed three times between 2012 and 2014, by three different organisations: The ILCD compatibility of selected GaBi processes across all branches was reviewed for the European Commission’s JRC by the Italian National Agency for new Technologies, Energy and Sustainable Economic Development (ENEA). In the light of the Product and Organisational Environmental Footprint (PEF/OEF) Initiative of the EU Commission, the Spanish “Centro de Investigaciones Energéticas, Medioambi-entales y Tecnológicas (CIEMAT)” reviewed GaBi data with focus on energy systems.

Both the two above reviews have been commissioned by the European Commission. To complement our responsibility concerning external reviews, thinkstep introduced a critical review process of its GaBi databases with the inspection and verification company DEKRA, the third external organisation to carry out a review. As LCA continues to be used more broadly in industry, companies require increased accuracy, transparency and credibility of their data sources in order to make the best-informed decisions. Recognising this and in order to ensure consistency and quality of its GaBi databases, thinkstep finalized the first round of an “on-going critical review process with DEKRA”. The DEKRA critical review of the GaBi Database verifies:

- Credible independent sources underpinning each dataset
- Up to date engineering know-how used in composing the dataset
- Accurate meta -information documenting the dataset

The review initially covers basic technologies, such as power plants, refineries and water treatment units underlying many other aggregated datasets and continues with datasets derived from these core models. In addition to the datasets themselves, the quality assurance processes at thinkstep are also subject to an audit. (Kupfer, Baitz et al 2019, GaBi, 4)

2 Implementing sustainability assessment in product design at ABM

Utilizing LCA in product development in SME at ABM: Recent years have been a game changer in increasing awareness to circular economy preference in product design. Eager consumers for sustainability information are B2B product manufacturers, suppliers or OEMs. The need for establishing process that enables a streamlined LCA at the early phase of product development to support customer decision making lead by sales and marketing appears repeatedly. ‘*We need more information on the impact on sustainability if we are to change our conventional fossil based material to bio-based material you offer’*- is frequently questioned. Many stakeholders are requesting LCAs for materials offered as fluently as one ask after technical data sheets or material safety data sheets. That causes a paradox in phases where material has been tailored according to customer needs under development project and final product manufacturing details are still unknown. Building “what-if scenarios” can offer solutions for evaluating material selection and production locations. The information from raw material providers offers preliminary information on sustainability, but ends up being short to be the final evidence on sustainability value. Since it is not possible to compare different LCA’s from individual plastic producers and follow ISO principles simultaneously, a need for scenario analysis tool for material selection comparison emerges. Stakeholders have strong understanding that transition to bio-based materials is needed, and that all bio-based are not equal to most sustainable option. Company applying LCA in this project has previously mainly relayed on sustainability information from raw material suppliers. The GWP weight of process steps added by ABM on final products environmental impact is unknown. Long supply chains and additional processing steps adds environmental burden that should be considered in the evaluation of sustainability. A tool and method is needed for assessment of the life cycle of products produced and marketed as “more sustainable alternatives”.

The role of plastic material manufacturing in consideration on the effect the final plastic products sustainability is relatively limited during product conversion phase, when considered as use phase. How the material is converted and distributed to customer has a significant weigh on final GWP of the products. The important aspects to be considered are recognized and acknowledged during material design process. Figure below adapted from Mendes et al (2018) helps building the total methodological approach combining phases and stages of LCA implementation in product development process (PDP). Final **Product* herein considered as ABM composite raw material or product as a plastic item in the final product system where ABM composite is seen as feedstock. LCA is modular by nature when studied PDP process resulting product is a feedstock for another product in lifecycle.

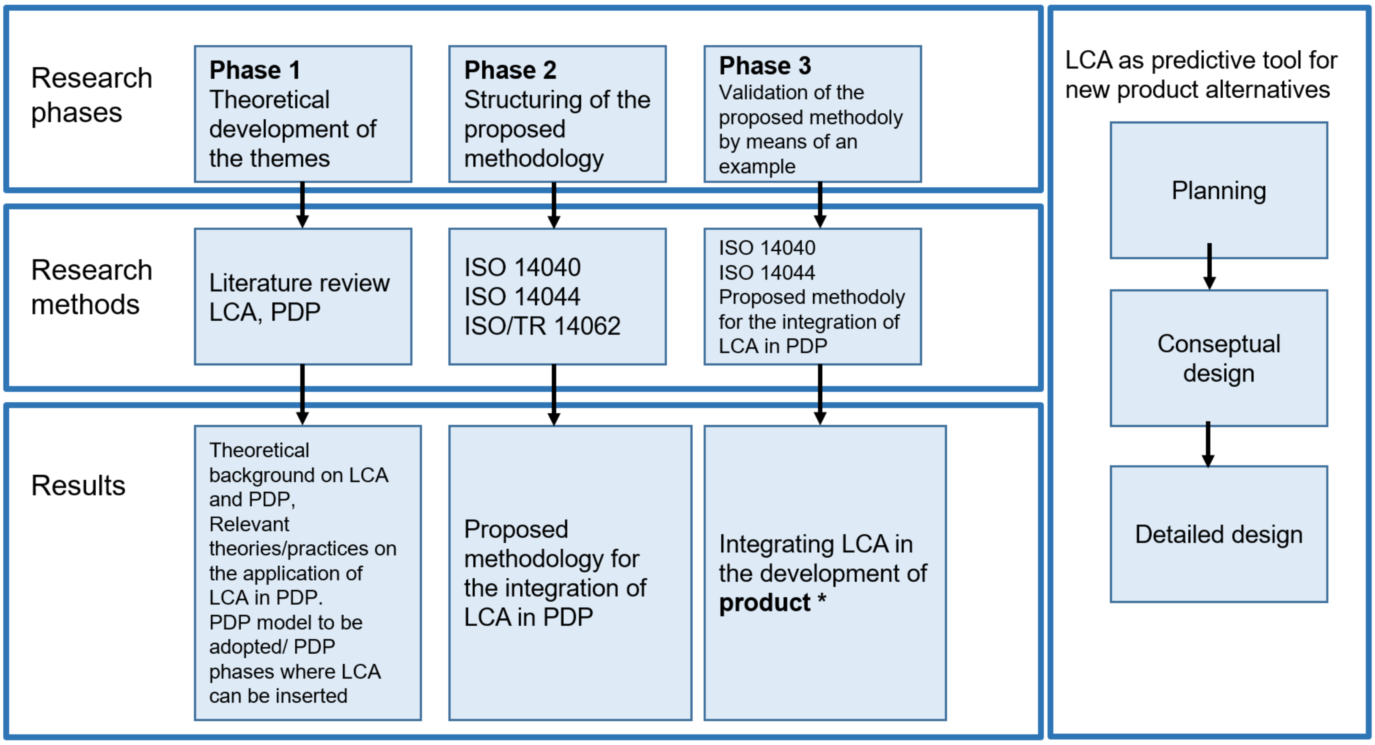


FIGURE 3 Integrating life cycle assessment in the product development process (figure adapted from Mendes et al 2018)

2.1 Ecological Design thinking

According to Bhander et al, (2003), a knowledge gap between the environmental scientist and the designer can be filled through an interface between LCA and CAD systems. LCA tools for designers might thus be better integrated into computer-aided design environments to help the designer identify waste of resources, and problematic process outputs, both directly and indirectly associated with the life cycle of the product online, as decisions are made within the product development process. The research proposes to present environmental information in a manner that facilitates and caters to the designer's learning profile through tools and methodologies. All approaches must take a life cycle view for the development of environmentally superior products; Approaches must be developed to extend the first life and post-first-life of products, e.g., design for reuse, remanufacture, and recycling; An interface computational tool and methodologies must support the analysis, synthesis, evaluation, and improvement of proposed designs from both structural and impact points of view. Today's concept of eco-design adds new activities to the traditional design process, while the structure stays the same. The problems identified imply that sustainable product design requires deeper analyses in the early phase of the product design process than is traditionally done in industrial design. Thus, the designer's work field will be enlarged to include more analysis activities related to the relationships between humans, consumption, and products, and more activities around organizing the use and disposal of the product. It is likely that if the focus on the relationship between products and environmental problems continues to grow, the demand for designers with special knowledge about sustainable product design will also increase. When product development includes design planning starting from material sourcing following step by step until the end life of the product movement from linear economy towards sustainable circular economy is more likely to occur. Preferably the end life of the product is circular and the recycling/ upcycling/ re-use of the material is taken into account at the early start of a design process. (Bhander at al 2003, 265-266)

Eco-design also goes beyond traditional knowledge. The product designer must be able to understand the whole context around the product and the system in which the product operates. There is a need for "metaknowledge" about product design. The introduction of LCA and industrial ecology forces the product designer to see the product in a wider perceptive. In the article from Bhander *et al.* the authors feel that LCA should be viewed as an important tool for broadening the understanding of a product's relation to environmental problems, but only in a form where the tool is more useful and better integrated into the product development process. The product's environmental performance should, through the concept of sustainable product development, be evaluated as to whether it fulfills a human need in a way that does not destroy future generations' ability to meet their needs. In the development of new products, it is crucial to evaluate the proposal solutions in a context that involves environmental impacts of the whole life of the product. LCA is a useful method for evaluation of new products in this context. (Bhander at al 2003, 265-266)

For a long time, eco-design was used mainly by large organizations with access to significant financial, research and development, human and technical resources and it used to form part of their voluntary activities. The legal regulations with regard to eco-design for energy using products (Directive 2009/125/EC) and the environmental requirements for construction products (Regulation (EU) No 305/2011), introduced, have changed the status of eco-design defining its new function. (Lewandowska, et al. 2014) On a European scale, initiatives have started such as discussions on the possibility of SMEs using eco-design (and the implementation of projects introducing LCA) to SMEs. Furthermore, the actions of the European Commission in relation to the development of a common methodology for the calculation of the product environmental footprint and the hopes for it being used in green public procurement, have made it possible to talk about a creation of favorable conditions for popularizing eco-design on an unprecedented scale. (Lewandowska et al, 2014, 1794)

2.1.1 System design principles

EEA has listed good practices listed for new and production methods: Biorefinery – producing more products from fewer resources, 3D printing with biomaterials, multipurpose crops and valorising residues bio-waste treatment, Composting and anaerobic digestion, Reducing and valorising food waste, Product and material lifespans, **Extending the lifetime of bio-based products** and Cascading the use of biomass.   System design principles listed by De Schoenmakere (2018): Prioritising innovation that diminishes materials use and keeps products and materials in circulation. Using bio-based non-biodegradable materials where their use provides a benefit over fossil alternatives, and where they can be effectively recycled and the end of their life. Using bio-based biodegradable materials where the risk of dispersion into the ecosystem is high, such as lubricants, materials subject to wear and tear and disposable products. Embedding technological innovation in wider system innovation that also tackles consumer behaviour, product use and waste management. Integrating these principles into research and innovation. (De Schoenmakere, 2018). To support these system design principles tools like Material circularity indicator can easily be implemented for evaluating product circularity value

2.1.2 Circularity evaluation tool

When considering the products whole lifespan, especially working together with the producer of the final product, the life cycle design as whole should be considered and examined from aspects of raw material circularity and product functionality. Does the new material enable transition from disposable to durable and does the durable material possess a circular nature? Or how to accomplish the circularity. For supporting this kind actions trough considering different scenarios, Ellen McArthur Foundation offers a tool for circularity evaluation. “While a circular economy is about systems thinking, the combination of design and business models and the effective flows and feedback loops, the creation of an analytical methodology and tool requires a more narrowly defined scope. The Material Circularity Indicator (MCI) developed in this paper therefore focuses on the restoration of material flows at product and company levels and is based on the following four principles: using feedstock from reused or recycled sources, reusing components or recycling materials after the use of the product, keeping products in use longer (e.g., by reuse/redistribution) and making more intensive use of products (e.g. via service or performance models). Given this scope, it is evident that improving the MCI of a product or a company will not necessarily translate as an improvement of the circularity of the whole system. Nonetheless, a widespread use of this methodology could form part of such a systems improvement.” (http://www.ellenmacarthurfoundation.org/circularity-indicators/)

MCI assigns a score for the product (or company) assessing how restorative or linear the flow of the materials for the product (or the company’s products) and how long and intensely the product (or the company’s products) is used compared to similar industry-average products. With the tool evaluation of total circularity index is made fluent. MCI (material circularity indicator) value being 1 means product being totally circular and closer to MCI 0, indicates product being linear by its nature, and not sustainable. Tools are available free of charge.
With company Level aggregator tool evaluation of product mass flows or revenue in ration to MCI, and the combined MCI index can be build.

Circularity indicator tool can be used in product development in customer communication as the B2B customer will complete or determine the information on how the industry average and lifespan of the final product is estimated. ABM provide material that can be seen a part of the final products carbon footprint. Material circularity indicator is also available as an option that can be implemented in the LCA software by software providers. These kind of tools enable environmental planning and communication framework with low threshold for initiating the use. This MCI example is offered for free, there’s then zero acquisition expense to start with sustainability evaluation for product manufacturing.

Decision support by Tool box

Literature review by Luglietti et al (2016, 202-205) discovered the “huge numbers of decision making frameworks were developed during the last decade. The general limitation spotted is the qualitative or semi-quantitative approach, which are not directly applicable on real business”. Responsible designers for the system design from its early stages, they are relevant decision-makers in sustainability terms. Unfortunately, designers are often unaware of all of the impacts (both economic and environmental ones) that the product they are creating will cause during its life. This is due by the absence of adequate tools able to match different sustainability aspects (or performance indexes) and relate them to any specific choice designers are considering during their work. (Luglietti et al. 2016, 202-205)

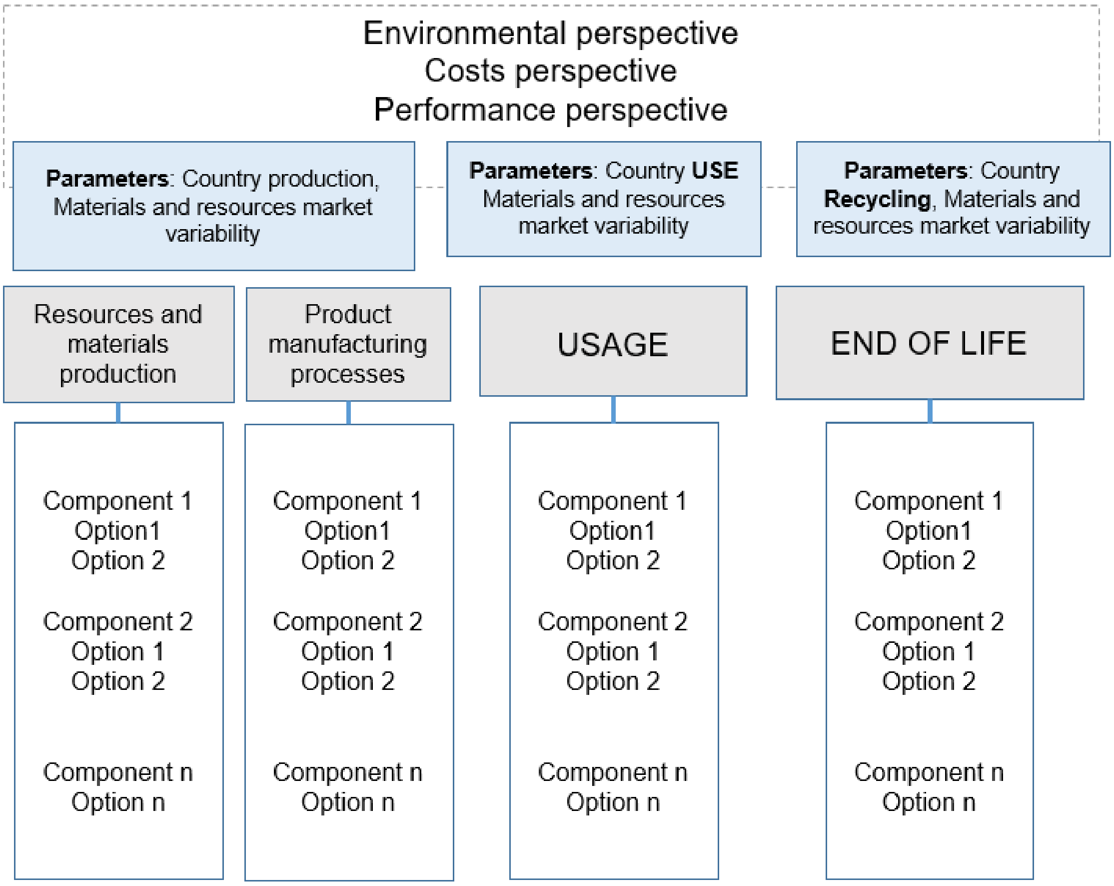


FIGURE 4 Decision support Tool box (adapted from Luglietti et al. 2016)

Tool box takes into account country of the production and use: which considers the energy mix used and the energy costs, materials and resources market variability, country recycling: which considers different waste management law. Example figure above is been development for both environmental and economic dimension. (Luglietti et al. 2016, 205) This type of tool box could be implemented as framework for product design and development projects where parameters and information from customer input for life cycle use phase is available. ABM share is in the earlier steps of product development. Material selection has more value as product design step since sustainability has become a metric in consideration for options.

2.1.3 LCA and risk management

Sustainability assessments will often reveal sustainability opportunities as well as risks; these opportunities are not always being identified and captured in enterprise risk management. Companies experience continued pressure to review and transform their business strategies to remain competitive. New types of risks are constantly emerging, including those inherent in the increased importance of environmental and social sustainability in business. (WBCSD, 2017, 4-6) Fifty years ago, the average life expectancy of an S&P 500 company was about 70 years. Today it is about 18 years and declining. What is causing this decline and how are the survival risks being assessed? What makes a business model sustainable? A sustainable business model must create, deliver and capture value. It must do this both short and long term. It must compete in the highly interactive, complex and non-linear global ecosystem which includes manifold and chaotic, social, economic, technical, political, legal and environmental factors (WBCSD, 2017, 32) A survey of USBCSD (Unites states business council for sustainable development) and WBCSD (World business council for sustainable development) member companies attending a risk management workshop showed that 70% agreed that their current practices do not address sustainability risk and 44% agreed that the frameworks need to provide more guidance to companies on how to embed sustainability into ERM. (WBCSD, 2017, 30)

How to proof and estimate the sustainability value or weigh of the product systems and how to communicate in a comparative way of the systems under critical evaluation? And to trust the outcome being objective and not *green washing*? In product development project the project definition phase should consider the sustainability aspect. Using LCA as a framework for risk assessment could be useful way to set goals during PDP initiation. Implementing LCA in product development is about identification of environmental impacts which is a risk management core process step when sustainability is a business goal. Transparent and well scoped LCA process will minimize the risk for unintended greenwashing and by using LCA methodology consistently signals out the company conducting LCA is willing to develop their sustainability and to discuss it openly.

On the other end of the risk spectrum lies idea of greenwashing, meaning creating positive image of sustainable product and environmentally friendly brand for marketing purposes without proof of scientifically evaluated impact on sustainability, as unethical activity it should be avoided in any means necessary. Greenwashing should be considered as a corporate risk as if exposed it could lead to business crisis. The change of unintentional greenwashing going hand in hand with supply chain management risks. Simultaneously the need to achieve more sustainable alternatives as raw materials is increasing in a fast pace. Environmental product declarations (EPDs) are not globally uniform and during product development of new materials, grafting the end product “eco label” can be challenging due to missing and variable information from material producers. LCA methodology and tools are then used to investigate the sustainability of production of raw material/ product. Implementing LCA in the product development phase supports future product stewardship when sustainability is a parameter among other properties from the beginning of the products history.

In considering company and sustainability reports, one of the problems is that of ‘greenwashing’. This is the use and misuse of the language of sustainability or imagery to disguise conventional, destructive practices. It includes the use of ‘green’ language to sell products that are not green to environmentally concerned people, for example. In their company reports, organisations are keen to place themselves in the best light by claiming to be greener than they really are. In the extreme, this behavior can lead to campaigns of misinformation, Company reports should always be read in the knowledge that they may contain an element of greenwash. (Sturges, 2016, 6)

Figure 5 below illustrates Risk assessment methodology for SME’s whose employers have difficulties allocating resources towards risk management in projects. If an example project is being imagined is simultaneously PDP and LCA related, combining **LCA steps** to methodology adapted from Marcelino-Sádaba et al. (2014), we see fluent overlapping with functions of risk assessment.

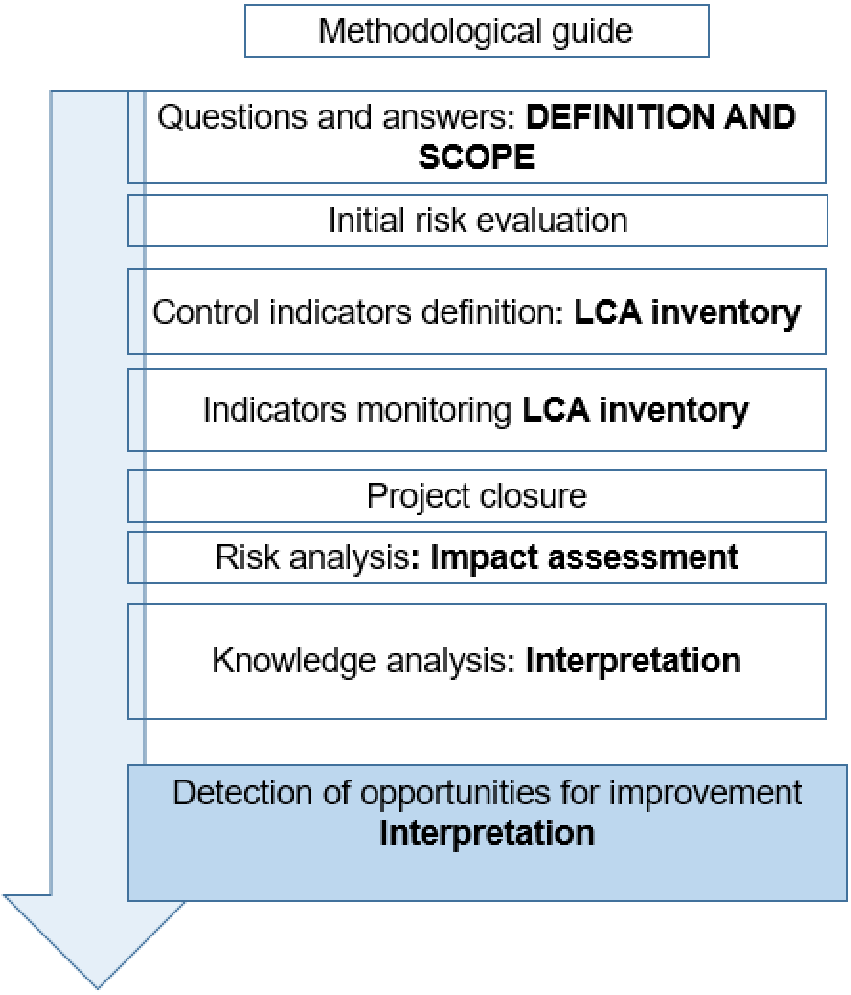


FIGURE 5 Implementation process of the risk management methodology. (adapted from Marcelino-Sádaba et al. (2014))

Marcelino-Sádaba et al. (2014) presented a project management methodology designed for small businesses (SMEs), who need to run projects beyond their normal operations. “These projects are critical to the survival of these organisations, such as the development of new products to adapt to the market or new legislation, management system implementations, etc. Very frequently, the managers of these projects are not project management professionals, so they need guidance to have autonomy, using minimal time and documentation resources.” In their study the difficulties of SME’s risk management were investigated via studying 72 local companies. During identifying strategic risk within projects; “Identifying risks in the project definition phase is a critical task, since the risks that can be detected are strategic and must be removed before taking the decision to start with the project. We have considered strategic risks those whose materialisation can lead directly to project failure and even jeopardise the very survival of the company.” Combining LCA as methodology in risk assessment in the early phase of PDP could help? Acquiring the information during project closure ; “the lessons learnt from project” The found knowledge can be combined to hot spots found via LCA.

According to a study by Barberio et al, (2014). *Combining life cycle Assessment and qualitative risk assessment*: *The case study of alumina nanofluid (NF) production;* “there are three main challenges in conducting an assessment of emerging technologies, i.e. wide range of possible applications, scale up and rebound effects. No one of these aspects could be covered in this case study. As it has considered only the production phase, without including application, use and end of life, the innovative functions of NF were not analyzed neither possible rebound effects could be clearly identified. Moreover, this study refers only to a pilot-line. Nevertheless, though the study here presented cannot be considered a full assessment of the NF, it has been an opportunity for testing and demonstrating the effectiveness of a combined use of Risk assessment and LCA. Their combined use should be encouraged, especially for emerging technologies, with the aim to take into consideration the safe-by-design concept and to stimulate a responsible and sustainable development based on economic growth, social values and reduction of environmental burdens(…) The first challenge of the framework application was to combine two different scales of spatial resolution: in fact, RA is site-specific and therefore high spatial resolution is required, while LCA is typically at regional/global scale and has low spatial resolution. The combined use of the two methods has required the definition of a common scope, which includes both site-generic and site-specific data. The RA was performed on the work environment by collecting site-specific data, such as the pollutant concentration and the worker exposure conditions, while site-generic characterization factors have been used in the LCA study. Both methods have presented difficulties with data availability but their integration has provided an opportunity for saving time and reducing costs. In fact, if the technological system is well defined, i.e. if processes are known and models and tools for the analysis are selected, a complete data collection at enterprises can be carried out for both studies simultaneously.” (Barberio et al 2014, 131-132)

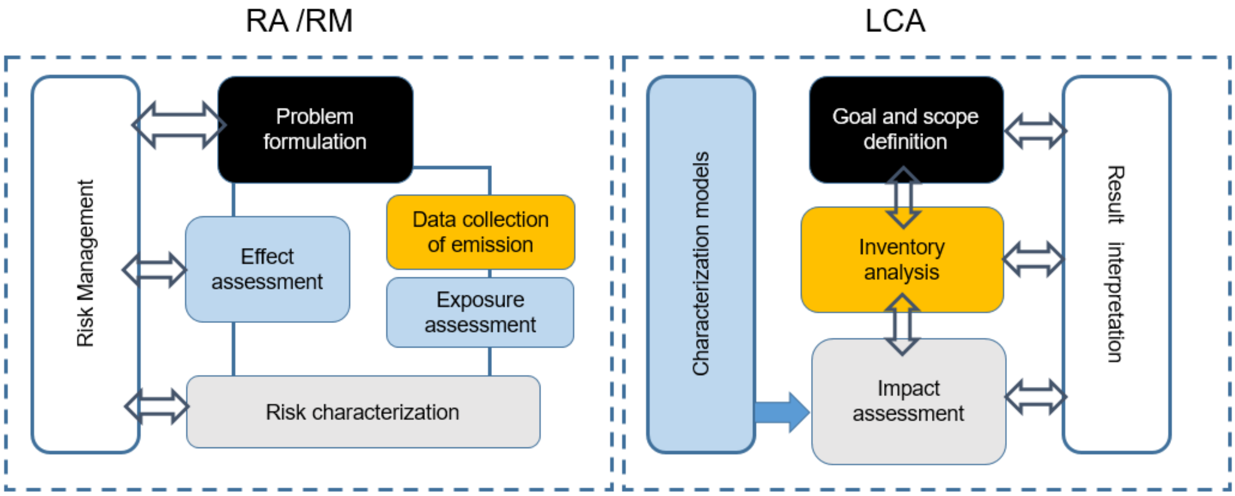


FIGURE 6 Risk assessment and LCA (Adapted from Barberio et al, 2014)

Similarities of of RA/RM and LCA are highlighted by matching colors in picture 6 above. Picture 6 is adabted from Barberio et al (2014) After immersing these similarities in their LCA RA study leading to outcome of 4 steps:

“Step 1. an LCA-based approach has been adopted for the **technological system** definition in order to consider the upstream and downstream stages and their relevance for the inventory and the impact assessment. The technological system definition is shared by both the qualitative RA (problem formulation) and the LCA (goal and scope definition);

2. **the data collection** combines information to develop the qualitative RA and the LCA study;

3. for the **risk evaluation** and impacts quantification, methods and assessment models have been chosen separately and applied independently;

4. **results interpretation** has been carried out in an integrated way as it gives important information on different aspects, i.e. the best production process performance and the workplace exposure.” (Barberio et al, 2014)

Figure 7 illustrates steps for conducting RA and LCA simultaneously, originally described by Barberio et al (2014, 124)

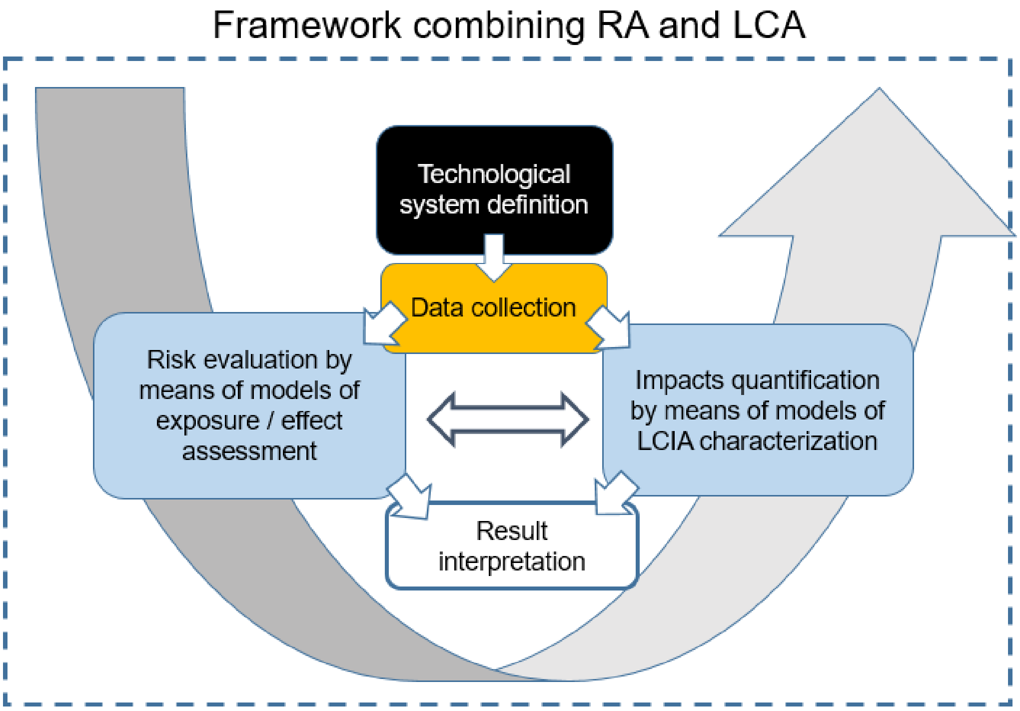


FIGURE 7 Proposal of methodological framework combining RA and LCA (adapted from Barberio et al 2014)

RA-LCA combination could be implemented in streamlined LCA, modular LCA where material selection is the key goal in impact conclusions. At the same time aspects like raw material supply chain and health and safety issues can be assessment during the product development process.

