Product Environmental Footprint (PEF) of Compound Feed with Organic Grass Protein Concentrate – A preliminary investigation

Version 1.2

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Contents

Acronyms

AF	Allocation Factor
AR	Allocation Ratio
CF	Characterization Factor
DNM	Data Needs Matrix
DQR	Data Quality Rating
EA	Economic Allocation
EC	European Commission
EF	Environmental Footprint
EI	Environmental Impact
EoL	End-of-Life
FU	Functional Unit
GR	Geographical Representativeness
GFLI	Global Feed LCA Institute
GHG	Greenhouse Gas
GWP	Global Warming Potential
GPC	Grass Protein Concentrate
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardisation
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LT	Lifetime
NMVOC	Non-methane volatile compounds
P	Precision
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
RF	Reference Flow
RP	Representative Product
SB	System Boundary
SC	Steering Committee
SS	Supporting study
TeR	Technological Representativeness
TiR	Time Representativeness

1. Summary

The goal of this study was to implement a product environmental footprint study of compound feed production with organic clover grass protein concentrate under the auspices of the Grass-prof project, funded by the Green Development and Demonstration program of the Ministry for the Environment in Denmark (GUDP, Ministry of Food, Agriculture and Fisheries). This document, as an explorative study, provides detailed and comprehensive technical guidance on how to conduct the PEF study for a new and innovative compound feed supplemented with grass-based proteinaceous feed produced in Ausumgaard biorefinery in Denmark in a transparent way. This proteinaceous feed is called protein concentrate which is produced from organic clover grass (from now on will be referred to as grass protein concentrate, GPC) through a specific technology developed in Denmark and is implemented in the Ausumgaard biorefinery plant.

This PEF report is not fully PEF compliant for the following reasons, but it can be considered as a preliminary attempt to implement PEF study of compound feed with GPC to be used for a variety of purposes; (i) in-house management, (ii) process improvement, (iii) early guidance on EF of compound feed production with GPC, and (iv) EF of food-producing animals fed with GPC. More importantly, this document also summarizes the challenges and limitations of implementing the PEF study for such a new and innovative compound feed and feed ingredient. The technology, used for GPC, is still in development phase so that the production efficiency is not still reached at the most optimal and stable conditions. Moreover, the data used to implement this study could not fully the requirements of the PEF compliant studies. Furthermore, we have not done an external review by the time of writing this report.

The scope of this PEF study is compound feed formulations for egg-laying hens in which organic GPC is used as a substitute for soybean meal and the rest of formulation is accordingly changed. However, the scope can be further expanded to cover the production of all types of compound feed with GPC produced in Denmark or in other European countries, as well as PEF study of food-producing animals fed with such compound feeds. Hence, the scope of this study covers the activities take place in Ausumgaard farm from grass cultivation to GPC product, and the compound feed production process to the final product ready to be sold to the market.

A cradle to gate system boundary was opted for this PEF study (Figure 1) as instructed by PEFCR Feed for Food Producing Animals. This includes three main life cycle stages, i.e., clover-grass cultivation its processing to GPC, and processing of feed ingredients into compound feed as well as all relevant inbound and outbound transportation which need mandatory company specific data collection. The production of auxiliaries, capital goods, energy carriers, packaging materials, etc. are also included but they also need secondary data to link the activity data to the background systems where the energy carriers, chemicals, and materials are produced to fulfill the requirements of the PEF studies.

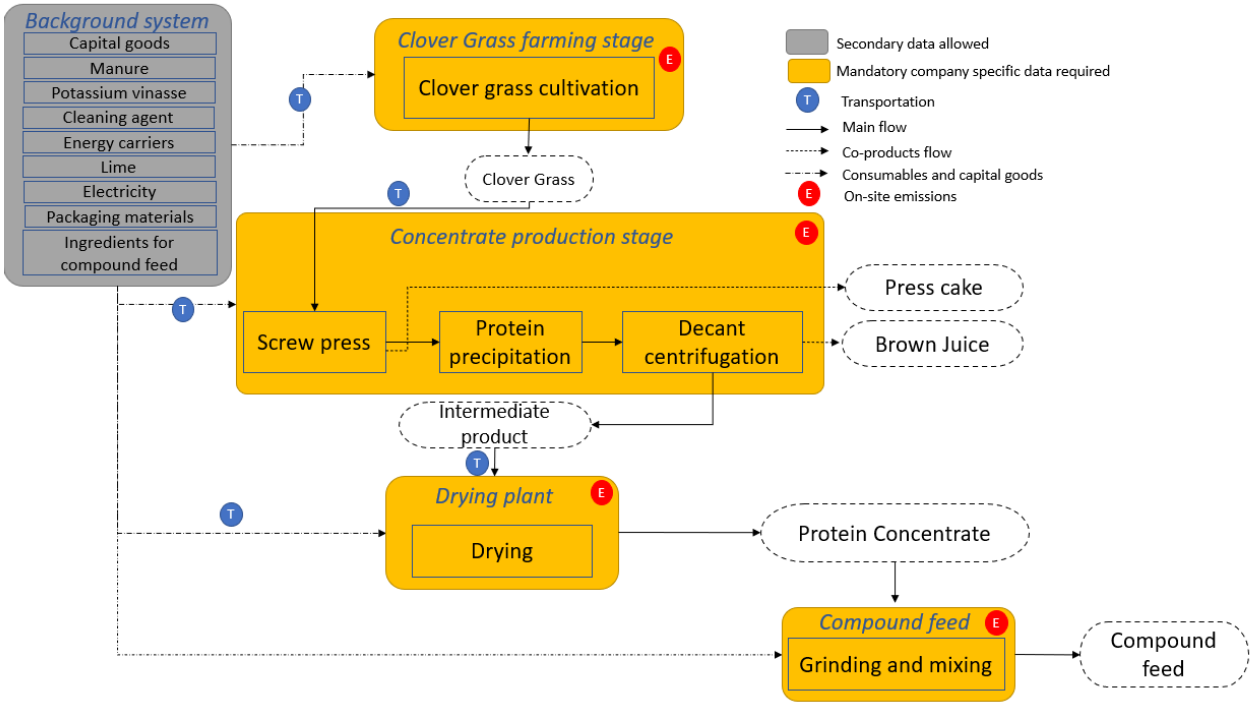

Figure 1. System boundary for compound feed production with GPC

In 12 out of 19 impact categories, including climate change, compound feed with GPC had lower environmental footprint. The EF of compound with organic GPC in the impact category of climate change is calculated at ~1085 kg $CO_{2,\ eq}$/t compound feed. The Climate change impact of compound feed with GPC was 12.7% lower than standard feed. The overall EF of compound feed with and without GPC can be seen in Table S1.

Other feed ingredients, including maize grain, wheat grain, and sunflower seed meal are the main contributors to the environmental footprint of compound feed with GPC. Regarding the environmental footprint of GPC, the cultivation stage had the highest contribution to the climate change impact category, i.e., 1.7 times as high as impacts of biorefinery stage. Direct emissions from the application of manure slurry and lime significantly dominated the EF of GPC production in this impact category.

This study suffers from some shortcomings and limitations. While GPC, produced in this project, is an organic product and the compound feed is made of organic ingredients, it was not possible to calculate the PEF of compound feed with organic ingredients. That is due to the fact that the current PEF secondary database lacks organic crops making us unable to perform the PEF of organic compound feed with and without GPC. Furthermore, the compound feed used here represents only an average formulation for egg-laying hens, hence, cannot be representative for other formulations and other animals.

Table S1. Environmental impacts of 1 tonne of compound feed for egg-laying hens with and without GPC.

Impact category	Reference unit	Standard compound feed	Compound feed with GPC	Difference
Acidification	mol H+ eq	11.86	12.03	1.39%
Climate change	kg CO2 eq	1222.32	1084.77	-12.68%
Climate change-Biogenic	kg CO2 eq	32.87	28.53	-15.19%
Climate change-Fossil	kg CO2 eq	1019.46	949.89	-7.32%
Climate change-Land use and land use change	kg CO2 eq	169.99	106.35	-59.84%
Ecotoxicity, freshwater	CTUe	29606.75	25552.58	-15.87%
Eutrophication marine	kg N eq	9.64	9.71	0.78%
Eutrophication, freshwater	kg P eq	0.20	0.20	0.26%
Eutrophication, terrestrial	mol N eq	47.77	47.62	-0.30%
Human toxicity, cancer	CTUh	3.92E-05	3.71E-05	-5.63%
Human toxicity, non-cancer	CTUh	1.32E-03	1.36E-03	3.04%
Ionising radiation, human health	kBq U-235 eq	71.97	63.29	-13.71%
Land use	Pt	231103.89	232284.99	0.51%
Ozone depletion	kg CFC11 eq	1.10E-05	3.19E-05	65.44%
Particulate Matter	disease inc.	1.15E-04	1.07E-04	-7.47%
Photochemical ozone formation - human health	kg NMVOC eq	3.35	3.02	-10.86%
Resource use, fossils	MJ	11000.51	9992.34	-10.09%
Resource use, minerals and metals	kg Sb eq	4.65E-03	4.05E-03	-14.88%
Water use	m3 depriv.	5419.83	6300.18	13.97%

2. Goal of the study

This document, as an explorative study, provides detailed and comprehensive technical details on how to conduct the PEF study for a compound feed which contains a new and innovative feed ingredient, i.e., organic grass-based proteinaceous feed produced in Ausumgaard biorefinery in Denmark. This proteinaceous feed is called protein concentrate which is produced from organic clover grass (from now on will be referred to as grass protein concentrate, GPC) through a specific technology developed in Denmark and is implemented in the Ausumgaard biorefinery plant.

The primary goal of this study was to implement a product environmental footprint study of compound feed with and without GPC under the auspices of the Grass-prof project, funded by The Green Development and Demonstration program of the Ministry for the Environment in Denmark (GUDP, Ministry of Food, Agriculture and Fisheries).

The intended audience is members of the Grass-prof project and also agricultural organizations, more specifically feed producing industry, that have shown an increased interest in products that perform well environmentally and can potentially replace imports of soybean. Thus, the goal was to work with the data generated by the project, by project members, and analyze the PEF of compound feed with and without GPC. The PEF of such a compound feed can later be used as input for the early assessment of PEF of feed producing animals fed with GPC or compound with GPC.

The methodology used herein is, as much as possible, in line with the PEFCR guidelines set by European Commission (European Commission. 2018), specific regulations of “PEFCR of feed for food producing animals” (European Commission. 2020). Furthermore, this was also supplemented with the LEAP guidelines (FAO 2014) when necessary as outlined in this report. However, any limitations that deviate this study from PEF regulations are mentioned in the methods and inventory section to let future improvements and make it PEF compliant.

This PEF report is not fully PEF compliant for the following reasons, but it can be considered as a preliminary attempt to implement PEF study of GPC to be used for a variety of purposes; (i) in-house management, (ii) process improvement, (iii) early guidance on EF of compound feed production with GPC, and (iv) EF of food-producing animals fed with GPC. More importantly, this document also summarizes the challenges and limitations of implementing the PEF study for such a new and innovative feed ingredient. This technology is still in development phase so that the production efficiency is not still reached at the most optimal and stable conditions. Moreover, the data used to implement this study could not fully the requirements of the PEF compliant studies. Furthermore, we have not done an external review by the time of writing this report.

