Ecological Evaluation of Processes from Renewable Resources

Doctoral Thesis

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Dedicated to

All people who still believe in sustainability.

May this work help us along the way!

Thanks

To each and everyone.

And most of all to Prof. Narodoslawsky who provided this interesting topic and enabled me to look still farther beyond my own nose.

To all members and co-workers at the department for their support and the possibility to talk about almost everything.

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Abstract

Processes from renewable resources face many challenges from an ecological point of view. These challenges have to be taken up already during development phase as there the least effort of time and money is necessary to change the process. Process developers do not have broad experiences in the field of ecologic sustainability of processes. However the sustainability of these processes is an important factor for their success. In order to support process developers a software tool for ecological assessment was created based on a methodology especially suitable for engineering purposes. Applying this tool to different processes utilizing renewable resources common ecologically problematic fields were identified. This ecological "hot spots" of renewables processing were summarized into heuristics. These provide indications of starting points for sustainable process development.

Kurzfassung

Prozesse auf Basis nachwachsender Rohstoffe müssen sich aus ökologischer Sicht vielen Herausforderungen stellen. Diese Punkte müssen bereits während der Prozessentwicklungsphase Beachtung finden, da hier der zeitliche und finanzielle Aufwand für Änderungen im Prozess am geringsten ist. Die Nachhaltigkeit von Prozessen auf Basis nachwachsender Rohstoffe stellt einen wichtigen Faktor für den wirtschaftlichen Erfolg dar, allerdings besitzen Prozessentwickler nur wenig Erfahrung im Bereich der ökologischen Nachhaltigkeit von Prozessen. Um Ingenieure während der Prozessentwicklung zu unterstützen wurde eine Software entwickelt die auf einer Bewertungsmethode basiert, die speziell für die Erfordernisse von technische Fragestellungen zugeschnitten ist. Durch die Anwendung dieser Software auf unterschiedliche Prozesse von nachwachsenden Rohstoffen wurden Problemfelder identifiziert, die solchen Prozessen gemein sind. Diese ökologischen „Hot Spot" dienten als Grundlage um Heuristiken aufzustellen, die Prozessentwicklern als Ausgangspunkte in ihrer Arbeit dienen können.

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1 Introduction

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains two key concepts:

- *The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority shuld be given; and*
- *The idea of limitation imposed by the state of technology and social organization on the environment's ability to meet present and future need."*[1]

This statement was made by the World Commission on Environment and Development in a report (the "Brundtland-Report") in 1987. This report is the basis for most of the efforts of sustainability and sustainable development which occurred since then.

Today much attention is given to the use of renewable resources as a way to achieve sustainability. These topics are discussed widely not only inside the scientific community but in politics and industry too. Technology based on renewables is believed as a sure bet to contribute and achieve sustainability of future mankind.

The experiences of the past decades (oil crisis and continually rising prices) have shown the vulnerability of the fossil based economy. The number of years that these resources are believed to last varies greatly, depending on the person asked. Nonetheless it is a fact that someday we will run out of crude oil and natural gas.

The remaining deposits are concentrated in politically unstable regions, leading to unsure provision of fossil feedstock. The effect of this can be seen in the increasing of numbers and intensity of conflicts in such regions.

Besides the primarily economic and political issues the ecologic consequences of the use of fossil resources must also be considered. Here two main areas of can be discerned. The influence of fossil CO_2 on the climate change and the influence of fossil based agriculture on the environment.

The impacts of the unchecked consumption of fossil resources can be perceived clearly. Environmental effects as eutrophication, acidification, ozone depletion and climate change have been influenced by human activities stronger than ever.

More extreme temperatures in summer and winter were measured in many regions of the world and the increasing numbers of floods, draughts, hurricanes and other natural disasters have additionally heated the discussion of our role in the change of the earth.

Scientists are warning now that we move toward a "point of no return" in climate change, polluting the natural compartments with too many emissions. The only chance to avert crossing this point would be a massive decrease of fossil resource usage. The logical alternative is a change to renewable resources. However, this may lead to further intensifying of cultivation practices in agriculture and the agricultural sector itself is critical from an ecologic standpoint.

Mankind depends on the management and harvest of biological resources. Therefore, their habitats have always been influenced by the conversion of ecosphere into cultivatable land and still are. This conversion has been the most evident change on our planets surface, leading to the fact that at the beginning of this century mankind has put about half of the planets surface to their service. This was accomplished by massive land degradation and loss of biodiversity worldwide.

However, not the amount of land use itself led to these results but the kind of cultivation is the problematic point. Industrialized societies developed a way to breach the limitations of biological resources by utilizing fossil feedstock. Due to this fact mankind was able to decouple industrial activities from biological productivity. Renewable resources as feedstock lost importance in many sectors to be replaced by fossil ones. A whole new industry branch, the petrochemical industry, arose from these circumstances. This industrial sector creates synthetic materials and fossil based chemicals that were able to compete with and often outperform goods from renewables. This change also influenced the agricultural sector where the intensity of cultivation was increased by applying synthetic fertilizers and pesticides along extensive use of machinery.

1.1 *Problem Definition*

Due to these facts there exist two groups promoting the feedstock change from fossil to renewable resources. One group argues from an economic point of view with the goal of breaking the dependency from a feedstock that gets scarcer and more contentious. The other group acts from an ecological viewpoint to ensure that earth is habitable in the future. Regardless their reasoning, both groups propose a feedstock change to renewable resources. This shall solve the problems of present and future generations.

The question is if this change alone will really lead to a more sustainable industry and lessen our environmental problems? More likely the whole industrial system will have to change.

A contribution to this effort has been done in this thesis. As the inclusion of the ecological viewpoint in process development is relatively new, process developers don't have much experience of the critical factors leading a process to sustainability. In the present work such ecological "hot spots" and critical factors shall be identified to create heuristics applicable to process development for renewable resource processes. Additionally an easy to use tool for engineers shall be introduced, enabling the developers to accomplish ecological assessment and support their decisions.

1.2 *Working Hypothesis*

Following the described lines of thought the following hypothesis shall be examined in this thesis to provide engineers with heuristics for process development for renewable resources:

- Processes from renewable resources are inherently more sustainable than processes from fossil ones.
- Switching from fossil to renewable feedstock without further changing the structure of economy will lead to sustainable industry.
- Process development plays a major role in ensuring the sustainability of processes from renewable resources.
- Ecological assessment during process development is the perfect tool to ensure sustainable processes.

These working hypotheses will be reviewed in Chapter 9.

2 Ecological Assessment for Process Development

When a change in feedstock to renewables is to be implemented many actors have to act in unison: e.g. agriculture, forestry, industry, transportation. A main challenge will be to change the processes itself according to demands of the new feedstock.

Processes on the base of renewable resources always have an "intrinsic" perception of being environmentally friendly and sustainable. As this property is a major selling point for products generated by these processes there is a necessity to prove their sustainability credentials in a rigorous manner that can withstand the scrutiny of a competitive market.

Here engineers and process developers will play a key role on the way in realizing these processes. To ensure sustainable processes and sustainable industry it is therefore, necessary to equip process developers for this task – regarding the background as well as working tools.

Measurement of environmental sustainability of technological processes and goods is necessary to provide support for decisions regarding ecological problems. The challenge is to translate matters of ecological sustainability into the language of engineers neither limiting the field of application in terms of variety of technologies nor disregarding ecological interrelations on which sustainable concepts are based.

Life cycle assessment (LCA) is a good basis for product and process evaluation as was shown due to many studies. It is able to account for all environmental impacts incurred by the provision of the good in question. Strict standards for LCA are laid down in the ISO standards of the 14.00X family [2].

The ISO standard divides the Life Cycle Assessment in four phases (Figure 2-1). In the first phase a goal and scope definition has to be done. This includes the definition of system boundaries which clarifies the content of the life cycle assessment.

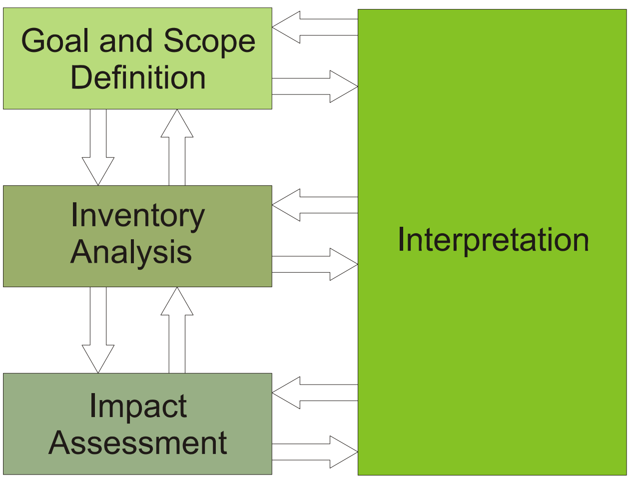


Figure 2-1: Structure of a Life Cycle Assessment according to the ISO 1400x norm

In the second phase data is collected and related to the process steps in question. Eco-inventories including all relevant input an output data of a process are assembled. If a process produces more than one product allocation methods have to be chosen.

In the following impact assessment phase the data is assessed according to the chosen methodology to obtain evaluation results. These results are then interpreted.

During the life cycle assessment results may be obtained that may propose a revision of prior phases, e.g. the system boundaries if a process has been excluded that now seems to be important. Therefore, LCA has to be seen as iterative process.

However, these standards only provide a guide how to proceed in the evaluation and do not prescribe a fixed evaluation method. In case of assessment of processes from renewable resources LCAs are further complicated as they face special methodological challenges. Firstly, many industrial renewable raw materials are by-products or surplus products from agricultural activities leading to other (more valuable) products. This leads to the fact that in contrast to conventional resources we face not linear value chains but more complex production networks. With multi-output processes the general problem of allocating the pressures of the agricultural sector arise (as agricultural production is not driven by generating the by product that is utilized). This may considerably influence the outcome of any assessment. In some cases the raw materials are even streams that are considered as waste, which makes a prudent valuation even more complicated.

The second challenge that has to be faced is the sustainability evaluation of processes leading to the same sort of goods on the base of different raw materials. This valuation must account for the different impacts from different raw material generations. Especially the difference between renewable and depletable raw material systems must be evaluated.

Next to these methodological challenges further requirements have to be met by ecological assessment for processes from renewable resources. It is a fact that a process will never be an ultimate solution and continuous optimization is necessary. This task contains making compromises as in improvements on one front often lead to disadvantages in others. When economical considerations are the basis of process development such decisions between benefits and drawbacks can be calculated easily as such tools have been provided and used constantly in the past decades. Comparing alternatives on ecological basis is much more difficult for an engineer as there exist many different problem fields where ecology is affected by processes, e.g. climate, health.

Most of the LCA are based on the problem oriented approach to impact assessment (Centrum vor Milieukunde Leiden, CML-method) [3],[4] resulting in various impact categories. They provide a reasonable communication and discussion tool for questions like which environmental problems are caused to which extent over the life cycle of a product. But in many "real world cases" improvements on one front, like reduction of greenhouse gas emissions, tend to lead to disadvantages in other areas. How to weight an increase in greenhouse gas emissions against a decrease in acidification potential?

Ecological assessment for process development has therefore, to lead to a highly aggregated number which can be compared easily. In order to be of interest for a process developer this aggregated number will have to be sound from a scientific vantage point of view as this is the basis for engineering. Instead of eco-indicators (e.g. EcoIndicator 99 [5][6]) that are based on weighing factors set by experts that are thus not undisputable, a tool for engineering puposes must have a more generally acceptable methodological base.

The Sustainable Process Index, which will be explained in detail in the next chapter, fulfills all the above mentioned demands.

3 The Sustainable Process Index

3.1 *Methodology Principles*

Energy which is consumed inside a system has to be renewed by provision from outside. This also holds true for the earth, a system of its own. The energy source here is the solar radiation. As society is highly dependent on energy as it is the driver of all life on earth the definition of a sustainable society has to be based on a sustainable energy provision.

Therefore, energy emitted from the sun represents the only energy source for a sustainable society. This energy is used by many natural processes which in themselves are sustainable. To collect and utilize this solar energy e.g. in form of photosynthesis, surface area is needed. This also holds true for anthropogenic utilization of solar radiation like photovoltaic panels.

Although available practically indefinitely solar radiation is a limited flow as it is received by our planets finite surface. Therefore, all natural as well as anthropogenic activities compete for surface to utilize the limited flux of solar energy that they need for sustaining themselves.

This concept was developed in parallel from two different points of departure. Rees and Wackernagel looked at the problem from the economical point of view whereas Narodoslawsky and Krotscheck focused on the engineering perspective. These approaches led to the "ecological footprint" [7] and the Sustainable Process Index (SPI) [8].

The Sustainable Process Index focuses on aspects of environmental sustainability for engineers and the factors they can influence most effectively. These factors are material and energy flows that processes exchange with their environments.

The SPI uses a concept for environmental sustainability taking into account the limitation in the natural income for setting criteria for the exchange of material flows between anthroposphere and the environment.

These criteria were developed by SUSTAIN [9]. The criteria are:

- Human activities must not alter long term storage compartments of global material cycles in quality as well as in quantity. If this principle is not adhered to resources will be depleted and substances accumulated in ecosphere, overstraining the natural cycles.
- Flows to local ecosphere have to be kept within the qualitative and quantitative range of natural variations in environmental compartments. If such flows exceed the amount a compartment can integrate the accumulating substances will alter the compartment. This alteration can lead to a local environment that is no longer able to sustain flora and fauna.

- Also preservation of a variety of species, landscapes and habitats has to be preserved or increased. Variety is an important factor for flexible response of natural systems to pressures.

3.2 *Methodology Calculations*

With some simple algorithms the Sustainable Process Index uses the lines of argument stated above to convert material and energy flows extracted from and dissipated to the ecosphere into area, the “ecological footprint”.

The engineering data needed for calculating the SPI and the ecological footprint of a process are the energy and mass flows. This data are roughly known already early in process development. The corresponding data for natural systems are the sedimentation rate of carbon in oceans, the natural concentrations of substances in soil and water, the exchange rates per area unit of airborne pollutants between forests and air as well as the replenishment rates for soil and water. Most of the natural flow and quality data allow a certain "regionalization" of the SPI wherever that is needed.

The calculated amount of surface represents the area required by nature to reintegrate the mass and energy flows consumed and produced by a process in a sustainable way. This means in a way that does not overextend or overstrain the global material cycles or regeneration rates of compartments. The larger this footprint, the higher is the ecological “cost” for this product.

The overall pressure P_{tot} consists of partial pressures calculated by Eq. (3-1)

$$P_{tot} = P_R + P_E + P_I + P_S + P_P \qquad (3\text{-}1)$$

P_R represents the pressure due to resource provision, P_E the pressure of energy and electricity provision. P_I and P_S stand for the installations needed to run the process and the support of the staff running it respectively. P_P is the pressure caused by emissions from the process.

As all these pressures in form of mass and energy flows are based on different units. They have to be converted to a common unit for summarizing them to an overall pressure of a process. This common unit is the limiting component of a sustainable industry, the surface area.

Utilizing the principles described above, a conversion of ecological pressure, represented by mass and energy flows, into area is possible. As is the case with the ecological pressure, the total surface area needed for a process, A_{tot}, consists of different partial areas representing the same environmental aspects as the partial pressures (Eq.3-2).

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \quad [m^2] \tag{3-2}$$

For the mathematical conversion of the ecological pressure to area usage different methods are applied depending on the kind of pressure.

3.2.A The raw material area A_R

This area summarizes the pressure derived from raw material provision. As a life cycle approach is used this area also takes into account pressures that are indirectly caused, like energy used for cultivating agricultural products or mining of ores.

The area of resource provision includes the provision of renewable resources A_{RR}, fossil resources A_{RF} and non renewable resources A_{RN}. Additionally this area takes into account pressures caused by the provision of intermediates A_{RI}, goods produced inside anthroposphere from other products without directly utilizing resources from ecosphere like chemicals or polymers (Eq.3-3).

$$A_R = A_{RR} + A_{RF} + A_{RN} + A_{RI} \quad [m^2] \tag{3-3}$$

For converting the raw material pressure into a footprint, different concepts have to be used depending on the feedstock.

3.2.A1 *Fossil Raw Material A_{RF}*

The same reasoning can be applied to fossil organic raw materials as they are also part of a global cycle (Figure 3-1). This global cycle possesses some bottlenecks, especially the mass flow into the long time storage, which is mainly the sedimentation onto the beds of the oceans. This step in the global cycle has a large timeframe and is responsible for the accumulation of carbon in other compartments as society is producing more carbon than this long time storage is able to store in the same time. Considering this fossil carbon can be treated as renewable resources albeit with a low rate of regeneration.

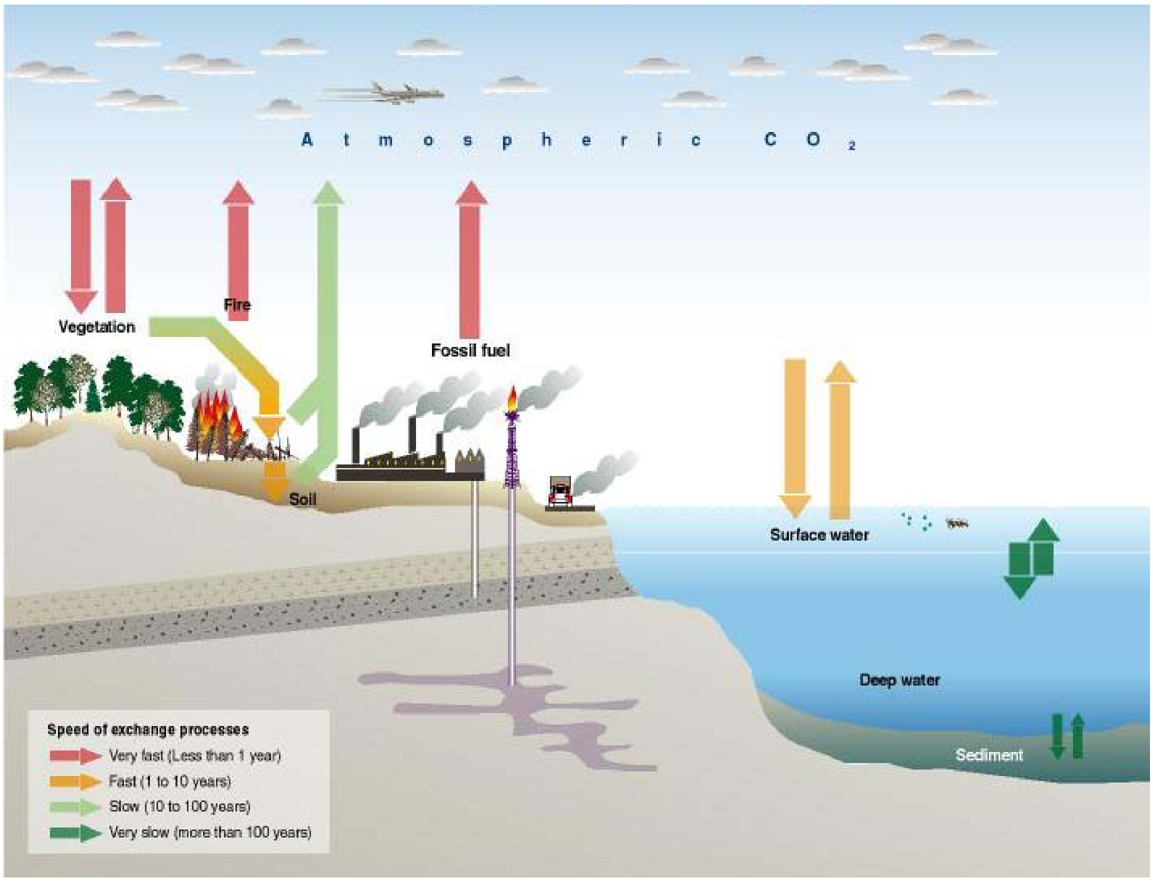


Figure 3-1: Flows of the Global Carbon Cycle and their relative exchange speed [10]

According to the first principle for a sustainable society described above only as much fossil material may be used as can be stored in the same time by long-term storage. In this case there is neither an alteration of the global cycle itself nor an unsustainable accumulation in other compartments like atmosphere.

The regeneration yield of fossil resources by sedimentation was calculated as 0.002kg/m^2 [11]. The resulting area is 500m^2 to provide one kg of organic sediment sustainable.

3.2.A2 *Renewable Raw Materials A_{RR}*

Renewable raw materials are basically products from agriculture, aquaculture and forestry and take part in the global carbon cycle. To close the carbon cycle for renewable resources the bottleneck in the cycle is the conversion of CO_2 into plants.

Therefore, area required for sustainable provision of these resources is the area needed to convert basic materials available in biosphere into biomass. This is in the case of agriculture for example the area required to grow wheat or sugar beets. Knowing the average yield y_R of agricultural products per area and the needed input (or feed) for growing products F_R the renewable raw material area can be calculated:

$$A_{RR} = \frac{F_R}{y_R} \quad [m^2] \tag{3-4}$$

Likewise the calculations in fields of renewable resource production other than agriculture like forestry apply.

3.2.A3 *Non Renewable Resources A_{NR}*

Non renewable resources are used inherently dissipative by society. Therefore, the impact for these materials is generally separated into two parts: the provision of the material and the reintegration into the biosphere at the end of their life cycle. The provision is taken into account within the raw material area A_{RN}, the reintegration is covered in the dissipation area (detailed below). The area A_{NR} takes into account the impact to provide a non renewable material to the factory gate.

Wherever no comprehensive data for this impact from these materials is available, the energy input (e.g. process heat, electricity and mechanical power) for mining and refining is taken as a proxy, as this usually provides the largest impact. Thus, if the energy demand E_D to process a non renewable resource F_{NR} is known, the area requirement can be calculated by

$$A_{RN} = \frac{F_{NR} \cdot E_D}{y_{EL}} \quad [m^2] \tag{3-5}$$

The yield y_{EL} characterizes the energy yield for industrial energy. This energy yield as well as the distribution of e.g. process heat and electricity may vary with the geographic context and technologies used to supply energy.

If even the energy use of the material provision is unknown, a rough estimation of consumed area is made via the retropagatoric method [12]. The price of the raw material C_N on the world market as well as the industrial energy price C_E is taken as base for the calculation of the energy demand E_D.

$$E_D = \frac{C_N \cdot 0.95}{C_E} \quad [\text{kWh/kg}] \tag{3-6}$$

This method assumes that energy costs are the predominant contributor (95%) to the price of the basic raw material. This estimation holds true for a large number of non renewables with only minor deviations from the factor 0.95 which is therefore, included in the calculation.

3.2.A4 *Intermediate Resources A_{RI}*

In most processes this resource category generates a large fraction of the ecological pressure as most processes use products from other processes. Intermediates are not resources taken from ecosphere to be processed in anthroposphere but are "anthropogenic" resources. They themselves do not inflict ecological pressure on the environment as they do not cross the boundary between anthroposphere and ecosphere. Nonetheless their production and provision results in ecological pressure. The use of resources, energy, emissions and the other categories is described in this chapter (Eq. 3-7).

$$A_{RI} = A_{R,RI} + A_{E,RI} + A_{I,RI} + A_{S,RI} + A_{P,RI} \quad [\text{m}^2] \tag{3-7}$$

Taking a closer look at intermediates, as well as any other product their life cycle can be broken down to mass and energy streams between ecosphere and anthroposphere, if one follows the process chain long enough. The calculation of the ecological pressure of intermediates is complicated by the fact that many of them are linked iteratively by common sources or processes. For example to produce diesel you have to transport crude oil, but for transportation you need diesel. This requires an iterative approach to the calculation of the processes and subsequent areas for intermediates.

3.2.B The energy supply area A_E

The area for sustainable energy provision consists of three parts: The area for provision of natural resource A_{ER}, the area for processing these resources A_{EP} and for converting them to energy A_{EC}.

$$A_E = A_{ER} + A_{EP} + A_{EC} \quad [m^2] \qquad (3\text{-}8)$$

This area varies considerably with the quality of the energy needed (different temperature levels of process heat, electricity or mechanical power etc.) and the transformation technology. As a rough guideline it can be said that the higher the quality of the energy service the higher the area required for supplying it.

3.2.B1 *Area of natural resource A_{ER}*

Each energy production utilizes some primary resource for the production process. This may be fossil resources like coal or crude oil. It may also be biomass, wind or solar radiation. As most of these resources either is derived from fossil or renewable feedstock the calculation methods applied here have been described above. In the case of e.g. solar panels utilizing solar radiation the amount of surface area is determined by the area claimed by the installation. The same holds true for wind and hydro power.

3.2.B2 *Area of energy processing A_{EP}*

Many energy carriers like coal, oil or fissible material cannot be directly used in their natural state. They have to be refined, processed and often transported over long distances. The processes mainly consist of intermediate input and emission outputs. These are calculated as described in the respective chapter of this thesis.

3.2.B3 *Area of energy conversion A_{EC}*

For converting the processed raw material into energy, installations and operating resources are needed. Installations are described in the next part while operating resources follow the calculation in the part describing the area for resource provision.

3.2.C The area for installation A_I and staff A_S

The economical point of view discerns investment goods and installation as well as staff costs as important factors of a process and as a main point of economic evaluation. However, many case studies applying the SPI have shown that these factors are much less important in evaluating environmental sustainability albeit they may not be neglected in specific cases.

The area for installation distinguishes direct area use A_{ID} and area for the provision of buildings and process installation A_{II}.

$$A_I = A_{ID} + A_{II} \quad [m^2] \tag{3-9}$$

3.2.C1 *Direct Land Use A_{ID}*

This represents the area used in the form of factory area or infrastructure area like roads. Here the conversion is not needed as land use is already measured in m^2 which can be applied directly.

3.2.C2 *Provision of buildings and process installation A_{II}*

Industrial installations are made of products from industrial processes like steel or concrete. According to the resources used for the process installations or buildings, e.g. renewables, fossil or non renewable resources, the methods shown above are applied for conversion of the pressure caused by their production to surface area.

If no material flows for installation are available, a rough estimation of the investment may be calculated via the retropagatoric method in the same way as described for non-renewable resources. The input data used for this pressure are costs which are usually known to the engineer to ensure economic success of a developed process. Costs are related to construction material input by using averaged industry data. The ecological area needed for this construction material mix can be calculated like provision materials.

As the timeframe of ecological process analysis is usually one year and investment goods serve over the full life time of a process, the impact of these utilized goods has to be depreciated much like in economical analysis.

3.2.C3 *Area for staff A_S*

Staff can be factored in by adding the "statistical area per inhabitant" a_{in} for the number of employees N_S needed for the process to the total area.

$$A_S = N_S \cdot a_{in} \quad [m^2] \tag{3-10}$$

This partial area however, is only worthwhile calculating when comparing alternatives with vastly differing workforces to provide the same good or service. In the case studies presented later the ecological pressure provided by staff is always excluded as irrelevant.

3.2.D The area for dissipation of products

Besides the raw material and energy provision areas the area for emission dissipation is always prominent. Even if the process itself does not produce much or no emission, as in the case of photovoltaic, the provision of resources and energy for the process generates emissions and waste.

The idea behind the calculation of this area is based on the second principle stated above that every emission must not alter the quality of the compartment (air, water and soil) it is emitted to. Therefore, every flow leaving the process has to be dissipated to the environment until a natural concentration is reached. So the amount of emitted substances must be related to natural rates of regeneration and natural concentration of the particular substance in the compartment in question.

The following method is applied to calculate the area needed for sustainable dissipation of substances: If there is a rate at which a given environmental compartment is renewed, any product stream can be 'diluted' by the newly added mass, until the concentration of the substance is equal to the quality of the initial compartment. Therefore,, it is necessary to know the natural concentration of different components as well as the rate of renewal of a certain environmental compartment.

Following this reasoning the area for sustainable dissipation can be calculated using the rate of renewal R_C of the environmental compartment, the natural concentration of the substance $c_{c,i}$ in the compartment c and the emission flow $F_{P,i}$ to this compartment. The index i describes a certain substance.

$$A_{P,c,i} = \frac{F_{P,i}}{(R_c \cdot c_{c,i})} \quad [m^2] \qquad (3\text{-}11)$$

This calculation has to be made for all emission flows leaving the process. The surface area of emission dissipation in a certain compartment that is added to the ecological pressure of the whole process is the largest area calculated for this compartment for any given flow. All emissions that result in a smaller area will be sustainable dissipated in this area as their concentration in the "replenished" compartment will stay below the natural level.

$$A_{P,c} = \max\ (A_{P,c,i}) \quad [m^2] \qquad (3\text{-}12)$$

Therefore, the area for all emissions consists of the sum of the largest area for the dissipation in the compartments of air A_{PA}, water A_{PW} and soil A_{PS} for any given flow leaving the anthroposphere.

$$A_P = A_{PA} + A_{PW} + A_{PS} \quad [m^2] \qquad (3\text{-}13)$$

3.2.D1 *Area for emissions in water A_{PW}*

The basis for the assimilation capacity in the compartment water is the seeping rate to the ground water body which is usually between 30 and 50% of the precipitation rate per m². The seeping ratio $r_{S,r}$ as well as the precipitation P_r varies from region to region.

With this data the replenish ratio $R_{W,r}$ of the compartment water for a certain region r can be calculated.

$$R_{W,r} = P_r \cdot r_{S,r} \quad [kg/m^2a] \qquad (3\text{-}14)$$

3.2.D2 *Area for emissions in soil A_{PS}*

Soil is replenished by the process of composting which is therefore, the base of the calculation. Composting biomass produces a 'soil-like' material that can be used to replenish top soil. The mass of compost resulting from 1m² of fresh biomass is the basic unit in this case as composting needs fresh biomass. This renewed soil is supposed to be empty of substances and thus emission flows can be sustainable dissipated in this renewed compartment.

Knowing the yield of humus soil from biomass y_S as well as the losses during conversion r_L the replenishment rate of soil R_S can be calculated.

$$R_S = y_S \cdot (1 - r_L) \quad [kg/m^2a] \qquad (3\text{-}15)$$

3.2.D3 *Area for emissions in air A_{PA}*

For the compartment air no replenish rate like for water and soil exists. Nonetheless forests emit substances into air due to a natural process. These exchange rates are the base for comparison of emissions into soil which are known for most relevant gases.

3.3 *Methodology Results*

The Sustainable Process Index was developed to apply ecological assessment to process development. For this purpose the impact per good or service unit resulting from a given process is of interest. This is represented by the overall footprint of a product a_{tot} (Eq.3-16).

$$a_{tot} = \frac{A_{tot}}{N_P} \quad [m^2/unit\ a^{-1}] \qquad (3\text{-}16)$$

N_P is the number of goods or services supplied by the process in question for a reference period. In general this reference period will be one year, as most natural and engineering flow data are available on a yearly base [13]. This leads to the unit of the ecological footprint, as area use [m^2] per produced goods during a reference period [unit a^{-1}].

The area derived from a specific process to provide a specific good or service can be related to the area that is statistically available to a person. This relation represents the "cost" in terms of ecologic sustainability of this particular good or service within the framework of a “natural budget”, the SPI (Eq.3-17)

$$SPI = \frac{a_{tot}}{a_{in}} \quad [cap/unit\ a^{-1}] \qquad (3\text{-}17)$$

Here a_{in} is the area per inhabitant in a given region. The lower the SPI the lower is the ecological impact of providing the good or service on the ecosphere.

From these results process engineers can obtain a number of information. Some are obvious, to retrieve others the engineers have to do further calculations or use assessment tools like SPIonExcel which will be presented in the next chapter.

With the overall footprint the engineer is able to assess different processes or process step alternatives, giving him support in his decisions from an ecological point of view. He is able to base his choice of process units on ecologic considerations and not only on economic ones.

Calculating the overall footprint of different process steps (Eq.3-16) within a process enables to identify the step in the life cycle that is the most problematic from the view point of sustainable development. This process step has to be the premium target for technological optimization and can be analyzed and optimized specifically by the engineer after its identification.

Taking a closer look at process steps, the partial areas in Eq.(3-2) allow the identification of the largest contribution to the overall impact in terms of its origin. Thereby the engineer is able to detect problematic spots inside or outside a process that may reduce its sustainability. It can be discerned if e.g. ecological problems arise because of emissions caused by the process or if the feedstock of a process derives from an unsustainable prechain which impairs ecological competitiveness of the process itself. With these results an engineer is able to develop alternative process units, add additional treatment technologies or change the raw material base accordingly.

The results of a SPI analysis also contain information relevant for politics and society as the SPI calculated by Eq.(3-17) gives an indication to the overall picture of individuals or society and their relationship with environment. The number indicates what fraction of the overall "ecological budget" of a person is used to provide a good or service.. When all goods used by a person are summarized the sustainability of this person's lifestyle can be evaluated. Figure 3-2 shows an example for this calculation

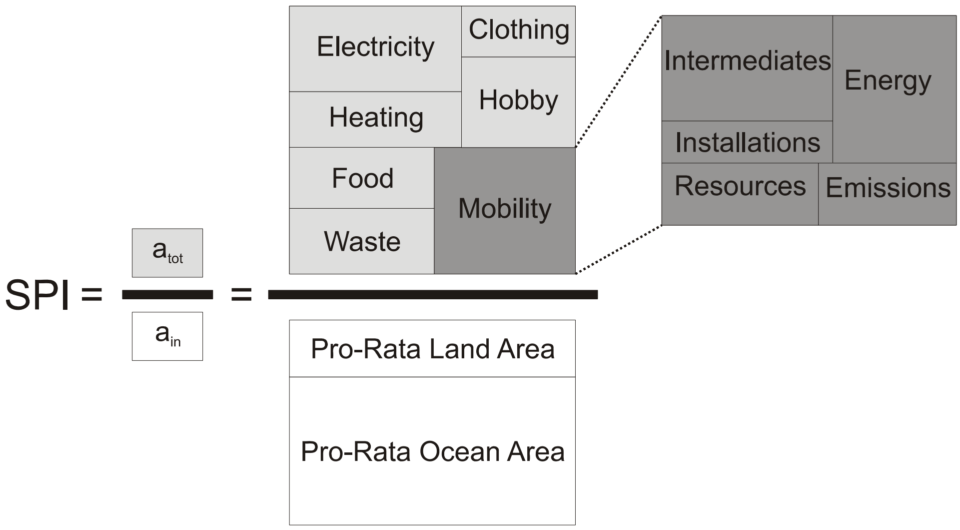


Figure 3-2: SPI of transportation

3.4 *From theory to practical experience*

The genesis of the Sustainable Process Index reaches back more than 10 years. During this time work has proceeded using this methodology. As every method applied to practical experience, the Sustainable Process Index had to be adapted to real life problems.

The description of the method in this chapter does not differ from the original descriptions in terms of principles and calculation rules, but it expands it to fit the requirements of today engineer's work and to make it easier to understand and work with. Therefore, some elements like the area for provision of intermediates had to be added. Other categories like area for staff support are still included, but from experience with the Sustainable Process Index it can be seen that they have almost no influence on the ecological footprint of industrial processes. However, this may not be true for the service sector.

In the beginning SPI application the process infrastructure showed a negligible influence in most processes. This holds especially true when looking at large scale industrial processes.

Over the years however, examples have been found that contradict this generalization. The influence of infrastructure on the ecological footprint of processes like street and railway transportation is strong. The reason for this is that road and rail networks are huge installations and maintenance is intensive compared to the amount of vehicles utilizing it. Other processes almost exclusively use infrastructure and no or negligible mass and energy flows during operation as water power plants. So the process at hand has to be considered thoroughly before neglecting the influence of infrastructure.

The first concept of the SPI added only the largest partial footprint of all emissions to the overall footprint, regardless of the compartment where the pressure arose. Experience showed that the addition of the largest partial footprints of each compartment led to better results.

Summarizing the experiences with the Sustainable Process Index methodology it can be said that for process development a lot of important information for engineers can be obtained regarding the environmental pressure of a process in development.

Still the method has its limitations and it is important to know about and accept them. No assessment method can answer all questions and the kind of question asked will define the best method to use. If the user is looking for toxic risk assessment the SPI is the wrong method, if he wants to focus on specific impacts like greenhouse gas potential he would be better off working with another method. But if an engineer wants to compare process alternatives and their overall ecological pressure to help him decide which one is more sustainable or needs information about ecological problematic process steps and flows inside a process he will find the SPI as a very valuable tool.

4 SPIonExcel

4.1 *Introduction*

This chapter deals with the software SPIonExcel. SPIonExcel was developed as life cycle assessment tool for the Sustainable Process Index methodology. The software introduced by Sandholzer et al. [7] can be used to easily and quickly calculate the ecological footprint and the SPI caused by a particular process. In order to ensure easy implementation it is programmed as a Microsoft Excel for Windows Macro and for wide distribution it is made available on the internet.

4.2 *Software Calculation*

SPIonExcel calculates the ecological footprint of a process and the SPI of a product or service through the input that characterizes the process given by an eco-inventory. The eco-inventories used for the calculation of the overall footprint contain engineering mass and energy flows of processes in terms of input and output flows. Thereby two different classes of inputs, impacts and intermediates, can be discerned (Figure 4-1).

Impacts are flows that cross the border of antroposphere and ecosphere and represent resource flows from ecosphere to antroposphere or emission flows in return. Examples are component flows like the emission flow of cadmium into a certain compartment. Another example would be substances that are not the result of an up-stream industrial process like raw natural gas or crude oil.

Intermediates are flows inside of antroposphere, meaning product streams exchanged between different processes inside of industrial production.

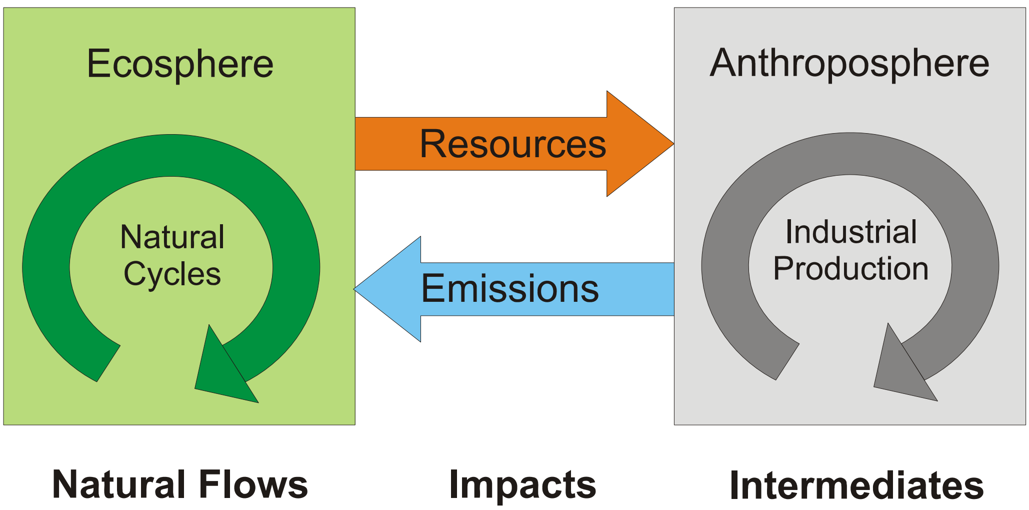


Figure 4-1: Distinction of natural flows, impacts and intermediates

Intermediates include services like electricity and transportation or waste going to treatment plants as well as products going to final consumption. Intermediates are produced via processes using themselves mass and energy flows. Therefore, their ecological pressure can be traced back to these flows, which in themselves can be either impacts or other intermediates. Net electricity for example consists of different electricity provision systems e.g. nuclear or biomass energy, which use mass and energy flows themselves for the provision of this intermediate.

Each intermediate has an underlying process with its specific inputs and outputs, be they other intermediates or impacts. Through more and more detailed examination of the processes in the life cycle of a given good or product, the ecological pressure of the process chain can theoretically be broken down to a point where only impacts (meaning direct flows from or to the ecosphere) are represented as causes for this pressure.

Every impact and intermediate has a calculated amount of area that mirrors the ecological pressure it causes for a given process (Eq. 4-1).

$$a_{part,n} = m_n \cdot y_{spec,n} \quad [\mathrm{m}^2/\mathrm{unit\ a}^{-1}] \tag{4-1}$$

This area, the partial footprint $a_{part,n}$, is caused by either an intermediate or an impact used or generated by the process. m_n is the amount of mass, energy, volume or distance (for transportation) of the flow n used or caused by the process, whereas the specific footprint $y_{spec,n}$ is the ecological pressure of one unit of this intermediate or impact.

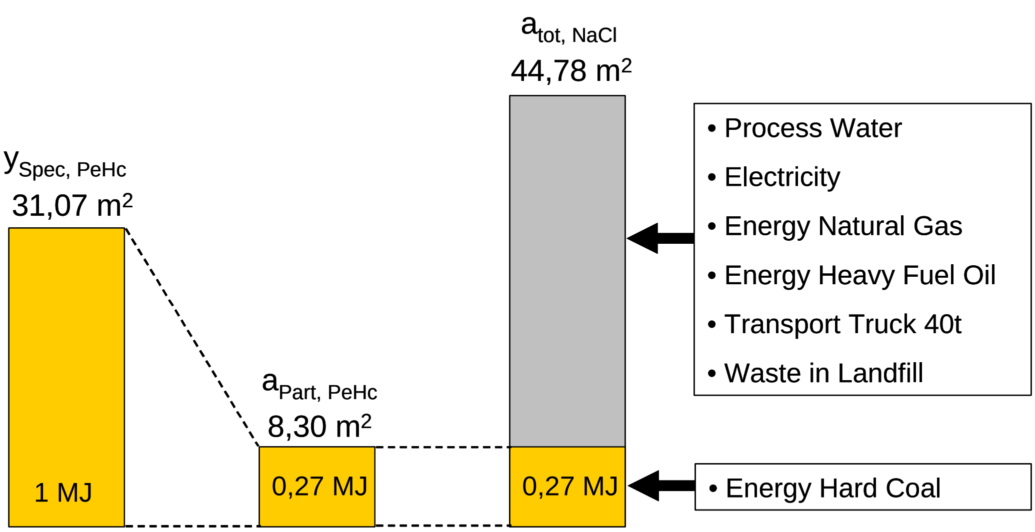


Figure 4-2: Calculation process for the total footprint $a_{tot,NaCl}$ for the production of sodium chloride on the example of process energy input of hard coal (PeHc). The specific footprint of 1MJ process energy of hard coal $y_{spec,PeHc}$ is multiplied with the amount put into the process m_{PeHc} 0,27MJ. The resulting partial footprint $a_{Part,PeHc}$ is summarized with the partial footprints of other inputs to form the total footprint $a_{tot,NaCl}$ of 1kg sodium chloride

All partial footprints calculated by the mass and energy inputs and outputs of all processes along the life cycle, are added up (according to the methodology described in the method section), and result in the overall ecological footprint a_{tot} for a unit of a desired product or service (Figure 4-2).

To assure a better overview of the origin of the contributions to the ecological footprint of a process, the inputs have been divided into categories. There are 7 different categories each represented by a different color:

- Area consumption (impact)
- Non renewables consumption (impact)
- Renewables consumption (impact)
- Fossil C consumption (impact)
- Emissions in air (impact)
- Emissions in water (impact)
- Emissions in soil (impact)
- Waste materials (impact)
- Product or processed input (intermediate)

Within the software these categories are discerned in the shown color code.

Area consumption, consumption of fossil carbon, renewable and non renewable resources are impacts whose partial footprints are summarized along with the partial footprints of intermediates used by the process. The dissipation of substances in water, air and soil are impacts where only the largest footprint of a specific flow (e.g. the emission from a certain process in the process chain) is added to the overall footprint, according to the general SPI method.

Waste materials as input are a special case of impacts. Their specific footprint is 0, because their intended use to society has already been fulfilled. They are not produced (as waste) for a special application even if there are processes that depend on them as feedstock, like steel production depends on scrap metal. Their ecological impact has already taken effect during their primal use before becoming a waste material. The waste material itself is like a new resource that just is there to be used, without any ecological pressure derived from a pre-chain. Waste materials do not contribute to the ecological footprint however, they are included in the eco-inventory none the less because they may be important inputs to the process. If they have to be transported or treated before entering a process, they will accrue an ecological footprint derived by these activities.

An example of a used eco-inventory and the resulting footprint of a process are given in Table 4-1.

Table 4-1: Eco-inventory for the production of 1kg sodium hydoxide

Feedstock	Sodium chloride	kg/kg	1.45E+00
Resources	Process Water	kg/kg	7.00E+00
Energy	Electricity	kWh/kg	2.96E-06
Emissions	Hg (water)	kg/kg	1.18E-06
	Dichloro monofluoro methane (air)	kg/kg	1.05E-05
Waste	Waste in disposal	kg/kg	2.33E-02
Byproducts	Chlorine	kg/kg	8.89E-01
	Hydrogen	kg/kg	5.00E-02

4.3 *Software Structure*

For calculating the SPI and the overall footprint the software is able to work with different Access databases.

Regarding the content three different kinds of databases can be discerned (Figure 4-3)

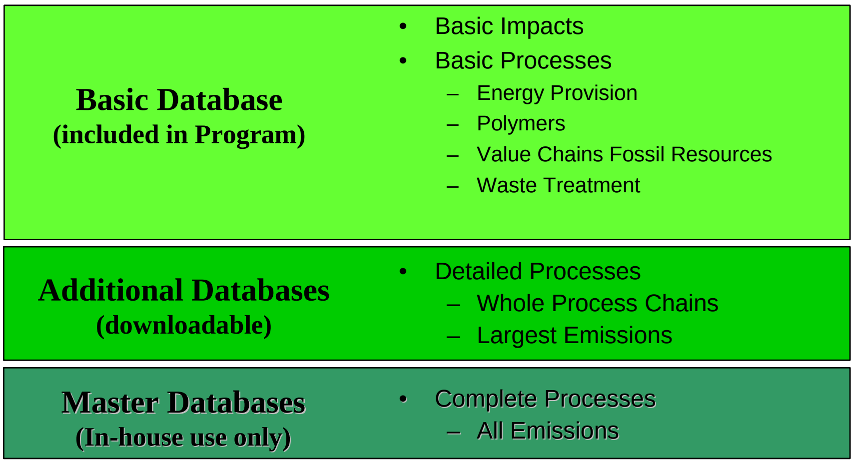


Figure 4-3: Database structure

The most important database which is implemented in the software is the basic database. This database includes the specific footprints of impacts (that is direct flows from and to the ecosphere) and a number of processes in the areas of transportation, electricity and energy provision, agricultural raw material provision as well as production of various chemicals and materials that are used as intermediates in various process life cycles. With these impacts and intermediates the user is able to assess a wide variety of processes without the necessity to collect specific data.

The processes leading to intermediates stored in the basic database, called "Short Processes" (identified in the database by the abbreviation SP), do not show the detailed input and output flows. However, the distribution of the footprint according to the impact categories area use, use of renewables, non renewables, fossil resources and emissions in air, water and soil are shown in the reports of the calculation. The information stored in the data base for Short Processes therefore, allows the analysis if the predominant ecological pressure of such a process is derived from an emission or a resource provision without providing further detail. With the intermediates provided by these Short Processes the user is able to create new processes with a minimum of effort. Fast results are obtained and the origin of the ecological pressure can be identified. This fulfills the requirements of most applications for an estimation of the ecological pressure of a process where a detailed eco-inventory of the whole life cycle is not of predominant interest.

Next to the basic database which can always be accessed it is possible to access at the same time data from one additional database. This can be chosen out of many thematic databases provided on the software homepage or created by the user herself. These thematic databases include more detailed data of the whole processes chain within the life cycle of a product or service.

The following thematic databases can be down loaded from the software homepage:

- Energy and Electricity Provision
- Transportation and Construction
- Chemicals and Materials
- Metals
- Polymers
- Agriculture
- Production and Use of Crude Oil
- Production and Use of Raw Natural Gas
- Production and Use of Hard Coal and Lignite
- Production and Use of Fissible Material

In these databases detailed process chains, from resource provision to end products are accessible. The processes (for differentiation these processes are identified by the abbreviation DP for Detailed Process) contain an eco-inventory including all relevant inputs and outputs used in the calculation of the partial footprints. However, for emissions and wastes only the flow with the largest impact in each one of the three emission categories air, water and soil is included (according to the methodology).

The third kind of database is the master database. This contains fully detailed processes, which include all emission flows. For each thematic database containing detailed processes exists a master database with the same processes but with all emissions. These databases are classified and only for in-house use and cannot be provided to software users for copyright protection reasons. The processes inside master databases contain the abbreviation FP for Full Process.

To work with the software and calculate ecological footprints full processes are not needed because detailed processes lead to the same results as both process types have the same footprint. Therefore, the master databases can be seen as complete eco-inventories to be utilized for other applications besides calculating the ecological footprint.

A very important point as far as data is concerned is the re-traceability to their source of origin. Therefore, each dataset in the respective database includes cells where the data source can be identified as well as a comment field where additional information, like additional assumptions used for the calculation, is stored.

4.4 *Software Outputs*

As a basic principle SPIonExcel calculates the ecological footprint of a process and the SPI of a product or service. However, the software can provide more information.

Additional information is given by the percentage fraction of the contribution of partial footprints to the overall footprint. This identifies which intermediate or impact inflicts the largest pressure on environment. The percentage is not only shown numerically but also in a color code showing the amount of the percentage. Low percentages are shown in grey and as they are increasing the color changes from white over yellow to red (for partial footprints contributing over 34%).

Additionally the distribution of the footprint according to the impact categories, (represented by the color code defined above) is presented. This distribution shows if the overall footprint is mainly derived from an emission, a resource provision or intermediates used in the process.

If a process has more than one product the overall footprint has to be allocated to the different products reflecting their share of the ecological pressure on environment. This can be done in different ways of which the software is able to apply five methods.

The first method is the allocation of the whole ecological pressure on one primary output. All by-products in this case have an ecological pressure of zero. This method is preferable when the by-products are waste or have no value. In the case of waste it has to be ensured that a possibly needed waste treatment is included in the eco-inventory of the process.

The second possibility, mass allocation, is to allocate according to the mass flows of the products. This is preferable when the products have about the same value or the value is not known. However, this method can often lead to high footprints for by-products regardless of the fact that they may not be of great value or even waste.

In such cases the third method, price allocation, should be applied. Here the ecological footprint may be allocated according to the price or value of the respective products (this requires that these prices are known and entered into the program). This allocation provides the possibility to distribute the overall footprint fairly between wanted main products, utilizable by-products and unwanted waste.

The fourth method enables to define the footprint of one or more products, calculating the undefined ones from the remaining deficiency of the overall footprint of the process. This calculation can be done either by mass or price allocation. With this method it is also possible to assign a product a bonus footprint meaning a negative footprint. This may be the case when due to the by-production of a good this good has not to be produced by another process. The footprint of the other process therefore, can be credited to the by-product.

Finally if no other method leads to a satisfactory result it is possible to allocate manually.

The software includes three major report methods that show the results not only numerically but also graphically.

The first method reports the results of single processes according to the distribution of the overall footprint to the impact categories. This report enables the user to compare products and processes as well as to analyze which input category contributes the largest fraction to the process footprint. Additionally the report shows the substances causing the largest partial footprint in their emission impact categories (and that therefore, are added to the overall footprint). With one look the user can see if the ecological problem of a process derives from an emission or a resource or rather from intermediates used. In case of emissions it can be discerned which emission is the critical one.

The second report method shows the distribution of the ecological footprint of a product or service along the life cycle. This report answers the question if the footprint primarily results from an up-stream process, the logistical requirements or the impact caused by an emission along the life cycle. The user is able to see which step of a process chain is critical from the view point of environmental sustainability.

The third option is the evaluation of a process chain. Every process in SPIonExcel consists of products and/or impacts. Products can be broken down further by opening their production processes. By showing and including the processes of the used intermediates and thereby the inputs - be they impacts or other intermediates - needed and caused by their production the software is able to break down a given process to all its impacts. These processes then can be linked together to a process chain producing an end product. This process chain is shown graphically by the software (Figure 4-4).

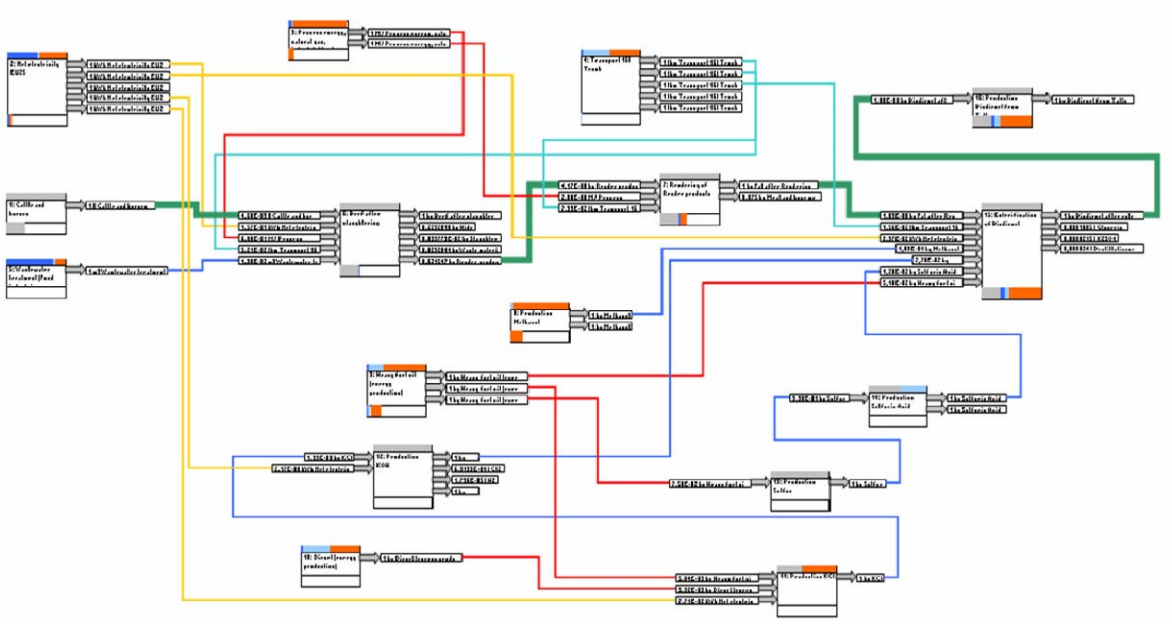


Figure 4-4: Example Process Chain built by SPIonExcel

The single processes are shown as boxes with inputs and outputs, connected by the mass and energy flows. The boxes also contain information about their footprint. In the upper bar the distribution of the process footprint is shown by means of the impact category color code. In the lower bar the same distribution is shown, but related to their contribution to the footprint of the end product. This helps to identify the problematic parts of the life cycle for a given product or service.

A fourth assessment option is the calculation of the distribution along industrial sectors. Here it can be discerned if the footprint derives from e.g. energy provision or transportation.

The software will be explained in detail in the next chapter.

4.5 *Detailed Software Description*

The software consists of two parts: the interactive part where the user is able to work with the software and the Microsoft Access databases where data is stored and retrieved by the software.

There exist two different kinds of databases. The most important one is the basic database. This database contains the impacts and short processes that are delivered with the software. Impacts and processes in the basic database cannot be deleted or changed by the user. However, the user can add further impacts and processes as will be described later.

The software accesses an additional database in which the user can save and edit his own processes and impacts besides the basic database. For this purpose the user is able to create as many additional databases as he likes. However, the software is only able to work with one additional database at a time, the active additional database, and cannot link processes along different additional databases. Linking processes from the basic database with an additional database is possible.

Due to the nature of the database programming the processes within cannot be calculated in an iterative way. For the iterative calculation which results in the correct overall footprints of the products an Excel sheet can be downloaded from the software homepage, where all processes contained in the additional databases available, are linked together iteratively. The results can than be included in the software as e.g. short processes.

The interactive part of the software can be divided in two subparts: the excel sheets where data are entered and results are displayed and the command bar which enables the user to navigate and execute the software. Many commands contained in the command bar are also available in a right mouse click menu. The commands available depend on the area the courser is clicked on.

These interactive parts, the excel sheets and the command bar, will be described in the next sections to show the possibilities and the content of the software. The use of the software is described in Chapter 4.6 where a step by step guide shows the creation of a process and the retrieving of process results.

For easier understanding the names of software commands will be written **bold** and names of objects in the software like excel sheets or command tabs additionally ***cursive***.

4.5.A Excel Sheets

The excel sheets contain all the information on the assessed processes. The impact sheet deals with impact data, whereas the data sheets contain the different processes saved in the databases. The process as well as the report sheet shows evaluation results. The regional sheet can be used to regionalize the data set of the software.

4.5.A1 *Impacts Sheet*

The ***Impact sheet*** is used to enter new impacts into the software and administrate existing ones. Impacts contained in the basic database as well as the active additional database can be shown here (Figure 4-5).

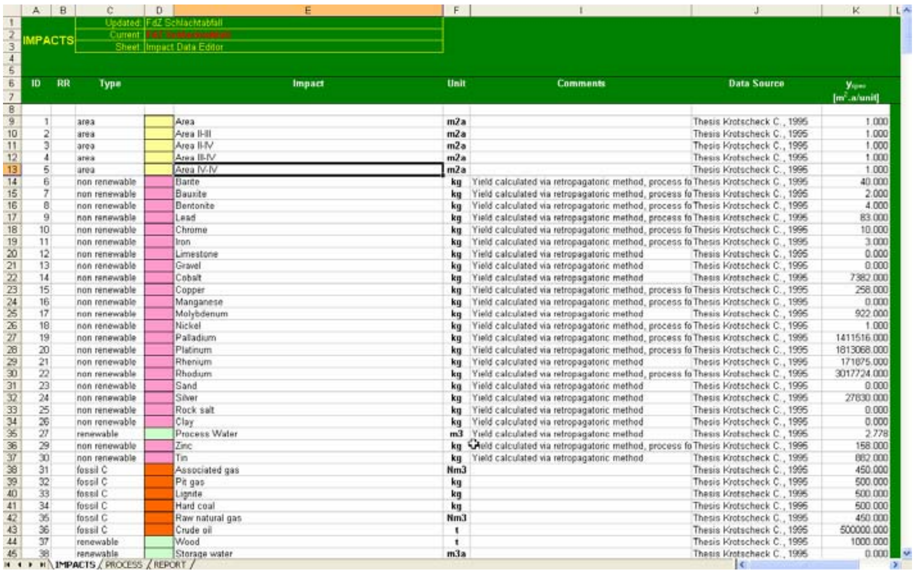


Figure 4-5: Impact sheet with basic database impacts

To create a new impact an impact name has to be entered into the ***Impact column*** of an empty line. Additionally the ***Impact category*** (e.g. fossil C) has to be defined in the ***Type field*** by entering the category name or using the right mouse button menu. Additionally the ***Unit*** and the ***Specific Yield*** **(*y_{spec}*)** of the impact have to be entered. The yield defines the ecological impact per unit.

In the case of emissions into water and soil the natural concentration of a substance in the defined compartment is entered instead of a specific yield.

If a substance concentration is not known it is possible to enter an ***Impact ID-number*** (identification) into the ***RR (reroute) column*** in order to set it equal to a comparative substance or the same substance in another compartment. Whenever the particular impact is chosen it will be rerouted to the impact with the ID put into the RR column. With this method substances can be subsumed to a certain category (e.g. aromatic hydrocarbons).

In case of lack of data for a compartment or when the compartment where the substance is emitted to is not known, the emission should be transferred to the compartment where the substance inflicts the largest ecological pressure.

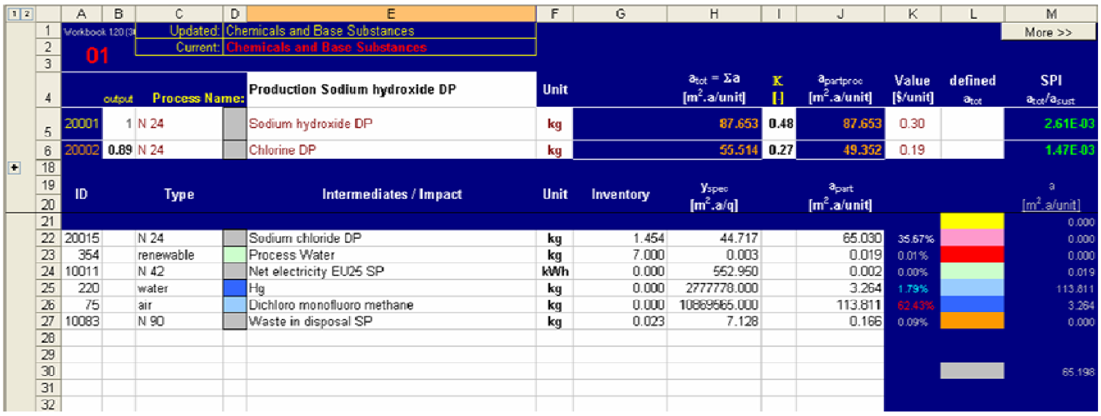
Next to the field containing the impact unit is the ***Comment field***. Here additional information is available e.g. descriptions of abbreviations or methodological comments. Next to this exists a column for defining the ***Data Source*** of the impact yield or the natural concentration.

Newly created or changed impacts can be saved with the **Save Impact Data** command in the command bar or the right mouse click menu.