Hotspots identification

According to Barthel et al. (2017, 21-25) Hotspots analysis is overarching methodological framework and guidance for product and sector level application. Social, economic or governance indicators not commonly included in LCA or where no single accepted methodology or indicator exists for a particular aspect, users may consider taking inspiration from methodologies.

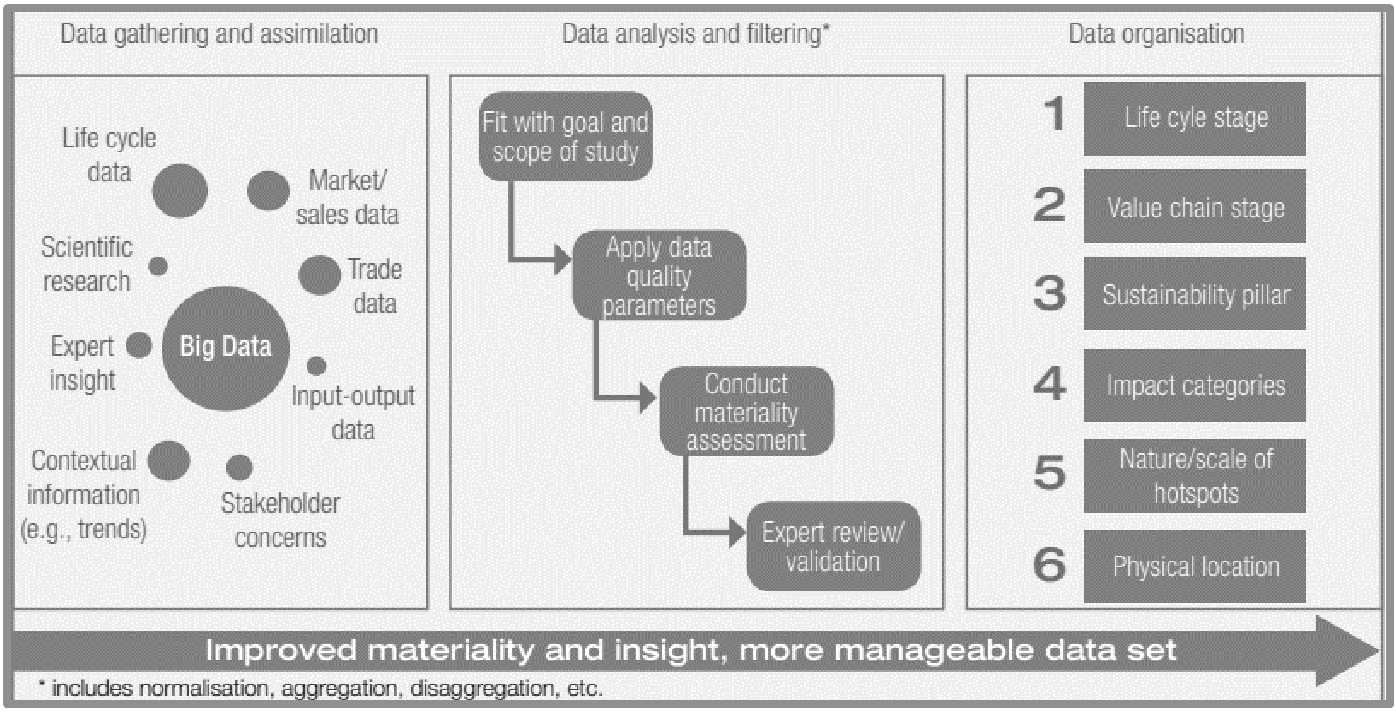


FIGURE 8 Common sources of data or information used in Hotspots Analysis (image offered by United Nations Environment Programme, Barthel et al 2017)

Cutting through “big data” by means of establishing data hierarchy. “Hotspots analysis generally draws on data from a wide range of both quantitative and qualitative data sources. This often leads to a large set of data, which then needs to be organized and prioritized before the analysis can take place. A number of data sources are shown in figure 8 above including LCA data, input-output data, trade or market common sources of data or information used in hotspots analysis data, scientific research, expert insight or input from stakeholders.” Barthel et al. (2017, 24)

2.2 Comparative LCA in design

Assessing sustainability and sustainability goals: Comparative LCA, especially between two different products is extremely sensitive to provide derived information that reliability and relevance can differentiate leading to false assumptions. LCA as methodology services its best purpose while conducting optimisation for production process and sustainable design, when LCA derived information is used as a tool to analyse the environmental performance of products. Or when considering the best practices for sustainable manufacturing of items.

When there are no significant resource limitations, comprehensive LCA can provide an ideal tool for improving and designing environmental performance. “In practice, however, problems such as limited data availability, reliability and relevance occur, and, given that a large proportion of the ultimate environmental costs of a product are determined at the design stage, this is the ideal time to address life cycle engineering aspects of the product.” (O’Neill et all 2003, 25) According to O’Neill *et al*, (2003, 24) the problem is that standard LCA methodologies address real commercial products in real systems of manufacture, use and disposal; they do not lend themselves to useful application at the design stage. Consequently, techniques have been developed that purposely adopt a simplified approach to LCA, so called streamlined or abridged life cycle assessments. These approaches have been recognised and encouraged by SETAC and ISO/TC 207 Environmental management.

According to Weidemas (2014) critique towards ISO standardised LCA:
ISO 14040/44 standards for LCA, either for a specific geography as, for example, the BPX 30-323 for France and the Product Environmental Footprint Guideline for the European Union, a specific sector with the so-called product category rules (PCRs) that seek to regulate the production and communication of LCA information for products within the product category, or a specific topic as in carbon or water footprints. Unfortunately, these guidelines, as currently published, sometimes cover the same product categories and markets without adequate or reasonable justification, and they reflect different interpretations of ISO 14044 with respect to system boundaries (cut-off rules, which unit processes to link to specific inputs, and rules for handling coproducts). Interestingly, all these interpretations claim to be based on— if not directly to be in accord with—ISO 14040/44. If this is really true, it points to a serious failure of ISO 14040/44 to fulfil its role as a standard, that is, to minimize or eliminate unnecessary variation. Different application areas, whether geographical, sectoral, or related to specific impact categories, may indeed require different kinds of data, specific definitions of functional units to make comparisons fair, and specific impact assessment methods. These are all issues that are not regulated in ISO 14040/44 and where specific guidelines are therefore relevant. Yet, all the current specific guidelines also specify further requirements for the life cycle inventory modelling that deviate more or less from the ISO 14044 requirements. These disparities in interpretation

of the ISO 14044 standard are not caused by differences across geographies, product groups, or impact categories and cannot be justified by reference to scientific disagreements. At best, the disparities can be explained by the vagueness of ISO 14044 on key methodological points, which makes it possible for everyone to get away with their own interpretation. Thus, a more unambiguous wording of ISO 14044 could help to reduce the current disparity in LCI modelling requirements in the geographical, sectoral, and impact-specific guidelines. The most critical vagueness in the current ISO 14044 relates to which unit processes to include in a product system and how to link these unit process data sets together. This has given rise to different interpretations, notably the attributional and consequential interpretation: An attributional product system is composed of the activities that have contributed to the production, consumption, and disposal of a product, that is, tracing the contributing activities backward in time (which is why data on specific or market average suppliers are relevant in such a system). A consequential product system is composed of the activities that are expected to change when producing, consuming, and disposing of a product that is, tracing the consequences forward in time (which is why data on marginal suppliers are relevant in such a system). (Weidema, 2014, 324)

ISO 14040 series revision in 2006 did not differentiate “attributional” and “consequential” models. Still, the ISO 14040 series is part of the overall ISO 14000 series on Environmental Management Systems (EMS), which has a commitment to continual improvement as a basic requirement as policy statement. It is therefore obvious that also the ISO 14040 series is concerned with improvements rather than measuring stationary situation. The introduction to ISO 14040:2006 where all the listed applications of LCA are about improvements: “LCA can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle, informing decision-makers, e.g. for the purpose of strategic planning, priority setting, product or process design or redesign, the selection of relevant indicators of environmental performance, marketing (e.g. implementing an Eco-labelling scheme, making an environmental claim, or producing an environmental product declaration).” (ISO.org)

2.2.1 Environmental Product Declarations

The eco-design directive has been extended in 2009 to all energy-related-products, like product which do not necessarily use energy, but have an impact on energy consumption (direct or indirect) and can therefore contribute to saving energy, such as windows, insulation material or bathroom devices (e.g. shower heads, taps). One of the most important topics of the Directive is the lifecycle evaluation, which wants to consider the energy consumption throughout the whole product lifecycle, from the raw materials selection to the waste production. Other standards developed for product classification including environmental aspects are the environmental labelling defined by ISO (ISO 14021, 14024 and 14025), which is can be applied to all product categories, and they consider the entire lifecycle with streamlined if needed. (Lugiletti et al (2016, 202)

Next step after Life cycle inventory and assessment is conducted in the communication about business sustainability can be conducted by sharing product specific environmental declarations, EPD communication is not globally uniform and can vary. From the existing ISO guidelines the type III recommendation is based on the full LCA behind the EPD intendent in communication.

ISO series for environmental communication:

ISO 14020 Environmental labels and declarations -General principles,

The ISO 14020 family covers three types of labelling schemes:

Type I is a multi-attribute label developed by a third party;

Type II is a single-attribute label developed by the producer;

Type III is an eco-label whose awarding is based on a full life-cycle assessment.

Important features to keep in mind from the type III declarations as the standard states: “Type III environmental declarations as described in this International Standard are primarily intended for use in business-to-business communication, but their use in business-to-consumer communication is not precluded. It is recognized that a developer of a Type III environmental declaration cannot precisely determine the audience. However, it is important to consider the information needs of different purchaser or user groups, for instance large businesses, small and medium sized enterprises (SMEs), public procurement agencies and consumers. Those responsible for developing Type III environmental declarations and programmes based on International Standard will need to pay due attention to the level of awareness of the target audience.” (ISO org.) In the practice of developing Type III environmental declarations, programmes or their declarations are referred to by various names such as Eco-Leaf, eco-profile, environmental declaration of product, environmental product declaration (EPD) and environmental profile. The development and operation of Type III environmental declaration programmes and the development and use of Type III environmental declarations are voluntary. This International Standard provides requirements for an organization choosing to develop and operate such a programme or to develop and use such declarations. (ISO org.)

Transparency behind comparative assertion

According to Type III environmental declarations –Principles and procedures (ISO 14025), the instructions for conducting environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function are clear, for example lit for information and functions to be provided. The general programme instructions shall be available to any person on request.

2.2.2 Accounting the environment via LCA

According to Bhander et al 2003, “The goal and scope definition phase may be the most critical of the LCA because this is where the detailed framework of the study is defined. An important function of the scope definition is to distinguish “nice to know” from “need to know” information for tackling the goal. The purpose of the scope definition is to identify and to define the object of the assessment and to limit it to include that which is significant for the LCA goal. The scope definition typically involves identifying the function(s) of the assessed systems, system boundaries, functional unit, data requirements, alternative products or services, key assumptions, and limitations of the product. (…) “

Bhander et al continued; “as a number of deficiencies in LCA are identified, strategies are presented to solve them. Designers seldom place high priority on environmental demands-there is simply not enough time for dealing with environmental issues in great detail. Product demands, such as durability, technical flexibility, aesthetics, and ergonomics are prioritized higher by the designer than environmental issues. The sustainable product designer will not only design new products with “greener” technologies and reduced environmental impact. The work will also be about organizing the use of products, and reducing the generation of byproducts. This implies that the working field of the designer will expand, and include more analysis and planning activities.” (Bhander et al 2003, 266)

As this description of low environmental prioritizing was concluded during 2003 times have now changed into situation where global corporations and increasing volume of SME’s, will provide information on their take on sustainability by means of environmental declarations, ecolabels, sustainability strategies and other continuously updated publications and by implementing sustainable design earlier on the product development phase.

2.3 Sustainable material transition from fossil to bio

Why there is a need for shifting into bio-sourced material use in production of durable and semi durable goods? The reduction of greenhouse gases in atmosphere. Produced material made from bio-based sources has certain amount of atmospheric carbon intake in them. If the used energy form in production is carbon neutral or optimal for the produced material, the material can be carbon neutral or carbon negative or positive, depending on the final net carbon intake/ release.   To study this LCA, as accounting the environment is used.

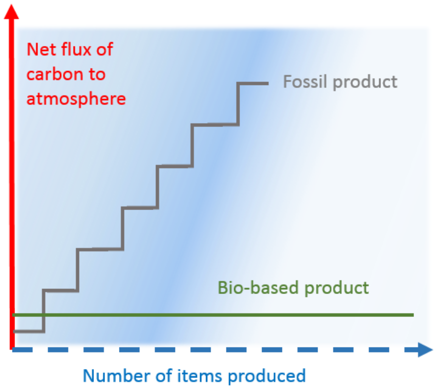


FIGURE 9 schematic net flux carbon into atmosphere(re-drawn according Vink and Davies, 2014)

Figure 9 above illustrates the significant difference between carbon cycle scales when fossil and bio-based plastics are used. During one year the crops for raw material production are grown and certain amount of carbon dioxide is bind from the atmosphere and certain ratio of carbon is released from the processes when bio- based product is produced. When this cycle continues with durable goods production, the carbon intake will grow when produced good quantities are cumulative and act as a replacement for fossil based materials.

2.3.1 End life options: composting vs recycling

In study released 2018 by Changwichan *et al* the eco efficiency of biopolymers was investigated. E/E (*E/E =Environmental impact reduction/ Total cost)* has become recognized as an indicator to promote the sustainable development of production systems that has been standardized by the International Organization for Standardization as described in ISO 14045, It attempts to include the economic and environmental aspects of a product in a single indicator with a view to increasing economic benefit while reducing environmental degradation. (Changwichan, K. 2018)

The E/E, a combination of environmental and economic indicators, was used to investigate the environmental and economic sustainability of different bioplastic production systems with different EoL scenarios. Bioplastics (PLA and PHAs) do not necessarily perform better than fossil-based plastic (PP) in the current situation where most of the plastic and bioplastics are landfilled; PBS, however, is seen to have the best E/E. That is due to electricity consumption in the resin production process. The quantity of electricity required for the PBS resin production process is significantly lower than others; 1.07, 1.09, and 0.13 kWh/kg for PLA, PHAs, and PBS resin, respectively. Introduction of recycling changes the results in favor of PLA. PLA coupled with 100% mechanical recycling showed the highest E/E, followed by PP, PBS and PHAs. Out of the four EOL options, 100% mechanical recycling always showed the highest E/E values for all types of plastic and bioplastics boxes. Based on the results of this study, the composting scenario of bioplastics did not show a better environmental and economic sustainability as it is intuitively forecasted. (Changwichan, K. 2018)

The environmental impacts for PLA disposal alternatives were assessed using the LCA methodology by Cosate et al. (2016). They reached the same conclusion as Changwichan, K ,: According their study the mechanical recycling presented the lowest environmental impacts, followed by the chemical recycling and composting. Similar results were found considering two different product systems. Electricity consumption exhibited the highest impacts amongst the inputs for chemical and mechanical recycling of PLA. The results can be explained by the fact that the recycling alternatives have recycled polymer as an output, which can be used again while the composting does not. This difference leads to a necessity of polymer replacement from the traditional route, causing higher environmental impacts. However, in situations that recycling is not possible, composting is a good alternative (Cosate et al, 2016)These two comprehensive LCA studies indicated that mechanical recycling presents fewer impacts than chemical recycling, (Piemonte et al 2013), (Cosate, M, 2016)

An article in Recycling technology by Richard McKinlay, (2019) states that "large-scale plants capable of processing at least 50 000 tonnes recycled/collected plastic per year are needed for economic viability. Although the cost of scaling-up and the investment needed have previously been prohibitive, companies are beginning to see the potential of this exciting technology. Virgin polymer producer Indorama has invested in companies in the USA and the Netherlands, while Plastipak has announced plans for a processing operation in Italy. Public awareness is prompting the plastic packaging sector into action and into investing in new recycling technologies to deal with waste materials. Huge investment is needed, as is further refinement of these processes, but we are very much moving in the right direction. According to McKinlay; when wanting to recycle everything, chemical recycling is the way to go. Mechanical recycling techniques will only take us so far. Chemical recycling can overcome the limits of mechanical recycling to produce high-quality end materials or recover value from non-recyclable materials. However, the increased cost and potential yield compromise of non-mechanical recycling means mechanical recycling still plays a vital role." (McKinlay, 2019)

2.3.2 Defining Bio-based, Biodegradable and Bio erodible

Circular economy takes in to account the end life, or new life for the material after purpose of existence for the product has come to end. Biodegradation back to biomass is most fundamental approach to solve the material balance. Material is degraded into source for new growth the circle can be closed. When considering energy and carbon release the degradation process is not the most sustainable option, at least according to the EU waste hierarchy. Re-use and recycling are preferred. Microorganisms utilize carbon substrates to extract chemical energy for their life processes. The carbon substrates become "food" that microorganisms use to sustain themselves. For this to occur, the carbon substrate needs to be transported inside the cell. Molecular weight is important but is not the only criterion for transport across cell membrane. Factors such as hydrophobic-hydrophilic balance and molecular and structural features also govern transport. Under aerobic conditions, the carbon is biologically oxidized to CO 2 inside the cell, releasing energy that is harnessed by the microorganism for its life processes. Under anaerobic conditions, CO_2 +CH_4 (landfill gas) are produced. Thus, a measure of the rate and amount of CO_2 or CO_2 +CH_4 evolved as a function of total carbon input to the process as a direct measure of the amount of carbon substrate being utilized by the microorganism (percent biodegradation). This is fundamental, basic biology and biochemistry that can be found in any biochemistry textbook. This forms the basis for various national (ASTM, EN, OECD) and international ISO) standards for measuring biodegradability or microbial utilization of chemicals and biodegradable plastics. (Ramani Narayan, 2011, 719)

A compostable is any polymer or plastic that can be converted into H_2O and CO_2 within a certain time scale and under specifically defined conditions, as specified in various standards, and that leaves no harmful residues behind. This material functionality applies to some bio-based polymers and to some fossil resource-based polymers. Polymers are biodegradable, if they can be more than 90 percent broken down by enzymes produced by living organisms (microbes). One definition relates to the raw material, the other, to the functionality of the material. (Ravenstijn, 2010,252)

TABLE 3 Average Biomass contents, Adapted from Nova Institute 2011

	Average biomass content of polymer
CA	50 %
PA	Rising to 60%
PBAT	Rising to 50%
PBS	Rising to 80%
PE	100 %
PET	30...35%
PHAs	100 %
PLA	100 %
PP	100 %
PVC	43 %
PUR	30 %

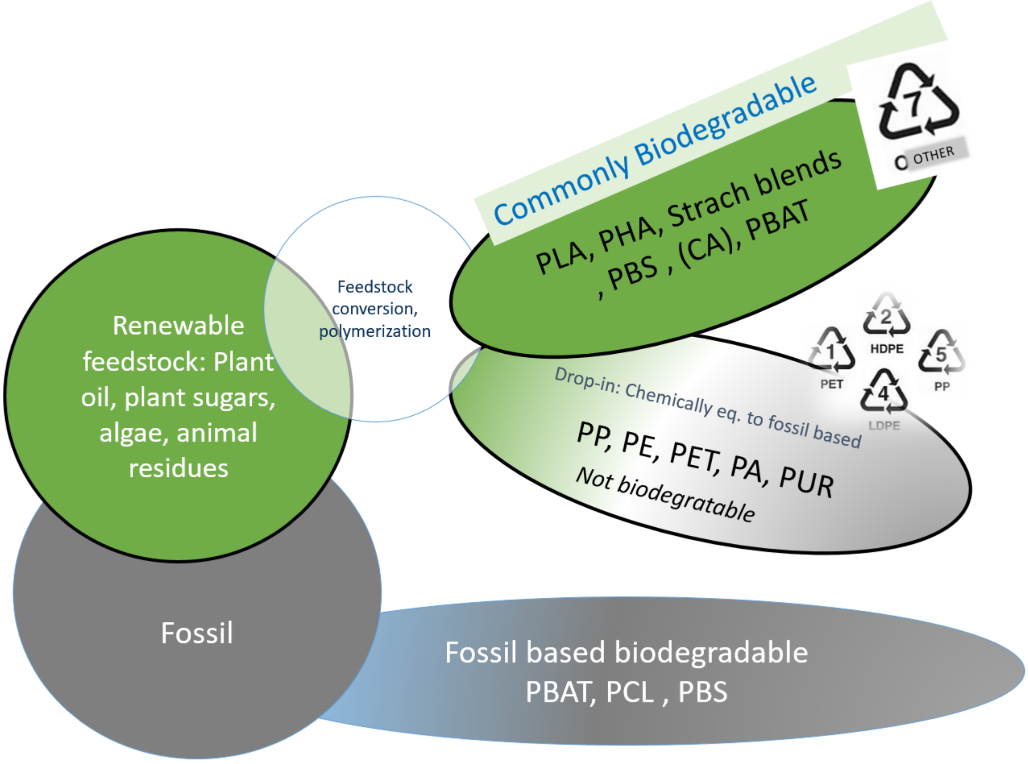


FIGURE 10 bio-based and/ or biodegradable , picture by Author

Polymer derived from natural resources can be chemically equivalent to fossil based polymer, i.e. are sometimes known as so called drop-in solutions, and therefore leading the polymer material being non-biodegradable. Non-biodegradable materials are more resistant to hydrolysis stress and can be recycled together with conventional fossil based counterparts. Biodegradable polymers in the other hand are processed as “other” as the fraction in plastic recycling is insignificant. Notable is that biodegradable polymer can simultaneously be derived from renewable feedstock or fossil based, or can be combination of both.

According to Segen's Medical Dictionary Bio erodible is referring to polymers/material that exhibit controlled degradation by incorporating pro-degradant additive master batches or concentrates. Such polymers oxidise and embrittle in the environment and start to lose material (erode).

2.3.3 Challenges in defining new sustainable polymeric materials

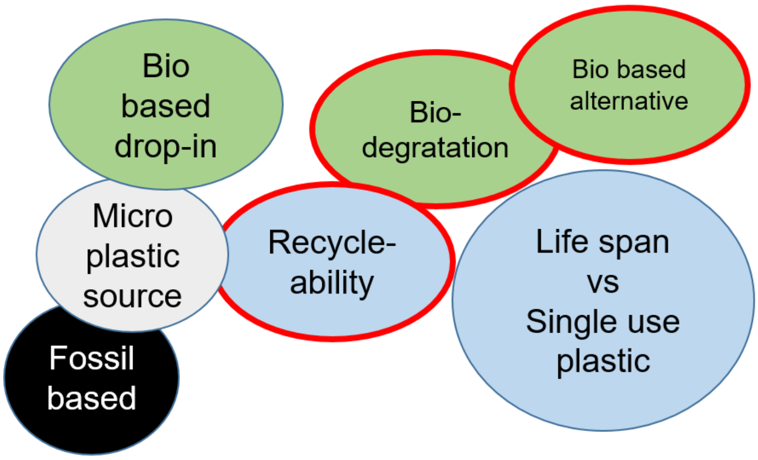


FIGURE 11 Defining plastics; new dimensions (Picture by Author)

In figure 11 above the Green colour represent circularity and biogenic carbon cycle. Drop-in is chemically equivalent to fossil based counterpart, usually not biodegradable (however, exceptions are found). Bio-based alternative is material more likely to be biodegradable. The challenges are in un-utilized technology or unavailable applications due missing commercialisation or material flows are marked with red outlines. Standardised declaration for material applications not forming micro plastics are missing. Life span is a vague term when material is used more than as single use plastic (SUP) if the product has no routes back to recycling or recycling infrastructure itself is absent.