This document is written according to the guidelines set by EU Joint Research Center including Product Environmental Footprint Category Rules Guidance (European Commission. 2018), Product Environmental Footprint Category Rules Feed for Food-Producing Animals (European Commission. 2020), and Suggestions for Updating the Product Environmental Footprint (PEF) Method (Zampori and Pant 2019). It should be highlighted that this document follows all the guidelines but where the requirements in this document are more specific for GPC than those of published guidelines, such specific requirements are specified and documented.

Terminology: shall, should and may

This report uses precise terminology to indicate the requirements, the recommendations and options that could be chosen when a PEF study is conducted.

● The term "shall" is used to indicate what is required in order for a PEF study to be in conformance with the PEFCR.

● The term "should" is used to indicate a recommendation rather than a requirement. Any deviation from a "should" requirement has to be justified when developing the PEF study and made transparent.

● The term "may" is used to indicate an option that is permissible. Whenever options are available, the PEF study shall include adequate argumentation to justify the chosen option.

3. Scope of the study

The scope of this PEF study is an average formulation for compound feed with and without GPC produced for egg-laying hens. The GPC used in the compound feed is the one which is produced in Ausumgaard biorefinery, as a proteinaceous ingredient for compound feeds. The following sections describe goal and scope of the PEF study in details.

3.1. Scope of study

The scope of this PEF study is an average formulation for a compound feed suitable for feeding egg-laying hens. The formulation has been modified by a compound feed producer (DLG) to replace soybean meal with organic GPC. In other words, GPC-data from Ausumgaard was used as the basis for new formulation of compound feed. The GPC used in this formulation is the one which is produced in Ausumgaard biorefinery in Denmark and is intended to be used as a proteinaceous feed ingredient in local animal farms. However, the scope can be further expanded to cover the production of GPC with other technologies in Denmark or in other European countries, as well as PEF study of food-producing animals fed with such a compound feed. Hence, the scope of this study covers the activities take place in Ausumgaard farm from grass cultivation to finished GPC product, and the processing of feed ingredients for compound feed production ready to be sold to the market.

This PEF study has been developed according to the stages shown in Figure 2. During these stages, the PEF study was conducted and potential barriers, limitations, and bottlenecks were identified, and possible solutions were proposed. As mentioned earlier, this report is not critically reviewed by external reviewers, so the review shown in Figure 2, refers to internal review by project partners.

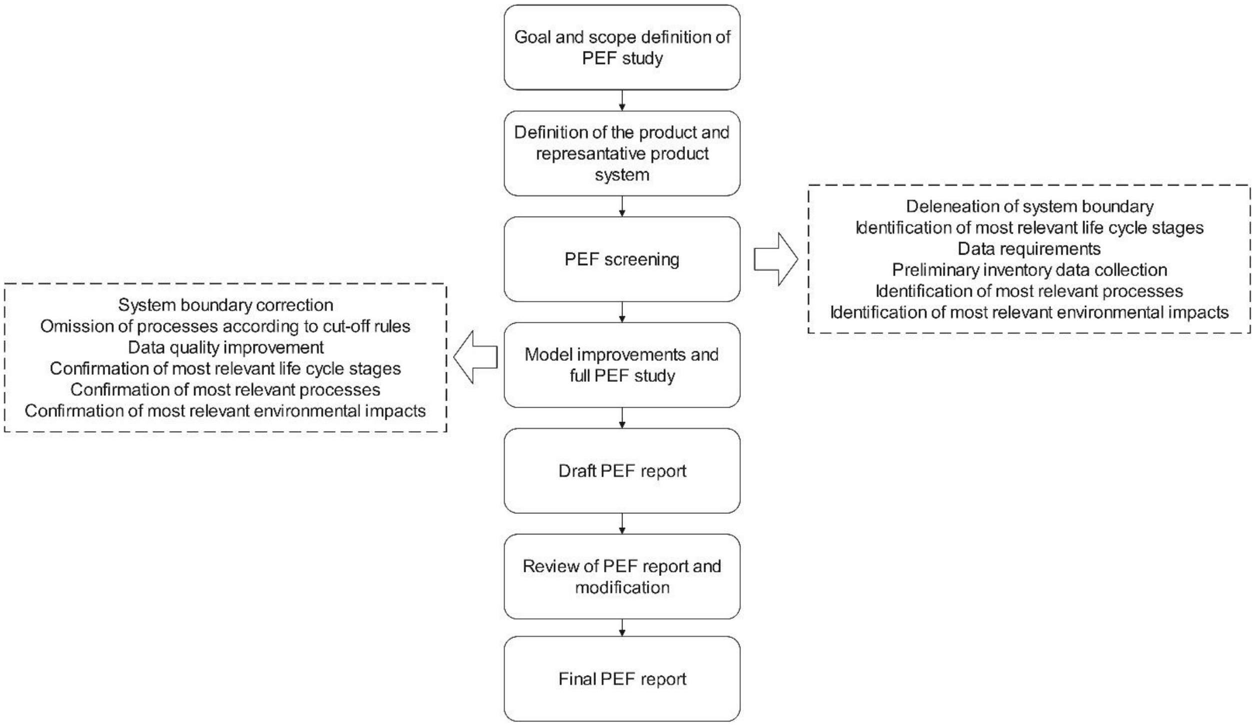

Figure 2. The steps followed in this PEF study

3.2. System boundary

A cradle to gate system boundary (Figure 3) was opted for this PEF study as instructed by PEFCR Feed for Food Producing Animals. This includes the production of feed ingredients, The transport of feed ingredients to the feed mill, feed production, and feed delivery to the farm. It needs to be highlighted that the feed delivery to the farm was excluded from the scope of this study. Furthermore, since the main purpose of this project is to calculate the environmental footprint of compound feed with GPC, all the processes associated with clover grass cultivation and its processing into GPC is included in the foreground system. Other feed ingredients are supplied from the background system so that secondary PEF database is used for its modeling purposes. Accordingly, clover-grass cultivation and its processing to GPC need mandatory company specific data collection. The production of auxiliaries, capital goods, energy carriers, packaging materials, etc. are also included but they also need secondary data to link the activity data to the background systems where the energy carriers, chemicals, and materials are produced to fulfill the requirements of the PEF studies. The short description of life cycle stages is shown in Table 1 and detailed description can be found in the relevant sub-sections.

It is worth mentioning that according to the updated guidelines on Product Environmental Footprint (PEF) method, processes and elementary flows may be excluded up to 3.0%, based on material and energy flows and the level of environmental significance (single overall score). The processes subject to cut-off shall be made explicit and justified in the PEF report, in particular with reference to the environmental significance of the cut-off applied. This cut-off has to be considered additionally to the cut-off already included in the background datasets (secondary data). This rule is valid for both intermediate and final products. The processes that in total account less than 3.0% of the material and energy flow and environmental impact for each impact category may be excluded from PEF studies (starting from the less relevant). A screening study is recommended to identify processes that may be subject to cut-off. The excluded processes are shown in the life cycle inventory data.

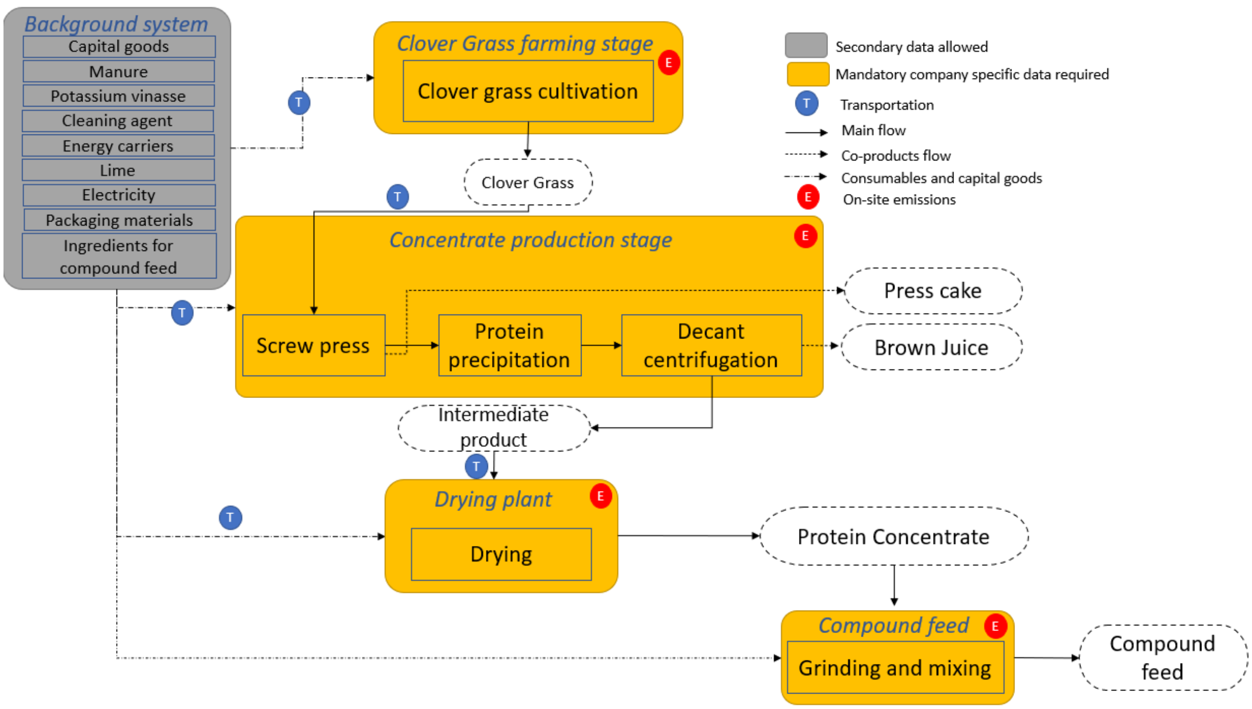

Figure 3. System boundary for the assessment of compound feed production with organic clover grass protein concentrate, including indication of the processes for which company-specific data are mandatory.

Table 1. Life cycle stages of the PEF study

Life cycle stage	Short description of the processes included
Organic grass cultivation	Organic grass used for GPC is cultivated in Ausumgaard farm and surrounding farms. The cultivation of organic grass requires the input of manure and biogas slurry as well as energy carriers, water, auxiliary materials and may involve land transformation. The full life cycle of the production of these products, including transport and depreciation of capital goods is in the scope of this PEF study.
Inbound transportation	The delivery of harvested grass to the biorefinery plant is part of the life cycle of GPC.
Production of GPC	GPC production is the core of this PEF study where the delivered grass is processed to the final product and leaves two important co-products namely press cake and brown juice.
Outbound transportation	The transportation of intermediate protein concentrate to the drying facility as well as transportation of co-products are included in the scope of this study.
Production of compound feed	The process includes grinding/milling and mixing of several feed ingredients for the production of final compound feed ready to sell into the market.
Processing of coproducts	The processing of the coproducts may belong to the scope of this PEF study. This depends on the adapted allocation approach which is described in details in its relevant section.