4.5.A2 *Data Sheet*

This excel sheet contains all information of a process. To insert new processes in a database the ecological inventory of a process must be entered here. It can consist of intermediates (which have a process of their own providing them) or impacts. For new processes the **Create New Process** command from the command bar can be used.

In Figure 4-6 an example for a datasheet is shown.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Workbook 1.20 (3		Updated:	Chemicals and Base Substances									More >>
2	01		Current:	Chemicals and Base Substances									
3													
4		output	Process Name:		Production Sodium hydroxide DP	Unit		$a_{tot} = \Sigma a$ [m².a/unit]	K [-]	$a_{partproc}$ [m².a/unit]	Value [$/unit]	defined a_{tot}	SPI a_{tot}/a_{sust}
5	20001	1	N 24		Sodium hydroxide DP	kg		87.653	0.48	87.653	0.30		2.61E-03
6	20002	0.89	N 24		Chlorine DP	kg		55.514	0.27	49.352	0.19		1.47E-03
18													
19–20	ID		Type		Intermediates / Impact	Unit	Inventory	y_{spec} [m².a/q]		a_{part} [m².a/unit]			a [m².a/unit]
21													0.000
22	20015		N 24		Sodium chloride DP	kg	1.454	44.717		65.030	35.67%		0.000
23	354		renewable		Process Water	kg	7.000	0.003		0.019	0.01%		0.000
24	10011		N 42		Net electricity EU25 SP	kWh	0.000	552.950		0.002	0.00%		0.019
25	220		water		Hg	kg	0.000	2777778.000		3.264	1.79%		113.811
26	75		air		Dichloro monofluoro methane	kg	0.000	10869565.000		113.811	62.43%		3.264
27	10083		N 90		Waste in disposal SP	kg	0.023	7.128		0.166	0.09%		0.000
28													
29													
30													65.198
31													
32													

Figure 4-6: Example datasheet for the process production of sodium hydroxide

In Figure 4-7 the basic information found in the upper part of a datasheet can be seen. This information is either given by the software or entered by the user.

In the ***Area A*** the ***Active Additional Database*** (Chemicals and Base Substances) is shown. Besides this active database the software contains a basic database which is always accessible.

Area B shows the ***Name*** of the process (Production Sodium Hydroxide) as well as of the ***Primary Product*** (Sodium Hydroxide). ***By-products*** (Chlorine) are shown below the primary product. If a process has more than one by-product the lines for products can be expanded by clicking on the ***+ Button*** on the left side of the datasheet (***Area C***).

Processes may have an abbreviation at the end of the process and product names. The abbreviation ***SP*** stands for Short Process. Processes contained in the basic databases are always Short Processes. They do not show the eco-inventory of the selected process but the distribution of the ecological footprint along the impact categories. Detailed Processes are shown with the abbreviation ***DP***. Such processes include the eco-inventories of the processes. However, in the categories of emissions only the largest emission is shown. Processes including all input data, thus also all emissions, have the abbreviation ***FP*** for Full Process.

Area D contains the ***Units*** of the (by-)products. These units as well as all input units in the software can be changed inside their metric systems (e.g. t, kg, g, mg, µg, ng). All values connected to this unit change accordingly.

In ***Area E*** the ***NACE-category*** (« Nomenclature statistique des Activités économiques dans la Communauté Européenne ») of the product is shown. This categorization was applied by the European Union based on the "International Standard Industrial Classification of all Economic Activities" developed by the United Nations. The categories define different industrial and service sectors. The software uses this information for calculating the distribution of the footprint along the industrial sectors. Changing or defining the category number is done either by entering it into the cell or by using the category list accessible by the right mouse click menu when the cursor is placed in ***Area E***.

Area F shows the ***Amount*** of product or by-product obtained from the process. The amount of primary product can not be changed and is always 1. This means that the process in a datasheet will always be based on one unit of the primary product. Mass and energy balances have to be normalized on this value.

Area G contains the ***Identification Number (ID)*** of a product. This number is automatically given to a product when the process is saved in a database and links products and processes.

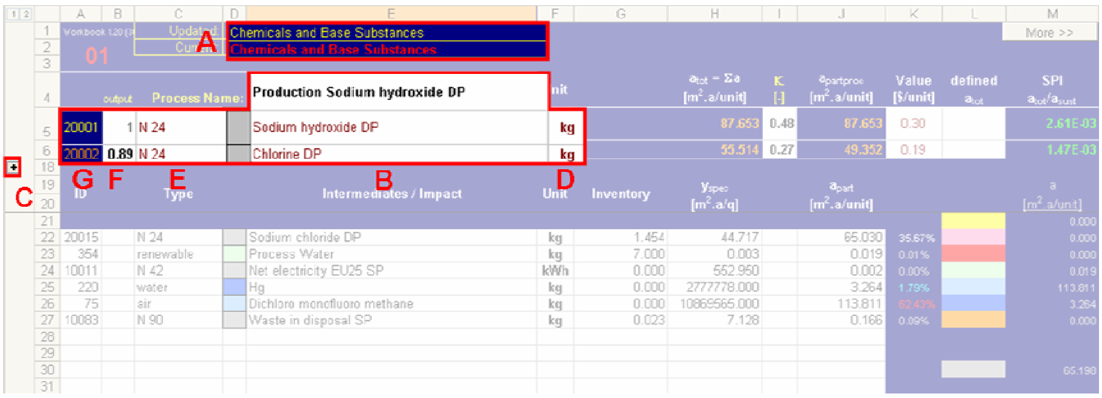


Figure 4-7: The database and product area of a datasheet

The mass and energy flows in and out of the process (excluding the products) are shown in the lower part of the datasheet, the input area (Figure 4-8).

Area H displays the names of the ***Intermediates*** or ***Impacts***. The cell next to the input names shows the color code which distinguishes the different impact categories: yellow for area depletion, green for renewable resource depletion, pink for non renewable depletion, orange for fossil resource depletion, light blue for emissions in air, dark blue for emissions in water and deep orange for emissions in soil. Intermediates are depicted with the color grey. The color is automatically displayed when the according input is chosen from the database. Otherwise it can be defined by the right mouse button menu when the cursor is in this area.

In addition there exists an impact category for waste as an input depicted in the color code by olive. These impacts have a specific footprint of 0 as they do not inflict any pressure on environment. They can be seen as anthropospheric resource that can be provided without changing the natural flows as the environmental pressure of their production is attached to the good from which the waste derives. However, when this waste provision is supported by other processes, e.g. transportation needed for collection, it accumulates a footprint that has to be taken into account. This has to be done by creating a process for the provision of this waste.

Area I shows the ***Unit*** of the impacts and intermediates. As with units of products these units too can be changed inside their metric systems, changing all linked values accordingly.

Area J contains the ***Amount*** of inputs as they are shown in the eco-inventory of the given process based on one unit of primary product. The ***Specific Footprint*** of this impact or intermediate can be seen in ***Area K***. This footprint marks the ecological pressure derived from the provision or emission of one unit of this flow. The specific footprint derives from calculations to sustainable embed or generate the flow into ecosphere as in the case of impacts. In the case of intermediates the specific footprint is calculated by the process which provides them. The specific footprints of emissions in water and soil are calculated by their natural concentration shown in the ***Impact Sheet*** and the compartment renewable rate defined in the ***Regional Sheet***.

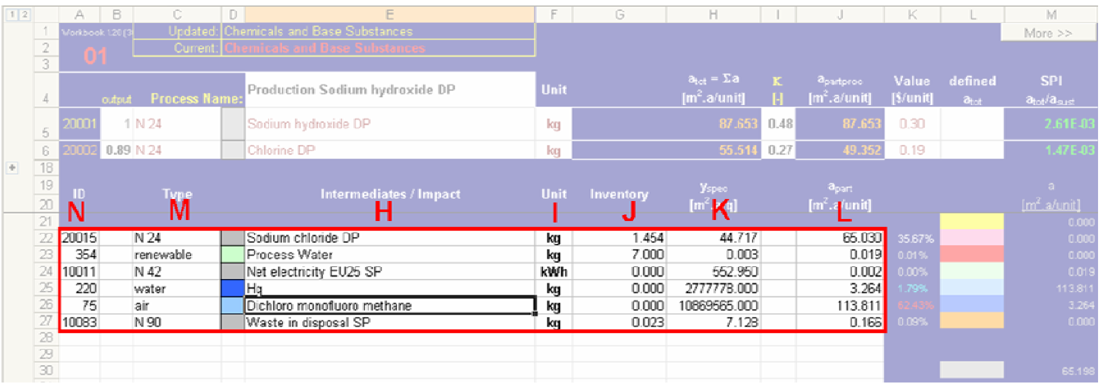


Figure 4-8: The input area of a datasheet

The amount of the impact or intermediate multiplied with the specific footprint results in the ***Partial Footprint*** shown in ***Area L***. The partial footprint is the ecological pressure which the impact or intermediate really adds to a process. These are then summarized to calculate the overall process footprint. In case of emissions only the partial footprint with the largest area for each compartment is added to the overall footprint according to the SPI methodology.

Area M shows the name of the ***Impact Category*** in case of impacts or the ***NACE-Category*** in case of intermediates. The ***ID-Number*** of the inputs is contained in ***Area N***. An ID with a number below 10000 describes an impact, a number between 10000 and 19999 a process from the basic database and a number from 20000 up a process from the active additional database.

The results of the calculations within a datasheet are shown in Figure 4-9.

The ***Overall Footprint*** of the primary product and eventual by-products are depicted in ***Area O***. This footprint is always based on one unit of product regardless the amount produced by the process.

Area Q shows the ***Partial Process Footprint*** $a_{PartProc}$ of the amount of products obtained by the process. This footprint results from the allocation of the process footprint along the products. The partial process footprint is not based on one unit of product like the overall footprint depicted in ***Area O*** but on the amount of product obtained from the process. The sum of all partial process footprints is the ***Process Footprint***.

Allocation of the process footprint along the products is defined by ***Allocation Factors*** shown in ***Area P***. The different allocation methods SPIonExcel is able to apply can be chosen in the right mouse click menu when clicking into this area. In order to apply price allocation the prices of the products have to be known. These prices are contained in ***Area R***.

In ***Area S*** a ***Defined Overall Footprint*** of a product can be entered. This may be of interest for products that add an ecological bonus to the process by avoiding its production by another process. At least one product must not have a footprint entered here as it has to receive the ecological footprint exerted by the production process that is not assigned to other products.

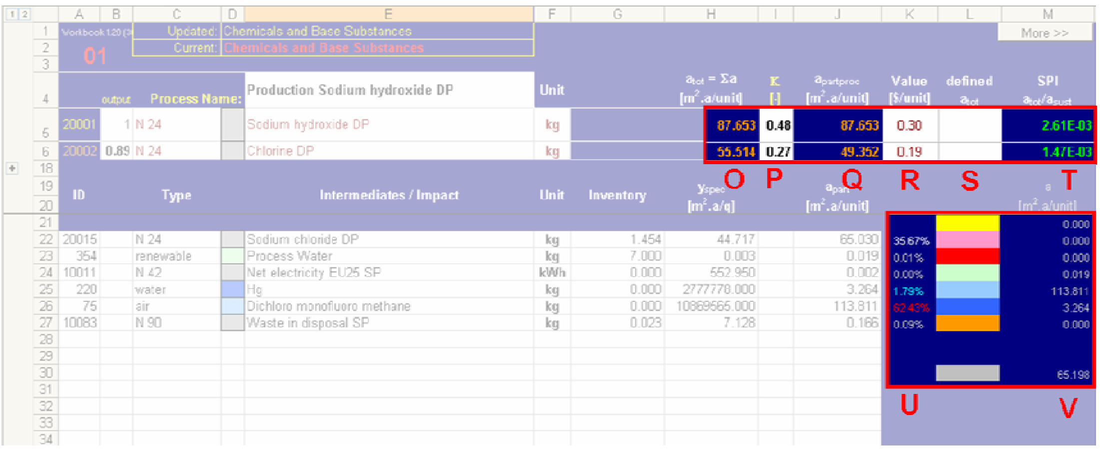


Figure 4-9: The results area in a datasheet

Area T shows the calculated Sustainable Process Index.

The distribution of the ecological pressure along the inputs and emissions of the given process are shown as ***Percentage*** of the process footprint in ***Area U***. The percentages are displayed in different colors depicting the fraction of the related input. Grey numbers show small percentages below 1%, blue numbers between 1 and 5%. The area between 5 and 25% is depicted in yellow, from there up to 50% in white. Percentages above 50% are shown in red.

Area V contains the ***Amount of the Overall Footprint*** distributed along the impact categories depicted by their color code.

By clicking on the ***More*** button in the upper right corner the screen moves to the left side of the datasheet. Here is the information area of the datasheet. It is shown in Figure 4-10.

The ***Back*** button scrolls the screen again to the right area of the datasheet.

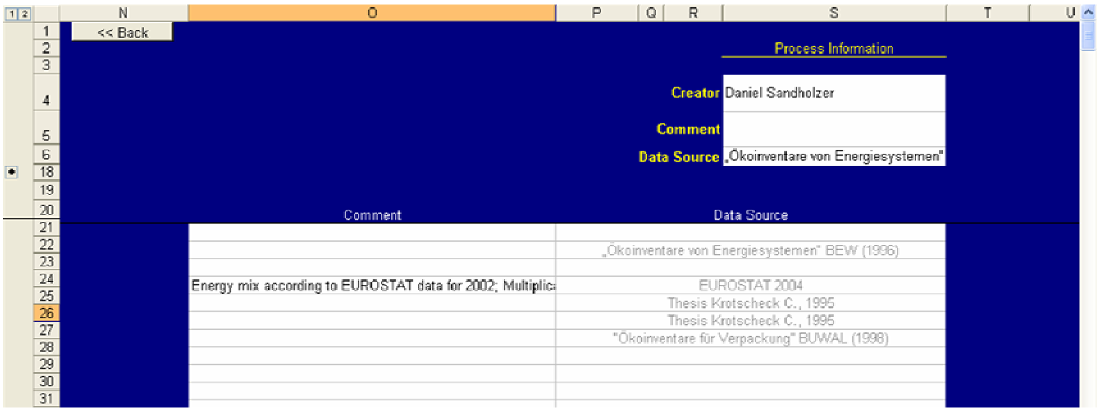


Figure 4-10: Second part of the Datasheet

In ***Area W*** (Figure 4-11) the identification data of the process are shown. These include the ***Creator*** of the process as well as the ***Data Sources*** for the eco-inventory. ***Comments*** by the creator can also be seen here giving information.

Area X shows the comments and data sources of the inputs and emissions used by the process that are saved in the databases. In case of impacts this information is taken from the input in the impact sheet for the given impact. The information shown for intermediates corresponds to the data in ***Area W*** on the datasheet of the given process.

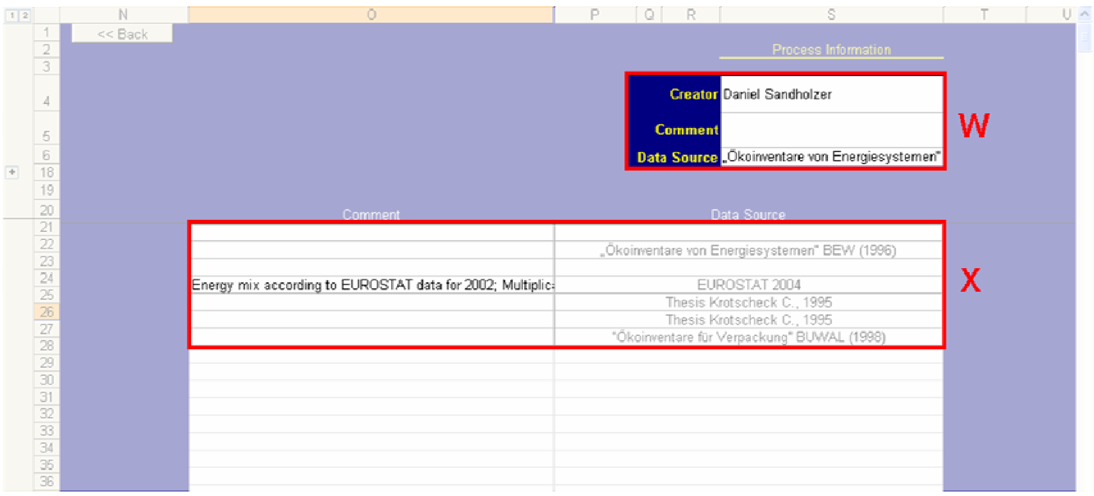


Figure 4-11: The information area of a datasheet

For a detailed explanation how to enter data into the datasheet please read Chapter 4.6 "Step by Step Guide".

4.5.A3 *Process Sheet*

This sheet shows a process chain if one has been built up(Figure 4-12). This is possible by the **Draw Process Chain** command in the command bar. A process chain can only be built from processes that have been opened in the form of datasheets in the software. Such process sheets will be called ***Open Datasheets*** further on.

The structure of process chains made by the software is shown in Figure 4-12. The process steps can be arranged manually for a better overview.

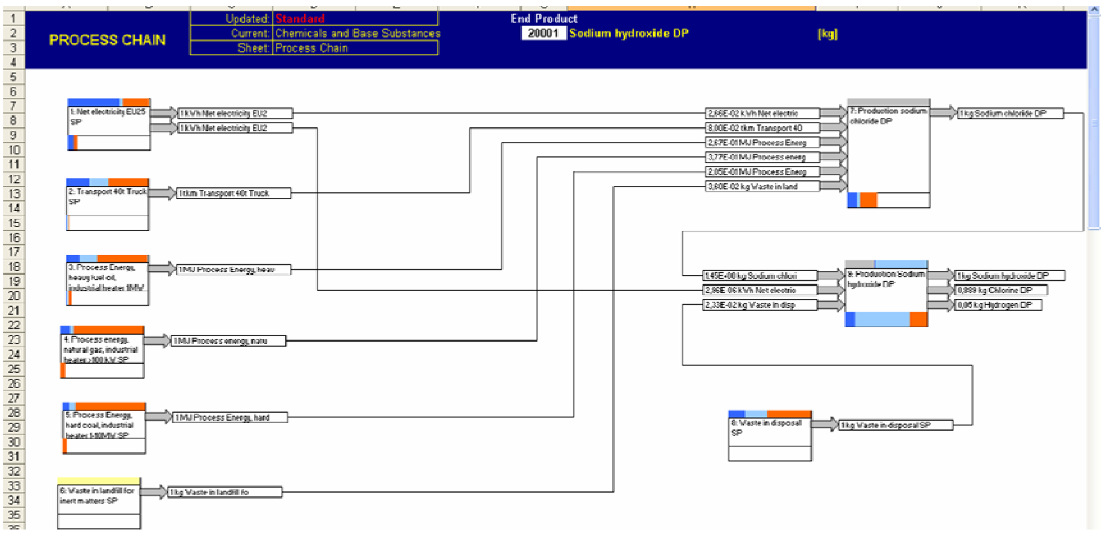


Figure 4-12: The Process Sheet

The ***Process Sheet*** contains various information (Figure 4-13).

Area A shows the ***End Product*** of the whole process chain that has been chosen before the chain was built, indicating the ***Product Name***, the ***Base Unit*** and its ***ID-Number***. By clicking on the ID with the right mouse button a different end product of the process chain can be chosen. For this a list containing all products provided by the open datasheets is shown. The according process chain will then be recalculated and displayed.

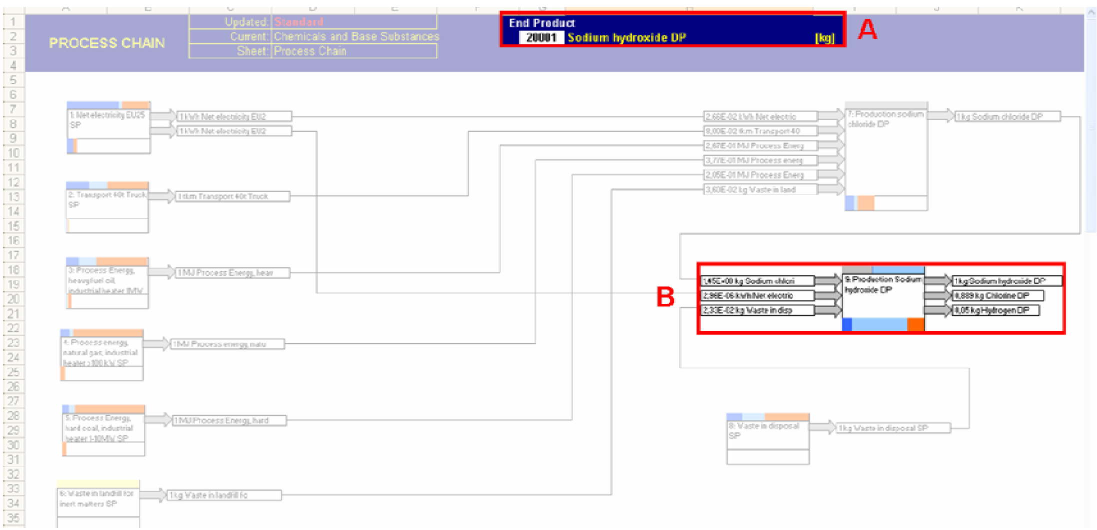


Figure 4-13: Contents of the Process Sheet

The boxes representing the different process steps of the process chain (***Area B***) can be arranged by drag and drop. The information in these boxes includes the process name as well as the intermediate inputs and the product outputs of the given process step. Outputs of one step that are inputs of another process step are graphically linked together via connection lines.

Additionally the upper and lower areas of the box show distribution bars of the ecological footprint depicted by the impact color code. The upper area shows the distribution of the footprint of the process and is based on the primary product obtained by this process step. The lower area shows the footprint of the whole process chain up to the given process step. This distribution bar is based on the end product of the whole process chain.

4.5.A4 *Result Sheet*

The ***Report Sheet*** contains the results of the process assessment calculated in the datasheets (Figure 4-14). These results can be displayed in three different ways, the "***Sheet Report***", the "***Chain Report***" and the "***Distribution Report***". The kind of report that shall be shown can be chosen in the command bar.

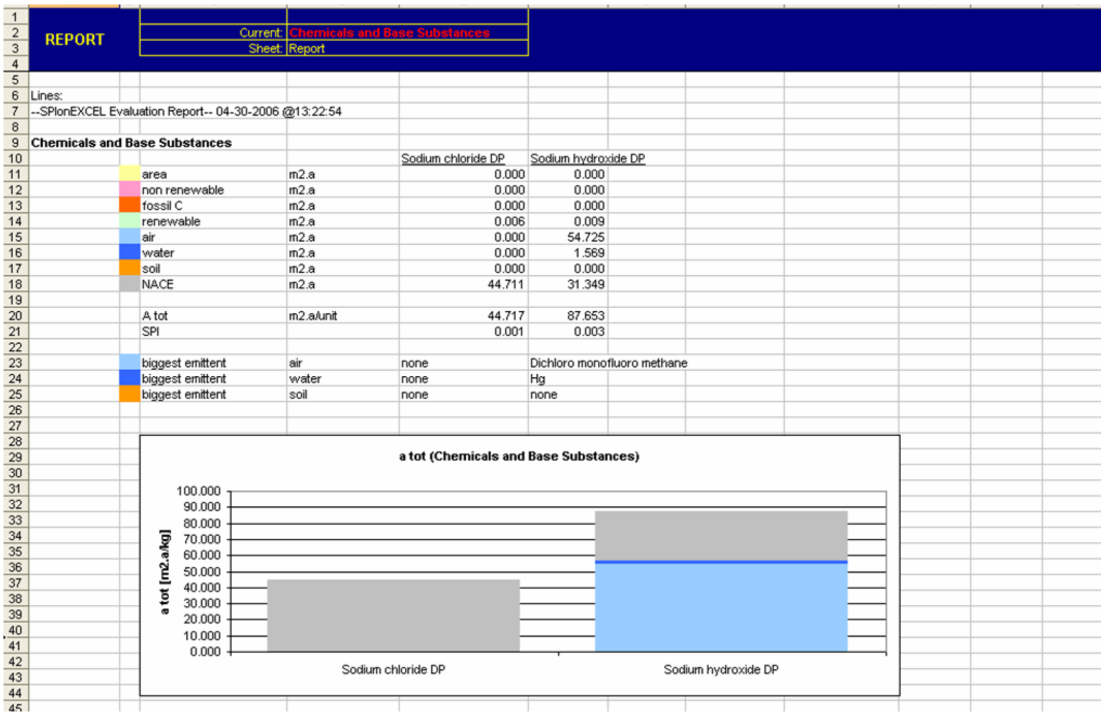


Figure 4-14: The Report Sheet

The ***Sheet Report*** can show the ecological footprints of open datasheets, meaning datasheets of processes that have been loaded from the database, and is based on the selected products. The footprints of which products shall be shown in this report can be chosen when executing the **Create Sheet Report** command (Figure 4-15). If more than one product is chosen, as was the case in the figure, the results are displayed side by side.

Area A shows the ***Partial Footprint*** arising from the respective impact category for the chosen product. The ***Overall Footprint*** as well as the resulting ***SPI*** of the chosen product can be seen in ***Area B***.

The ***Emissions*** to the compartments of water, air and soil which contribute the largest pressure in their compartment are named in ***Area C***. If instead of an emission name the word ***None*** is shown the process does not emit substances in the respective compartment.

The ***Distribution*** of the ecological footprint is shown graphically in ***Area D*** using the software color code.

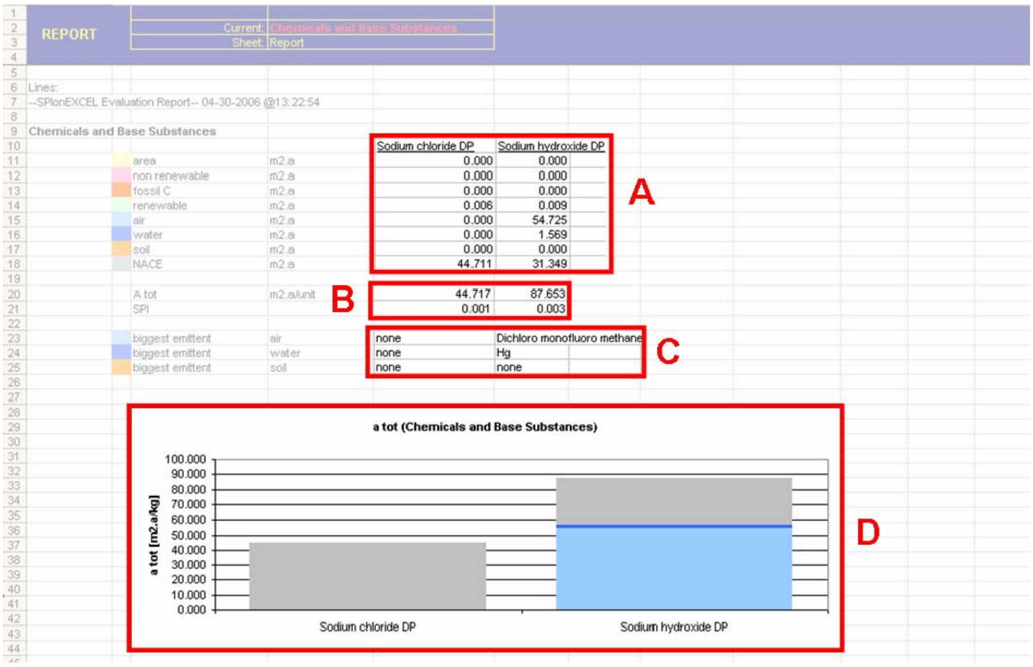


Figure 4-15: Content of the Sheet Report

The ***Chain Report*** shows the results depicted in the process chain (Figure 4-16). It can only be calculated when a process chain has been built prior. The results of this report are based on the end product of the process chain.

Area E shows the ***Partial Footprints*** along the impact categories. The ecological impact of intermediates along the process chain is scaled to the end product of the process chain. Therefore, the numbers represent the environmental pressure arising by the use of the particular intermediate for the production of the end product.

Area F shows the resulting ***Partial Process Footprints***. It has to be differentiated between process steps inside the process chain and supporting processes. Supporting processes add the whole amount of ecological pressure depicted here to the ecological pressure along the process chain whereas the footprint displayed for processes inside the process chain include the footprint of the prior chain as well as the ecological pressure added by this step.

Area G shows the ***Emission*** in the compartments air, water and soil that inflicts the greatest pressure along the process chain. When such an emission is caused by a short process from the basic database it will be stated as "emission inflicted by prechain".

Area H shows graphically the increase of the overall footprint along the process chain as well as the fraction supporting processes add.

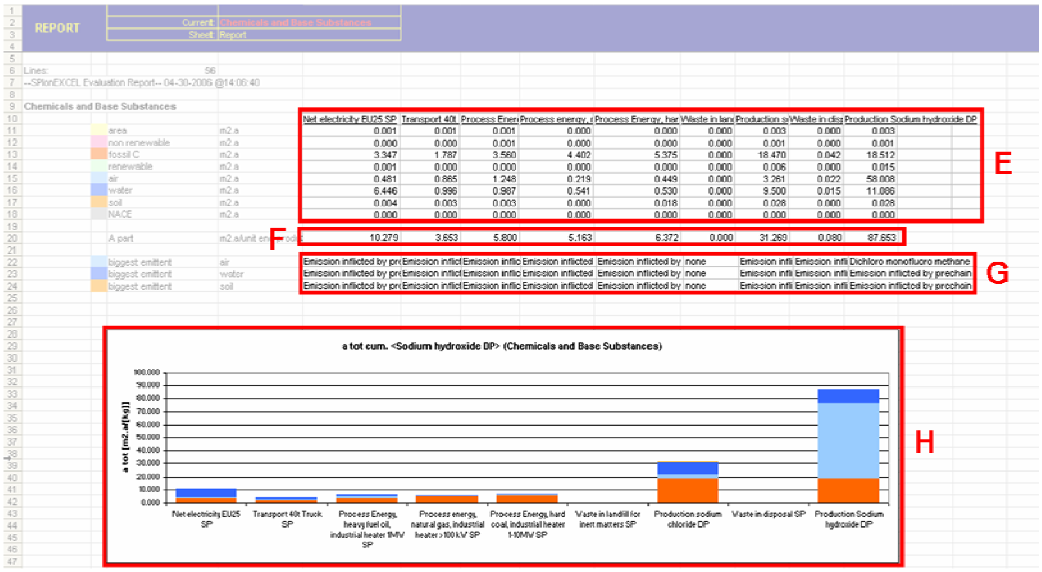


Figure 4-16: Content of the Chain Report

The ***Distribution Report*** allows to calculate the distribution of the overall footprint of a product along the industrial sectors. This is done based on the classification of the intermediates used in a process according to the NACE-categories. The different kinds of impacts caused directly by a process are summarized in the ***Direct Process Interaction*** category.

Area I shows the ***Amount of the Overall Footprint*** along the distribution categories as well as the ***Percentage***. ***Area J*** displays the percentage graphically.

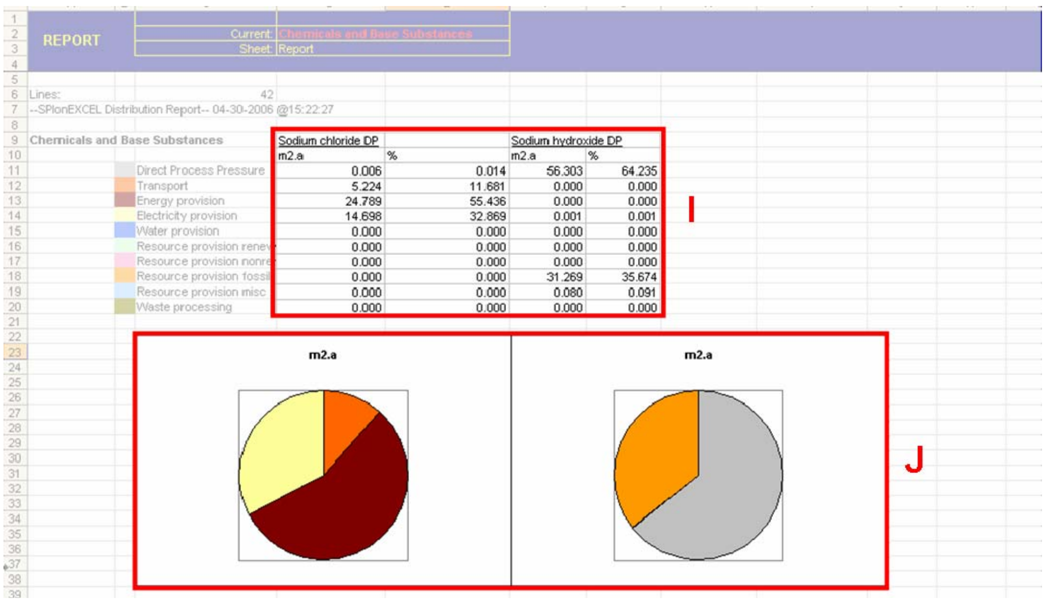


Figure 4-17: Content of the Distribution Report

4.5.A5 *Regional Sheet*

The ***Regional Sheet*** can only be accessed via the **Show Sheet Selection** command in the command bar. It shows data used by the software to calculate the specific footprints of emissions in water and soil as well as for the SPI (Figure 4-18).

The data can be changed by the user to regionalize the assessment. Data include the ***Precipitation*** and ***Seeping Ratio*** of the region as well as its ***Compost Yield*** and ***Losses***.

The ***Area*** that is available per inhabitant can be changed here too. The data can always be reset by clicking the ***Reset to Defaults*** button.

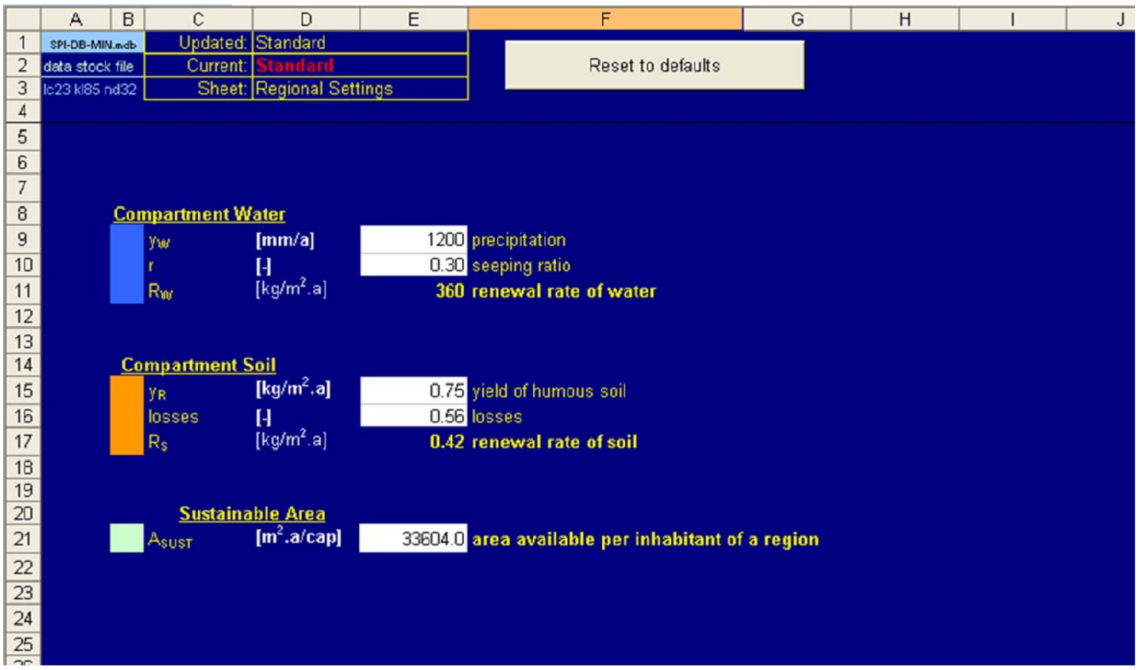


Figure 4-18: The Regional Sheet

4.5.B Command Bar

The command bar gives access to the commands needed to navigate and execute the software. Some commands are also available by clicking the right mouse button. These options vary depending on the location of the mouse curser and the sheet selected. In the following the commands contained in the command bar will be explained moving from left to right.

4.5.B1 *Section Sheets*

4.5.B1a Show Sheet Selection

This command ***opens*** the ***Sheet Selection box*** (Figure 4-19). The box enables the selection of the ***Impact, Process*** and ***Results Sheets***. Additionally the ***Regional Sheet*** and the ***DATA00 Sheet*** can be accessed here. The DATA00 Sheet is the master datasheet which the software uses as pattern model when it opens a datasheet either by loading or creating a process. These two sheets can only be chosen via the ***Sheet Selection box***.

If any datasheets are open they will be displayed here too.

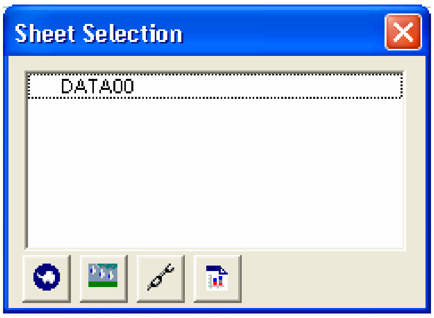


Figure 4-19: The Sheet Selection Box

As the DATA00 Sheet is the master datasheet it contains no information but is only the graphical template for all datasheets. If you change something in the DATA00 Sheet e.g. the width or the title of a column, all datasheets opened afterwards will be changed accordingly.

4.5.B1b Edit Impacts

This command ***activates*** the ***Impact Sheet*** for editing and entering impact data.

4.5.B1c Process

This command ***activates*** the ***Process Sheet*** for showing and building process chains.

4.5.B1d Report

This command ***activates*** the ***Report Sheet*** for displaying and analyzing the ecological assessment of processes.

4.5.B2 *Data*

4.5.B2a New Data Sheet

This command ***creates a new empty datasheet***. This datasheet can be used for creating a new process like the command **Create New Process**.

4.5.B2b Process Info

This command ***shows the additional information*** of a process which has been entered for the active process by opening the ***Process Information box*** (Figure 4-20). This information box contains the creator of the process and the data source as well as further comments by the creator.

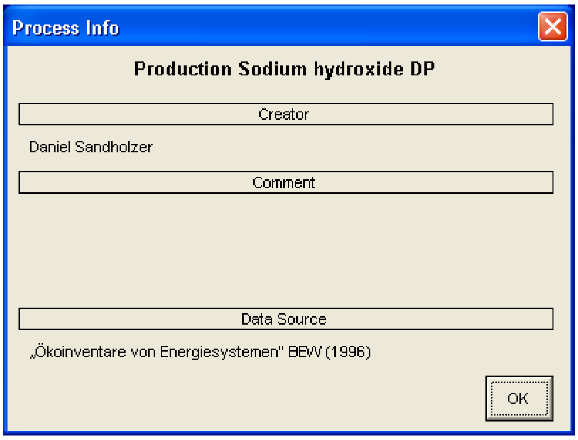


Figure 4-20: The Process Information box

4.5.B2c Clear Line

This command ***clears the active line*** of the ***Datasheet***. It is only applicable in the area that contains the inputs and emissions of the given process.

4.5.B2d Clear Data

This command ***clears all data*** contained in the ***Datasheet*** including the inputs, emissions, products and further information like creator, data source and comments.

4.5.B2e Refresh Data Sheet

This command ***refreshes the whole Datasheet***, recalculating all footprints. This command can be used when changes in inputs to a process have been made to include the new results in the assessment. If the process is saved after the changes have been made the software refreshes the datasheet automatically before saving it.

4.5.B2f Refresh Line

This command ***refreshes*** and recalculates the contents of ***a single line*** in the input area of a ***Datasheet***.

4.5.B2g Insert Line

This command ***inserts an empty line*** into the input area of a ***Datasheet***.

4.5.B2h Remove Line

This command ***removes a line*** from the input area of a ***Datasheet***. The data contained in this line is also removed.

4.5.B2i Delete Data Sheet

This command ***deactivates*** the active ***Datasheet*** and deletes it from the screen. This may be needed when too many datasheets are already open as Microsoft Excel is only able to work with a limited number of datasheets. In addition some software features like the building of a process chain do not work when the number of datasheets exceeds fifty.

The data is still saved in the database and can be loaded again if needed.

4.5.B2j Delete All Data Sheets

This command has the same effect as the **Delete Data Sheet** command except that ***all open Datasheets*** will be ***deactivated***.

4.5.B3 *Processes*

4.5.B3a Create new process

This option enables the user to ***create a new process***. For this purpose the ***Create New Process box*** opens (Figure 4-21). Here the user enters the name of the process as well as of the primary product. Additionally the base unit of the primary product and the NACE-category can be chosen here.

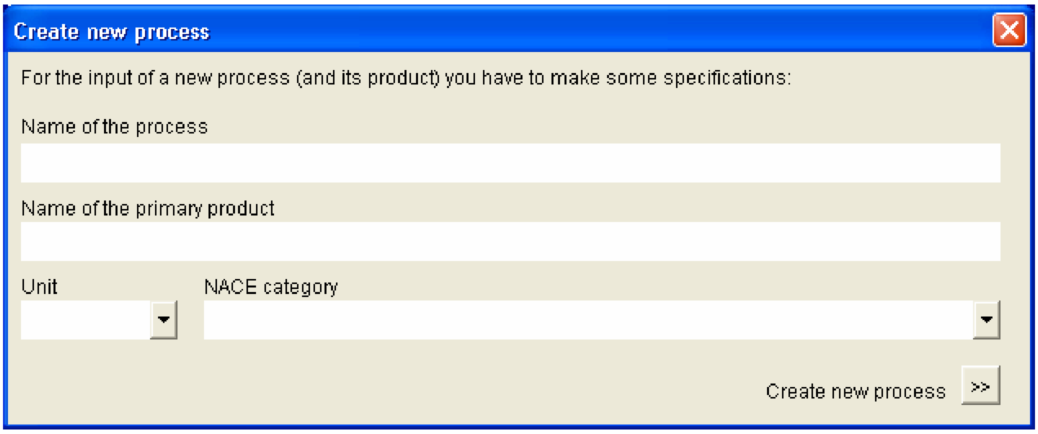


Figure 4-21: The Create new process box

With a click on the ***Create New Process button*** a new datasheet will be created containing the information entered into the ***Create New Process box***. By-products as well as the eco-inventory of the process have to be entered in the ***Datasheet*** directly.

4.5.B3b Show process data

This option enables the user to ***search the database*** for processes.

The ***Show Process Data box*** opens after using this command (Figure 4-22). Here the user can enter a search term of the product name. The search term may not be the whole product name. The software automatically finds all products beginning with the entered word or word fragment. If the entered search term is expected to be contained in the middle or end of a product name, the wildcard * may be used before the word fragment.

The search for a product can be constricted for a NACE-category.

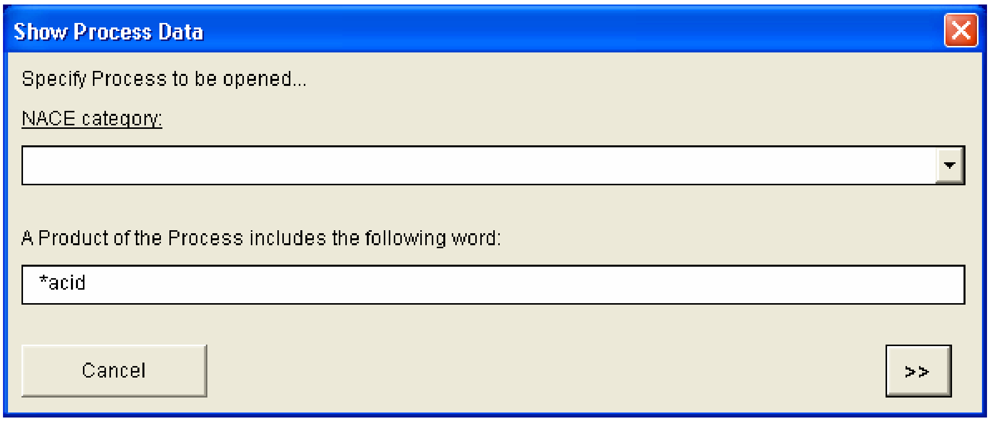


Figure 4-22: The Show Process Data box

Products that fit the search term are shown in the ***Impact/Process Selection box*** (Figure 4-23). Here the product names as well as their units, specific footprints, NACE-categories, ID-numbers and process names are shown. Either by selecting a product and clicking the OK button or double-clicking it, the process producing the selected product will be ***opened in a new Datasheet***.

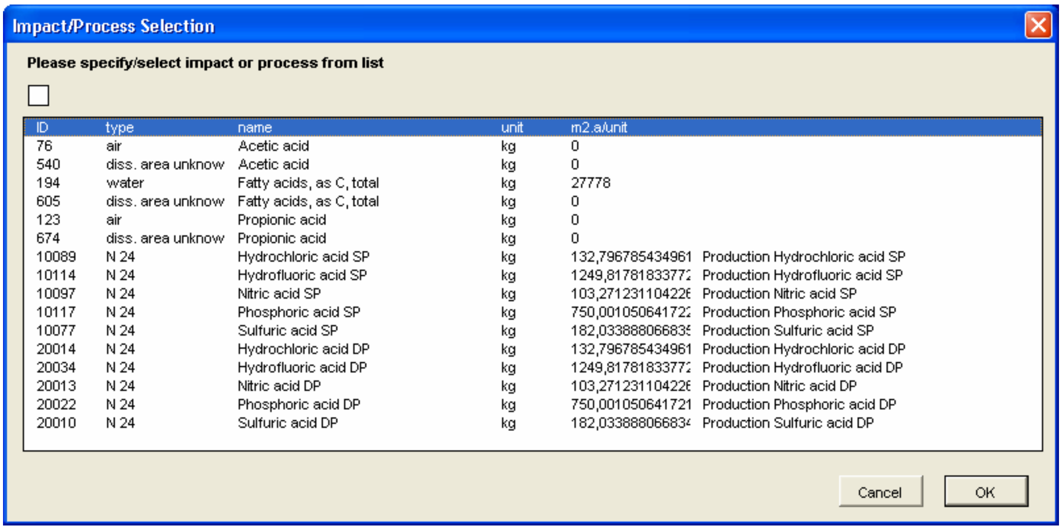


Figure 4-23: The Impact/Process Selection box

It is also possible to enter a product ID-number instead of a search term. As the ID-number is unique the related process will be opened instantly into a new ***Datasheet***. If an intermediate is marked in a ***Datasheet***, the ID number will show up in the search form when applying the **Show Process Data** command.

4.5.B3c Show all process data

With this command ***all processes of intermediates*** in the input area of a given process ***are opened*** in new ***Datasheets***. This option can only be chosen if a process has been loaded to a ***Datasheet***. Due to this command the user does not have to open each sub-process on its own.

4.5.B3d Save process data

This command ***saves the process*** to the database. If the process did not have an ID before it will be saved as a new process and assigned an ID-number. If the ID-number already exists the user is able to choose to overwrite the process containing the old data with the new one. Alternatively the new data can be saved with a new number by choosing the NO-option. Saving an already existing process with a new ID-number is also possible by clearing the old ID before executing the **Save Process Data** command.

Processes in the basic database cannot be changed or saved in order to prevent modifications of the basic database.

4.5.B3e Delete process

This command ***deletes a process*** from the database. You need to know and enter the ID number of the process to delete it.

It is not possible to delete processes from the basic database.

4.5.B4 *Impacts*

4.5.B4a Load impact data

This command ***loads the impact data*** into the ***Impact Sheet***. To clarify which impacts shall be loaded the ***Load Impact Data box*** is opened (Figure 4-24).

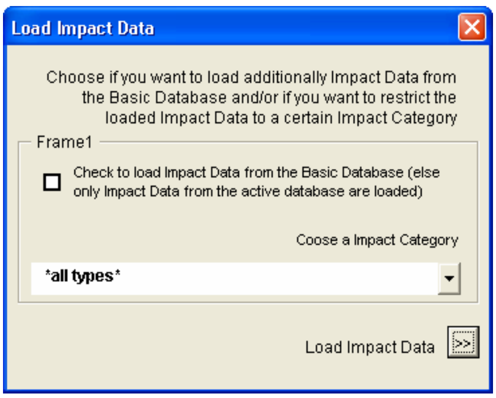


Figure 4-24: The Load Impact Data box

It can be defined if only the impacts of the open database shall be loaded into the ***Impact Sheet*** or if the impacts of the basic database shall be loaded too. Additionally it is possible to constrict the impacts loaded to a certain impact category.

Pushing the ***Load Impact Data button*** retrieves the chosen impacts from the databases into the ***Impact Sheet***.

4.5.B4b Save impact data

This command ***saves*** new or modified ***impacts*** to the open database. It is not possible to save an impact to the basic database directly (see Chapter 4.5.B6d).

4.5.B4c Delete Impact

This command ***deletes an impact*** from the database. To delete the impact its ID-number must be known. Impacts from the basic database cannot be deleted.

4.5.B5 *Process Chain*

4.5.B5a Draw Chain

This command enables the ***drawing of a process chain*** in the ***Process Sheet***. Executing this command opens the ***Draw Chain – End Product Selection box*** (Figure 4-25). Here it is possible to choose the end product of the process chain. The calculation results will be based on one unit of this end product.

After choosing an end product the ***Process Chain*** from there is built. To be included into this ***Process Chain*** a process has to be opened in a ***Datasheet***.

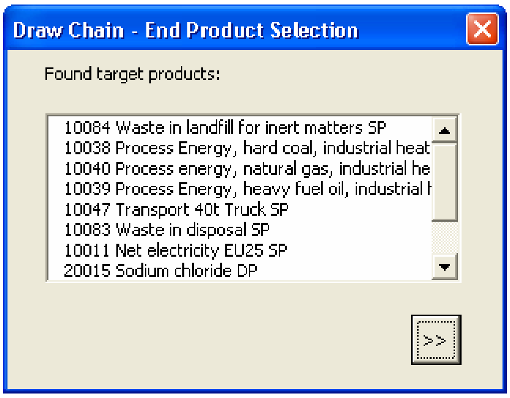


Figure 4-25: The Draw Chain – End Product Selection box

4.5.B5b Clear chain

This command ***clears*** a drawn ***Process Chain*** from the ***Process Sheet***.

4.5.B5c Refresh Chain

This command ***updates the chain*** by using new data from the ***Datasheets***. This is necessary after modifying data in a ***Datasheet***, when the ***Process Chain*** has already been built as the recalculation is not done automatically.

4.5.B6 *Database*

4.5.B6a Show database list

This command enables the user to ***switch between different databases***. For this purpose the ***Databases box*** is opened (Figure 4-26).

Here all databases implemented into the software can be seen. To implement new ones either the **Open Database** command or the equivalent button in the ***Databases box*** can be chosen. The same holds true for deleting a database.

The name of the active database can be seen in the upper bar of the box. To switch between the databases the new database has to be double clicked.

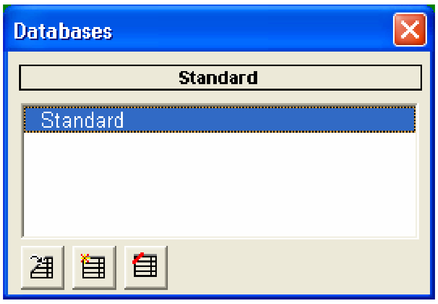


Figure 4-26: The Databases box

4.5.B6b Create New Database

This command ***creates a new database***. The newly created database is based on the active database. This means that the new database contains all processes and impacts which where contained in the active database.

The software has an implemented database called "Standard" which is empty. This database should not be used for saving processes to it but for creating new empty databases.

4.5.B6c Open Database

This command ***implements a database*** on your hard disk into the software. A browser window opens where you can locate the database that shall be implemented.

4.5.B6d Transfer Data

This command enables the user to ***transfer impacts and/or processes*** from an active database ***into the basic database***. This is the only possibility to add data to the basic database.

For choosing which kind of data shall be transferred the ***Transfer Data box*** is opened. Here the amount of impacts and processes is shown for the active database as well as the basic database. The kind of data that is to be transferred has to be checked before clicking the ***Begin Transfer button***.

After transfer the impacts and/or processes are available in the basic database. The ID of these data is assigned by the software in ascending order starting with the lowest existing ID in the basic database.

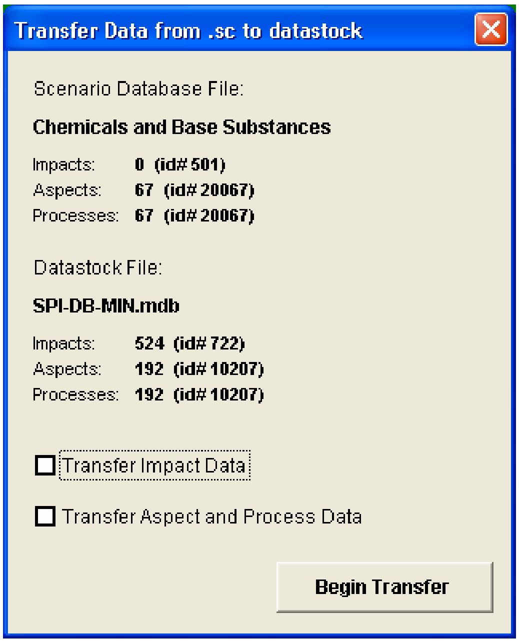


Figure 4-27: The Transfer Data box

4.5.B6e Change Basic Database

This command ***changes the basic database***. Such changes will be needed seldom. However, the change of the basic database may be interesting if different basic databases contain the same processes and impacts but other values for them because of e.g. regionalization or different data sources.

4.5.B7 *Report*

4.5.B7a Create Sheet Report

This command allows the ***creation*** of a ***Sheet Report*** (see Chapter 4.5.A4 Result Sheet). To choose the products for which the results shall be reported the ***Create Sheet Report box*** allows checking the products of the open ***Datasheets*** (Figure 4-28).

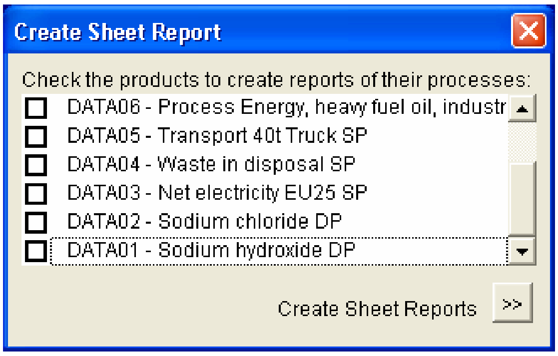


Figure 4-28: The Create Sheet Report box

4.5.B7b Create Chain Report

This command allows to ***report the results*** of a ***Process Chain*** (see Chapter 4.5.A4 Result Sheet). The ***Process Chain*** has to be drawn before it can be reported.

4.5.B7c Create Distribution Report

This command allows the ***creation*** of a ***Distribution Report*** (see Chapter 4.5.A4 Result Sheet). To choose the products for which the results shall be reported the ***Create Distribution Report box*** allows to select the products of the open ***Datasheets*** (Figure 4-29).

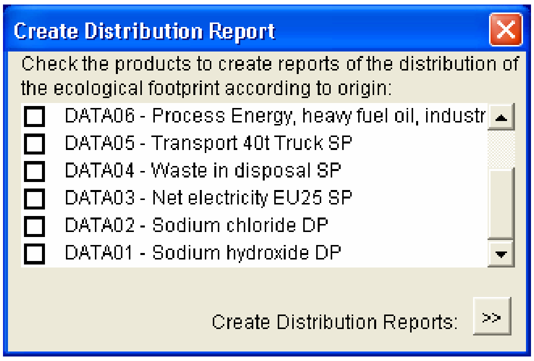


Figure 4-29: The Create Distribution Report box

4.5.B7d Clear Report

This command ***clears*** the ***Report Sheet***.

4.6 *Step by Step Guide*

This step by step tutorial guides a user to create a process. It deals with all important factors of entering data into the datasheet and utilizing the allocation and result options of the software.

The example process is the production of sodium hydroxide. Inputs in the software are written *cursive*. Commands are written **bold**.

4.6.A Step 1 Creating a new Process

After launching the software, first thing to create a process is clicking the **Create New Process** command in the Processes tab (Figure 4-30).

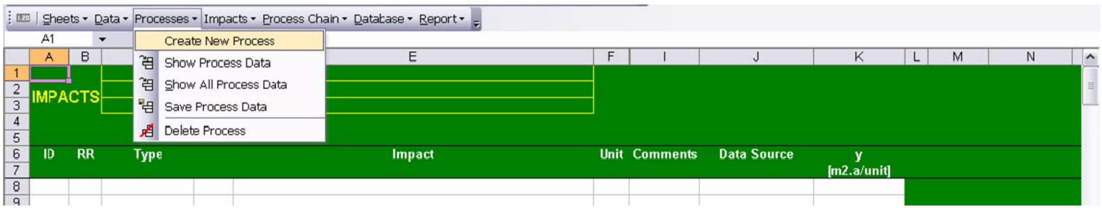


Figure 4-30: Creating a new process 1

An input window opens where the name of the process has to be specified (Figure 4-31). Additionally the name of the primary product as well as its unit has to be entered. Last thing to choose is the NACE-category which characterizes the industrial sector the process belongs to.

In this case the name of the process is *Production Sodium hydroxide* and the primary product is *Sodium hydroxide*. The unit *kg* and the NACE-category *24 – Production of chemicals and polymers* can be chosen from the drop down menus.

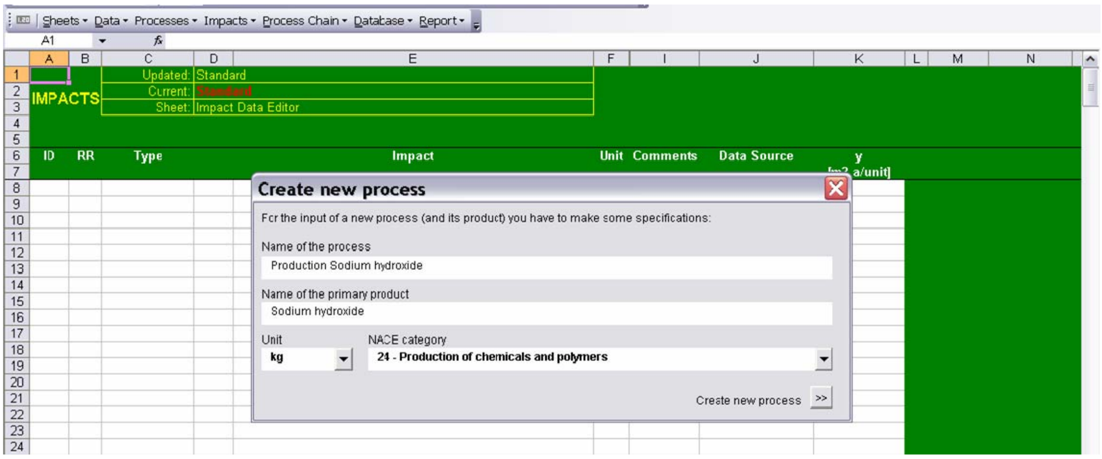


Figure 4-31: Creating a new process 2

When the information has been entered the data will appear in a new datasheet (Figure 4-32).

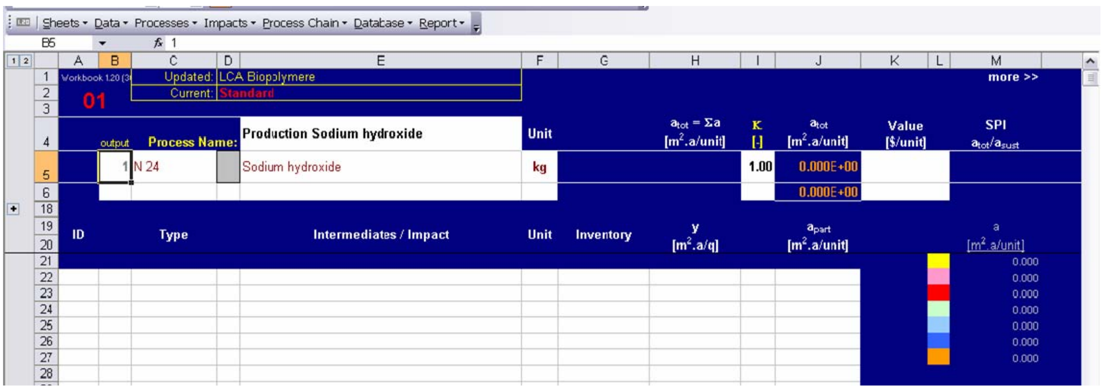


Figure 4-32: Creating a new process 3

4.6.B Step 2 Entering By-Products

If more than one product can be obtained by a process the by-product names have to be put into the cells directly below the name of the primary product (Figure 4-33).

In this case the first by-product is *Chlorine (by-product)*.