The EUs single use plastic directive states: “Plastic products should be manufactured taking into account their entire life span. The design of plastic products should always take into account the production and use phase and the reusability and recyclability of the product. In the context of the directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 -on the reduction of the impact of certain plastic products on the environment PE/11/2019/REV/1, to be undertaken pursuant to Article 9(5) of Directive 94/62/EC, the material and product suppliers should take into account the relative properties of different packaging materials, including composite materials, on the basis of life cycle assessments, addressing in particular waste prevention and design for circularity. "As at the same time the reduction of single use plastics and shift towards using recyclable/re-usable products comes into action, the circular models for re-using plastic products are developing. In Finland the collection of plastic material for mechanical recycling via melting process only covers packaging materials and not anything made from plastic that is re-usable. To have items circulating and their material collected at the end of the life span, the material flows must be recognised and products and services planned so that reusable materials will be also recycled before quitting the incineration as EoL for plastics.

Fossil free energy 2050 – future plan: "A fully decarbonized EU energy system by 2050, in line with the EU's commitment under the 2015 Paris Agreement, and on the basis of a set of scenarios that explore the extent to which energy efficiency, smart electrification and green molecules can be the drivers for this transition in the EU's power, heat and transport sectors. " (Cambridge Econometrics, 2019)
New materials emerging that mimic nature's processes: Bio-based polymers and biodegradation processes are still not considered as natural polymers in EU terminology. Definition of natural polymers according to Article 3: "plastic means a material consisting of a polymer within the meaning of Article 3(5) of Regulation (EC) No 1907/2006, to which additives or other substances may have been added, and which can function as a main structural component of final products, with the exception of natural polymers that have not been chemically modified." (Natural polymers are polymer molecules that are fabricated by the nature, such as proteins, starches, cellulose and DNA.)

Maija Pohjakallio, Sulapac company's Sustainability Director, states that new definitions for bio-based and biodegradable materials are needed to achieve more consistent consumer communication: "With the new certificate, we could start using the term 'microplastic-free' to also communicate more clearly with consumers. This would be a much more precise message than 'plastic-free', which is now being used in various meanings by different stakeholders. 'Microplastic-free' is also more unambiguous than the adjective ‘biodegradable’, which is ill-defined and often confused with the expression ‘bio-based’. A microplastics-free label would provide consumers important information for sustainable choice making.” These aims can and should be discussed further to prevent the confusion in the larger audience, as companies wish to complicate the plastic terminology. Micro plastic free under what timeframe, and how it is proved and detected?

3 Introduction to composite materials

Composite materials offer advantages for tailoring mechanical properties according variable applications needs. Composites are used in various industries including sporting gear, aerospace materials, transportation structures, Houseware, chemical engineering, electrical industries and construction materials. Composites are combinations of two materials in which one of the materials called the reinforcing phase, is in the form of fibers, sheets or particles and is embedded in other materials called matrix phase. The reinforcing material and the matrix material can be eg. metal, ceramic or polymer. Composites are used because overall properties of the composites are superior to those of the individual components. Composites consist of two (or more) distinct constituents or phases, which when married together result in a material with entirely different properties from those of the individual components. Typically, a manmade composite would consist of a reinforcement phase of stiff, strong material, frequently fibrous in nature, embedded in a continuous matrix phase. The latter is often weaker and more compliant than the former. Two of the main functions of the matrix are to transmit externally applied loads, via shear stresses at the matrix-reinforcement interface, to the reinforcement and to protect the latter from environmental and mechanical damage (Taha, El-Sabbagh, and Taha, 2010, 108)

3.1.1 Bio Composites

Bio composites are composite materials comprising one or more phase(s) derived from a biological origin. In terms of the reinforcement, this could include plant fibers such as cotton, flax, hemp and the like, or fibers from recycled wood or waste paper, or even by-products from food crops. Regenerated cellulose fibers (viscose/rayon) are also included in this definition, since ultimately they too come from a renewable resource, as are natural ‘nano fibrils’ of cellulose and chitin. Matrices may be polymers, ideally derived from renewable resources such as plants, vegetable oils or starches. Alternatively, and more commonly at the present time, synthetic, fossil-derived polymers preponderate and may be either ‘virgin’ or recycled thermoplastics such as polyethylene, polypropylene, polystyrene and polyvinyl chloride, or virgin thermosets such as unsaturated polyesters, phenol formaldehyde, polyurethanes and epoxies (Taha et al 2010)

3.1.2 Bio-based (bio fibre) Composites

Reasons for using glass fibres in composites as an alternative for bio-based fibres lies in the differences in properties. Bio-based composites exhibit often unsatisfactory properties as, or resulting from inadequate processing conditions, resulting in filler agglomeration and poor filler dispersion within the matrix, variations in natural fiber properties, often due to geographical and seasonal variability, anisotropy of the natural fibers themselves, high linear coefficient of thermal expansion for natural fibers, and incompatibility between typically hydrophilic natural fibers and hydrophobic polymer matrices resulting in poor interfacial adhesion between the phases. A chemical modification of natural fibers are often performed in order to enhance the properties of the interface between fiber and matrix. A more recent method of modification, involves the deposition of a nanosized cellulose coating onto the natural fibers or dispersing a nanosized cellulose in natural fiber reinforced composites. This method has been shown to improve the fiber-matrix interface and the overall mechanical performances. Such composites have been addressed as hierarchical, multiscale, nano-engineered, nanostructured composites. (Fink, 2014,10-11)

TABLE 4 Mechanical properties for composite fibres (Adapted from Fink, 2014)

Material	Density [g cm^{-1}]	E-modulus [G Pa]
E-glass	**2.55**	**73**
Hemp	1.5	70
Aramid (Kevlar ™)	1.47	60-150
Carbon fibre	1.7-2.2	250-
Flax	1.4	60-80
Jute	1.46	10-30
Sisal	1.33	38
Coir	1.25	6
Cotton	1.51	12

3.1.3 Conventional glass fiber composites

Conventional glass fiber can be applied as composite reinforcement in in bio-based matrix (typical bio sourced Polyamide) or more commonly in fossil based polymers

Due to glass fiber's low material costs compared to aramid and carbon fibers, glass fiber reinforcement is the most widely used composite material. Glass fibers are available in the widest variety of product forms, ranging from short chopped fibers that are randomly oriented within the matrix to unidirectional continuous fiber composites. The biggest advantage of glass fiber composites, especially those with E-glass, is fairly good tensile strength at a low material cost. The biggest disadvantage of glass fiber is its relatively low modulus compared with aramid and especially carbon fiber. In addition, glass fiber composites have somewhat higher densities than aramid and carbon fiber composites. While both thermosets and thermoplastic materials can be injection molded, by far the greatest number are injection molded using thermoplastics (Campbell, F. C. 2010, 375)

Energy consumption

On average, 27.7 MJ of primary energy are consumed to produce one kilogram of CFGF (continuous filament glass fibre), of which 67% is due to the glass melting process (extraction and transport of raw materials, furnace). In this case natural gas represents 55% of this energy consumption. Although primary energy is mostly consumed at the furnace stage, a significant part (27%) of energy is consumed during the downstream process, mainly for drying and by utilities like recycling lines. (Glass fibre Europe, 2016)

3.1.4 ABM glass fiber

ABM offers glass fibre composites with novel feature of biodegradation and a degradable glass fibre. Conventional Composite materials are known to be avoided in sustainable product design due to property of being almost impossible to recycle or fractionate into original elements due to the complex structure and chemical bonding of different materials inside the composite structure. In case of ABM glass fiber composites, during degradation water will diffuse onto the matrix and the surface of the bioresorbable glass fibers and surface erosion reaction of fibers takes place as presented in figure 12 below. The first elements to dissolve out of glass fibers in water solution are sodium, calcium, phosphate and magnesium ions, and these alkalis will form basic hydroxides in the interphase forming a high local pH. The reaction is water diffusion controlled, which causes the surface erosion of glass fiber once the water has penetrated into the interphase. The formed basic products will come in contact the surrounding matrix and may also diffuse through the micro fissures deeper into the matrix. (…) causing hydrolytic chain scission which occur faster at a high pH environment than via an acidic autocatalytic reaction caused by polymer degradation products. This base catalysed polymer degradation erodes the interphase, which further increases the degradation rate and thus produces capillaries i.e. interconnected pores. (Lehtonen et al , 2012)

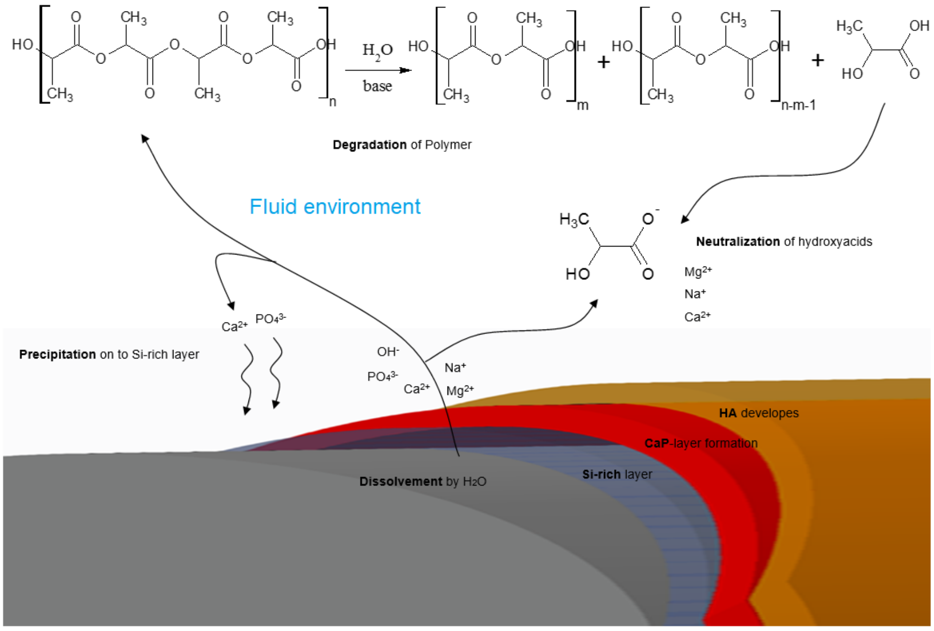


FIGURE 12 degradation mechanism of bioresorable glassfiber PLA composite (Lehtonen et al 2012)

ABM Glass fibers enables creation of mechanically strong bio-composites comparable with conventional glass fiber reinforced products but whose end-of-life options differ from conventional glass fiber composites. Composting and possibility for developing novel biological/chemical recycling streams.

3.2 Building block monomers from renewable sources

The following topics cover previous life cycle information for bio-based polymers under this project: PLA and PBS polymers. According to Lunt et al (2014, p23) the term “New Polymers” is used in the context that these products are generally based on known technologies, which were once considered none-commercially viable i.e. PLA from lactic acid. Poly (hydroxyalkanoates) or PHA’s from sugars, starch based blends, TPS, polypropylene carbonate, PTT and furanics. The key differentiator from “conventional plastics” is that these materials are typically new to the plastics industry as the industry attempts to move away from petroleum as the key raw material resource and reduce their environmental footprint or become more “sustainable”. A notable exception to the above classification is nylon 11 which is derived from castor oil and has been in commercial use since the 1950’s but is now being recognized for its renewable origin. Other new polyamides such as nylons 6,10, 10,10, and 10,12, all partially based on castor oil, are now emerging. Polybutylene succinate, PBS is included here since although it has been available for some time; its production from renewable resources has just become viable.

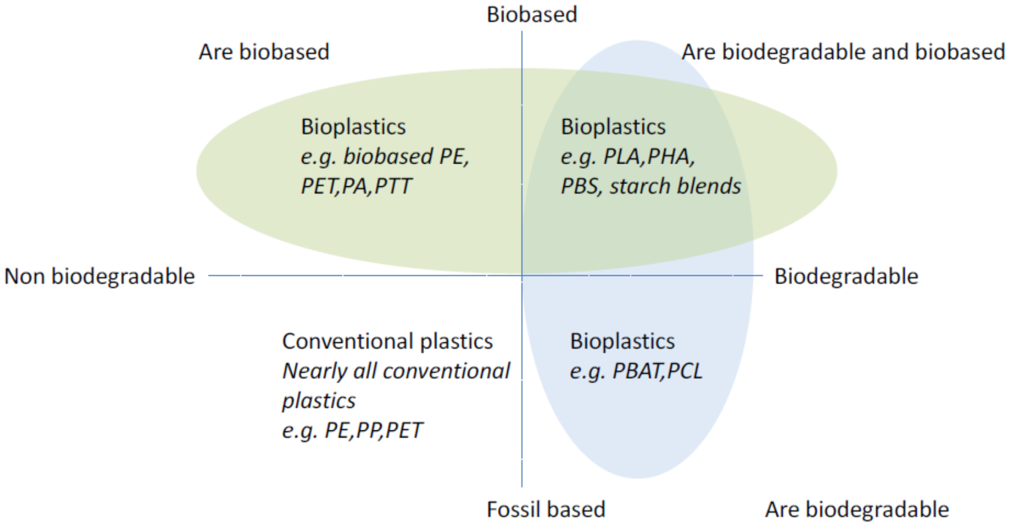


FIGURE 13 Classification of Bioplastics Based on Biodegradability (European Bioplastics)

Classification of bio-plastics: bio-based and non-biodegradable such as polyethylene synthetized from bio-mass or renewable sources; bio-based and bio-degradable such as poly lactic acid (PLA), and poly butylene succinate PBS; and non-bio-based and bio-degradable such as poly butylene succinate PBS, and polycaprolactone (PCL) (Tokiwa et al., 2009). PBS can be derived both from natural and petroleum based feedstock. According Lovett and De Bie (2016) significant difference is seen, when bio-sourced polymers PET, PE and PLA are compared by the feedstock quantity needed to provide 1 kg polymer. In their study PLA consumed 1.6 kg carbohydrates per 1 kg polymer, Bio-PE consumed 4 kg of carbohydrates and Bio-PET consumed 5 kg.

3.2.1 Bio-based PLA

Multiple LCA studies are found around PLA production hence PLA being the major bio-based polymer on the market. NatureWorks published a LCA for PLA in 2014 (Vink, Davies et la) where NatureWorks updated their ecoprofile data for Ingeo production in 2003, 2007, and 2010. All the earlier ecoprofiles were calculated using the Boustead Model, which has also been used by the European trade group PlasticsEurope (Brussels) since the early 1990s. Since 2011, PlasticsEurope has been updating the ecoprofiles for major fossil-based polymers using different life cycle assessment (LCA) consultants and updated databases. To ensure consistency and ease of comparison, NatureWorks has just updated the Ingeo ecoprofile it published in 2010 using the GaBi (version 6.3) LCA software and the latest available databases. The system boundaries where from crops to polymer pellet; cradle to gate for polymer raw material.

About land use: According to Vink and Davies "A range of land use numbers for PLA production exist in the literature. Land use depends on the crop (e.g., corn, sugar beets, sugarcane); the average local/regional yields; the existence of coproducts; the allocation procedure used (e.g., in corn wet mill, CWM); the percentage of sugar or starch in the crop; and, of course, the efficiencies of processing the crop, the starch/sugar conversion, the fermentation and polymerization, converting the original starch or sugar into the final polylactide polymer. In the case of Ingeo, the gross corn use is about 2.67 kg corn (15% moisture)/kg Ingeo. However, 100% of the corn is not used for Ingeo production, only the starch fraction. The percentage of starch in the corn is 57.2%, so the net corn use is $2.67 \cdot 0.572 = 1.572$ kg corn (15% moisture)/kg Ingeo. The remaining part of the corn (the oil, the gluten, the fibers, etc.)—and thus the land use associated with them—is allocated to the other CWM products (such as corn oil, corn gluten feed, and corn gluten meal). Using an average corn yield over the last 10 years for Nebraska and Iowa of 10.9 tons/ha, the corn yield becomes 1.028 kg corn (15% moisture)/m2 weight. From this it can be concluded that about 1.572/1,028 = 1.53m2 land is needed to produce 1 kg Ingeo. Running the Ingeo production plant at full capacity (150,000 t) would mean a net land use of 22,950 hectare. According to Carus and European Bioplastics (Berlin), the available global agricultural area is about 5 Mrd hectares. At full production, Ingeo would need 0.00046% this land. "

Global warming potential compared

As PLA is produced from renewable agricultural sources, hence it is known for its eco-friendliness. Though the technology used by NatureWorks for mass production of PLA is from corn, also sugarcane is used as the input for producing lactic acid. Sugarcane based production of lactic acid has been developed by Purac, by setting up lactic acid plant in Thailand . Purac's 75,000 MT/year lactide monomer plant operating in Thailand from 2011.

In general, PLA can be produced using a direct polycondensation reaction and ringopening polymerization approaches. The majority of commercial producers find that ring-opening polymerization is preferable for better control of the process and better production quality. In the environmental credit analysis of PLA, there are two major aspects that need to be considered; the PLA manufacturing process and the postconsumer PLA product disposal. Several research projects on life cycle analysis of PLA mass production have been conducted in recent years. Two of the life cycle analyses of PLA production have been undertaken by NatureWorks and Purac. (Ebnesajjad S., 2013 45)

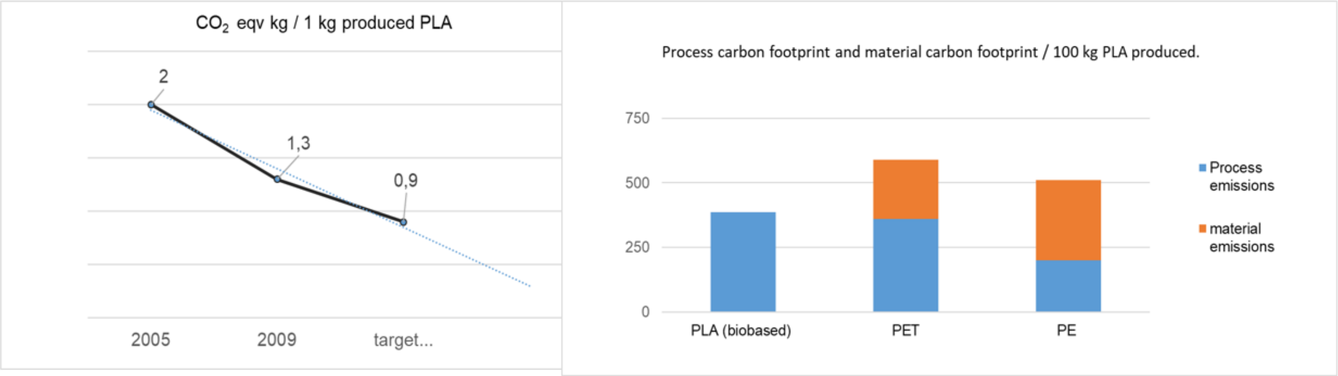


FIGURE 14 PLA production CO2 emissions illustrated

Figure 14 above adapted from Ramani Narayan,(2011) shows that PLA production technology is developing to be more environmentally efficient and the emissions comes from process itself, compared to petroleum based materials that cause emission trough raw material conversion streams. Switching the manufacturing base (the origins of the carbon) from petro-fossil carbon feedstock to bio-renewable carbon feedstock offers an intrinsic zero material carbon footprint value proposition. This can be seen by reviewing biological carbon cycle. PLA has a lower total carbon footprint—385 kg CO 2 emission per 100 kg plastic manufactured versus 519 kg CO 2 emission per 100 kg plastic manufactured.
This is because the material carbon footprint for the PLA plastic is zero, whereas PE/PP has a material carbon footprint o314 kg CO 2 emissions per 100 kg plastic manufactured. (Narayan, 2011, 717-718)

”PLA is a fast-growing polymer market segment with an estimated annual growth rate of 10 to 15% to 2025. Biodegradable and industrially compostable, PLA is one of the first renewable polymers able to compete with existing polymers, combining unique functional properties like transparency, gloss and stiffness. PLA is currently used in a broad range of markets, including food packaging, single-use tableware, textiles, oil and gas, electronics, automotive and 3D printing. (Corbion, 2019)”

3.2.2 Bio-based/ biodegradable PBS

Polybutylene succinate (PBS) is a biodegradable plastic that decomposes into water and carbon dioxide through available microorganisms in the environment (soil, compost etc). PBS has a rather high heat resistance amongst the general biodegradable resins, and PBS has high compatibility with many fibers. Since 2016 PTT MCC Biochem company has produced and sold bio-based PBS (BioPBS™) which consists of an succinic acid derived from natural resources and 1,4-butanediol. (PTT MCC Biochem)

A new Generation of a 100% Bio-sourced PBS was released on the market where 1,4-BDO is produced via E.coli bacteria by Genomatica. The company developed and patented a strain producing 1,4-butanediol (BDO) in 2011 in partnership with DuPont Tate & Lyle, Genomatica built an industrial-scale plant that produced 5 million pounds of BDO in 5 weeks. The BASF chemical company licensed the BDO strain and fermentation process to construct a "world-scale production facility" of BDO in early 2013. Before Genomatica's BDO strain was developed, BDO was exclusively produced from petrochemical sources. (Cotton, Reed, 2016)

PTT-MCC Biochem, is a joint venture formed in 2011 between Mitsubishi Chemical Corporation and PTT Public Company Limited of Thailand. PTT Public Company Limited or simply PTT is a Thai state-owned listed oil and gas company. Formerly known as the Petroleum Authority of Thailand, PTT-MCC was established to develop and produce polybutylene succinate (PBS), a biodegradable plastic made from succinic acid and butanediol (BDO) with proprietary technology. The company has built its first PBS plant in Map Ta Phut, Rayong, Thailand, with a capacity of 20 ktpa. The PBS plant was operational in the first half of 2015, and will consume around 14 ktpa of succinic acid at full capacity, just in time for BioAmber's start-up in early 2015 of its 30 ktpa bio-succinic acid plant in Sarnia, Ontario, Canada. (De Guzman, 2014) After the commissioning of both the Sarnia bio-succinic acid plant and PTT-MCC's PBS plant in Thailand, BioAmber will exclusively supply a minimum of 80% (11.2 ktpa) of PTT-MCC's total bio-succinic acid needs until the end of 2017.

The take-or-pay volume committed by PTT-MCC over the 3-year period represent half of the total annual quantity of bio-succinic acid that PTT-MCC plans to purchase from BioAmber. (De Guzman, 2014) Bad news followed after BioAmber may have been the most ambitious of the projects. The company raised about $80 million in a 2013 stock offering and put the funds into building a succinic acid plant in Sarnia, Ontario. However, saddled with a heavy debt load and few customers, it closed the plant and filed for bankruptcy 2018. Soon after LCY Biotechnology, a new company formed by LCY Group and Visolis, has bought the idle BioAmber plant in Sarnia. LCY says it hopes to begin producing biobased chemicals via fermentation after about six months, though it may not make succinic acid. LCY is a Taiwanese chemical maker that was recently acquired by the investment company KKR. (Bomgardner, M, 2018) PBS production key manufacturers across the globe are listed in the market research news as follows (2019) SK Chemicals, Mitsubishi, Anqing Hexing Chemical, Eastman, BASF, Dupont, Yifan Xinfu Pharmaceutical, Showa Denko.

PBS sustainability

According to a LCA study by Moussa, Young et al 2012, The production of succinic acid includes three unit processes: production of maleic anhydride, succinic anhydride and succinic acid. The following possible variations in feedstock and energy sources were considered:

“1. 100% fossil sources used for both the succinic acid and 1,4-butanediol (1,4 BDO). Succinic acid is produced via the hydrogenation of maleic anhydride followed by the hydrolysis of succinic anhydride. Maleic anhydride can be produced either from the direct oxidation of benzene or catalytic oxidation of n-butane. 1,4 BDO is produced using acetylene and formaldehyde.

2. The polymerization of succinic acid and 1,4 BDO produces the polymer, 100% bio-based feedstock that is converted into succinic acid via fermentation of sugar. Commercial producers include Myriant, DSM, and (BioAmber). 1,4 BDO can also be derived via the hydrogenolysis process.

3. 1,4 BDO can be produced directly from sugar or biomass, as produced by Genomatica”

The study by Moussa et al. revealed that the total GHG emission resulting from the production of 1 kg PBS dry pellets is 6.6 kg CO2-eq as distributed across the main processes, the GHG emissions compare to previous analysis by Showa Denko K.K. that assessed a similar material with varying assumptions on thermal and electrical energy, biomass feedstock cultivation, and system boundaries. According to the study by Moussa, Young; the GHG contribution distribution was found to be following: BDO 39%, Succinic Acid 45 % (Includes: Maleic Anhydride: 27% Succinic Anhydride: 16%), PBS to Dry Pellets 16%. Cumulative Energy Demand (CED) Indicator; Results indicated a CED of 140 MJ/kg PBS pellet across the process-level contributors. This is somewhat intuitive: energy use is reflected directly in the CED indicator, and correlates strongly to the greenhouse gases associated with the GWP indicator, and less-so to the air and multi-media environmental quality indicators (acidification and toxicity). Energy use has a strong influence on the environmental LCA results. (Moussa et al, 2012, 2-5)

According GaBi dataset for PLA the primary energy demand is 65.6 MJ/kg (Primary data from NatureWorks ,2014) and for PBS (during 2019 modelled data) the value for raw material is 66.3 MJ/kg. According to the VDI standard 4600 (VDI 1997) primary energy is defined as the “energy content of energy carriers that have not yet been subjected to any conversion”. As a consequence, the cumulative energy demand method uses the technical conversion efficiency between energy source and generated electricity or heat, to calculate the primary energy demand per unit of energy generated. In energy efficiency study by Changwichan (2018) The quantity of electricity required for the PBS resin production process is significantly lower than others; 1.07 kWh/kg for PLA, and 0.13 for PBS resin.

The study of Moussa et al. “employed SimaPro software for the LCA and relied on background data from the ecoinvent database. Challenges due to data quality and data availability for such new processes and feedstock create uncertainties in the analysis of potential environmental profiles. The lack of primary and empirical data related to the manufacturing of PBS, necessitated the use of secondary and tertiary data to characterize environmental impacts of the PBS manufacturing process. This study relied on PBS data from the polymer “Bionolle” and the respective model for its production: Bionolle is a 100% petroleum-based PBS manufactured by the major manufacturer of this polymer, Showa Denko of Japan”. Moussa et al discussed from the results that their study suggests that “process energy use is a dominant driver for LCA indicator results. Therefore it is valid to question whether feedstock type or energy type will be more important in the fuller environmental sustainability analysis. Further work, it is suggested, should be designed to separate the variables of both feedstock/energy, and fossil-based/biobased – and perhaps also to consider hybrid fossil-biobased systems.”

3.2.3 Product use phase and life span evaluation

Material aging and durability in different applications is part of life span evaluation. To study the properties for durability different test can be performed. Weathering resistance can be studied by means of acceleration. Materials will be exposed under solar imitating radiation that is multiplied by factors in relation to benchmark climate. Humidity, wetting and temperature fluctuations are added according to standards.

In many structural applications, fibre reinforced composite materials are exposed to the long-term action of both mechanical stresses and environmental ageing processes. In the case of glass fibre reinforced polymers (GFRPs), it has long been recognized that the strength of the fibre- reinforcement is very sensitive to humidity. Under the combined action of moisture and applied stress, a delayed failure of the glass reinforcement is induced which can significantly alter the durability of GFRP structures. Termed ‘stress corrosion cracking’ (SCC), this phenomenon is a concern in many applications. Despite a considerable research effort into this area, there is still a lack of a predictive durability model that can account for the reduction of the fatigue life of GFRP materials under SCC conditions. (Martin, R. 2008)

Final acceleration factor is material depended. According to study from Yang, Li, Zhang (2006) in which The UV dosage and humidity/ condensation cycles were compared to natural out door aging in China with two locations and two polymer types (Polyethylene, polycarbonate; Lasa, Wuhan) findings lead to acceleration factors as high as between 36 to 67. Similar phenomena has been detected in comparing natural out door weathering and accelerated weathering aging effects at ABM test facility, natural Finnish out door weathering has less effect to properties than accelerated weathering with equivalent acceleration factor according UV radiation dosage. Temperature and humidity plays significant role in degradation of hydrolysis sensitive materials.