3.3. Geographical boundary

The results of this PEF study are only valid for an average compound feed formulation for egg-laying hens. The GPC, used in the feed formulation, is the one produced through the technology developed in Denmark and is in use in Ausumgaard biorefinery plant and for all the feed compounds that use this specific product as feed ingredient. There are also other similar technologies to produce protein concentrate from green biomass such as the technology which is used in BioRefine® (https://biorefine.dk/). The results of this PEF study are not valid for other GPC which is produced by other technologies. However, the associated guidelines set herein, and the experience achieved from early environmental assessment through PEF approach can be employed to implement the PEF study for any GPC and other compound feeds. Furthermore, the results are also valid for the early assessment of EF of food-producing animals which are fed with GPC produced in Ausumgaard biorefinery. Accordingly, the geographical boundary is limited to Denmark, and to the GPC produced in Ausumgaard biorefinery and cannot be expanded for other technologies and countries in European Union unless they use this specific product for compound feed production.

3.4. Functional unit

Feed is an intermediate product which means that no functional unit is considered as such (European Commission. 2020). The declared unit (equal to reference flow) is considered instead. The reference flow is 1 ton of compound feed with and without GPC as finished product, ready for sale. That is, 1 ton of compound feed with and without protein concentrate with a dry matter content of 90%. All quantitative input and output data collected in this study shall be calculated in relation/scaled to this reference flow. The key aspects of the functional unit are shown in Table 2. All flows used in the assessment were scaled to the unit of assessment, so that their output would be 1 ton of protein concentrate.

Table 2. Key aspects of the functional unit

What?	Average compound feed for egg-laying hens.
How much?	1 tonne of compound feed with and without GPC, formulated for egg-laying hens.
How long?	Minimum storage life as defined in article 17 of Regulation (EC) No 767/2009 of the European Parliament and the Council of 13 July 2009 on the placing of the market and use of feed[1]. Feed is normally consumed in a short period after delivery. Losses during storage are uncommon and may be neglected.

3.5. EF impact assessment

This PEF study shall calculate the PEF-profile including all impact categories shown in Table 3. According to the latest PEFCR Guidance 6.3 (European Commission. 2017), biogenic carbon dioxide ($CO_{2\text{-biogenic}}$) uptake and capture shall not be recorded. This has been more discussed in section 6.

It is important to mention that the methods used to assess the different impact categories are not equally robust (PEF Guidance 6.3). According to the European Commission, the impact assessment methods used to calculate the EF of a product can be classified in three groups, from the more robust to the less robust:

- Group I: climate change, ozone depletion, particulate matter

- Group II: Ionising radiation, Photochemical ozone formation, Acidification, Eutrophication (terrestrial, marine and freshwater),

- Group III: land use, water use, resource use (mineral and energy carriers), ecotoxicity, human toxicity (cancer and non-cancer)

The differences of robustness have been taken into account by the European Commission to determine the weighting factors, when weighted PEF results are calculated.

[1] Available at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0767&from=EN

Table 3. EF impact categories with respective impact category indicators and characterization models. The CFs that shall be used are available at: http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

Impact category	**Indicator**	**Unit**	**Robustness**
Acidification	Accumulated Exceedance (AE)	mol H+ eq	II
Climate change (Total)	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	I
Climate change-Biogenic (methane)		kg CO_2 eq	I
Climate change-fossil		kg CO_2 eq	I
Climate change-Land use and land use change		kg CO_2 eq	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	I
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	II
Eutrophication marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	II
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	III
Human toxicity, non-cancer		CTUh	III
Ionizing radiation, human health	Human exposure efficiency relative to U235	kBq U^{235} eq	II
Land use	· Soil quality index [2] · Biotic production · Erosion resistance · Mechanical filtration · Groundwater replenishment	· Dimensionless (pt) · kg biotic production · kg soil · m3 water · m3 groundwater	III
Particulate Matter	Impact on human health	disease incidence	I
Photochemical ozone formation - human health	Tropospheric ozone concentration increase	kg NMVOC eq	II
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	III
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	III
Water use	User deprivation potential (deprivation weighted water consumption)	m^3 world eq	III

4. Life cycle inventory

An inventory of all material, energy and waste inputs and outputs and emissions into air, water and soil for the product supply chain shall be compiled as a basis for modelling the PEF. This is called the life cycle inventory. In general, there are two types of inventory data:

[2] This index is the result of the aggregation, performed by JRC, of the 4 indicators provided by LANCA model as indicators for land use

1- Company-specific data (also called activity data): it refers to directly measured or collected data representative of activities at a specific facility or set of facilities. It is synonymous to "primary data".
2- Secondary dataset: refers to data not from specific process within the supply-chain of the company performing the PEF study. This refers to data that is not directly collected, measured, or estimated by the company, but sourced from a third-party life-cycle-inventory database or other sources. Secondary data includes industry-average data (e.g., from published production data, government statistics, and industry associations), literature studies, engineering studies and patents, and can also be based on financial data, and contain proxy data, and other generic data. Primary data that go through a horizontal aggregation step are considered as secondary data.

Data needs matrix (DNM) can be used to decide whether company-specific data or secondary data shall be used for each process.

4.1. Data needs matrix

The Data Needs Matrix shall be used to evaluate all processes required to model the product in scope on their data requirements (see Table 4). It indicates for which processes company-specific data or secondary data shall or may be used, depending on the level of influence the company has on the process. The following three cases are found in the DNM and explained below:

1. **Situation 1**: the process is run by the company performing the PEF study.
2. **Situation 2**: the process is not run by the company performing the PEF study, but the company has access to (company-)specific information.
3. **Situation 3**: the process is not run by the company performing the PEF study and this company does not have access to (company-)specific information.

4.2. Agricultural production modeling

The consumption of chemical and organic fertilisers causes on-site emissions to air, soil, and water. Depending on the fertilizer type, soil temperature and pH, type of the crop, etc. various forms of emissions occur. The emissions from fertilisers shall be distinguished per fertiliser type and cover as a minimum:

- NH_3, to air (from N-fertiliser application)
- N_2O, to air (direct and indirect) (from N-fertiliser application)
- CO_2, to air (from lime, urea and urea-compounds application)
- NO_3, to water unspecified (leaching from N-fertiliser application)
- PO_4, to water unspecified or freshwater (leaching and run-off of soluble phosphate from P-fertiliser application
- P, to water unspecified or freshwater (soil particles containing phosphorous, from P-fertiliser application)

In order to keep consistency among various PEFCRs, the emission factors for fertilisers are determined by considering Tier 1 emission factors of IPCC 2006 and summarised in Table 4.

Table 4. Emission factors for fertilisers and lime (Zampori and Pant 2019, European Commission. 2020)

Emission	Compartment	Emission factor	Reference
N_2O (synthetic fertiliser and manure; direct and indirect)	Air	0.022 kg N_2O/ kg N fertilizer applied	(Zampori and Pant 2019)
NH_3 (synthetic fertiliser)	Air	0.12 kg NH_3/ kg N fertilizer applied	(Zampori and Pant 2019)
NH_3 (manure)	Air	0.24 kg NH_3/ kg N manure applied	(Zampori and Pant 2019)
NO_3^- (synthetic fertiliser and manure)	Water	1.33 kg NO_3^-/ kg N applied	(Zampori and Pant 2019)
P based fertilisers	Water	0.05 kg P/ kg P applied	(European Commission. 2020)
CO_2 (urea application)	Air	1.57 kg CO_2/kg Urea-N 0.73 kg CO_2/kg Urea	(Nemecek, Bengoa et al. 2019)
CO_2 (limestone ($CaCO_3$) application)[1]	Air	0.44 kg CO_2/kg limestone	(Nemecek, Bengoa et al. 2019)
CO_2 (dolomite ($CaMgCO_3$) application)	Air	0.48 kg CO_2/kg dolomite	(Nemecek, Bengoa et al. 2019)

[1] No differentiation has been made between different types of limes.

The use of agricultural machinery for performing field operations (e.g., sowing, harrowing, harvesting) as well as off-road transportation and some specific operations at grass protein concentrate plant (e.g., loading) is accompanied by the consumption of diesel fuel and their associated exhaust emissions. Such emissions should be accounted in the inventory data of PEF studies. PEFCR guidelines have not determined emission factors from combustion of diesel fuel in agricultural machinery, hence, emission factors suggested in ecoinvent report No. 15, "Life Cycle Inventories of Agricultural Production systems" (Nemecek, Kägi et al. 2007) are suggested herein (Table 5). The missing emission factors were then completed from EMEP/EEA air pollutant emission inventory guidebook 2019 (Ntziachristos and Samaras 2019).

Table 5. Air emission factors for diesel fuel combustion

Substance	EF [g / kg diesel]	Reference
Carbon dioxide (CO_2)	3.12E+03	(Nemecek, Kägi et al. 2007)
Sulfur dioxide (SO_2)	1.01E+00	(Nemecek, Kägi et al. 2007)
Methane (CH_4)	1.29E-01	(Nemecek, Kägi et al. 2007)
Benzene (C_6H_4)	7.30E-03	(Nemecek, Kägi et al. 2007)
Cadmium (Cd)	1.00E-05	(Nemecek, Kägi et al. 2007)
Chromium (Cr)	5.00E-05	(Nemecek, Kägi et al. 2007)
Copper (Cu)	1.70E-03	(Nemecek, Kägi et al. 2007)
Dinitrogen monoxide (N_2O)	1.20E-01	(Nemecek, Kägi et al. 2007)
Nickel (Ni)	7.00E-05	(Nemecek, Kägi et al. 2007)
Zink (Zn)	1.00E-03	(Nemecek, Kägi et al. 2007)

Benzo(a)pyrene ($C_{20}H_{12}$)	3.00E-05	(Nemecek, Kägi et al. 2007)
Ammonia (NH_3)	2.00E-02	(Nemecek, Kägi et al. 2007)
Selenium (Se)	1.00E-05	(Nemecek, Kägi et al. 2007)
Hydrocarbons (HC, as NMVOC)	1.92E+00	(Ntziachristos and Samaras 2019)
Nitrogen oxides (NO_x)	33.37E+00	(Ntziachristos and Samaras 2019)
Carbon monoxide (CO)	7.58E+00	(Ntziachristos and Samaras 2019)
Particulates	9.40E-1	(Ntziachristos and Samaras 2019)
CO_2 from combustion of lubricant oil	2.54E+00	(Ntziachristos and Samaras 2019)
Substance	**EF [g / kg Natural Gas]**	**Reference**
Sulfur dioxide (SO_2)	2.03E-02	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Nitrogen oxides (NO_x)	1.56E+00	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Hydrocarbons (HC, as NMVOC)	9.42E-02	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Methane (CH_4)	4.71E-02	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Carbon monoxide (CO)	1.32E+00	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Carbon dioxide (CO_2)	2.69E+00	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Dinitrogen monoxide (N_2O)	4.71E-02	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Ammonia (NH_3)	0.00E+00	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)
Particulates	4.71E-03	(Malene Nielsen, Ole-Kenneth Nielsen et al. 2015)

LCI of cultivation stage for a reference flow of 1 ton of GPC is shown in Table 6.