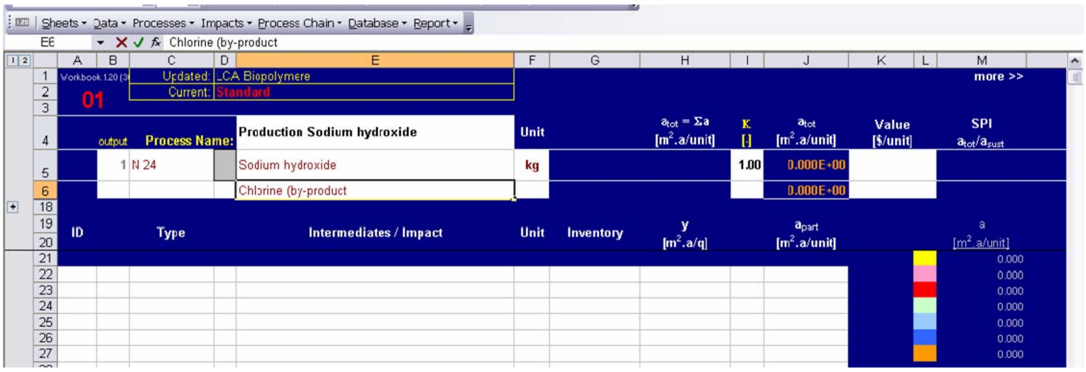


Figure 4-33: Entering of By-Products 1

After entering the product name the amount of output has to be specified (Figure 4-34). Note that the output of the primary product is always 1.

The amount of Chlorine output is *0.89* of a unit that has not yet been defined.

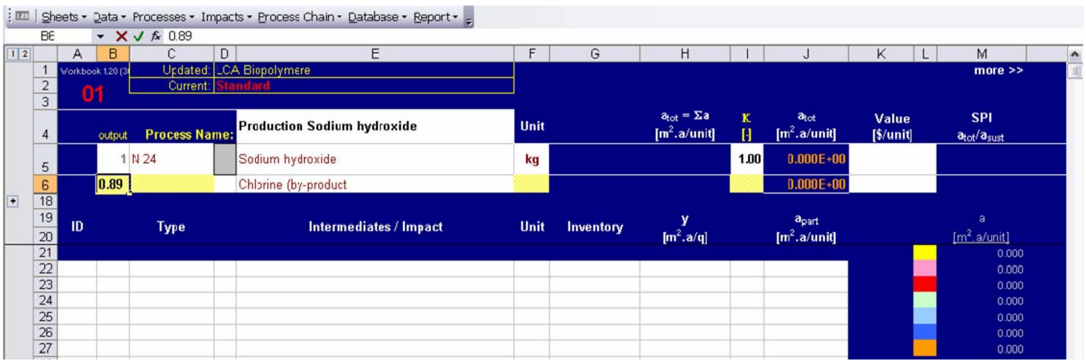


Figure 4-34: Entering of By-Products 2

In the next cell the NACE-category has to be entered, in the given case *24* for *Production of Chemicals and Polymers* (Figure 4-35). This can be done either by entering the number into the field or by right clicking on the cell. The category can then be chosen from the NACE-list.

Finally the unit of the product has to be specified. The unit of chlorine is *kg*.

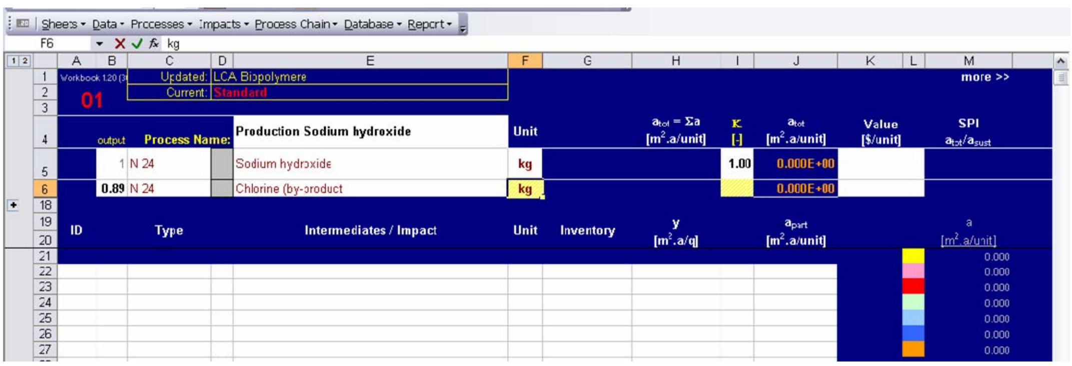


Figure 4-35: Entering of By-Products 3

If there is more than one by-product of a process additional input cells can be accessed by clicking the +-button on the left frame (Figure 4-36).

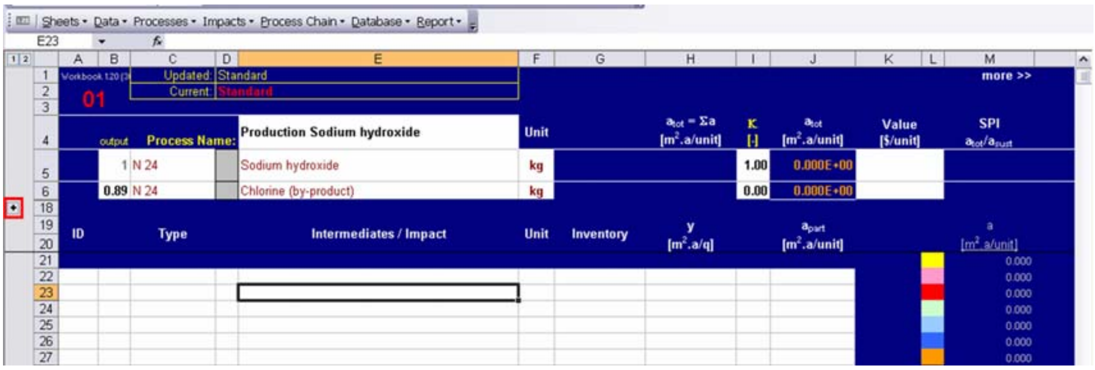


Figure 4-36: Entering of By-Products 4

Entering another product in these cells follows the same procedure as described before (Figure 4-37).

The process Production Sodium Hydroxide not only produces sodium hydroxide and chlorine but *0.05 kg Hydrogen (by-product)*.

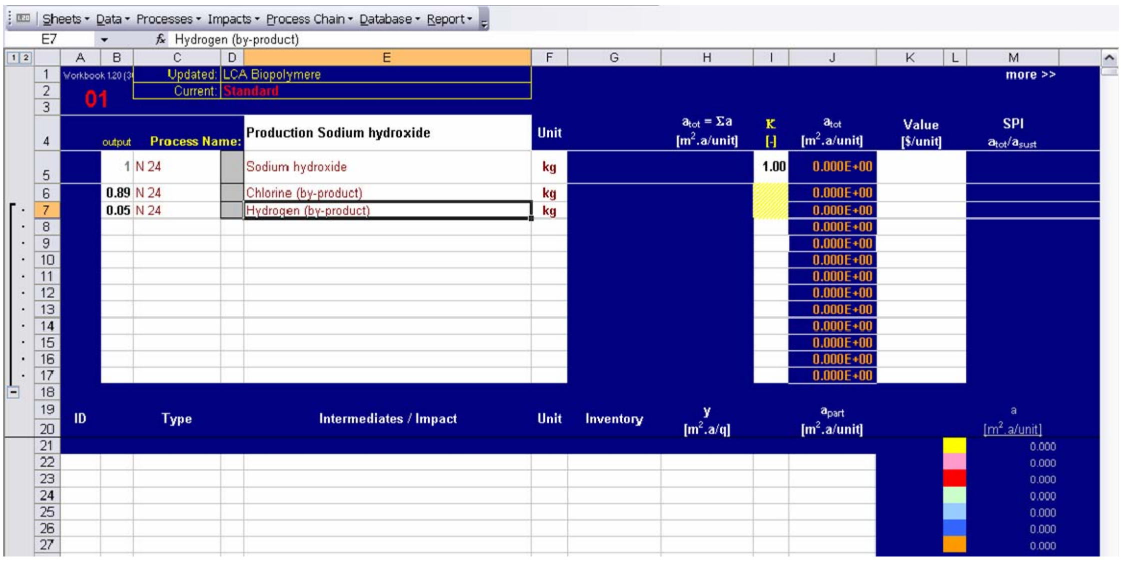


Figure 4-37: Entering of By-Products 5

4.6.C Step 3 Entering the Eco-Inventory

For entering the eco-inventory into the datasheet the name of the intermediate or impact has to be typed into the input cell (Figure 4-38). The name can be fragmentary as the software will show all possible inputs. It is not necessary to use the wildcard * after the name when searching with name fragments, only in front of it if the fragment stands in the middle or at the end of a word.

For example *wat* can be entered into the input cell.

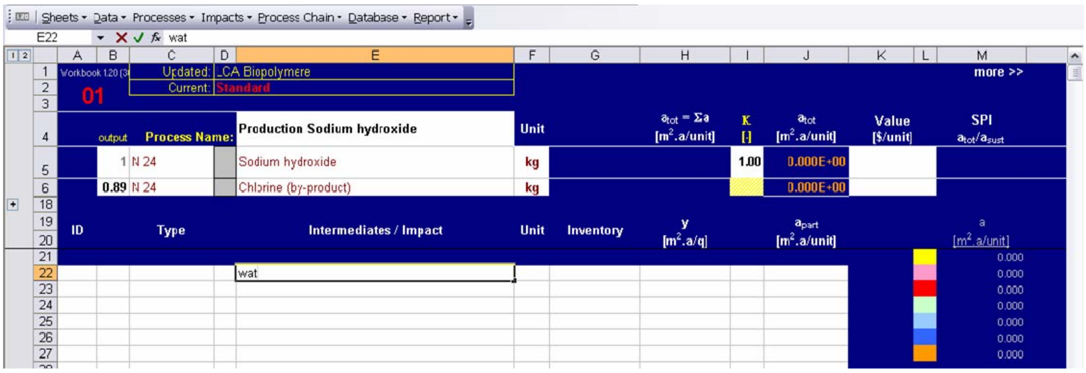


Figure 4-38: Entering the Eco-Inventory 1

A window will pop up showing all possible intermediates and impacts according to the input (Figure 4-39).

For the process the impact *process water* with the unit *kg* from the category *renewable* has to be chosen.

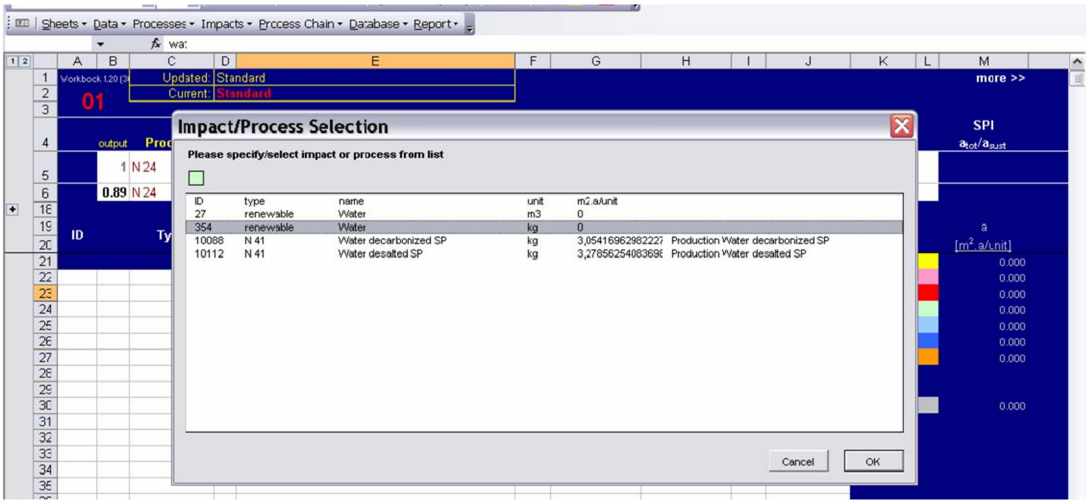


Figure 4-39: Entering the Eco-Inventory 2

The chosen input appears in the datasheet (Figure 4-40).

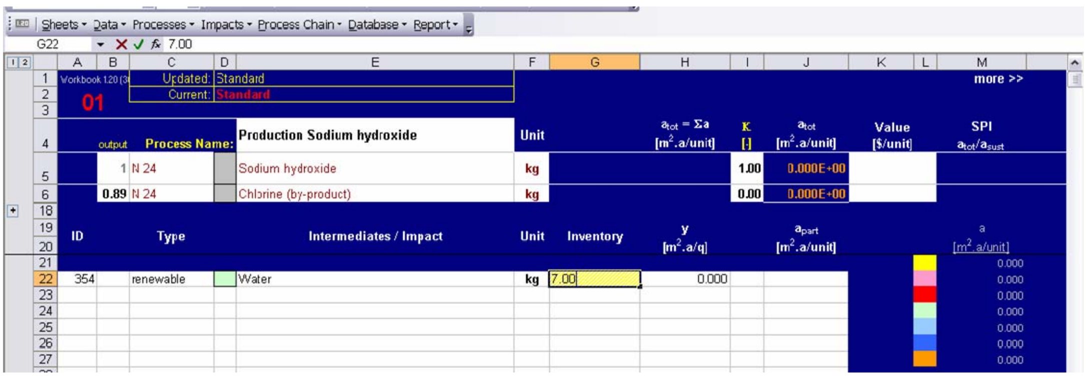


Figure 4-40: Entering the Eco-Inventory 3

The input row includes the input ID - a number used by the program to link inputs and data – the type of input which can be an impact category or a NACE-category along with its color code, the input name, its unit and the specific footprint of the input. The specific footprint is the ecological pressure one unit of the input causes.

To calculate the partial footprint of the process caused by this input the amount of the input used has to be entered into the inventory cell.

This process uses *7.00* kg of water.

Further inputs can be entered similarly into the datasheet (Figure 4-41).

The process needs different intermediates to produce sodium hydroxide. One is *Sodium chloride* (*1.454* kg) another one is *Net electricity EU25*.

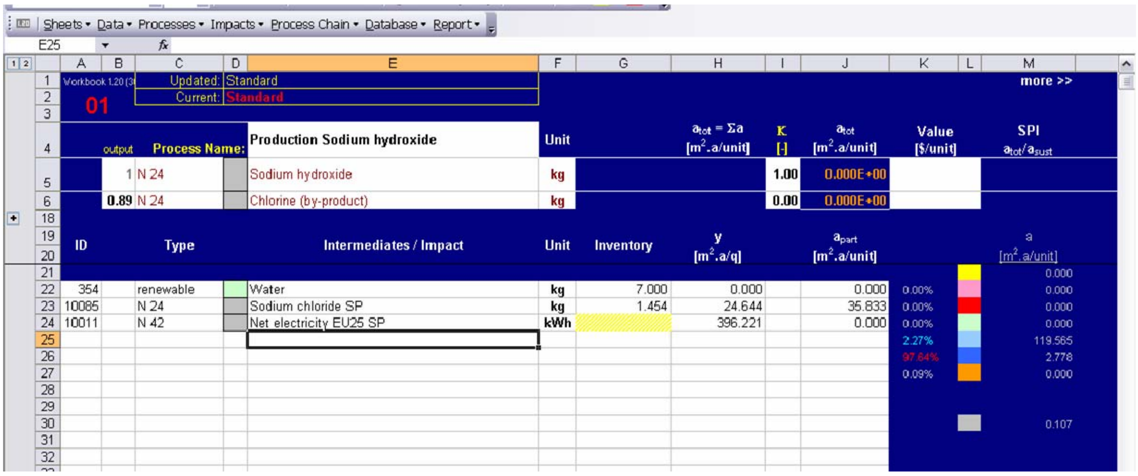


Figure 4-41: Entering the Eco-Inventory 4

The unit of *Net electricity EU25* is *kWh* but it can be changed by the user in the metric system for example into *kJ* (Figure 4-42). The specific footprint of the input changes according to the unit. If an amount has already been entered into the inventory cell, this also changes according to the new unit.

After changing the unit the amount of intermediate used can be entered. The process uses 0.010*kJ Net electricity EU25*.

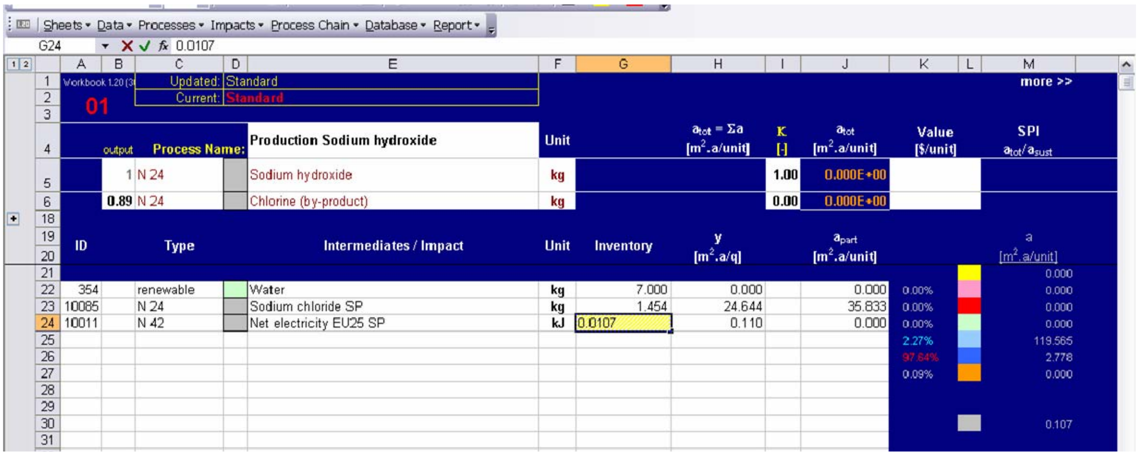


Figure 4-42: Entering the Eco-Inventory 5

To complete the input of the life cycle inventory further inputs have to be entered (Figure 4-43).

These inputs are emission of *Hg* to *water*, *0.001 g*; *Dichloro monofluoro methane* to *air*, *0.011 g* and *Waste in disposal*, *0.023 kg*.

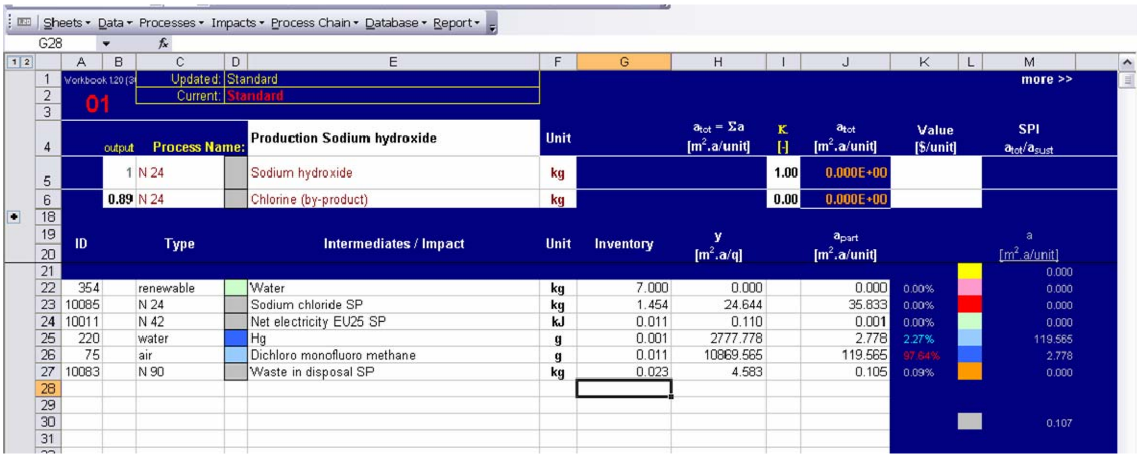


Figure 4-43: Entering the Eco-Inventory 6

4.6.D Step 4 Saving a Process

To calculate the overall footprint, either the command **Refresh Data Sheet** has to be used or the data has to be saved to the database (Figure 4-44). Applying the second command the datasheet is automatically refreshed. To save the entered data the command **Save Process Data** has to be chosen.

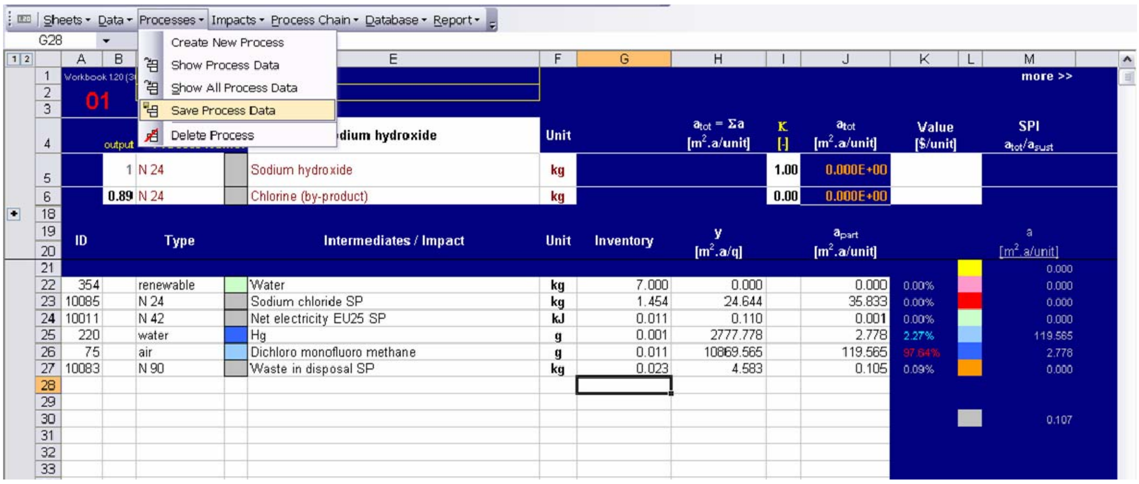


Figure 4-44: Saving a Process 1

After saving the process the products are assigned an ID-number by the software (Figure 4-45). The overall footprint is shown next to the product unit and is related to this unit. The cell next to the footprint shows the allocation of the footprint, in this case the footprint is allocated only to the primary product. On the right side of the Datasheet the SPI can be seen. Next to the partial footprints of the inputs the percentage of this input related to the overall footprint is shown. Next to this the amount of the footprint distributed to the different impact categories (represented by their colors) are displayed. Note that the grey color stands for intermediates produced by other processes or grey energy.

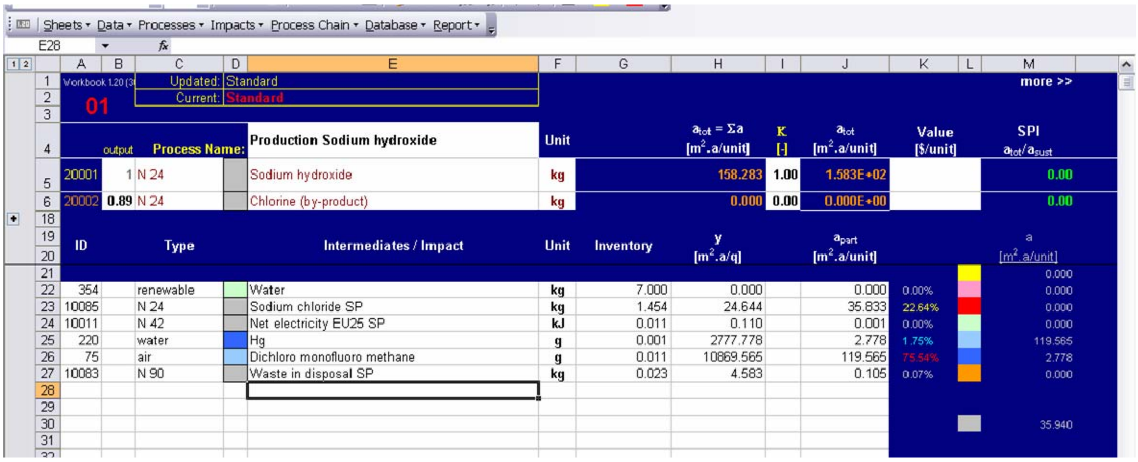


Figure 4-45: Saving a Process 2

4.6.E Step 5 Allocation

For changing the allocation method right click into the allocation cell (Figure 4-46). A menu will show up, presenting the three allocation options: **Only Primary Output**; **Related to Output**; **Related to Value**. While the option **Only Primary Output** allocates the overall footprint to the primary product only, the two other options allocate the footprint, **Related to Output** according to the mass output of the products, **Related to Value** according to the value entered in the value cells before the allocation method is applied.

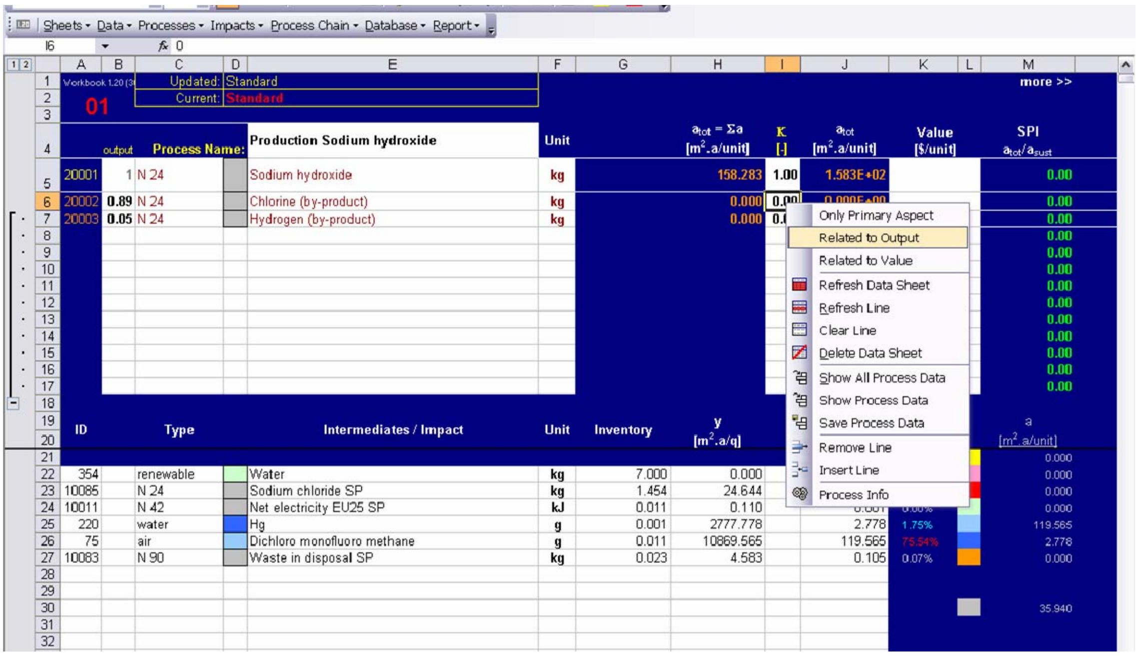


Figure 4-46: Allocation 1

Choosing either **Related to Output** or **Related to Value** the overall footprint for the products is allocated anew (Figure 4-47). Note that the footprints shown are calculated per unit of product and not based on the amount produced by the process.

Shown in the screenshot are the allocated footprints according to the **Related to Output** option.

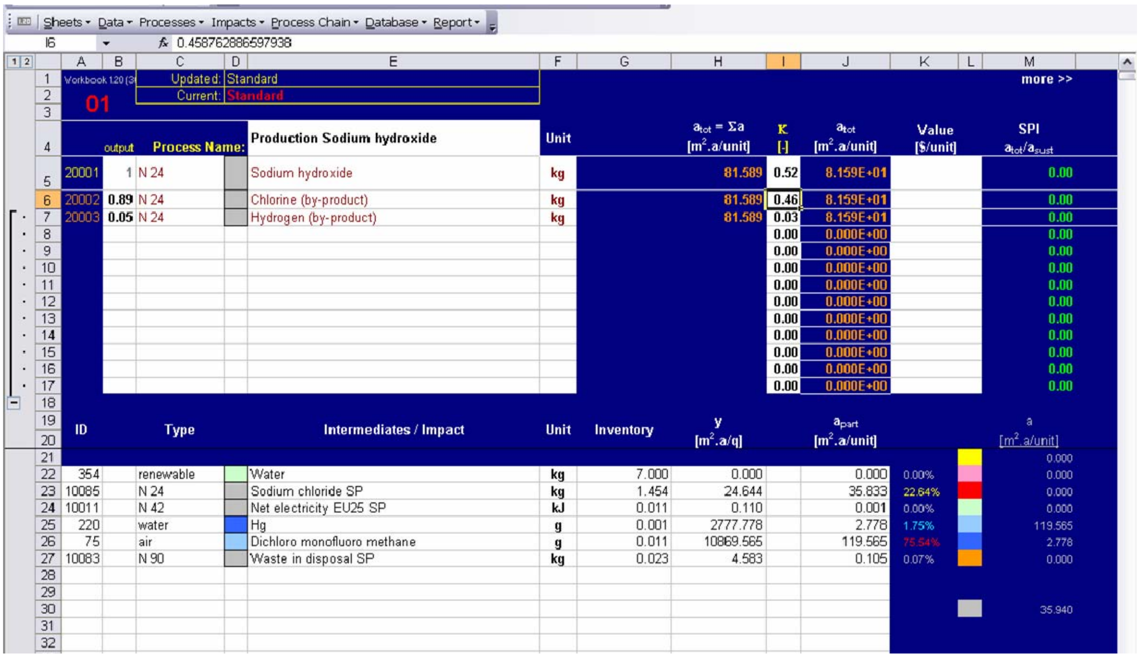


Figure 4-47: Allocation 2

4.6.F Step 6 Sheet Report

After entering a process the SPIonExcel software is able to display different reports (Figure 4-48). The first option is to create a datasheet report. To create the report click on the option **Create Sheet Report** in the Report tab.

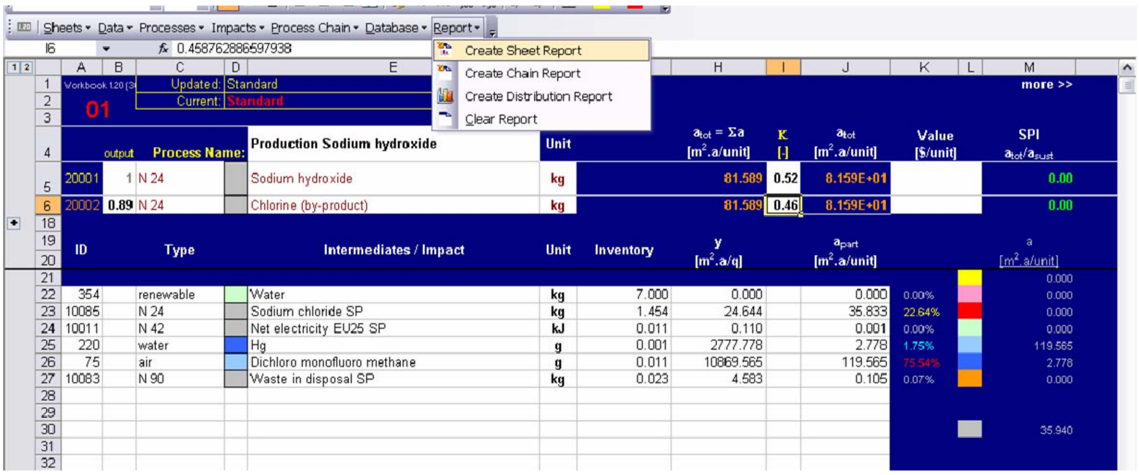


Figure 4-48: Sheet Report 1

A box will open up showing all products produced by processes in opened datasheets (Figure 4-49). Check the products to create reports for them.

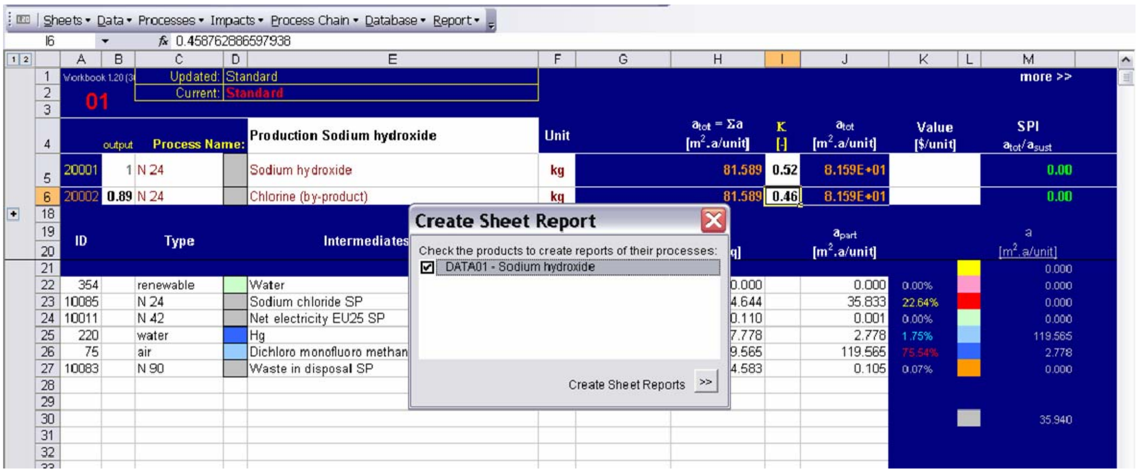


Figure 4-49: Sheet Report 2

The report created by this option shows the distribution of the footprint according to the impact categories (Figure 4-50). Also a graph is created representing the impact categories with their colors. Furthermore the emissions that create the largest impact in the three emission categories are shown.

This kind of report is well suited to compare different products.

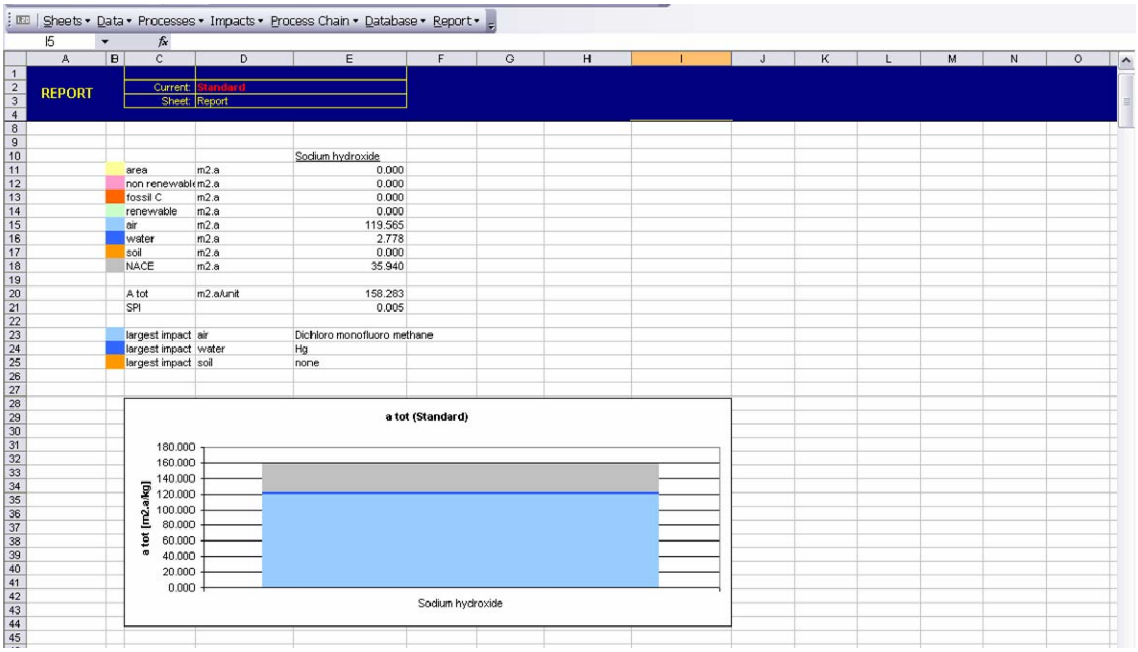


Figure 4-50: Sheet Report 3

4.6.G Step 7 Distribution Report

The second report option is the distribution report (Figure 4-51). To create it, the **Create Distribution Report** option in the Report tab has to be chosen.

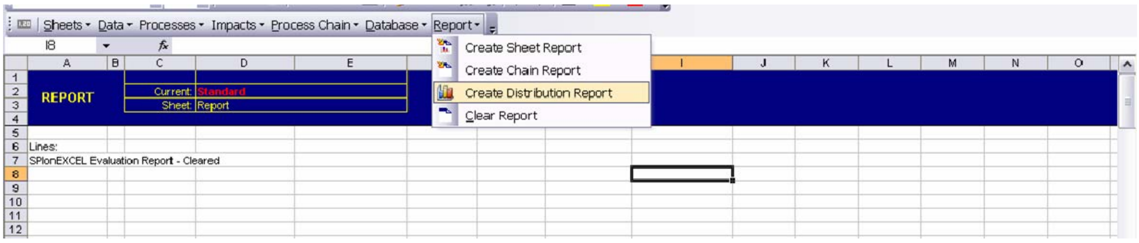


Figure 4-51: Distribution Report 1

As in the Sheet Report creation a window opens up showing all products in opened datasheets (Figure 4-52). Here the products for which a report is wanted have to be marked. If more than one product is marked the results are shown side by side.

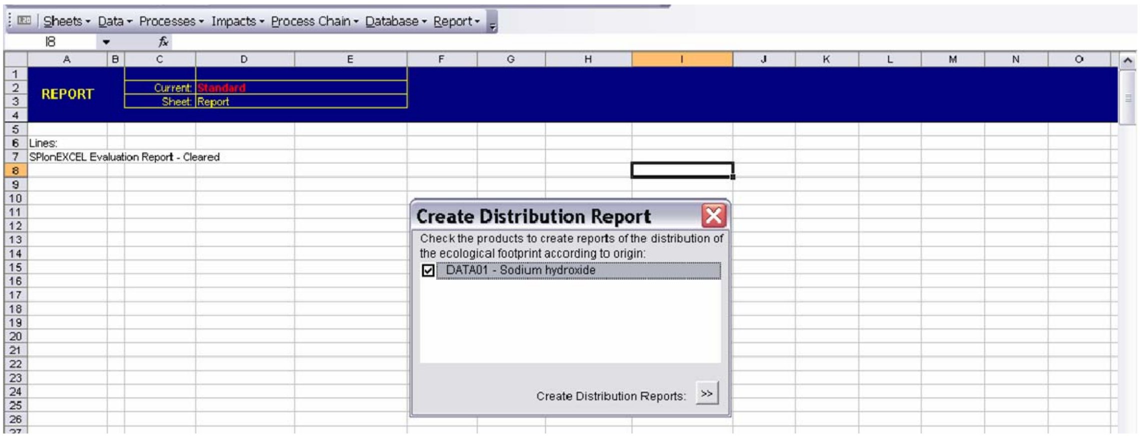


Figure 4-52: Distribution Report 2

This report shows the distribution of the overall footprint according to its origin (Figure 4-53). Origin can mean the industrial sector of provision like electricity provision, waste treatment or transport as well as resource origin like resource provision fossil or renewable. Also shown is the amount of the footprint created by impacts caused of the process itself.

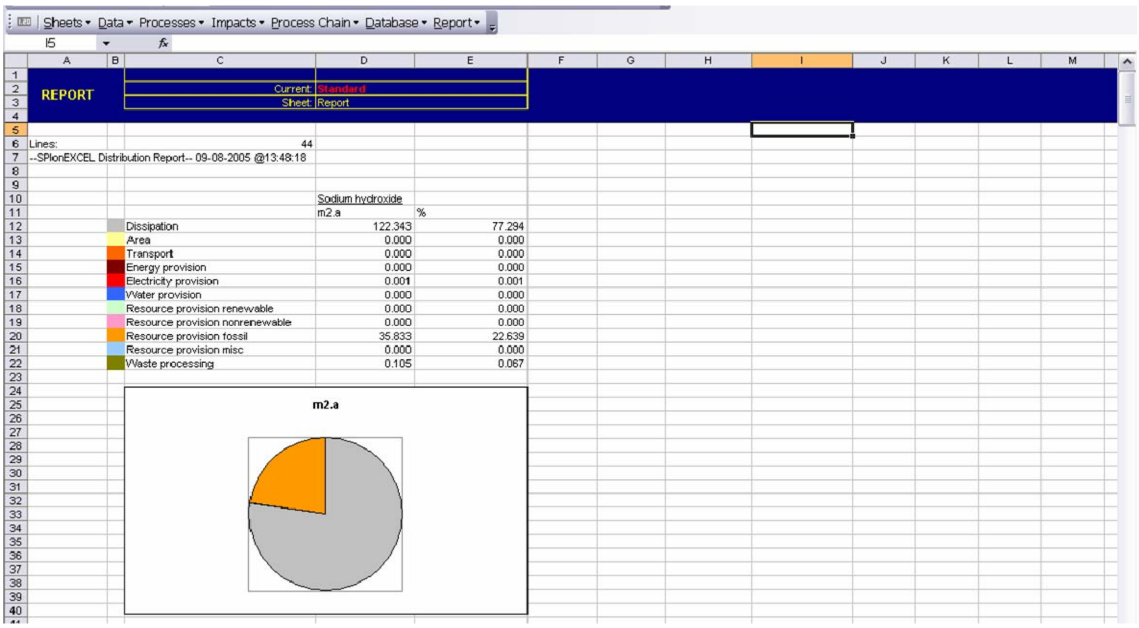


Figure 4-53: Distribution Report 3

4.6.H Step 8 Process Chain

The third result option is calculating the ecological footprint along a process chain (Figure 4-54). For this a process chain has to be build first. To do this the **Create Process Chain** command in the Process Chain tab has to be executed.

Figure 4-54: Process Chain 1

A window opens showing all products of opened datasheets (Figure 4-55). To create a process chain the end product has to be selected.

In our case choose *Sodium hydroxide*.

Figure 4-55: Process Chain 2

The process chain at the moment contains only one process, the production of sodium hydroxide (Figure 4-56). This is because only opened datasheets are included into a process chain and only the process *Production Sodium Hydroxide* is active at the moment. Therefore, to create a longer process chain, more processes have to be opened.

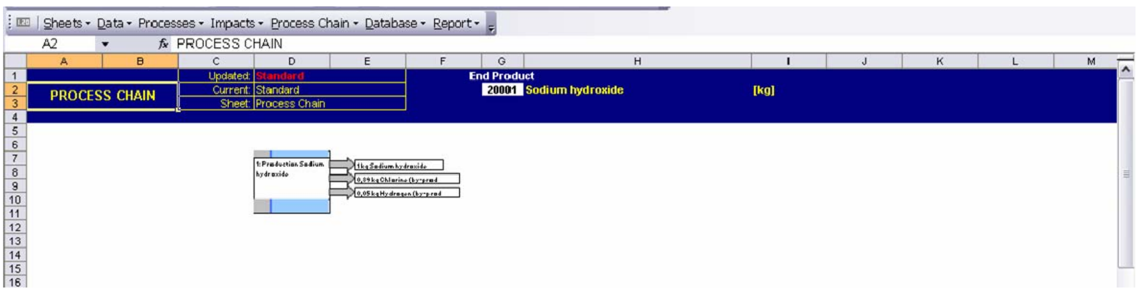


Figure 4-56: Process Chain 3

4.6.I Step 9 Opening of Sub-Processes

To open other processes there exist two possibilities (Figure 4-57). One is mostly used for opening single processes. This is done with the **Show Process** command in the Process tab.

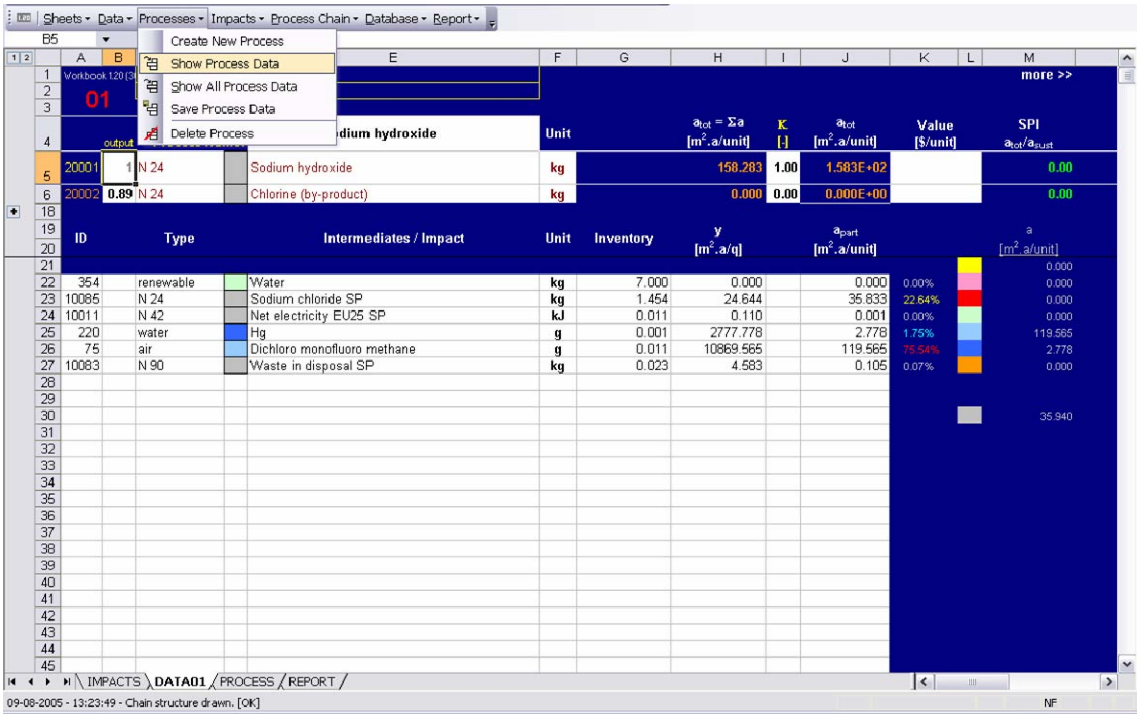


Figure 4-57: Opening of Sub-Processes 1

The command opens a box where the name of the product that shall be displayed can be chosen (Figure 4-58). This can be done by either entering the product name or the product ID-number. If a intermediate is marked when the command is executed, the product ID is directly put into the search field.

To open the process for *sodium chloride* its name is typed into the search field.

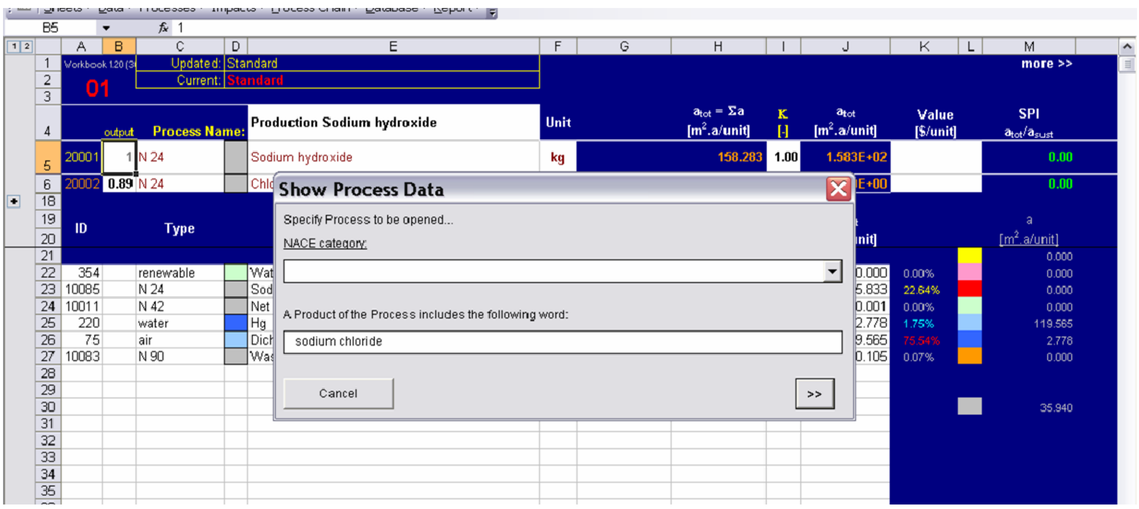


Figure 4-58: Opening of Sub-Processes 2

The other possibility to open processes is the **Show all Processes** command (Figure 4-59). This command loads all processes of intermediates existing on the active datasheet to new datasheets. This option safes much time when many processes have to be opened.

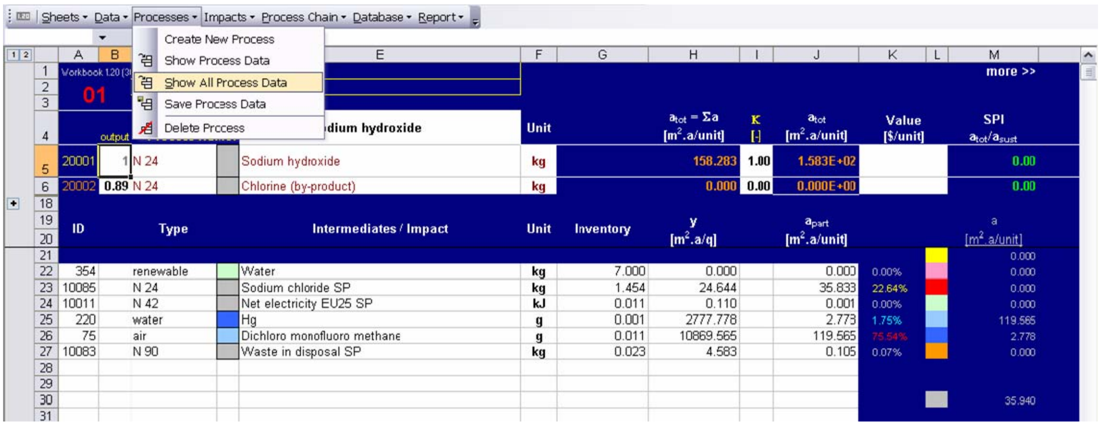


Figure 4-59: Opening of Sub-Processes 3

The chosen process will open in a new datasheet (Figure 4-60). If the **Show all Processes** command was used the software will continue loading automatically the processes of all intermediates contained in the active datasheet.

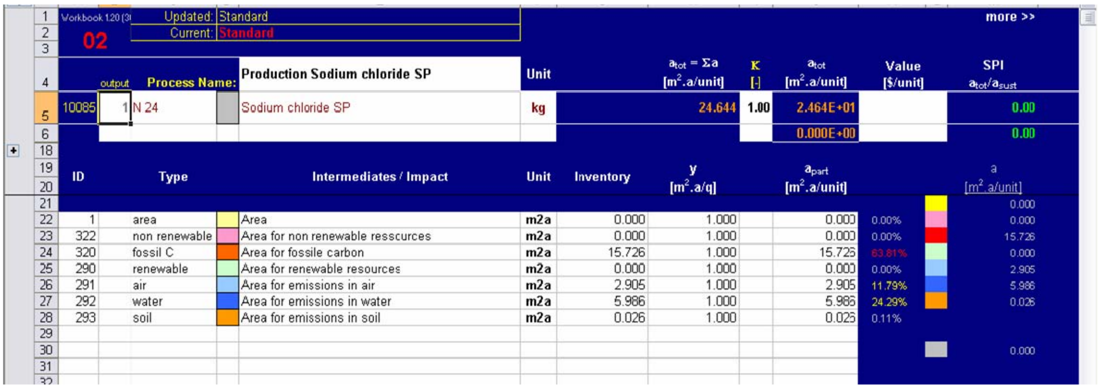


Figure 4-60: Opening of Sub-Processes 4

4.6.J Step 10 Advanced Process Chain

After opening all processes that shall be included into a process chain the **Create Process Chain** command in the Process Chain tab builds the full process chain (Figure 4-61).

Figure 4-61: Advanced Process Chain 1

Because of the opened processes there is a wider range of products to choose from.

Choose *Sodium hydroxide* again.

The process chain now built is more complex (Figure 4-62). It shows the three sub processes of sodium hydroxide production and the production itself as process boxes, the mass and energy flows connecting them.

The process chain is not clearly arranged after building but through dragging it is possible to arrange the process boxes and flow lines to the requirement of the user.

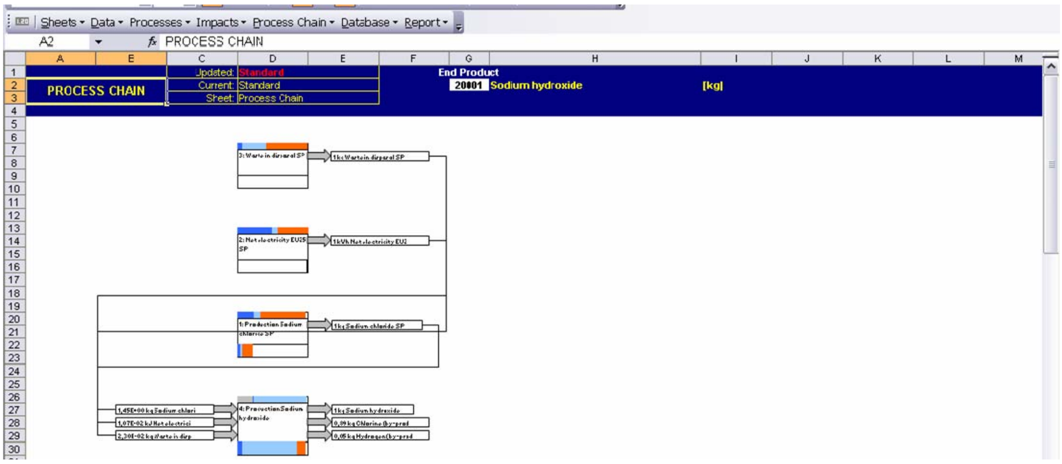


Figure 4-62: Advanced Process Chain 2

After rearranging the process chain, the structure is easier to assess (Figure 4-63). In the upper bar of each box, the distribution of the ecological footprint according to the impact categories is shown related to the process represented in the box. The lower bar shows the same distribution but related to the end product.

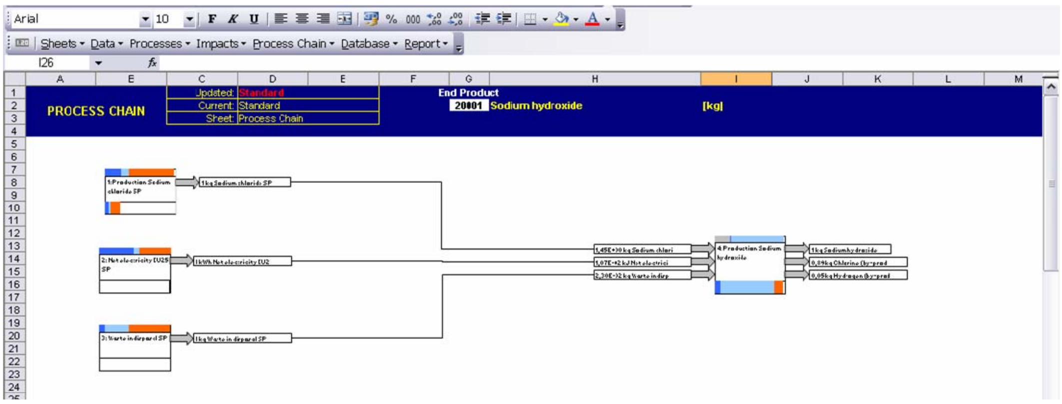


Figure 4-63: Advanced Process Chain 3

4.6.K Step 11 Chain Report

Using the command **Create Chain Report** in the Report tab the footprint distribution along the process chain can also be displayed as graph (Figure 4-64). This kind of report is only available when a process chain has been built.

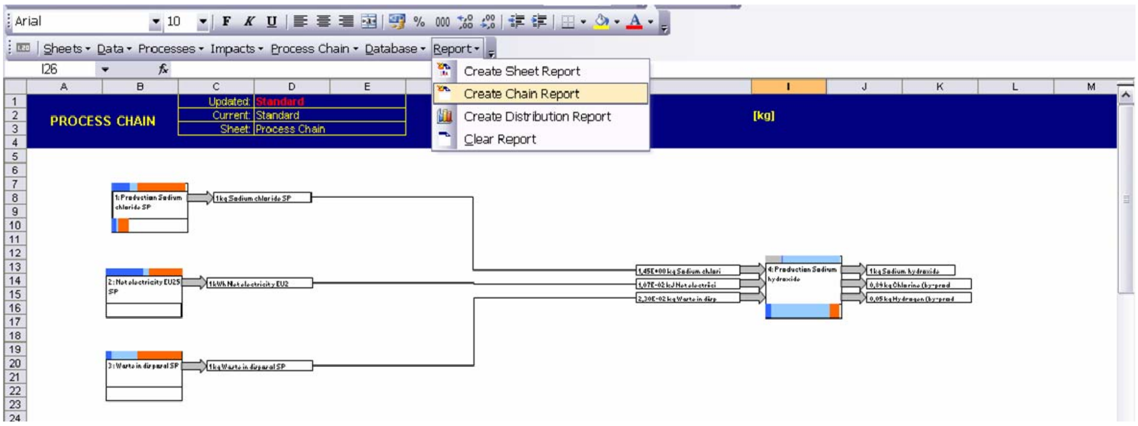


Figure 4-64: Chain Report 1

This report shows the distribution of the ecological footprint along the process chain based on the end product (Figure 4-65). Also shown is the emission with the largest impact in the three emission categories along the process chain.

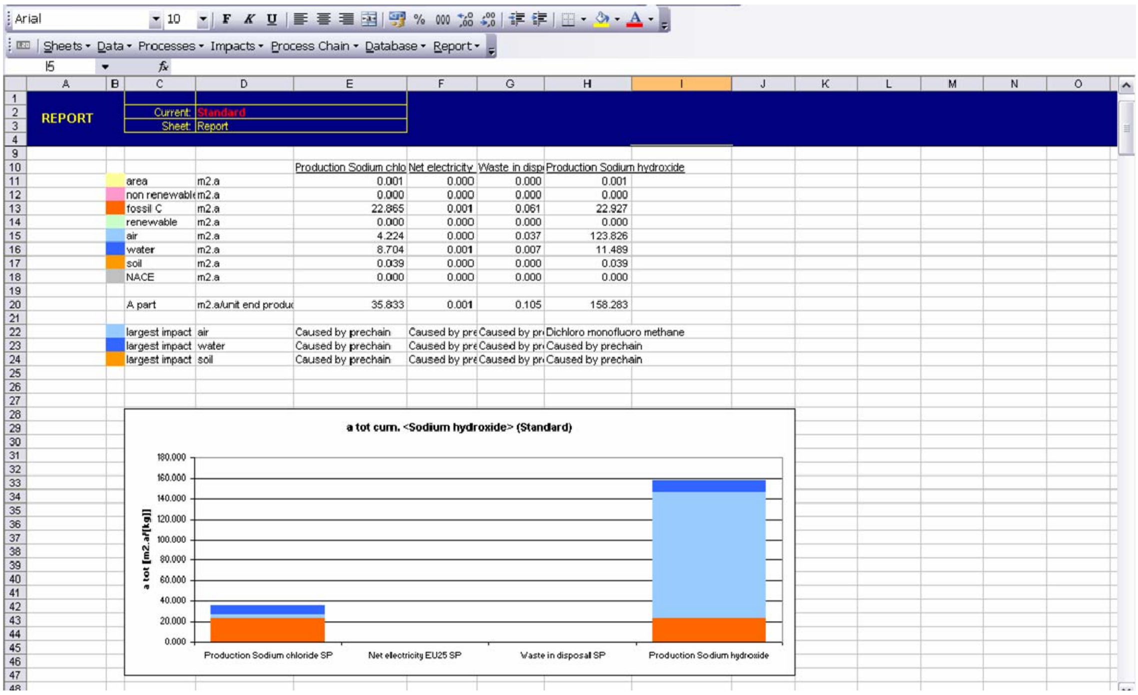


Figure 4-65: Chain Report 2

5 Case Study Biodiesel

5.1 *Introduction*

The use of vegetable oil in engines is over 100 years old. As Rudolf Diesel presented his engine in the year 1900 it was running on peanut oil. Soon after this the European countries started looking for cheap native vegetable oil as fuel in their colonies. As fossil fuel became more available and cheaper this trend stopped.

With the oil crisis in the 1970s research on vegetable oil as fuel was taken up again, but the direct use of vegetable oil presented a problem for the engines used then. Their high viscosity led to incomplete combustion and polymerization of the oil formed deposits on injector nuzzles till the engine broke down.

A way to avoid these problems was found in biodiesel. First all fuels derived from vegetable oils either by pyrolysis, microemulsification or transesterification were named biodiesel. Soon due to the advantages of product and process, only fuels derived by transesterification were called biodiesel.

In the 1980s first applications of biodiesel from rapeseed oil were presented and soon biodiesels from vegetable oils were seen as the future fuels. Next to vegetable oils also the utilization of tallow and recycled frying oil as feedstock was applied.

Because of the "European Directive for the Promotion of the Use of Biofuels" published by the European Council and the European Parliament 2003 the increase in biodiesel production in the last years was immense. Due to this directive each European country enrolled to reach a 5.75% of biodiesel fraction in diesel fuels till 2010.

In the year 2004 the amount of produced gasoline fuels was over 1200 billion tons worldwide. The largest part of this is fossil fuels (Figure 5-1). Biofuels play a minor role and biodiesel is almost nonexistent compared to total production [49].