4 Materials and methods

The LCA case studied in this work consists on comparing five different polymeric materials in parallel scenarios where locations (raw material production) and EoL option effects are compared. The products herein are imaginary composites. Composites are assessment in “what if “- scenarios built to fulfill the purpose of the LCA case. LCA case is to study the effect of the material selection in similar products going through identical processes. Twenty two (22) different Scenarios for material alternatives are presented in table 7, in 4.2.3. The excluded phases and cut of criteria are described in 4.2.5

The assessment is carried out by using thinkstep's Bioplastics Tool built in GaBi and operated by GaBi Envision software 2019. LCA methodology is based on Environmental Footprint 2.0 (ILCD/EF 2.0), datasets used are based on the 2019 GaBi databases (thinkstep, 2019). This is modelled based on principles and approaches outlined in ISO 14040 and ISO 14044.

4.1 LCA Goal

The goal is to build parallel scenario sets where variables are compared one by one

-The transportation distance and location of the manufacturing and their effect to the share in the products total GWP (cradle-to-gate). Five polymer matrix materials in composite with fixed quantity of glass fibres are compared in scenarios to evaluate the weight of various EoL on material GWP build up (cradle-to-grave). The outcome from Gabi data is discussed and interpreted together with literature results from previous LCA’s for materials (glass fibre data from industry and with ABM bio-glass fibre production data available). After conduction scenario what if analyses for sets of 5 materials in different scenarios, the difference between environmental impacts is investigated from view point: “Global vs Local” and EoL options. After interpretation phase for the results, the LCA tool competence for future product development is discussed.

Goal is to have answers to questions after conducting of the assessment and interpretation:

- How does manufacturing location and transportation distances affect to the total composite Global Warming Potential?
- What is the effect of EoL scenarios to total composite GWP?
- The objective is to assess improvements by material selection and obtain the product's environmental profile and to identify the impacts and hotspots with most significant impact or most significant impact categories.

The function and functional unit

Functional unit is 1 kg polymer-glass fibre composite compound with fixed share of 30% Glass fibres and 70% Polymer.

4.2 Assumptions and limitations

The life-cycle system boundaries are from source of resources to the production of plastics pellet (cradle-to-gate), and did not consider the effects of further processing and use phase before end-of-life. Product lifespan is studied via accelerated weathering test that enable evaluation for assumption as the product lifespan.

4.2.1 Carbon equivalence

TABLE 5 CO2 equivalent environmental factors used in LCI

	Climate Change (fossil)	**Climate Change (biogenic)**	**Carbon uptake**
CO2 from air, biogenic	0	0	**-1**
CO2 to air, biogenic	0	0	0
CO2 to air, fossil	1	0	0
CH4 to air, fossil	**36.8**	0	0
CH4 to air, biogenic	0	**34**	0
N2O to air	**298**	0	0

The used characterization factors are listed in the table above for the Climate change impacts and carbon uptake as they are recognized in the GaBi bioplastic tool.

4.2.2 Study for application lifespan evaluation

Materials including two types of glass fibre were studied for their weatherability properties to evaluate the applications they fir according their lifespan.

Biopolymer composites including commercial E-glass fibre that is not biodegradable and ABM bioresorbable/ biodegradable glass fibre. ABM produced bioplastic composite including 30% *Bio*-glass fibre has successfully passed certification for product biodegradability and compostability (industrial composting process) according DIN EN 13432:2000 and has the right to use the compostable certified symbol.

Weathering exposure was conducted with Atlas Xenotester model 440, manufactutrer Cromocol, SE. Method simulates accelerated natural environment selected factor of solar radiation to be compared. Exposure consist of controlled Xenon light and non-stop cycles of rain and humidity. BST, Black surface temperature can rise up to 65 degrees. Parallel black sample was investigated to study the elevated tempeteraturs effect to the accelared weathering. Filters according to ISO 4892-2 (plastics) means simulation of direct solar radiation (Daylight): EUV = 60 W/m². Central European benchmark climate is selected for equivalent annual radiation dosage leading to acceleration factor 9.5. What must be understood that acceleration factors of 10 and higher are extremely material and environment specific. Therefore there is no universal acceleration factor.

TABLE 6 Weathering cycle conditions

ISO 4892 standard Method A(Solar radiation and rain simulation)					
1	102 min	50 %RH	38 °C	65 °C (BST)	nonstop cycles, Broad band UV
2	18 min	rain	38 °C	---	

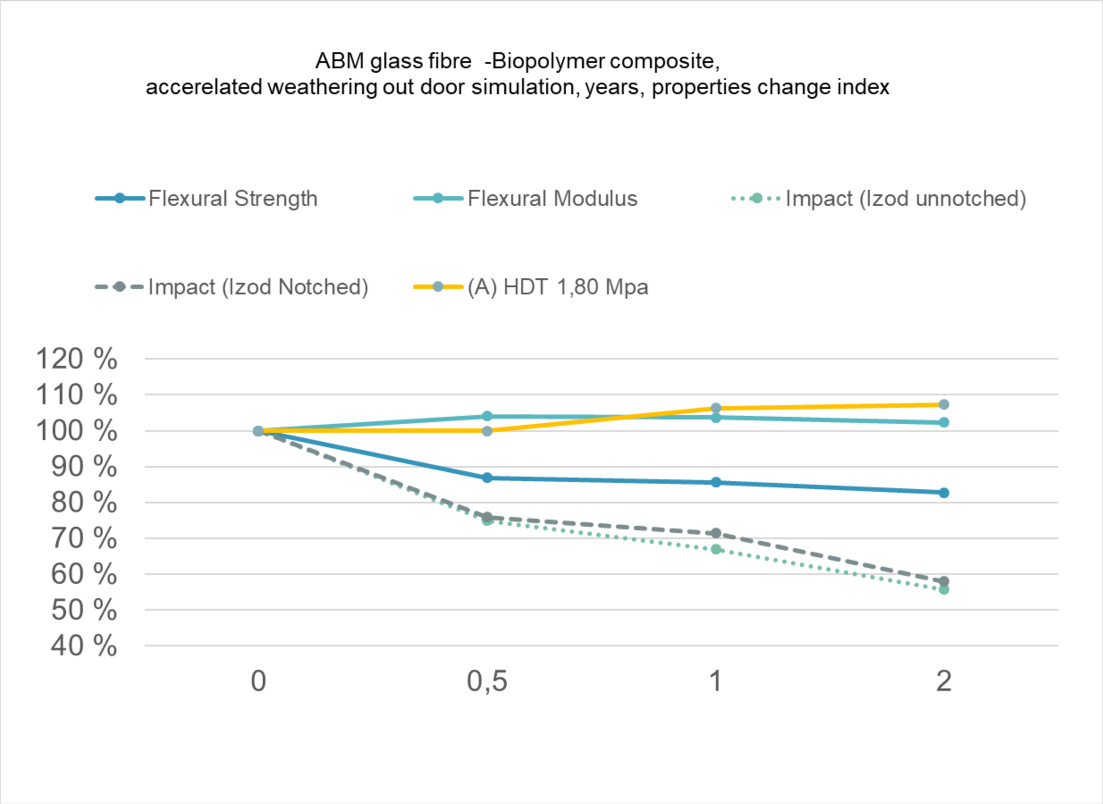


FIGURE 15 ABM glass fibre- PLA/PBS composite and accelerated weathering effect to material strength

Figure 15 above is a takeout from weathering study for ABM composite including PLA, PBS, additives and biodegradable glass fibre.

After accelerating up to 2 years in outdoor solar radiation and rain, south Europe as benchmark climate, the impact strength had decreased to level 55-60% from original level index 100. The water diffusing inside the polymer starts hydrolysis reaction in PLA and glass fibre material starts the degradation together with the biodegradation, when the water will diffuse onto the surface of bioresorbable glass fibres and the surface erosion reaction of fibres takes place. Flexural strength, modulus and heat deflection temperature are preserved quite well.

The correlation to indoor weathering is still under investigations, since the durable and semi-durable applications ABM materials are targeted to be used upon are aging in indoor conditions. Indoor conditions are causing less severe stress to material (chemically and by means of UV radiation).

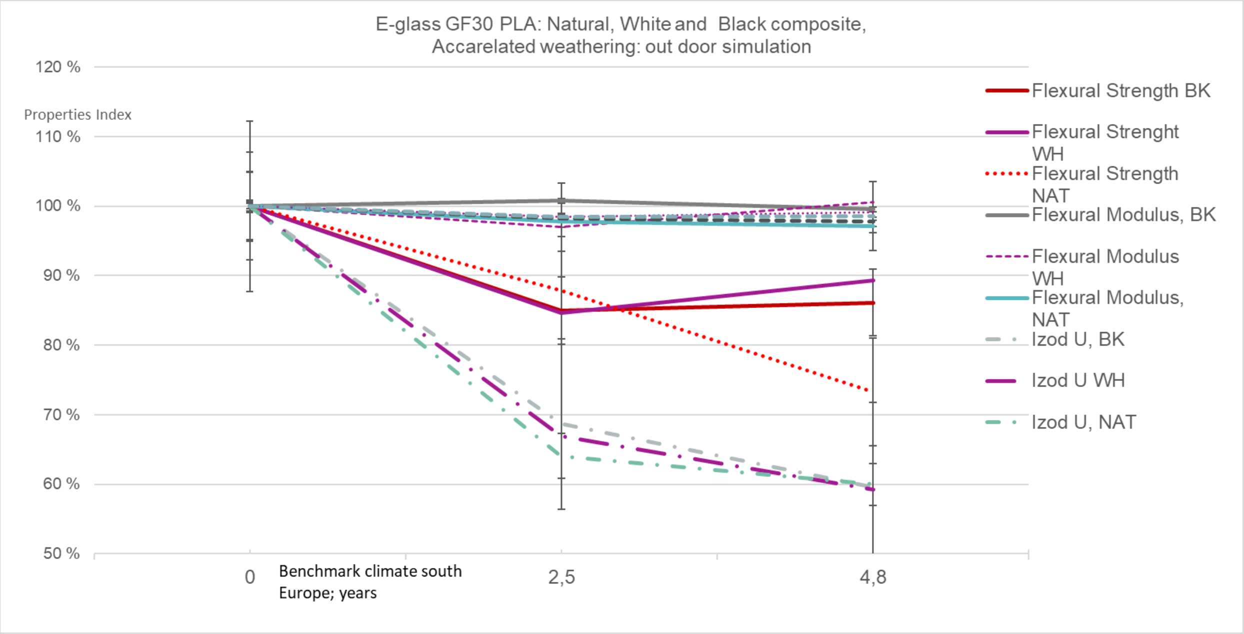


FIGURE 16 E-glass fibre PLA composite accelerated weathering

From FIGURE 15 and FIGURE 16 above can be seen that both composites have weathering resistance, ABM glass fibre containing composites start decreasing earlier and both E-glass (in Figure 16) and ABM composite (in Figure 15) contain flexural strength to high degree during accelerated weathering up to 2 years. If application materials are targeted to indoor use, the expected life span can be many times longer. Impact strength weakens, still the final product properties rely on the final application product geometry and fibre orientation achieved during manufacturing.

4.2.3 Life cycle impact assessment (LCIA) and inventory

These input parameters can be determined according plan to create scenarios for raw material compositions and their end of life –options. Input parameters for product conversion to another product was excluded since focus in this scope is to study the manufacturing of the product that is a pellet form raw material used in product manufacturing. More detailed description follows.

TABLE 7 LCA scenarios in study

Scenario no.	Polymer	Location	EoL
1	PA	*Global	n.a. Cradle to gate
2	PP		
3	ABS		
4	PLA		
5	PBS		
6	PA	Local	
7	PP		
8	ABS		
9	PLA		
10	PBS		
11	PA	Local	Incineration
12	PP		
13	ABS		
14	PLA		
15	PBS		
16	PA		50% recycled, 50% Incinerated
17	PP		
18	ABS		
19	PLA		
20	PBS		
21	PLA		composted
22	PBS		

*Global: added 21 t km shipping distance

The scenarios selected for LCA study consist on five “what if” material selections scenarios that are compared in sub-scenarios:

Scenarios 1-5 for composites scoped cradle to gate, without EoL for investigating the transportation’s share on GWP for products. “what if material is produced and transported to use by shipping distance equivalent to CN-EU, What if electricity grid has lower emissions than in EU”

Scenarios 6-10 are a sub scenario set to study the effect of different electricity grid emissions used in manufacturing. “What if materials are produced in EU electricity grid, compared to scenarios 1-5”

Scenarios 11-22 system boundaries include EoL options. In these scenarios the five “what if material” sets are studied against impact of different End of life options: 11-15 by Incineration, 16-20 By recycling at 50%-50% incinerated and 21,22 by Composting when possible; for two materials out of five.

4.2.4 System boundaries

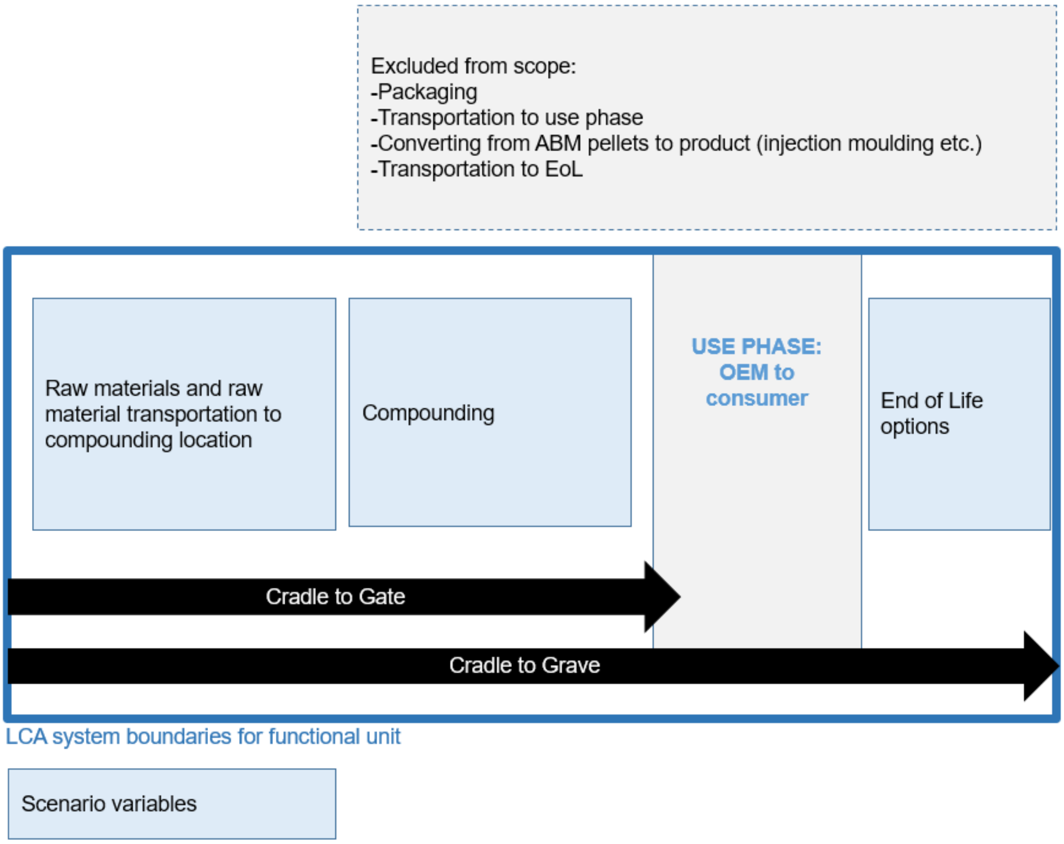


FIGURE 17 visualization for Gabi Bioplastics tool input variables selected inside/outside the LCA system

In figure 17 above the blue frame is representing the system boundaries for studied product “material selection what if” –scenarios.
In scenarios 11-15 the additional transportation for simulating “Global” is set assumed to be in transportation to conversion by shipping 21 000 km. Otherwise raw material transportations are limited to 500 km by truck for each step.
Details for scenario inputs are found in appendix 1.

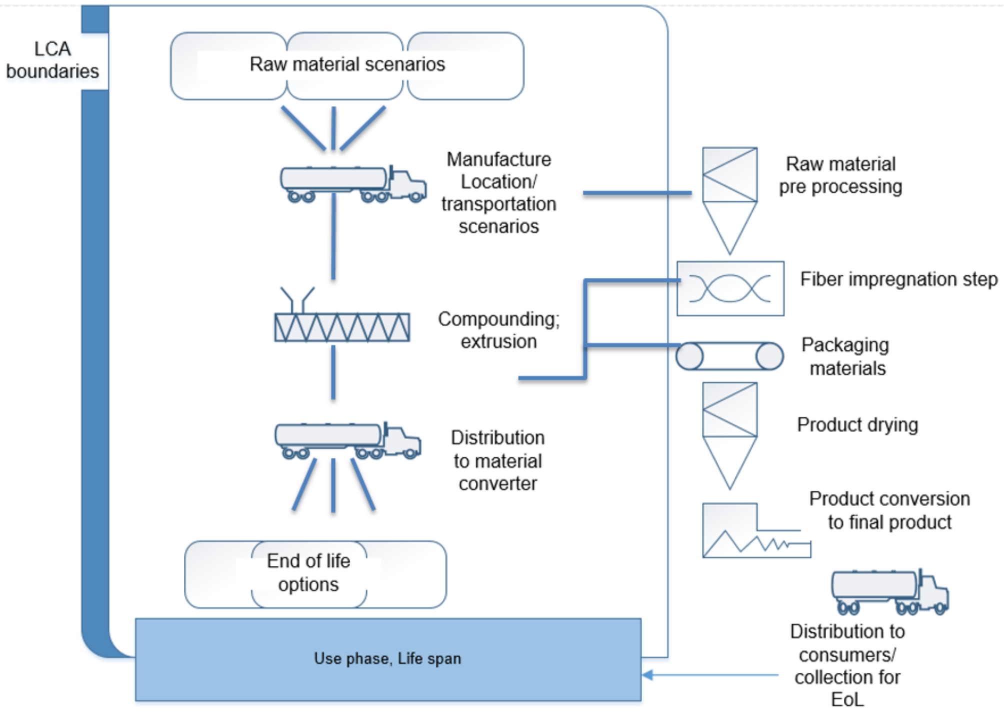


FIGURE 18 Visualization for LCA system boundaries in study

For recognizing the product elemental steps missing from tool, visualisation for different process phases is represented in figure 18 above. Limitations are described in more details next.

4.2.5 Limitations and out-scoping

Bio-based content

Bio-based content can vary depending on the polymer supplier. As mentioned before, the one PBS polymer provider certifies the bio based content being "50-85%". In this LCA the PBS bio-based content is assumed to be 100%.
PLA is assumed to be 100% bio-based as material supplier(s) state. The FIGURE 18 Visualization for LCA system boundaries in study, above illustrates the significant elements in the product creation inside and outside system boundaries.

The fibre Impregnation option

Glass fibres can be implemented in to compound product directly by feeding shorter cut fibre bundles in the compounding process. When long glass fibre reinforced compounds are produced, the impregnation process occurs when the dry continuous glass fibre filament is introduced and wetted by the polymer in the die specially designed for this purpose. Then the final strand is cut to its final pellet length. There is no input data available for the impregnation step (Pultrusion-extrusion) at time being. Assumption is that all five materials would undergo the same polymer-fibre impregnation step and the effect in parallel scenarios would be equal. Nevertheless, as dataset is not available at time being for impregnation/ fibre wetting with polymer by pultrusion, the step is excluded from the scope.

Raw material pre-processing and drying

The assumption is that biopolymer/ conventional fossil based polymer raw material arrives in a form that allows straight forward processing without need for drying the material. Still drying is needed as once the material container is opened for use, it needs to be kept in dry conditions. Material provider offers dry material, leading to assumption that material drying is part of the raw material data set input impact. The need to keep the material dried ads a processing step with electricity input value left outside from system boundaries in this LCA. Drying and packaging after compounding is left out from the scope justification is the overall goal to study material selection what if –scenarios from the material cradle to crave (EoL option effects) and assumption of drying process being equal to all material scenarios is done. What must be recognized is that some polymers like PP usually do not have demand for pre drying and hydrolysis sensitive polymer like bio based PLA need dried air/ drying during product transportation inside compounding process. Nevertheless, materials arrive as dried and assumption for bio based material drying being implemented can be done, as PLA data is from primary dataset.

Additives

Variable chemical compounds are added for adjusting colour, UV stability, for hydrolysis prevention, process plasticizing and moulding –ability etc.

Cut -off criteria 5% or less is assumed being equal to all compounded materials in scenarios. Specification of the quantity material environmental significance associated with unit processes or product system is therefore excluded from a study.

Conversion process

When ABM product, granulate pellets are delivered to customer, the final step is to transform the plastic blend in to a product. Usually or most likely the process is injection moulding. This step is left out due to the variables; for example the size of the final component has impact to the process energy consumption. These information are unknown in “what if-material selection scenarios”. Injection moulding conversion can add up to a 30% share of the product’s final GWP. (Jiajia Zheng, 2019) and should be acknowledged when customer uses LCA information from ABM compound. As the life span of the ABM product is interconnected to the customer application. Therefore durable and semi durable applications are focused on as ideal material instead of singe use products.

Supply chain length

Raw material transportation to manufacturing location is considered in limited extend: From raw material provider’s closest harbour to ABM factory gate. Variation can occur according to availability of natural resources and shifts in market. The supply chain effect on the global warming potential can be more significant than seen in the LCA. Minerals for non-plastic part can be transported from various locations. The bio-based polymer feedstock crops from fields to polymerization steps and to factory gate are not visible. The PLA polymer dataset from GaBi is established together with the PLA producer NatureWorks and the dataset contains the whole formation of the raw material, including feedstock transportation in supply chain. Other materials investigated are based on generalized data. Supply chain hidden in “Raw material selection” as raw material data set is considered from cradle-to-gate.

Packaging materials

Depending on product delivery the plastic product is packed in 25 kg bags (aluminium foil and polymer layers) or in cardboard *octabin* container (approx 750 kg) with plastic film lining. Both options include a wooden pallet.

Packaging materials are considered to be fully recyclable. Still it is unknown if customer recycle packaging materials as possible to conduct in Finland. There might be demand for separate sustainability evaluation for optimal packaging methods and materials.

Auxiliary unit processes outside scope

Production for pellet/granule material includes processes that are left out from the scope.As raw material selection being the core in comparative scenario building, the main scenario of chosen material compounds is then assessment in a parallel coherent scenarios with concurrent variable inputs when possible (EoL of composting is possible for all polymers). Waste from production is not included in the evaluation. Production scrap material is treated recycled when possible, or send to incineration facility nearby. Production loss is quantitatively variable. The percentage amount of scrap from production is in relation to production batch size. The smaller batches, the more scrap is produced, due to start-up phase. Waste share from the batch size is usually less than 0.5% at maximum as recorded at ABM, and percentage is used as input in scenarios.

4.3 Life Cycle inventory (LCI) and Unit processes

Transportation

See appendix 4 for Transportation data details.

Compounding

There is a difference between polymer granulate/resin, polymer compound and polymer part. As compounds can be produced and used in thousands of specific recipes, GaBi primarily provides granulate data, which can be used individually to add additives to produce individual compounds and to set up individual polymer part data. (Kupfer, Baitz et al 2019, GaBi, 122) ABM material production and comparison consist of granulate form raw materials and their data from cradle-to-gate, the gate being after entering ABM compounding facility for product manufacturing process and then leaving gate. The final ABM compound forms the product that can be then assessed from cradle-to-grave as the selected functional unit in scenarios; Locations, EoL options. For each material, several different processing technologies are often available. For example, for the production of PP, polypropylene, “polymerisation in fluidised bed reactor” and “vertical stirred reactor” are both technologies that are applied. For each relevant technology, an individual process model is created. In Gabi Chemical and plastics production sites are often highly integrated. Modelling a single substance product chain is possible by isolating integrated production lines. As the users of the dataset are not always able or willing to determine the exact technology for the production of their upstream materials, a representative production mix or consumption mix is also provided. The share of production or consumption was determined, separately from the dataset for each relevant technology. For chemicals with different possible production routes, the technology mix represents the distribution of the production mix of each technology inside the reference area. For example, the production of standard polypropylene in the different regions is based on different polymerization technologies, including the fluidised bed reactor and the vertical stirred reactor. For standard polypropylene the main process models are mixed according to their share in industrial applications with an average polypropylene dataset to avoid inappropriate isolation measures it is essential to have engineering and technical information to accurately model those systems. A well-arranged online overview of important parts of the chemical network is given on the Plastics Europe Homepage. Country-specific consumption mixes are useful, because chemical and plastic products are traded worldwide, meaning that a chemical or plastic material, which is provided in a certain country, can be imported from other countries (Kupfer, Baitz et al 2019, GaBi, 119)

Material data

PLA dataset is on the other hand production site specific and based on one industry data: Natureworks Ingeo PLA derived from corn, made in US. PLA can be produced from other carbohydrate crops having even higher yields/ ha crops. PLA producer Purac /Total Corbion predominantly uses the highest yielding feedstock’s regionally available: raw sugar from sugarcane is used in their factories in Thailand and Brazil, dextrose from corn is used by lactic acid Sugar production plant in USA and raw sugar from sugar beet is used by our factories in Spain and the Netherlands. In time of shortage, the plants can run on imported or other feedstocks; the factory in Thailand could, for example, also run on cassava starch. In addition to bioplastics production, the lactic acid produced in these factories is also used as food ingredients, biochemical ingredients and medical materials.

According to Lovett, De Bie 2016 and Balde et al. possible carbohydrate yields:

TABLE 8 crops carbohydrate yields converted to PLA

	Corn, NL	Sugar beet, NL
carbohydrate yields [ton] /cultivated ha	6	11
converted to PLA polymer	3.75	6.9

“The CO_2 uptake from the atmosphere, calculated using the biomaterial storage approach 1.833 kg CO2/kg PLA. It is important to note that this storage is reversible and adds carbon emissions in the future, when the product is incinerated or biologically degraded at its end-of-life.”
(Morão, de Bie 2019)

4.3.1 End-of-life –composting

There was no available industrial data for EoL for PBS biodegradation, therefore the data set was built for bio-based PBS polymer and adapted according to the PBS carbon content. The data set represents the enclosed composting of sugarcane based bioplastic. For the biowaste a content of 45 % dry matter and a C:N ratio of 29.5. The composition of the biowaste was reduced to bioplastic only adding necessary additives to allow a composting process. Enclosed composting systems partly or fully take place in closed halls or so-called composting boxes or rotting tunnels. The advantage of closed systems is that exhaust air can be collected and cleaned. Those systems are especially used for the composting of sewage sludge or fermentation residues, to reduce the emission of ammonia (odour nuisance) but are also common for biowaste. Enclosed composting uses the same process of aerobic decomposition of organic matter by bacteria and other microorganisms as does open composting and is also referred to as 'In-

Vessel Composting'. It is assumed that up to 20% of methane-emissions are degraded by biofilters. The most positive effect can be seen by the reduction of ammonia (90%-100%). This can also be applied by the use of acid scrubbers. Mean technology was assumed for air purification. Environmental impacts for waste collection and transport of the waste are not included in the data set, as transportation(s) is another input parameter in the system boundaries.