Table 6. Life cycle inventory of clover-grass cultivation for a reference flow of 1 t GPC

Inputs	**Unit**	**Quantity**	**Comment**
Grass seed	kg	7.16	
Manure slurry	kg	16358.31	73.6 kg N and 12.27 kg P
Lime (CaCO3)	kg	153.36	
Potassium Vinasse	kg	44.47	0.16 kg N and 0.18 kg P
Land occupation	m^2.a	7667.96	
Land transformation	m^2	n/a	
Water	m^3	0.00	
Diesel fuel	L	79.59	
Electricity	kWh	0.00	
Shed	kg	9.05	
Tractor	kg	0.17	
Seeder	kg	0.00	
Drum	kg	0.11	
Broadcaster	kg	0.02	
Manure/slurry spreader	kg	0.01	
Cutter	kg	0.63	
Agricultural Trailer	kg	0.63	

Transportation, Slurry	tkm	40.38	
Transportation, Lime	tkm	109.50	
Transportation, potassium vinasse	tkm	708.24	
Outputs	**Unit**	**Quantity**	**Comment**
Grass	kg	32665.51	
N_2O, synthetic fertiliser and manure	kg	1.62	Air
NH_3, manure	kg	17.70	Air
NO_3^-, synthetic fertiliser and manure	kg	98.08	Water
P, Water	kg	0.62	Water
CO_2, limestone	kg	67.48	Air
CO_2, diesel combustion	kg	211.08	Air
SO_2, diesel combustion	g	68.33	Air
CH_4, diesel combustion	g	8.73	Air
Benzene (C6H4), diesel combustion	g	0.49	Air
Cadmium (Cd), diesel combustion	g	0.001	Air
Chromium (Cr), diesel combustion	g	0.003	Air
Copper (Cu), diesel combustion	g	0.12	Air
N_2O, diesel combustion	g	8.12	Air
Nickel (Ni), diesel combustion	g	0.005	Air
Zink (Zn), diesel combustion	g	0.07	Air
Benzo(a)pyrene (C20H12), diesel combustion	g	0.002	Air
Ammonia (NH3), diesel combustion	g	1.35	Air
Selenium (Se), diesel combustion	g	0.001	Air
HC, as NMVOC, diesel combustion	kg	0.130	Air
NOx, diesel combustion	kg	2.26	Air
CO, diesel combustion	kg	0.513	Air
PM, diesel combustion	kg	0.06	Air
CO_2 from lubricant, diesel combustion	kg	0.172	Air

4.3. Biorefinery modeling

Default emission factors, shown in Table 7, was used to estimate the elementary flows (direct emissions) from combustion of diesel fuel. Life cycle inventory for biorefinery stage is presented in Table 10.

Table 7. Life cycle inventory of grass biorefinery for a reference flow of 1 t GPC

Inputs	**Unit**	**Quantity**	**Comment**
Fresh grass	kg	32665.51	
Electricity, processing	kWh	108.77	
Electricity, drying	kWh	280.07	
Acidic cleaning agent	kg	2.20	
Alkaline cleaning agent	kg	10.80	
Water	m^3	0.48	
Antifoam	kg	1.30	
Natural gas	m^3	85.02	LHV = 36.6 MJ/ m^3, 47.1 MJ/kg, 0.777 kg/m^3
Packaging materials	kg	3	
Diesel, loading	L	8.1	
Diesel, heating	L	56.92	

Buildings, biorefinery	kg	17.01	
Buffer feed tank	kg	0.33	
Screw press	kg	1.12	
Heat exchanger	kg	0.22	
Centrifuge	kg	0.14	
Pipes	kg	0.19	
Transport container	kg	0.11	
Telescopic loader	kg	0.216	
Buffer juice tank	kg	0.11	
Transport, packaging materials	tkm	3.30	
Transport, grass	tkm	257.24	
Transport, acidic cleaning agent	tkm	0.21	
Transport, antifoam	tkm	0.14	
Transport, alkaline cleaning agent	tkm	1.02	
Transport, intermediate product	tkm	85.59	
Outputs	**Unit**	**Quantity**	**Comment**
Protein concentrate	kg	1000	
Brown juice	kg	18740	
Press cake	kg	12125	
CO_2, diesel combustion	kg	237.152	Air
SO_2, diesel combustion	g	76.770	Air
CH_4, diesel combustion	g	9.805	Air
Benzene (C6H4), diesel combustion	g	0.555	Air
Cadmium (Cd), diesel combustion	g	0.001	Air
Chromium (Cr), diesel combustion	g	0.004	Air
Copper (Cu), diesel combustion	g	0.129	Air
N_2O, diesel combustion	g	9.121	Air
Nickel (Ni), diesel combustion	g	0.005	Air
Zink (Zn), diesel combustion	g	0.076	Air
Benzo(a)pyrene ($C_{20}H_{12}$), diesel combustion	g	0.002	Air
Ammonia (NH_3), diesel combustion	g	1.52	Air
Selenium (Se), diesel combustion	g	0.001	Air
HC, as NMVOC, diesel combustion	kg	145.94	Air
NOx, diesel combustion	kg	2536.64	Air
CO, diesel combustion	kg	576.158	Air
PM, diesel combustion	kg	71.45	Air
CO_2 from lubricant, diesel combustion	kg	193.07	Air
SO_2, natural gas combustion	g	1.34	Air
NOX, natural gas combustion	g	102.81	Air
NMVOC, natural gas combustion	g	6.22	Air
CH_4, natural gas combustion	g	3.11	Air
CO, natural gas combustion	g	87.12	Air
CO_2, natural gas combustion	kg	177.55	Air
N_2O, natural gas combustion	g	3.11	Air
NH_3, natural gas combustion	g	0.00	Air
TSP, natural gas combustion	g	0.31	Air
PM_{10}, natural gas combustion	g	0.31	Air

PM$_{2.5}$, natural gas combustion	g	0.31	Air

4.4. Feed milling operation

There are four data-points for which it is mandatory to use company-specific data (e.g. primary data). Not using primary data for these processes means that the PEF study is not compliant with this PEFCR.

These four data points are:

1. The list of feed ingredients
2. The nutritional analysis of the feed ingredients (hereafter referred to as nutritional analysis data)
3. Energy consumption in feed mill operations
4. Outbound transport to livestock farm

The list of feed ingredients entails the following data:

- Types and quantities of feed materials
- Types and quantities of feed additives
- Type and quantities of pre-mixtures

The bill of materials shall add up to 100% of the weight of the compound feed. No cut-off is allowed. Table 8 summarizes the formulation of an average compound feed for egg-laying hens. The formulation is changed to be modified for replacing soybean meal with GPC.

For crops and processed feed ingredients used in the feed mill the country of origin shall be recorded if this information is provided in the transaction to the feed business operator. In this study such information was not available so the average of global production for feed ingredients was used.

Table 8. Two compound feeds with and without grass protein concentrate and the inventory data for milling operations.

Standard compound feed	**Percentage (%)**	**Unit**	**Compound feed with GPC**	**Percentage (%)**	**Unit**
Corn	34.10%		Corn	23.24%	
Wheat	20.00%		Wheat	22.00%	
Sunflowercakes	10.00%		Sunflowercakes	10.00%	
rapeseed cakes	5.90%		rapeseed cakes	5.90%	
Wheat bran	5.90%		Wheat bran	6.00%	
Fishmeal	5.40%		Fishmeal	5.00%	
Oats	5.00%		Oats	15.00%	
Soycakes	4.70%		Soycakes	2.00%	
Grass Protein Concentrate	**Na**		Grass Protein Concentrate	2.01%	
chalk	7.38%		chalk	7.30%	
Vitamins/minerals etc.	1.62%		Vitamins/minerals etc.	1.55%	
Electricity	0.088	kWh/kg compound feed	Electricity	0.088	kWh/kg compound feed
Heat	0.037	kWh/kg compound feed	Heat	0.037	kWh/kg compound feed

The nutritional analysis data is especially relevant for PEF studies of animal products. The nutritional analysis data needed for the purpose of the PEF study are:

- Nitrogen (N), Phosphorus (P) content in g/kg
- Ash (g/kg)
- Copper (Cu), Zinc (Zn) content in g/kg (from all sources)
- Gross Energy (MJ/kg gross calorific value or HHV) and digestible energy fraction19 (% of gross energy)
- Fossil carbon content

Some specific elements of the feed composition may require some differentiation of the nutritional modelling associated with the use stage (e.g. effect on enteric fermentation or effect on animal performances). It that case, this information should be communicated to the downstream partner involved in LCA modelling, and shall be properly justified.

Feed companies have access to the nutritional analysis data. When the Feed PEF study is not performed directly by a feed company, the commissioner of the study should contact the feed company at stake to obtain the nutritional analysis data. Considering the sensitive nature of this information, it is recommended to use confidentiality agreements for the transfer of information. Typical nutritional analysis data can be found in country datasets or if not available at http://www.feedipedia.org/. Actual nutritional analysis data are those measured by the feed company. The method chosen to report nutritional analysis data, (i.e. using typical or actual values) shall be reported. The nutritional analysis data shall be reported as additional technical information.

Generic data for energy consumption (i.e., the energy needed for milling and compound feed production) was used. Generic data from ecoinvent database was used for this purposes.

Data can be derived on different levels of accurateness which needs to be determined in relation to the scope of the study:

- If the feed operation is not part of assessing differences in a comparison between alternatives or changes in time the minimum level of accurateness shall be average feed mill data determined for 1 year of normal operation (Normal operation is data corrected for calamities).
- If comparisons are made (between alternatives or in time) that include changes in the feed mill operation (e.g. pelleting or not, temperature, pressure etc.) specific feed mill processing data shall be collected (e.g. production line or sub-production line). This can preferably be done based on measurements or if measurements are not possible on the basis of an analysis where use of energy and auxiliary materials is derived from technical specifications of equipment. Also, if specific data are collected all use of energy and auxiliary materials of the feed mill shall be divided over the specific products. Thus, any estimate of specific energy and auxiliary materials use for a feed product shall be done based on allocating the use of the complete factory to sub-processes. How this is done shall be motivated and recorded.

4.5. Outbound transport

Primary data shall be collected for outbound transport (i.e. feed delivery to the livestock or fish farm). This may be done with different levels of accuracy, as indicated in the hierarchy below from the most accurate to the least accurate, depending on data availability.

- Fuel consumption for farm-specific delivery and transport means
- Farm specific delivery distance and transport mean
- Average fuel consumption per tonne delivered, for the feed type under study and transport
- means (the average is specific to the feed under study, but the farm specific delivery distance is not available).
- Average distance from mill to farms in scope, per type of feed (ruminants, poultry, pork, fish; other) and transport mean (the average is not specific to the feed under study and the farm specific delivery distance is not available, but the average is at least distinguished according to the main feed types).

The data availability determines the level of accuracy. The quality of data collected for outbound transport is proportionate to the level of accuracy. If actual fuel use data of outbound transport can be collected, because there is a suitable accounting system in place, these data shall be used. Fuel use data will be connected to secondary LCI data for fuel production and combustion.