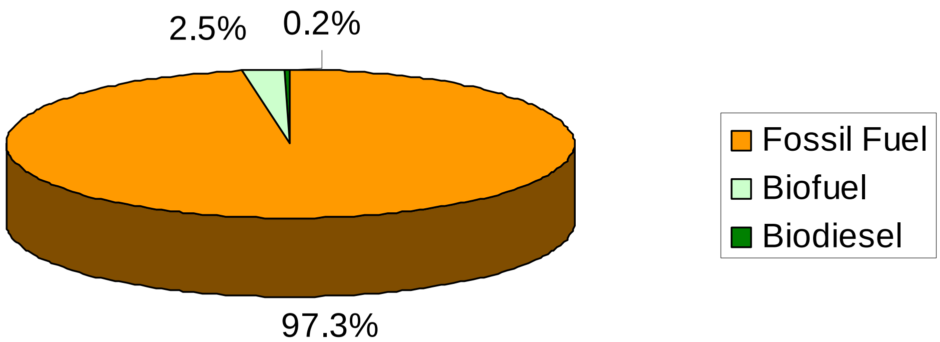


Figure 5-1: Distribution of the fuel type produced 2004 worldwide

The feedstock for biodiesel production is mainly rapeseed oil, to smaller part sunflower oil (Figure 5-2). Other vegetable oil feedstock comes from soy beans and oil palms. The category Others includes sources as tallow and recycled frying oil [43].

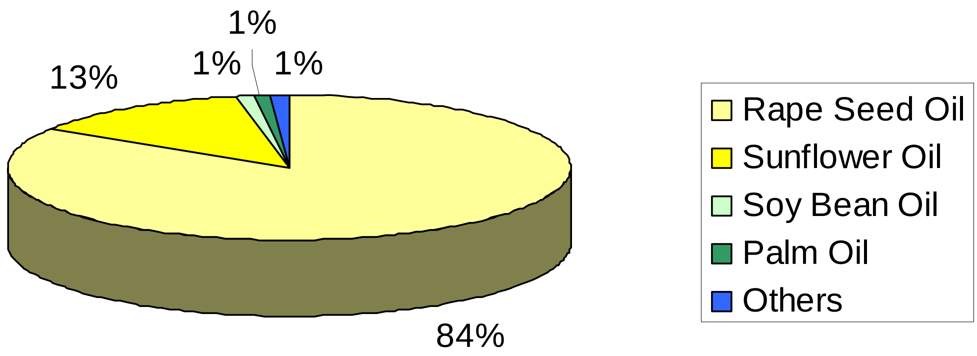


Figure 5-2: Distribution of source for biodiesel production

Biodiesel is synthesized from vegetable oil with lower alcohols, mainly methanol, producing fatty esters and triglycerol (Figure 5-3).

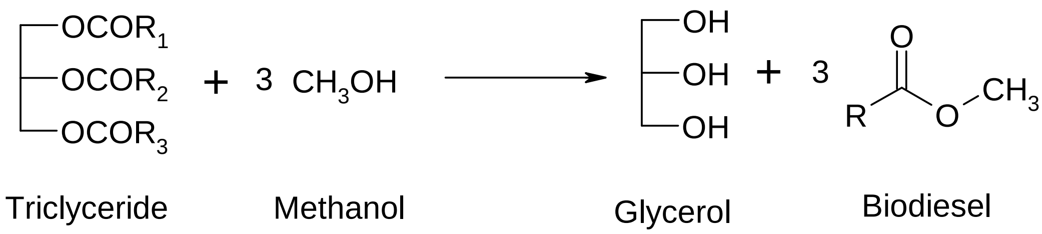


Figure 5-3: Synthesis of biodiesel from vegetable oil

This chapter deals with biodiesels derived from different feedstock, vegetable oils and others, as well as compares them to the direct use of vegetable oil and fossil diesel. As the intended use of any fuel is powering of engines the base of comparison is 1 MJ of engine output due to combustion.

5.2 *Data Sources*

Most of the data that have been considered in this case study are from well-established published data sources.

- Data on energy have been taken from ESU-ETHZ [15]. ESU-ETHZ represents the electricity production of the UCPTE countries (European energy net) at the beginning of the nineties. The electricity mixes for the European countries was calculated with data from EUROSTAT [22] for the year 2002. The applied electricity mix represents the EU25 countries.

- Transportation systems have been taken from ESU-ETHZ [15]. The data of road infrastructure represent Swiss road infrastructure, including many tunnels and winding mountain roads. The impact of road infrastructure is therefore, high in comparison to the EU average.
- Data on process chemicals and waste treatment come from ESU-ETHZ [15] and BUWAL [23]. In general the data quality of process chemicals is lower than for energy systems as modeling of process chemicals is highly aggregated. The published data represents standardized technology for Europe.
- Data on the transesterification and combustion process have been taken from BIODIEPRO [45].
- Data on production of rapeseed oil have been taken from Chapter 7.12.
- Data on production of sunflower oil have been taken from Chapter 7.15.
- Data on production of soybean oil have been taken from Chapter 7.14.
- Data on production of tallow have been taken from Chapter 7.11.
- Data on production of false flax oil have been taken from Chapter 7.13.
- Data on provision of crude oil Europe have been taken from Chapter 7.16.
- Data on the exhaust emissions of all biodiesel except from sunflower come from Faber [46].
- Data on the exhaust emissions for sunflower biodiesel come from Altin et al. [46].
- Data on the exhaust emissions for sunflower biodiesel come from Putnam et al. [44].
- Data on the exhaust emissions for fossil diesel come from ESU-ETHZ [15].

5.3 *Biodiesel from Rapeseed Oil*

5.3.A Technical Background

Rapeseeds are the most used feedstock for biodiesel production at the moment. Especially in Germany biodiesel is almost exclusively processed from rapeseed oil [43].

In the transesterification process additional by-products can be obtained: glycerol and potassium phosphate. While potassium phosphate is a waste with no value glycerol can be sold as it is a raw material for many processes. An additional benefit of this glycerol is the renewable background which, especially in cosmetic industries is preferred compared to synthetic glycerol.

5.3.B Process

The process of utilization of biodiesel from rapeseed oil is a two step process.

First rapeseed oil is transesterificated producing rapeseed methyl ester and glycerol. In this step the chemicals methanol, potassium hydroxide and sulfuric acid are consumed. Additionally process water and energy are needed. A transportation need was calculated based on the average distance between the rapeseed oil processing facility and the biodiesel production site. Due to lack of data the emissions arising during the transesterification are not included. The emissions produced due to energy consumption are included in the related modules.

The second step is the combustion of rapeseed methyl ester biodiesel in an engine. Assessed in this step are only the exhaust emissions occurring during combustion.

Infrastructure of the transesterification process and the combustion engine are not included. The process and system borders are shown in Figure 5-4.

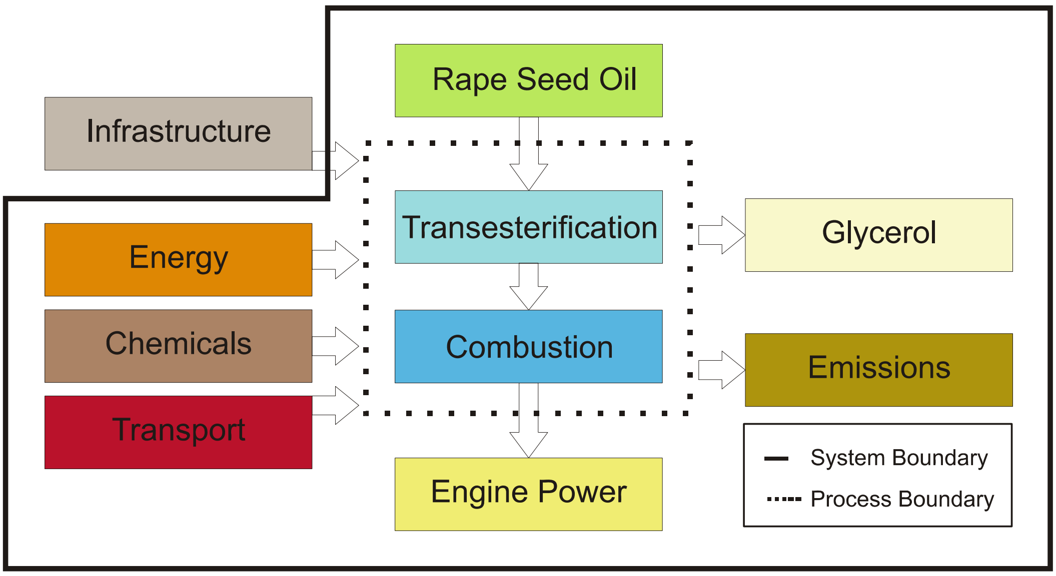


Figure 5-4: Process structure and system boundaries of the ecological assessment of the utilization of biodiesel from rapeseed oil

5.3.C Eco-Inventory

Table 5-1 shows the eco-inventory for the production of 1kg biodiesel from rapeseed oil, Table 5-2 for 1MJ resulting engine output.

Table 5-1: Eco-inventory for the production of 1kg biodiesel from rapeseed oil

Feedstock	Refined Rapeseed Oil	kg/kg	1.000
Resources	Process Water	kg/kg	0.036
Energy	Electricity	kWh/kg	0.033
	Extra Light Fuel Oil	MJ/kg	1.623
Chemicals	Methanol	kg/kg	0.100
	Potassium hydroxide	kg/kg	0.013
	Sulfuric acid	kg/kg	0.012
Transportation	16t Truck	tkm/kg	0.015
Byproducts	Glycerin	kg/kg	0.1005
	K2PO4	kg/kg	0.0215

Table 5-2: Eco-inventory for the production of 1MJ engine output

Feedstock	Biodiesel from Rapeseed Oil	kg/MJ	0.071
Emissions	NO_x (air)	g/MJ	1.050

5.3.D Results

Taking a look at the pressure on environment obtained by the different process steps it can be seen that the process itself plays a minor role (Figure 5-5). The largest contributor to the ecological footprint is the supply chain of the process, the provision of rapeseed oil. Inside the process the transesterification step inflicts about as much ecological pressure as the exhaust emissions when the biodiesel is combusted in an engine.

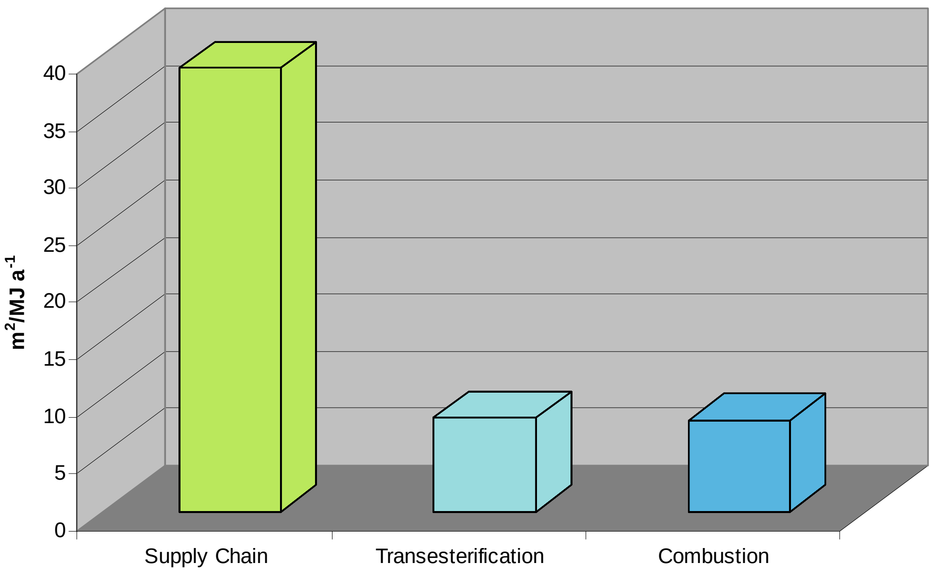


Figure 5-5: The ecological footprint for 1MJ produced energy over the process steps

The production of biodiesel from rapeseed oil and its combustion in an engine accumulates a process footprint of 55.03m^2. Due to price allocation (biodiesel 0.68€/kg; glycerol 0.26€/kg) the footprint results in 639.57m^2/kg a^{-1} biodiesel, 239.84m^2/kg a^{-1} glycerol and 53.32m^2/MJ a^{-1} energy.

The origin of the footprint of the engine power can be attributed to the greatest part to the feedstock (Figure 5-6). The exhaust emissions occurring during the combustion plays also an important role for the environmental pressure. Energy and chemical input inflict about the same amount of pressure but each is only half of the pressure obtained by emissions. Chemicals have a little more influence as energy because of the large amount methanol used. Transportation as well as resource depletion is negligible.

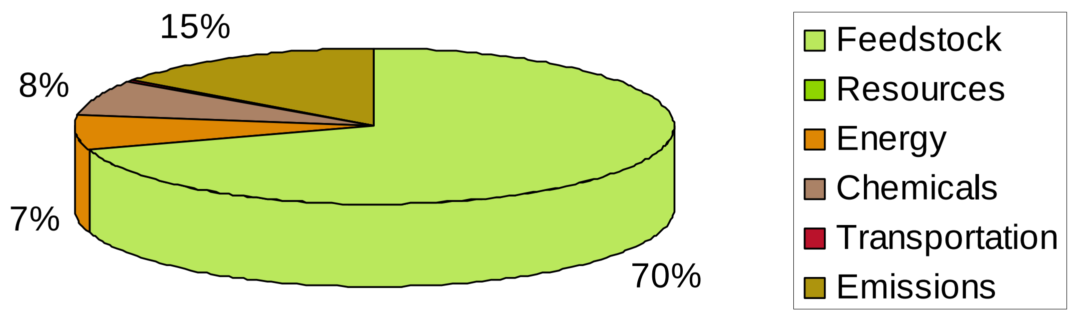


Figure 5-6: Distribution of the ecological footprint of 1MJ engine power utilizing biodiesel from rapeseed oil with price allocation

5.4 *Biodiesel from Sunflower Oil*

5.4.A Technical Background

An often used alternative to rapeseed oil for biodiesel production is sunflower oil [47]. However, the amount of sunflower oil applied to the transesterification process is a lot smaller than rapeseed oil.

As with the biodiesel production from rapeseed oil by processing sunflower oil the byproducts glycerol and potassium phosphate are obtained. Glycerol as valued byproduct can be sold.

5.4.B Process

The process of utilization of biodiesel from sunflower oil works similar to the production of biodiesel from rapeseed oil and is a two step process.

The first step, transesterification consumes methanol, potassium hydroxide and sulfuric acid producing biodiesel and glycerol. Process water and energy as well as transportation are further inputs in this process step. Emissions are not accounted for in particular but included in the provision of energy consumption.

The second step is the combustion of sunflower methyl ester biodiesel in an engine. Assessed in this step are only the exhaust emissions occurring during combustion.

Infrastructure of the transesterification process and the combustion engine are not included. The process and system borders are shown in Figure 5-7.

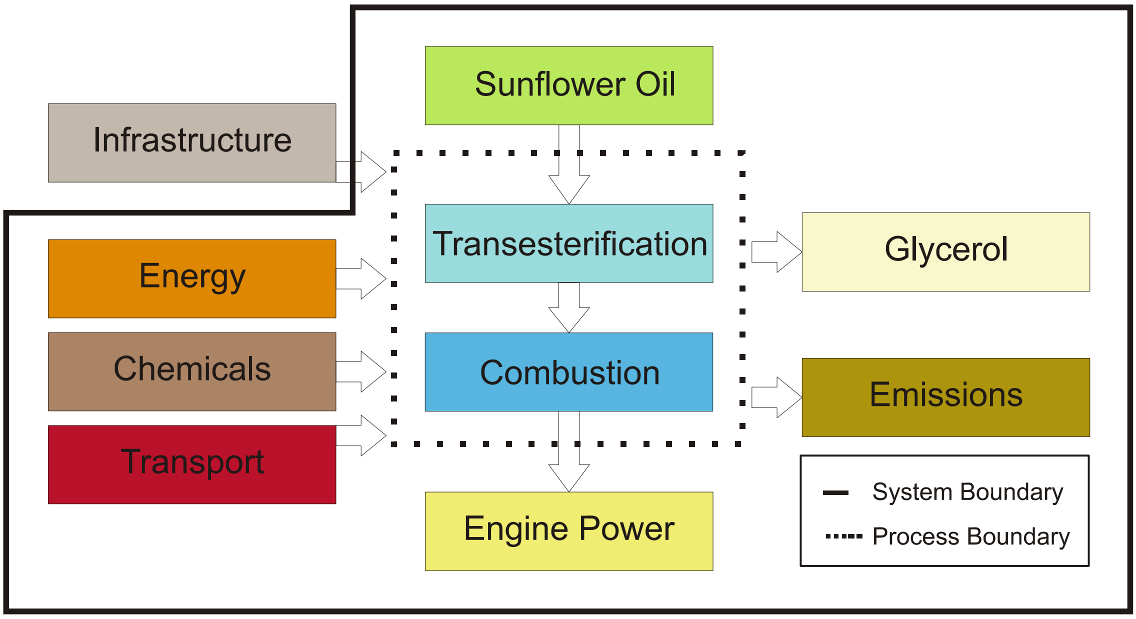


Figure 5-7: Process structure and system boundaries of the ecological assessment of the utilization of biodiesel from sunflower oil

5.4.C Eco-Inventory

Table 5-3 shows the eco-inventory for the production of 1kg biodiesel from sunflower oil, Table 5-4 for 1MJ resulting engine output.

Table 5-3: Eco-inventory for the production of 1kg biodiesel from sunflower oil

Feedstock	Refined Sunflower Oil	kg/kg	1.000
Resources	Process Water	kg/kg	0.036
Energy	Electricity	kWh/kg	0.033
	Extra Light Fuel Oil	MJ/kg	1.623
Chemicals	Methanol	kg/kg	0.100
	Potassium hydroxide	kg/kg	0.013
	Sulfuric acid	kg/kg	0.012
Transportation	16t Truck	tkm/kg	0.015
Byproducts	Glycerin	kg/kg	0.1005
	K2PO4	kg/kg	0.0215

Table 5-4: Eco-inventory for the production of 1MJ engine output

Feedstock	Biodiesel from Sunflower Oil	kg/MJ	0.073
Emissions	NO_x (air)	g/MJ	1.047

5.4.D Results

Looking at the ecological footprint obtained by the different process steps it can be seen that the supply chain plays the key role for the produced energy although its pressure is lower than in the case of rapeseed oil (Figure 5-8). Transesterification and combustion of the biodiesel apply about the same amounts of pressure on environment.

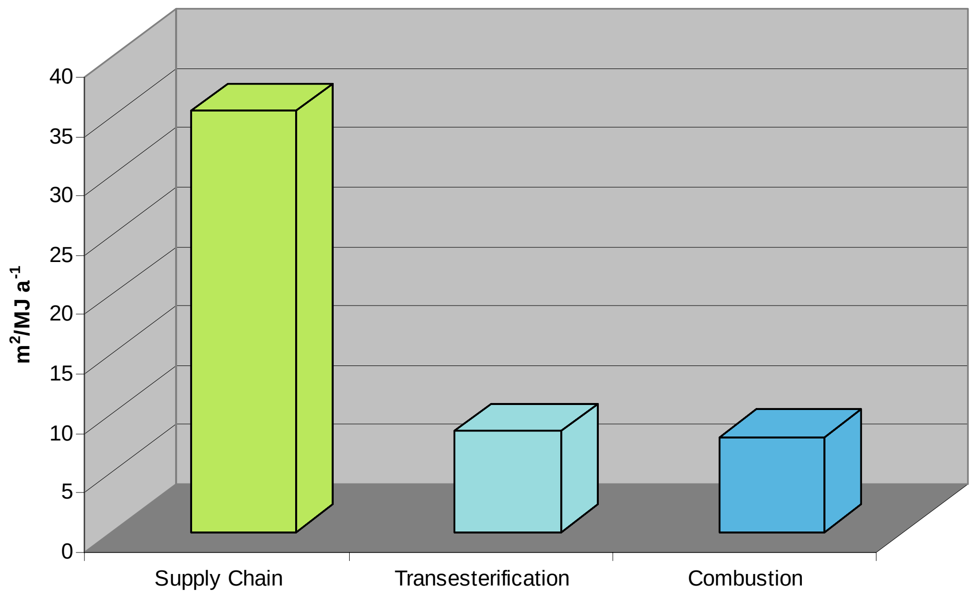


Figure 5-8: The ecological footprint for 1MJ produced energy over the process steps

The production of energy from sunflower oil via biodiesel results in a process footprint of 51.91m^2. Due to price allocation (biodiesel 0.68€/kg; glycerol 0.26€/kg) the overall footprints result in 578.79m^2/kg a^{-1} for biodiesel of sunflower oil, 217.05m^2/kg a^{-1} for glycerol and 50.31m^2/MJ a^{-1} for engine power.

The origin of the ecological footprint for engine power lies mostly in the feedstock sunflower oil (Figure 5-9). Emissions play a minor, but nonetheless important role for the overall pressure on environment. Chemicals and energy obtain the same amount of the inflicted pressure while transportation and resource depletion influence is not detectable.

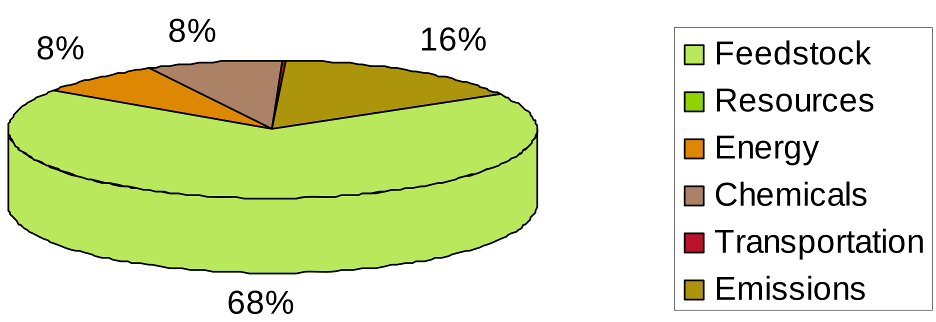


Figure 5-9: Distribution of the ecological footprint of 1MJ engine power utilizing biodiesel from sunflower oil with price allocation

5.5 *Biodiesel from Soybean Oil*

5.5.A Technical Background

A feedstock that may have future potential for biodiesel production is soybean oil [46]. Soybeans are cultivated in larger amounts than rapeseed, especially in the US. At the moment most of the soybean oil is used by food or cosmetic industries.

As in each biodiesel production from vegetable oils the value by-product glycerol can be obtained.

5.5.B Process

The utilization of biodiesel from soybeans in an engine consists of two process steps.

The first step is the transesterification of soybean oil to biodiesel. For this, chemicals in the form of methanol, potassium hydroxide and sulfuric acid are used. Furthermore energy and transportation input is needed as well as the resource process water.

In the second process step the biodiesel is combusted in an engine producing engine power. Thereby exhaust emissions occur.

Infrastructure of the transesterification process and the combustion engine are not included. The process and system borders are shown in Figure 5-10

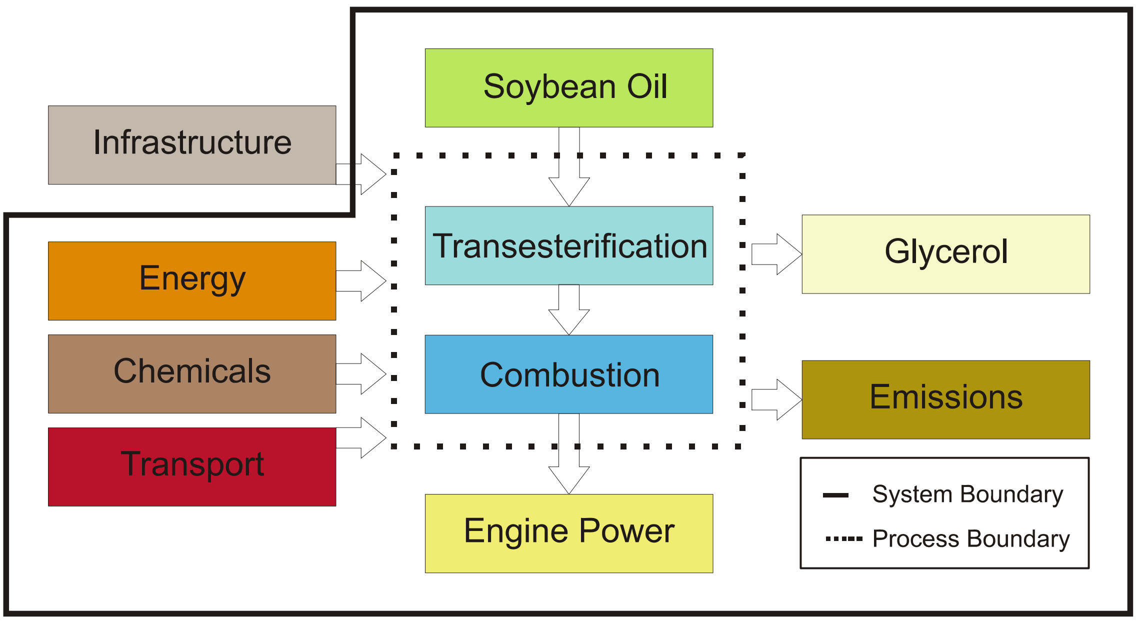


Figure 5-10: Process structure and system boundaries of the ecological assessment of the utilization of biodiesel from soybean oil

5.5.C Eco-Inventory

Table 5-5 shows the eco-inventory for the production of 1kg biodiesel from soybean oil, Table 5-6 for 1MJ resulting engine output.

Table 5-5: Eco-inventory for the production of 1kg biodiesel from soybean oil

Feedstock	Refined Soybean Oil	kg/kg	1.000
Resources	Process Water	kg/kg	0.036
Energy	Electricity	kWh/kg	0.033
	Extra Light Fuel Oil	MJ/kg	1.623
Chemicals	Methanol	kg/kg	0.100
	Potassium hydroxide	kg/kg	0.013
	Sulfuric acid	kg/kg	0.012
Transportation	16t Truck	tkm/kg	0.015
Byproducts	Glycerin	kg/kg	0.1005
	K2PO4	kg/kg	0.0215

Table 5-6: Eco-inventory for the production of 1MJ engine output

Feedstock	Biodiesel from Soybean Oil	kg/MJ	0.071
Emissions	NO_x (air)	g/MJ	1.047

5.5.D Results

The accumulation of ecological pressure along the process steps shows that the supply chain exerts the largest influence on the process footprint (Figure 5-11). The transesterification and combustion still add to the footprint significantly but to a much lower level.

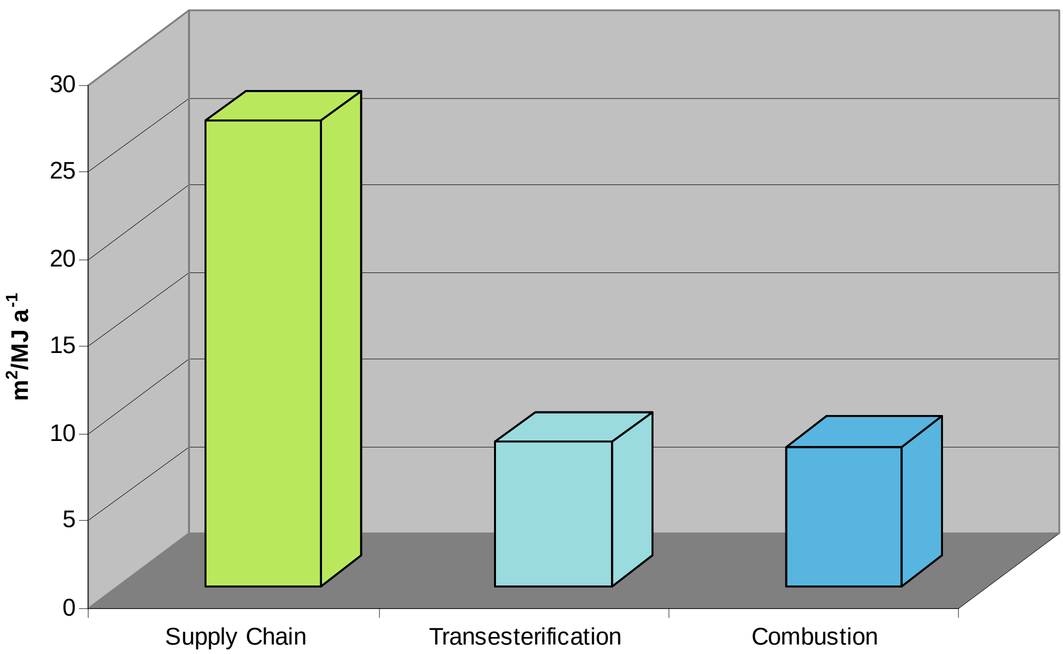


Figure 5-11: The ecological footprint for 1MJ produced energy over the process steps

The process adds up to a process footprint of 42.93m². Applying price allocation (biodiesel 0.68€/kg; glycerol 0.26€/kg) the overall footprints are 474.20m²/kg a^{-1} for biodiesel from soybean oil, 177.82m²/kg a^{-1} for glycerol and 41.66m²/MJ a^{-1} for engine power.

The majority of the footprint is obtained by the feedstock usage (Figure 5-12). Another important contributor to the ecological pressure is the exhaust emissions. Chemicals and Energy play a lesser but nonetheless equally important role. Transportation and resource depletion are of minor importance.

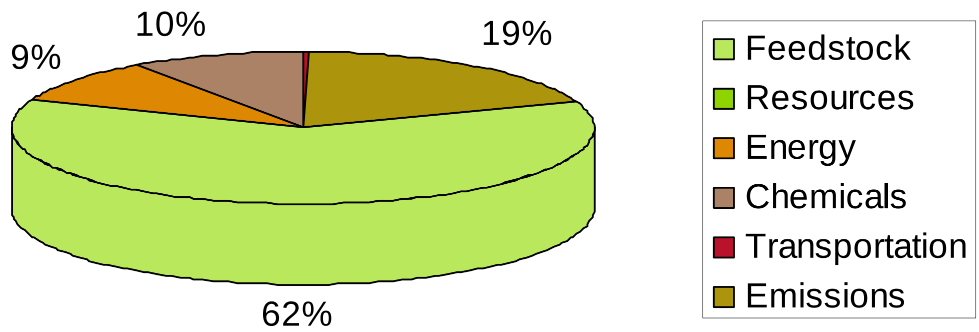


Figure 5-12: Distribution of the ecological footprint of 1MJ engine power utilizing biodiesel from soybean oil with price allocation

5.6 *Biodiesel from Tallow*

5.6.A Technical Background

Vegetable oils are not the only feedstock source for biodiesel production. Animal fats can also be utilized for this process [29]. Tallow is mostly obtained either during the slaughtering of cattle or the rendering process of meat and bone meal production.

5.6.B Process

Like the other utilization processes the combustion of biodiesel from tallow is a two step process.

The first process step obtains the biodiesel by transesterification of tallow utilizing methanol beside other chemicals. Energy and transportation need as well as process water consumption also occur during this process step.

The second step utilizes the biodiesel to produce engine power due to combustion. In this process step exhaustion emissions are obtained.

Infrastructure of the transesterification process and the combustion engine are not included. The process and system borders are shown in Figure 5-13.

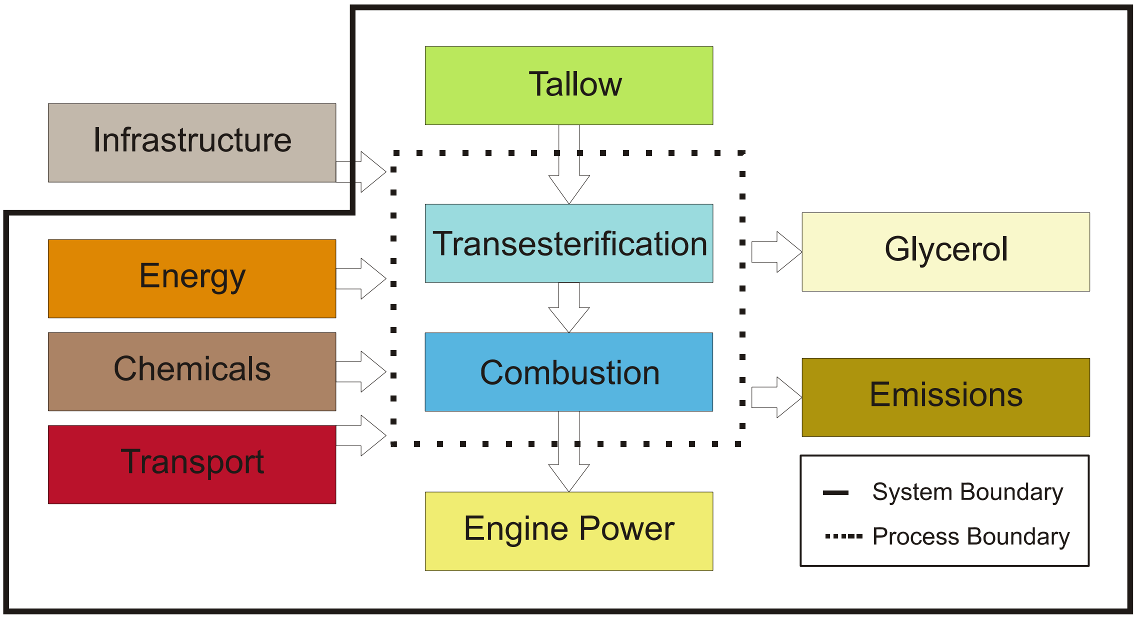


Figure 5-13: Process structure and system boundaries of the ecological assessment of the utilization of biodiesel from tallow

5.6.C Eco-Inventory

Table 5-7 shows the eco-inventory for the production of 1kg biodiesel from rapeseed oil, Table 5-8 for 1MJ engine output.

Table 5-7: Eco-inventory for the production of 1kg biodiesel from tallow

Feedstock	Tallow from Rendering	kg/kg	0.591
	Tallow from Slaughtering	kg/kg	0.435
Resources	Process Water	kg/kg	0.036
Energy	Electricity	kWh/kg	0.030
	Extra Light Fuel Oil	MJ/kg	2.040
Chemicals	Methanol	kg/kg	0.109
	Potassium hydroxide	kg/kg	0.027
	Sulfuric acid	kg/kg	0.012
Transportation	16t Truck	tkm/kg	0.016
Byproducts	Glycerin	kg/kg	0.101
	K2PO4	kg/kg	0.022

Table 5-8: Eco-inventory for the production of 1MJ engine output

Feedstock	Biodiesel from Fat	kg/MJ	0.071
Emissions	NO_x (air)	g/MJ	1.001

5.6.D Results

Comparing the accumulated footprint along the process steps it can be seen that supply chain still plays the major role in the production process (Figure 5-14). Unlike the utilization of biodiesel from vegetable oils the use of biodiesel from tallow results in a higher footprint during the transesterification step. The environmental pressure inflicted by the combustion step is a little lower than the second step.

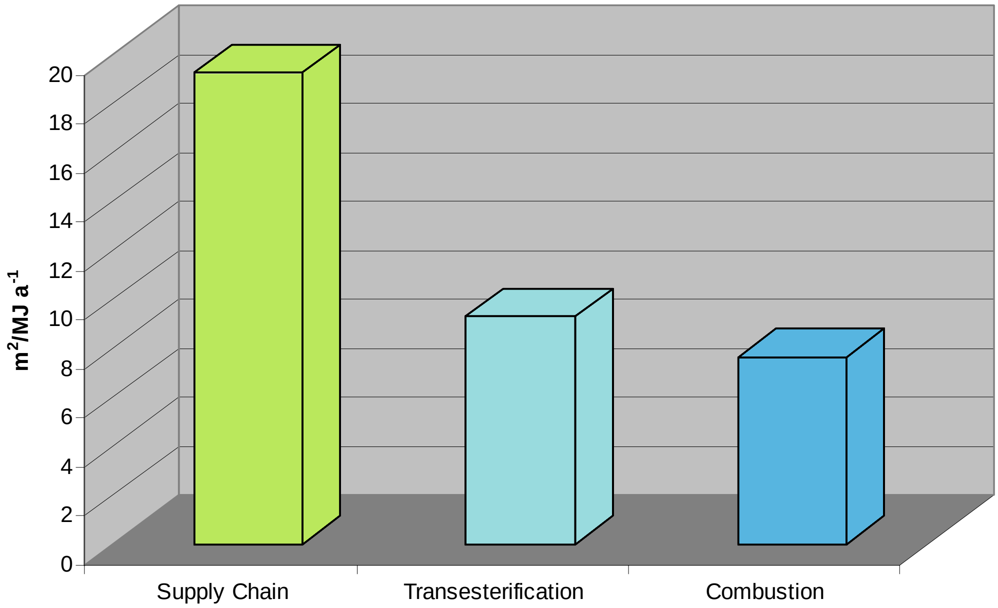


Figure 5-14: The ecological footprint for 1MJ produced energy over the process steps

The process for producing 1MJ energy from tallow biodiesel accumulates in a process footprint of 36.20m^2. Due to price allocation (biodiesel 0.68€/kg; glycerol 0.26€/kg) the overall footprints result in 390.03m^2/kg a^{-1} for biodiesel from tallow, 146.26m^2/kg a^{-1} for glycerol and 35.16m^2/MJ a^{-1} for engine output.

The distribution of the overall footprint shows that the feedstock inflicts the largest pressure on environment (Figure 5-15). Exhaust emissions are also a large contributor as well as chemicals and energy. Resources and transportation are too small to be of concern.

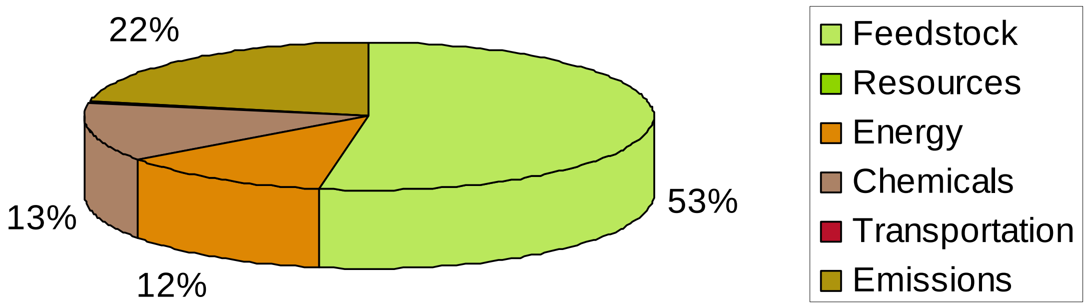


Figure 5-15: Distribution of the ecological footprint of 1MJ engine power utilizing biodiesel from tallow

5.7 *Biodiesel from Recycled Frying Oil*

5.7.A Technical Background

Frying oil has to be collected after usage and cannot be applied to the sewage directly. The collected frying oil is then utilized as feedstock. In the past it was mostly processed to soap and cleaning agents but with the growing demand of biodiesel it has been discovered as feedstock for transesterification as well.

Recycled frying oil itself is a waste and therefore, does not have a specific footprint. The transportation need arising for the process includes the collection of the oil.

5.7.B Process

The production of engine power utilizing biodiesel from recycled frying oil is done in two process steps.

First frying oil is collected, and processed to biodiesel utilizing energy, chemicals resources and transportation. No byproducts can be obtained during this transesterification process.

In the second step the combustion of biodiesel is done in an engine. In this step only the exhaust emissions occurring during combustion are assessed.

Infrastructure of the transesterification process and the combustion engine are not included. The process and system borders are shown in Figure 5-16.

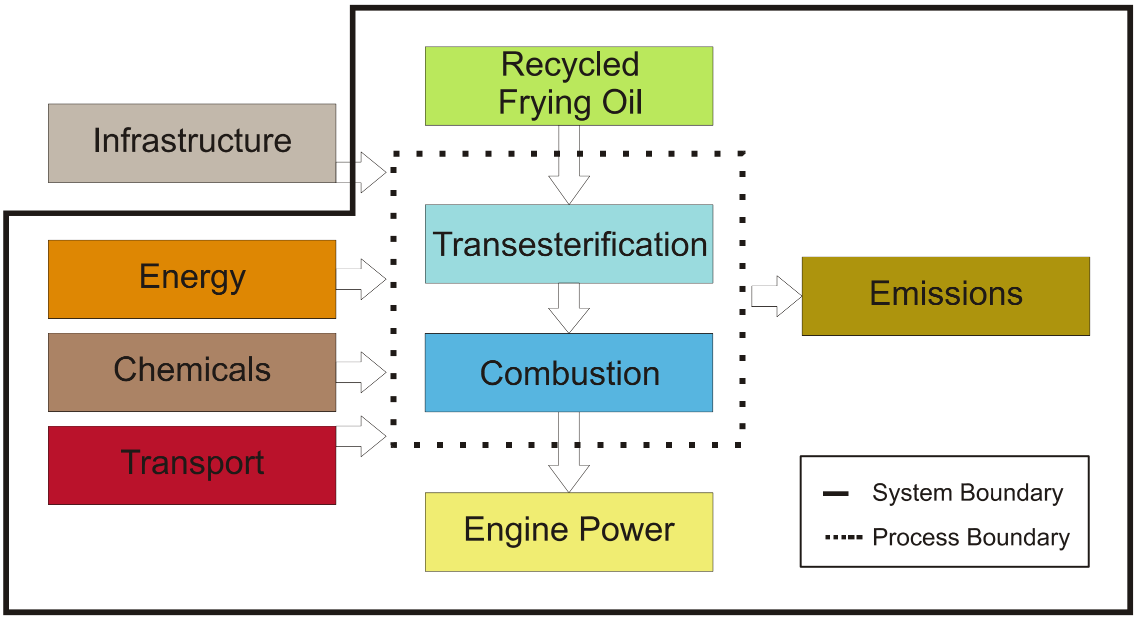


Figure 5-16: Process structure and system boundaries of the ecological assessment of the utilization of biodiesel from recycled frying oil

5.7.C Eco-Inventory

Table 5-9 shows the eco-inventory for the production of 1kg biodiesel from recycled frying oil, Table 5-10 for 1MJ resulting engine output.

Table 5-9: Eco-inventory for the production of 1kg biodiesel from recycled frying oil

Feedstock	Recycled Frying Oil	kg/kg	1.000
Resources	Process Water	kg/kg	0.036
Energy	Electricity	kWh/kg	0.033
	Extra Light Fuel Oil	MJ/kg	1.623
Chemicals	Methanol	kg/kg	0.100
	Potassium hydroxide	kg/kg	0.013
	Sulfuric acid	kg/kg	0.012
Transportation	16t Truck	tkm/kg	0.050

Table 5-10: Eco-inventory for the production of 1MJ engine output

Feedstock	Biodiesel from Recycled Frying Oil	kg/MJ	0.071
Emissions	NO_x (air)	g/MJ	1.118

5.7.D Results

As recycled frying oil itself does not have a specific footprint the supply chain of the process does not add to the pressure on the environment as it does, methodically speaking, not exist(Figure 5-17). The process steps of transesterification and combustion inflict the ecological pressure of the process equally.

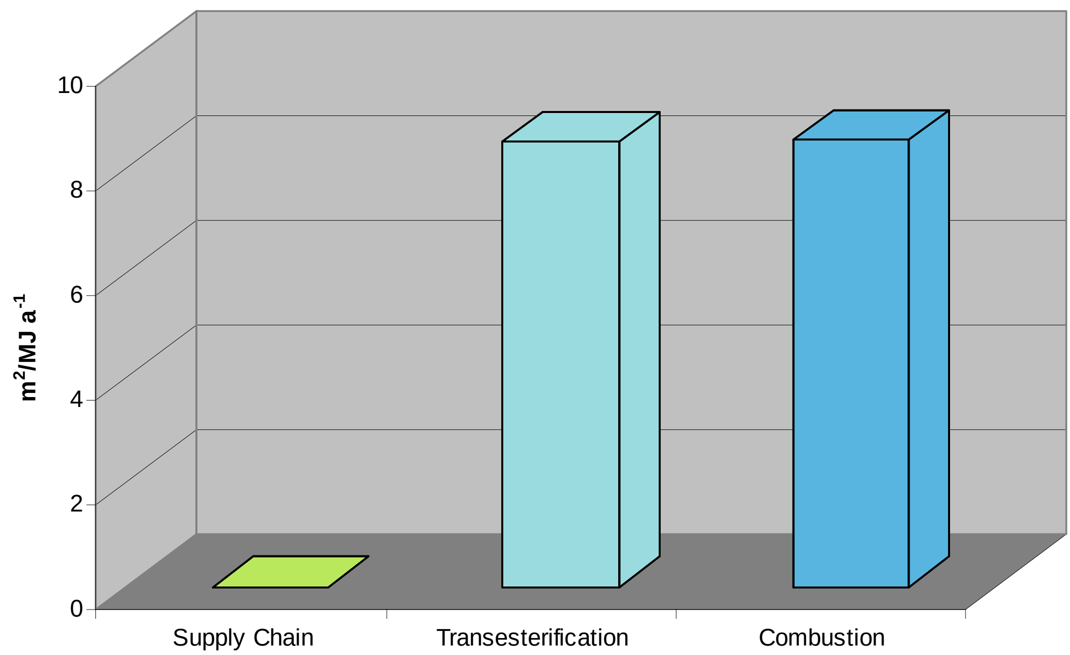


Figure 5-17: The ecological footprint for 1MJ produced energy over the process steps

The resulting process footprint cannot be allocated on any byproducts obtained by the process. Therefore, the overall footprint of biodiesel from recycled frying oil is 122.57m^2/kg a^{-1} and for engine power 17.05m^2/MJ a^{-1}.

As the feedstock does not add to the overall footprint the largest contribution to the ecological pressure are the exhaust emissions, inflicting half of the footprint (Figure 5-18). The other half is shared equally by energy and chemicals. Transportation does not add more to the overall footprint as in the previous processes but due to the low overall footprint the percentage share of this category increases.

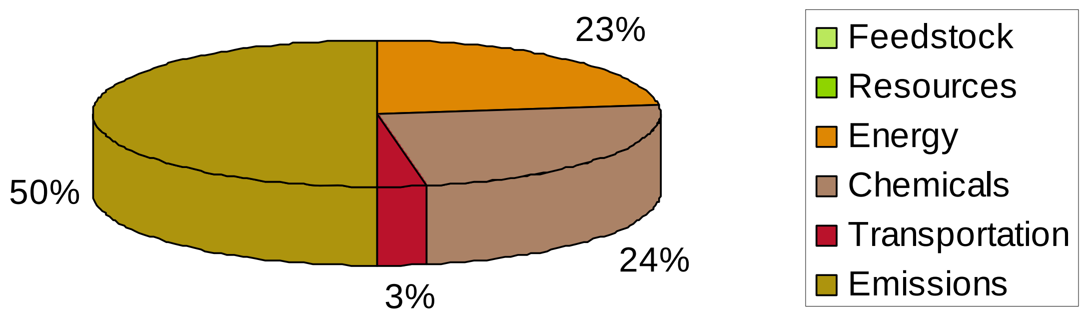


Figure 5-18: Distribution of the ecological footprint of 1MJ engine power utilizing biodiesel from recycled frying oil

5.8 *False Flax Oil as Diesel Substitute*

5.8.A Technical Background

The transesterification step is responsible for the high processing costs when producing biodiesel. The processing of e.g. vegetable oil from seeds is cheaper by far. Therefore, an omission of the transesterification step on the way from feedstock to engine power seems favorable. The direct utilization of vegetable oils in an engine is working well within certain limits as has been shown through the history of engines and which first promising results from fleet tests foretell.

An alternative to biodiesel is therefore, the usage of vegetable oil. New oil plants can be utilized too. Such an alternative is false flax oil. An additional advantage from an ecological point of view can be seen in the fact that false flax is almost exclusively grown organically. Such organically cultivated false flax has been used as input here.

5.8.B Process

The process of utilization of false flax oil consists only of one process step as the oil is directly combusted in an engine. Therefore, only exhaust emissions occur during this step and no chemicals or energy is needed.

Process infrastructure is not included in the ecological assessment. The process and system boundaries are shown in Figure 5-19.

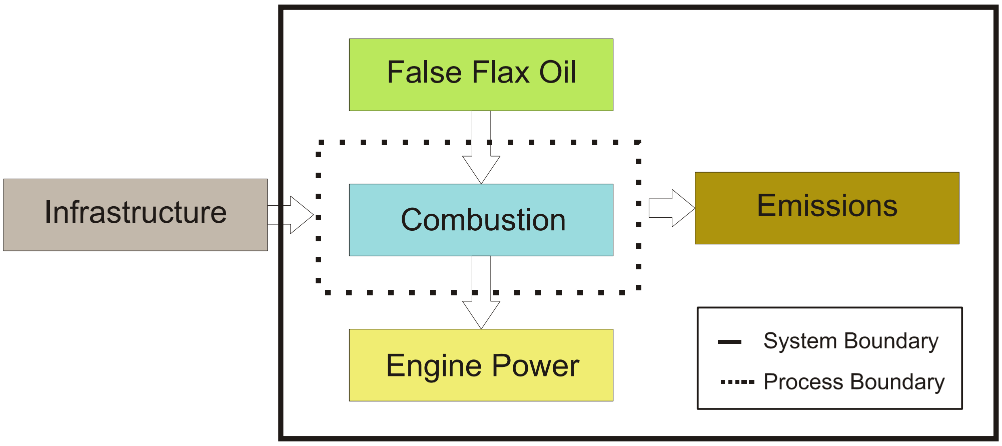


Figure 5-19: Process structure and system boundaries of the ecological assessment of the direct utilization of false flax oil

5.8.C Eco-Inventory

Table 6-1 shows the eco-inventory for the production of 1MJ engine output utilizing false flax oil directly.

Table 5-11: Eco-inventory for the production of 1MJ engine output

Feedstock	False Flax Oil	kg/MJ	0.075
Emission	NO_x (air)	g/MJ	1.050

5.8.D Results

The production of energy from false flax oil accumulates an ecological footprint of 19.95m²/MJ a⁻¹.

The feedstock false flax oil is the largest contributor to the footprint (Figure 5-20). The only other influence on environment is exerted by exhaust emissions.

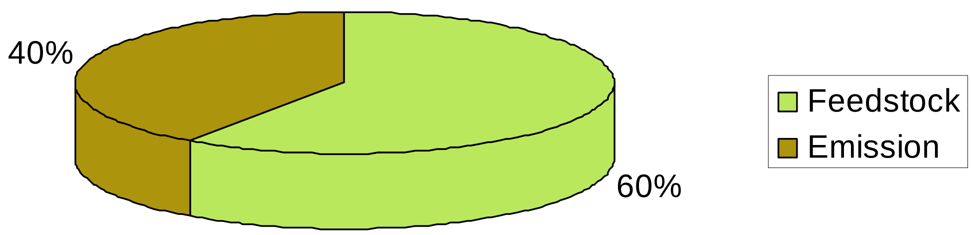


Figure 5-20: Distribution of the ecological footprint of 1MJ engine power utilizing false flax oil

5.9 *Fossil Diesel*

5.9.A Technical Background

The fuel used for engines in the majority of cases is fossil diesel. This is produced from crude oil in a refinery along many other byproducts.

5.9.B Process

The utilization of fossil diesel in an engine is a two step process.

In the first step crude oil is refined to produce diesel. This refinery step is situated in Europe in this assessment. Therefore, the crude oil has to be provided for an European refinery. The details of this provision are described in Chapter 7.16.

In the refinery chemicals and energy are consumed by the process while emissions and waste material is obtained. For the refinery step the infrastructure is included.

The produced diesel is combusted in an engine in a second step. In this step infrastructure is not included.

The process and system borders are shown in Figure 5-4.

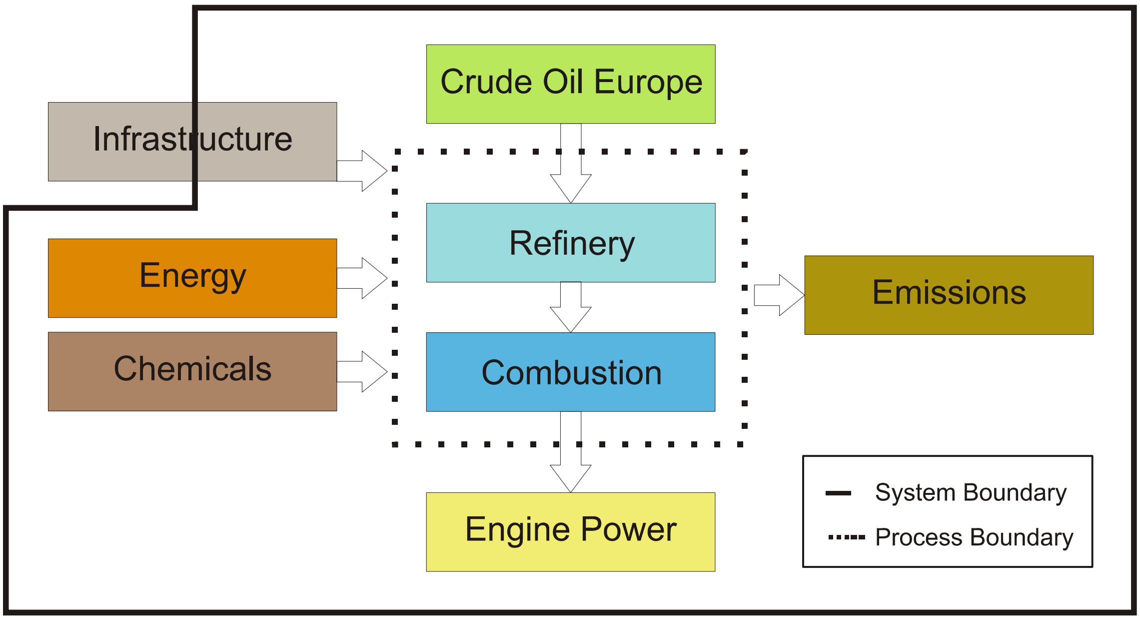


Figure 5-21: Process structure and system boundaries of the ecological assessment of the utilization of fossil diesel (including infrastructure for refinery, excluding infrastructure for combustion)

5.9.C Eco-Inventory

Table 5-12 shows the eco-inventory for the production of 1MJ engine output from fossil diesel. The eco-inventory for the production of fossil diesel is not shown here as it is very complex. For detailed data on this it is referred to ESU-ETHZ [15].

Table 5-12: Eco-inventory for the production of 1MJ engine output

Feedstock	Diesel ex refinery	kg/MJ	0.063
Emission	NO_x (air)	g/MJ	0.972

5.9.D Results

As is in most cases for renewable fuels the supply chain of feedstock provision exerts the largest amount of ecological pressure for fossil diesel too (Figure 5-22). The refinery adds less to the process footprint as the combustion. This is due to the high optimization level refineries already have in contrary to biodiesel transesterification processes, as this process is known and applied for many decades.

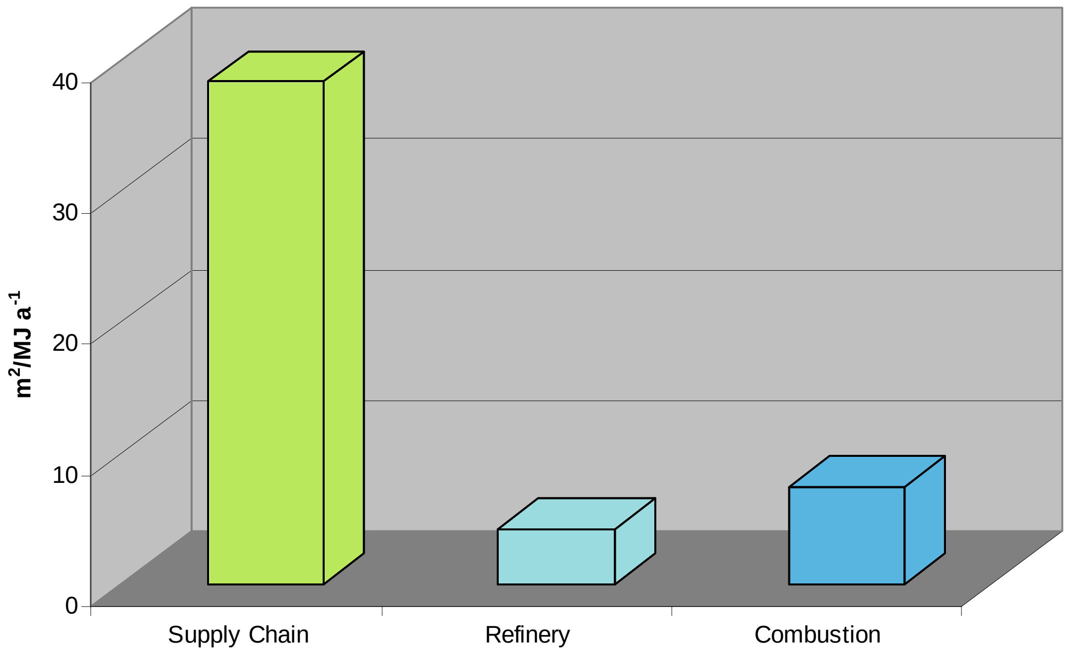


Figure 5-22: The ecological footprint for 1MJ produced energy over the process steps

The overall footprint of fossil diesel ex refinery is 681.36$m^2/kg\ a^{-1}$, for its engine power 50.01$m^2/MJ\ a^{-1}$.

Most of the overall footprint comes from the feedstock crude oil that is processed in the refinery. The exhaust emissions occurring during combustion inflict large environmental pressure too. Energy input is also an important contributor whereas chemicals, resources and infrastructure are negligible. The fact that the processing categories chemicals and energy only add a very small part to the overall footprint emphasizes the advanced optimization level of the processing.

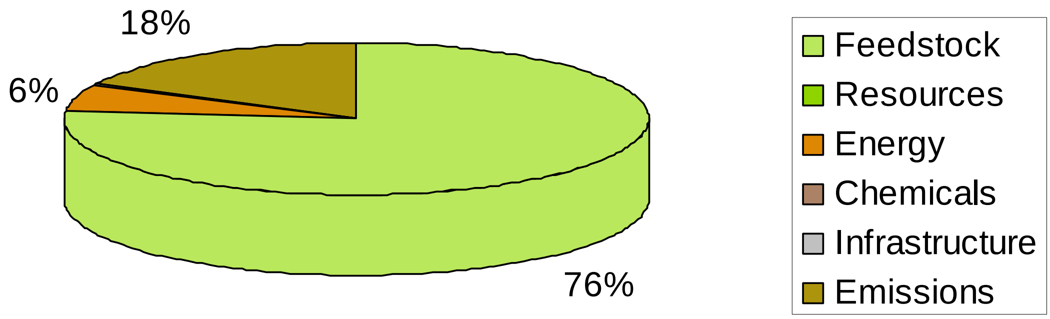


Figure 5-23: Distribution of the ecological footprint of 1MJ engine power utilizing fossil diesel

5.10 *Conclusion*

Remarkable results can be seen when the ecological pressure inflicted by combustion of different kinds of fuels in an engine is compared (Figure 5-24).

All biodiesel fuels derived from crops are in the same range of the ecological footprint as fossil diesel. Biodiesel from rapeseed and sunflower oil inflicts even more pressure on environment than their fossil competitor. This is due to the fact that cultivation of these crops needs large amounts of input for producing relatively small amounts of vegetable oil. These vegetable oils are then processed in an energy consuming transesterification step.

Utilizing low value materials like tallow for biodiesel production decreases the ecological footprint of the resulting engine power to a range where ecological advantage compared to fossil diesel is reached.

A larger decrease in the ecological footprint is possible still. Direct use of vegetable oil in engines omits the transesterification step which exerts additional pressure on environment and is therefore, not only problematic from an economical point of view.

Nevertheless the missing transesterification step is not the primary reason that the case study of direct vegetable oil utilization in this chapter results in such a low footprint. What influences this result even more is the fact that the utilized false flax oil was cultivated organically therefore, needing no fertilizer or pesticides input.

The lowest footprint in this comparison is obtained by the usage of biodiesel from recycled vegetable oil. The pressure accumulated due to the transesterification step is counterbalanced by the fact that the waste feedstock recycled frying oil does not exert a pressure by its provision.

Therefore, it can be said that the utilization of oil crops may not inherently lead to a sustainable fuel. This fact is of importance even more as these kinds of biodiesel are treated as the future for the fuel sector at present.

Interpreting this results interesting feedstock for biodiesel are either low value by-products of agriculture, organically cultivated crops or waste materials.