The process starts with the pre-treatment a process step used for the adjustment and optimization of the input substrate (rotting feedstock) before the rotting process. It can be described as a mixing process of available input materials (e.g. green waste, garden waste, structure materials, sieving rest, water).For the composting model the process of pre-treatment determines purpose of the entire model which can also be seen as the functional unit: Composting of x kg bio-waste. Basic input flow is bio-waste from Austria. Important for the application of this process routines is to control the process relevant parameters for the rottingprocess which are: C/N ratio = should be between 20 and 40 and Dry matter in rotting = should be between 25 and 50 percent.

Rotting is the core process of the composting model. The rotting process is an aerobic biological degradation and alteration process influencing nearly solely the organic compounds of the rotting feedstock. Inputs for the rotting process is rotting feedstock from pre-treatment as well as energy and fuels: Electricity and fuel (for wheel loader) is needed through the entire composing process (pre-treatment, rotting and post-treatment). Default values for power and diesel consumption are literature. The used degradation rate in the compost model is 60 % for carbon and 50% for nitrogen. Leachate is collected and used for irrigation of windrow piles. Screenings are used again as bulking material. According to ThinkStep consultant emissions from the composting process are based on Literature. The following emissions factors are applied: CH_4: 710 g/ t waste input; N_2O 68 g/t waste input, NH_3 63 g/waste input and NMVOC 60 g/t waste input. Specific emission factors were defined based on C and N degradation rate. Emissions containing these substances have been allocated to the specific waste input. This is done by calculation factors. These factors determine e.g. how much of C is emitted as CH_4. N emissions not emitted as N_2O or NH_3 are assumed to be N_2 emissions with no further environmental relevance. Therewith N_2 emissions are neglected. Calculation factors have been applied for: CH4, NMVOC, NH3, N2O. These factors include the information from different composting technologies Post-treatment is necessary to enable defined compost quality. It can be described as a sieving process. Output fractions are compost, sieving rest and impurities (not applied for this process). Mass substances are divided between compost and sieving rest. Information on build PBS biodegradation model was provided by Yannick Bernard, Senior Consultant Chemicals & Life Science at Think-Step during building data set for this project.

4.3.2 LCIA Impact Categories

Table below lists the used Bioplastic LCA tool's environmental impacts in what if scenarios. More detailed information on methodologies behind these parameters is presented earlier in Introduction part 1.3 EF 2.0 Indicators described

Environmental Footprint 2.0 (ILCD/EF 2.0)

TABLE 9 Impact categories

Details for selected LCI(A) indicators
Climate Change Details
GWP [kg CO2 eq.] / FU
Primary energy from non-renewable resources (net cal. value) [MJ]
Primary energy from renewable resources (net cal. value) [MJ]
Blue water consumption [kg]
Carbon uptake [kg CO2 eq.]
Climate Change (fossil) [kg CO2 eq.]
Climate Change (biogenic) [kg CO2 eq.]
Water scarcity [m^3 world equiv.]
Acidification terrestrial and freshwater [Mole of H+ eq.]
Eutrophication freshwater [kg P eq.]
Eutrophication marine [kg N eq.]
Eutrophication terrestrial [Mole of N eq.]
Photochemical ozone formation - human health [kg NMVOC eq.]
Resource use, energy carriers [MJ]
Resource use, mineral and metals [kg Sb eq.]

5 Results

After applying scenario inputs in GaBi tool, output data is collected and the resulting data is presented. Significant differences or details of interest are visualised using graphs. The following assessment results indicate how end-of-life disposal by incineration plays a significant role when investigating the polymer choice impact the global warming potential. Transportation weigh is less significant compared to fossil based polymer products environmental impact after incineration. Fossil based PP and ABS global shipping added 10-15% weigh to GWP, Incineration ads over 100% to PP based product GWP and 47% to ABS based products GWP at the end of the life span. For bio based PLA- and PBS-based products the weigh from incineration is significantly less compared weigh from shipping; PBS- based product +3% and for PLA based product: +0.7%, before carbon uptake crediting. Nevertheless the transportation distances and used energy form in material converting and product conversion phases are also hot spots in the GWP build up. Composting effect assessment in the EoL of life span was found challenging to evaluate, due to missing technology and the gaps in consideration of CH4 emissions and its utilization. The Bio based PA-based product consumes more recourses during material conversion to polymer and therefore the high level carbon uptake is not sufficiently compensating to the GWP of the polymer share, compared to PLA and PBS.

5.1 Scenarios 1-5 and 6-10: Global vs Local

To study the effect of long shipping distance to GWP burden and the effect of electricity used at location, scenarios where divided to local with no shipping, with EU grid mix electricity. In global scenarios shipping distance of 21,000 km was added, and to evaluate the possibility of lower grid mix CO_2 /kWh burden as counter effect, the CH grid mix with aprox. 50% lower GWP was selected. (See FIGURE 35 Absolute GWP of electricity grid mix datasets in GaBi Professional 2017 & 2018 Edition)

These following scenarios 1-10 cover the lifecycle from cradle to gate focusing on the impact from location and transport of the material (material as product)

TABLE 10 Transportation share from the GWP kg /kg CO2 eq.

	Product Global vs Local									
	PA GF30		**PP GF30**		**ABS GF30**		**PLA GF30**		**PBS GF30**	
	Global	Local	Global	Local	Global	Local	Global	Local	Global	Local
	Scenario 1	**Scenario 6**	**Scenario 2**	**Scenario 7**	**Scenario 3**	**Scenario 8**	**Scenario 4**	**Scenario 9**	**Scenario 5**	**Scenario 10**
Transportation share of the impact , GWP	4 %	1 %	15 %	5 %	10 %	3 %	12 %	4 %	13 %	4 %
total GWP with carbon uptake credited	3,8	3,7	2,1	2,0	3,0	2,9	1,2	1,1	0,6	0,5
compounding locations electricity grid share on GWP	1 %	3 %	4 %	10 %	3 %	7 %	3 %	8 %	3 %	9 %

Transportation impact from 1000 km by truck (local) is between 1-5% of the total Global warming potential (CO_2 eq.), and when the shipping distance of 21,000 km is added (global), the share increases to 10-15%. Difference from the electricity grid mixes shows in the share when compounding location is altered. The impact from EU grid mix brings more burden to the GWP.

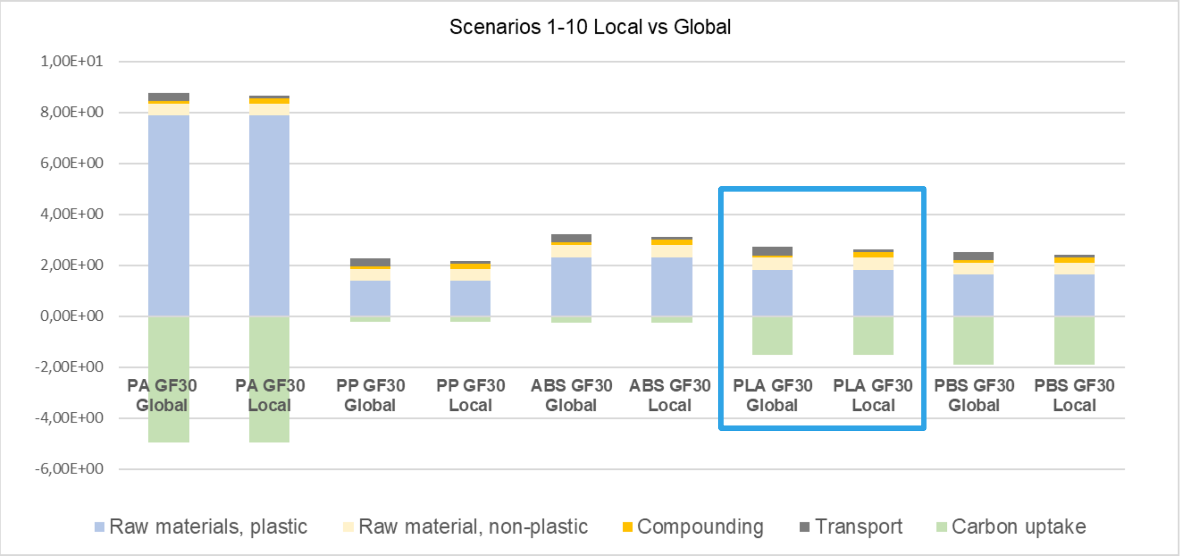


FIGURE 19 Scenarios 1-10 local vs global, GWP (CO2 eq.)

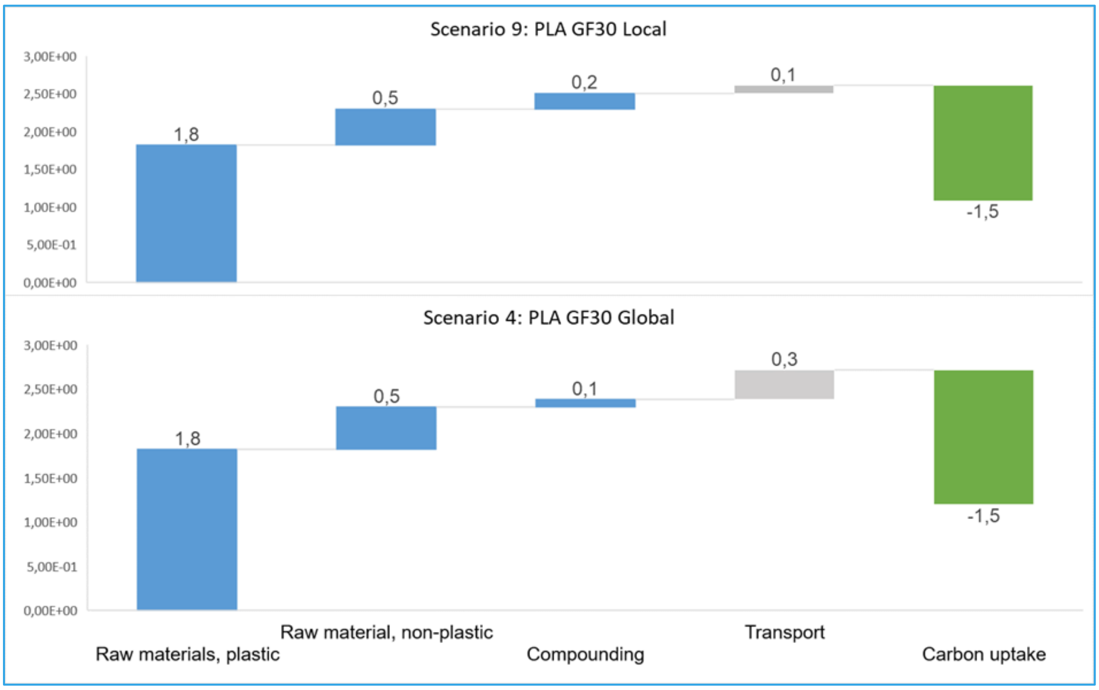


FIGURE 20 PLA GF30 global and local GWP build up

Table 10 and figures 19 and 20 above indicate how transportation weigh in the GWP approximately triples when global system is compared to local. Counter wise impact on the GWP build up comes from the production location. When compounding is done in location where the grid mix data has lower carbon emissions, as the transition to hydro, wind and solar power has significant effect on the electricity grid-Mix data in selected location leading to lighter carbon burden from compounding process. A factor of 2.5 higher impact appears when EU grid mix data is used. After carbon credited the GWP difference between local and global is 0.1 kg/kg CO2 eq. The results indicate the relevance of the energy form used. If high quantities of energy is embodied during material compounding, the energy source has a significant impact.

5.2 Scenarios 11-22: EoL options, cradle to grave

Next scenarios were built to predict/estimate the impact of the End-of-Life options. All data for each scenarios input (appendix 1.) and output (appendix 2.) are located at the end of this document.

TABLE 11 EoL scenarios EF 2.0 indicators

Composite EoL Scenarios:	**11 PA**	**12 PP**	**13 ABS**	**14 PLA**	**15 PBS**	**16 PA**	**17 PP**	**18 ABS**	**19 PLA**	**20 PBS**	**21 PLA**	**22 PBS**
	EoL:1 Incineration					EoL:2: recycling					EoL:3 Compost	
EF 2.0 Climate Change (fossil) [kg CO2 eq.] Carbon uptake credited	5,30E+00	3,47E+00	4,34E+00	1,10E+00	-2,82E-01	2,83E+00	2,77E+00	2,22E+00	8,69E-01	2,27E+00	1,70E+00	4,20E-01
EF 2.0 Climate Change (fossil) [kg CO2 eq.]	8,67E+00	2,18E+00	3,12E+00	2,61E+00	2,42E+00	8,67E+00	2,93E+00	3,12E+00	2,61E+00	1,04E-02	2,69E+00	2,58E+00
EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	6,35E-02	5,78E-03	4,70E-03	4,67E-03	1,44E-02	3,37E-02	4,75E-03	2,86E-03	4,21E-03	3,46E-01	2,32E-03	1,21E-02
EF 2.0 Water scarcity [m³ world equiv.]	1,59E+02	8,27E-01	1,05E+00	1,40E+00	5,28E-01	8,21E+01	4,53E-01	5,60E-01	7,94E-01	9,18E-03	1,24E+00	1,46E-01
EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	1,01E-01	1,04E-02	1,36E-02	1,25E-02	1,15E-02	5,37E-02	7,81E-03	8,48E-03	8,80E-03	6,73E-05	1,20E-02	9,85E-03
EF 2.0 Eutrophication freshwater [kg P eq.]	2,41E-03	4,94E-06	1,18E-05	1,41E-05	1,27E-04	1,24E-03	4,01E-06	7,51E-06	9,35E-06	2,70E-03	1,28E-05	1,27E-04
EF 2.0 Eutrophication marine [kg N eq.]	3,64E-02	2,21E-03	3,15E-03	3,23E-03	4,70E-03	1,90E-02	1,25E-03	1,78E-03	2,00E-03	2,07E-02	3,08E-03	4,01E-03
EF 2.0 Eutrophication terrestrial [Mole of N eq.]	3,71E-01	2,46E-02	3,36E-02	3,20E-02	3,49E-02	1,93E-01	1,37E-02	1,90E-02	2,01E-02	4,38E-03	3,02E-02	2,74E-02
EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	3,00E-02	7,42E-03	9,46E-03	8,37E-03	6,66E-03	1,61E-02	4,30E-03	5,38E-03	5,33E-03	3,41E+01	8,01E-03	4,87E-03
EF 2.0 Resource use, energy carriers [MJ]	1,16E+02	7,56E+01	8,35E+01	4,97E+01	4,65E+01	6,44E+01	4,33E+01	4,52E+01	3,39E+01	5,80E-07	4,15E+01	3,77E+01
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	1,23E-06	5,19E-07	6,84E-07	8,77E-07	8,25E-07	7,27E-07	3,52E-07	4,16E-07	5,92E-07	2,27E+00	7,12E-07	6,57E-07
Carbon uptake [kg CO2 eq.]	-4,97E+00	-2,22E-01	-2,61E-01	-1,53E+00	-2,77E+00	-2,60E+00	-1,60E-01	-1,54E-01	-8,46E-01	-1,13E+00	-9,88E-01	-2,16E+00
EoL burden [kg CO2 eq.]	8,57E-01	1,04E+00	5,73E-01	3,22E-01	1,04E+00	4,28E-01	1,10E+00	2,86E-01	1,61E-01	1,04E-02	8,15E-02	1,82E-01
EoL credits beyond system [kg CO2 eq.]	n.a.	n.a.	n.a.	n.a.	n.a.	-1,12E+02	-1,08E+00	-4,14E+01	-2,59E+01	-8,81E-01	n.a.	n.a.

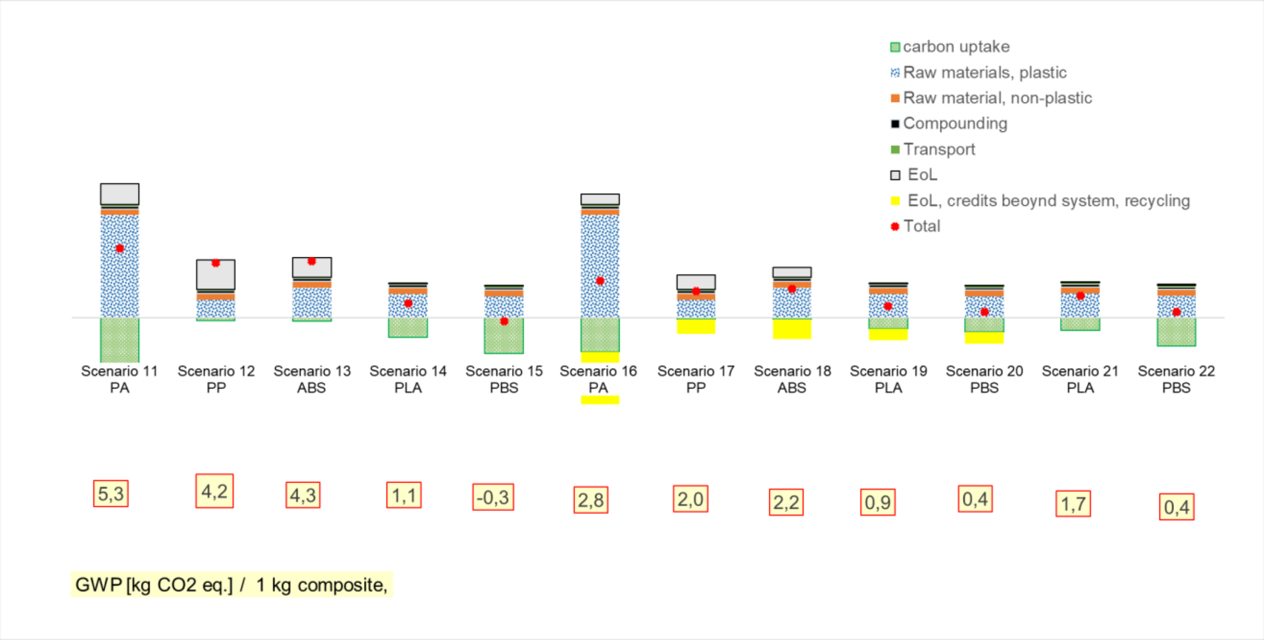


FIGURE *21 Total GWP for materials detailed, scenarios 11-22*

Figure 21 above represents the LCA output for material and process phases viewed as their Global warning potential impact.

TABLE *12 Scenarios sorted by GWP with carbon uptake credited in the impact*

Total GWP (Cradle to Grave) [GWP CO2 eq.]		
Scenario 15 (PBS inci.)	-0,3	most
Scenario 22 (PBS compost)	0,4	desirable
Scenario 20 (PBS 50% recycled)	0,4	
Scenario 19 (PLA 50% recycled)	0,9	
Scenario 14 (PLA inci.)	1,1	
Scenario 21 (PLA compost)	1,7	
Scenario 17 (PP 50% recycled)	2,0	
Scenario 18 (ABS 50% recycled)	2,2	
Scenario 16 (PA 50% recycled)	2,8	
Scenario 12 (PP inci.)	4,2	
Scenario 13 (ABS inci.)	4,3	
Scenario 11 (PA inci.)	5,3	least desirable

Table 12 above ranks the data from figure 21.

According to the analysis the most reduced contribution to global warming potential and the most sustainable alternative is a PBS composite when incinerated. PBS recycled follows, PLA and PP are similar when recycled. Fossil based polymers incinerated lead to more weigh to GWP.

In the figure 21 above, the composite impact scenarios are sorted by polymer material and EoL scenarios are compared. From EoL options composting is possible for two materials, PLA and PBS based composites. After credit beyond system is applied from recycling as the recycled 50% material is assumed to be immediately returned to feedstock. Carbon uptake is also credited and after recycled impact carbon uptake is reduced. The final GWP values are ranked from most sustainable outcomes to least desirable.

Primary energy is mainly used in polymer production. PA 1010 conversion from feedstock to polymer consumes most energy in comparison to other polymer options (Scenarios 11, 16, Figure 22)).

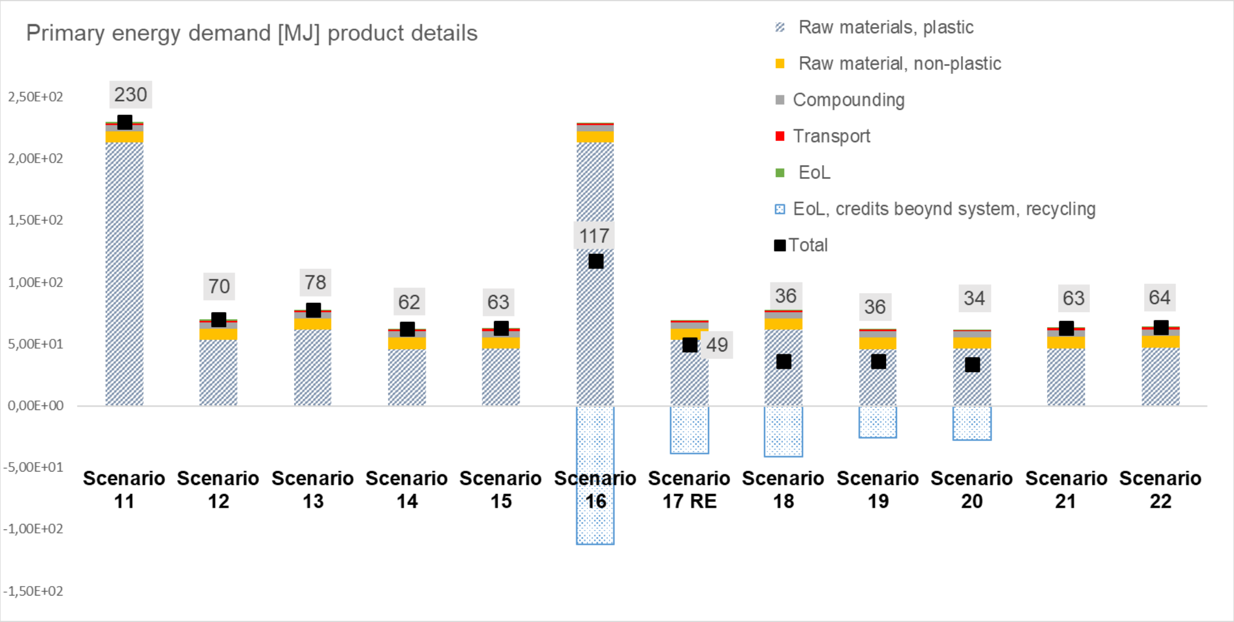


FIGURE *22 Primary energy demand in EoL scenarios 11-22 MJ/kg*

Recycling rewards by returning embodied energy to product system and that leads to positive scenario outputs. PBS, PLA and ABS containing composites with 50% recycled feedstock are in the same level by primary energy demand.

TABLE 13 PED for scenarios 11-22 ranked according to energy consumption

Total PED [MJ/kg] product	
20: PBS 50% recycled	34
19: PLA 50% recycled	36
18: ABS 50% recycled	36
17: PP 50% recycled	49
14: PLA inci.	62
15: PBS inci.	63
21 :PLA compost	63
22: PBS compost	64
12: PP inci.	70
13: ABS inci.	78
16: PA 50% recycled	117
11:PA inci.	230

5.2.1 Polymer choice and impact

Next figure is focused on the polymer impact as material choice in relation to carbon uptake and end of life options. Transportation and compounding are excluded to illustrate the polymer effect. The carbon intake into bio-based feedstock overtakes the carbon release during polymer manufacturing process and trough all three EoL options; seen in scenarios 15, 20 and 22.

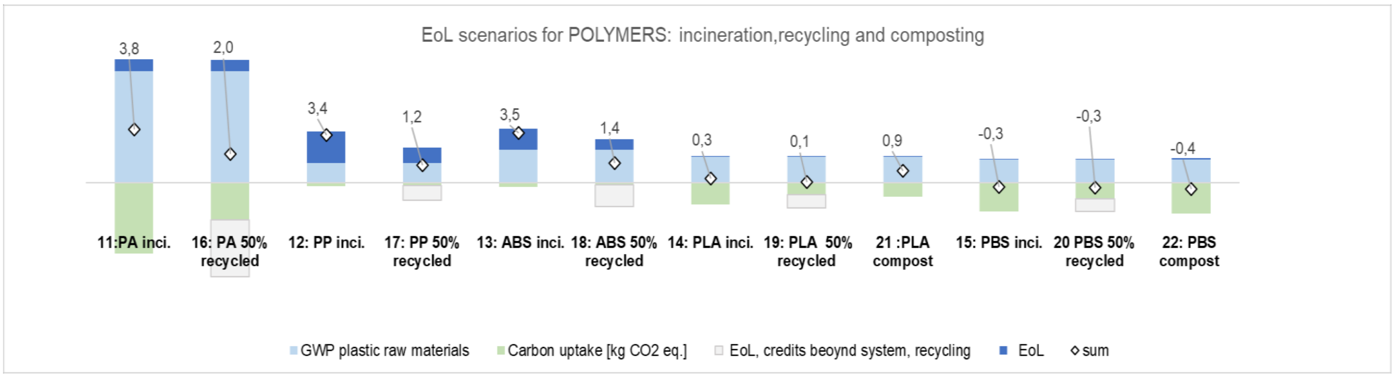


FIGURE 23 each material type End-of life options compared by credits in and beyond system, scenarios 11-22

TABLE 14 Polymer share from the total GWP impact

Effect seen via polymer choise [GWP CO2 eq.]	
22: PBS compost	**-0,4**
20 PBS 50% recycled	**-0,3**
15: PBS inci.	**-0,3**
19: PLA 50% recycled	**0,1**
14: PLA inci.	**0,3**
21 :PLA compost	**0,9**
17: PP 50% recycled	**1,2**
18: ABS 50% recycled	**1,4**
16: PA 50% recycled	**2,0**
12: PP inci.	**3,4**
13: ABS inci.	**3,5**
11:PA inci.	**3,8**

Since the unit processes compounding and transportation is ruled out, the carbon uptake effect is emphasized in the figures above. When carbon uptake is credited from total GWP, the impact of renewable feedstock is seen. The PA 1010 derived from castor oil embodies atmospheric carbon, still the polymerization for polyamide consumes more energy than other bio-based polymers and final sum for GWP is relatively higher compared to PLA and PBS bio-based polymers. EoL via incineration; PLA and PBS has insignificant burden compared to PA, PP and ABS.

Next figure 24 indicates the energy consumption for functional units (to gate) and blue water consumption for polymer materials (to gate) and added the primary energy credit when material is recycled (feedstock 50% recycled), the whole composite credited. The composite has significantly higher impact to final material, as higher energy flows needed for material creation.