Because in the current study there was not any specific livestock farm in the scope, and the main objective was to compare two compound feeds with and without GPC, outbound transport was excluded from the scope.

4.5. Handling multi-functional processes

The biorefinery provides more than one function, i.e., press cake and brown juice, hence it is “multifunctional”. In this situation, all inputs and emissions linked to the process shall be partitioned between the GPC and the other co-functions in a principled manner. According to Product Environmental Footprint (PEF) method (Zampori and Pant 2019) systems that involve multi-functionality shall be modelled in accordance with the following decision hierarchy.

1. Subdivision or system expansion

As per ISO 14044, wherever possible, subdivision or system expansion should be used to avoid allocation. Subdivision refers to disaggregating multifunctional processes or facilities to isolate the input flows directly associated with each process or facility output. System expansion refers to expanding the system by including additional functions related to the co-products. It shall be investigated first whether it is possible to subdivide or expand the analyzed process. Where subdivision is possible, inventory data should be collected only for those unit processes directly attributable to the goods/services of concern. Or, if the system may be expanded, the additional functions shall be included in the analysis with results communicated for the expanded system as a whole rather than on an individual co-product level.

2. Allocation based on a relevant underlying physical relationship

Where it is not possible to apply subdivision or system expansion, allocation should be applied: the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects relevant underlying physical relationships between them (ISO 14044:2006).

Allocation based on a relevant underlying physical relationship refers to partitioning the input and output flows of a multi-functional process or facility in accordance with a relevant, quantifiable physical relationship between the process inputs and co-product outputs (for example, a physical property of the inputs and outputs that is relevant to the function provided by the co-product of interest). Allocation based on a physical relationship may be modelled using direct substitution, if it is possible to identify a product that is directly substituted.

To demonstrate whether the direct substitution effect is robust, the user of the PEF method shall prove that (1) there is a direct, empirically demonstrable substitution effect, AND (2) it is possible to model the substituted product and to subtract the life cycle inventory in a directly representative manner: If both conditions are fulfilled, model the substitution effect.

Or

To allocate input/output based on some other relevant underlying physical relationship that relates the inputs and outputs to the function provided by the system, the user of the PEF method shall demonstrate that it is possible to define a relevant physical relationship by which to allocate the flows attributable to the provision of the defined function of the product system: If this condition is fulfilled, the user of the PEF method may allocate based on this physical relationship.

3. Allocation based on some other relationship

Allocation based on some other relationship may be possible. For example, economic allocation refers to allocating inputs and outputs associated with multi-functional processes to the co-product outputs in proportion to their relative market values. The market price of the co-functions should refer to the specific condition and point at which the co-products are produced. In any case, a clear justification for having discarded 1) and 2) and for having selected a certain allocation rule in step 3) shall be provided, to ensure the physical representativeness of the PEF results as far as possible.

Allocation based on some other relationship may be approached in one of the following alternative ways:

(i) Is it possible to identify an indirect substitution effect and may the substituted product be modelled and the inventory subtracted in a reasonably representative manner? If yes (i.e., both conditions are verified), model the indirect substitution effect.

Or

(ii) Is it possible to allocate the input/output flows between the products and functions on the basis of some other relationship (e.g. the relative economic value of the co-products)? If yes, allocate products and functions on the basis of the identified relationship.

However, PEFCR Feed for Food Producing Animals (European Commission. 2020) has suggested specific allocation rules for different stages of compound feed production (Table 9). Hence, the suggested allocation approaches have been used specifically in this PEF study.

Table 9. Specific allocation approach suggested by PEFCR Feed for Food Producing Animals for different stages of compound feed production.

Process	**Allocation rule**	**Modelling instructions**
Transport	Physical allocation	Allocation of transport emissions to transported products shall be done on the basis of physical causality, such as mass share, unless the density of the transported product is significantly lower than average so that the volume transported is less than the maximum load. Allocation of empty transport kilometers shall be done on the basis of the average load factor of the transport that is understudy. If no supporting information is available, it shall be assumed that 100 percent additional transport is needed for empty return, which equals the utility rate of 50%.
Allocation of co-products from a crop at the farm	Economic allocation	Economic allocation shall be conducted on the basis of the method and default allocation factors. If primary data are collected for feed ingredients economic allocation shall be done according to the procedure described in the LEAP feed guidelines.
Processing of feed ingredients	Economic allocation	Economic allocation shall be conducted on the basis of the method and default allocation factors. If primary data are collected for feed ingredients economic allocation shall be done according to the procedure

		described in the LEAP feed guidelines.
Feed mill operations, i.e. compound feed production (electricity, gas, water use,…)	Two situations shall be distinguished for the feed mill operations: 1) Specific feed mill data are available (see section 9.1.3): no need to allocate 2) Average feed mill data are available (see section 9.1.3): mass allocation shall be used (average consumption per tonne of feed produced)	

4.6. Dealing with multi-functionality in biorefinery stage

As described in the section 4.4 and was also shown in Table 9, economic allocation is suggested when dealing with multifunctionality problem in processing stage. Press cake and brown juice are two important co-products of the clover-grass biorefining process with multiple applications. Press cake can be used either for biogas production or fibrous and bulky feed materials. Brown juice has high COD and can be easily digested in anaerobic reactors to produce biogas. Therefore, they have real markets and can be sold to different sectors. Their market values of GPC, brown juice, and press cake were used to allocate the environmental burdens to three co-functions. The following selling prices were used:

- Press cake: 209 DKK/ton
- Brown juice: 50 DKK/ton
- GPC: 10,000 DKK/ton

Accordingly, the allocation factors shown in Table 10 were used.

Table 10. Allocation factor used to evaluate the impact of different allocation methods on EF of GPC

Co-products	**Economic allocation**
Press cake	18.81%
Brown juice	6.95%
GPC	74.24%

5. Environmental Footprint impact assessment

Once the Life Cycle Inventory (LCI) has been compiled, the EF impact assessment shall be undertaken to calculate the environmental performance of the GPC, using all the EF impact categories and models. EF impact assessment includes four steps: classification, characterization, normalization and weighting. Results of a PEF study shall be calculated and reported in the PEF report as characterized, normalized, and weighted results for each EF impact category and as a single overall score based on the weighting factors provided. Results shall be reported for (i) the total life cycle, and (ii) the total life cycle excluding the use stage.

All inputs and outputs inventoried during the compilation of the LCI shall be assigned to the EF impact categories to which they contribute ("classification") using the classification data available at https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

Characterization refers to the calculation of the magnitude of the contribution of each classified input and output to their respective EF impact categories, and aggregation of the contributions within each category. This is carried out by multiplying the values in the LCI by the relevant characterization factor for each EF impact category. All characterization factors are available online at https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

Following the steps of classification and characterization, the EF impact assessment shall be complemented with normalization and weighting. Normalization is the step in which the life cycle impact assessment results are divided by normalization factors to calculate and compare the magnitude of their contributions to the EF impact categories relative to a reference unit. As a result, dimensionless, normalized results are obtained. These reflect the burdens attributable to a product relative to the reference unit. Within the PEF method the normalization factors are expressed per capita based on a global value. The normalization factors, shown in Table 11, were used for this purpose. Normalized environmental footprint results do not, however, indicate the severity or relevance of the respective impacts. In PEF studies, normalized results shall not be aggregated as this implicitly applies weighting. Characterized results shall be reported alongside the normalized results.

Table 11. Global normalization and weighting factors for environmental footprint.

Impact category	**Normalization factor**	**Weighting factor**
Acidification	55.5	0.0664
Climate change (Total)	7760.0	0.2219
Climate change-Biogenic (methane)		
Climate change-fossil		
Climate change-Land use and land use change		
Ozone depletion	0.0234	0.0675
Ecotoxicity, freshwater	11800.0	
Eutrophication marine	28.3	0.0312
Eutrophication, freshwater	2.55	0.0295
Eutrophication, terrestrial	177.0	0.0391
Human toxicity, cancer	3.85E-5	
Human toxicity, non-cancer	4.75E-4	
Ionizing radiation, human health	4220.0	0.0537
Land use	1330000.0	0.0842
Particulate Matter	6.37E-4	0.0954

Photochemical ozone formation - human health	40.6	0.051
Resource use, fossils	65300.0	0.0892
Resource use, minerals and metals	0.0579	0.0808
Water use	11500.0	0.0903

Weighting is a mandatory step in PEF studies and it supports the interpretation and communication of the results of the analysis. In this step, normalized results are multiplied by a set of weighting factors (in %) which reflect the perceived relative importance of the life cycle impact categories considered. Weighted results of different impact categories may then be compared to assess their relative importance. They may also be aggregated across life cycle impact categories to obtain a single overall score.

In this PEF study, we used openLCA 1.11.0 to calculate the EF, characterization, normalization, and weighting.

6. Interpretation of Product Environmental Footprint's results

The partial or full substitution of soybean meal by GPC in compound feed can enhance the environmental impacts of the feeds. As indicated in Table 12, in 12 out of 19 impact categories, the modified compound feed with GPC exhibits better environmental impacts than the standard compound feed. The extent of the changes in environmental impacts varies from one category to another.

In the impact category of climate change, one of the most debated environmental issues, a reduction of approximately 12% was observed. This reduction was achieved with GPC contributing only 2% w/w to the compound feed. The climate change of the standard compound feed was estimated at approximately 1222 kg $CO_{2,eq}$ per tonne of final product, while that of the modified compound feed decreased to around 1085 kg $CO_{2,eq}$. The GPC has already demonstrated a lower climate change impact compared to soybean and soybean meal (Figure 4). The extent of the difference largely depends on the origin of soy production and its subsequent processing into soybean meal.

Table 12. Environmental impacts of 1 tonne of compound feed for egg-laying hens with and without GPC.