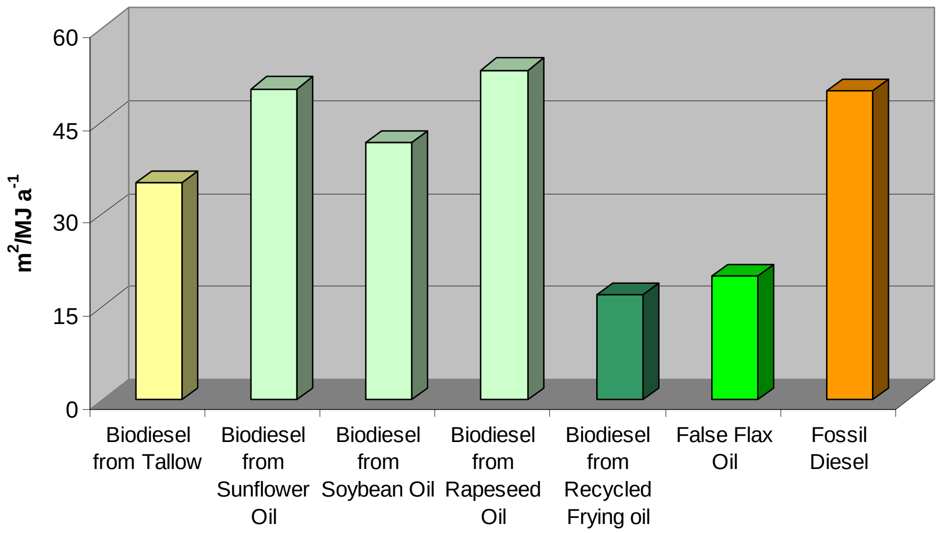


Figure 5-24: Comparison of the ecological footprint resulting from the utilization of different fuels in a combustion engine

When taking a look at the origin of the footprint along the input categories it can be seen that the feedstock of the transesterification or refinery process is the major contributor (Figure 5-25). Even in the case of the low impact fuel derived from false flax oil the feedstock influence surpasses all other contributors. The only process where feedstock has no influence at all is the combustion of biodiesel from recycled frying oil as the utilized waste has no footprint from its supply chain.

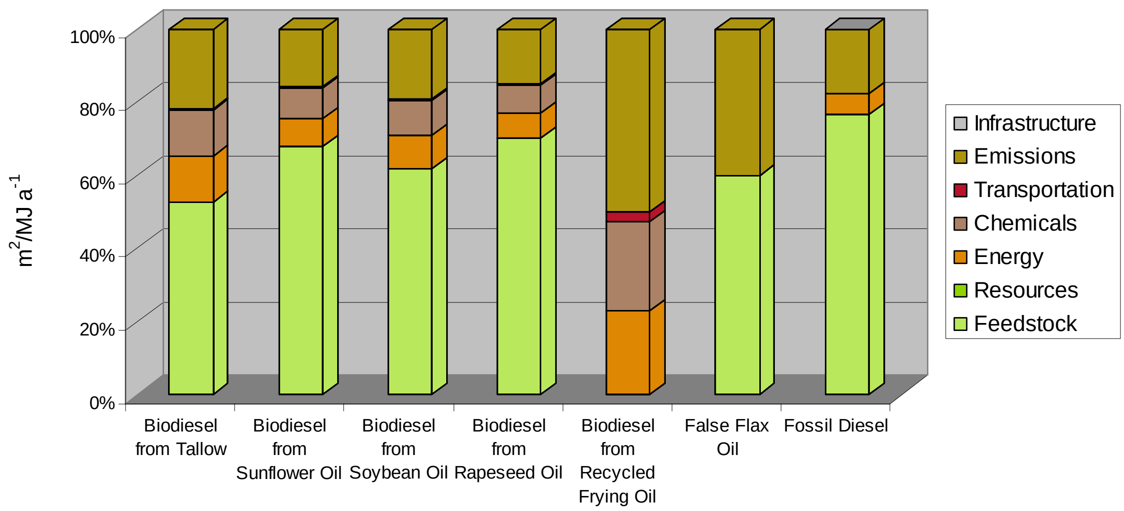


Figure 5-25: Comparison of the distribution of the ecological footprint along the input categories of the utilization of different fuels

The importance of the contributions during the transesterification and combustion step varies. However, emissions play a relevant role which is comprehensible as in the second process, the combustion, only emissions arise. That fact is specific for energy production due to combustion. In other processes emissions play a less prominent role as will be shown in the following case studies.

When the supply chain of the feedstock is included into the distribution it can be seen that the influence of energy increases at the expense of the feedstock. This shift of importance is especially radical in the case of false flax oil where more than half of the supply chain contribution arises from energy use for pressing the oil from the feedstock false flax seeds.

Nonetheless the influence of the feedstock is important, especially when feedstock is obtained from conventional agriculture. This holds not only true for crops but also for tallow as the breeding of animals from which tallow is obtained exerts a high pressure on the environment.

The influence of categories like resource depletion and infrastructure is negligible. Transportation need is of minor importance too compared to the other input categories. This even holds true for fossil diesel where the crude oil has to be transported thousands of kilometers to refineries in Europe.

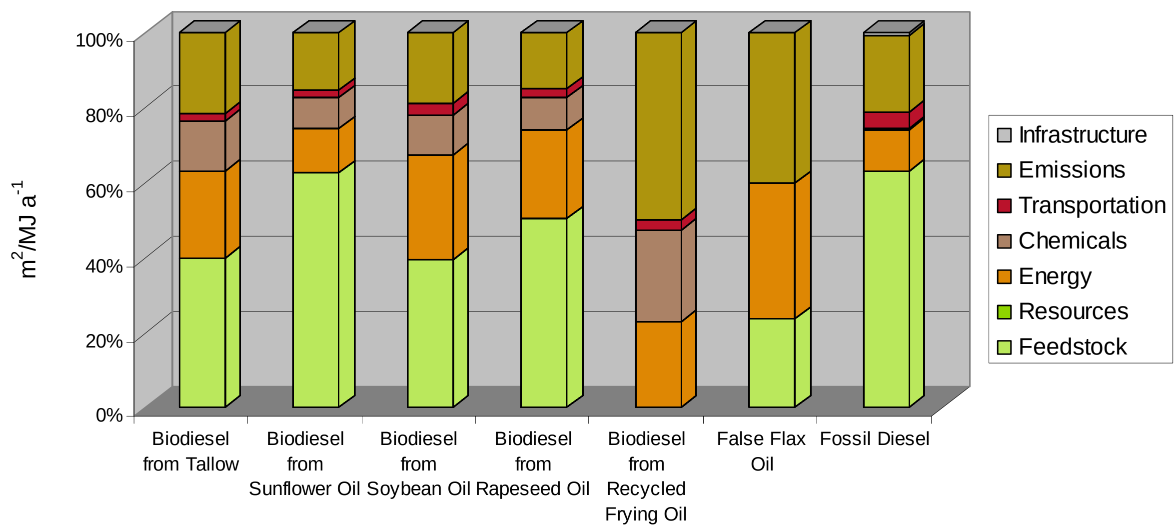


Figure 5-26: Comparison of the distribution of the ecological footprint along the input categories of the utilization of different fuels including the supporting processes

6 Case Study Poly(hydroxyalkanoates)

6.1 *Introduction*

In 2003 an estimated 100 million tons of plastics, derived mainly from fossil feedstock, were produced [20]. Because of high logistic complexity, quality problems and costs recycling is done only for a small part of the used plastic goods. The large amounts remaining are either deposited as landfill or combusted for utilizing at least a part of the contained energy.

Regarding these facts research concerning plastics made from renewable resources is becoming more important. Utilizing renewable resources would not only lead to a decrease in fossil resource consumption but also in lower net CO_2 emissions to the compartment air. Additionally biopolymers are mostly biodegradable, allowing users to compost them after utilization.

Therefore, the task of developing processes leading to biopolymers has been addressed by many research groups, leading to different biopolymers most prominent poly(hydroxyalkanoates) and poly(lactic acid). This chapter deals with processes producing poly(hydroxyalkanoates).

Poly(hydroxyalkanoates), (PHA)s are produced intracellular by many bacteria in the form of PHA granules. Depending on the genera the bacteria can consist of up to 90% (dry weight) PHA.

Built in hydroxyalkanoates blocks often differ in chain length, whereas (R)-3-hydroxybutyric acid represents the major fraction. Three main types of biopolymers can be discerned, short-chain-length PHA consisting of monomer units with C_3 to C_5, medium-chain-length PHA (C_6 to C_{14}) and a mix of both with C_4 to C_{14} monomer units. Due to the difference in chain length the properties of the biopolymers vary.

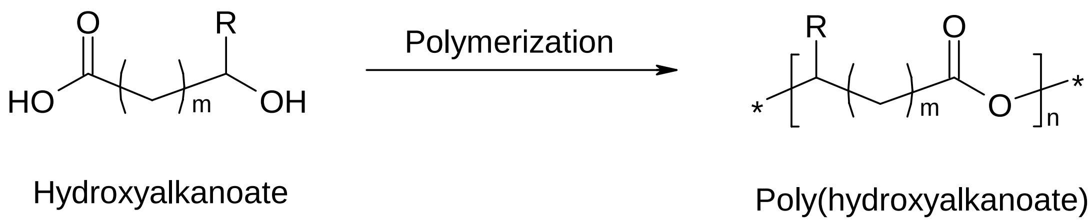


Figure 6-1: Reaction of hydroxyalkanoate monomers to Poly(hydroxyalkanoate)

PHA is produced by bacteria when nutrient supply is unbalanced, meaning that carbon source is available in excess but at least one essential growth nutrient like the nitrogen source is depleted [21]. In this case PHA functions as carbon and energy source for the bacteria and is polymerized to become insoluble inside the cell. The phase transition ensures that these valuable components cannot leak out of the cell.

The extracted polymers show very similar properties to common fossil based polymers like polyethylene or polypropylene. The molecular mass can vary from 50 to 1000 kDa depending on the sources fed the bacteria and their genera. Additionally the polymer is biodegradable, non toxic and biocompatible which enables special application, in that fossil polymers cannot comply with.

The functional equality of biopolymer goods over fossil polymer ones during use and deposition is undeniable, but production processes have to be examined to ensure the main driver of biopolymer production, ecological superiority. That this is not always the case, especially for biopolymers, has been shown before [13]. In this chapter the production of PHA from different feedstock materials will be evaluated and discussed.

6.2 *Data Sources*

Most of the data that have been considered in this case study are from well-established published data sources.

- Data on energy have been taken from ESU-ETHZ [15]. ESU-ETHZ represents the electricity production of the UCPTE countries (European energy net) at the beginning of the nineties. The used electricity mix represents the EU25 average calculated with data from EUROSTAT [22] for the year 2002.
- Transportation systems have also been taken from ESU-ETHZ [15]. The data for road infrastructure represent Swiss road infrastructure, including many tunnels and winding mountain roads. The impact of road infrastructure is therefore, at the upper margin in comparison to the EU average.
- Data on process chemicals and waste treatment comes from ESU-ETHZ [15] and BUWAL [23]. In general the data quality of process chemicals is lower than for energy systems as modeling of process chemicals is highly aggregated. The published data represent standard technology for Europe.
- Data for production of fossil polymers has been taken from ESU-ETHZ [15]. Published data represent standard process technology as well as a crude oil feedstock mix for Europe.
- Data on production of yeast extract has been taken from Chapter 7.8.
- Data on the production of whey and whey powder comes from Chapter 7.4 and 7.5.

- Data on the fermentation process has been taken from Sandholzer [26]. For all fermentations except the whey base case the data applied were for the yield and energy optimized case.
- Data on the production of biodiesel and renewable glycerol has been taken from the case study Biodiesel (see Chapters 5.3 and 5.6).
- Data on the production of synthetically glycerol are described in Chapter 7.1.
- Data on production of yeast extract are described in Chapter 7.8.
- Data on the fermentation yield comes from FdZ [29].
- Data on production of yeast extract are described in chapter 7.8.
- Data on the production of sugar cane raw juice is described in chapter 0
- Data on production of yeast extract are described in chapter 7.8.
- Data on the fermentation yield comes from Braunegg [30].
- Data on the production of slaughter house waste is described in chapters 7.10.

6.3 *PHA from whey*

6.3.A Introduction

Whey accrues during cheese production in a ratio of approximately 9t whey to 1t of cheese. At present the largest part of whey is used to produce whey powder for human or animal nutrition. This process uses large amounts of energy for concentrating the whey by evaporation producing a good of low market value. Due to this fact the process is highly uneconomical and must be seen more as a waste treatment as whey cannot be committed to sewage untreated because of its high biological oxygen demand (BOD5 34000 mg/kg)[14]. At the moment a big amount of whey just “vanishes” somewhere into the ecosphere.

A growing demand in proteins led to additional utilization of whey but a large surplus still exists and has to be treated. This is the economic and ecologic background of this case study.

The following ecological assessment was done in scope of an EU-project [50]. The goal of the assessment for PHA from whey was the identification of ecological “hot spots” in the developed process and a comparison of PHA from whey with fossil polymers and the production of whey powder.

6.3.B Process

For easier assessment the process has been divided in five process steps.

First whey has to be collected from dairies in the vicinity (an average distance of 50km is assumed) and transported to the facility where it is concentrated to higher protein content (with a concentration factor of five).

In the next step an ultrafiltration process separates a retentate containing proteins that can be utilized as a marketable co-product[18]. The remaining whey concentrate (containing about 20% weight lactose) is treated in a chemical hydrolyzation step.

Afterwards the biopolymer PHA is produced in a fermentation. To retrieve the polymer from the biomass in the last process step the cells are disrupted and filtered.

The system boundaries of the ecological assessment are shown in Figure 6-2. Infrastructure and employees have not been included, because of their marginal influence on the overall footprint.

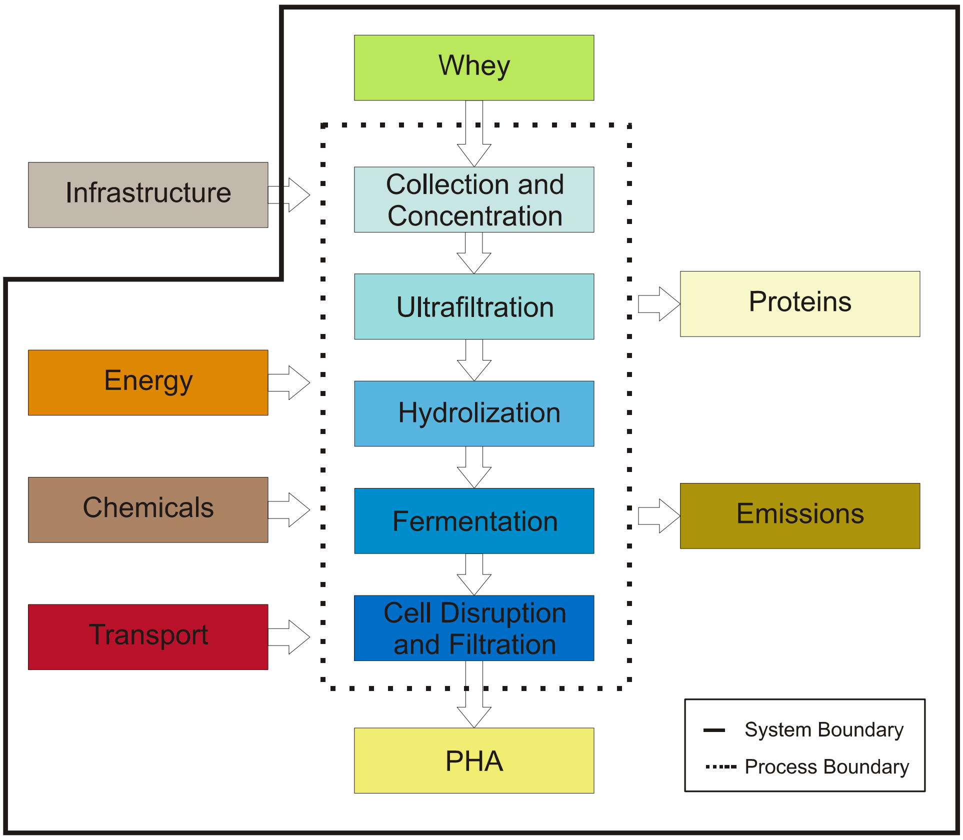


Figure 6-2 Process structure and system boundaries of the ecological assessment of PHA production from whey

The impact assessment was carried out for a so called "base case". This was calculated with the data provided by the project partners based on 300l scale experiments. The EU-25 average electricity mix was used for this case. The nutrient solution used for fermentation was calculated based on the assumption that 50% of the needed salts were reused.

Due to the definition that whey is a waste from dairy industries the supply chain for whey production (mainly the agricultural production of milk) was excluded in a first level of analysis.

The PHA produced by the experiments had a M_W of about 700kDa and a PDI (polydispersity index, measures the distribution of molecular weights in a given polymer) of about 2.2 [17].

6.3.C Eco-Inventory

Table 6-1 shows the eco-inventory for the production of 1kg synthetic glycerol.

Table 6-1: Eco-Inventory for the production of 1kg PHA from whey

Feedstock	Whey	kg/kg	126.870
Resources	Process Water	kg/kg	67.722
Energy	Electricity	kWh/kg	15.107
	Extra Light Fuel Oil	MJ/kg	32.270
Chemicals	Yeast extract	kg/kg	0.160
	Hydrochloric acid	kg/kg	0.140
	Sodium hydroxide	kg/kg	0.150
	Sodium chloride	kg/kg	4.549
	Potassium chloride	kg/kg	0.114
	Inorganic chemicals	kg/kg	1.000
Transportation	28t Truck	kg/kg	0.906
Emissions	Na (water)	kg/kg	1.795
Byproducts	Ultrafiltration Retentate	kg/kg	0.334

6.3.D Results

Looking at the partial footprints accumulated by the different process steps as shown in Figure 6-3 it can be seen that the fermentation step is the main contributor to the ecological pressure derived from the process. Other process steps contribute only a minor part to the overall process footprint. The supply chain adds no partial footprint as whey is treated as waste and therefore, possesses a specific footprint of $0m^2/kg\ a^{-1}$.

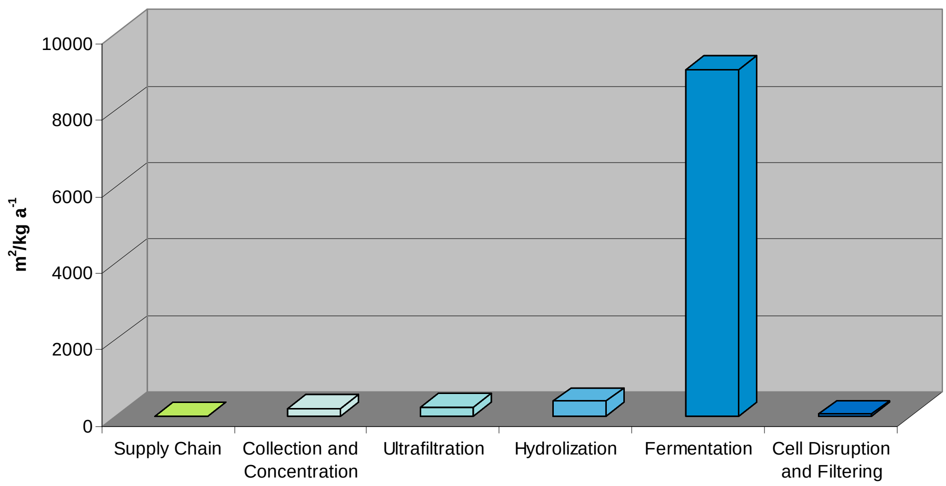


Figure 6-3: Ecological footprint for 1kg PHA from whey along the process steps

The production of 1kg PHA from whey results in a process footprint of 9965.45m^2. In the process step two, ultrafiltration, the byproduct proteins is recovered from the filtration retentate. As the price for filtration retentate and permeate are almost the same, mass allocation was applied. This results in an ecological footprint of 9861.90m^2/kg a^{-1} for PHA from whey and 309.86m^2/kg for retentate proteins.

Analyzing the fermentation step further reveals the main part of the ecological footprint is caused by energy provision, mainly electricity (Figure 6-4). This high electricity input is generated by the need for agitation in the fermentation. Additionally the fermentation process (and with it agitation) takes a relatively long time (over 100 hours) in the pilot plant for which data are available.

Other flows in this process step - heating energy for fermentation and pasteurization, the necessary process chemicals and emission of used nutrient salts to water - provide only about an seventh of the overall footprint.

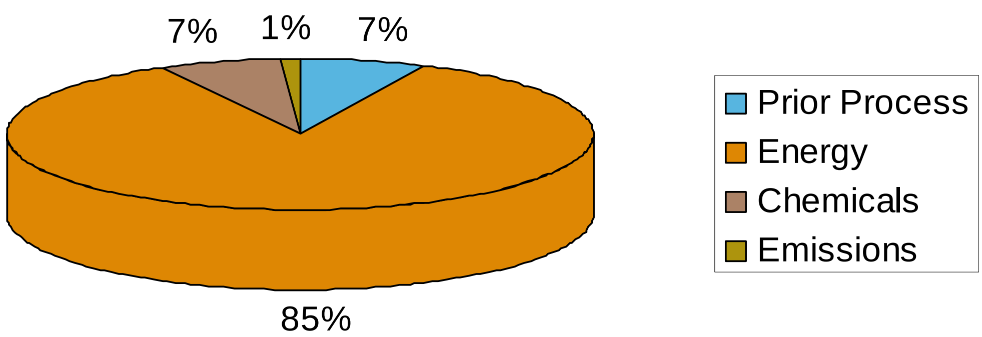


Figure 6-4: Distribution of the partial footprint of the fermentation step

Considering the whole process, electricity is still the main contributor to the ecological footprint (Figure 6-5). Chemicals, process energy and transportation of the whey to the facility also add to the ecological footprint, but to a much smaller extent.

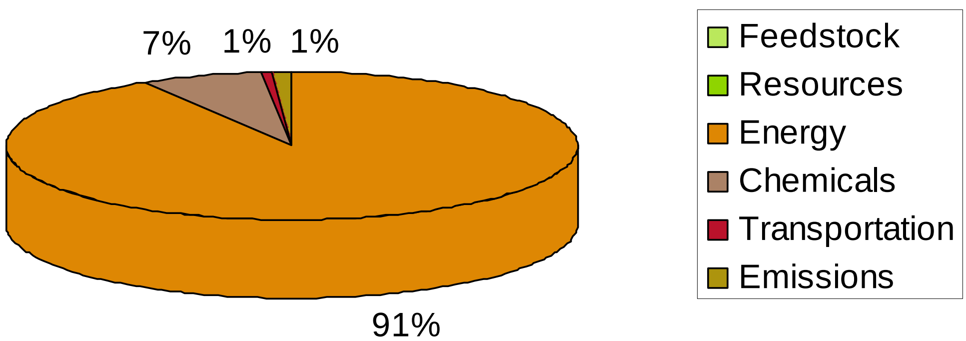


Figure 6-5: Distribution of the ecological footprint of 1kg PHA from whey

6.3.E Comparison with Fossil Polymers

The fossil polymers compared to PHA where chosen according to the potential of PHA to replace them. Polyethylene terephthalate (PET), Polystyrene (PS), Polyethylene (PE) and Polypropylene (PP) show very similar specifications to PHA in their main applications and are therefore, prime targets for replacement.

As can be seen in Figure 6-6, the production of 1 kg PHA based on 300l scale experiments inflicts a higher ecological pressure than the production of equal amounts of all comparable fossil polymers.

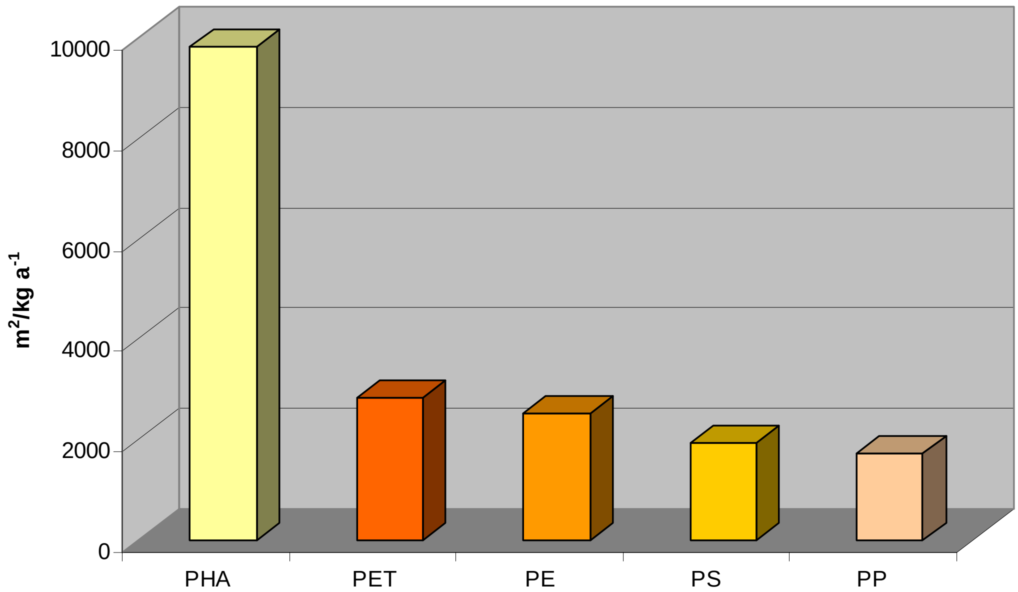


Figure 6-6: Comparison of PHA from whey with fossil Polymers

It has to be taken in account that the production process for PHA from whey is still a new process just entering the pilot plant scale. Production of fossil polymers on the other hand has been perfectly optimized during the last decades. To reach ecological competitiveness the process for PHA production has to be optimized likewise. Optimization potentials were therefore, analyzed in different scenarios with variation of parameters like yield or energy consumption.

6.3.F Optimization Potentials

Ecological assessment shows that process-yield and energy consumption are of paramount importance to the ecological pressure of PHA production. Energy consumption is by far the main contributor of ecological pressure in the whole process. Process yield is the factor which defines the amount of product on which the pressure caused by the process is burdened.

The 300L scale pilot plant processed about 0.008 kg PHA per kg whey, meaning a yield of 0.188 kg PHA per kg lactose. Laboratory research on a 10L scale has shown that an increase of PHA production to about 1.7 weight percent (yield of 0,418 kg PHA/kg lactose) is possible. Using this optimization potential the ecological footprint is lowered significantly to 4393.35m^2/kg a^{-1} (from 9861.90m^2/kg a^{-1} in the base case based on the pilot plant experiments).

As already shown the energy input especially for the fermentation step is very high. However, fermentation can be optimized to 1kWh/kg a^{-1} produced PHA as shown by an industrial scale PHA production, whereas the pilot process now uses about 14kWh/kg a^{-1} PHA[19]. Other electricity input may also be optimized, but due to the high electricity consumption by the fermentation step, this optimization has to be prioritized. The decrease of the ecological footprint utilizing the electricity optimization potential is substantially, resulting in 2362.90m^2/kg a^{-1} PHA produced.

Taking both optimization steps into account PHA from whey is reaching the region where its ecological pressure on environment is lower than fossil polymers. The decrease of the ecological footprint due to these optimizations is resulting in 1392.20m^2/kg a^{-1} PHA. In comparison polypropylene, the fossil polymer inflicting the lowest ecological pressure, has a footprint of 1726.39m^2/kg a^{-1}. The decrease of the ecological footprint applying the different optimizations can be seen in Figure 6-7.

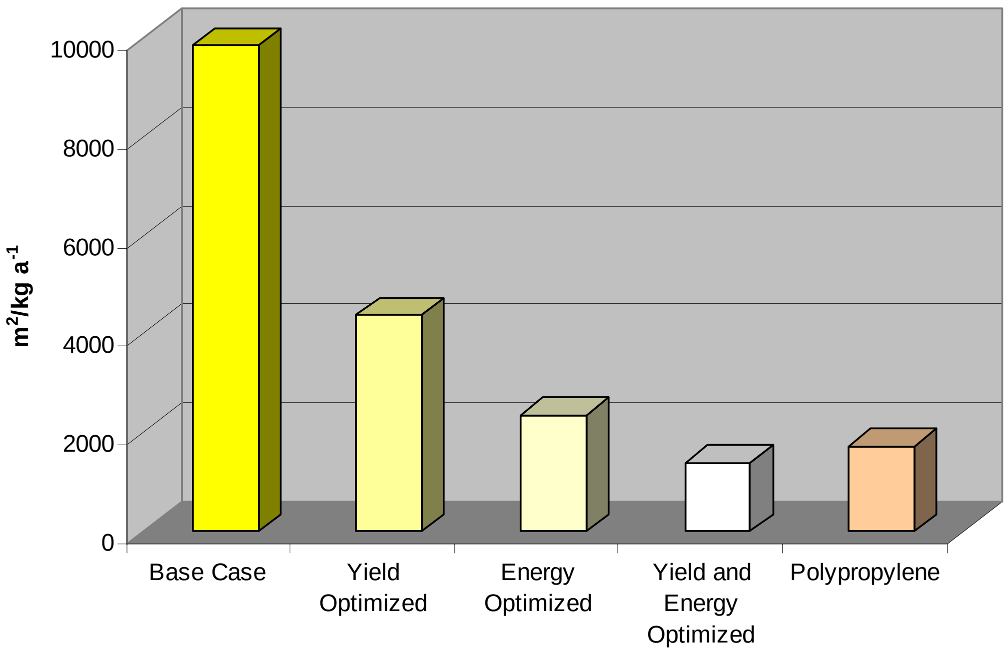


Figure 6-7: Ecological footprint of PHA from whey applying different optimization potentials compared with polypropylene

Taking a look at the footprint accumulated by the process steps it can be seen that still fermentation inflicts the greatest ecological pressure, but is not that prominent as in the base case (Figure 6-8). Second biggest contributor, although with a large distance, is the hydrolyzation.

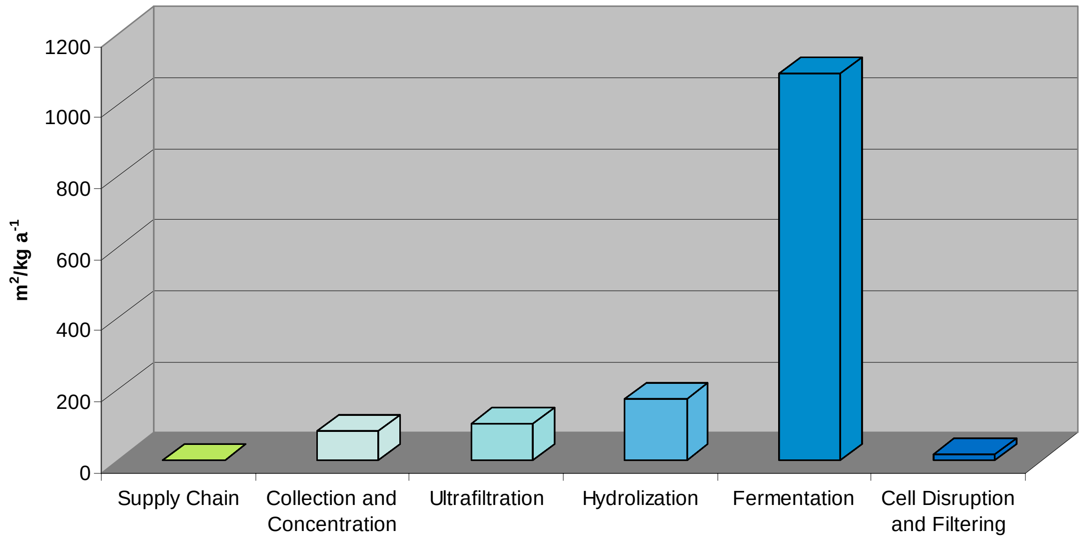


Figure 6-8: The ecological footprint for 1kg optimized PHA from whey along the process steps

Due to the energy optimization the influence of energy input decreases, although energy is still the major contributor to the ecological footprint. Chemicals now also play an important role, whereas transportation and emissions add small contribution to the overall footprint.

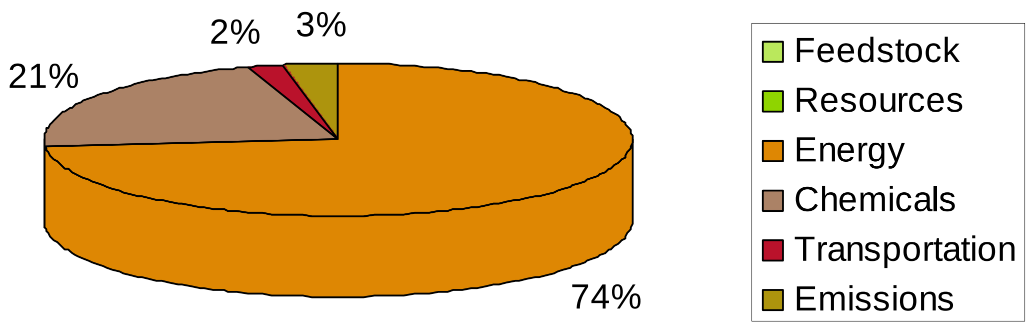


Figure 6-9: Distribution of the ecological footprint of 1kg optimized PHA from whey

6.3.G Comparison Whey Powder

At the moment many dairies process whey to whey powder which can be used as milk powder substitute. The ecological footprint for whey powder amounts to 375.38 $m^2/kg\ a^{-1}$ powder. In order to compare whey powder to PHA from whey the ecological impact was calculated according to the price of the products. The price of whey powder is approximately 0.5 €/kg [18]. A price for PHA from whey of 2-5€/kg was estimated for economic assessment, although the higher price could only be obtained for special applications. With the prices of both possible products the ecological footprint of the contribution to the value chain could be calculated, leading to the ecological pressure based on the product value created by the process (Figure 6-10).

It can be seen that without optimization PHA production exerts a larger pressure on environment per value created as the process of whey powder production. If the optimization potentials in yield and energy consumption are applied, the picture changes and PHA made by the process based on the pilot plant gains ecological superiority based on produced value. The production of such PHA will lead to a decrease of the environmental impact per € earned over the value chain compared to whey powder.

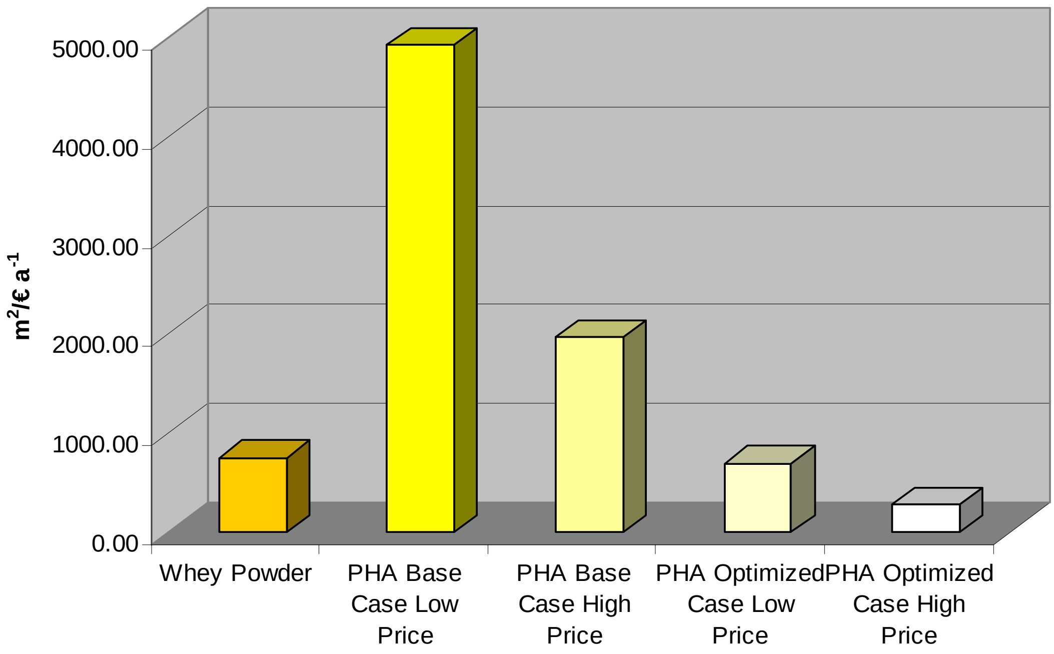


Figure 6-10: The ecological footprint of the value generated by whey powder and PHA production

6.3.H Including the Supply chain

In case of a successful introduction to the market and large scale production of PHA from whey, the feedstock whey cannot be treated as waste anymore. This eventual strong demand for the feedstock will lead to a reappraisal which will add a specific footprint to whey derived from its provision process, cheese production.

Under these circumstances a reassessment of the process has to be made to ensure ecological superiority of PHA in the optimized case to fossil polymers. The ecological pressure derived from whey production is shown in Chapter 7.4.

Comparison of the process steps shows that fermentation still is the largest contributor, but the feedstock whey now occupies second position (Figure 6-11).

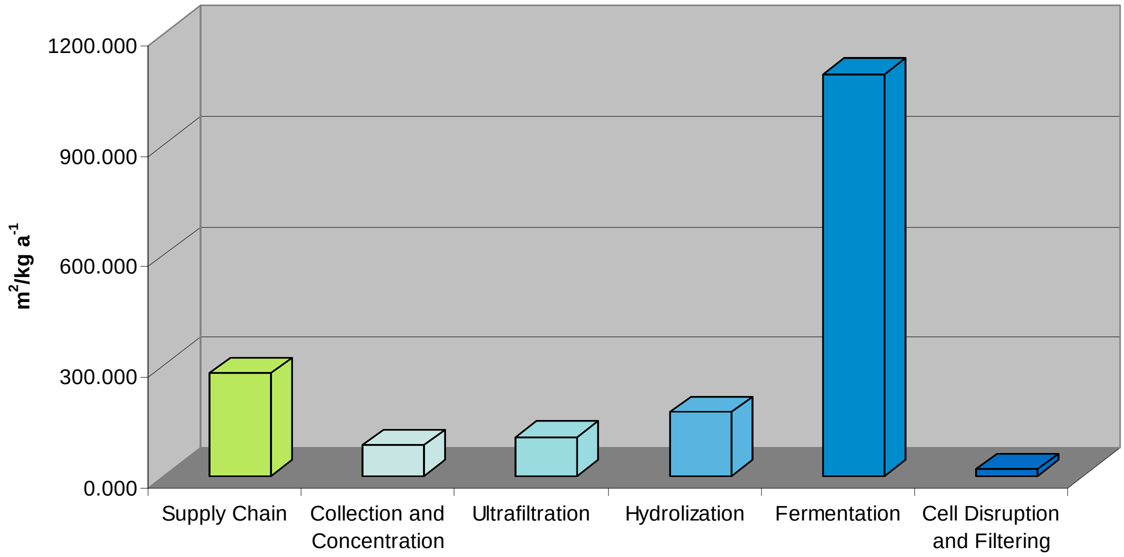


Figure 6-11: The ecological footprint for 1kg optimized PHA from whey including supply chain along the process steps

Also at the distribution of the ecological footprint the influence of the feedstock can be seen although energy and chemicals still plays a more important role. Next to these two inputs emissions and transportation are rather unimportant contributors.

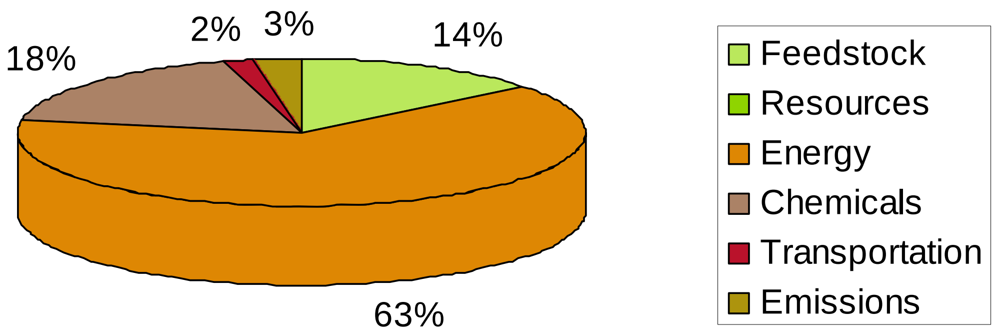


Figure 6-12: Distribution of the ecological footprint of 1kg optimized PHA from whey including supply chain

6.3.I Summary

Whey seems to be an economical interesting feedstock for fermentation processes due to the low price and the surplus of whey emerging during cheese production. From an ecological point of view PHA from whey is no less interesting as it promises to be more sustainable than fossil polymers. However, in order to ensure this advantage all possible optimization potentials have to be utilized like production processes for fossil polymers have done for decades.

Even when whey is treated as valued material and the supply chain of whey production is included in the ecological assessment the ecological footprint equals the footprint of the fossil polymer exerting the lowest pressure on environment, polypropylene. Compared to other fossil polymers like polyethylene or polystyrene PHA will be ecologically favorable even with supply chain included.

The optimization potentials addressed in this case study are obvious potentials. The process itself is not even yet in pilot plant phase. Until large scale production is realized other optimization potentials will arise, making the process hopefully even more sustainable still.

Compared to current practice of processing whey to whey powder, the production of PHA from whey is to be favored from an ecological point of view. However, this holds only true if the optimization potentials are realized, otherwise whey powder will stay ecologically if not economically superior.

The energy input has the most prominent influence on the ecological footprint, especially electricity usage. Due to the high amount of nutrient salts needed for fermentation chemicals play an uncharacteristically important role in the footprint. The pressure added by transportation is low as the average distance for whey delivery to the process facility is only about 50km. For large scale facilities this transportation need will rise and may equal the influence of the feedstock (corresponds to an average transportation distance of 400km). Emissions also play a minor role, but here data integrity is low as for processes in development emission data are seldom available. However, as emissions due to the energy input are already included in the energy footprints (and emissions of energy provision for a process in the majority of cases exceed the emissions of the process itself) the error is negligible.

6.4 *PHA from Glycerol*

6.4.A Technical Background

Instead of whey, glycerol can be used as low price carbon source for PHA fermentation.

Glycerol can be either synthesized from propene or obtained as by-product of transesterification or saponification of fatty acids. Large amounts of the by-product glycerol are obtained from biodiesel production resulting in a low price product.

6.4.B Process

The process for PHA production from glycerol is a two step process. First glycerol is fermented. For the fermentation process the process inputs and parameters for the optimized PHA production from whey have been applied. The fermentation inputs besides the feedstock glycerol are energy and chemicals.

For the second process step, cell disruption and filtration, only energy input is needed.

The assessment is done for three different kinds of glycerol. Glycerol feedstock is obtained during biodiesel production from tallow as well as glycerol from biodiesel production from rapeseed oil (RME). This shows that the ecological pressure derived from the supply chain may vary depending on the feedstock of native glycerol production. The third feedstock is synthetic glycerol.

Process infrastructure is not included in the ecological assessment. Figure 6-13 shows the process structure and the system boundaries of PHA production from glycerol.

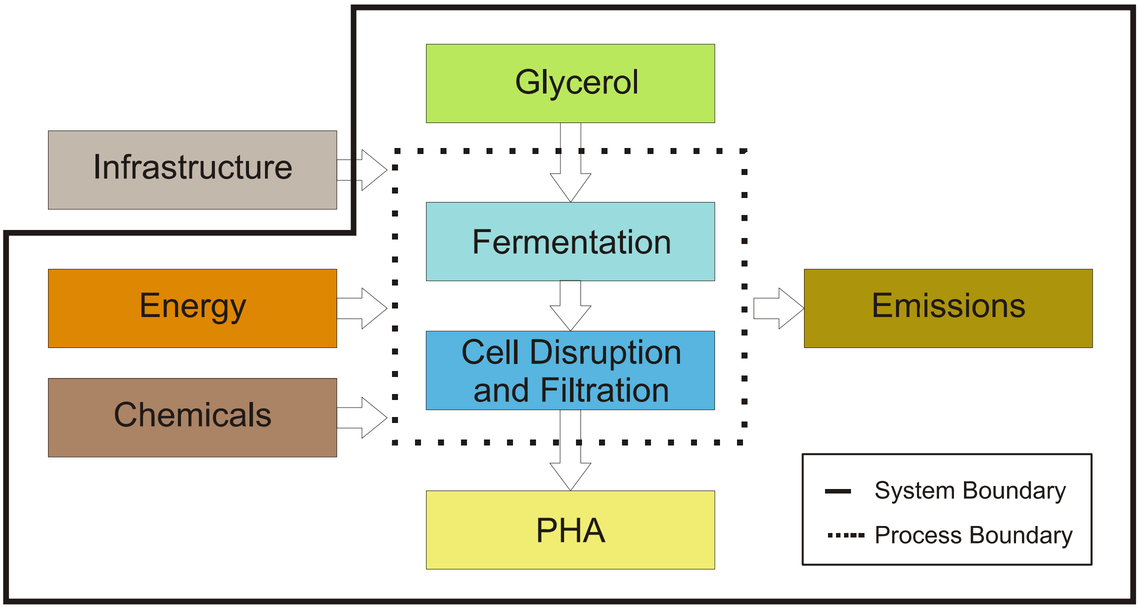


Figure 6-13: Process structure and system boundaries of the ecological assessment of PHA production from glycerol

6.4.C Eco-inventory

Table 6-2 shows the eco-inventory for the production of 1kg PHA from glycerol.

Table 6-2: Eco-Inventory for the production of 1kg PHA from glycerol

Feedstock	Glycerol	kg/kg	4.900
Resources	Process Water	kg/kg	0.857
Energy	Electricity	kWh/kg	1.018
	Extra Light Fuel Oil	MJ/kg	10.040
Chemicals	Yeast extract	kg/kg	0.072
	Sodium chloride	kg/kg	2.054
	Potassium chloride	kg/kg	0.051
	Inorganic chemicals	kg/kg	0.452
Emissions	Na (water)	kg/kg	0.810

6.4.D Results

6.4.D1 *Glycerol from Rapeseed Oil*

The production process of PHA from glycerol obtained from rapeseed methyl ester production inflicts slightly less ecological pressure during the process than by the supply chain (Figure 6-14). During the process the intensive energy use for fermentation is responsible for the large impact. The disruption of the bacteria cells and separation of the polymer exerts only a small pressure on environment.

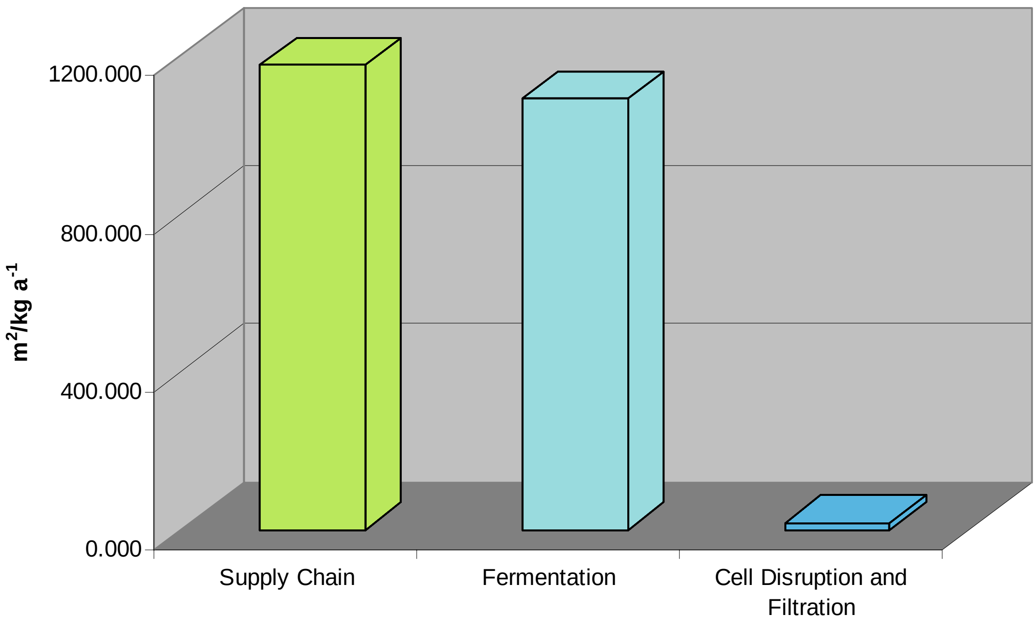


Figure 6-14: The ecological footprint for 1kg PHA from RME glycerol

The production process results in an ecological footprint of 2285.31m^2/kg a^{-1} PHA from glycerol from RME.

About the half of this footprint arises from the ecological pressure for feedstock provision (Figure 6-15). Another major part, about a third, comes from energy input. Chemicals result in a considerable pressure on environment too, whereas emissions and especially resources are of minor importance.

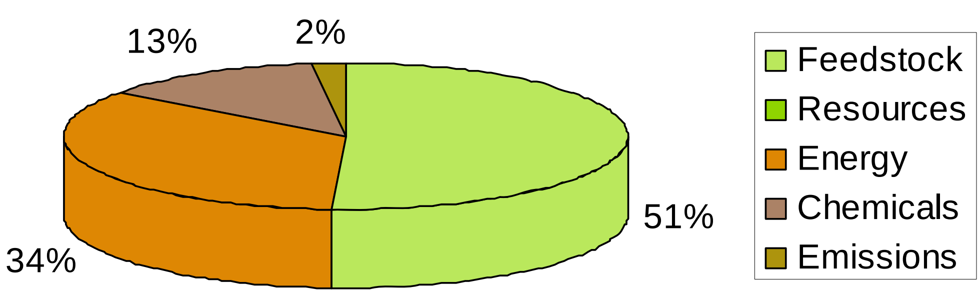


Figure 6-15: Distribution of the ecological footprint of 1kg PHA from RME glycerol

6.4.D2 *Glycerol from Tallow*

The production of PHA from glycerol from tallow biodiesel inflicts most ecological pressure on the environment due to the fermentation step (Figure 6-16). The supply chain also plays an important role whereas the second process step adds almost no footprint.

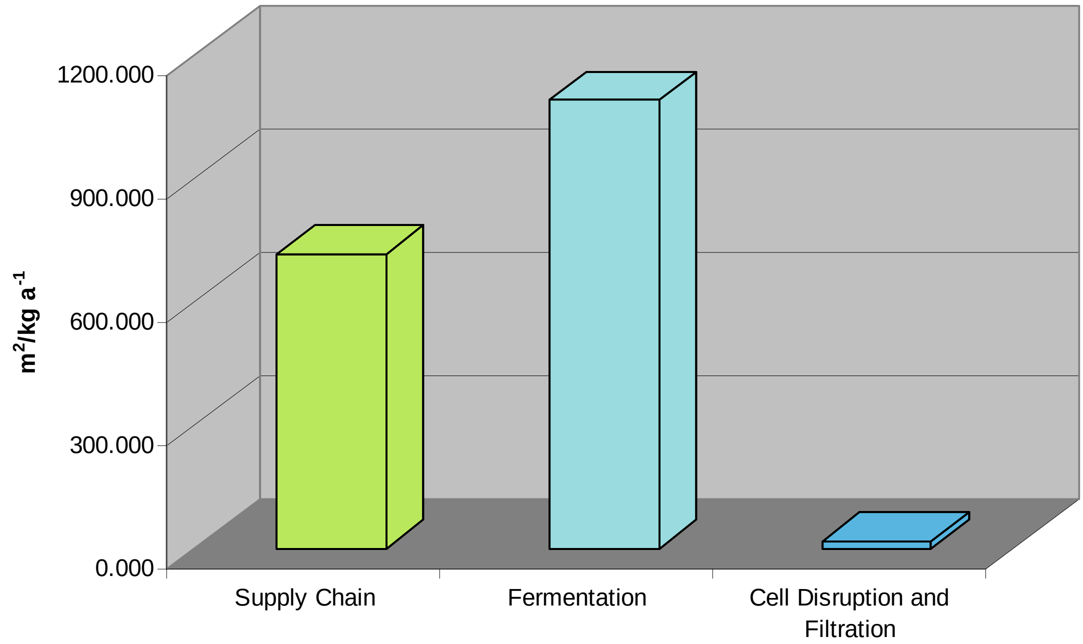


Figure 6-16: The ecological footprint for 1kg PHA from tallow glycerol

The production of PHA from glycerol made from tallow leads to an ecological footprint of 1826.78m^2/kg a^{-1}.

The majority of this footprint comes from energy input. This is a difference to the PHA from glycerol obtained from rapeseed oil. Glycerol from tallow has a lower footprint than the one from rapeseed oil. The footprint of PHA from rapeseed oil glycerol is caused first by the feedstock and second by the energy. For PHA from tallow glycerol this is reversed. The influence of chemicals and emissions don't change much compared to the distribution for PHA from rapeseed biodiesel glycerol, although the fraction of the ecological footprint inflicted by chemicals rises a little.

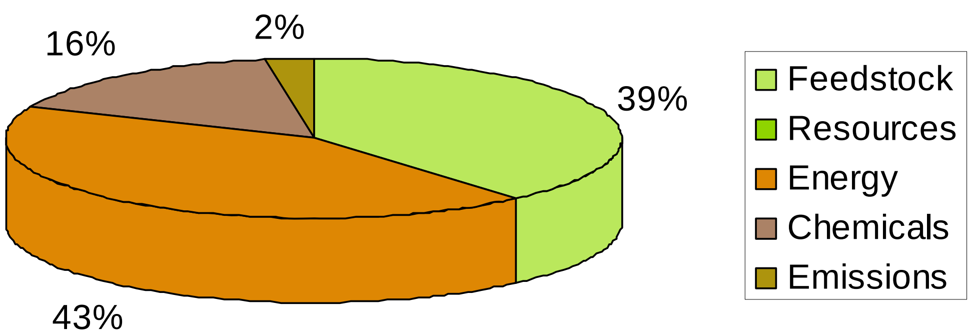


Figure 6-17: Distribution of the ecological footprint of 1kg PHA from tallow glycerol

6.4.D3 *Synthetic Glycerol*

Synthetic glycerol may be a competitive feedstock for fermentation to native glycerol, depending on the market price. Due to the situation on the crude oil market the price of synthetic glycerol has risen. However, because of strong demand the prices for vegetable oils have increased too. Under these uncertain circumstances a comparison between native and synthetic feedstock seems reasonable.

Looking at the process producing PHA from synthetic glycerol it can be seen that the supply chain inflicts a much larger ecological pressure on the environment than the process steps (Figure 6-18). This is due to the high energy inputs needed to synthesize glycerol from propylene and the fact that propylene provision already accumulates a large footprint. Along the process chain, as became already clear in prior chapters, the fermentation step surpasses the cell disruption and filtration step by far.

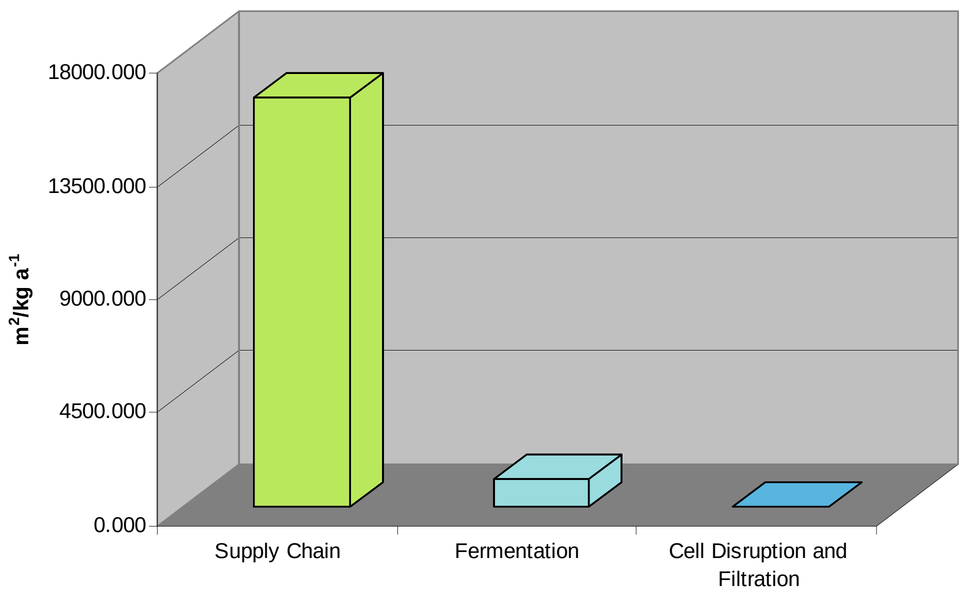


Figure 6-18: The ecological footprint for 1kg PHA from synthetic glycerol

PHA from synthetic glycerol exerts an ecological footprint of 17417.10$m^2/kg\ a^{-1}$ during the process. The big influence of feedstock on the footprint can be seen in Figure 6-19. Of the remaining inputs energy still represents the largest factor, followed by chemicals.

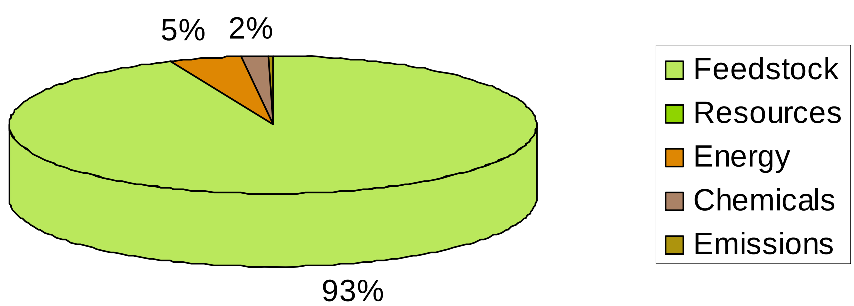


Figure 6-19: Distribution of the ecological footprint of 1kg PHA from synthetic glycerol

6.4.D4 *Comparison of PHAs from different glycerol feedstock*

Glycerol is a feedstock frequently used for fermentations. However, the origin of the glycerol strongly affects the ecological pressure of the product, PHA in our case. Regardless of which glycerol is utilized, the feedstock adds at least about 40% to the total footprint of the product. As the fermentation process remains the same for each feedstock, the difference in the footprint is determined only by the supply chain.

6.5 *PHA from Biodiesel*

6.5.A Introduction

Not only the by-product of biodiesel production, glycerol, can be used as a carbon source for fermentation but also biodiesel itself. The disadvantage of using a high value product like biodiesel as feedstock is equalized by the advantage of higher PHA yields.

6.5.B Process

The process for PHA production from biodiesel is similar to the above process from glycerol a two step process. As base for assessment the fermentation process for optimized PHA production was taken.

In the first process step biodiesel is fed to the fermentation reactor, that also needs the inputs energy and chemicals. Cell disruption and filtration, the second process step uses only energy input.

The assessment is done for two kinds of biodiesel, one from rapeseed oil, the other from tallow. Process infrastructure is not included in the ecological assessment. Figure 6-20 shows the process structure and the system boundaries of PHA production.

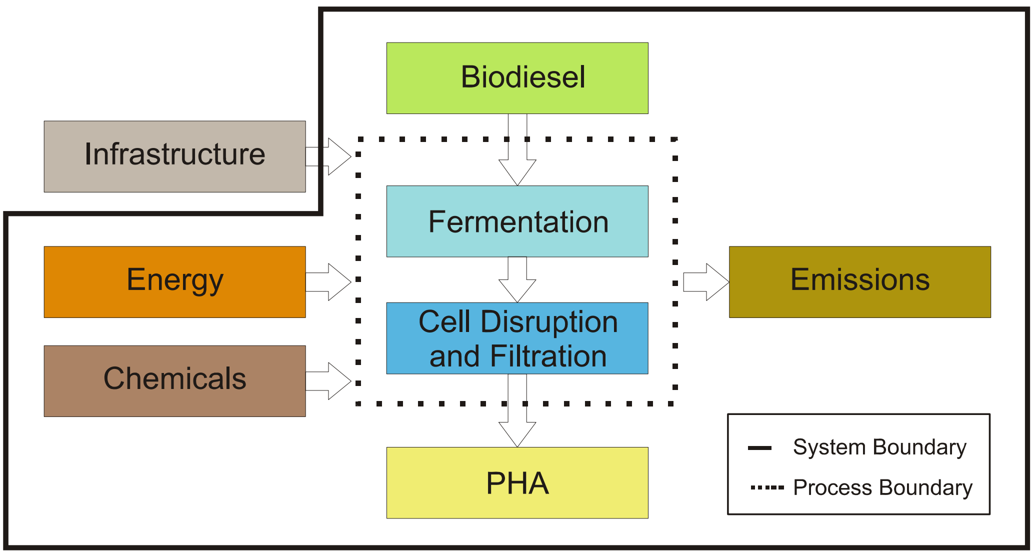


Figure 6-20: Process structure and system boundaries of the ecological assessment of PHA production from biodiesel

6.5.C Eco-inventory

Table 6-3 shows the eco-inventory for the production of 1kg PHA from biodiesel.

Table 6-3: Eco-Inventory for the production of 1kg PHA from biodiesel

Feedstock	Biodiesel	kg/kg	4.900
Resources	Process Water	kg/kg	0.857
Energy	Electricity	kWh/kg	1.018
	Extra Light Fuel Oil	MJ/kg	10.040
Chemicals	Yeast extract	kg/kg	0.072
	Sodium chloride SP	kg/kg	2.054
	Potassium chloride	kg/kg	0.051
	Inorganic chemicals SP	kg/kg	0.452
Emissions	Na (water)	kg/kg	0.810

6.5.D Results

6.5.D1 *Rapeseed Biodiesel*

The ecological pressure accumulated along the production chain results to almost equal parts from the supply chain and the fermentation step (Figure 6-21). The second process step can be neglected.