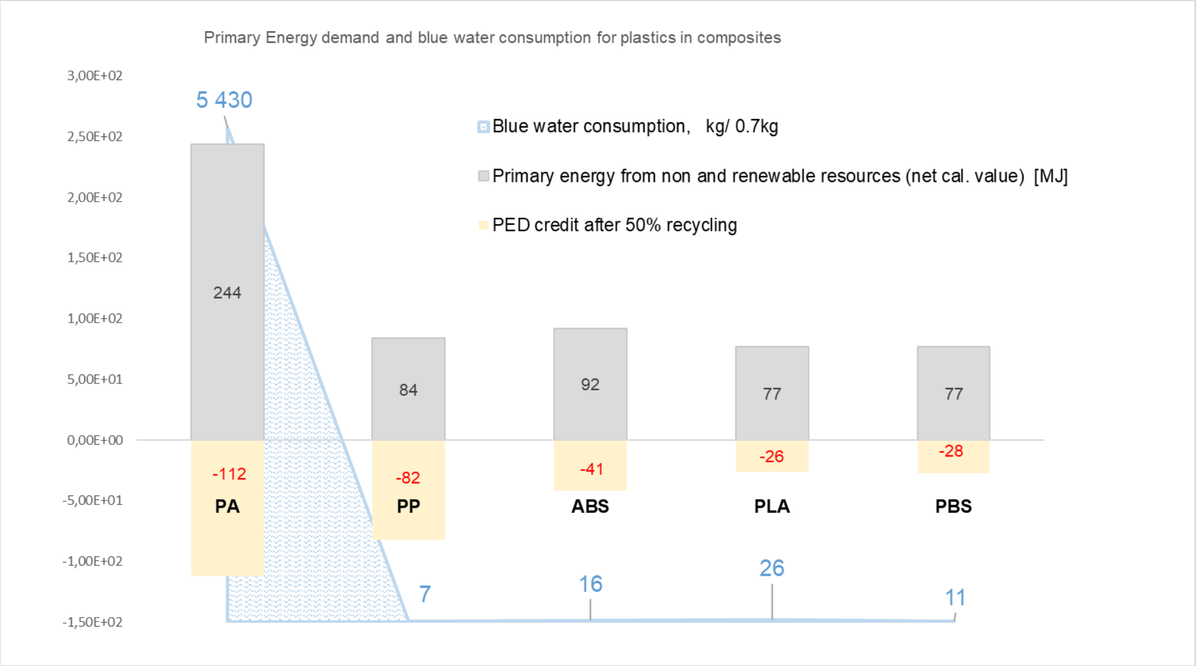


FIGURE 24 Primary energy demand and blue water consumption for plastic share

Figure above shows significant difference in water consumption for polymer materials. Over 5 400 kg of water is needed for forming the functional unit PA polymeric raw material part. Polyamide polymerization differs from others by complexity. For other polymers: PP 7 kg, ABS 16 kg, PLA 26 kg and PBS 11 kg of water is used in making of polymer share of the product, which is the 70% share from functional unit. In the same figure can be seen the energy consumption reduction potential during 50% recycling crediting for polymer share of the composite product. Following FIGURE 25 shows the ratio between raw materials by their energy consumption during raw material production in supply chain. As seen, the polymer share from Figure below presents the glass fibre share form the product (30% weigh from functional unit) and the energy demand share being from 4% to 20% depending on the polymer demand for energy. Primary energy demand major share comes from polymer production process, the main and auxiliary processes of polymerization.

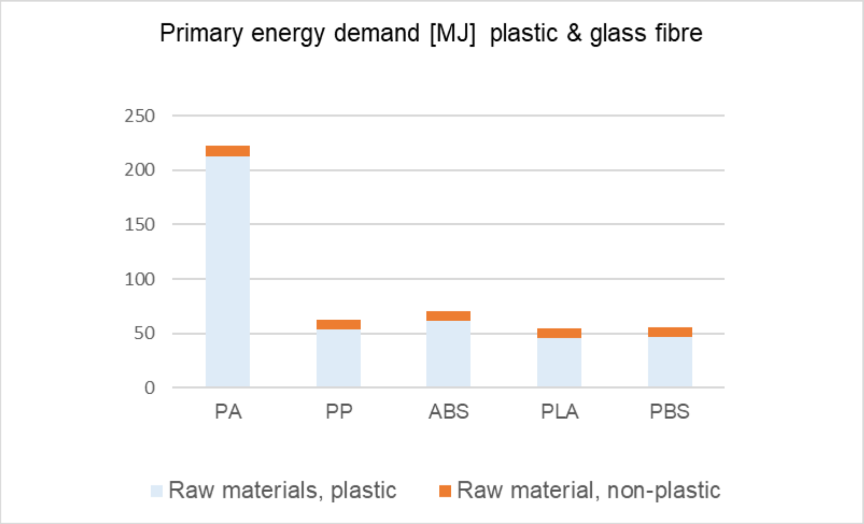


FIGURE 25 Glass fibre share on material energy demand

Impact parameters for resource use and environmental impacts are presented in relation to each other using scenarios 11-15, Local and EoL by incineration. Since the glass fibre share is fixed 30% of the composite weigh, the differences are related to the polymer choice impact in the product. According to the used GaBi 2019 dataset polymers use energy from renewable sources with different ratios. Bio-based materials use from double to quadruple amount of renewable energy compared to fossil based PP, ABS with their 11 and 12 % renewable energy share. Fossil based energy is more likely interlocked in fossil based material production. The Gabi data for polymer primary energy forms are listed below.

TABLE 15 PED from renewable or non-renewable sources on scenarios

Primary energy from		
polymer choise in composite	from **renewable** resources	**non** renewable resources
PA	53 %	47 %
PBS	41 %	59 %
PLA	36 %	64 %
PP	12 %	88 %
ABS	11 %	89 %

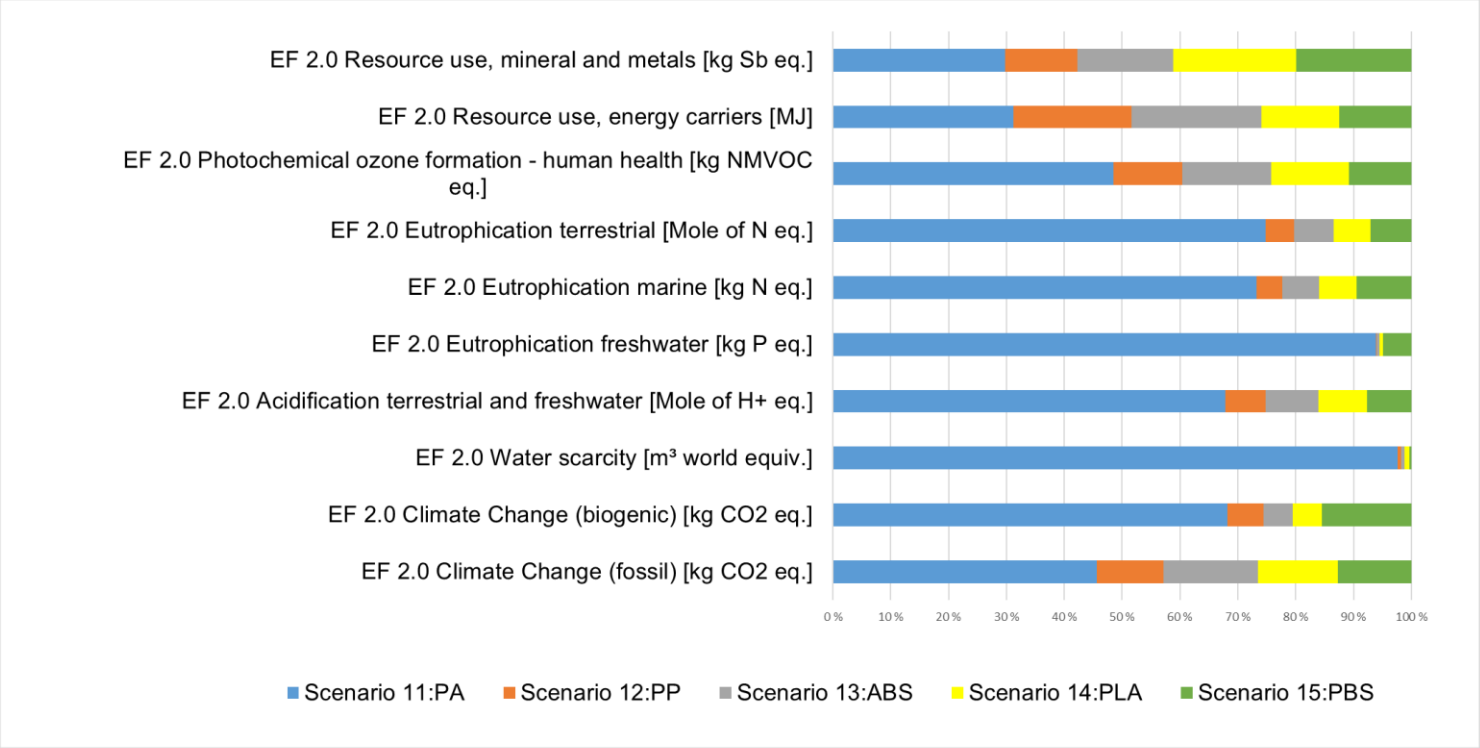


FIGURE 26 Impacts for scenarios 11-15 (composite EoL by incineration)

PA 1010 derived from castor oil has the largest impact according to impact indicators from FIGURE 26. PP and ABS being fossil based have less impact on freshwater acidification or terrestrial eutrophication. Nevertheless, the bio-based PLA, feedstock from corn, does not significantly differ from fossil based materials.

5.2.2 Sensitivity test

Sensitivity check for imaginary scenarios where material selection, EoL options and transportation variation was done prior studying the selected 1-22 what if – scenarios. Below is a takeout of one sensitivity check for giving an example.

TABLE 16 Sensitivity test, selected inputs and outputs

	PLA GF30 "bad case"	**PLA GF30 "good case"**	**PA GF 30 "bad case"**
electricity Grid	DE	EU	DE
EoL	inci.	90% recycled	inci.
Transport km SHIP	50000	0	50000
Transport km Truck	5000	250	0
sum GWP cut off (carbon uptake credited)	**2.07**	**0.97**	**5.97**
sum GWP avoided burden (carbon uptake credited)	**1.64**	**0.92**	**5.10**
cut-off (no credits and no burden for recycled input)			
Total	**4.43**	**3.31**	**11.80**
Raw materials, plastic	1.82	1.82	7.88
Raw material, non-plastic	0.48	0.48	0.48
Compounding	0.28	0.21	0.29
Conversion*	0.78	0.78	0.80
Transport	1.05	0.02	0.72
EoL	0.02	0.00	1.60
Carbon uptake [kg CO2 eq.]	-1.58	-1.56	-5.03
Avoided burden (credit and burden on recycled input)			
Total	**3.92**	**2.09**	**10.80**
Raw materials, plastic	1.82	1.82	7.88
Raw material, non-plastic	0.48	0.48	0.48
Compounding	0.28	0.21	0.29
Conversion*	0.78	0.78	0.80
Transport	1.05	0.02	0.72
EoL	0.02	0.002	1.60
EoL, credits beyond system	-0.51	-1.22	-0.92
Carbon uptake [kg CO2 eq.]	-1.50	-0.39	-4.90

*conversion, injection moulding is excluded from scope. Considered as part of the product use phase

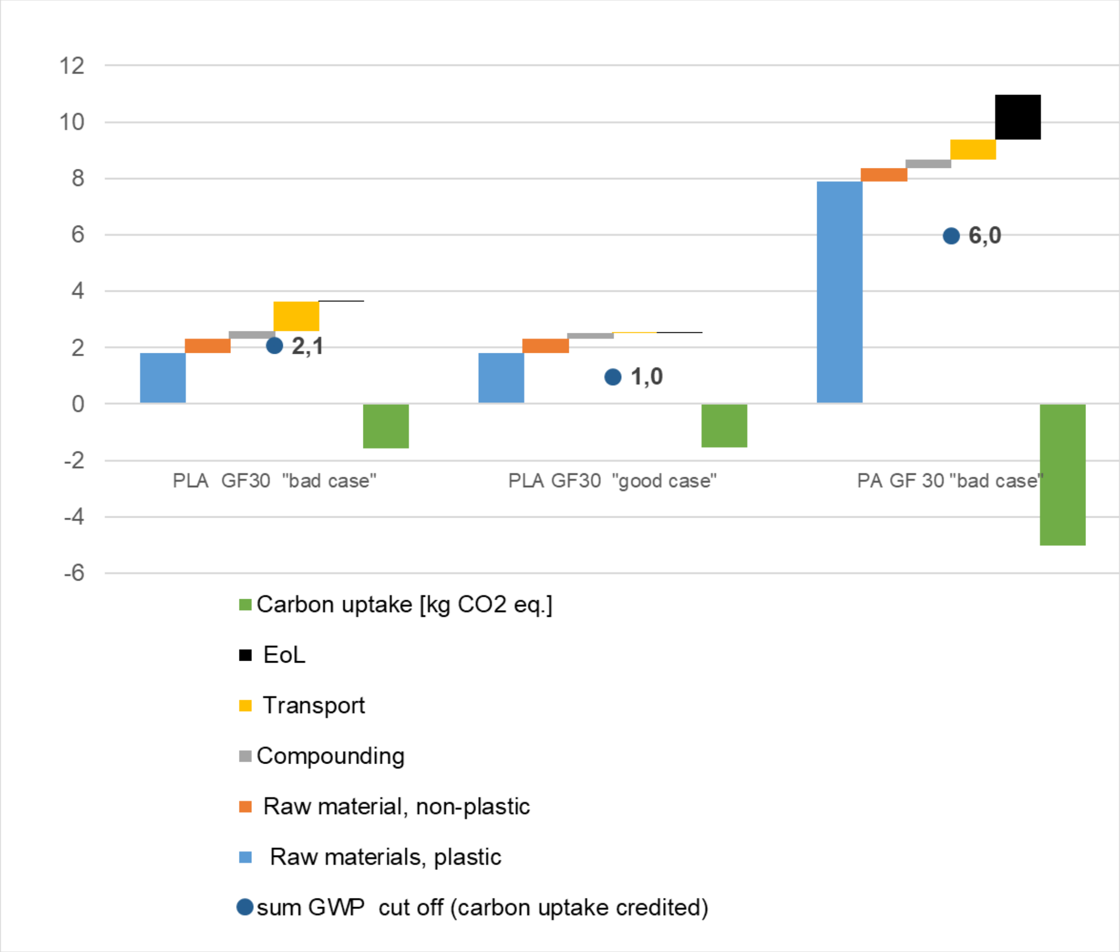


FIGURE 27 Sensitivity test for two scenario materials

Figure 27 above illustrates GWP output data from
TABLE 16 Sensitivity test, selected inputs and outputs. Transportation weigh and method, EoL effect and electricity grid selections were tested in different scenarios for investigating constancy and reliability of the LCA shadow calculation in using tool in Envision software. Functions were found reliable after repetitions by changing input parameters.

6 DISCUSSION

6.1 Interpretation of LCA results

Figure 28 below represents a summary of material selection scenarios carbon footprints. The summary below is showing the scenario material options from cradle to gate. The graph indicates the significance of the carbon uptake when it is credited from total GWP, reducing material impact.

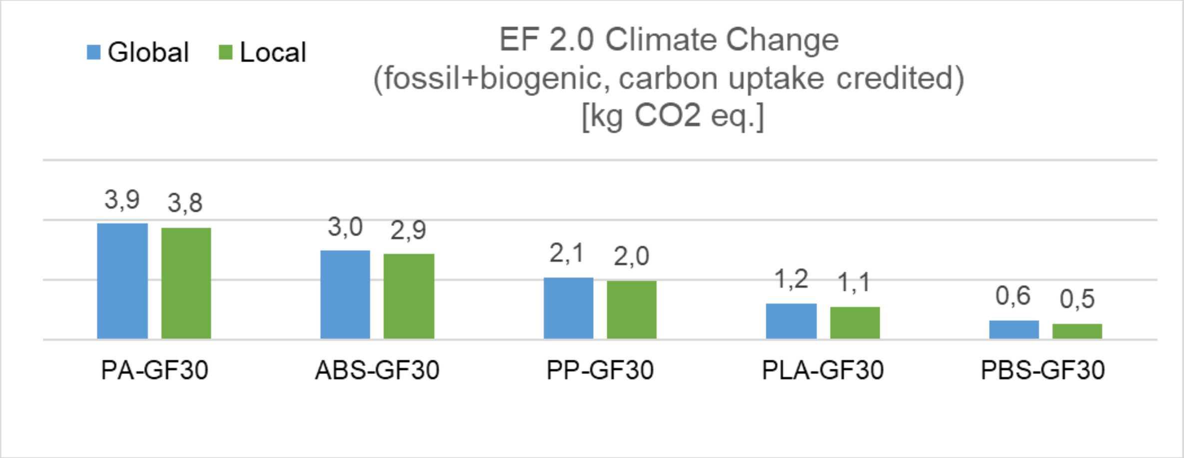


Figure 28 GWP for materials cradle to gate (scenarios 1-10, Global and local)

When impact categories are ranked according to the EoL effect to impact: FIGURE 21 Total GWP for materials detailed, scenarios 11-22, and by material selection by investigating the data without conversion and transport the outcome was ranked as follows in Table 17 from least to most impacting. Overall Global warming potentials after different EoL life consideration in scenario analyses (Incineration, recycling, composting) is ranked in the table 17.

TABLE 17 EoL impact ranking by GWP

sce. No.	**EF 2.0 Climate Change**	GWP fossil	GWP biogenic	EoL burden	Carbon uptake	sum [kg CO2 eq.]
15	PBS-GF30 incineration	2.4	0.01	0.07	-2.8	-0.3
20	PBS-GF30 recycled	2.4	0.001	-0.87	-1.1	0.4
22	PBS-GF30 composted	2.6	0.01	0.08	-2.2	0.5
19	PLA-GF30 recycled	2.6	0.00	-0.89	-0.8	0.9
14	PLA-GF30 incineration	2.6	0.005	0.018	-1.5	1.1
21	PLA-GF30 composted	2.7	0.002	0.003	-1.0	1.7
17	PP-GF30 recycled	2.9	0.00	-1.02	-0.2	1.8
18	ABS-GF30 recycled	3.1	0.005	-0.75	-0.2	2.2
16	PA-GF30 recycled	8.7	0.03	-3.24	-2.6	2.9
12	PP-GF30 incineration	2.2	0.01	2.24	-0.2	4.2
13	ABS-GF30 incineration	3.1	0.005	1.48	-0.3	4.3
11	PA-GF30 incineration	8.7	0.06	1.60	-5.0	5.4

For PBS and PLA polymer the incineration appears being sustainable option due to carbon uptake near the LCA cradle, Also the lower emission during incineration gives them an advantage. Nevertheless what must be kept in mid is the aim to transition to fossil free energy, then the incineration of biopolymers is not an option as they form a microscopic fraction from all plastics ending up in the incineration process. The recycled material has less impact due to its contribution to products as carbon uptake from material feedstock is reduced. This finding can be challenged due to data nature being from modelling and assumption rather than from industry. PP incineration has a significant effect to CO_2 release quantity. Overall PBS has a lower carbon footprint compared to PLA, but when composting is considered for EoL, PBS has a higher impact. That is due to the model where methane is formed. Described earlier in 4.3.1 End-of-life –composting. If methane would be compensated as side stream and handled and considered as circular energy or raw material feedstock, the situation could differ. Both PBS’s data: feedstock and EoL composting data is modelled.

PLA: PBS stoichiometric carbon ratio is approx. 6:8 leading to different CO2 emissions during combustion. Composting process includes anaerobic emissions (methane, and consumes energy throughout the process).Value corrected substitution method of recycling as EoL is not final as material will lose properties and cannot be fully returned or new product cannot be 100% based on recycled materials, at least in current technology environment, until chemical recycling is use. In current situation incineration is the used EoL option for plastics outside recycling.

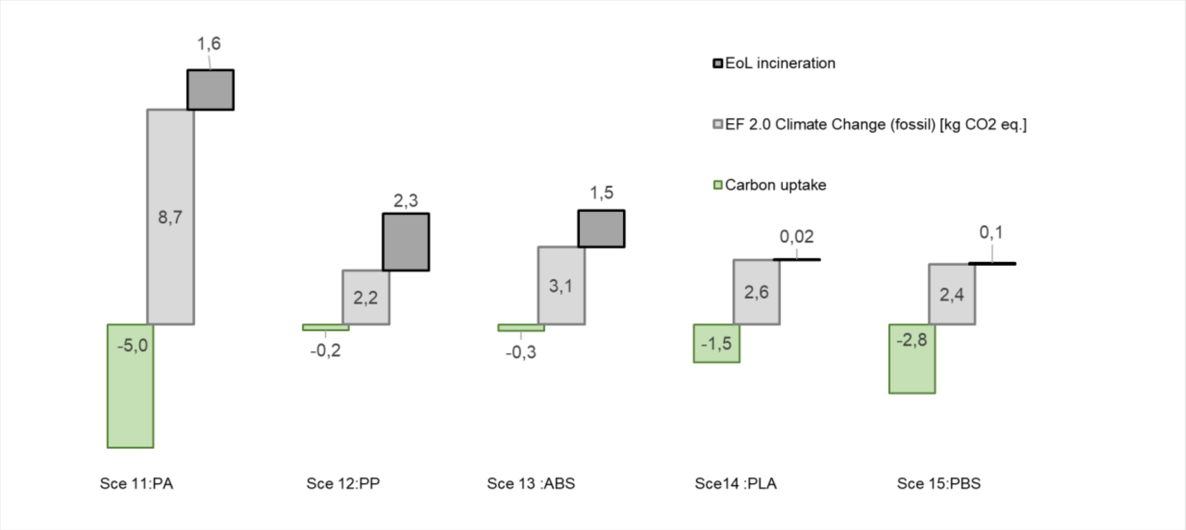


FIGURE 29 Five materials composite scenarios during incineration as EoL Option

Glass fibre data compared

From table 18 is seen the primary energy demand for glass fibre manufacturing from three sources: ABM glass fibre data for elemental flows; energy and water is under investigation. As the manufacturing process is scaled up, the ABM data is for taken from status when ongoing manufacturing capacity is under 50%. The energy consumption for glass fibre manufacturing can be assumed to be more efficient after production is scaled up to full capacity. Compared to the LCA build for Glass fibre Europe industry data, the Gabi database has more weigh on the energy consumption than ABM and literature data is from Glass fibre Europe data (2016). According to this data, there is no significant risk of greenwashing by using the Glass fibre data from Gabi 2019 dataset when energy consumption is investigated as part of the final product. Still what must be strongly emphasised is that the data for ABM fibre is not complete. The whole supply chain is not recorded under this LCA. And there is a different energy grid mix and energy sources that are not shared under this LCA. Primary energy from for electricity and the minor or non-existent share for natural gas as heating form for glass melting has significant negative or positive environmental effect that need to be acknowledged and studied in the future. The continuous evolution of processes and the consequent of need for updating of data are LCA's strengths. The environmental impacts and sustainability of products is not a static state but a constantly assessment change.

TABLE 18 Glass fibre manufacturing energy input

Raw material Glass fibre cradle to gate / 1kg

Literature	**Gabi 2019**	**ABM**	
1.5	1.58		**Climate Change (fossil) [kg CO2 eq.]/ kg GF**
27.7	*30.3*	*28.9*	**Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]**
12	8.15		**[kg] water / kg GF**

6.1.1 Risk assessment

TABLE 19 Risk break down structure during LCA

Level 0	Level 1	Level 2	Level 3	Risk identifications trough LCA implementation
Project	Management	Corporate	Experience / Stability	Streamlined LCA dataset will be outdated after project/ after certain time, LCA should be re-inspected, re-calculated to meet the industry's latest status and ABM product stewardship development.
		Customer & Stakeholder	Requirements, contractual	Environmental impact information LCA can be used in comparative assessment outside ABM and scope, customer uses information on their own PED communication giving false claims. Keeping up with the given bio-based content and evaluated environmental impacts (supply variation).
	Extrernal	Natural environment	Physical, servises	Biodiversity aspects which is so far not considered in LCA, Changes of macro plastics which evolve into micro and Nano plastics (soluble polymer, disintegration), some inevitable pathways would remain which still needed to be considered over time (composting emissions?).
		Cultural,	Political, legal, regulatory , interest groups	Sustainable product will be transported in supply chain for longer distances due availability of desired biomaterials being lower. Additional weigh to the final environmental impact from use phase conversion and transportation mitigates the gain from carbon uptake during feedstock formation. Country of EoL/ recycling: considering different waste management laws.
		Economic	Labour and finance	The health and safety issues while processing novel compounds and raw materials. Unexpected material costs, price ingreases.
	Technology	Requirements	Scope uncertainty, conditions of use, complexity	Shelf life of the product in use phase: between compounding and converting can be unknown. There can be unexpected scrap or loss of material if compostable compounds, sensitive to hydrolysis are stored in "tropical conditions"
		Perfomance	Tech maturity, performance	Customer location electricity grid choice leading negative effect to the GWP and EoL by country variations, material processing parameters not adjusted according new materials. Missing EoL, life cycle.
		Application	Physical resources	Feedstock polymer supply variation and quality variations, batch to-batch consistency. Raw material availability changes in the market.

RBS outline for project according Hall and Hulett, (2002) was used in table 19 as risk assessment frame. After the interpretation of the LCA results, the lessons learned during product development combined to life cycle system thinking is collected in to risk assessment. LCA reveals that the hotspots for adding extra weigh to product environmental impact are not from ABM product manufacturing process. Material selection itself continues as the main impact during ABM product manufacturing. Opportunities to improve environmental performance of the product come from supply chain: transportation distances and choice of energy form. To avoid GWP burden ABM recommends usage of fossil free energy options during conversion process; use phase; injection molding etc.