Impact category	Reference unit	Standard compound feed	Compound feed with GPC	Difference
Acidification	mol H+ eq	11.86	12.03	1.39%
Climate change	kg CO2 eq	1222.32	1084.77	-12.68%
Climate change-Biogenic	kg CO2 eq	32.87	28.53	-15.19%
Climate change-Fossil	kg CO2 eq	1019.46	949.89	-7.32%
Climate change-Land use and land use change	kg CO2 eq	169.99	106.35	-59.84%
Ecotoxicity, freshwater	CTUe	29606.75	25552.58	-15.87%
Eutrophication marine	kg N eq	9.64	9.71	0.78%
Eutrophication, freshwater	kg P eq	0.20	0.20	0.26%
Eutrophication, terrestrial	mol N eq	47.77	47.62	-0.30%
Human toxicity, cancer	CTUh	3.92E-05	3.71E-05	-5.63%
Human toxicity, non-cancer	CTUh	1.32E-03	1.36E-03	3.04%
Ionising radiation, human health	kBq U-235 eq	71.97	63.29	-13.71%
Land use	Pt	231103.89	232284.99	0.51%
Ozone depletion	kg CFC11 eq	1.10E-05	3.19E-05	65.44%
Particulate Matter	disease inc.	1.15E-04	1.07E-04	-7.47%
Photochemical ozone formation - human health	kg NMVOC eq	3.35	3.02	-10.86%
Resource use, fossils	MJ	11000.51	9992.34	-10.09%
Resource use, minerals and metals	kg Sb eq	4.65E-03	4.05E-03	-14.88%
Water use	m3 depriv.	5419.83	6300.18	13.97%

Impact category	Reference unit	GPC, Ec	Soy, GLO	Soy, EU+28	Soymeal, GLO	Soymeal, EU+28
Acidification	mol H+ eq	32.01	11.36	19.46	7.11	9.11
Climate change	kg CO2 eq	1091.47	4505.64	1545.75	2795.70	3064.29
Climate change-Biogenic	kg CO2 eq	3.20	47.43	53.90	31.54	44.10
Climate change-Fossil	kg CO2 eq	1084.56	1283.24	1452.73	879.84	1068.96
Climate change-Land use and land use change	kg CO2 eq	3.71	3174.97	39.12	1884.31	1951.23
Ecotoxicity, freshwater	CTUe	413.42	28845.52	29065.05	17832.12	17256.89
Eutrophication marine	kg N eq	16.84	10.90	17.23	6.64	7.20
Eutrophication, freshwater	kg P eq	0.47	0.49	0.39	0.30	0.39
Eutrophication, terrestrial	mol N eq	56.84	42.90	79.29	26.54	32.74
Human toxicity, cancer	CTUh	4.04E-06	8.03E-05	8.87E-05	4.92E-05	5.73E-05
Human toxicity, non-cancer	CTUh	9.71E-05	2.93E-03	3.97E-03	1.77E-03	2.11E-03
Ionising radiation, human health	kBq U-235 eq	14.48	108.86	144.31	73.98	97.25
Land use	Pt	9652.47	593597.21	531849.66	357000.04	334722.89
Ozone depletion	kg CFC11 eq	1.11E-03	1.64E-05	1.82E-05	1.09E-05	1.49E-05
Particulate Matter	disease inc.	3.41E-05	1.13E-04	1.58E-04	7.02E-05	8.21E-05
Photochemical ozone formation - human health	kg NMVOC eq	0.93	3.97	4.13	2.93	4.38
Resource use, fossils	MJ	9357.65	14038.67	15291.77	9800.43	12526.51
Resource use, minerals and metals	kg Sb eq	3.68E-04	6.66E-03	7.48E-03	4.41E-03	6.10E-03
Water use	m3 depriv.	39.38	2854.01	6373.68	1725.97	1248.49
Weighted results (single score)	per person	0.130	0.281	0.254	0.176	0.194

Figure 4. Environmental impacts of GPC production with economic allocation compared with soybean and soybean meal production.

The units are per 1 ton of GPC, 917.73 kg soybean meal, and 1204.3 kg soybean, based on their average crude protein content. GLO stands for average of global production and EU+28 refers to the average of EU production. The nutritional data for feed components, as suggested in

PEFCR compound feed animals were taken from http://www.feedipedia.org/. Accordingly, it was assumed that soybean has a DM content of 88.7% and a crude protein content of 39.6% of DM, and soybean meal has a DM of 87.9% and crude protein of 52.34% of DM.

The contribution analysis demonstrated that maize grain, wheat grain, soybean meal, and sunflower seed meal were the key contributors to the climate change of the standard compound feed. As depicted in Figure 5, soybean meal is the third contributor after maize grain and wheat grain. In the modified formulation, the soybean meal decreased by half and was replaced with GPC. Such modification in the compound feed has caused that the overall climate change impact decreased by almost 12%.

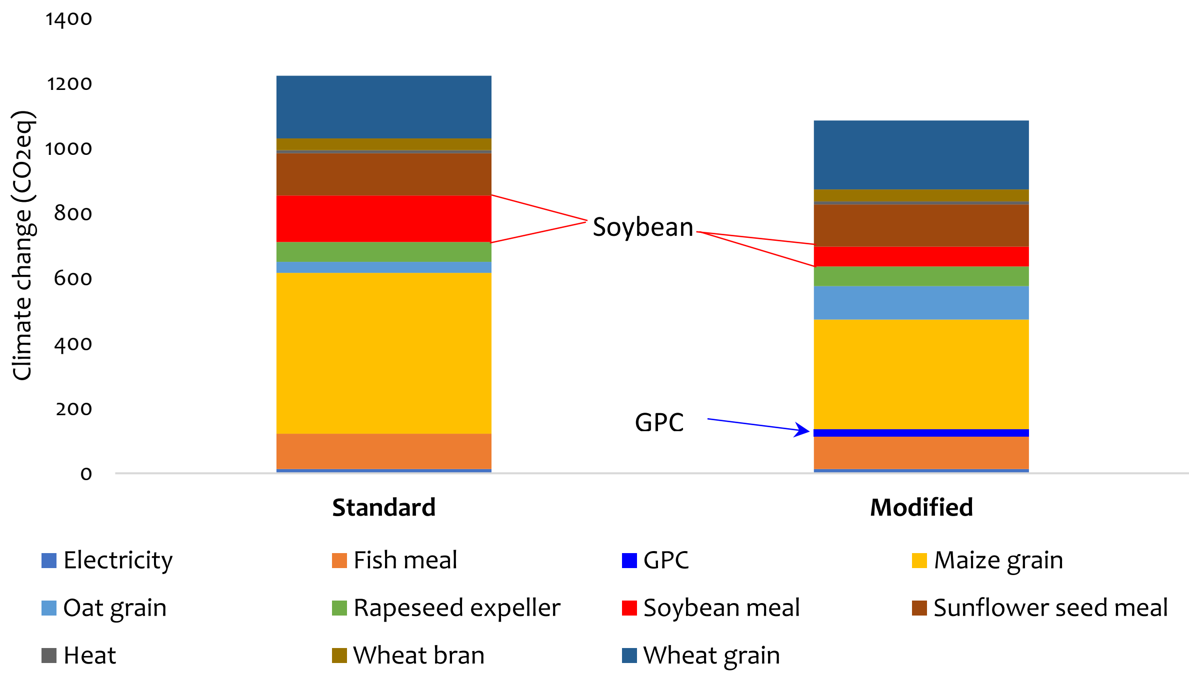

Figure 5. Contribution analysis on climate change impact of compound feed with and without GPC.

As shown in Table 12, acidification is one of the seven impact categories for which compound feed with GPC has higher impacts than standard compound feed. The contribution of soybean meal to acidification of standard compound feed is about 3% while this impact category is dominated by maize grain (44%), wheat grain (23%), and sunflower seed meal (9%). In the modified compound feed with GPC, although the contribution of maize grain and soybean meal was decreased to 30% and 1%, GPC contributed by 5%, oat grain by 15%, and wheat gain by 25% (Figure 6). Such changes cause that compound feed with GPC exhibits 1.39% higher impact than standard compound feed.

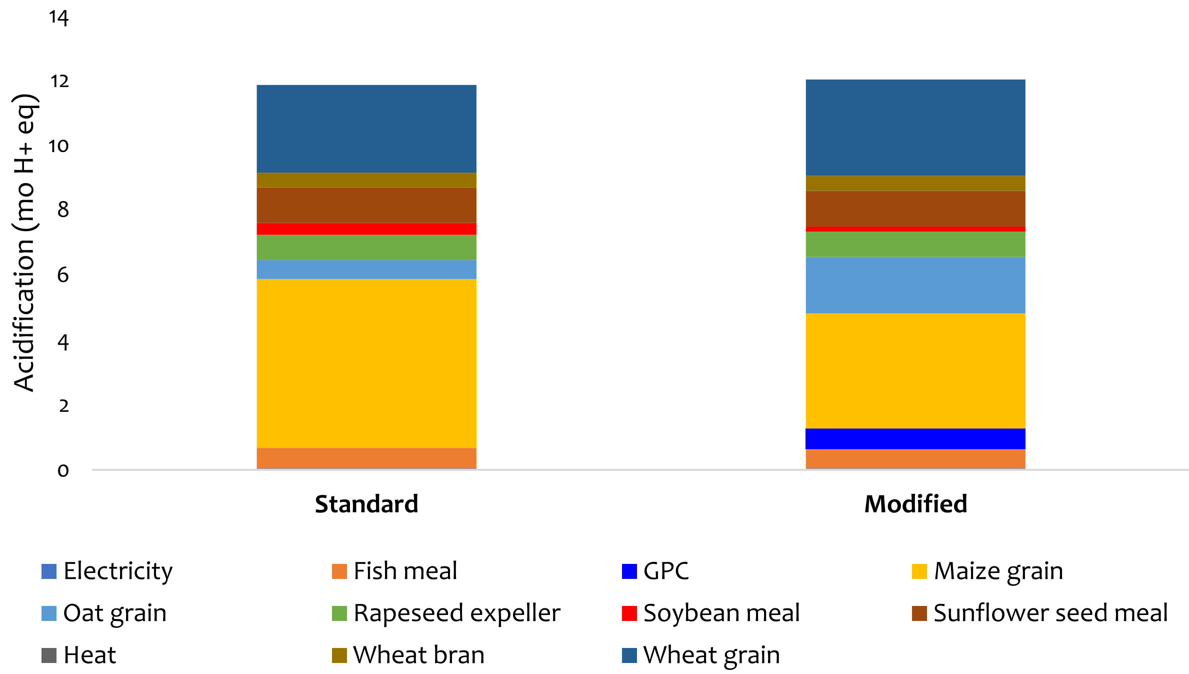

Figure 6. Contribution analysis on climate change impact of compound feed with and without GPC.

The weighed impacts and single score results for compound feeds with and with GPC are shown in Table 13. Overall, modified compound feed with GPC has lower environmental impact than standard compound feed. It is well evident that the GPC which is produced in Denmark is a promising substitute for soybean meal and can decrease dependencies on soybean imports. The use of GPC in the compound feed can bring about environmental advantages and decrease the environmental footprint of livestock breeding. However, attempts are still needed to further improve the production process of GPC in both cultivation phase and biorefinery phase.

Table 13. Weighted environmental impacts and total single score for compound feed with and without GPC.

Impact category	Single score unit	Standard compound feed	Compound feed with GPC
Acidification	per person	1.419E-02	1.439E-02
Climate change	per person	3.495E-02	3.102E-02
Climate change-Biogenic			
Climate change-Fossil			
Climate change-Land use and land use change			
Ecotoxicity, freshwater	per person		
Eutrophication marine	per person	1.062E-02	1.071E-02
Eutrophication, freshwater	per person	2.321E-03	2.327E-03
Eutrophication, terrestrial	per person	1.055E-02	1.052E-02
Human toxicity, cancer	per person	0.000E+00	0.000E+00
Human toxicity, non-cancer	per person	0.000E+00	0.000E+00
Ionising radiation, human health	per person	9.158E-04	8.054E-04
Land use	per person	1.463E-02	1.471E-02
Ozone depletion	per person	3.177E-05	9.193E-05
Particulate Matter	per person	1.723E-02	1.603E-02
Photochemical ozone formation - human health	per person	4.205E-03	3.793E-03
Resource use, fossils	per person	1.503E-02	1.365E-02
Resource use, minerals and metals	per person	6.491E-03	5.650E-03
Water use	per person	4.256E-02	4.947E-02
Total		**0.1737**	**0.1732**

This study suffers some shortcomings and drawbacks so the results cannot be considered PEF compliant. It should be highlighted that although GPC was an organic product, the PEF of final compound feed with GPC cannot be labeled as PEF of an organic product. The current PEF secondary database lacks background data on organic feed ingredients. Hence, we took this study as an exercise to investigate to what extent organic GPC can decrease the environmental footprint of a specific compound feed. The inventory data collected for compound feed production was not fully PEF compliant. For instance, (i) the origin of feed ingredients was not provided, (ii) the outbound transportation was not included in the model, (iii) the nutritional analysis data for compound feed with and without GPC was not provide.