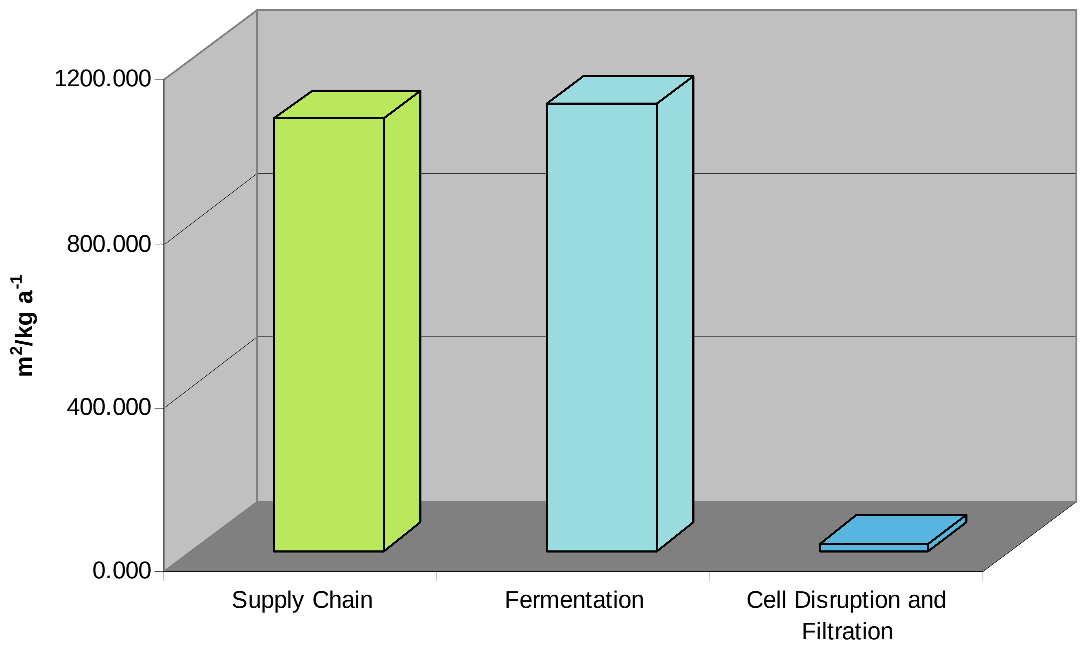


Figure 6-21: The ecological footprint for 1kg PHA from RME biodiesel

The process results in an ecological footprint of 2164.11$m^2/kg\ a^{-1}$ PHA from RME biodiesel.

The largest part of this footprint arises from feedstock. Energy input has a big influence too (Figure 6-22). Chemical input has also to be considered from an ecological point of view, whereas emissions do not inflict much ecological pressure on the environment.

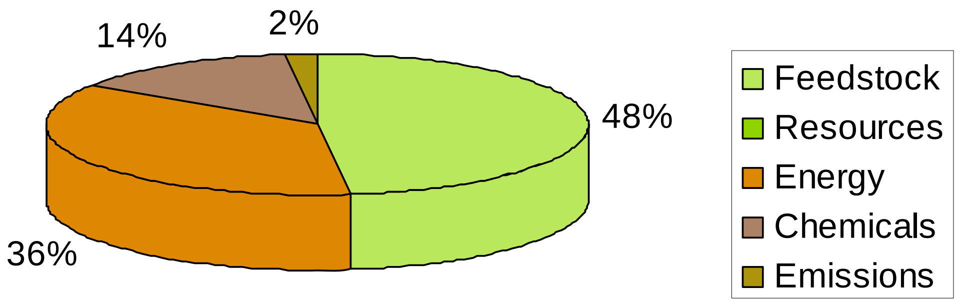


Figure 6-22: Distribution of the ecological footprint of 1kg PHA from RME biodiesel

6.5.D2 *Biodiesel from Tallow*

The main part of the ecological pressure lies on the side of the process, although the influence of the supply chain cannot be neglected (Figure 6-23). Inside the process the fermentation step is dominant.

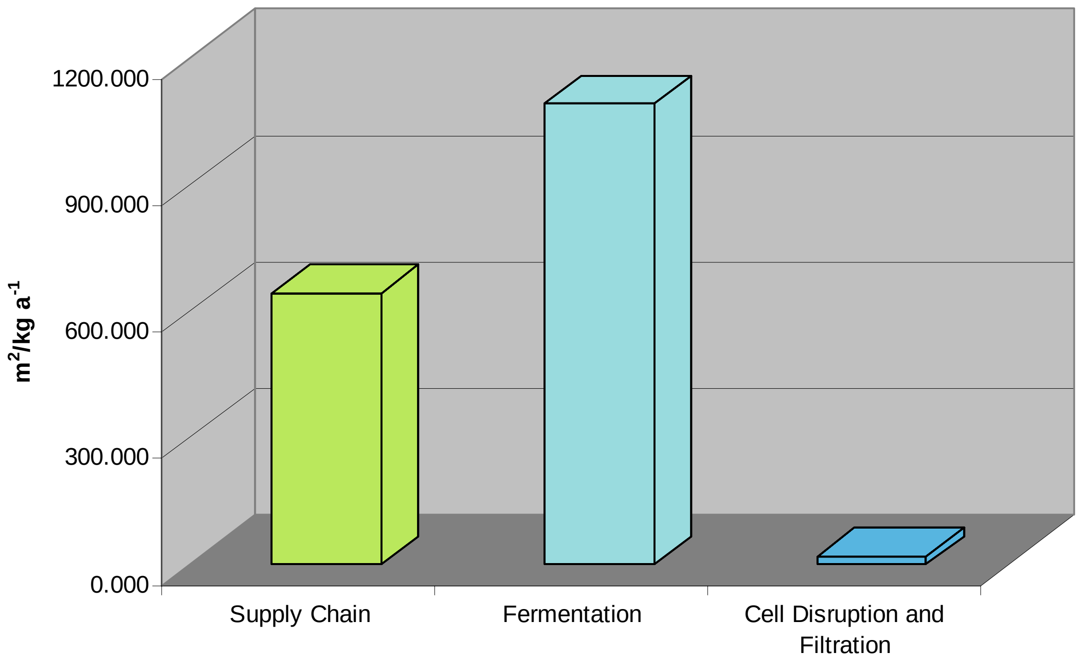


Figure 6-23: The ecological footprint for 1kg PHA from tallow biodiesel

The production of PHA from tallow biodiesel obtains an ecological footprint of 1752.87m^2/kg a^{-1}.

Most of the footprint is added by the provision of energy, the influence of the feedstock following closely (Figure 6-24). Additionally chemical are an important factor. Emissions play a minor role.

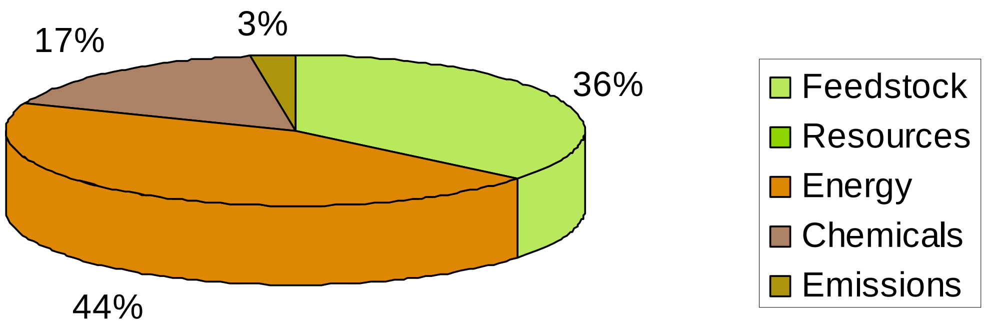


Figure 6-24: Distribution of the ecological footprint of 1kg PHA from tallow biodiesel

6.5.D3 *Comparison of PHAs from different biodiesel feedstock*

Compared to the case of PHA produced from glycerol, using biodiesel leads to similar results. Biodiesel from rapeseed oil inflicts a greater pressure on environment than biodiesel from tallow. This difference can also be seen in the produced PHA.

6.6 *PHA from Sugar Cane Molasses*

6.6.A Introduction

As PHA can be produced from lactose, any kind of sugar containing feedstock may be used for fermentation. In countries that produce sugar from sugar cane, the waste product of molasses can be an interesting feedstock for fermentation.

Molasses obtained from sugar production consists still of 50% fermentable sugars. In Brazil a pilot plant is already producing PHA on a large scale utilizing this source [19]. An interesting side aspect at this plant is that the processing facility produces its own electricity and process energy by burning sugar cane bagasse.

6.6.B Process

The process for PHA production from sugar cane molasses contains two process steps. In the first sugar cane molasses is fermented to PHA. For this process the inputs and parameters for the optimized PHA production from whey have been applied. Next to the feedstock molasses fermentation inputs are energy and chemicals.

Cell disruption and filtration is the second process step and consumed only energy.

Process infrastructure is not included in the ecological assessment. Figure 6-25 shows the process structure and the system boundaries of PHA production.

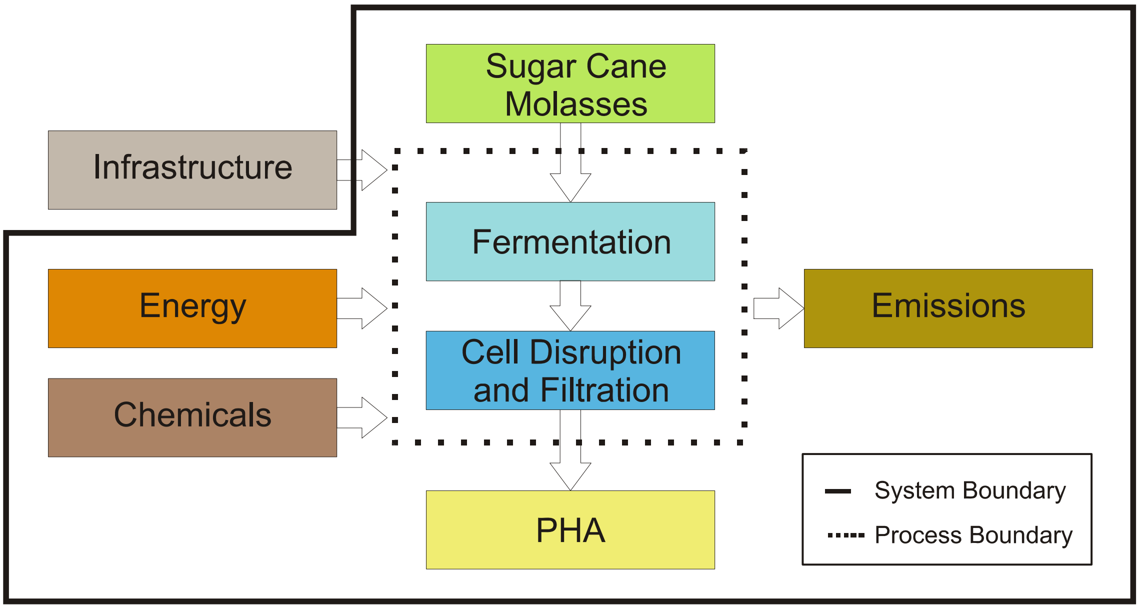


Figure 6-25: Process structure and system boundaries of the ecological assessment of PHA production from sugar cane molasses

6.6.C Eco-inventory

Table 6-4 shows the eco-inventory for the production of 1kg PHA from sugar cane molasses.

Table 6-4: Eco-Inventory for the production of 1kg PHA from sugar cane molasses

Feedstock	Sugar Cane Molasses	kg/kg	2.000
Resources	Process Water	kg/kg	30.572
Energy	Electrictiy from Bagasse	kWh/kg	1.018
	Steam from Bagasse	MJ/kg	4.781
Chemicals	Yeast extract	kg/kg	0.072
	Nutrient Salts	kg/kg	2.557
Emissions	Na (water)	kg/kg	0.810

6.6.D Results

Looking at the process steps it can be seen that the fermentation step inflicts the highest ecological pressure. The supply chain only plays a minor role and the second process step, cell disruption and filtration, is almost nonexistent.

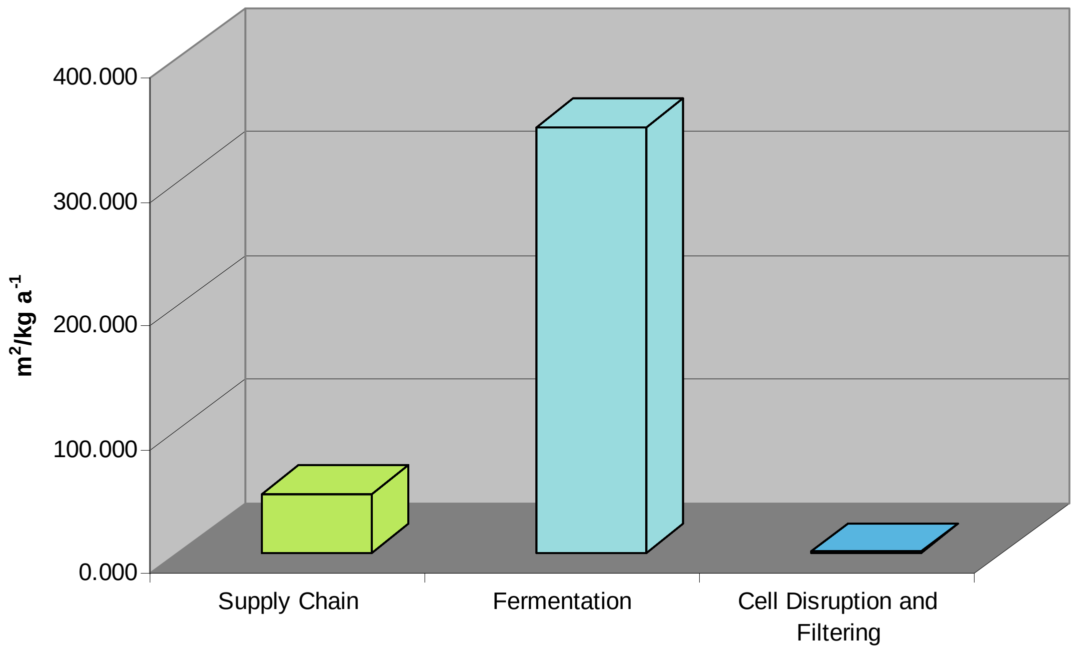


Figure 6-26: The ecological footprint for 1kg optimized PHA from sugar cane molasses

The production process results in an ecological footprint of 391.92m^2/kg a^{-1} PHA from sugar cane molasses.

Looking at the origin of the footprint it can be seen that the largest contributor is chemical input (Figure 6-27). Emissions and feedstock add to the footprint to the same amount, but much lower than chemicals and energy adds the least. This is due to the fact that the energy consumed is provided by the combustion of biomass. Chemicals then gain dominance in inflicting ecological pressure because of the high amount of nutrient salts utilized.

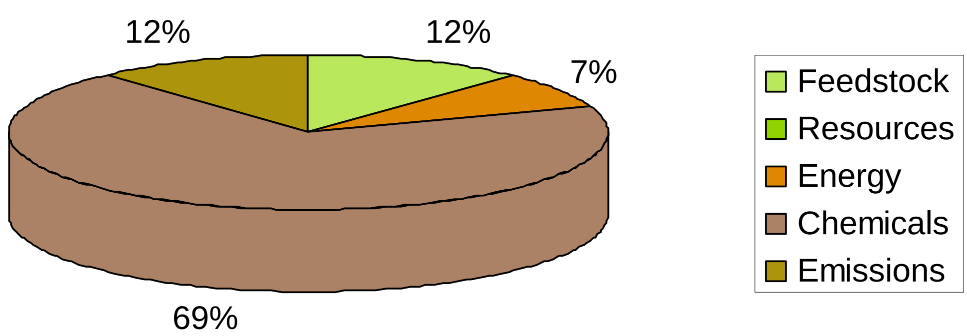


Figure 6-27: Distribution of the ecological footprint of 1kg optimized PHA from sugar cane molasses

This process shows the potentials in decrease of the ecological footprint when renewable energy sources are utilized.

6.7 *PHA production utilizing alternative Nitrogen Sources*

6.7.A Introduction

Meat and bone meal is the product of slaughter house waste that has undergone a rendering process. In Austria about 230,000 tons of slaughter house waste is processed each year resulting in about 100,000 tons of meat and bone meal [35].

As a result of the BSE (Bovine spongiform encephalopathy also "mad cow disease") crisis that began in 2000 the use of meat and bone meal as animal fodder was forbidden [36]. With this ban a valued material turned suddenly to waste that had to be disposed of.

Research for new utilization of meat and bone meal and slaughter house waste respectively was supported by the Austrian government [29] as the huge amount of meat and bone meal represents heavy economic burden.

One possibility of utilizing this material is the production of PHA via fermentation. In contrary to the previously discussed process from whey, the feedstock used was not the carbon source but the complex nitrogen source replacing the yeast extract. Two different feedstock routes can be chosen, first the utilization of meat and bone meal as fermentation feedstock, secondly a direct use of slaughter house waste without the rendering step.

Slaughter house waste and meat and bone meal are not the only waste materials that can replace yeast extract. Another possibility is to use spent brewers yeast derived after the brewing process of beer.

These three alternative nitrogen sources shall be compared to show the influence of utilizing different waste materials on the production process of PHA.

6.7.B Process

The production process for PHA with utilization of alternative nitrogen sources consists either of three or two steps. This depends on the alternative nitrogen source. Slaughter house waste and meat and bone meal have to be hydrolyzed before they can be fed to the fermentation process. Yeast extract from spent yeast can be applied directly to the fermentation process and does not need a prior treatment. The hydrolysis step utilizes chemicals to obtain certain pH values during the process and energy for heating and stirring.

The fermentation and cell disruption steps were treated as described in Chapter 6.5 PHA from Biodiesel. Process infrastructure is not included in the ecological assessment. Figure 6-13 shows the process structure and the system boundaries of PHA production.

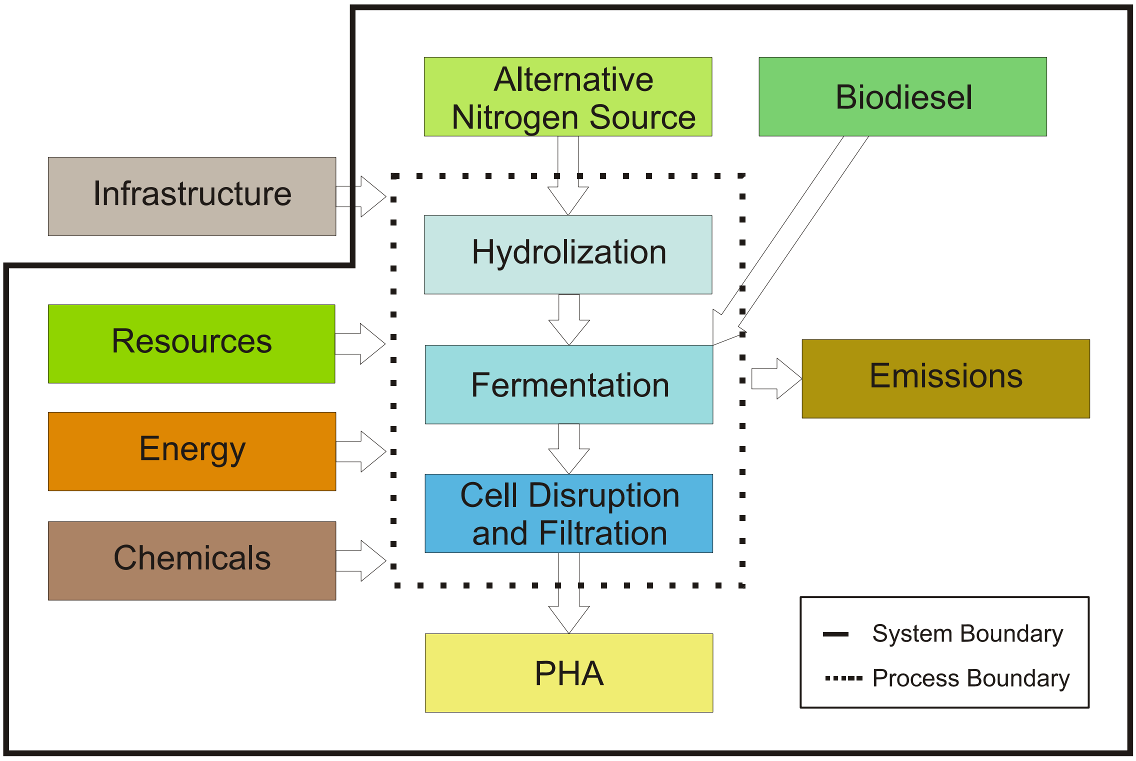


Figure 6-28: Process structure and system boundaries of the ecological assessment of PHA production utilizing alternative nitrogen sources

6.7.C Eco-Inventories

6.7.C1 *Slaughter House Waste*

Table 6-5 shows the eco-inventory for the production of 1kg hydrolyzed slaughter house waste, Table 6-6 for PHA utilizing hydrolyzed slaughter house waste.

Table 6-5: Eco-Inventory for the production of 1kg hydrolyzed slaughter house waste

Feedstock	Rendering Materials	kg/kg	6.550
Energy	Electricity	kWh/kg	0.184
	Extra Light Fuel Oil	MJ/kg	2.456
Chemicals	Hydrochloric acid	kg/kg	0.091
	Sodium hydroxide	kg/kg	0.098

Table 6-6: Eco-Inventory for the production of 1kg PHA utilizing slaughter house waste

Feedstock	Biodiesel from Fat	kg/kg	1.710
Energy	Electricity	kWh/kg	1.018
	Extra Light Fuel Oil	MJ/kg	10.040
Chemicals	Nutrient Solution	kg/kg	35.685
	Hydrolyzed Slaughter House Waste	kg/kg	0.072
Emissions	Na (water)	kg/kg	0.810

6.7.C2 *Meat and Bone Meal*

Table 6-7 shows the eco-inventory for the production of 1kg hydrolyzed meat and bone meal, Table 6-8 for PHA utilizing hydrolyzed meat and bone meal.

Table 6-7: Eco-Inventory for the production of 1kg hydrolyzed meat and bone meal

Feedstock	Meat and Bone Meal	kg/kg	1.195
Energy	Electricity	kWh/kg	0.184
	Extra Light Fuel Oil	MJ/kg	2.456
Chemicals	Hydrochloric acid	kg/kg	0.091
	Sodium hydroxide	kg/kg	0.098

Table 6-8: Eco-Inventory for the production of 1kg PHA utilizing meat and bone meal

Feedstock	Biodiesel from Fat	kg/kg	1.710
Energy	Electricity	kWh/kg	1.018
	Extra Light Fuel Oil	MJ/kg	10.040
Chemicals	Nutrient Solution	kg/kg	35.685
	PHA Rendering Material	kg/kg	0.072
Emissions	Na (water)	kg/kg	0.810

6.7.C3 *Yeast Extract from Spent Brewers Yeast*

Table 6-9 shows the eco-inventory for the production of 1kg PHA utilizing yeast extract from spent yeast.

Table 6-9: Eco-Inventory for the production of 1kg PHA utilizing yeast extract from spent yeast

Feedstock	Biodiesel	kg/kg	4.900
Resources	Process Water	kg/kg	0.857
Energy	Electricity	kWh/kg	1.018
	Extra Light Fuel Oil	MJ/kg	10.040
Chemicals	Yeast extract from Spent Yeast	kg/kg	0.072
	Sodium chloride	kg/kg	2.054
	Potassium chloride	kg/kg	0.051
	Inorganic chemicals	kg/kg	0.452
Emissions	Na (water)	kg/kg	0.810

6.7.D Results

6.7.D1 *Slaughter House Waste*

Utilizing slaughter house waste as complex nitrogen source does not change the picture very much compared to yeast extract. Still the fermentation step where the nitrogen source is consumed contributes the highest ecological pressure (Figure 6-29). The hydrolization step exceeds the cell disruption and filtration step in inflicting ecological pressure.

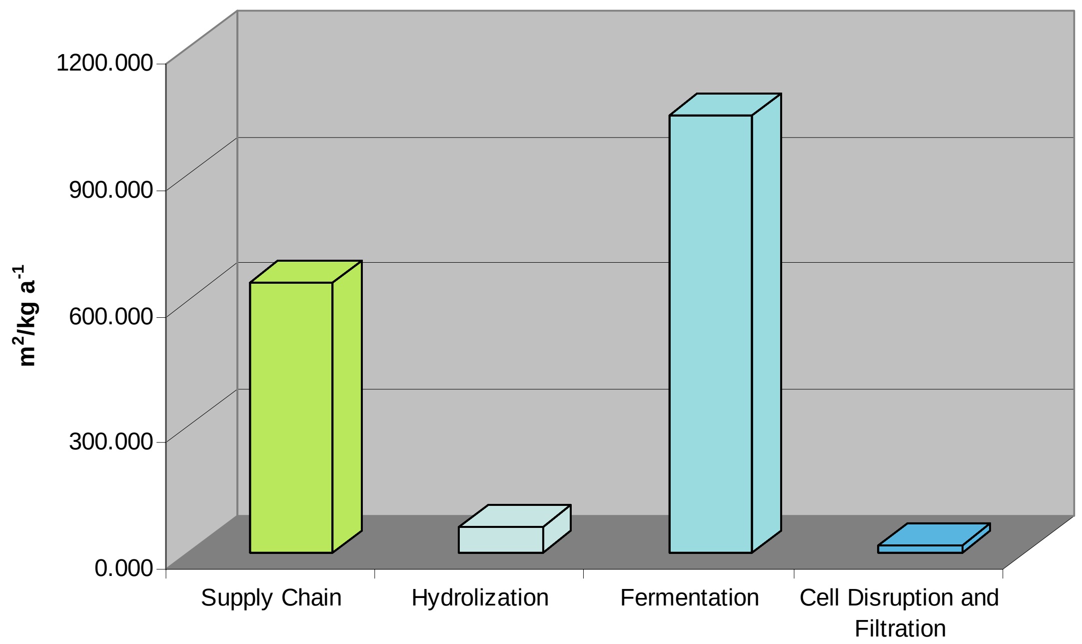


Figure 6-29: The ecological footprint for 1kg optimized PHA utilizing slaughter house waste

The overall footprint for PHA utilizing slaughter house waste is 1748.78m^2/kg a^{-1}.

Along the input categories energy and feedstock still play the major roles, while chemicals are less important (Figure 6-30).

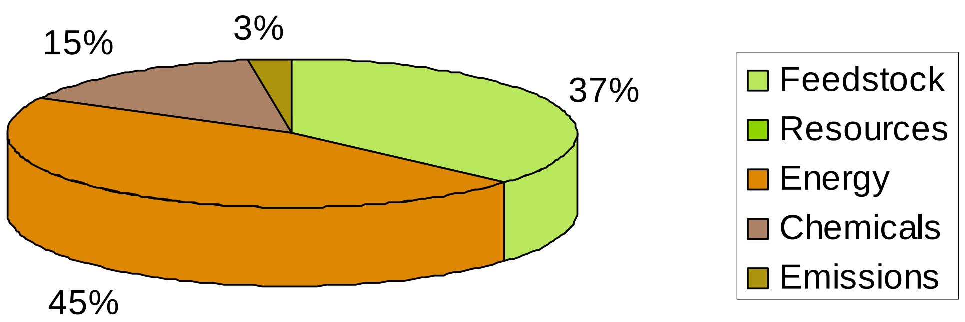


Figure 6-30: Distribution of the ecological footprint of 1kg optimized PHA utilizing slaughter house waste

6.7.D2 *Meat and Bone Meal*

The distribution of the footprints along the process step utilizing meat and bone meal as nitrogen source does not change much either (Figure 6-31). For hydrolization the accumulated ecological pressure is not as high as for slaughter house waste.

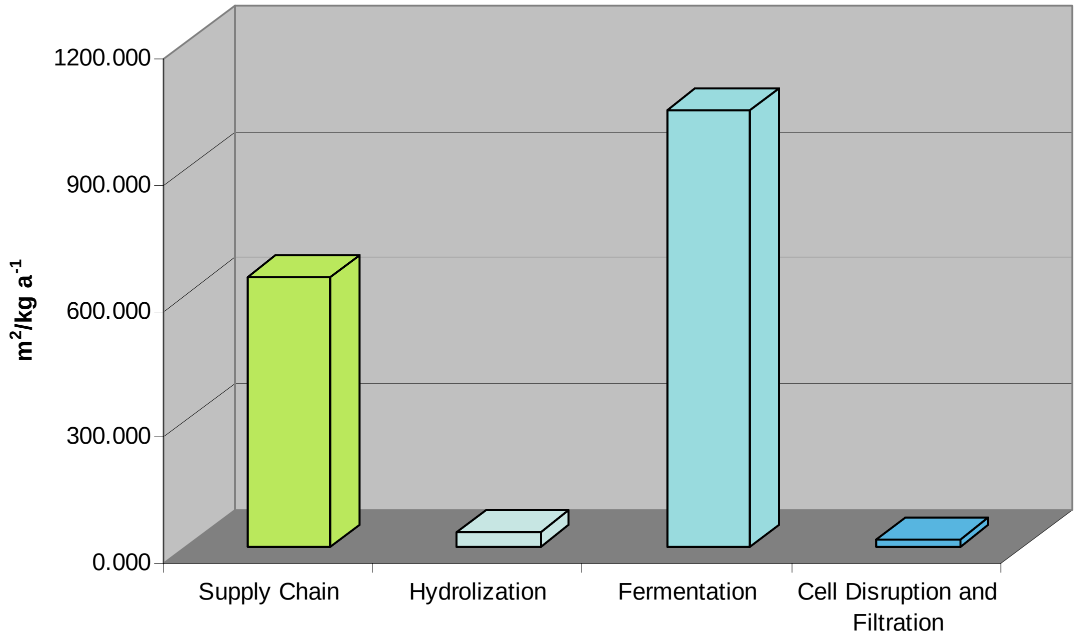


Figure 6-31: The ecological footprint for 1kg optimized PHA utilizing meat and bone meal

The production of PHA utilizing meat and bone meal results in a footprint of 1736.01 $m^2/kg\ a^{-1}$.

As in the case described before the energy input inflicts the highest pressure, followed by the feedstock whereas chemicals play a subsidiary role.

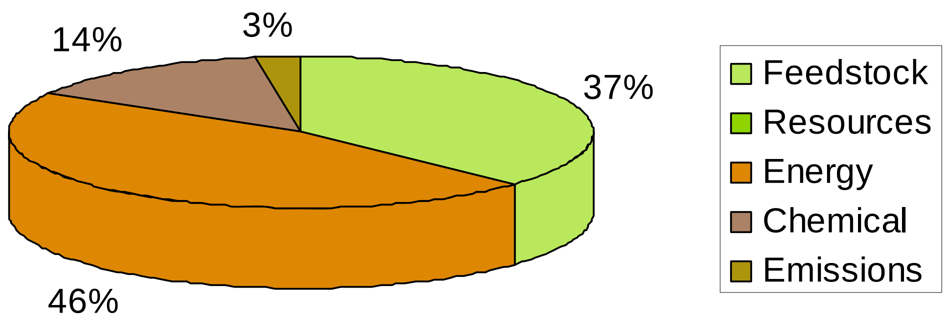


Figure 6-32: Distribution of the ecological footprint of 1kg optimized PHA utilizing meat and bone meal

6.7.D3 *Yeast Extract from Spent Brewers Yeast*

The use of yeast extract from spent yeast does not need a hydrolization step prior fermentation. However, the ratio between the process step stays the same (Figure 6-33).

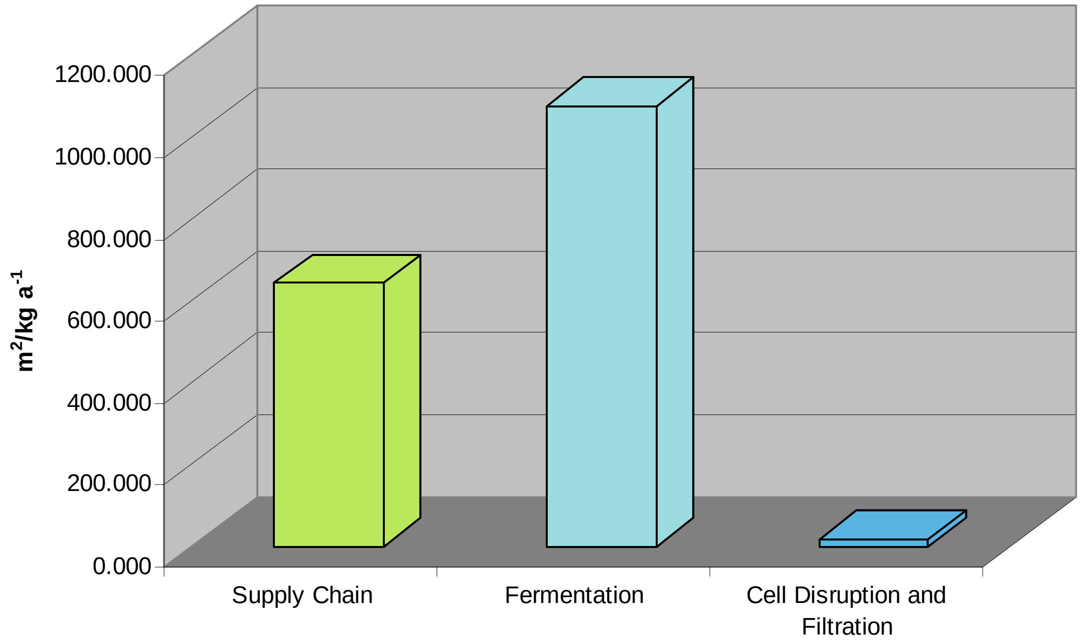


Figure 6-33: The ecological footprint for 1kg optimized PHA utilizing yeast extract from spent yeast

The resulting footprint for the production of PHA utilizing yeast extract from spent yeast is 1735.06m^2/kg a^{-1}.

The distribution of the footprint along the input categories still shows energy and feedstock as main contributors. Chemicals also play an important role whereas emissions are of minor influence.

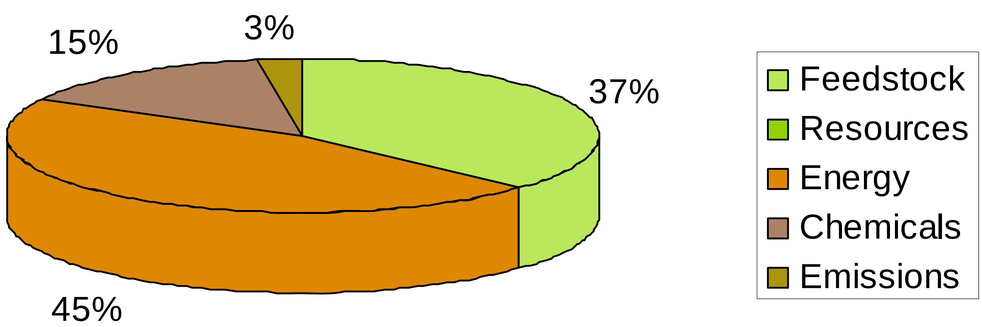


Figure 6-34: Distribution of the ecological footprint of 1kg optimized PHA utilizing yeast extract from spent yeast

6.7.D4 *Comparison of the utilization of alternative nitrogen sources*

Comparing the calculations for the PHAs utilizing alternative nitrogen sources with PHA consuming normal yeast extract it can be said that the difference in the resulting footprint is negligible (Figure 6-35).

The nitrogen sources have significant differences for their specific footprints ranging from 490.61m^2/kg a^{-1} for yeast extract from spent yeast to 729.09m^2/kg a^{-1} for normal yeast extract. However, due to the low amount of yeast extract needed for fermentation processes this difference does not affect the overall footprint of the resulting PHAs significantly.

The data on which the footprint calculation of the nitrogen sources is based has to be referred as imprecise. These results can therefore, just be taken as rough estimation. Nonetheless the conclusion, that for the small amounts of input the kind of nitrogen source does not matter, can be seen as accurate as uncertainties in the data equalizes along all four data sets.

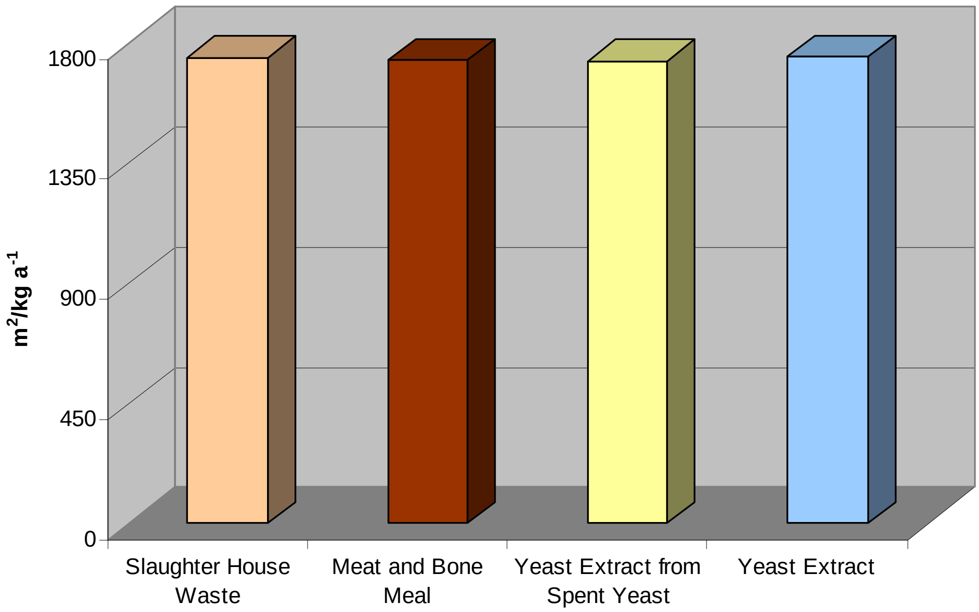


Figure 6-35: Comparison of PHA utilizing different nitrogen sources

6.8 *Conclusion*

An interesting possibility is to compare the footprints of the biopolymers produced by the processes described in this chapter. In this way the pros and cons of the presented feedstock and processes for PHA production can be discussed.

Figure 6-36 shows that the footprints of the polymers lie in a relatively small range from 2300 m^2/kg a^{-1} to 1500 m^2/kg a^{-1} with only one biopolymer clearly more sustainable. This is PHA derived from sugar cane molasses. This results from the clean energy that is utilized for this process as the whole amount of steam and electricity is produced within the production facility by combustion of sugar cane bagasse. The fact that the utilization of a renewable energy source leads to such a big decrease in the ecological footprint emphasizes the influence of energy on PHA production processes.

The results of the unoptimized production of PHA from whey are not show as the resulting biopolymer does not even reach competitiveness with fossil polymers. As example for the footprint of fossil polymers polypropylene is shown as it is the synthetic polymer with the lowest footprint.

The differences in the ecological footprints consist mainly of the ecological pressure that is obtained by the supply chain of the utilized feedstock. The partial footprints derived from the energy and chemical consumption vary only little with the exception of PHA from sugar cane molasses.

The figure shows that the change of the complex nitrogen source does not have a great influence on the footprint. Therefore, from an ecological point of view it can be said that the kind of nitrogen sources does not influence the sustainability of the product to a great extent.

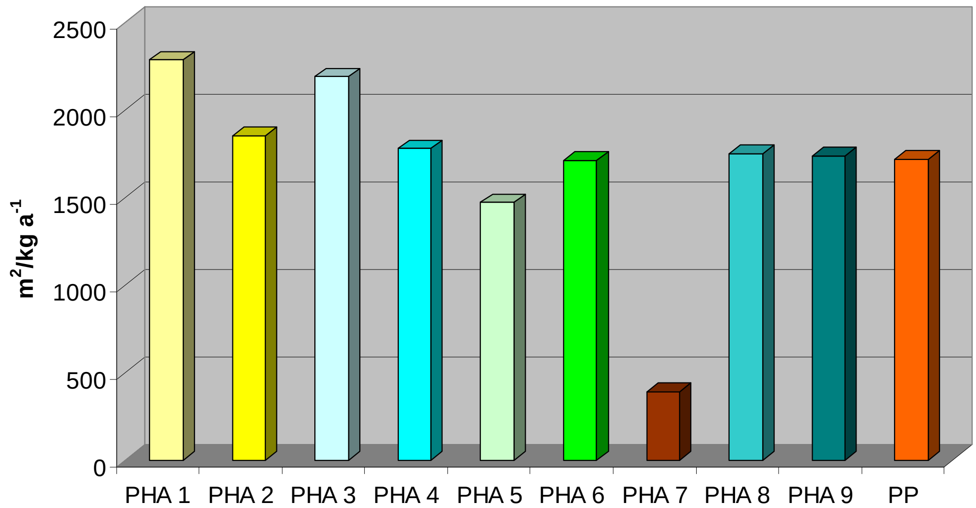


Figure 6-36: Comparison of the ecological footprint of PHA derived from different feedstock and Polypropylene (PHA numbers: 1 Rapeseed Glycerol; 2 Tallow Glycerol; 3 Rapeseed Biodiesel; 4 Tallow Biodiesel; 5 Whey optimized; 6 Whey including supply chain; 7 Sugar Cane Molasses; 8 Slaughter House Waste; 9 Meat and Bone Meal)

The results seem promising as the fermentation step for all processes was one major contributor and the data for this fermentation step was obtained from a pilot plant. It can therefore, be said that the optimization potential is high still and will lead to a further decrease of the ecological footprint. As all biopolymers are in a region around (or already lower than) the footprint of polypropylene, the most sustainable synthetic polymer, due to such a further decrease ecological competitiveness and superiority will be reached.

Taking a look on the distribution of the footprint along the process input categories it can be seen that the footprint results on the most part either from the energy consumption during the process or the footprint introduced due to the utilization of the feedstock (Figure 6-37). Other factors like chemicals, transportation and emission play a minor role whereas the input of process chemicals inflicts the biggest environmental pressure of these categories by far.

In the case of PHA from sugar cane molasses chemicals play the major role as the feedstock has a very low footprint and clean energy is utilized. Another deviation from the average distribution can be seen for the biopolymers obtained from whey. When whey is treated as waste the feedstock does not inflict an environmental pressure. When whey is treated as value material the input category is very low as even as valued waste the footprint accumulated by whey provision is small.

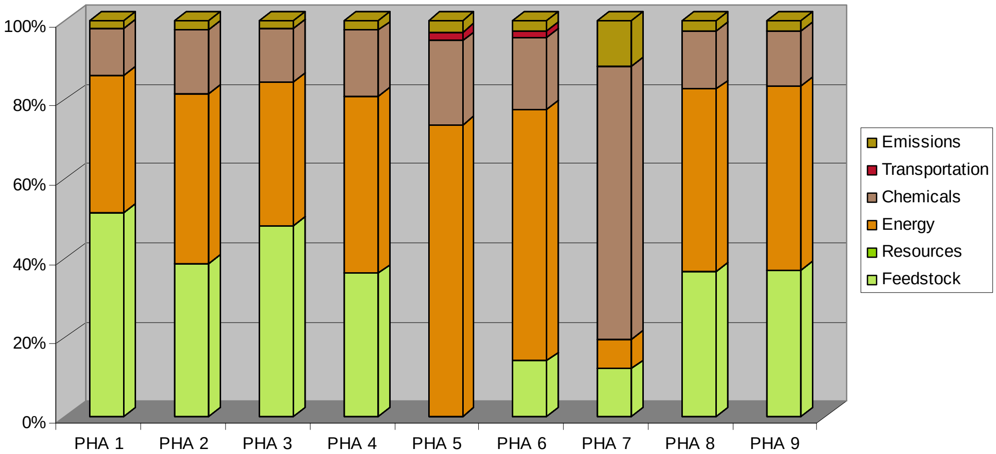


Figure 6-37: Comparison of the distribution of the ecological footprint along the input categories of the different PHAs (PHA numbers: see Figure 6-36)

This picture shifts more to the side of energy provision if the supporting processes (see Chapter 7 Supporting Processes) and their distribution along the input categories are included instead of the feedstock category (Figure 6-38).

Now for all processes the influence of the energy input along the whole process chain is greater than of the feedstock. However, in the cases where the feedstock I obtained from agriculture the ecological pressure obtained along this agricultural supply chain is a major contributor to the overall footprint too.

In some cases now chemicals are of equal importance as feedstock.

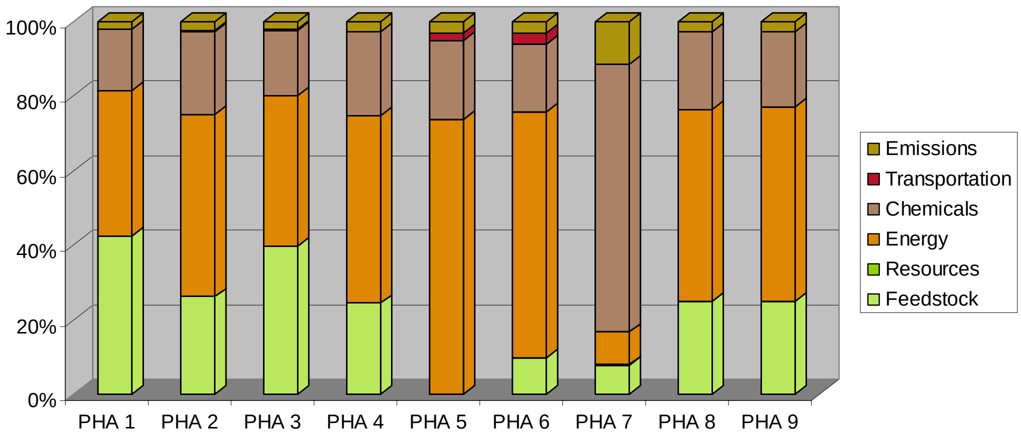


Figure 6-38: Comparison of the distribution of the ecological footprint along the input categories of the different PHAs including the supporting processes (PHA numbers: see Figure 6-36)

7 Supporting Processes

7.1 *Introduction*

The processes in this chapter represent the primary supply chains for the biodiesel and biopolymer production assessed in the previous chapters as well as their synthetic alternatives.

7.2 *Data Sources*

Most of the data that have been considered in this case study are from well-established published data sources.

- Data on energy have been taken from ESU-ETHZ [15]. ESU-ETHZ represents the electricity production of the UCPTE countries (European energy net) at the beginning of the nineties. The electricity mixes for the European countries was calculated with data from EUROSTAT [22] for the year 2002. The applied electricity mix represents the EU25 countries.
- Data on process chemicals and waste treatment comes from ESU-ETHZ [15] and BUWAL [23]. In general the data quality of process chemicals is lower than for energy systems as modeling of process chemicals is highly aggregated. The published data represents standardized technology for Europe not including production infrastructure.
- Data on the production of synthetically glycerol are taken from Borken et al.[28]. This highly aggregated data represents German production.
- Transportation systems have been taken from ESU-ETHZ [15]. The data of road infrastructure represent Swiss road infrastructure, including many tunnels and winding mountain roads. The impact of road infrastructure may therefore, high in comparison to the EU average.
- Data on the usage of tractors in agriculture comes from Borken et al.[28]. Based on the axle load occurring during work the strain of the tractor influencing emissions and diesel consumption was calculated.
- Data on agricultural production comes from ÖKL [27].
- Data on fertilizers has been taken from Patyk und Reinhardt [33]
- Data on pesticides comes from Gaillard et al. [32]
- Data on milk and cheese production was taken from LCA Food [16] and LAVI [18].
- Data on whey powder production comes from LCA Food [16].
- Data on agricultural production of sugar cane comes from Probas [31].

- Data on processing of sugar cane have been taken from Hirschberg [41].
- Data on pure yeast production is based on own calculations
- Data on beer and malt production has been taken from Freiberger [24]and Lammbräu [25]
- Data for autolysis was calculated based on Kanegae [42]
- Data on the rendering process comes from FdZ [29].
- Data on rapeseed oil processing comes from Reinhardt [48]. Based on these data the processing of sunflower and soybean oil has been calculated.
- Data on false flax oil processing are based on own calculations

7.3 *Synthetic Glycerol*

7.3.A Technical Background

Most glycerol is obtained by transesterification of fatty acids and fats like the biodiesel process (see Chapter 5). This glycerol is known as native or natural glycerol. To be able to assess the ecological benefits of such native glycerol from renewable resources a comparison with synthetic glycerol has to be done. Additionally glycerol, either native or synthetic, is often used as fermentation feedstock [39].

7.3.B Process

The assessed process uses the industrial common process route. This process utilizes chlorine and sodium hydroxide as chemical inputs. Due to distillation needs the energy input, especially for steam is high. The production was assessed as one step process excluding process infrastructure. The process structure and system boundaries are shown in Figure 6-2.

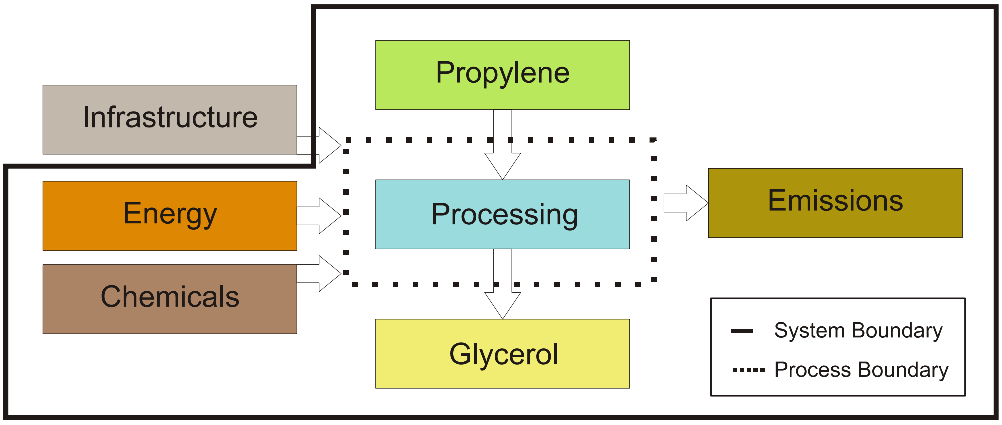


Figure 7-1: Process structure and system boundaries of the ecological assessment of synthetic glycerol production

7.3.C Eco-Inventory

Table 7-1 shows the eco-inventory for the production of 1kg synthetic glycerol.

Table 7-1: Eco-Inventory for the production of synthetic glycerol

Feedstock	Propylene	kg/kg	0.800
Energy	Electricity	kWh/kg	0.900
	Steam	MJ/kg	63.000
Chemicals	Chlorine	kg/kg	2.000
	Sodium Hydroxide	kg/kg	1.400
Emissions	Sox (air)	kg/kg	0.028
	Benzene (water)	kg/kg	0.000

7.3.D Results

The production of synthetic glycerol results in a footprint of 3327.956m^2/kg glycerol. The majority of this footprint results from the energy input, especially steam usage (see Figure 6-2). Additionally the feedstock, propylene, already accumulates a high ecological pressure in its provision. Chemicals play a lesser role and the influence of emissions on the footprint is of minor importance.

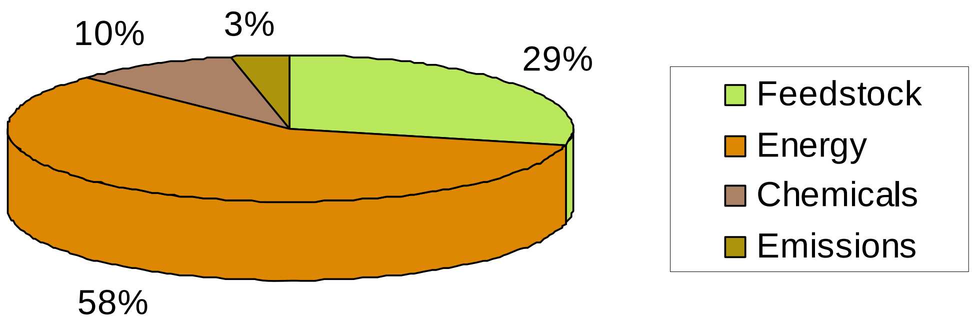


Figure 7-2: Distribution of the ecological footprint of 1kg synthetic glycerol

Compared to native glycerol produced via the biodiesel production synthetic glycerol results in a footprint at least factor 10 higher. The reason for this lies in the higher depletion of fossil carbon for synthetic glycerol (factor 20). This depletion can be traced back for about one third to the resources needed for the feedstock propylene; the rest is mostly depleted for steam production.

7.4 *Whey*

7.4.A Technical Background

Whey occurs during cheese production from milk. Although cheese is the primary product of this process and whey is an unwanted byproduct if not outright waste, much more whey than cheese is produced. Another byproduct of the process is cream [40].

A growing demand in proteins led to additional amounts of whey that were processed but a large surplus still exists and has to be treated as waste material. This is the economic and ecologic background of this case study.

Normally whey is treated as waste material as processing whey results in higher costs than the revenue from its products. In this case whey has a specific footprint of $0m^2/kg$. When industrial processes start using whey in big scale this fact will change as the product value surpasses the processing costs. Therefore, it is necessary to allocate an ecological footprint to whey according to the price obtained by dairies at the moment.

7.4.B Process

The process for producing cheese is assessed as two step process with the first step of producing milk. The agricultural supply chain feeds dairy cows with three different fodders to obtain milk. Corn and soy meal are fed directly, whereas cleaver and grass have to be pretreated to silage. For providing fodder and tending the dairy cows energy and transportation (via tractor) as well as fertilizers and pesticides are needed.

The second step is the production of cheese where whey occurs. Milk is converted consuming water and energy as well as producing emissions into water

Process infrastructure is not included in the ecological assessment. Figure 7-3 shows the process structure and the system boundaries of whey production.

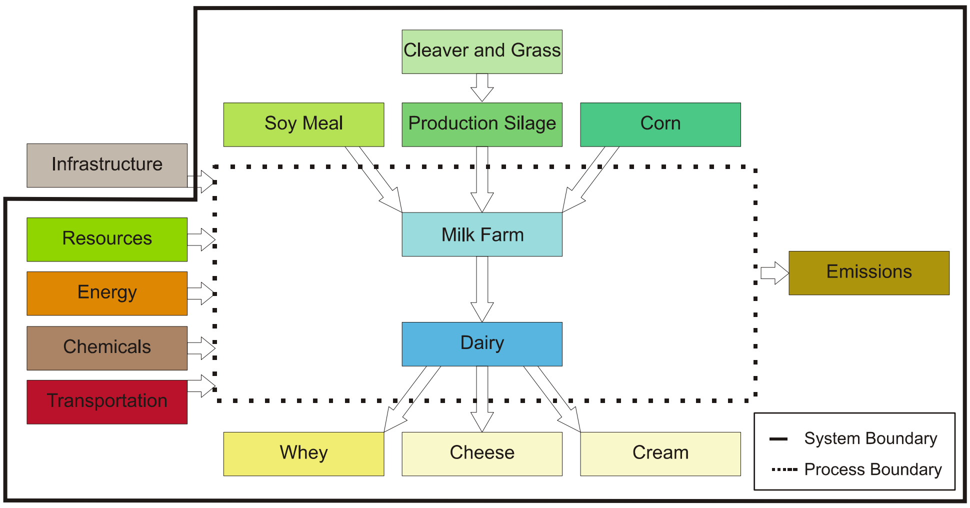


Figure 7-3: Process structure and system boundaries of the ecological assessment of whey production

7.4.C Eco-Inventory

Table 7-2 shows the eco-inventory for the production of 1kg milk,

Table 7-3 of 1kg cheese.

Table 7-2: Eco-Inventory for the production of 1kg milk

Feedstock	Clover-Grass Silage	kg/kg	3.650
	Soy Meal	kg/kg	0.183
	Grain Corn	kg/kg	0.183
Energy	Electricity	kWh/kg	0.074
	Extra light fuel oil	MJ/kg	0.001
Transportation	Tractor (<70 kW), light workload	h/kg	0.009

Table 7-3: Eco-Inventory for the production of 1kg cheese

Feedstock	Milk	kg/kg	10.000
Resource	Process Water	kg/kg	15.000
Energy	Electricity	kWh/kg	0.596
	Extra light fuel oil	MJ/kg	4.800
Emissions	Phosphor (water)	kg/kg	0.001

7.4.D Results

Looking at the ecological pressure applied by the process steps it can be seen that the supply chain input has the greatest influence (Figure 7-4). The process itself accumulates a much lower ecological footprint whereas the production of milk inflicts a greater pressure on environment than the cheese production.

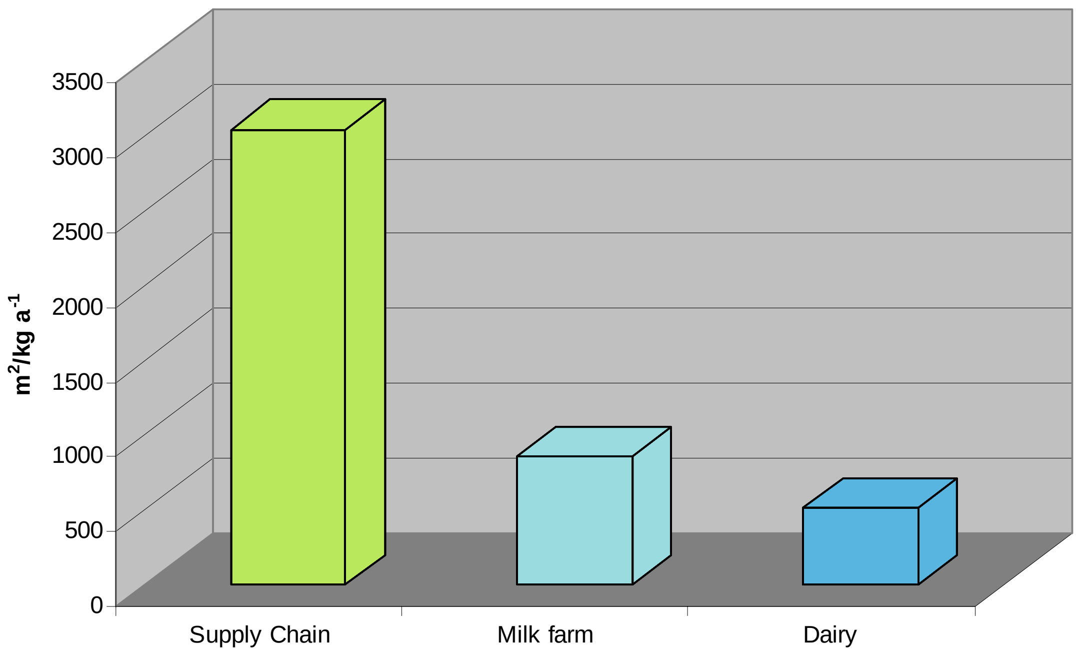


Figure 7-4: The ecological footprint for 1kg produced primary product along the process steps

The process of producing 1kg of cheese results in a process footprint of 4490.97 m^2. This footprint has to be allocated onto the three products cheese, whey and cream. Application based on price allocation (cheese 4.15€/kg, whey 0.46ct/kg, cream 0.76€/kg) leads to ecological footprints of 4448.5 m2/kg cheese, 4.93 m2/kg whey and 811.67 m2/kg cream.

The distribution of this footprint (Figure 7-5) shows that the major contributor for cheese production is the process feedstock milk whereas the energy provision and emissions play a minor role. The consumption of process water has almost no impact. Another important factor of the ecological pressure is the transportation and work input of tractors during milk production.

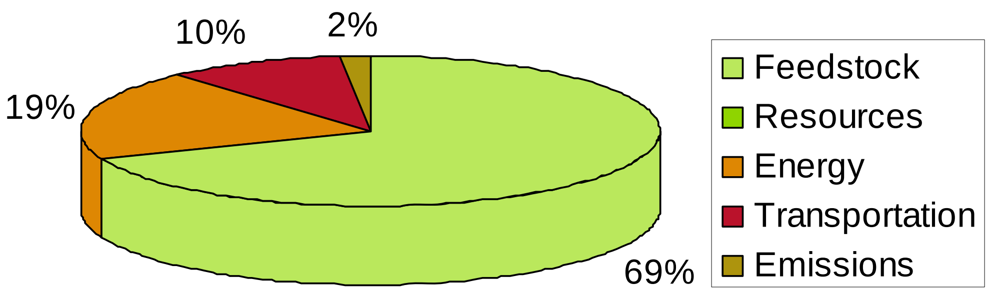


Figure 7-5: Distribution of the ecological footprint of 1kg whey with price allocation

7.5 *Whey Powder*

7.5.A Technical Background

Although whey is an (in the amount that it is obtained) unwanted waste of cheese production it has to be treated before deposing or processed otherwise. Most dairies process whey to whey powder and sell the product as animal nutrition.

At the present time the largest part of whey is used to produce whey powder for human or animal nutrition. This process uses large amounts of energy concentrating the whey by evaporation producing a good of low market value. The processing costs of whey powder production exceed the revenue but it is still more profitable than the necessary waste treatment else wise as whey cannot be committed to sewage untreated because of its high biological oxygen demand (BOD5 34000 mg/kg)[14]. Therefore, at the moment a big amount of whey just "vanishes" somewhere into the ecosphere.

7.5.B Process

The process for producing whey powder is relatively simple although energy intensive as the whey is dried from over 90% water content to about 3%.

Before drying the whey is transported to the processing facility from nearby dairies. This transportation may not be needed if the facility is directly next to a large dairy but the structure of cheese production in middle Europe is build mostly upon smaller dairies. Therefore, even large dairies with a whey powder facility get much of their whey from nearby dairies.