6.1.2 Sensitivity and uncertainty

"Often, sensitivity analysis is carried out in LCAs to test system boundaries, (allocation approaches, parameter values and characterization methods). Temporal effects on both the life cycle inventory (LCI) and life cycle impact assessment (LCIA) results are rarely concerned e.g. landfill emission under different time horizons and the time-dependency of characterization models". (Guo, Murphy, 2012, 230) Due to the magnitude of the database content and the knowhow of ThinkStep engineers, most information is available or can be developed. If a substance for which no LCA data exists is needed and is not available as a dataset, the GaBi Master database uses information for a chemically/physically-related substance and creates a "precautionary principle" scenario (rather slightly over estimate than underestimating the impact) for the substance causing the gap. If the influence of the "precautionary principle" scenario on the overall result is smaller than 5%, the scenario can stay (gap closing insignificantly overestimates to the actual value). If the influence on the result is higher, more information is gathered or the sensitivity is quantified. The GaBi database has acceptable cut-offs of, if the environmental relevance on the overall result can be justified as small. An example of a justifiably small environmental relevance is a known inconsistency in a mass or energy balance with known rea-son, such as missing or imprecise quantified mass information in the input. These can be minor variations in moisture content or minor amounts of diffuse water input, reaction or combustion air, which is directly taken from the atmosphere and normally not quantified in a "bill of material" or process flow chart. Known inconsistencies in a mass or

energy balance with known reason on the output side can be undocumented “emissions” or energy flows such as evaporated water, used air, “clean” off-gas streams or off-heat. These cut-offs are acceptable, if their quantification would raise the effort drastically and in parallel would only marginally improve the overall results. All GaBi unit processes aim to reflect actual physical and thermodynamic laws. The mass balance of the key substances and fuels in the input must match the product, waste and emission output. As a general rule in GaBi unit process modelling, the mass and energy balances are closed and cut-offs are avoided. Projects and data collections with industry and associations showed that on the unit process level mass balance inconsistencies of less than 1% are achievable with practically feasible effort. On the unit process level of GaBi datasets, a best practice value of < 1% cut-offs (or un-known omissions, sources or sinks) is applied for flows that are less environmentally relevant.
(Kupfer, Baitz et al 2019, GaBi, 32)

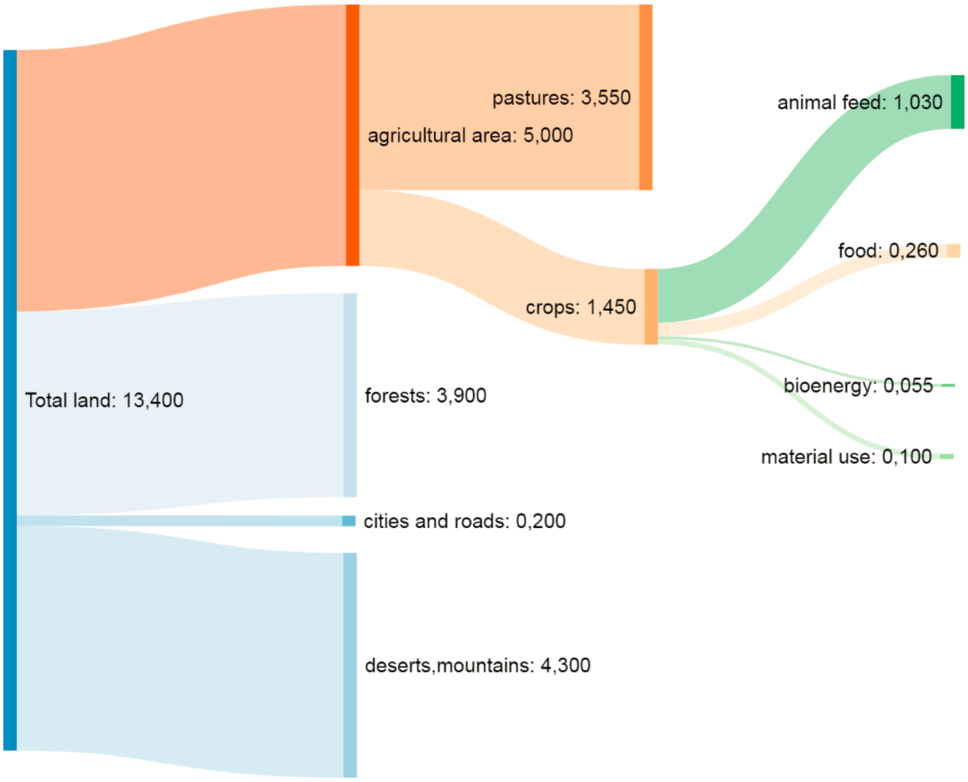
6.2 Sustainability of bio-based polymers

Situation review for Land use: biomaterials vs. food

A misconception held by general public about global land use creates a challenge against change towards sustainable development. Misconception about allocated land use is about competition between crops for human food consumption and for material production appear in public debate. Population growth and increase of wealth and thus increase in consumption of more refined goods leads to completion. Demand increase in meat vs. crops consumption is the main issue in land use sustainability problematics. This view is supported via LCA’s by PLA (Poly lactic acid) producer’s calculations concerning land use. More detailed discussion is located earlier in part presenting PLA feedstock **3.2.1**

According to OECD 2016 and 2018 released reports, by 2050 the world’s population will reach over 9 Mrd, over 20 percent higher than today. Nearly all of this population increase will occur in developing countries. Urbanization will continue at an accelerated pace, and about 70 percent of the world’s population will be urban (compared to 50 percent today). Income levels will be many multiples of what they are now. In order to feed this larger, more urban and richer population, food production (net of food used for biofuels) must increase by 70 percent. Annual cereal production will need to rise to about 3 Mrd tons from 2.1 Mrd today and annual meat production will need to rise by over 200 million tons to reach 470 million tons. Feeding a world population of 9+ Mrd people in 2050 would require raising overall food production by some 70 percent between 2005 and 2050. (OECD, 2016)

FIGURE 30 Global land use Mrd ha (diagram data derived from data from Nova insitut 2008, picture by author)



Currently only a minimal portion of cultivated land area is used for providing raw material for bioplastics production. In relation to global agricultural area, the land use for bioplastics production is 0.016% and the influence of growth leads to predicted share of 0.021% by the year 2022, equivalent to land use of 1.03 million ha. When total material use coverage is over 100 million ha.

The bioplastics industry has grown by 20-30% a year. BCC Research forecast that the global market for biodegradable polymers would grow at a compound average growth rate (CAGR) of more than 17 percent through 2012, and this rate of growth has actually been exceeded. Bio-based plastics are predicted to make up 5% of all manufactured plastics in 2020, and 40% of all manufactured plastics in 2030. (Dolften, 2012) According to the Nova institute, after 2018 the share was 2% of the production volume of petrochemical-based polymers. The land cultivation area statistic clearly indicates that excessive consumption of meat pays a significant role when considering sustainable land use to feed humankind in the near future and that land used for bioplastics does not directly compete with food.

Example on scale: Consumer electronics waste and market growth

Globally, production of electronic goods has been the fastest growing manufacturing sector over the last 15 years. (Samp, 2017) Electronic waste is formed when consumers update their equipment to new version on the market and simultaneously planned obsolesce is not successfully regulated by legislations, leading the consumer electronics market growth increase. According to Baldé, et al.(2014), E-waste is a term used to cover all items of electrical and electronic equipment (EEE) and its parts that have been discarded by its owner as waste without the intent of re-use or recycling. In 2014 published report by the global e-waste monitor stated that 41.8 million tons of e-waste was generated worldwide. The quantity included 12.8 million tons of small equipment, 11.8 million tons of large equipment, 7.0 million tons of temperature exchange equipment (freezing and cooling equipment), 6.3 million tons of screens and monitors, 3 million tons of Small IT and 1 million tons of lamps. The amount of worldwide e-waste generation is expected to hit a record high of 49.8 million tons in 2018, and continuing with an annual 4-5 percent growth. (Baldé, 2016, 50) 76-80 percent (equalling 34.1-35.8 Million tons) from all the e-waste produced is been handled undocumented and in inferior conditions. Recyclable materials in e-waste are a valuable source of material that could provide a valuable resource under urban mining process, in which the waste is seen as a source for harvesting materials instead of conventional mining or production of virgin feedstock production as process. The amount of plastic fraction in e-waste is around 8 600 kilo tons annually. (Baldé, 2016, 50)

According to European bioplastics, 2018, only 34 kilotons production capacity is targeted for electronics segment. There's a gap where waste segment could be replaced with renewable material selection and cumulative CO_2 release could be reduced.

TABLE 20 comparison of e-waste plastic part to PLA land use.

Plastics share from e -waste [kg]	8.60E+06	(Baldé, 2016)
Area needed to produce equal amount of PLA (corn, 1 kg yield / 1.53 m^3) [ha]	1.32E+03	(Vink, Davies,2014)
Word total arable surface area used for crops [ha]	1,45E+09	(Nova Institute 2008)
Share from arable crops area, if the e-waste polymer part would be produced from PLA	0.00009 %	

Table 20 above is an imaginary scale comparison derived from land use data. When comparing to bioplastics land use, only replacing the plastic share of e-waste to bio sourced PLA polymer (Poly lactic acid polymer), the required land area would be approx. 1300 ha, depending the source of crops for carbohydrates used. That would only equal to 0.0001 percent share of the total land area used for material production. The continuously growing consumption of electronics plastic share would be replaced with bio sourced materials the carbon intake from the atmosphere would increase.

Sustainable development via material efficacy

Example from the portable electronics industry: Manufacturers of mobile phones will use much less material, as these devices are very small and compact. Furthermore, these devices can enable better communication between users and in many cases obviate the need for some travel, for paper communications, etc. Notwithstanding the fact that such devices require relatively small quantities of materials, the fact that China Mobile Limited report a saving of 18,000 tonnes of production materials usage in their 2011 Sustainability report is impressive, and could be regarded as an example of strong sustainability within this sector. They also report a cumulative avoidance of 6000 tonnes of plastic waste due to operating improvements. Since plastic waste is a major problem world-wide at the present time, this is a welcome development. (Sturges, 2016, 7)

Future will tell if a balance between continually increasing demand for products and their environmental foot print will appear via sustainable product design and resource efficacy.

6.2.1 Obstacles in the way of using of biomaterials

The concept of replacing oil-, gas-, and coal-based materials by those of similar performance derived directly or indirectly from nature on a significant (and thus large) scale is an appealing one. There are the immediate problems publicly known: The price: bio-polymers and bio-composites with competitive property profiles are not cheap, the variability: the properties of biomaterials depend on geography and fluctuations of weather, the uncertainty of supply, which fluctuates with annual weather patterns. There are probably ways of solving these problems, but they are not the ultimate difficulty. It is on a different scale.

The world has now consumed itself into a corner in which there is not enough productive land to grow both the food we need and at the same time grow structural biomaterials or biofuels on a really large scale. Many studies conclude that the population carrying capacity of the planet is close to saturation. Space, water, and fertile land are the essentials for human habitation and activity. Large-scale replacement of man-made materials by those of nature no longer appears possible. (Ashby M. 2012, 343) There are many viewpoints on how bioplastics are seen in the fight against climate change. The carbon intake and natural carbon cycle in material production is focused on and the challenge of material use efficacy is faced. Before replacing materials with bio based, the circularity of existent fossil based materials should come into realisation.

6.2.2 The Dimensions in material selection

Targeted application set the limitations for materials. Different quantities of different materials are needed to achieve same desired properties. Not only the environmental impact, but also other issues must be considered in the ecological design during material selection. Product planner must consider how the product can full fill the life-span lasting until the designed end-of-life, balancing cost, sustainability and material property vice. Surprising issues like material being challenging to process, short shelf life or additional energy needed to overcome viscosity variations in compounding can appear during product development.

Example on such balancing is found from Book Materials and the Environment : Eco-Informed Material Choice, by Ashby (2012).

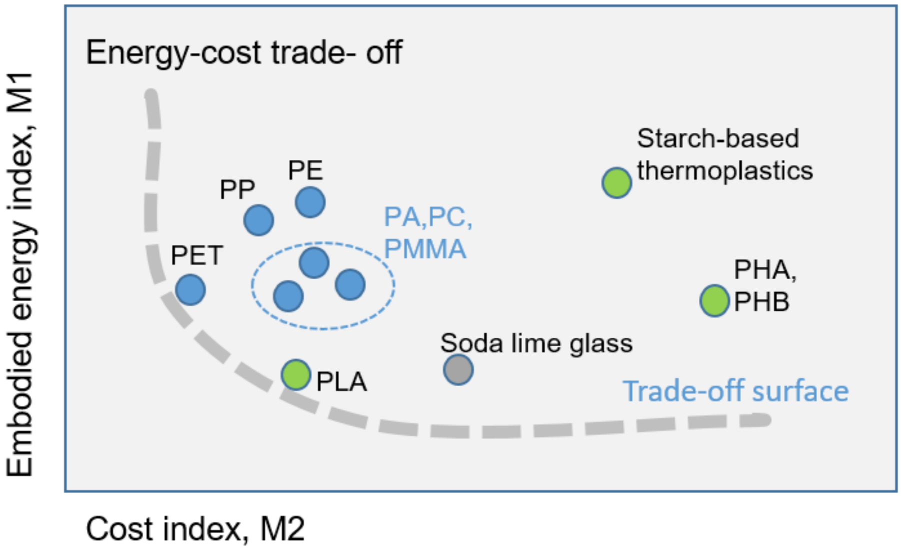


FIGURE 31 Embodied energy and cost trade off (figure adapted from Ashby M, 2012)

Figure 31 above is a trade-off plot with M1 (embodied energy of the material creation with density factor) on one axis and M2 (Cost with material density factor) on the other. The choice with the lowest embodied energy (and carbon footprint) is polylactide, PLA. The least expensive is polyethylene terephthalate, PET. Both lie on the trade-off surface, making them better choices than any of the others. (Ashby M. 2012) Before the trade off the materials where plotted against target application, in this case it was a certain strength and material wall thickness needed to carry the load of the target application. After plotting material property the cost and embodied energy where applied for finding the trade-off area.

Expertise from material science and from application design is needed to support sustainable material selection.

6.3 Areas of significance and enhancement opportunities

The most critical step in LCA is the delimitation of the area as the product involves extensive industrial ecosystems. For the results of a completed evaluation to be clear and usable, the delineation must be well defined from the outset. Implemented LCA tool is suitable for building predictive scenarios when selecting the raw material for product manufacturing is focused on. LCA tool used has limited capacity to describe the whole product life cycle, especially the circularity, since the final product manufacturing is located outside ABM gates. When working together with OEM the conversion steps and product performance in the life cycle can be studied further. Nevertheless, In addition to the actual environmental impact, the life cycle assessment method can be used as a tool for process improvement and risk assessment. At the critical stage of LCA, it was noted that the end-of-life alternatives studied were not yet practically implemented. According to the literature, separate recycling of bioplastics, both mechanical and chemical, is recognized as a potential technology, but not yet practically feasible or commercialised. The final disposal of plastics is primarily energy for incineration and only a small fraction of the polymers are recycled. In the recycling process, the bioplastics fraction is seen as a disadvantage that is separated into combustion waste or ends up as impurity in recycled oil-based plastics. Composting for bioplastics composites with PLA or PBS polymer is possible and its effect was evaluated. The life cycle assessment found that the greatest environmental impact of all products comes from the production of the polymeric raw material itself, before it enters the ABM gates and that was the core question to tackle; are ABM products sustainable after adding supply chain burden and process steps to raw materials.

6.3.1 Policy and business implications

Results from this LCA could be used to support statements favouring bio- based polymer options over fossil based when studied PP, ABS are seen as baseline. Plastic item producers that are looking for replacement materials that are mass produced and technically equivalent for the currently used materials and with better environmental performance. LCA Study informs businesses of alternative potential options, which could offer better environmental and economic performances in comparison of the polymer choice in the product. Polymeric raw material suppliers offer their own LCA data for consideration that show significant reduction of GWP compared to fossil based polymers. After compounding; adding composite fibre reinforcement and transportation weigh and conducting congruent and transparent life cycle assessment for material selection scenarios using PP and ABS from fossil sources, ABM can continue supporting this statement for bio-based ABM composite being sustainable alternative as raw material.

Nova institute recently published an open letter to Joint Research Center (JRC) on bio-based polymers for LCA recommendation: “If a comparative LCA between bio-based and petrochemical polymers is to be carried out today, the effects of a scenario for the year 2050 should always be calculated in addition. To this end, LCA experts from JRC should define the key framework data of the 2050 scenario (reduced impact of agriculture and forestry, increased impact of crude oil extraction, improvement in bio-processing, electricity mix with high share of renewables). Bio-based polymers are considered as a sustainable solution for the circular economy of the future. That is why, for a fair comparison, it is so important to consider how they perform not only in the present, but in particular in the future. This is not accounted for in the methods prevailing today. The consideration of timeframe and accumulation of atmospheric carbon into solid object should be target and rewarded in LCA modelling drop-in and alternative solutions for fossil based materials. The Carbon uptake in products is not direct carbon emission at end of life as the fossil free energy targets of the future are not directly supported in LCA when it is possible to consider incineration of material as energy source, as pseudo circular event. That causes distortion in the public debate on how the single use plastics are now handled and seen; “energy production as sustainable positive alternative", as timeframe in LCA for GWP models is 100 years and during next 30 years transition to fossil free energy should be achieved. (Carus, vom Berg, Scharf, Puente(2019))

6.3.2 Standardisation for EoL under construction

New definitions for materials are needed as standards are not able to cover all formations and new types of materials. Bio-based material as a part in a closed circular economy is a relatively new phenomena, leading standardisation behind from enabling the categorising of material types end life characteristics. What it the approved outcome and emissions from industrial composting if product is partially bio-based? How to separate the sustainability value if polymer is biodegradable but not bio-based? Common consumer can easily feel confused or mislead. Greenwashing is a non-favourable stigma for consumer product brand to have. The various biodegradability test method standards from ASTM and ISO are considering the biodegradability in different biological environments via measuring the degradation. However, these test methods have no pass / fail criteria, and so should not be used to claim biodegradability in any environment. Strict adherence to the test method's reporting. (Kabasci, 2013, 355)

Over the last years composters and environmental organizations have raised questions concerning the detection of biodegradable plastics in bio-waste and doubted their distinguishability from conventional plastics. Apart from the Seedling logo, which makes compostable plastics well recognizable, common NIR detection systems found at recycling plants are able to distinguish between different types of plastics, including compostable ones. The tests described in the EN 13432 are, for practical reasons, carried out at laboratory level and confirm biodegradation and disintegration under the defined composting conditions. Despite the fact that the actual conditions found in composting plants can differ from the laboratory, EN 13432 has proven to be sufficient in covering composting practices in reality over the last 13 years. (European Bioplastics, 2015)

Standard with Pass /fail criteria:

EN 14995:2006 Plastics. Evaluation of compostability. Test scheme and specifications, SFS EN 13432 Packaging. Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging.

EN 14995 standard criteria for the plastic material the percentage of biodegradation shall be at least 90 % in total or 90 % of the maximum degradation of a suitable reference substance after a plateau has been reached for both plastic material and reference substance. Plastic materials shall contain a minimum of 50 % of volatile solids which exclude largely inert materials: *leading to situation where No more than 50% mineral filling is possible.* "Given that biodegradability shall be determined for each plastic material/organic component, significant shall mean any organic constituent present in more than 1 % of dry weight of that material. And the total proportion of organic constituents, not tested on biodegradability, shall not exceed 5 %." - No Natural ingredients without testing individually. Each constituent > 1% must comply with the requirements.
Only if the studied *packaging* material is of natural origin and chemically unmodified, the testing is not required, still if the material is combination of similar materials mixed to another type, the material must be studied by each component. This information combined to disintegration criteria limit: the fraction with size> 2 mm higher than 10%, can cause issues in the material development, as long fibre reinforced composites can have high mineral content and the testing of individual components is time and resource consuming step for achieving certification for material biodegradability. Biodegradable plastics are categorised as packaging. At the same time EU is banning and /or reducing single use plastics.

6.3.3 Biomass from second generation sources

Availability of Second Generation Feedstock. If there is still issues against land use for cultivating feedstock directly for polymer material production, there are alternative option that should be considered and further developed.

Largest group of potential secondary feedstock for conversion to sugars is ligno cellulosics. Common ligno cellulosics include: Woody Biomass, Forest residues, Wood waste, Non-Woody Biomass, Agricultural residues; Straws (wheat, barley, rice), Bagasse (sugarcane, sweet sorghum), Stover (corn, milo) Algae, Organic Waste, Animal waste, Sewage sludge. Lunt representing Agricultural utilization research organization (2014) stated: “Today, demand for such feedstock is driven primarily by the search for alternative energy sources to petroleum. The bioplastics industry is a very small proportion (less than 1% of all plastics). The global plastics industry is estimated at around 230 million tons but is projected to experience significant growth over the next 5-10 years. To produce bioplastics from these feedstock we are primarily looking at conversion to sugars which can then be further utilized to produce the basic building blocks for bioplastics. For bioplastics use we do not need a large proportion of the global biomass availability. However, sugars for bioplastics will probably compete with sugars for fuel or be a more value added side stream from a biorefinery or co-located biomass to sugar producing facility. “(Lunt, 2014, 102)

Old waste = new feedstock?

Recent example comes from a local residue problem: Local old cellulose fibre mill has left waste fibres that were too short for further processing by dumping them into a lake, where during decades the short cellulose fibre mass has built up to be millions of cubic square meters of wet slurry mass, known as zero-fibre that could be used to produce polymers. (Ministry of Agriculture and forestry, 2019)

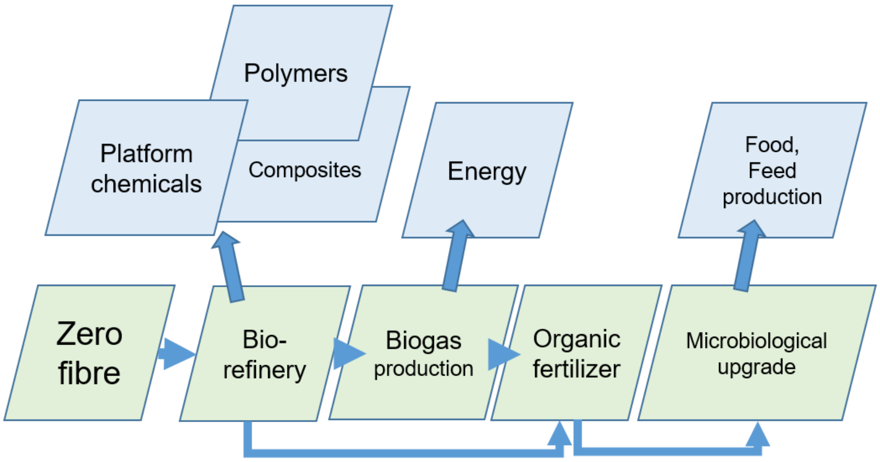


FIGURE 32 Zero fibre example (adapted from Hakalehto, 2018)

Biorefinery technology and business area development is the bottleneck or more likely the closed cap waiting to be opened for enabling the utilization of "useless" biomasses waiting around to be utilized in material production.

6.3.4 Missing technologies

Recycling of complex bio-based composite products

"A large amount of plastics waste is currently incinerated for energy production. According to Hopewell et al., 2009, the recycling of plastics saves more energy than is produced by incineration. The study by Morris, 2005, compared the recycling of municipal waste with landfilling and incineration. According to the LCA model, the recycling caused lower environmental impacts than solid waste disposal or combustion, even if energy is recovered from landfill gases and combustion. Environmental impacts were evaluated, among other things, with energy usage, GHG emissions, eutrophication and acidification. All indicators suggested that the environmental burden of recycling is lower than that of landfilling or incineration. In the same study proposes that the economic value for the pollution prevention caused by recycling outweighs the costs of recycling."(Karvinen, 2015, 31) Polymer recycling requires significantly lower quantity of energy than extraction and polymerization of novel material.

How to recycle if the cycle of materials back to origins is non-existent? Building scenario analysis based on "what if the EoL option is composting" when in actual world there is no collection streams for materials enabling industrial composting of bio-based durable products. The polymer recycling in Finland is focused on packaging materials, leaving out all other plastic materials. The modularity in product design enabling reassembly and fractionizing materials at EoL is crucial to have them circulating back to re-polymerization or mechanical recycling facilities, whose status are also non-existent.

6.4 LCA tool competence

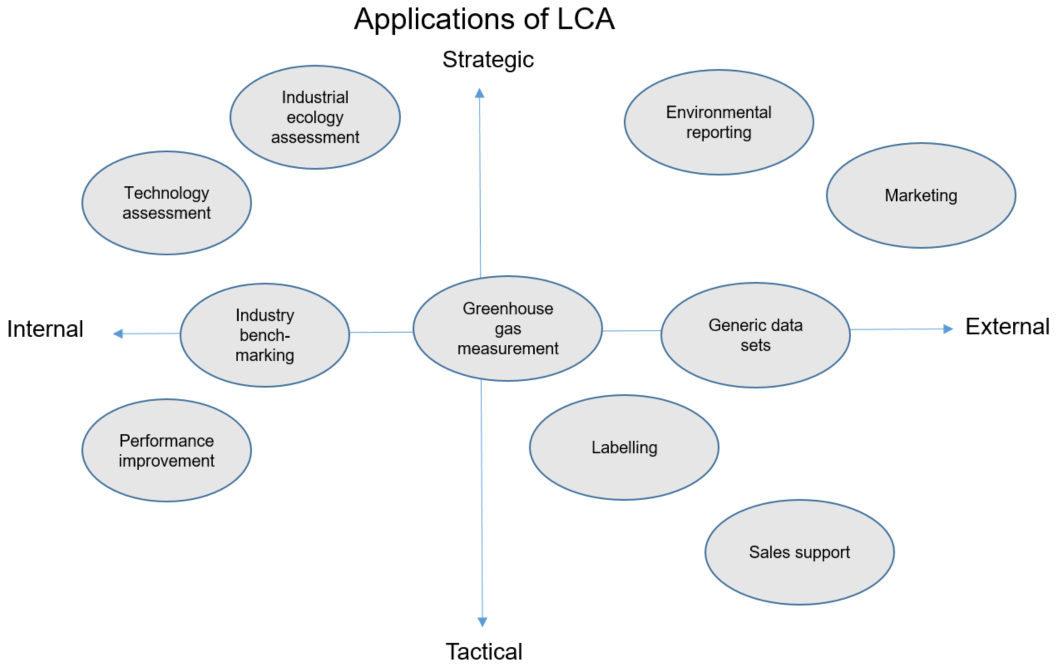


FIGURE 33 Applications of LCA, adapted from Khali (2015)

During LCA implementation the various dimensions of sustainability evaluation were met. Those dimension are presented in figure 33 adapted from Khali (2015). Sales support and marketing is important external action to help the market entry for novel materials. LCA derived information is needed to have more credible data on impacts of choosing between materials for products. Performance improvement and industry benchmarking is recognised important during product development. Applications of LCA are also overlapping and supporting each other.

Transparency and IPR

Contradiction between company trade secrets and transparency in environmental performance communication is appearing when you need to declare your products being environmentally friendly without opening out the whole recipe of your product compound. Understanding the limited nature of LCA when raw material system is investigated in manner that considerers manufactured raw material conversion being part of the use phase, the interfaces between product category rules and formation of the final product are assumed or out-scoped. The final product in nature during its formation and second use phase, the actual lifespan after product is converted to the final product has a significant meaning when sustainability of the product is designed. The LCA for raw material is simultaneously an attributional and a consequential product system. When product in this LCA leaves to factory gates and enters use phase, the tracing of the consequences forward in time has a significance in the circular nature of the product. The mutual goal of raw material producer (ABM) and user (customer manufacturing plastic items) is important to be acknowledged. Figure 34 below illustrates this and challenges ahead: missing technologies enabling the full circularity of bio-based polymer composites.

The used ThinkStep Bioplastic tool in envision contains selection of conversion parameters in scenarios building that enable evaluation of the conversion method; Injection moulding, extrusion, thermoforming, film making, blow moulding, foaming. This feature has appeared valuable function in cases where customer planning to replace materials with bio-based alternatives or during design of a new product consisting on multiple parts assembled that is partially replaced with bio-based materials. In this LCA study the conversion step was allocated outside system boundaries, the missing cap can be filled together with client, to build a complete model for the product lifecycle, including energy consuming conversion phase(s).The shadow calculation function in the tool enabled streamlined LCA with fixed dataset values. When all the input parameters are shared together with the out coming impact results, the transparency of the tool is plausible.
With the tool used it’s possible to conduct comparison for materials, to provide the proof of sustainability by comparing to alternatives manufactured outside ABM without comparing separate LCAs with unequal product category rules and system boundaries. Material comparison in modular LCA in what if –scenarios using both primary data and secondary data is not recommended. Used datasets are from database, and can be considered as literature or secondary data: Industry average compared. One material dataset is recognized as primary data: PLA dataset based on information collected from one manufacturer. PBS data is fully modelled, secondary data.