It should be also highlighted that the PEF of GPC was not also modeled under optimal conditions. Model has developed under the unsteady state production both at farm level and biorefinery level. There is a lack of reflection on crop rotation and optimization of rotation for reduced impacts and increased production and profitability. Furthermore, grass protein has currently a higher protein content (~50%) compared to the primary data used in the model (~47%). This requires an updated model under most optimal conditions. Regarding the cultivation phase, emissions from grass cultivation still has high uncertainty and the default emission factors proposed in PEFCR cannot well reflect the actual emissions and impact of management practices such as crop rotation.

It is worth noting that for future studies other parameters should be further included when PEF of grass protein is evaluated. Among others are omega 3 content in GPC and other compounds that give GPC better nutritional value. Furthermore, transition in energy market and having more renewable energies in the grid can help to decrease the PEF of compound feed with GPC.

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Definitions

Activity data - This term refers to information which is associated with processes while modelling Life Cycle Inventories (LCI). The aggregated LCI results of the process chains that represent the activities of a process are each multiplied by the corresponding activity data and then combined to derive the environmental footprint associated with that process. Examples of activity data include quantity of kilowatt-hours of electricity used, quantity of fuel used, output of a process (e.g. waste), number of hours equipment is operated, distance travelled, floor area of a building, etc. Synonym of "non-elementary flow.

Acidification – EF impact category that addresses impacts due to acidifying substances in the environment. Emissions of NOx, NH3 and SOx lead to releases of hydrogen ions (H+) when the gases are mineralized. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.

Additional environmental information – Environmental information outside the EF impact categories that is calculated and communicated alongside PEF results.

Additional technical information – Non-environmental information that is calculated and communicated alongside PEF results.

Aggregated dataset - Complete or partial life cycle of a product system that next to the elementary flows (and possibly not relevant amounts of waste flows and radioactive wastes) lists in the input/output list exclusively the product(s) of the process as reference flow(s), but no other goods or services. Aggregated datasets are also called "LCI results" datasets. The aggregated dataset may have been aggregated horizontally and/or vertically.

Allocation – An approach to solving multi-functionality problems. It refers to "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006).

Attributional – Refers to process-based modelling intended to provide a static representation of average conditions, excluding market-mediated effects.

Average Data – Refers to a production-weighted average of specific data.

Background processes – Refers to those processes in the product life cycle for which no direct access to information is possible. For example, most of the upstream life-cycle processes and generally all processes further downstream will be considered part of the background processes.

Benchmark – A standard or point of reference against which any comparison may be made. In the context of PEF, the term 'benchmark' refers to the average environmental performance of the representative product sold in the EU market.

Bill of materials – A bill of materials or product structure (sometimes bill of material, BOM or associated list) is a list of the raw materials, sub-assemblies, intermediate assemblies, subcomponents, parts and the quantities of each needed to manufacture the product in scope of the PEF study. In some sectors it is equivalent to the bill of components.

Characterization – Calculation of the magnitude of the contribution of each classified input/output to their respective EF impact categories, and aggregation of contributions within each category. This requires a linear multiplication of the inventory data with characterization factors for each substance and EF impact category of concern. For example, with respect to the EF impact category "climate change", CO_2 is chosen as the reference substance and kg CO_2-equivalents as the reference unit.

Characterization factor – Factor derived from a characterization model which is applied to convert an assigned life cycle inventory result to the common unit of the EF impact category indicator (based on ISO 14040:2006).

Classification – Assigning the material/energy inputs and outputs tabulated in the life cycle inventory to EF impact categories according to each substance's potential to contribute to each of the EF impact categories considered.

Climate change - All inputs or outputs that result in greenhouse gas emissions. The consequences include increased average global temperatures and sudden regional climatic changes. Climate change is an impact affecting the environment on a global scale.

Co-function - Any of two or more functions resulting from the same unit process or product system.

Commissioner of the EF study - Organization (or group of organizations) that finances the EF study in accordance with the PEF method and the relevant PEFCR, if available (definition adapted from ISO 14071/2014, point 3.4).

Company-specific data – It refers to directly measured or collected data from one or multiple facilities (site-specific data) that are representative of the activities of the company. It is synonymous to "primary data". To determine the level of representativeness a sampling procedure may be applied.

Company-specific dataset – It refers to a dataset (disaggregated or aggregated) compiled with company-specific data. In most cases, the activity data is company-specific while the underlying sub-processes are datasets derived from background databases.

Comparative Assertion – An environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function (including the benchmark of the product category) (adapted from ISO 14044:2006).

Comparison – A comparison, not including a comparative assertion, (graphic or otherwise) of two or more products based on the results of a PEF study and supporting PEFCRs.

Co-product – Any of two or more products resulting from the same unit process or product system (ISO 14040:2006).

Cradle to Gate – A partial product supply chain, from the extraction of raw materials (cradle) up to the manufacturer's "gate". The distribution, storage, use stage, and end of life stages of the supply chain are omitted.

Cradle to Grave – A product's life cycle that includes raw material extraction, processing, distribution, storage, use, and disposal or recycling stages. All relevant inputs and outputs are considered for all of the stages of the life cycle.

Critical review – Process intended to ensure consistency between a PEFCR and the principles and requirements of the PEF method.

Data Quality – Characteristics of data that relate to their ability to satisfy stated requirements (ISO 14040:2006). Data quality covers various aspects, such as technological, geographical and time-related representativeness, as well as completeness and precision of the inventory data.

Data Quality Rating (DQR) - Semi-quantitative assessment of the quality criteria of a dataset based on Technological representativeness, Geographical representativeness, Time-related representativeness, and Precision. The data quality shall be considered as the quality of the dataset as documented.

Delayed emissions - Emissions that are released over time, e.g. through long use or final disposal stages, versus a single emission at time t.

Direct elementary flows (also named elementary flows) – All output emissions and input resource use that arise directly in the context of a process. Examples are emissions from a chemical process, or fugitive emissions from a boiler directly onsite.

Direct land use change (dLUC) – The transformation from one land use type into another, which takes place in a unique land area and does not lead to a change in another system.

Directly attributable – Refers to a process, activity or impact occurring within the defined system boundary.

Disaggregation – The process that breaks down an aggregated dataset into smaller unit process datasets (horizontal or vertical). The disaggregation may help making data more specific. The process of disaggregation should never compromise or threat to compromise the quality and consistency of the original aggregated dataset

Downstream – Occurring along a product supply chain after the point of referral.

Ecotoxicity, freshwater – Environmental footprint impact category that addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.

EF communication vehicles – It includes all the possible ways that may be used to communicate the results of the EF study to the stakeholders (e.g. labels, environmental product declarations, green claims, websites, infographics, etc.).

EF compliant dataset – Dataset developed in compliance with the EF requirements provided at http://eplca.jrc.ec.europa.eu/LCDN/developer.xhtml.

Elementary flows – In the life cycle inventory, elementary flows include "material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation" (ISO 14040, 3.12). Elementary flows include, for example, resources taken from nature or emissions into air, water, soil that are directly linked to the characterization factors of the EF impact categories.

Environmental Footprint (EF) Impact Assessment – Phase of the PEF analysis aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (based on ISO 14044:2006). The impact assessment methods provide impact characterization factors for elementary flows in order to aggregate the impact to obtain a limited number of midpoint indicators.

Environmental Footprint (EF) Impact Assessment method – Protocol for quantitative translation of life cycle inventory data into contributions to an environmental impact of concern.

Environmental Footprint (EF) Impact Category – Class of resource use or environmental impact to which the life cycle inventory data are related.

Environmental Footprint (EF) impact category indicator – Quantifiable representation of an EF impact category (based on ISO 14000:2006).

Environmental impact – Any change to the environment, whether adverse or beneficial, that wholly or partially results from an organisation's activities, products or services (EMAS regulation).

Eutrophication – Nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilized farmland accelerate the growth of algae and other vegetation in the water. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of substances emitted into a common measure expressed as the oxygen required for the degradation of dead biomass. Three EF impact categories are used to assess the impacts due to eutrophication: Eutrophication, terrestrial; Eutrophication, freshwater; Eutrophication, marine.

External Communication – Communication to any interested party other than the commissioner or the practitioner of the study.

Flow diagram – Schematic representation of the flows occurring during one or more process stages within the life cycle of the product being assessed.

Foreground elementary flows - Direct elementary flows (emissions and resources) for which access to primary data (or company-specific information) is available.

Foreground Processes – Refer to those processes in the product life cycle for which direct access to information is available. For example, the producer's site and other processes operated by the producer or its contractors (e.g. goods transport, head-office services, etc.) belong to the foreground processes.

Functional unit – The functional unit defines the qualitative and quantitative aspects of the function(s) and/or service(s) provided by the product being evaluated. The functional unit definition answers the questions “what?”, “how much?”, “how well?”, and “for how long?”.

Gate to Gate – A partial product supply chain that includes only the processes carried out on a product within a specific organization or site.

Gate to Grave – A partial product supply chain that includes only the distribution, storage, use, and disposal or recycling stages.

Global warming potential – Capacity of a greenhouse gas to influence radiative forcing, expressed in terms of a reference substance (for example, CO_2-equivalent units) and specified time horizon **(**e.g. GWP 20, GWP 100, GWP 500, for 20, 100, and 500 years respectively)**.** It relates to the capacity to influence changes in the global average surface-air temperature and subsequent change in various climate parameters and their effects, such as storm frequency and intensity, rainfall intensity and frequency of flooding, etc.

Human toxicity – cancer – EF impact category that accounts for adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to cancer.

Human toxicity - non cancer – EF impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.

Indirect land use change (iLUC) – It occurs when a demand for a certain land use leads to changes, outside the system boundary, i.e. in other land use types. These indirect effects may be mainly assessed by means of economic modelling of the demand for land or by modelling the relocation of activities on a global scale.

Input flows – Product, material or energy flow that enters a unit process. Products and materials include raw materials, intermediate products and co-products (ISO 14040:2006).

Intermediate product – Output form a unit process that is input to other unit processes that require further transformation within the system (ISO 14040:2006). An intermediate product is a product that requires further processing before it is saleable to the final consumer.

Ionising radiation, human health – EF impact category that accounts for the adverse health effects on human health caused by radioactive releases.

Land use – EF impact category related to use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in quality multiplied by the area).

Life cycle – Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO 14040:2006).

Life cycle approach – Takes into consideration the spectrum of resource flows and environmental interventions associated with a product from a supply-chain perspective, including all stages from raw material acquisition through processing, distribution, use, and end of life processes, and all relevant related environmental impacts (instead of focusing on a single issue).