Input next to the process feedstock and transportation need is only energy for drying. Emissions occur in the evaporated water. Process infrastructure is not included in the ecological assessment. The process structure and system boundaries are shown in Figure 6-2.

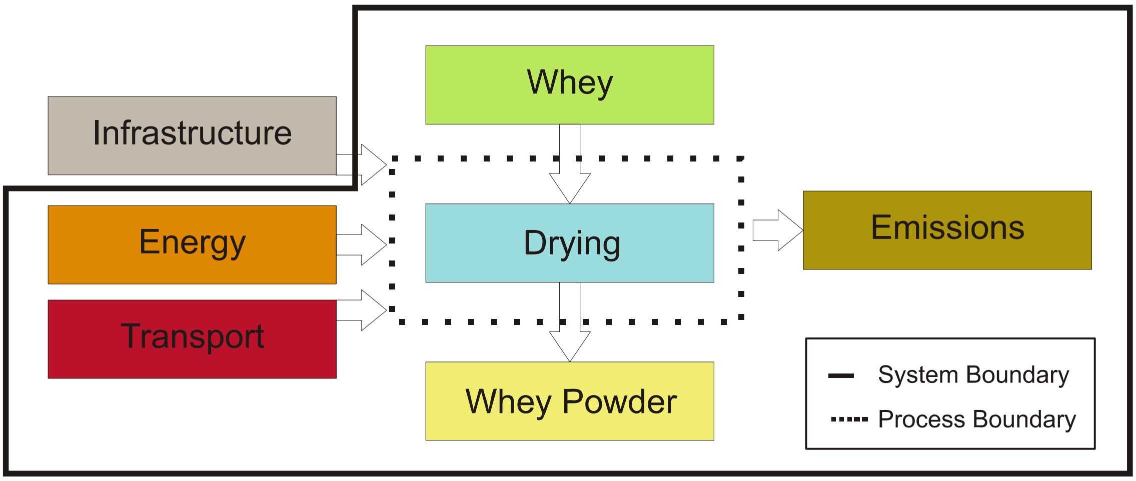


Figure 7-6: Process structure and system boundaries of the ecological assessment of whey powder production

7.5.C Eco-Inventory

Table 7-4 shows the eco-inventory for the production of 1kg whey powder.

Table 7-4: Eco-Inventory for the production of 1kg whey powder

Feedstock	Whey	kg/kg	7.800
Energy	Electricity	kWh/kg	0.354
	Extra Light Fuel Oil	MJ/kg	7.155
Transport	28t Truck	tkm/kg	0.056
Emissions	P (water)	g/kg	0.110

7.5.D Results

The given process results in an ecological footprint of 375.38m^2/kg whey powder.

When whey is treated as waste the feedstock has a specific footprint of 0m^2/kg and does not add to the ecological pressure. In this case energy is the most prominent contributor to the ecological footprint of whey powder production (Figure 7-7). Emissions and transportation play a minor role.

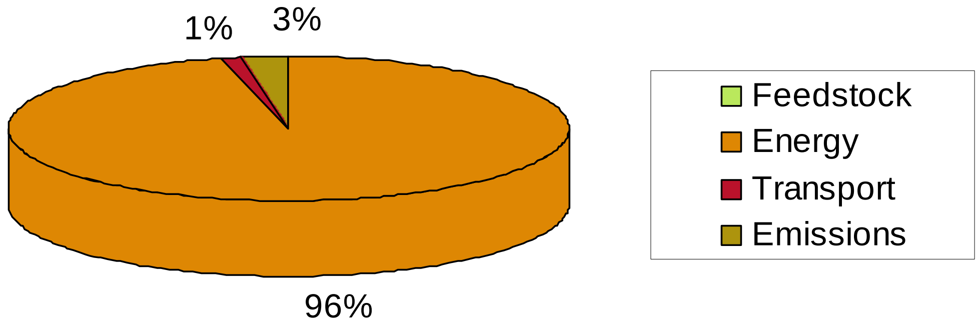


Figure 7-7: Distribution of the ecological footprint of 1kg whey powder treating whey as waste

In foresight the process must also be assessed with a price allocated footprint for whey, as whey may change from waste material to value feedstock in future renewable based industries. In this case whey obtains a specific footprint of 4.93m^2/kg. The ecological footprint of whey powder increases to 413.84 m^2/kg. As the amount of other inputs besides whey does not change the picture (Figure 7-8) does not shift dramatically. Energy still plays the major role for the process. However, the second position of contributors now is occupied by the feedstock whey, emissions and transport apply a much smaller ecological pressure.

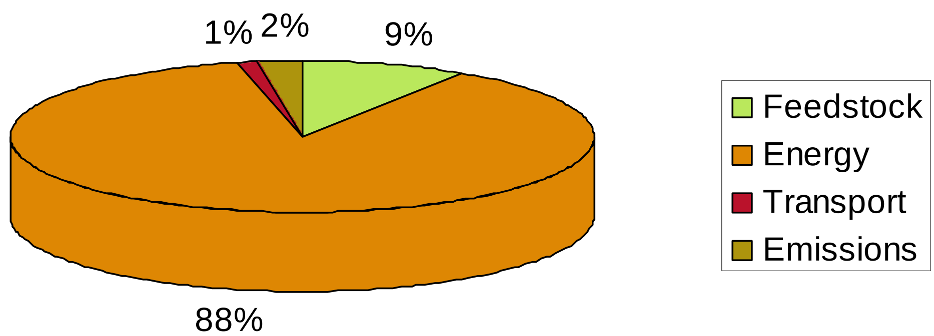


Figure 7-8: Distribution of the ecological footprint of 1kg whey powder including the whey supply chain

7.6 *Sugar Cane Molasses*

7.6.A Technical Background

In the tropical and subtropical climate zones the feedstock for sugar production is sugar cane. As plant with one of the most effective photosynthesis ratios of flora it is perfectly adapted to these areas.

Next to sugar a sugar processing plant also produces the byproducts molasses and bagasse. Bagasse, the remains of the sugar cane, is mostly burned directly in the processing facilities to provide electricity and process energy. Excess electricity is sold to near cities. Because of this fact most sugar cane processing plants are able to do without any energy provision from outside the plant.

Molasses is either used as fermentation feedstock or animal feed [41].

7.6.B Process

The production of sugar from sugar cane, where molasses is obtained too, is done in three steps.

First the feedstock sugar cane is put to a reception step, where it is cleaned, shred and sugar is extracted with hot water. Next to raw juice the byproduct bagasse arises. This is mostly burned for electricity and steam production while the remains are used as animal feed.

In the second step the raw juice is mixed with lime to precipitate impurities and stop the conversion from sucrose to glucose and fructose. The clear juice is then concentrated.

In the last step raw sugar is crystallized out of the thick juice and processed further on to obtain brown or white sugar. Molasses is the liquid that remains after crystallization.

Process infrastructure is not included in the ecological assessment. The process structure and system boundaries are shown in Figure 7-9.

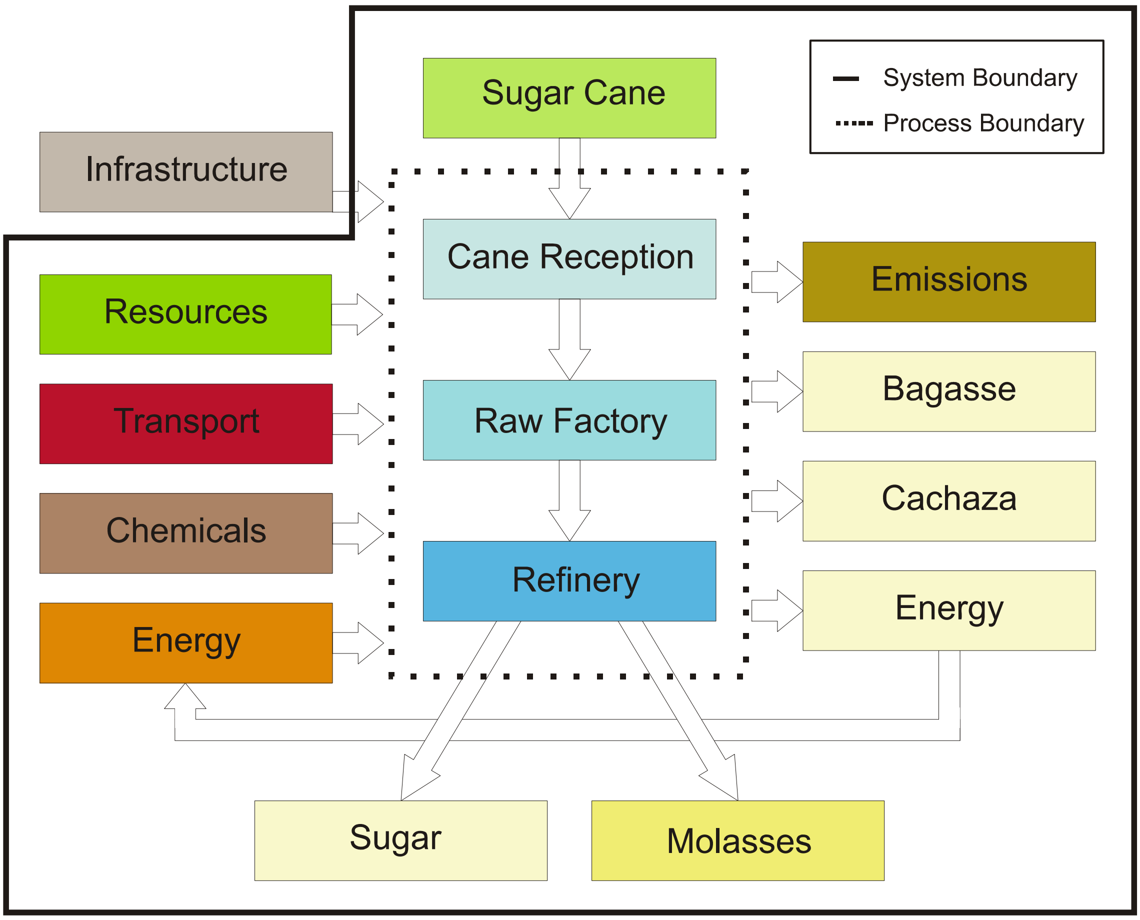


Figure 7-9: Process structure and system boundaries of the ecological assessment of sugar cane molasses production

7.6.C Eco-Inventory

Table 7-5, Table 7-6 and Table 7-7 show the eco-inventory of the process steps Cane Reception with the product sugar cane raw juice, the raw factory with the product sugar cane thick juice and the refinery with the product sugar.

Table 7-5: Eco-Inventory for the production of 1kg sugar cane raw juice

Feedstock	Sugar Cane	kg/kg	0.965
Resources	Process Water	kg/kg	0.290
Chemicals	Organic chemicals	g/kg	0.101
	Inorganic chemicals	g/kg	0.011
Emissions	Waste in landfill for inert matters	kg/kg	0.067
Byproducts	Bagasse	kg/kg	0.256
	Electricity from Sugar Cane	kWh/kg	0.035
	Steam from Sugar Cane	kg/kg	0.422

Table 7-6: Eco-Inventory for the production of 1kg sugar cane thick juice

Feedstock	Sugar Cane Raw Juice	kg/kg	5.065
Energy	Steam from Sugar Cane	kg/kg	2.137
	Electricity from Sugar Cane	kWh/kg	0.100
Chemicals	Coke (hard coal)	kg/kg	0.009
	Limestone, CaCO3	kg/kg	0.138
	Inorganic chemicals	g/kg	0.268
	Sodium hydroxide	g/kg	3.372
	Organic chemicals	g/kg	0.079
	Glycerol	g/kg	2.393
	Hydrochloric acid	g/kg	0.010
	Lubricant oil	g/kg	0.012
	Sulfur	g/kg	0.359
	Sulfuric acid	g/kg	2.872
Byproducts	Dry bagasse	kg/kg	0.244

Table 7-7: Eco-Inventory for the production of 1kg sugar

Feedstock	Sugar Cane Thick Juice	kg/kg	1.891
Resources	Process Water	kg/kg	1.605
Chemicals	Sodium hydroxide	g/kg	0.183
	Lubricant oil	g/kg	0.064
	Sodium silicate	g/kg	1.208
	Glycerol	g/kg	0.010
	Inorganic chemicals	g/kg	15.140
	Polyethylene wax	g/kg	0.050
Byproducts	Sugar Cane Molasses	kg/kg	0.305

7.6.D Results

Looking at the process it can be seen that the largest contribution comes from the sugar cane supply chain due to the high inputs in cultivation (Figure 7-10). Compared to this the partial footprints added by the process steps are very small. This is not only because of the large amount of agricultural inputs but also to the fact that the total energy needed for the process is provided by burning of bagasse. Therefore, a much lower footprint is obtained than if energy was produced by burning fossil fuels or producing electricity from lignite or nuclear power plants.

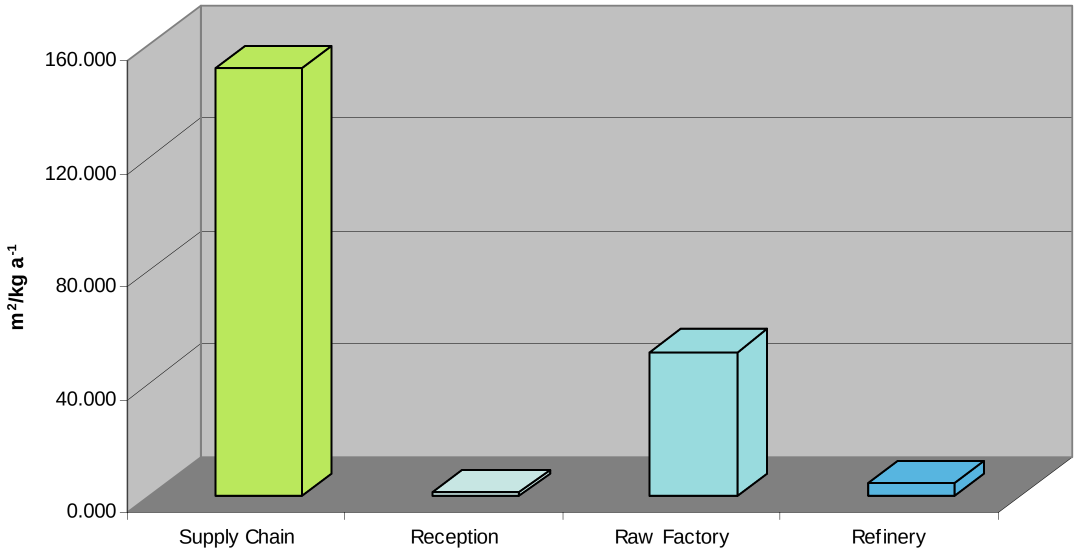


Figure 7-10: The ecological footprint for 1kg sugar along the process steps

The sugar production process results in a process footprint of 208.42m^2 for 1kg sugar. Due to price allocation the footprints of products and byproducts are 174.19m^2/kg for sugar (value 0.38€/kg), 29.80m^2/kg for molasses (value 0.065€/kg), 1.92m2/kg for dry bagasse (value 0.0046€/kg), 13.13m^2/kWh for electricity from bagasse (value 0.058€/kg) and 5.18m^2/kg for steam (value 0.023€/kg).

As was shown in the previous figure most of the ecological footprint derive from feedstock. The remaining footprint obtained during the process comes equally from energy and process chemicals whereas used resources and emissions play a minor role (Figure 6-2).

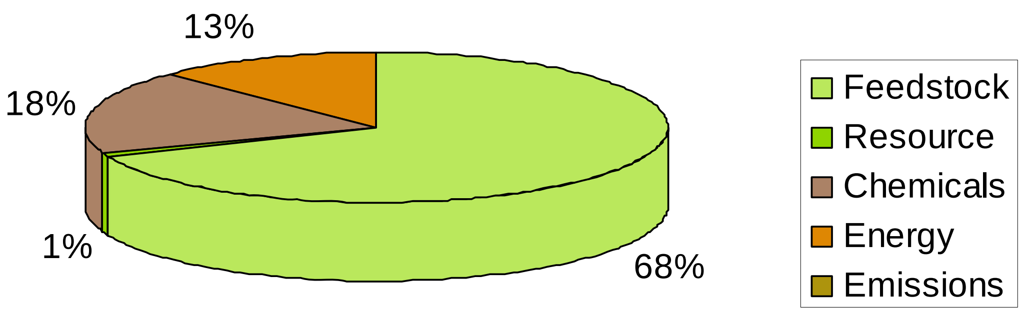


Figure 7-11: Distribution of the ecological footprint of 1kg molasses with price allocation

7.7 *Yeast Extract from Pure Yeast*

7.7.A Technical Background

Fermentation processes require complex nitrogen sources additionally to the carbon source. Yeast extract is a nitrogen source often used in such biotechnological processes. Yeast extract is obtained after autolysis of pure yeast, a process where yeast cells are heated under alkaline conditions to decompose the cells into its complex components.

Pure yeast is obtained after a fermentation process consuming molasses. Molasses used in this assessment was produced from sugar cane. If obtained from sugar beets, the results would be slightly higher.

7.7.B Process

The process of producing yeast extract from pure yeast is a two step process.

The first step is growing of pure yeast on molasses. This is done as in a fermentation consuming chemicals and energy. Due to lack of data no emissions are included.

In a second step the yeast is processed in an autolysis step to deactivate the cells. For this step also chemicals and energy are needed.

Process infrastructure is not included in the ecological assessment. The process of producing beer is shown in Figure 7-12.

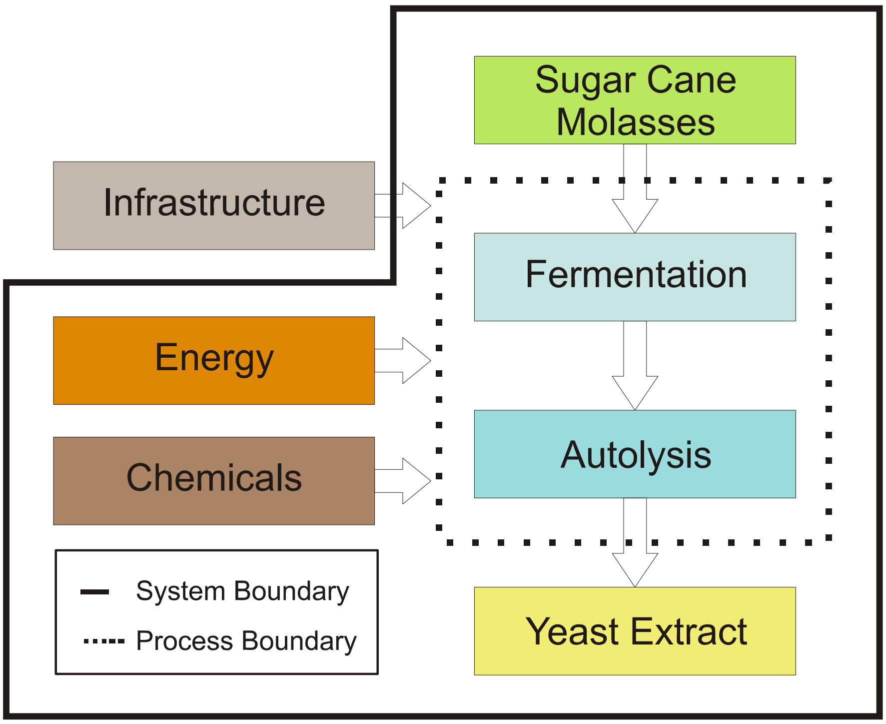


Figure 7-12: Process structure and system boundaries of the ecological assessment of yeast extract production from pure yeast

7.7.C Eco-Inventory

Table 7-8 shows the eco-inventory for the production of 1kg of pure yeast, Table 7-9 of 1kg dry yeast extract.

Table 7-8: Eco-Inventory for the production of 1kg pure yeast

Feedstock	Sugar Cane Molasses	kg/kg	1.667
Energy	Electricity	kWh/kg	0.191
	Steam production	MJ/kg	8.095
Chemicals	Inorganic chemicals	kg/kg	0.090

Table 7-9: Eco-Inventory for the production of 1kg yeast extract

Feedstock	Yeast	kg/kg	2.000
Energy	Natural Gas	MJ/kg	0.920
Chemicals	Sodium hydroxide	kg/kg	0.002
	Hydrochloric acid	kg/kg	0.001

7.7.D Results

Most ecological pressure during yeast extract production arises in the process step of fermentation (Figure 7-13). The influence of the autolysis step is much smaller. The supply chain for providing sugar cane molasses even exerts a larger pressure on environment than the autolysis.

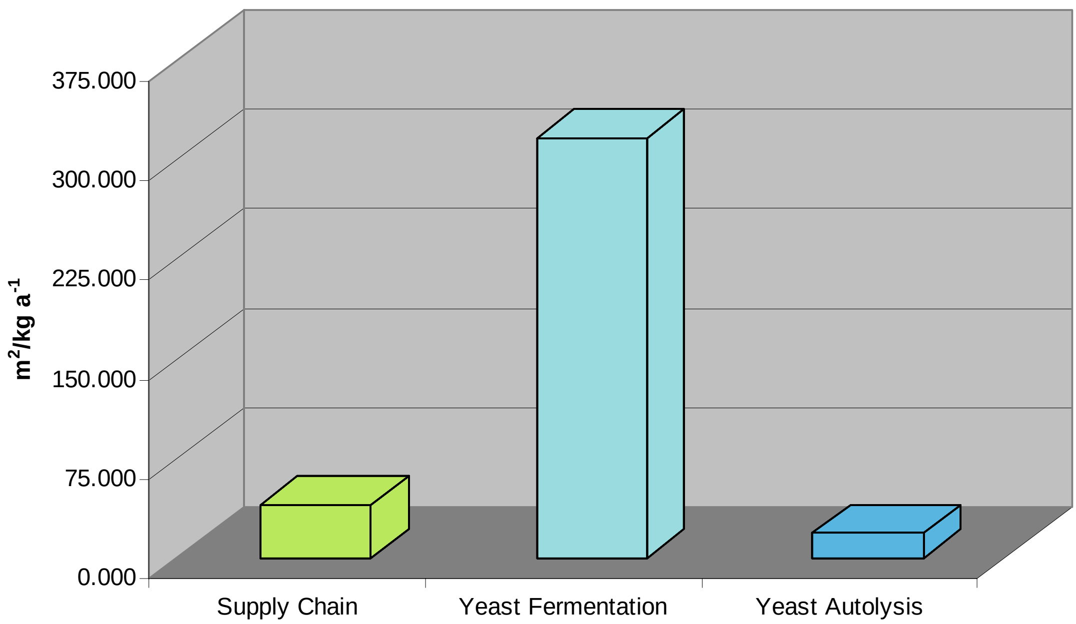


Figure 7-13: The ecological footprint for 1kg yeast extract from pure yeast along the process steps

The production of yeast extract results in an overall footprint of 729,08m^2/kg a^{-1}. The majority of this footprint is derived from energy consumption (Figure 7-14) whereas feedstock and use of chemicals only play a minor role.

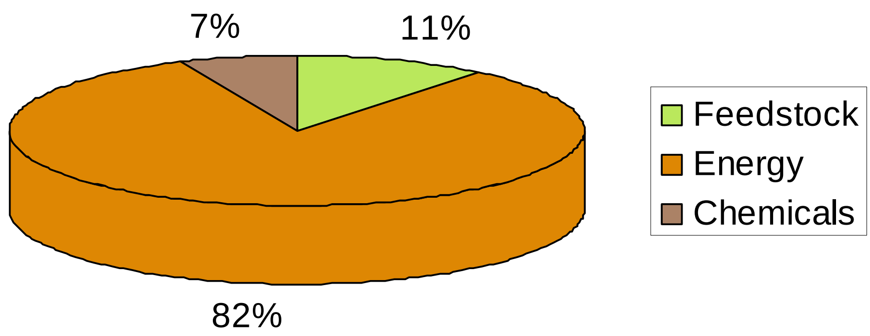


Figure 7-14: Distribution of the ecological footprint of yeast extract from pure yeast

7.8 *Yeast Extract from Spent Yeast*

7.8.A Technical Background

Not only yeast extract from pure yeast can be used for fermentation. Spent brewers yeast can replace pure yeast in the autolysis step as is described in literature [34]. Spent brewers yeast is a byproduct of beer production. The feedstock for beer is barley and hop alongside water.

7.8.B Process

The process of producing yeast extract is a three step process.

The first step is malting of barley. Barley is germinated and afterwards quickly dried resulting in barley malt.

In the second process step beer is brewed and spent brewers yeast obtained as byproduct. Hot water is added to the malt and the resulting slurry is heated further to convert the malt starch into maltose sugar. The brew is filtered afterwards obtaining brewer grains, a byproduct mostly sold as animal nutrition. After adding hop and yeast the brew undergoes a fermentation process. Before the beer is bottled the spent yeast is filtered.

The third process is autolysis of the spent brewers yeast. The yeast slurry is heated up under caustic conditions. After the autolysis reaction has taken effect the slurry is neutralized and filtered to obtain dry yeast extract. This process step has been calculated very roughly with the average concentration of spent yeast (about 100g dry matter per liter) and the industrial energy input needed for heating and evaporating the slurry.

Hop as well as process infrastructure was not included into the assessment because of lack of data. Process infrastructure is not included in the ecological assessment. The process of producing beer is shown in Figure 7-15.

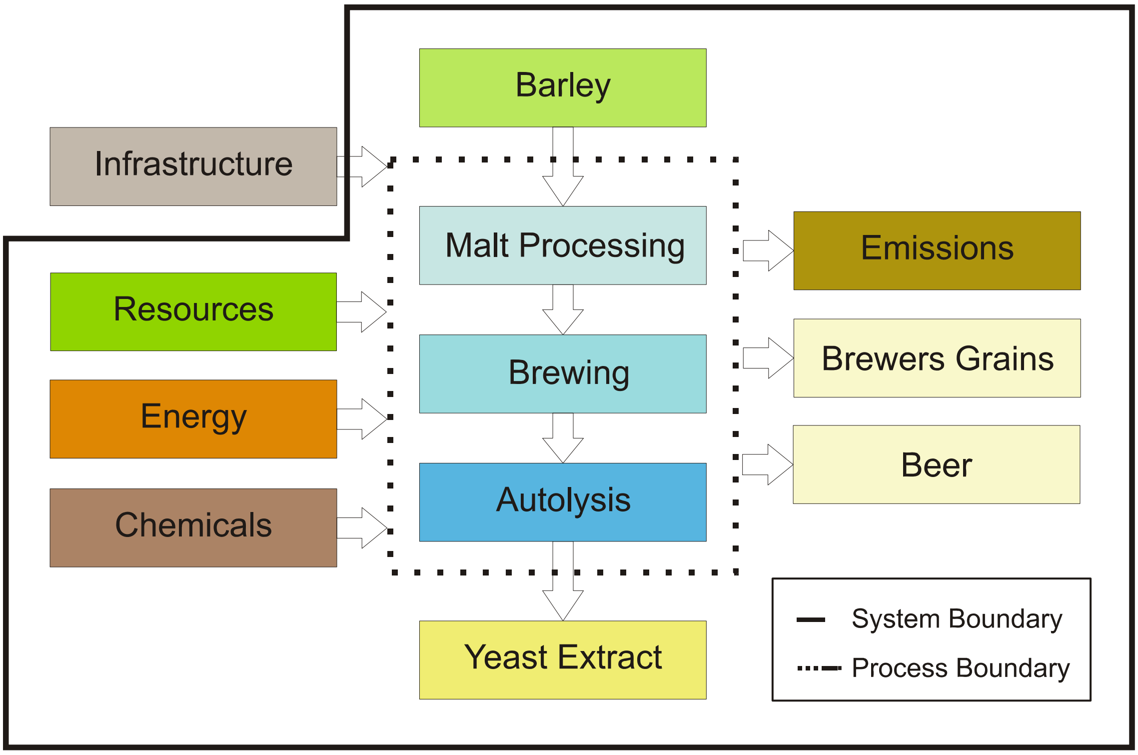


Figure 7-15: Process structure and system boundaries of the ecological assessment of beer production

7.8.C Eco-Inventory

Table 7-10 shows the eco-inventory for the production of 1kg of barley malt, Table 7-11 of 1l beer and Table 7-12 of 1kg dry yeast extract.

Table 7-10: Eco-Inventory for the production of 1kg barley malt

Feedstock	Barley	kg/kg	1.221
Energy	Natural Gas	MJ/kg	3.010
	Electricity	kWh/kg	0.104

Table 7-11: Eco-Inventory for the production of 1l beer

Feedstock	Barley Malt	kg/l	0.167
	Hop	kg/l	0.002
Resources	Process Water	m3/l	0.004
Energy	Electricity	kWh/l	0.089
	Natural Gas	MJ/l	1.023
	Extra Light Fuel Oil	MJ/l	0.073
	Diesel	kg/l	0.001
Chemicals	Sodium hydroxide	kg/l	0.003
Emissions	P (water)	g/l	0.031
	NOx (air)	g/l	0.035
Byproducts	Brewers grains	kg/l	0.186
	Spent brewers yeast	l/l	0.049

Table 7-12: Eco-Inventory for the production of 1kg yeast extract

Feedstock	Spent Brewers Yeast	l/kg	10.000
Energy	Natural Gas	MJ/kg	30.531
	Sodium hydroxide	kg/kg	0.002
Chemicals	Hydrochloric acid	kg/kg	0.001

7.8.D Results

As can be seen in Figure 7-16 the autolysis has the greatest influence on yeast extract production. This is due to the high energy input. This holds true equally for the brewing step. Compared to this the ecological pressure inflicted by malting and the supply chain are very small.

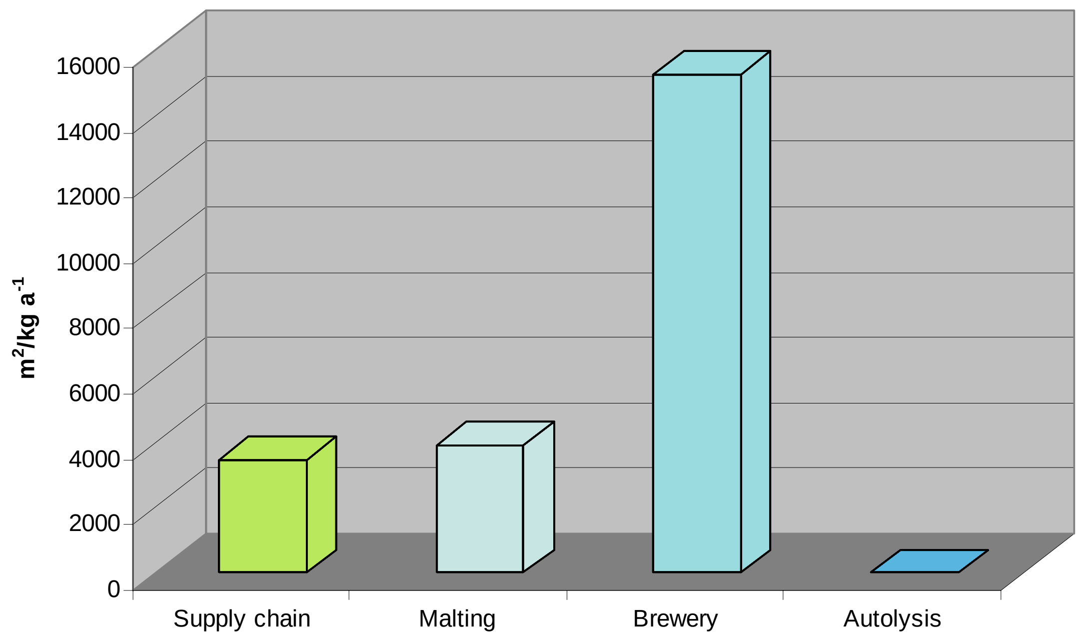


Figure 7-16: The ecological footprint for 1kg yeast extract along the process steps

The beer production process results in an ecological footprint of 117.18m^2/l beer produced. Applying price allocation (beer 0.44€/l, brewers grains 0.08€/kg, spent yeast 0,2€/l) the resulting footprints are 110.94m^2/l for beer, 20.17m^2/kg for brewer grains and 50.38 m^2/l for spent yeast.

Taking a look at the distribution of the footprint it can be seen that due to the high electricity and heat input for malting and brewing energy is the major contributor (Figure 7-17). Nonetheless the agricultural feedstock production of barley adds more significantly to the ecological footprint as other factors like chemicals and emission.

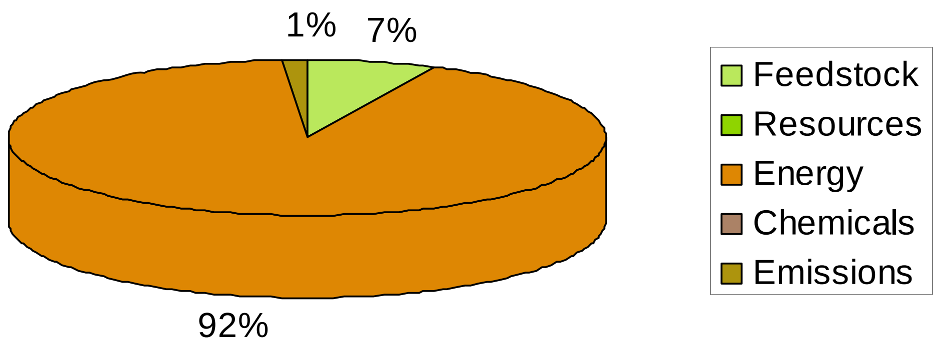


Figure 7-17: Distribution of the ecological footprint of 1l spent brewers yeast with price allocation

7.9 *Slaughter House Waste*

7.9.A Technical Background

Slaughtering of animals, especially cattle slaughtering, results not only in the primary product of meat but also in byproducts like tallow, pet food and fertilizer. Additionally slaughter house waste is obtained, often to a large amount depending on the slaughtered animal. Due to health risk the slaughter house waste must be treated in rendering facilities. For future applications this waste can also be treated as valuable good when used as feedstock for fermentation [29].

7.9.B Process

The process taken as example for slaughter house waste production is slaughtering of cattle, as here the amount of slaughter house waste related to meat is highest. Additionally the effort of cattle breeding is higher than other breeding for meat production. The slaughter house waste from cattle slaughtering will therefore, accrue the highest ecological footprint for this product, defining its upper limit of ecological pressure obtained.

Slaughtering of cattle is a two step process. First cattle have to be bred consuming agricultural goods: wheat, soy meal and corn silage. For the agricultural supply chain as well as cattle breeding tractor work, fertilizers, pesticides and energy are needed.

The second step, the slaughtering process itself, consumes energy and the resource water.

Slaughtering of cattle delivers many byproducts next to beef. Meat not suitable for human food applications is used as pet food, hide processed to leather, tallow is used for soap, cooking or biodiesel and the ingredients of the alimentary system are taken as fertilizer. Slaughter house waste on the other hand has to be collected and processed further to meat and bone meal in a rendering facility.

Process infrastructure is not included in the ecological assessment. The assessed process and system boundaries are shown in Figure 7-18.

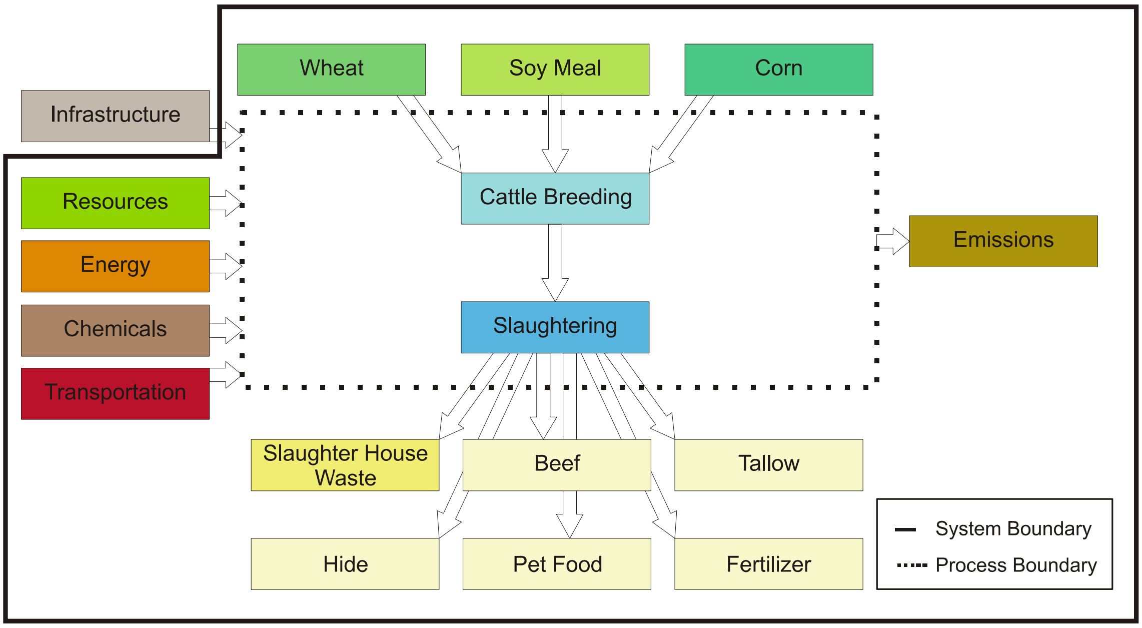


Figure 7-18: Process structure and system boundaries of the ecological assessment of beef production

7.9.C Eco-Inventory

Table 7-13 shows the eco-inventory for the production of 1kg cattle (live weight) and Table 7-14 of 1 kg beef.

Table 7-13: Eco-Inventory for the production of 1kg cattle

Feedstock	Corn Silage	kg/kg	31.500
	Soy Meal	kg/kg	0.700
	Wheat	kg/kg	1.050
Chemicals	Inorganic chemicals	kg/kg	0.007
Energy	Electricity	kWh/kg	0.154
	Extra Light Fuel Oil	MJ/kg	0.033
Transportation	Tractor (<70 kW), light workload	h/kg	0.016

Table 7-14: Eco-Inventory for the production of 1kg beef

Feedstock	Cattle	kg/kg	2.058
Resources	Process Water	m^3/kg	2.495
Energy	Electricity	kWh/kg	0.000
	Natural Gas	MJ/kg	0.206
Emissions	BOD5	kg/kg	0.045
Byproducts	Tallow	kg/kg	0.221
	Pet Food	kg/kg	0.013
	Hide	kg/kg	0.160
	Fertilizer	kg/kg	0.100
	Rendering Materials	kg/kg	0.563

7.9.D Results

Analyzing the ecological pressure along the process steps it can be seen that the supply chain inflicts the highest pressure by far. Inside the process itself cattle breeding cause a higher footprint than slaughtering.

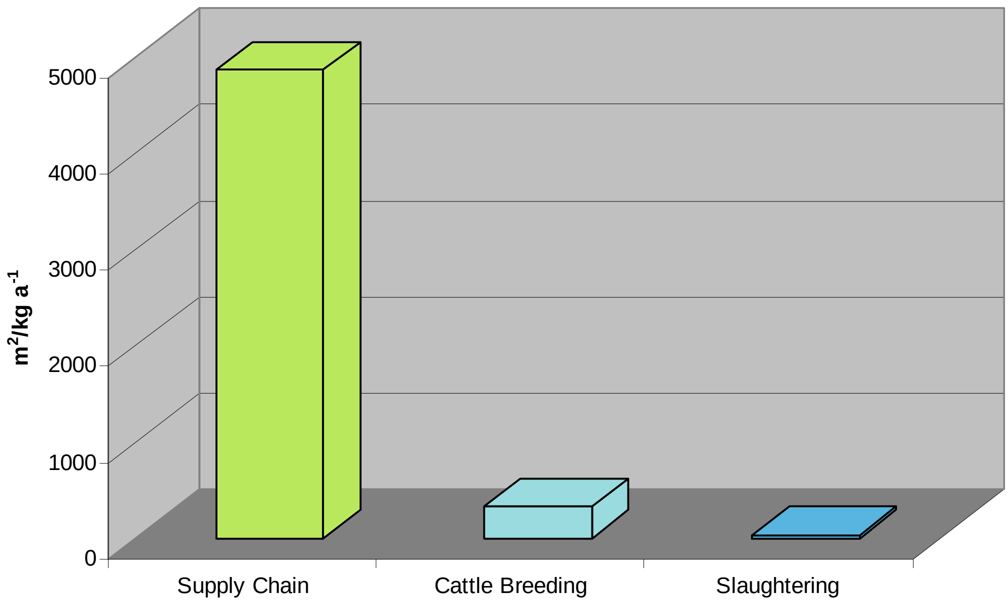


Figure 7-19: The ecological footprint for 1kg beef along the process steps

The slaughter house process results in a process footprint of 6689.74m^2 for 1kg produced beef. Applying price allocation the footprints result in 6176.46 m^2/kg for beef (value 3.60€/kg), 343.14 m^2/kg for tallow (value 0.20€/kg), 2230.39 m^2/kg for pet food (value 1.30€/kg), 2058.82 m^2/kg for hide (value 1.20€/kg), 19.27 m^2/kg for fertilizer (value 0.011€/kg) and 137.25 m^2/kg for slaughter house waste (value 0.08€/kg).

The largest contributor to the ecological footprint is the feedstock for cattle breeding whereas the influence of the input resources, energy and chemicals are negligible (Table 7-13).

Taking a closer look on the distribution of the feedstock it can be seen that mainly the agricultural provision of corn silage inflicts the ecological pressure.

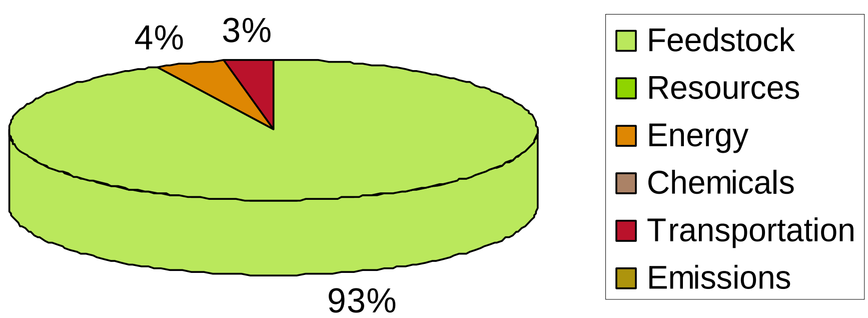


Figure 7-20: Distribution of the ecological footprint of 1kg slaughter house waste with price allocation

7.10 *Meat and Bone Meal*

7.10.A Technical Background

Meat and bone meal (MBM) is a complex substance, a byproduct from rendering industry that obtains tallow from slaughter house waste. MBM consists of about 50% protein, 35% ash, 8-12% fat, and 4-7% moisture. In the past it has been used in Europe to improve the amino acid profile of animal nutrition. At the moment MBM is mostly burned, partly for electricity production (especially in Great Britain), which then is entitled as sustainable electricity from renewable resources.

7.10.B Process

Meat and bone meal is a byproduct derived from slaughter house waste due to a rendering process. As primary product tallow is obtained.

The inputs for rendering are the feedstock slaughter house waste and energy. Transportation demand from slaughter houses to the rendering facility represents an average value for Great Britain. Emissions of non methane volatile organic compounds arise during the process.

Slaughter house waste input comes from cattle slaughtering (see chapter 7.9). Process infrastructure is not included in the ecological assessment. The assessed process and system boundaries are shown in Figure 7-21.

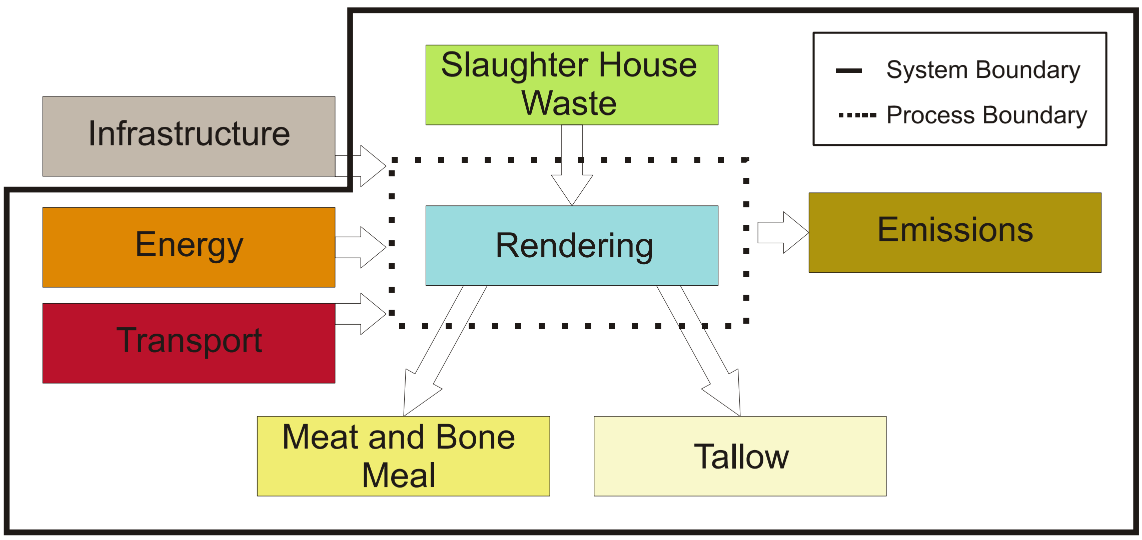


Figure 7-21: Process structure and system boundaries of the ecological assessment of meat and bone meal production

7.10.C Eco-Inventory

Table 7-15 shows the eco-inventory for the production of 1kg meat and bone meal.

Table 7-15: Eco-Inventory for the production of 1kg meat and bone meal

Feedstock	Slaughter House Waste	kg/kg	4.762
Energy	Natural Gas	MJ/kg	2.286
Transportation	16t Truck	tkm/kg	0.084
Emissions	NMVOC (air)	g/kg	0.414
Byproduct	Tallow	kg/kg	1.143

7.10.D Results

The rendering process results in a process footprint of 693.07m^2 per 1kg meat and bone meal. As the value of 0.2€/kg for tallow is the same as for meat and bone meal, mass allocation was applied. The resulting footprint for meat and bone meal as well as tallow is therefore, 323.43m^2/kg product.

Even for this process that uses a great amount of energy the major contributor to the ecological footprint is the feedstock (Figure 7-22). Energy plays a minor role whereas transportation is almost negligible.

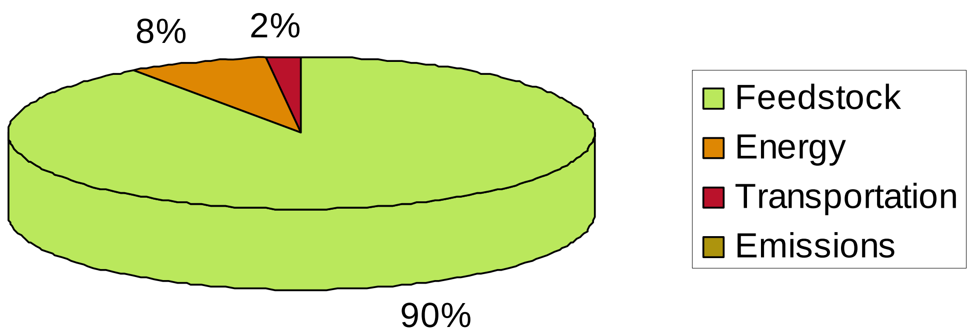


Figure 7-22: Distribution of the ecological footprint of 1kg meat and bone meal

7.11 *Tallow*

Tallow can be obtained either from the slaughtering or rendering process. For details see either chapter 7.9 Slaughter House Waste or chapter 7.10 Meat and Bone Meal.

7.12 *Rapeseed Oil Production*

7.12.A Technical Background

Rapeseeds were cultivated mostly for animal feed and vegetable oil production in the past. As the prices for diesel have increased a great deal in the past years, rapeseed oil has also become an interesting feedstock for biodiesel production. An important fact for this is its low price compared to other readily available vegetable oils. Today rapeseeds are the third most cultivated oil plant behind soy beans and oil palms.

Ripe rapeseeds normally contain about 45% oil, 25% proteins and 25% carbohydrates [43].

7.12.BProcess

The process for producing rapeseed oil can be divided in three steps.

First rapeseeds have to be dried using energy input. Without drying the water content in the obtained oil would be too high. This step also includes transportation of the seeds to the processing facility, calculated for the average European transportation need of rapeseeds.

In the second step the dry rapeseeds are put to an extraction step with hexane. This process step consumes energy and solvent to produce crude vegetable oil and rapeseed pulp for animal feed as byproduct.

In the third step the crude oil is refined to make it stable against oxidation and, in case of intended food application, edible.

Emissions of the process are not assessed because of lack of data. Emissions that arise due to energy usage and transportation are included. Process infrastructure is not included in the ecological assessment. The assessed process and system boundaries are shown in Figure 7-23.

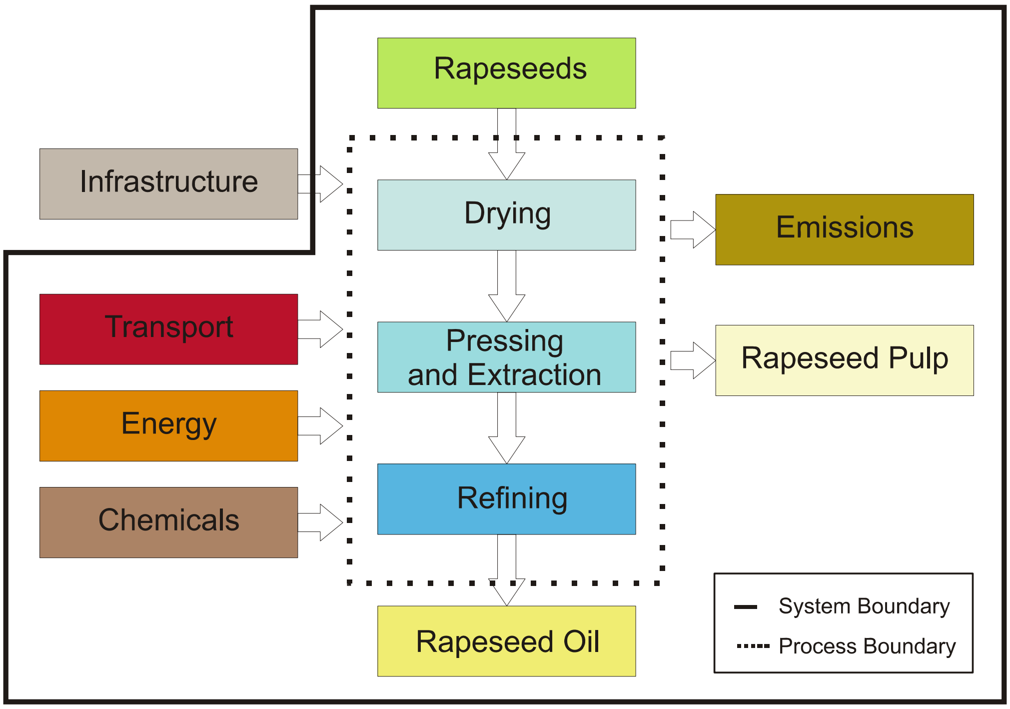


Figure 7-23: Process structure and system boundaries of the ecological assessment of rapeseed oil production

7.12.CEco-Inventory

Table 7-16 shows the eco-inventory for the production of 1kg dry rapeseeds, Table 7-17 of 1kg crude rapeseed oil and Table 7-18 of 1kg refined rapeseed oil.

Table 7-16: Eco-Inventory for the production of 1kg dry rapeseeds

Feedstock	Rapeseeds	kg/kg	1.086
Energy	Electricity	kWh/kg	0.020
	Extra light fuel oil	MJ/kg	0.005
Transportation	Freighter inland waterways	tkm/kg	0.168
	Railway	tkm/kg	0.036
	40t Truck	tkm/kg	0.036

Table 7-17: Eco-Inventory for the production of 1kg crude rapeseed oil

Feedstock	Dried Rapeseed	kg/kg	2.469
Energy	Electricity	kWh/kg	0.085
	Steam	MJ/kg	1.432
Chemicals	Organic chemicals	kg/kg	0.002
Byproducts	Rapeseed Pulp	kg/kg	1.469

Table 7-18: Eco-Inventory for the production of 1kg rapeseeds oil

Feedstock	Crude Rapeseed Oil	kg/kg	1.042
Energy	Electricity	kWh/kg	0.006
	Steam	MJ/kg	0.308
Chemicals	Inorganic chemicals	kg/kg	0.006

7.12.DResults

Taking a look at the influence of the process steps on the resulting process footprint it can be seen that the process itself does not play a major role (Figure 7-24). The main contributor to the ecological pressure of rapeseed oil production is the supply chain for rapeseeds.

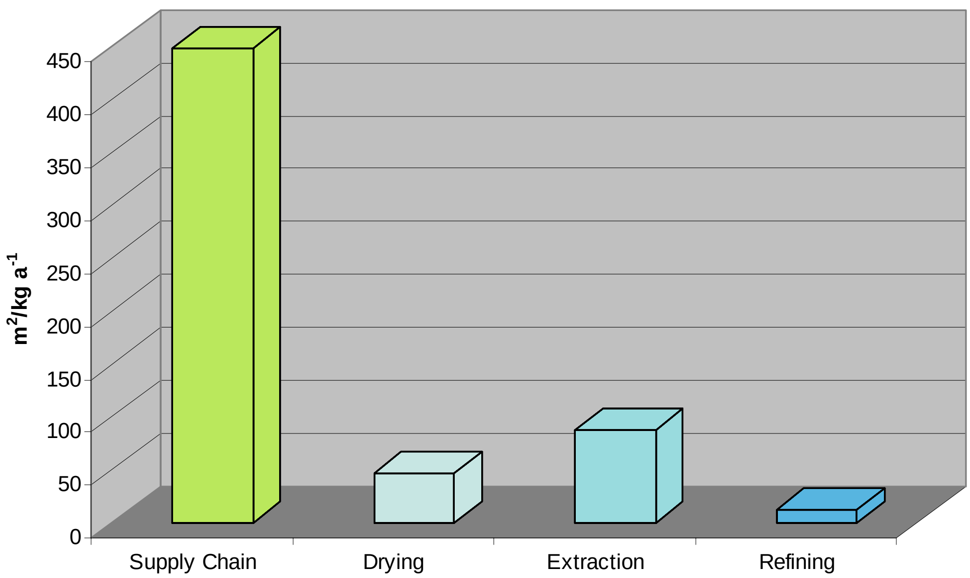


Figure 7-24: The ecological footprint for 1kg rapeseed oil over the process steps

Inside the process the step of oil extraction applies the highest ecological pressure on environment. This is due to the high energy need for reprocessing the extraction solution and separating the crude oil.

Along the production process a process footprint of 802.72m^2 per kg produced rapeseed oil arises. Due to price allocation (crude rapeseed oil 0.96€/kg; rapeseed pulp 0.093€/kg) the resulting footprint of 738.10m^2/kg for refined rapeseed oil and 42.23m^2/kg for rapeseed pulp were obtained.

This footprint is to a large content caused by the feedstock (Figure 7-25). Another important factor is the energy input during the process for drying, extracting and refining. Transportation and chemical input play a minor role.

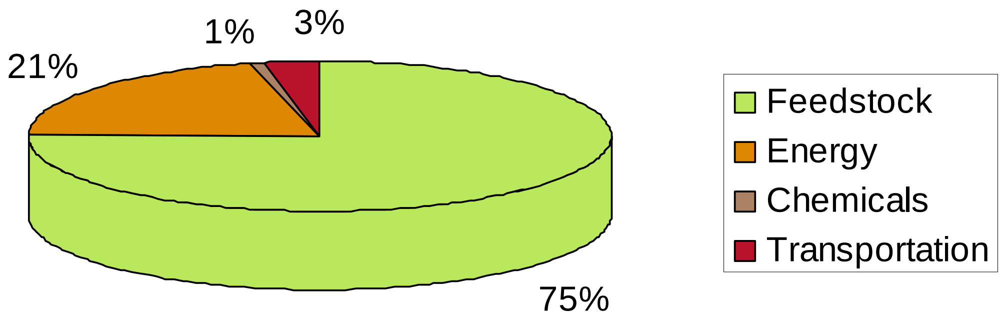


Figure 7-25: Distribution of the ecological footprint of 1kg rapeseed oil

7.13 *False Flax Oil Production*

7.13.A Technical Background

False flax was a major topic of discussion among organic farmers in the last years. False flax is perfectly suited for mixed cultivation and can be grown without any application of fertilizers and pesticides. Although this abdication of conventional agricultural inputs decreases the crop yield, the effort for cultivation decreases too.

False flax contains a high amount of unsaturated fatty acids (>50%) mainly alpha-linoleic acid and linoleic acid. Additionally the oil is very rich on natural antioxidants, making it long term stable under everyday life conditions. These facts added to the interest of directly using false flax oil as engine fuel for cars [44].

7.13.B Process

The process of obtaining false flax oil is not done on large industrial scale. Therefore, no extraction with hexane is applied but false flax seeds are crushed and pressed mechanically.

Before this step false flax is dried. The obtained crude oil is then directly used as engine fuel, false flax pulp can be used as animal feed.

The agricultural production of false flax is done as mixed cultivation with peas. The cultivation was done organically, meaning without fertilizer and pesticide input.

Emissions of the process are not assessed because of lack of data. Emissions for energy usage and transportation are included. Process infrastructure is not included in the ecological assessment. The assessed process and system boundaries are shown in Figure 7-26

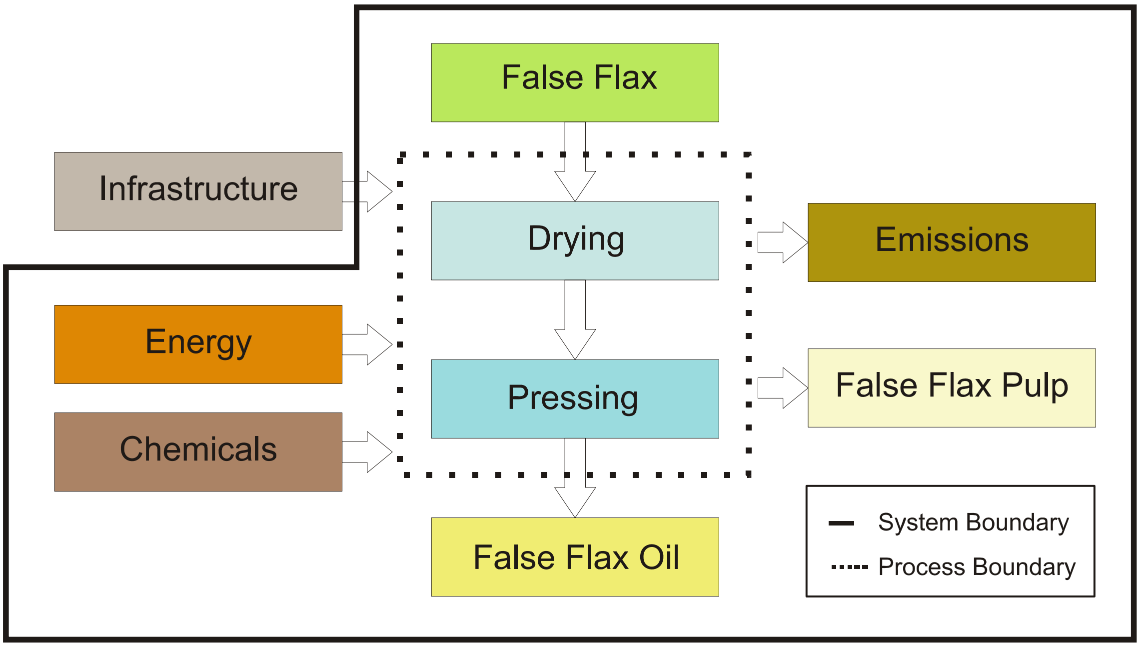


Figure 7-26: Process structure and system boundaries of the ecological assessment of false flax oil production

7.13.CEco-Inventory

Table 7-16 shows the eco-inventory for the production of 1kg dry false flax and Table 7-17 of 1kg false flax oil.

Table 7-19: Eco-Inventory for the production of 1kg dried false flax

Feedstock	False Flax Seeds	kg/kg	1.075
Energy	Electricity	kWh/kg	0.020
	Extra Light Fuel Oil	MJ/kg	0.005

Table 7-20: Eco-Inventory for the production of 1kg false flax oil

Feedstock	Dried False Flax Seed ex Storage	kg/kg	2.802
Energy	Electricity	kWh/kg	0.093
	Extra Light Fuel Oil	MJ/kg	0.936

7.13.DResults

Looking at the ecological pressure inflicted by the process it can be seen that the extraction step accumulates most of the process footprint (Figure 7-27). This is mainly due to the high energy input needed for mechanical extraction of the oil. The supply chain also inflicts considerable footprint, but because of the organic cultivation it is a lot lower than it would be with conventionally cultivated feedstock. Drying still has a distinct influence due to the energy demand.