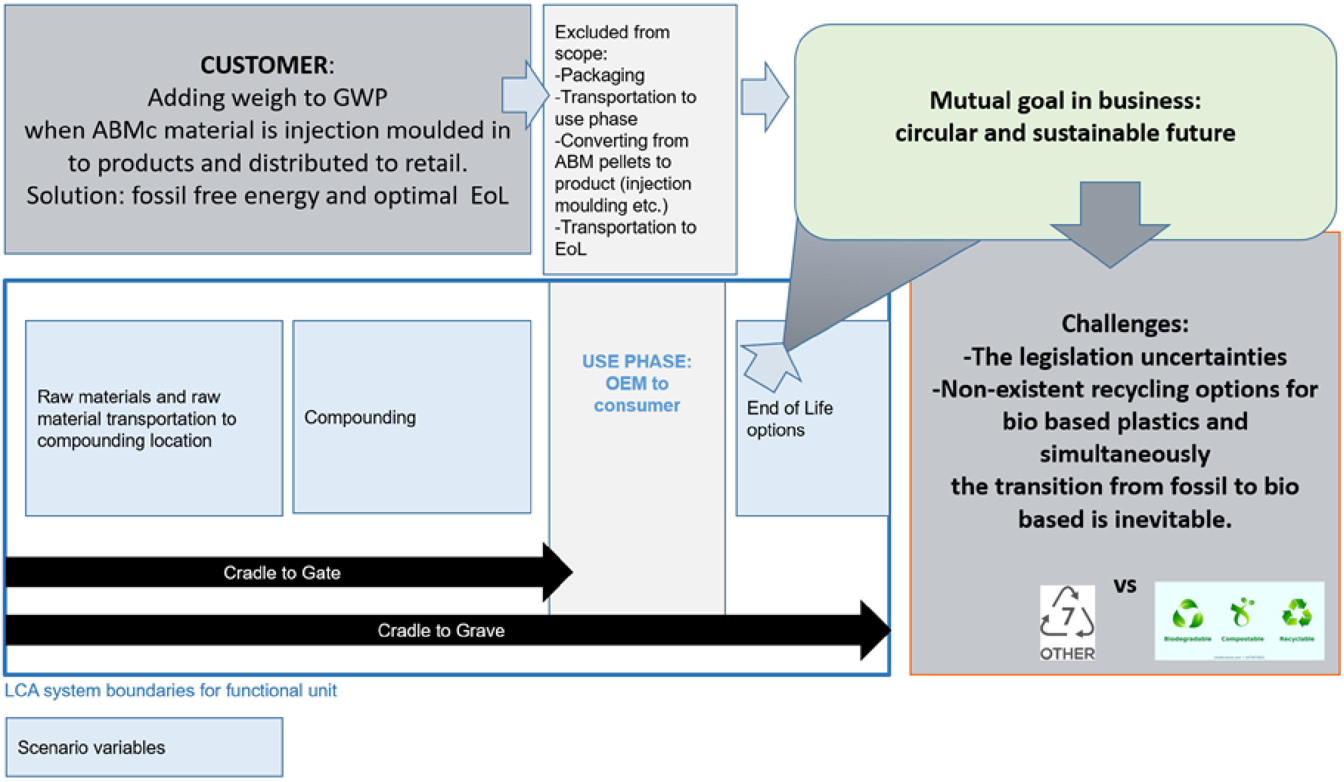


FIGURE 34 Scoping LCA with mutual goals in B2B, picture by Author

The grey and green areas in figure 34 above are also the recognised targets for sustainability development. “What if “-scenarios for EoL options are not existing as industrial applications in use. The industrial composting contributes to the GWP and simultaneously the organic recycling can be considered as contribution to greenhouse gas savings through replacement of mineral fertilizers and carbon sequestration in soil.

Towards final implementation of LCA to the product design

During this LCA implementation project the need to have clearly structured discussion is more pronounced. The awareness of need for transparency has grown. For the ABM company; proving our sustainability and stakeholders; support customers to develop more sustainable material selection in their components and products. To communicate the modular “what if material” –scenario based LCA results to external stakeholders according ISO standard, the modularity aspect: ISO Type III eco declarations” LCA-based data for materials, parts and other inputs that are used in the manufacture or assembly of other products may be used to contribute to Type III environmental declarations for those other products. Under such circumstances, the LCA-based data for the materials, parts and other inputs shall be referred to as *information modules* and may represent the whole or a portion of the life cycle for those materials or parts. Information modules may be used to develop a Type III environmental declaration or may be combined to develop a Type III environmental declaration for a product, provided that the information modules are adjusted in accordance with the PCR (Product category rules) for the product category. If the information modules combined to develop a Type III environmental declaration for a product do not cover all stages of the life cycle of the product, then any omissions shall be stated and justified in the PCR document. An information module may be, but does not have to be, a Type III environmental declaration."(ISO.org)

Type III environmental declarations are intended to allow a purchaser or user to compare the environmental performance of products on a life cycle basis. Therefore comparability of Type III environmental declarations is critical. The information provided for this comparison shall be transparent in order to allow the purchaser or user to understand the limitations of comparability inherent in the Type III environmental declarations. *Type III environmental declarations not based on an LCA covering all life cycle stages, or when based on different PCR, are examples of declarations that have limited comparability and that must be stated clearly. (ISO org)*

6.4.1 Suggestions for future

LCA functions well supporting product development for raw material choice impact evaluation. The sustainability or environmental impact should be considered as one of the many characterisation metrics for a product as important as Mechanical properties, durability under environmental stress, meeting application acceptance criteria, cost of the material production, and sustainably compared to earlier version of the same product or compared to the alternative fossil based material. After implementing the LCA sustainability advantage of bio based alternatives can be detected and acknowledged. The limitations come from data background should be strongly recognised and further developed when more data is available. The difference in data back ground: Primary vs. secondary data, industry average vs. primary data from one provider, challenges the fairness in comparability of the materials in scenarios, but must be accepted as best alternative available at the time being.

Additional value through biodegradability

The additional value through biodegradation during products EoL, comes also in situations when plastic items are disposed in controlled environment or are degrading in application and scenarios where ending up in natural environment in absolute non avoidable. Can functional additives in plastics end up in industrial composting act as nutritional agents when composite is turned into soil? The methane emission from anaerobic composting captured for energy or feedstock use has potential that should be investigated technology vice. Returning and recycling of electronic parts, portable electronics with short life spans/ module changes could be studied if the urban mining and separation of the valuable metals from the plastic frame with the help of biodegradation / controlled Glass fibre eroding could be studied.

6.4.2 Primary energy demand

Energy used in production is a significant elemental flow. The sources for energy production being fossil based are strongly impacting to the GWP from energy production. As seen in dataset visualising below (Fig. 34), the transition away from fossil fuels is shown in source datasets.

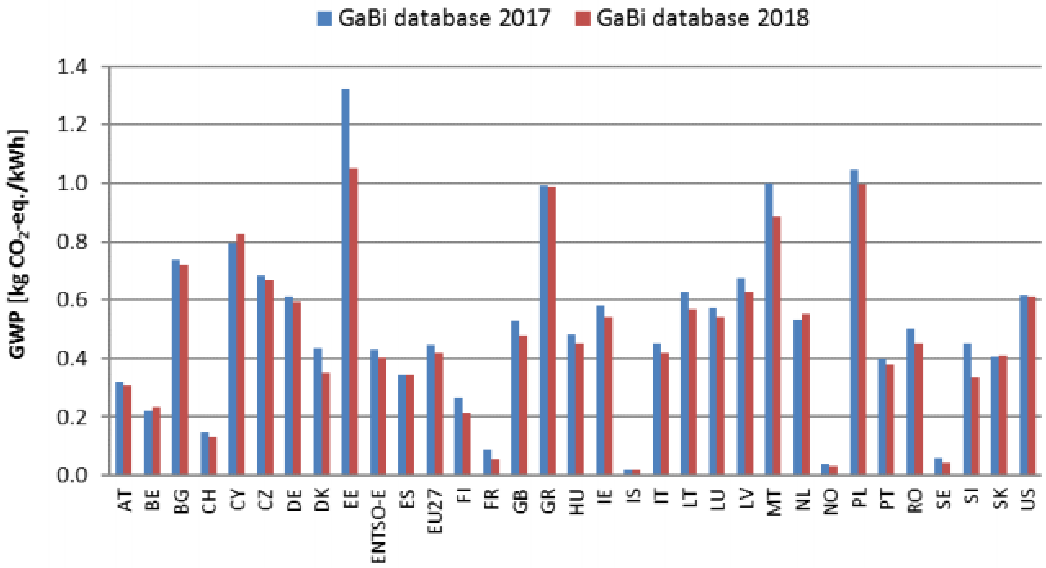


FIGURE 35 Absolute GWP of electricity grid mix datasets in GaBi Professional 2017 & 2018 Edition

From figure 35 is seen the GWP for electricity grid mixes. The energy carrier mix for electricity generation is a combination from share of following sources: Nuclear, Lignite, hard coal, coal gasses, Natural gas, Heavy fuel oil, biomass (solid), Biogas, waste, hydro, wind, photovoltaic, Solar thermal, geothermal and peat. According to Gabi update information for Finland (FI) the GWP per supplied unit of electricity in Finland has decreased by 20 % from 265 g CO2-eq./kWh in 2013 to 212 g CO2-eq./kWh in 2014. The decrease is related to higher electricity output from hydro power plants, as well as higher production from wind power plants and imports from Sweden. In countries like China, India, Brazil, Indonesia or Turkey, the electricity production has increased by 4 to 8 %. In China, in contrast to previous years, the incremental electricity was not covered by electricity from coal. Around two third of the 220 TWh of the incremental electricity generation (5,679 TWh total gross production) was generated by hydropower. In 2014, around 25 GW of new installed hydropower plants have been connected to the grid. Thereof, with 13.8 GW installed capacity, the hydro power plant Xiluodu, the third largest hydropower plant in the world. The remaining incremental electricity in China was predominantly generated from wind, photovoltaic, nuclear and natural gas. In India, Indonesia and Turkey, the incremental electricity was produced from fossil fuels, mostly coal or natural gas. In Brazil, 70 % of the incremental electricity was produced from fossil fuels, the remaining from biomass and wind. (GaBi Databases February 2018 2018 Edition Upgrades & improvements)

According Xin Li et al. (2017, 2779–2785), in order to maintain the 2°C climate change target, global carbon intensity of electricity generation needs to achieve a short-term target of 600 g/kWh by 2020. This target is important for China, which has been the largest consumer and producer of electricity since 2011. China has set ambitious targets to reduce its electricity carbon intensity in the 13th five-year plan. For a large country as China, the outcomes of these policies rely on the implementation strategies and effectiveness of each province. In Xin Li’s study, estimated carbon intensities of power generation in China’s provinces by 2020 was reported. Results show that despite progress in renewable energy growth most provinces are expected to have carbon intensities well above 600 g/kWh by 2020. Estimation on the carbon intensity of power generation in China’s provinces by 2020, the carbon intensities in most provinces are over 700 g/kWh by 2020. Very few provinces such as Hubei, Qinghai, Sichuan and Yunnan can fulfil the 600 g/kWh target by 2020. These provinces are mostly dependent on hydropower. For other provinces, Gansu is only able to fulfil the target with higher operating hours and more renewable energy capacities installed. At national level, carbon intensities vary between 861 and 821 g/kWh. (Xin L., 2017) Selecting fossil neutral energy has high significance in the environmental impact of the product life span when compounding ABM products and converting ABM products to plastic items is conducted.

6.5 Conclusions

LCA case during the implementation revealed that the manufacturing location and transportation distances effect on the total composite GWP is still being left behind by the material selection impact. When carbon uptake is credited the GWP of products was significantly lower compared to fossil based PP and ABS. For example in scenario no.4 PLA glass fibre composite was investigated from cradle-to-gate: Polymer share of the GWP was 67%, Glass fibre 19%, Transportation (global) share was 11% and selected location production location electricity grid weigh was 4% of the total GWP of the product. Carbon uptake during raw material feedstock production constitutes a -56% share of the GWP giving the bio-based materials an environmental advantage. PLA data is based on the industry metrics by NatureWorks using corn as feedstock in polymer production. In the EoL scenarios incineration was more a favourable option compared to composting. That is due to the dataset's anaerobic emissions of methane, and when the consumed energy throughout the process is taken into consideration. Fossil based products produce significant burden when EoL is conducted by incineration. LCA tool performance was found suitable in building multiple “what if-scenarios” and implementation of the LCA turned out to be valuable as stakeholders and customers are eager for information about ABM products sustainability. After conducting LCA with addition of transportation and processing impacts and comparing EoL options, materials studied were found to be a sustainable alternative in attributional consideration. Risk assessment emphasized the challenges in the consequential viewpoint when product system is composed of the activities that are expected to change disposing of a product, tracing the consequences forward in time as the future circularity of the materials are still under the development as projects are ongoing in the industry and in the academia to solve bio-based material circulation and the emergence of best practices to recycle bio-based plastics is under way.

The challenge and transparency of data comparability is been accepted as increased understanding of how easily claims can become misleading when comparing overly different industrial ecosystems and products. Product functionality as part of the life cycle assessment has been acknowledged. Previously the emphasis has been on the environmental burden of product production by raw material impacts. From now on also functionality, durability and recyclability have been highlighted and deepened as part of the R&D strategy.
Sales and marketing and product development management enthusiasm has grown with the understanding of life cycle analysis. New development projects have started that form into action through added LCA thinking and processes.
Aim to design products with the biodegradation as function more specific and to support future cleantech and circular economy processes aligning. More focus has emerged on when and how and why a plastic product should be composted.

The possibility to combine LCA system thinking in the product development phase has proved to be more valuable than expected. Modular material selection scenarios for raw materials, as information offered to stakeholders has met the needs and requests. After this project LCA mindset and communication has been also implemented into the company culture. The next steps should include conducting more specific LCAs for EPDs and gaining more datasets for future project scenarios. The collection of own specific elemental flows and metrics to meet and complete with data from LCA consultants, follows. Material performance during product life span and in EoL is been reckoned as important metric in sustainability and circularity dimension.

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APPENDICES

Appendix 1. Input tables

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
1.1. Functional Units =1																							
Product quantity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Quantity of product(s) to be considered
1.2 System boundary																							
Cradle to	Gate	Gate	Gate	Gate	Gate	Gate	Gate	Gate	Gate	Gate	Grave	Grave	Grave	Grave	Grave	Grave	Grave	Grave	Grave	Grave	Grave	Grave	System boundary. Cradle to Gate or Cradle to grave
Cut-off or avoided burden	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off	Avoided burden	Avoided burden	Avoided burden	Avoided burden	Avoided burden	Avoided burden	Avoided burden	System boundary. Cut-off = no credits and no burden for recycled input. Avoided burden = credits and burden on recycled input
2. Product related Information																							
2.1. Composition	scenarios																						
2.1.1. Product Part 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Weight (per Functional Unit)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	[g] Weight of Product Part 1 per Functional Unit
Polymer	PA 10.10	PP	ABS	PLA	PBS	PA 10.10	PP	ABS	PLA	PBS	PA 10.10	PP	ABS	PLA	PBS	PA 10.10	PP	ABS	PLA	PBS	PLA	PBS	Choose the polymer
Share in Compound	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	[%] Share of Polymer
Non-polymer material 1	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	GF	Choose non-polymer material 1
Share in Compound	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	[%] Share of non-polymer material 1

3. Polymer Processing																							
3.1. Product Part 1	scenarios																						
3.1.1. Compounding	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Location	CH	CH	CH	CH	CH	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	EU28	[] National grid mix selecter for electricity used in the compounding process
Compounding process																							
Compounding Process Type	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Gen.	Please chose weather you would like to use the generic process values or use your own input values
User specific compounding																							
Electricity consumption	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	1,73	[MJ] Electricity consumed per 1 kg of granulate input
Compressed Air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[Nm³] Amount of compressed air used per 1 kg of granulate input
Lubricating_Oil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[kg] Amount of lubricating oil used per 1 kg of granulate input
Material loss	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	0,005	[kg] Amount of material loss per 1 kg of compound
Water used	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	[kg] Amount of water used per 1 kg granulate input
Waste Water	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	[kg] Waste water per 1 kg granulate input
Transportation to Compounding	scenarios																						
Polymer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Truck	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	[km] Distance truck transport (default = 100 km)
Non-polymer material 1																							
Ship	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[km] Distance seaborne transport start - destination (default=100km)
Rail	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[km] distance start - end, default = 100 km
Truck	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	[km] distance start - end, default = 100 km
4. Use Phase	scenarios																						
4.1. Product Transport to Customer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Ship	**21000**	**21000**	**21000**	**21000**	**21000**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[km] Distance seaborne transport (default = 0 km)
Truck	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	[km] Distance truck transport (default = 100 km)
5. End Of Life Treatment	scenarios																						
5.1. Product Transport to EoL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Truck	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	500	500	500	500	500	500	500	500	500	500	500	500	[km] Distance truck transport (default = 100 km)
5.2. EoL Scenarios	scenarios																						
5.2.1. Product Part 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Composting	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0	0	0	0	0	0	0	0	0	0	**100**	**100**	[%] Waste to Composting in End of Life Treatment
Incineration	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	**100**	**100**	**100**	**100**	**100**	**50**	**50**	**50**	**50**	**50**	0	0	[%] Waste to Incineration in End of Life Treatment
Landfill	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0	0	0	0	0	0	0	0	0	0	0	0	[%] Waste to Landfill in End of Life Treatment
Recycling	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0	0	0	0	0	**50**	**50**	**50**	**50**	**50**	0	0	[%] Waste to Recycling in End of Life Treatment

Appendix 2. Selected Indicator outputs

Scenario	11	12	13	14	15	16	17	18	19	20	21	22
	EoL:1 Incineration					EoL:2: recycling					EoL:3 Composting	
EF 2.0 Climate Change (fossil) [kg CO2 eq.] Carbon uptake credited	1,36E+01	3,13E+00	3,38E+00	4,14E+00	-3,50E-01	6,07E+00	2,77E+00	2,96E+00	1,76E+00	2,17E+00	1,70E+00	4,20E-01
EF 2.0 Climate Change (fossil) [kg CO2 eq.]	8,67E+00	2,18E+00	3,12E+00	2,61E+00	2,42E+00	8,67E+00	2,93E+00	3,12E+00	2,61E+00	2,42E+00	2,69E+00	2,58E+00
EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	6,35E-02	5,78E-03	4,70E-03	4,67E-03	1,44E-02	3,37E-02	4,75E-03	2,86E-03	4,21E-03	1,35E-03	2,32E-03	1,21E-02
EF 2.0 Water scarcity [m³ world equiv.]	1,59E+02	8,27E-01	1,05E+00	1,40E+00	5,28E-01	8,21E+01	4,53E-01	5,60E-01	7,94E-01	2,95E-01	1,24E+00	1,46E-01
EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	1,01E-01	1,04E-02	1,36E-02	1,25E-02	1,15E-02	5,37E-02	7,81E-03	8,48E-03	8,80E-03	4,32E-03	1,20E-02	9,85E-03
EF 2.0 Eutrophication freshwater [kg P eq.]	2,41E-03	4,94E-06	1,18E-05	1,41E-05	1,27E-04	1,24E-03	4,01E-06	7,51E-06	9,35E-06	-1,77E-05	1,28E-05	1,27E-04
EF 2.0 Eutrophication marine [kg N eq.]	3,64E-02	2,21E-03	3,15E-03	3,23E-03	4,70E-03	1,90E-02	1,25E-03	1,78E-03	2,00E-03	3,27E-04	3,08E-03	4,01E-03
EF 2.0 Eutrophication terrestrial [Mole of N eq.]	3,71E-01	2,46E-02	3,36E-02	3,20E-02	3,49E-02	1,93E-01	1,37E-02	1,90E-02	2,01E-02	6,73E-03	3,02E-02	2,74E-02
EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	3,00E-02	7,42E-03	9,46E-03	8,37E-03	6,66E-03	1,61E-02	4,30E-03	5,38E-03	5,33E-03	2,17E-03	8,01E-03	4,87E-03
EF 2.0 Resource use, energy carriers [MJ]	1,16E+02	7,56E+01	8,35E+01	4,97E+01	4,65E+01	6,44E+01	4,33E+01	4,52E+01	3,39E+01	1,01E+01	4,15E+01	3,77E+01
EF 2.0 Resource use, mineral and metals [kg Sb eq.]	1,23E-06	5,19E-07	6,84E-07	8,77E-07	8,25E-07	7,27E-07	3,52E-07	4,16E-07	5,92E-07	1,67E-07	7,12E-07	6,57E-07

	Scenario 11	**Scenario 12**	**Scenario 13**	**Scenario 14**	**Scenario 15**	**Scenario 16**	**Scenario 17**	**Scenario 18**	**Scenario 19**	**Scenario 20**	**Scenario 21**	**Scenario 22**
Primary energy from non renewable resources (net cal. value) [MJ]	1,16E+02	7,56E+01	8,35E+01	4,97E+01	4,65E+01	6,44E+01	4,33E+01	4,52E+01	3,39E+01	1,01E+01	4,15E+01	3,77E+01
Primary energy from renewable resources (net cal. value) [MJ]	1,30E+02	1,04E+01	1,03E+01	2,83E+01	3,26E+01	6,91E+01	5,97E+00	6,85E+00	1,80E+01	1,87E+00	2,24E+01	2,67E+01
Blue water consumption [kg]	5,45E+03	2,82E+01	3,25E+01	4,08E+01	3,15E+01	2,81E+03	1,39E+01	1,96E+01	2,61E+01	1,13E+01	3,06E+01	1,62E+01
Carbon uptake [kg CO2 eq.]	-4,97E+00	-9,52E-01	-2,61E-01	-1,53E+00	-2,77E+00	-2,60E+00	-1,60E-01	-1,54E-01	-8,46E-01	-2,47E-01	-9,88E-01	-2,16E+00

GWP [kg CO2 eq.] / 1 FU

Total	8,67E+00	2,18E+00	3,12E+00	2,61E+00	2,42E+00	8,67E+00	2,93E+00	3,12E+00	2,61E+00	2,42E+00	2,69E+00	2,58E+00
Raw materials, plastic	7,87E+00	1,38E+00	2,32E+00	1,82E+00	1,63E+00	7,87E+00	1,38E+00	2,32E+00	1,82E+00	1,63E+00	1,85E+00	1,66E+00
Raw material, non-plastic	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,78E-01	4,86E-01	4,86E-01
Compounding	2,17E-01	2,21E-01	2,17E-01	2,09E-01	2,09E-01	2,17E-01	2,21E-01	2,17E-01	2,09E-01	2,09E-01	2,14E-01	2,15E-01
Transport	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,03E-01	1,35E-01	1,35E-01
EoL	1,60E+00	2,24E+00	1,48E+00	1,80E-02	6,78E-02	8,00E-01	1,10E+00	7,41E-01	9,02E-03	3,39E-02	3,27E-03	8,40E-02
EoL, credits beoynd system, recycling						-4,04E+00	-1,08E+00	-1,49E+00	-9,04E-01	-2,12E+00		

Primary Energy Demand Details	**Scenario 11**	**Scenario 12**	**Scenario 13**	**Scenario 14**	**Scenario 15**	**Scenario 16**	**Scenario 17**	**Scenario 18**	**Scenario 19**	**Scenario 20**	**Scenario 21**	**Scenario 22**
Total	2,30E+02	7,01E+01	7,78E+01	6,20E+01	6,32E+01	1,17E+02	4,93E+01	3,61E+01	3,60E+01	-4,07E+00	6,32E+01	6,38E+01
Raw materials, plastic	2,13E+02	5,32E+01	6,14E+01	4,59E+01	4,63E+01	2,13E+02	5,32E+01	6,14E+01	4,59E+01	4,63E+01	4,66E+01	4,71E+01
Raw material, non-plastic	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,16E+00	9,31E+00	9,31E+00
Compounding	5,19E+00	5,19E+00	5,19E+00	5,19E+00	5,19E+00	5,19E+00	5,23E+00	5,19E+00	5,19E+00	5,19E+00	5,33E+00	5,33E+00
Transport	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,46E+00	1,91E+00	1,91E+00
EoL	8,57E-01	1,04E+00	5,73E-01	3,22E-01	1,04E+00	4,28E-01	1,62E-01	2,86E-01	1,61E-01	5,20E-01	8,15E-02	1,82E-01
EoL, credits beoynd system, recycling						-1,12E+02	-3,85E+01	-4,14E+01	-2,59E+01	-6,67E+01		

Blue Water Consumption Details	**Scenario 11**	**Scenario 12**	**Scenario 13**	**Scenario 14**	**Scenario 15**	**Scenario 16**	**Scenario 17**	**Scenario 18**	**Scenario 19**	**Scenario 20**	**Scenario 21**	**Scenario 22**
Total [kg] / 1kg products	5,44E+03	2,04E+01	2,47E+01	3,30E+01	2,37E+01	2,80E+03	1,39E+01	1,18E+01	1,83E+01	3,58E+00	3,05E+01	1,61E+01
Raw materials, plastic	5,43E+03	6,72E+00	1,60E+01	2,57E+01	1,14E+01	5,43E+03	6,72E+00	1,60E+01	2,57E+01	1,14E+01	2,61E+01	1,16E+01
Raw material, non-plastic	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,47E+00	2,51E+00	2,51E+00
3. Compounding	1,78E+00	1,78E+00	1,78E+00	1,77E+00	1,77E+00	1,78E+00	1,79E+00	1,78E+00	1,77E+00	1,77E+00	1,81E+00	1,81E+00
5. Transport	7,90E-03	7,90E-03	7,90E-03	7,90E-03	7,90E-03	7,90E-03	7,90E-03	7,90E-03	7,90E-03	7,90E-03	1,03E-02	1,03E-02
7. EoL	3,95E+00	9,44E+00	4,46E+00	3,08E+00	8,06E+00	1,98E+00	2,37E+00	2,23E+00	1,54E+00	4,03E+00	2,76E-02	1,85E-01
7. EoL, credits beyond system , recycling						-2,64E+03	-6,48E+00	-1,07E+01	-1,32E+01	-1,61E+01		

Appendix 3. Indicator details

EF 2.0 Photochemical ozone formation - human health (kg NMVOC eq.) Photochemical ozone creation potential (POCP)

Photochemical ozone formation, Van Zelm et al 2008 as applied in ReCiPe2008 Model: Photochemical ozone creation potential (POCP) is calculated as the emission-weighted combination of the CF of Non- methane VOCs (generic) and the CF of CH_4. Emission data (Vestreng et al. 2006) refer to emissions occurring in Europe (continent) in 2004, i.e. 14.0 Mt-NMVOC and 47.8 Mt-CH_4. (Fazio et al, JCR, 2018)

EF 2.0 Resource use, Resource depletion energy carriers (MJ)

As suggested by van Oers et al. (2002), and implemented in CML method since 2009 version, a separate impact category for fossil fuels is defined, based on their similar function as energy carriers. CFs for fossil fuels are expressed as MJ/MJ, i.e. the CF is equal to 1 for all fossil resources. (Fazio et al, JCR, 2018)

EF 2.0 Resource use, mineral and metals (kg Sb eq.)

The overall approach (abiotic resource depletion – ADP, Guinée et al., 2002 and Van Oers et al., 2002) CFs are given as Abiotic Depletion Potential (ADP), quantified in kg of antimony-equivalent (Sb-eq) per kg extraction. The CFs recommended are the ones in the CML method, version 4.8 (2016)
(Fazio et al, JCR, 2018)

Appendix 4. Transportation data details

By Truck

For CO2 emissions, the calculations are based on the emission factors according to where a constant relation of 3.175 kgCO2/kg fuel for fuel consumption is assumed. A medium density of 0.832 kg/l (diesel), results in 2.642 kgCO2/l diesel, The emission factor for laughing gas (nitrous oxide, N2O) is assumed to be constant for each emission class and each category of driving road. The emission factor for ammonia (NH3) is set as constant throughout all categories.

The following systems and emissions are excluded:

Vehicle production ,Vehicle disposal , Infrastructure (road) ,Noise ,Diurnal losses and fuelling losses, Evaporation losses due to Hot-Soak-Emission ,Oil consumption, Cold-Start Emissions, Emissions from air conditioner (relevance < 1%), Tire and brake abrasion

(Kupfer, Baitz et al 2019, GaBi, 110-111)

By Shipping

Gabi dataset Inputs: Fuel and cargo, Outputs: Cargo and combustion emissions (carbon dioxide, carbon monoxide, methane, nitrogen oxides, nitrous oxide, NMVOC, particulate matter PM 2.5, sulphur dioxide). Vessel production, end-of-life treatment of the vessel and the fuel supply chain (emissions of exploration, refinery and transportation) are not included in the dataset. The datasets are mainly based on literature data from the International Maritime Organization, technical information, emission data from the European Energy Agency and the Intergovernmental Panel on Climate Change, IPCC.

(Kupfer, Baitz et al 2019, GaBi, 114)

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