Life cycle Assessment (LCA) – Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006).

Life cycle impact assessment (LCIA) – Phase of life cycle assessment that aims at understanding and evaluating the magnitude and significance of the potential environmental impacts for a system throughout the life cycle (ISO 14040:2006). The LCIA methods used provide impact characterization factors for elementary flows to in order to aggregate the impact to obtain a limited number of midpoint and/or damage indicators.

Life cycle inventory (LCI) - The combined set of exchanges of elementary, waste and product flows in a LCI dataset.

Life cycle inventory (LCI) dataset - A document or file with life cycle information of a specified product or other reference (e.g., site, process), covering descriptive metadata and quantitative life cycle inventory. A LCI dataset could be a unit process dataset, partially aggregated or an aggregated dataset.

Material-specific – It refers to a generic aspect of a material. For example, the recycling rate of PET.

Multi-functionality – If a process or facility provides more than one function, i.e. it delivers several goods and/or services ("co-products"), then it is "multifunctional". In these situations, all inputs and emissions linked to the process will be partitioned between the product of interest and the other co-products according to clearly stated procedures.

Non-elementary (or complex) flows – In the life cycle inventory, non-elementary flows include all the inputs (e.g. electricity, materials, transport processes) and outputs (e.g. waste, by-products) in a system that need further modelling efforts to be transformed into elementary flows. Synonym of activity data.

Normalization – After the characterization step, normalization is the step in which the life cycle impact assessment results are multiplied by normalization factors that represent the overall inventory of a reference unit (e.g. a whole country or an average citizen). Normalized life cycle impact assessment results express the relative shares of the impacts of the analyzed system in terms of the total contributions to each impact category per reference unit. When displaying the normalized life cycle impact assessment results of the different impact topics next to each other, it becomes evident which impact categories are affected most and least by the analyzed system.

Normalized life cycle impact assessment results reflect only the contribution of the analyzed system to the total impact potential, not the severity/relevance of the respective total impact. Normalized results are dimensionless, but not additive.

Output flows – Product, material or energy flow that leaves a unit process. Products and materials include raw materials, intermediate products, co-products and releases (ISO 14040:2006).

Ozone depletion – EF impact category that accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example long-lived chlorine and bromine containing gases (e.g. CFCs, HCFCs, Halons).

Partially disaggregated dataset - A dataset with a LCI that contains elementary flows and activity data, and that only in combination with its complementing underlying datasets yield a complete aggregated LCI data set.

Partially disaggregated dataset at level-1 - A partially disaggregated dataset at level-1 contains elementary flows and activity data of one level down in the supply chain, while all complementing underlying datasets are in their aggregated form.

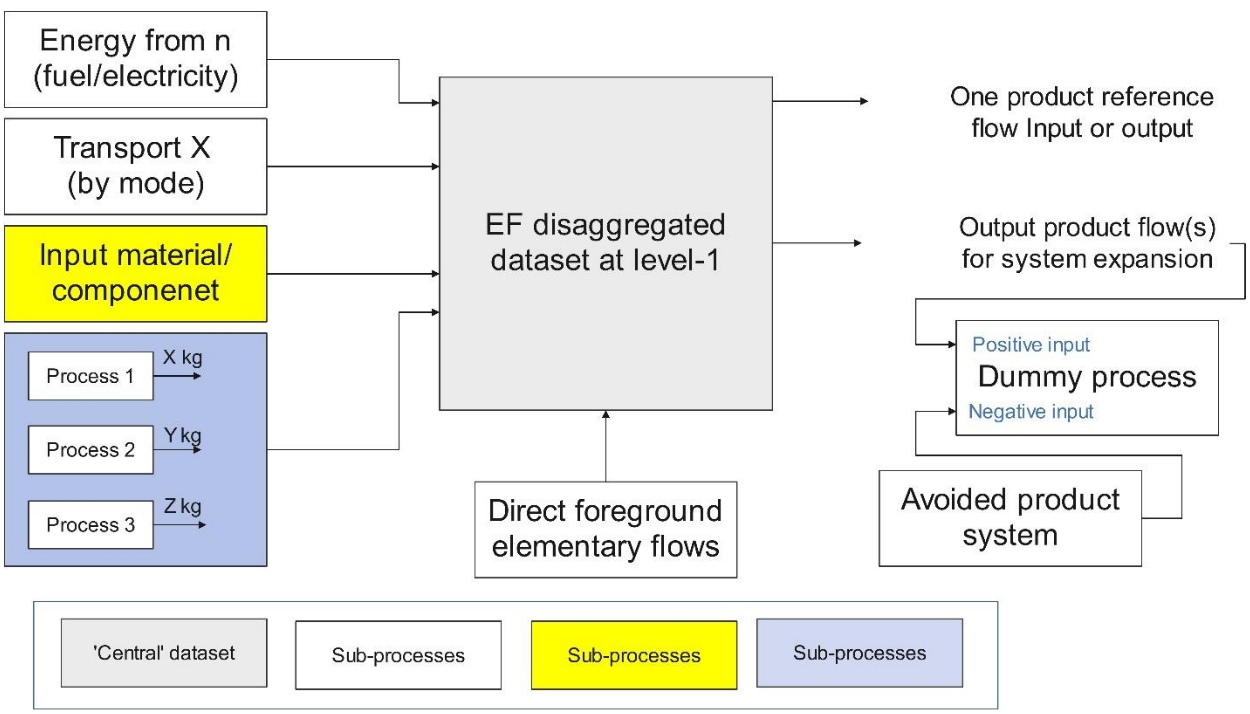

Figure 7. Example of dataset partially disaggregated at Level-1

Particulate Matter – EF impact category that accounts for the adverse health effects on human health caused by emissions of Particulate Matter (PM) and its precursors (NOx, SOx, NH3).

PEF profile – The quantified results of a PEF study. It includes the quantification of the impacts for the various impact categories and the additional environmental information considered necessary to report.

PEF report – Document that summarizes the results of the PEF study.

PEF study of the representative product (PEF-RP) – PEF study carried out on the representative product(s) and intended to identify the most relevant life cycle stages, processes, elementary flows, impact categories and any other major requirements needed for the definition of the benchmark for the product category/ sub-categories in scope of the PEFCR.

PEF study – Term used to identify the totality of actions needed to calculate the PEF results. It includes the modelling, the data collection, and the analysis of the results. It excludes the PEF report and the verification of the PEF study and report.

Photochemical ozone formation – EF impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manmade materials through reaction with organic materials.

Primary data - This term refers to data from specific processes within the supply chain of the user of the PEF method or user of the PEFCR. Such data may take the form of activity data, or foreground elementary flows (life cycle inventory). Primary data are site-specific, company-specific (if multiple sites for the same product) or supply chain specific. Primary data may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, material/product balances, stoichiometry, or other methods for obtaining data from specific processes in the value chain of the user of the PEF method or user of the PEFCR. In this method, primary data is synonym of "company-specific data" or "supply-chain specific data".

Product – Any goods or services (ISO 14040:2006).

Product category – Group of products (or services) that can fulfil equivalent functions (ISO 14025:2006).

Product Category Rules (PCRs) – Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories (ISO 14025:2006).

Product Environmental Footprint Category Rules (PEFCRs) – Product category specific, life cycle based rules that complement general methodological guidance for PEF studies by providing further specification at the level of a specific product category. PEFCRs help to shift the focus of the PEF study towards those aspects and parameters that matter the most, and hence contribute to increased relevance, reproducibility and consistency of the results by reducing costs versus a study based on the comprehensive requirements of the PEF method. Only the PEFCRs listed on the European Commission website (http://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm) are recognized as in line with this method.

Product flow – Products entering from or leaving to another product system (ISO 14040:2006).

Product system – Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product (ISO 14040:2006).

Raw material – Primary or secondary material that is used to produce a product (ISO 14040:2006).

Reference flow – Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit (based on ISO 14040:2006).

Releases – Emissions to air and discharges to water and soil (ISO 14040:2006).

Representative product (model) - The RP may be a real or a virtual (non-existing) product. The virtual product should be calculated based on average European market sales-weighted characteristics of all existing technologies/materials covered by the product category or sub-category. Other weighting sets may be used, if justified, for example weighted average based on mass (ton of material) or weighted average based on product units (pieces).

Resource use, fossil – EF impact category that addresses the use of non-renewable fossil natural resources (e.g. natural gas, coal, oil).

Resource use, minerals and metals – EF impact category that addresses the use of non-renewable abiotic natural resources (minerals and metals).

Sensitivity analysis – Systematic procedures for estimating the effects of the choices made regarding methods and data on the results of a PEF study (based on ISO 14040: 2006).

Site-specific data – It refers to directly measured or collected data from one facility (production site). It is synonymous to "primary data".

Subdivision – Subdivision refers to disaggregating multifunctional processes or facilities to isolate the input flows directly associated with each process or facility output. The process is investigated to see whether it may be subdivided. Where subdivision is possible, inventory data should be collected only for those unit processes directly attributable to the products/services of concern.

Sub-processes - Those processes used to represent the activities of the level 1 processes (=building blocks). Sub-processes may be presented in their (partially) aggregated form (see Figure 1).

Sub-sample - A sample of a sub-population.

Supply chain – It refers to all of the upstream and downstream activities associated with the operations of the user of the PEF method, including the use of sold products by consumers and the end-of-life treatment of sold products after consumer use.

System boundary – Definition of aspects included or excluded from the study. For example, for a "cradle-to-grave" EF analysis, the system boundary includes all activities from the extraction of raw materials through the processing, distribution, storage, use, and disposal or recycling stages.

System boundary diagram – Graphic representation of the system boundary defined for the PEF study.

Temporary carbon storage - happens when a product reduces the GHGs in the atmosphere or creates negative emissions, by removing and storing carbon for a limited amount of time.

Uncertainty analysis – Procedure to assess the uncertainty in the results of a PEF study due to data variability and choice-related uncertainty.

Unit process – Smallest element considered in the LCI for which input and output data are quantified (based on ISO 14040:2006).

Unit process, black box – Process chain or plant level unit process. This covers horizontally averaged unit processes across different sites. Covers also those multi-functional unit processes, where the different co-products undergo different processing steps within the black box, hence causing allocation problems for this dataset.

Unit process, single operation - Unit operation type unit process that cannot be further subdivided. Covers multi-functional processes of unit operation type.

Upstream – Occurring along the supply chain of purchased goods/ services prior to entering the system boundary.

User of the PEFCR – a stakeholder producing a PEF study based on a PEFCR.

User of the PEF method – a stakeholder producing a PEF study based on the PEF method.

User of the PEF results – a stakeholder using the PEF results for any internal or external purpose.

Water use – It represents the relative available water remaining per area in a watershed, after the demand of humans and aquatic ecosystems has been met. It assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived (see also http://www.wulca-waterlca.org/aware.html).

Weighting – Weighting is a step that supports the interpretation and communication of the results of the analysis. PEF results are multiplied by a set of weighting factors, which reflect the perceived relative importance of the impact categories considered. Weighted EF results may be directly compared across impact categories, and also summed across impact categories to obtain a single overall score.