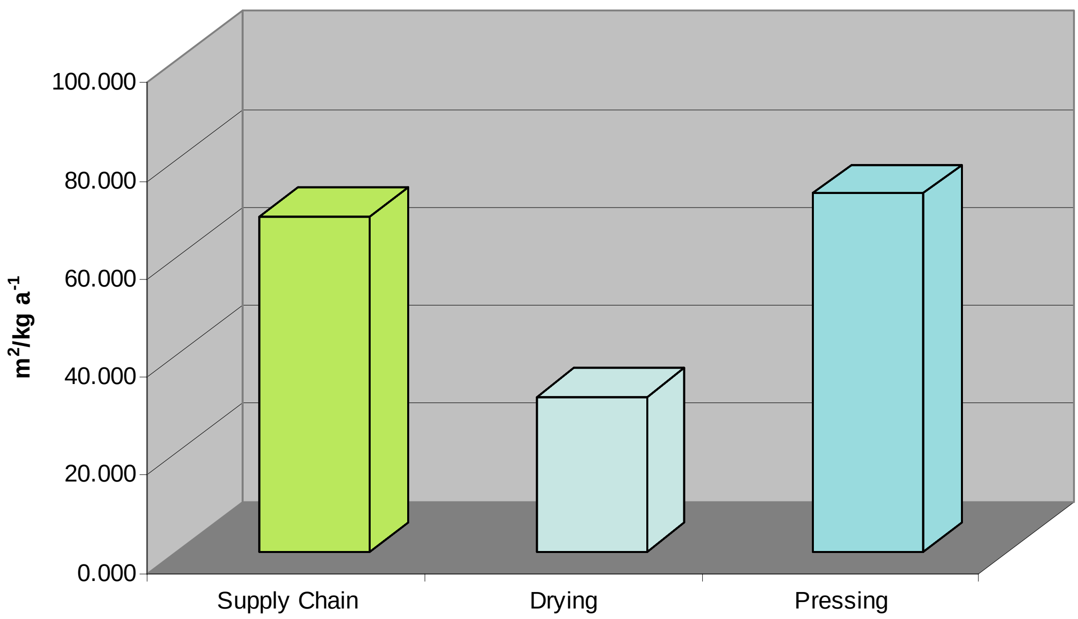


Figure 7-27: The ecological footprint for 1kg produced good over the process steps

The process of producing false flax oil results in a process footprint of 173.11m^2 per kg false flax oil. Applying price allocation (crude false flax oil 0.96€/kg; false flax pulp 0.093€/kg) results in an ecological footprint of 158.95m^2/kg for false flax oil and 9.33m^2/kg false flax pulp.

The high energy input inflicts the largest impact on the ecological footprint (Figure 7-28). Feedstock is high still, but a lot lower than for other processes utilizing agricultural feedstock..

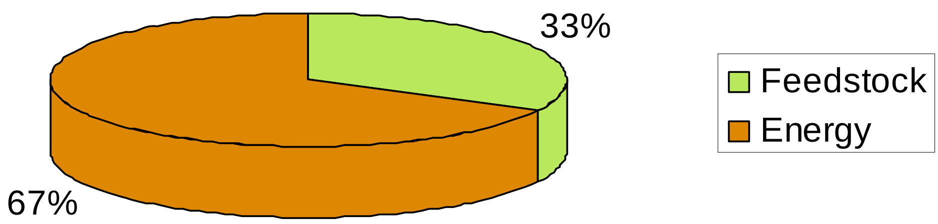


Figure 7-28: Distribution of the ecological footprint of 1kg rapeseed oil

7.14 *Soybean Oil*

7.14.A Technical Background

Soybeans are an important global crop, grown for its oil and protein. The bulk of the crop is solvent extracted for vegetable oil and the defatted soy meal is used for animal feed. A very small proportion of the crop is consumed directly for food by humans.

In the year 2003 30.6 million metric tons of soybean oil was produced worldwide [38]. This constitutes for about half of worldwide edible vegetable oil production and 30% of all fats and oils produced, including animal fats and oils derived from tropical plants.

The major unsaturated fatty acids in soybean oil triglycerides are linolenic acid and oleic acid. Soybean meal remaining after solvent extraction of soybean flakes contains 50% protein content [37].

7.14.B Process

The production process of soybean oil is similar to rapeseed oil. The soybeans are dried and transported to the processing facility. The oil is extracted utilizing hexane and refined in a consecutive step. In the extraction step soybean meal is obtained.

Emissions of the process are not assessed because of lack of data. Emissions for energy usage and transportation are included. Process infrastructure is not included in the ecological assessment. The assessed process and system boundaries are shown in Figure 7-29.

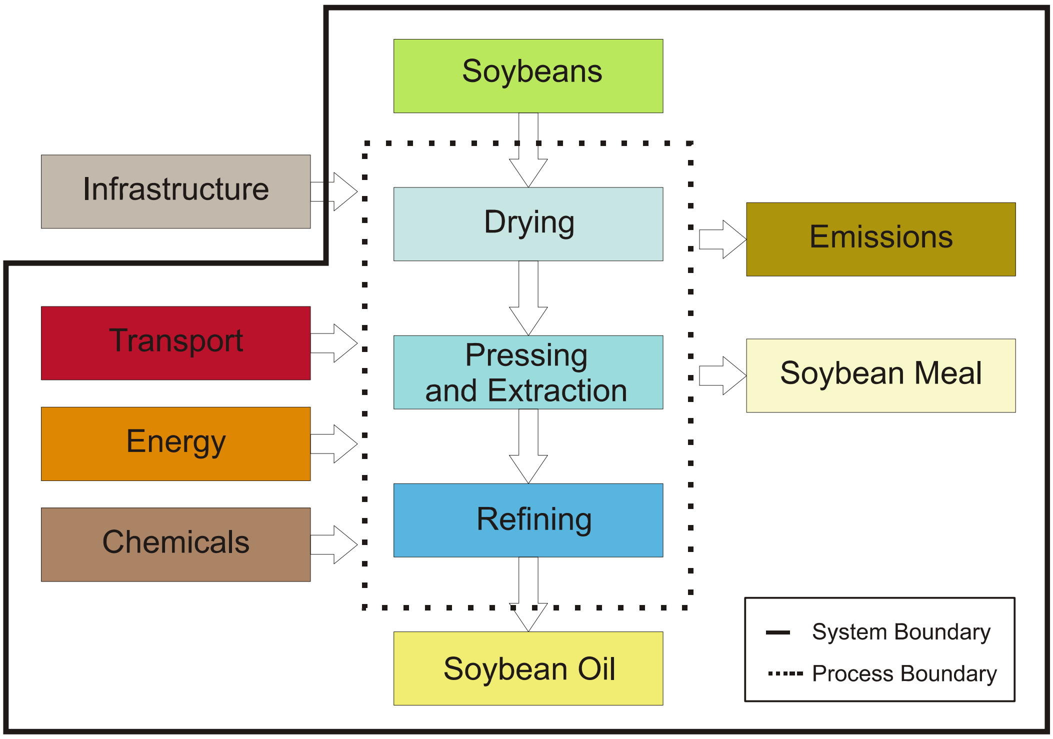


Figure 7-29: Process structure and system boundaries of the ecological assessment of soybean oil production

7.14.CEco-Inventory

Table 7-21 shows the eco-inventory for the production of 1kg dried sunflower seeds ex storage, Table 7-22 for 1kg crude sunflower oil and Table 7-23 for 1kg refined sunflower oil.

Table 7-21: Eco-Inventory for the production of 1kg dried soybeans

Feedstock	Soybeans	kg/kg	1.086
Energy	Electricity	kWh/kg	0.020
	Extra Light Fuel Oil	MJ/kg	0.005
Transportation	Freighter inland waterways	tkm/kg	0.168
	Railway	tkm/kg	0.036
	40t Truck	tkm/kg	0.036

Table 7-22: Eco-Inventory for the production of 1kg crude soybean oil

Feedstock	Dried Soybeans	kg/kg	2.469
Energy	Electricity	kWh/kg	0.085
	Steam production	MJ/kg	1.432
Chemicals	Organic chemicals	kg/kg	0.002
Byproducts	Soybean Pulp	kg/kg	1.469

Table 7-23: Eco-Inventory for the production of 1kg refined soybean oil

Feedstock	Crude Soybean Oil	kg/kg	1.042
Energy	Electricity	kWh/kg	0.006
	Steam production	MJ/kg	0.308
Chemicals	Inorganic chemicals	kg/kg	0.006

7.14.DResults

A look on the accumulation of ecological pressure along the production process shows that the supply chain of soybean cultivation exerts the major part of the overall pressure. Within the process the extraction step contributes the largest part of the ecological footprint. Drying also plays an important role while the refining step does not add much to the overall pressure on environment.

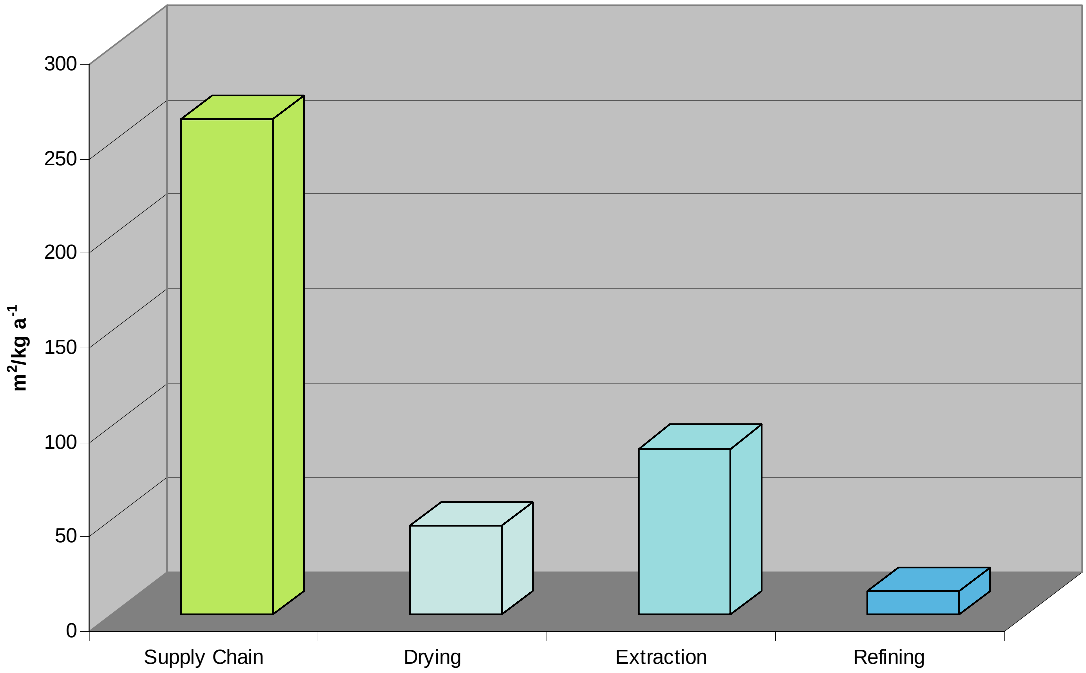


Figure 7-30: The ecological footprint for 1kg produced good over the process steps

The process of soybean oil production obtains a process footprint of 407.81m^2. The price allocation between soybean meal and crude soybean oil (crude soybean oil 0.96€/kg; soybean meal 0.093€/kg) result in an ecological footprint of 21.15m^2/kg a^{-1} for soybean meal and 375.74m^2/kg a^{-1} for refined soybean oil.

Feedstock is the major influencer for this process from an ecological point of view whereas energy also plays an important role. Transportation and chemical influence in comparison are small.

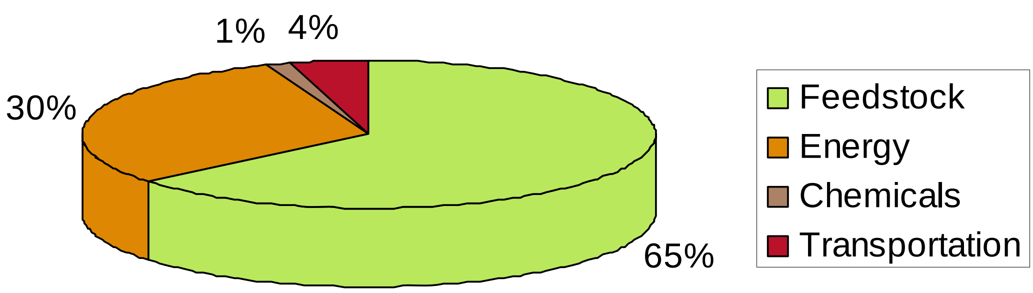


Figure 7-31: Distribution of the ecological footprint of 1kg soybean oil

7.15 *Sunflower Oil*

7.15.A Technical Background

Common use of sunflower seeds is as snacks, especially in Europe, China and the United States and as food for birds. The seeds can also be used directly in cooking and salad.

Extracted from the seeds sunflower oil is a good much more important than the seeds themselves. It is used for cooking, as carrier oil in cosmetic industries and to produce biodiesel. The cake remaining after the seeds have been processed for oil is used as a livestock feed.

7.15.B Process

The process of obtaining sunflower oil follows the same route as for rapeseed oil. First sunflower seeds are dried and transported to the processing facility. Afterwards the oil is extracted with hexane. The obtained crude oil is refined in a third step, the byproduct of the extraction step, sunflower pulp, can be used as animal feed.

Emissions of the process are not assessed because of lack of data. Emissions for energy usage and transportation are included. Process infrastructure is not included in the ecological assessment. The assessed process and system boundaries are shown in Figure 7-32.

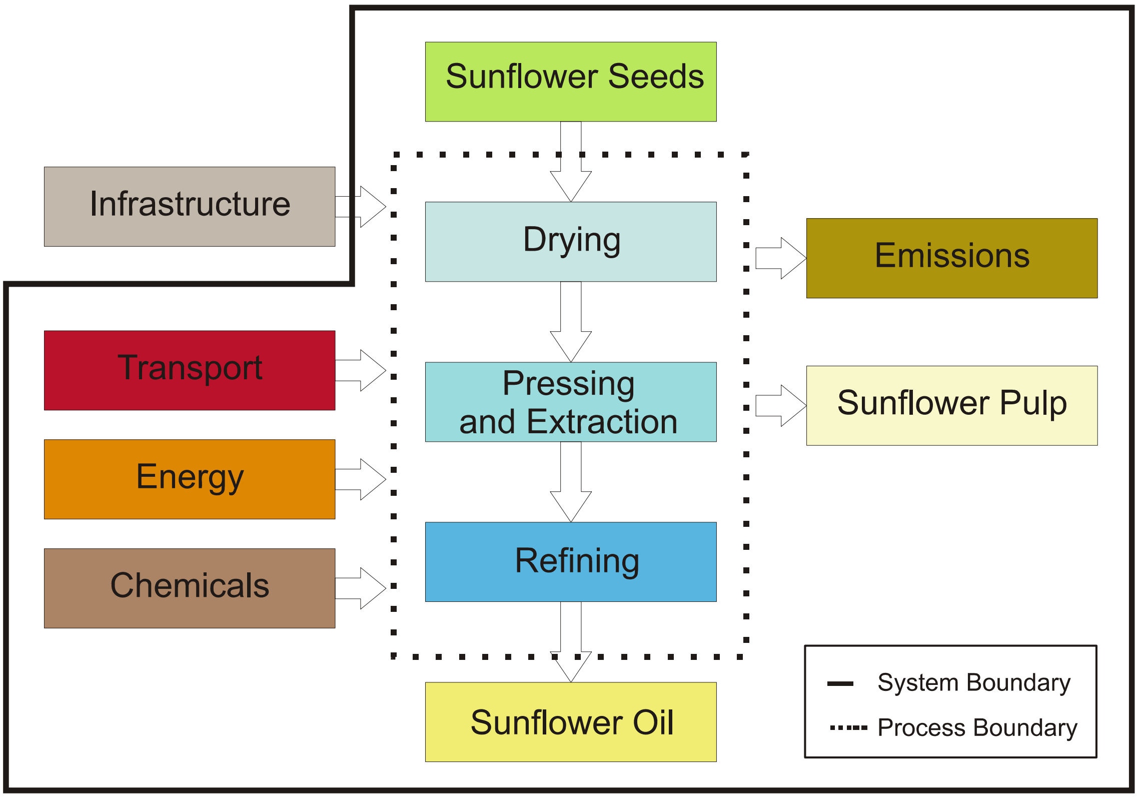


Figure 7-32: Process structure and system boundaries of the ecological assessment of sunflower oil production

7.15.C Eco-Inventory

Table 7-24 shows the eco-inventory for the production of 1kg dried sunflower seeds ex storage, Table 7-25 for 1kg crude sunflower oil and Table 7-26 for 1kg refined sunflower oil.

Table 7-24: Eco-Inventory for the production of 1kg dried sunflower seeds

Feedstock	Sunflower Seeds	kg/kg	1.086
Energy	Electricity	kWh/kg	0.020
	Extra Light Fuel Oil	MJ/kg	0.005
Transportation	Freighter inland waterways	tkm/kg	0.168
	Railway	tkm/kg	0.036
	40t Truck	tkm/kg	0.036

Table 7-25: Eco-Inventory for the production of 1kg crude sunflower oil

Feedstock	Dried Sunflower Seeds	kg/kg	2.469
Energy	Electricity	kWh/kg	0.085
	Steam production	MJ/kg	1.432
Chemicals	Organic chemicals	kg/kg	0.002
Byproducts	Sunflower Seed Pulp	kg/kg	1.469

Table 7-26: Eco-Inventory for the production of 1kg refined sunflower oil

Feedstock	Crude Sunflower Oil	kg/kg	1.042
Energy	Electricity	kWh/kg	0.006
	Steam production	MJ/kg	0.308
Chemicals	Inorganic chemicals	kg/kg	0.006

7.15.D Results

When the ecological pressure obtained by the different process steps is compared it can be seen that the supply chain already exerts the largest amount by its provision. Inside the process chain itself the extraction step plays the major role, followed by drying. The refining of crude sunflower oil does not add much to the process footprint.

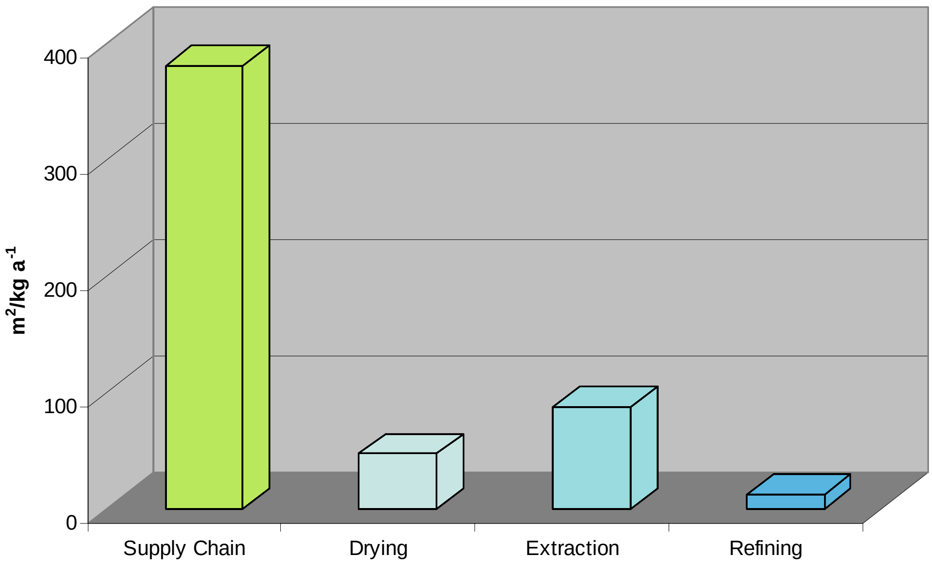


Figure 7-33: The ecological footprint for 1kg produced good over the process steps

The process of sunflower oil production accumulates a process footprint of 526.01m^2. Due to price allocation (crude sunflower oil 0.96€/kg; sunflower pulp 0.093€/kg) an overall footprint of 27.46m^2/kg a^{-1} for sunflower pulp and 484.28m^2/kg a^{-1} for refined sunflower oil is obtained.

The majority of the ecological footprint for sunflower oil is exerted by the feedstock sunflower seeds. The influence of energy is also considerable. This is due to the high energy demand during drying and extraction. Transportation and chemicals only are responsible for small parts of the overall footprint.

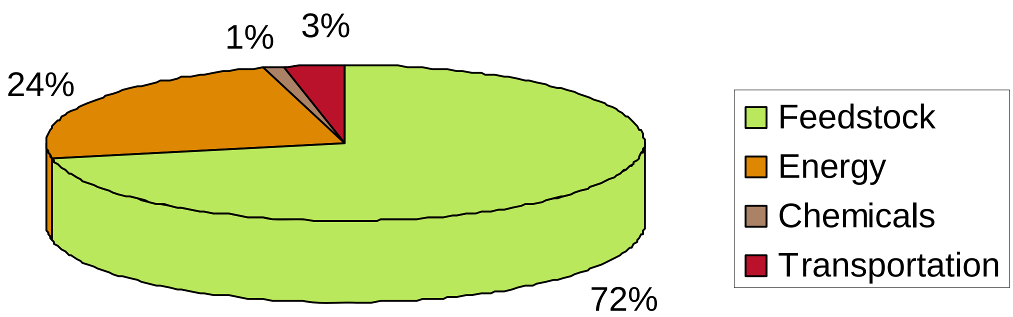


Figure 7-34: Distribution of the ecological footprint of 1kg sunflower oil

7.16 *Crude Oil Europe*

7.16.A Technical Background

Crude oil is the most important feedstock of synthetic industries and plays a major role in our society. The provision of crude oil is a key factor of our economic systems. This provision consists not only on the exploration and production of crude oil but includes also the transportation from the different regions of the world where oil is produced to the refineries. The provision for crude oil displayed here depicts the situation for an European refinery.

7.16.B Process

The process of providing crude oil for a European refinery consists of three process steps.

First oil has to be exploited as not all oil fields are worth of extracting the crude oil. In a second step the crude oil is produced and first refining steps are applied. In a third process step the crude oil has to be transported from its place of origin to a European refinery.

The infrastructure of extracting and providing crude oil are included into the assessment.

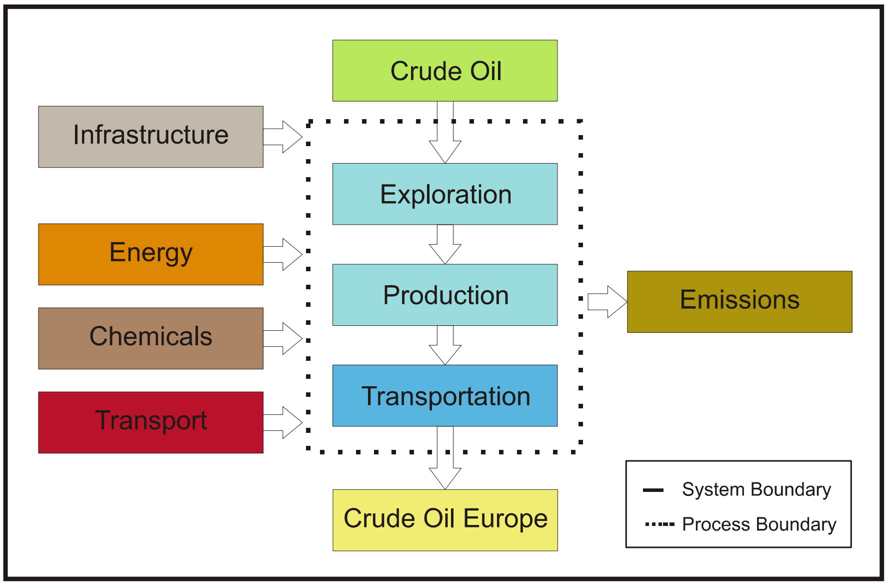


Figure 7-35: Process structure and system boundaries of the ecological assessment of crude oil provision f

7.16.CEco-Inventory

The provision of crude oil for Europe is very complex as the good is produced and transported to Europe from all over the world. A display of the eco-inventory is therefore, not possible. Detailed information about these process steps provides ESU-ETHZ [15].

7.16.DResults

A look on the process chain shows that the extraction of the resource crude oil from ecosphere inflicts the largest part of the ecological pressure. Compared to this, the following process steps play a minor role. Within the process chain the transportation exerts the largest pressure on environment. The production of the crude oil is responsible for a distinctive fraction too. The exploration step accumulates no large pressure on environment compared to the rest.

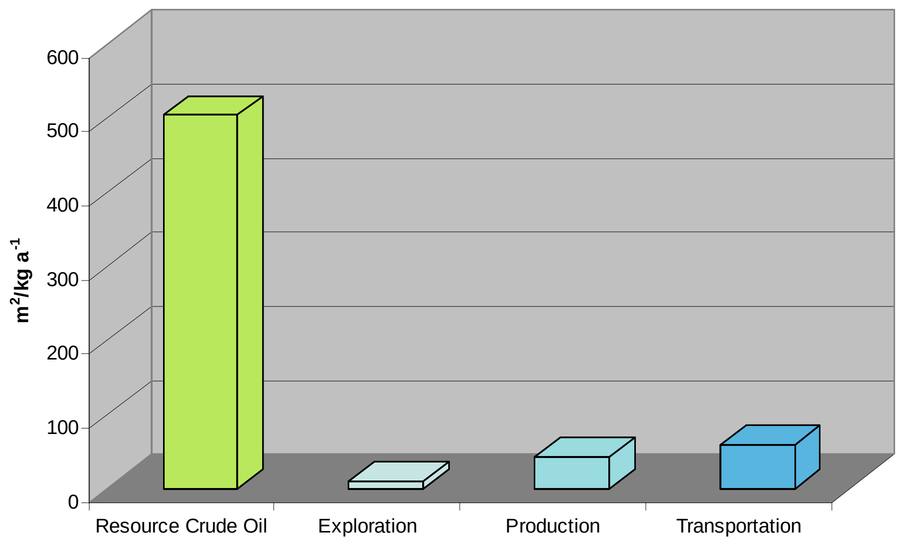


Figure 7-36: The ecological footprint for 1kg produced good over the process steps

The provision process for 1kg crude oil in Europe results in an ecological footprint of 614.40m^2/kg a^{-1}.

The majority of this footprint derives from the depletion of fossil resources, the feedstock of crude oil provision. Energy plays a major role for the environmental pressure too. Transportation and emissions also inflict considerable amounts of pressure whereas chemical input, resources and infrastructure are negligible.

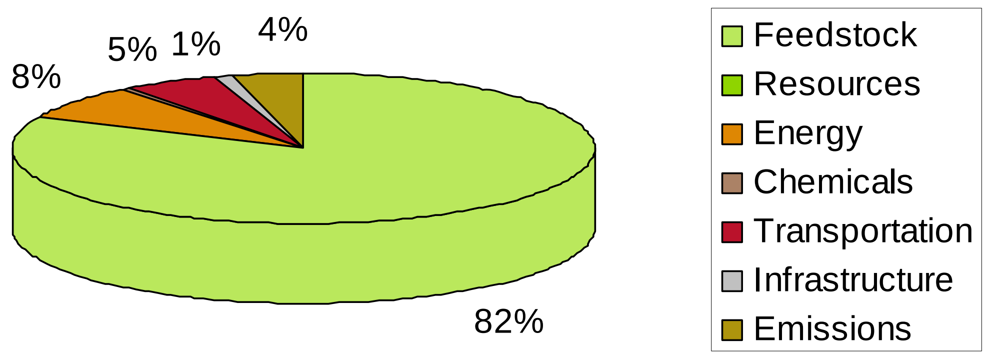


Figure 7-37: Distribution of the ecological footprint of 1kg crude oil provided in Europe

8 Heuristics for Renewable Resources Processes

The previous chapters have shown different processes that derive from renewable resources. Ecological problematic areas of these processes have been identified by evaluation with the SPI. Most prominent among them are energy input, chemicals and feedstock from agricultural production.

This chapter will discuss the role of these factors in a sustainable process and their influence in a sustainable society.

8.1 *Energy*

Energy is in almost all processes the largest contributor to the ecological pressure. However, energy is a very general term summarizing different subcategories. For a better understanding of the ecological implication of energy we have to discern between two energy categories used in industries: electricity and process heat.

Electricity is used mostly for running pumps, agitators and other machinery. Especially biotechnology uses much mechanical energy. Electricity is produced from different sources: nuclear fission, fossil resources like oil or natural gas, coal and renewables like wind, water or biomass. Figure 8-1 shows the distribution of the production methods for electricity for the EU25 countries in the year 2002 [23].

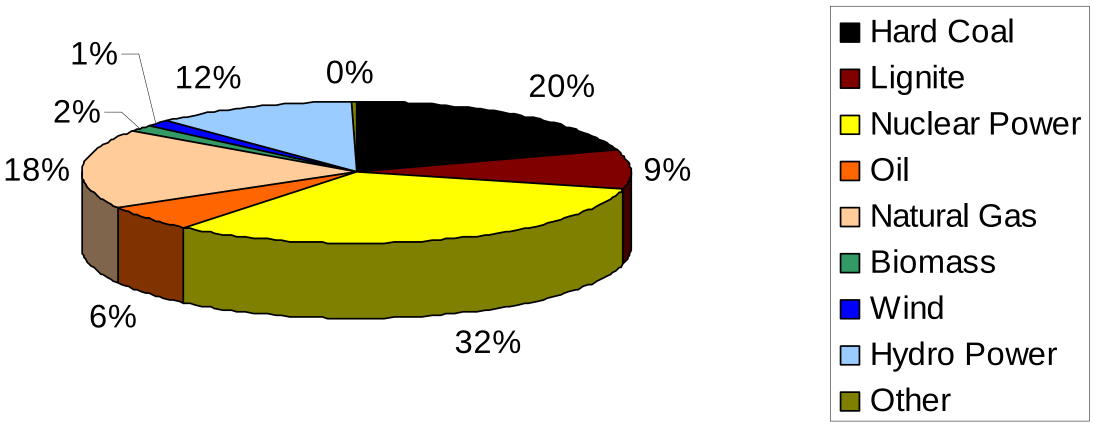


Figure 8-1: Distribution of electricity production for the EU25 countries

Process heat in form of direct heat or steam is often used to maintain elevated temperatures for reactions, for separating processes like distillation or drying. It is mostly produced from hard coal, fuel oil or natural gas.

Figure 8-2 and Figure 8-3 show the contribution of electricity and heat for processes from renewable resources discussed in the Case Studies Chapters. As some processes use the same process data they are shown summarized.

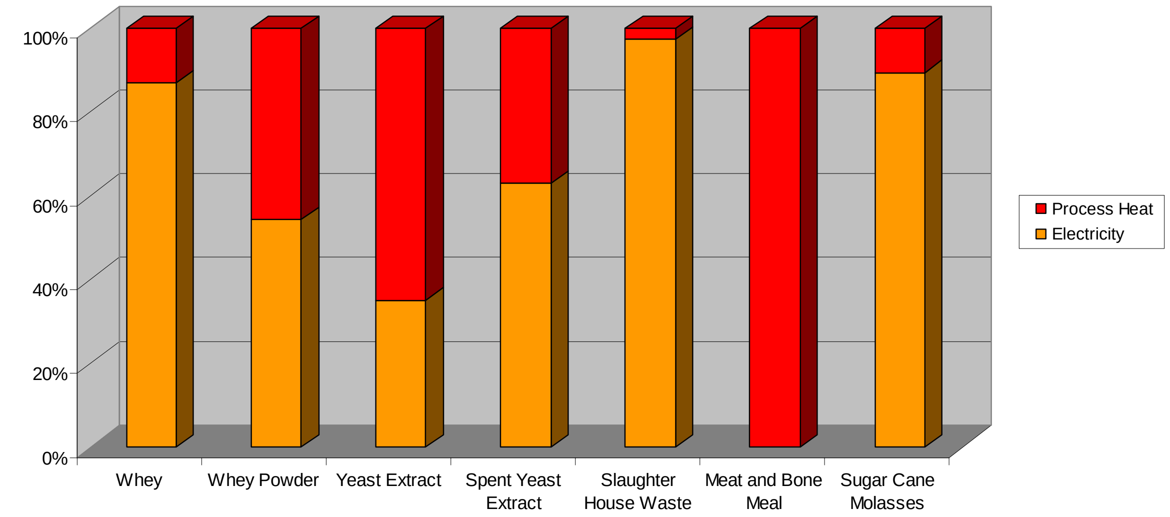


Figure 8-2: Distribution of energy input for production of renewable products 1

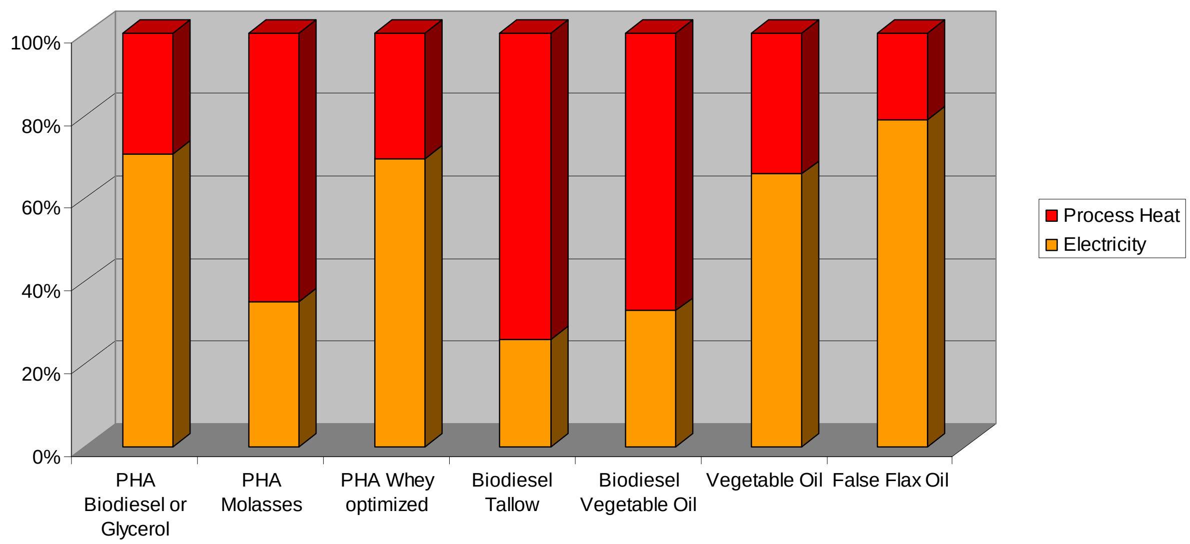


Figure 8-3: Distribution of energy input for production of renewable products 2

It can be seen that in most processes electricity plays a major role. Nonetheless process heat is an important factor, too.

8.1.A Electricity

Electricity is needed in almost all industrial processes, often in large amounts. Nonetheless in most processes it is not seen as critical factor for economical competitiveness. This derives from the fact that electricity is usually a "cheap" input compared to process chemicals and raw material.

Renewable resource based processes seem to be especially electricity intensive. This fact arises on the one hand from the development phase those processes are in as most of them are either in an early development stage or have just been applied in industries in the last couple of years. Such processes are usually not optimized to their full extend yet and even when optimization has taken place, electricity optimization is not a priority. On the other hand renewable resource processing does need inherently more energy than comparable synthetic processes on fossil base. The reason for this is the fact that much more masses have to be processed when dealing with renewables and in case of fermentations this may also take much more time for reacting leading to a higher electricity demand as large fermenters have to be operated for long time.

Different kinds of electricity production cause different ecological pressure. In Figure 8-4 can be seen that the provision systems span a wide range of ecological pressure whereas the renewable electricity production systems lie at the lower end. The ecological footprints of the provision type can be related to its percentage of the electricity mix (Figure 8-1).

It becomes apparent that the provision types that exert the largest pressures on environment are most prominent ones in the electricity mix. The only exception is hydro power that plays a major role in some European countries (e.g. Austria, Norway).

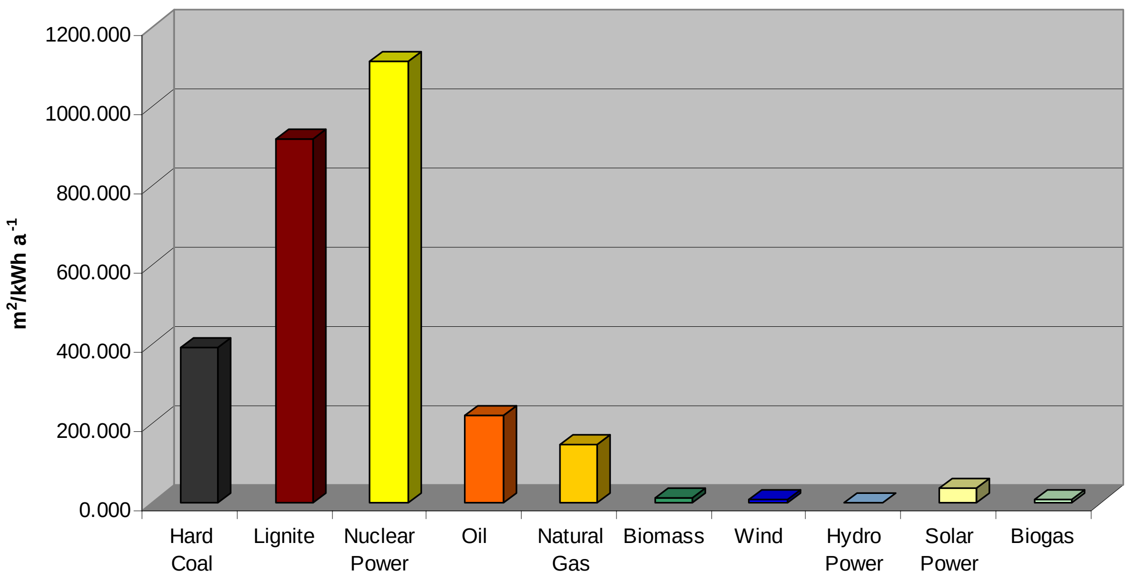


Figure 8-4: Ecological footprints of 1kWh electricity produced by different systems

This fact leads to the conclusion that electricity consumption itself is not the problem. Problematic is the provision of this electricity in the current energy system. That a change to sustainable provision systems is possible was pointed out by different studies, e.g. by Zachhuber [52]. Additionally utilizing a sustainable electricity provision would lead to a further decrease of the environmental pressure as the provision and production systems are iteratively linked. So electricity from biomass would lower the ecological footprint of its biomass feedstock supply chain and vice versa.

8.1.B Process Heat

Concerning process heat the picture is less diverse as heat is almost exclusively produced from fossil resources. Some factories utilize alternative heat production like burning of waste obtained during processing but this currently only covers a small fraction.

As the amount of process heat needed in industries is large optimization is already advanced here. Via heat exchanger lot of energy demand can be saved and the engineering methods for this optimization are commonly known.

8.1.C Energy Change

What can be deducted from these results is the fact that not only the energy consumption of a process itself has to be considered during development of sustainable processes. The energy provision itself will have to change if sustainable industry has to be achieved.

How would the picture change if these energy systems are altered to sustainable systems? In order to estimate such a scenario a sustainable electricity and process heat mix has been assembled consisting only of processes from renewable resources. The mix was selected according to the work of Zachhuber [52]. The data for the energy provision processes was taken from this work too, based on an energy system that is feasible for Austria. Other countries may have different mixes due to Austria's large availability of hydro power. It has to be clarified that these mixes are only assumptions for future energy generation systems and shall only show the potentials of such an energy change for processes based on renewables from an ecological viewpoint.

Electricity is provided by solar power plants, biogas plants and combined heat and power generation plants (cogeneration) besides the traditional processes of hydro, wind and biomass power. The assumed electricity mix is shown in Figure 8-5.

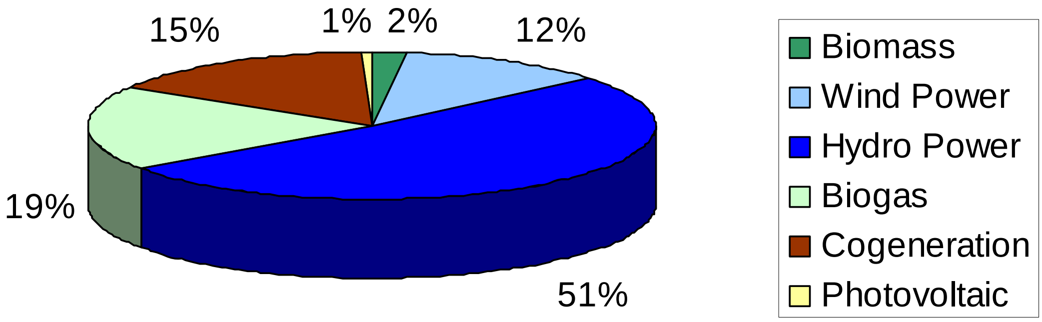


Figure 8-5: Sustainable electricity mix

The ecological footprint for such an electricity mix would be 4.53m^2/kWh a^{-1}. Compared to this the footprint of electricity for the EU25 countries at the moment is 552.95m^2/kWh a^{-1}. This means a change to a sustainable electricity mix would decrease the pressure on environment from this input category by about 99%. The reason for this tremendous decrease is shown in Figure 8-6. Here can be seen that the electricity provision inflicting the largest pressure on environment in this mix, photovoltaic, has only a footprint of 35.06m^2/kWh a^{-1} whereas the least unsustainable electricity generation from fossil resources, natural gas, accumulates 147.65m^2/kWh a^{-1}.

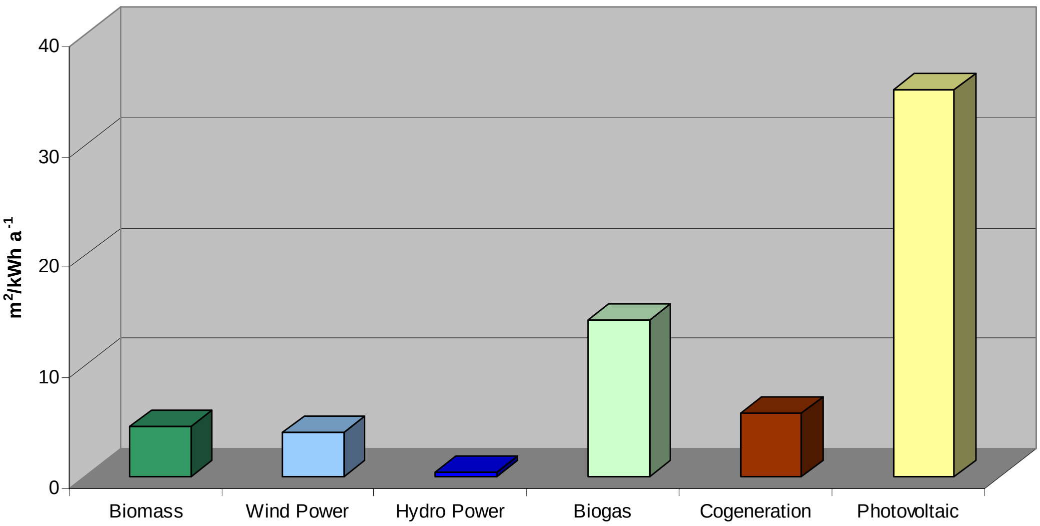


Figure 8-6: Ecological footprints of sustainable electricity provision

In the case of process heat the energy mix assumed is shown in Figure 8-7. Most of the process heat here is provided by thermal utilization of wood chips. The remaining heat demand is covered by cogenerated heat from combined heat and electricity as well as biogas plants.

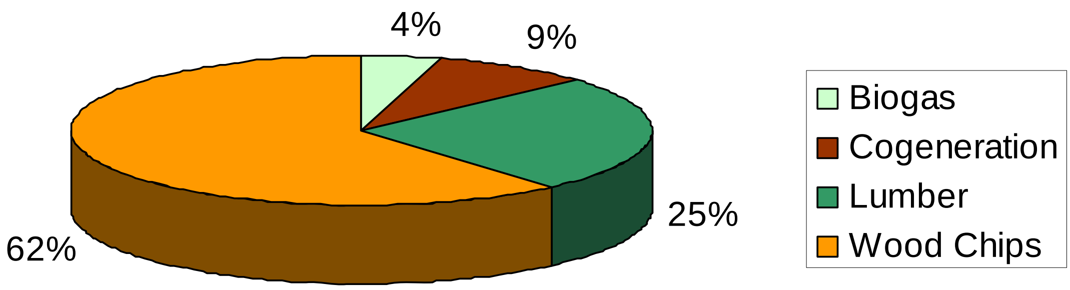


Figure 8-7: Sustainable process heat mix

The ecological footprint of the resulting process heat would be $4.02 m^2/MJ\ a^{-1}$. Comparing this value with the footprints of process heat from fossil resources e.g. $44.45 m^2/MJ\ a^{-1}$ produced from hard coal and $19.58 m^2/MJ\ a^{-1}$ from natural gas a substantial decrease can be achieved. The ecological footprints of the process heat provision systems can be seen in Figure 8-8.

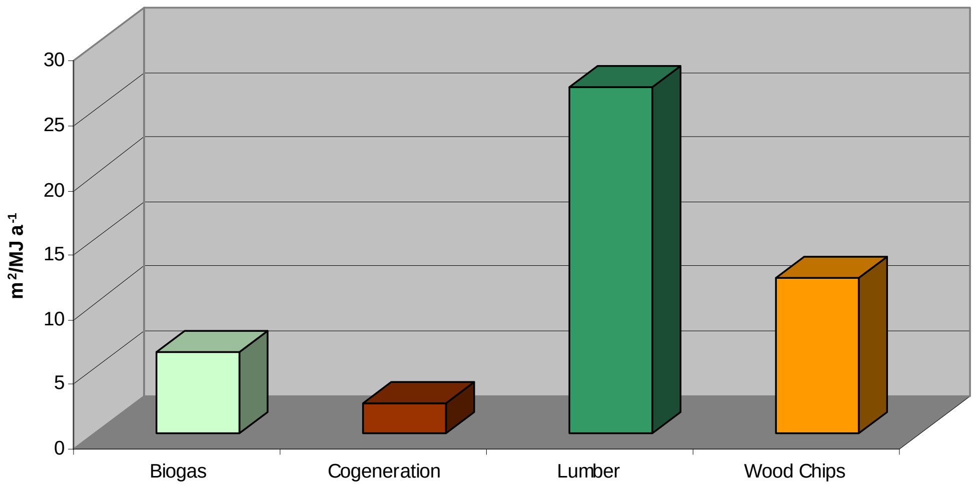


Figure 8-8: Ecological footprints of sustainable heat provision

Comparing the decrease of the pressure on environment for electricity and process heat it strikes out that electricity is able to lessen its footprint much more than process heat. The reason for this is that in the case of process heat the really unsustainable types of energy generation, nuclear power and lignite, are not applied and the still problematic one, hard coal, seldom. So process heat is mostly generated by the combustion of oil or gas, which inflicts relatively low pressure on environment compared to the other types. In electricity generation this trend is just the other way round. Here the "unclean" provision types produce most of the energy.

When this sustainable energy mixes are applied the footprints of renewable based products decrease dramatically leading in all cases to products more sustainable than their fossil counterparts. This holds true even if fossil goods are produced with this sustainable energy mix too, meaning that in this case only the feedstock derives from fossil sources.

The decrease of the ecological footprints can be seen in Figure 8-9 and Figure 8-10.

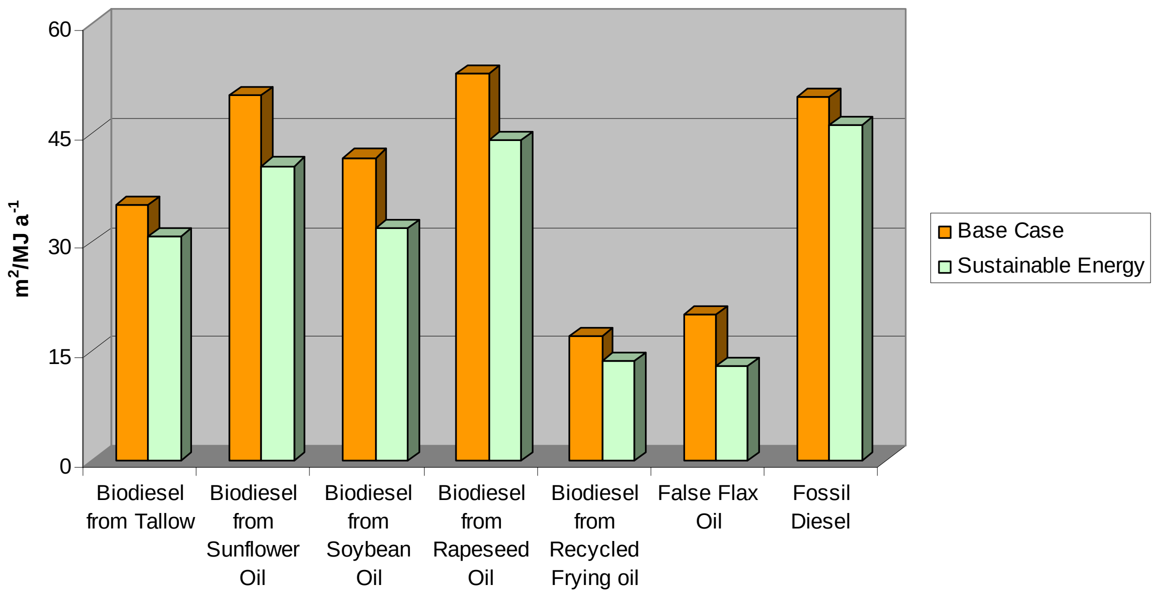


Figure 8-9: Footprints of the Case Study Biodiesel for the base case and sustainable energy

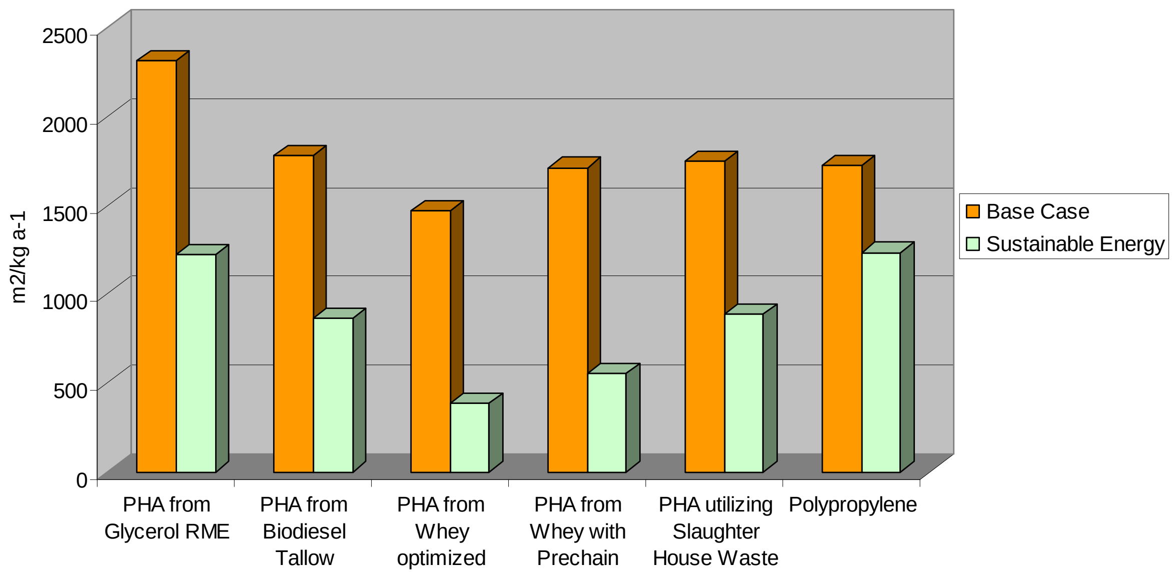


Figure 8-10: Selective footprints of the Case Study Biodiesel for the base case and sustainable energy

In the shown results only the energy input for the processes covered in this thesis were changed to the renewable energy mix. The specific footprints of all intermediates used in this processes are still based on the unsustainable energy mixes reflecting the present situation.

The effect of this will be addressed in the next Chapter.

8.1.D Summary

As was shown the energy provision system has a large influence on processes. This holds especially true for processes from renewable resources as they consume much energy.

The energy consumption of such processes can therefore, be seen as problematic point in renewable processes and has to be regarded already during process development. Nonetheless energy optimization will not suffice as its provision especially for electricity inflicts high pressure on environment. Therefore, energy systems will have to be changed to sustainable energy generation from renewable resources in order to make a step forward on the way to reach sustainable industry.

However, this is a task that process developers do not have the power to influence. This has to be taken up by politics and society in a general way in order to achieve sustainability.

8.2 *Feedstock*

Feedstock also plays a major role for processes from renewable resources. However, this effect does not always arise, depending on the kind of feedstock. If the feedstock is a waste or low value product it does not influence the ecological footprint prominently.

However, many processes utilize feedstock cultivated solely for this process. This cultivation is mainly done by agriculture to a lesser extend by forestry and aquaculture.

8.2.A Agriculture Feedstock

The origin of industrial renewable feedstock is almost always conventional agriculture (except for pulp and paper industry) which inflicts high pressure on environment. To grow agricultural crops with the maximum feasible yield large amounts of fertilizer have to be used as the soil is not able to provide the nutrients needed. This comes from the fact that yield has surpassed the natural biological productivity by far. Additionally farmers often overstrain the soil by cultivating similar agricultural crops successive instead of rotating the cultivated crop in a way that allows the soil to regenerate. That leads to still higher fertilization demand creating a vicious circle especially for monocultures.

Due to large areas in which the same goods are cultivated they are more susceptible for fungal decay and pest. This leads to additional inputs of pesticides in conventional agriculture weakening the capacity of the soil further as benevolent insects and fungi are killed too. The high intensity of cultivation created a high demand of machining mostly in form of agricultural machines like tractors and combine harvesters. This machination need consumes large amounts of (diesel) fuel.

Figure 8-11 and Figure 8-12 show the fraction the agricultural inputs described above hold on the overall footprint of agricultural crops. The data for the production of these goods was taken from Kösslbacher [54]. This diploma thesis is also referred to for more information on the ecological impacts of agriculture.

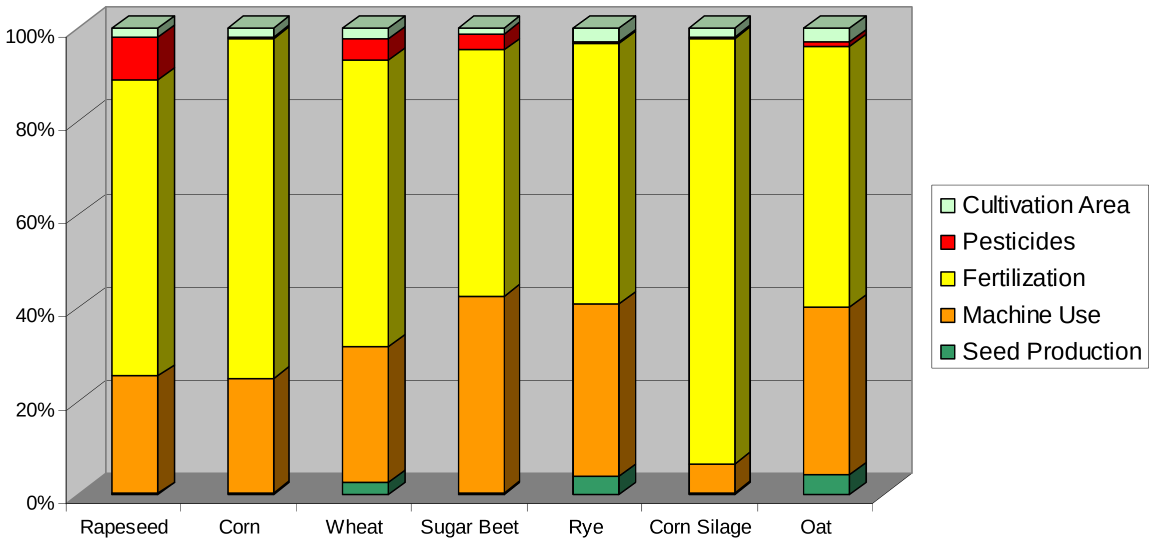


Figure 8-11: Distribution of the ecological footprint along the inputs of conventional cultivation 1

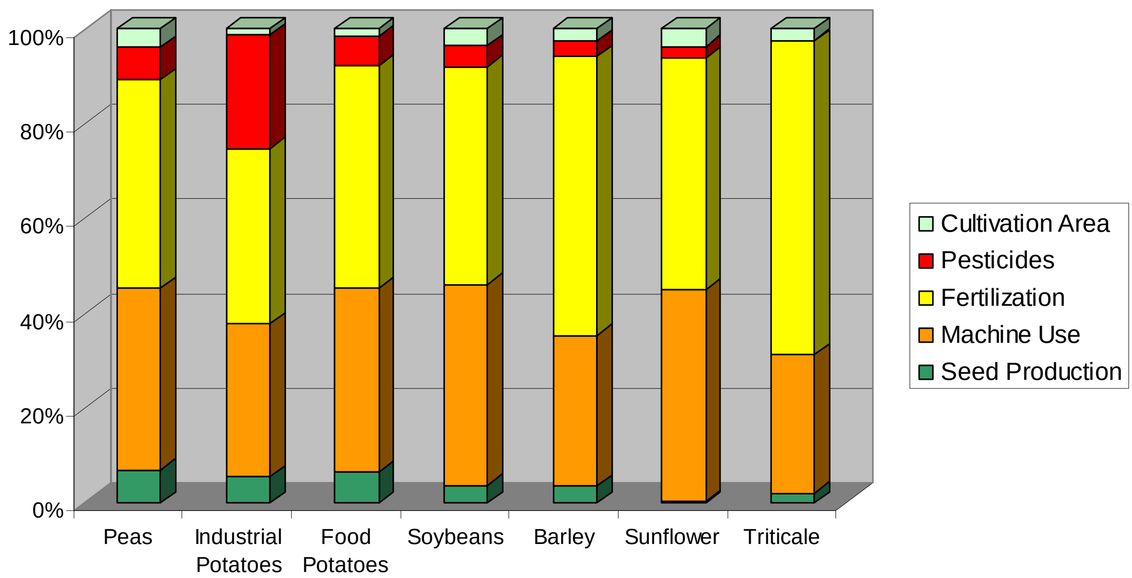


Figure 8-12: Distribution of the ecological footprint along the inputs of conventional cultivation 2

The distribution shows that fertilizer input is the main contributor to the ecological pressure during conventional cultivation. Machine use also inflicts high pressure on environment. Pesticides in contrary don't generally have such a great influence on the environment. The area needed for cultivation and the production of the seeds are small in comparison.

A possibility to lower the pressure on environment is a change in cultivation from conventional practice to organic farming. Organic cultivation means abandoning synthetic fertilizers and pesticides. Figure 8-13 and Figure 8-14 show the footprint distribution of organic cultivation along the input categories.

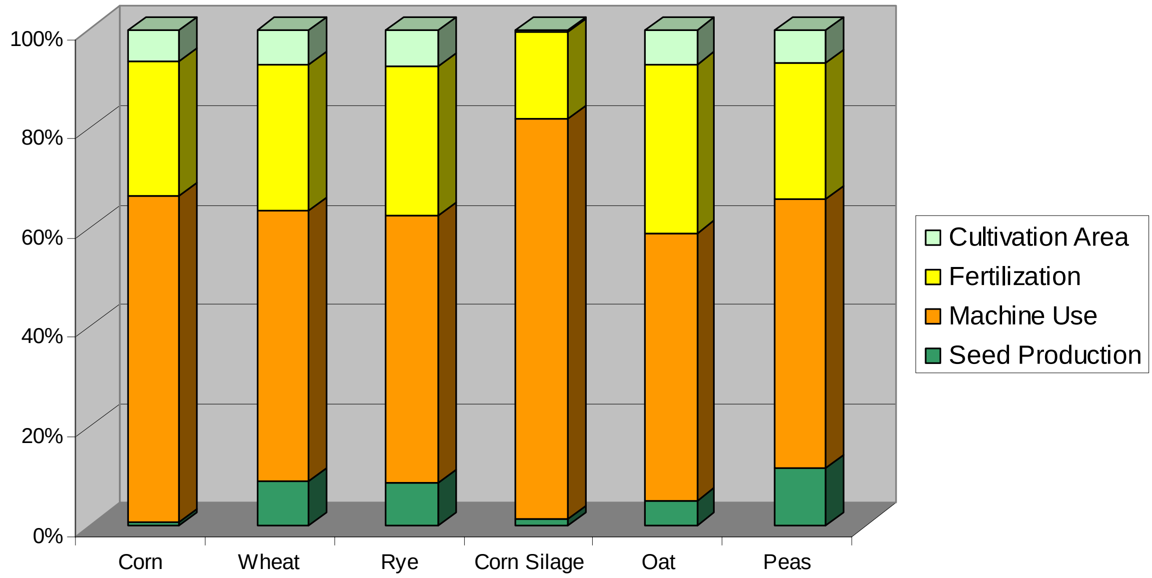


Figure 8-13: Distribution of the ecological footprint along the inputs of organic cultivation 1

When organic cultivation is applied, the ecological footprint decreases and the distribution shifts. This shift is most noticeable in the decrease of the influence of fertilization. That is obtained due to the low fertilizer input allowed in organic cultivation. The largest contributor in organic cultivation due to this shift is the machine use. The influence of seed production rises as the overall footprint decreases and cultivation area plays also a bigger role as organic agriculture has a lower yield and therefore, needs more area per unit of produced good compared to conventional agriculture.

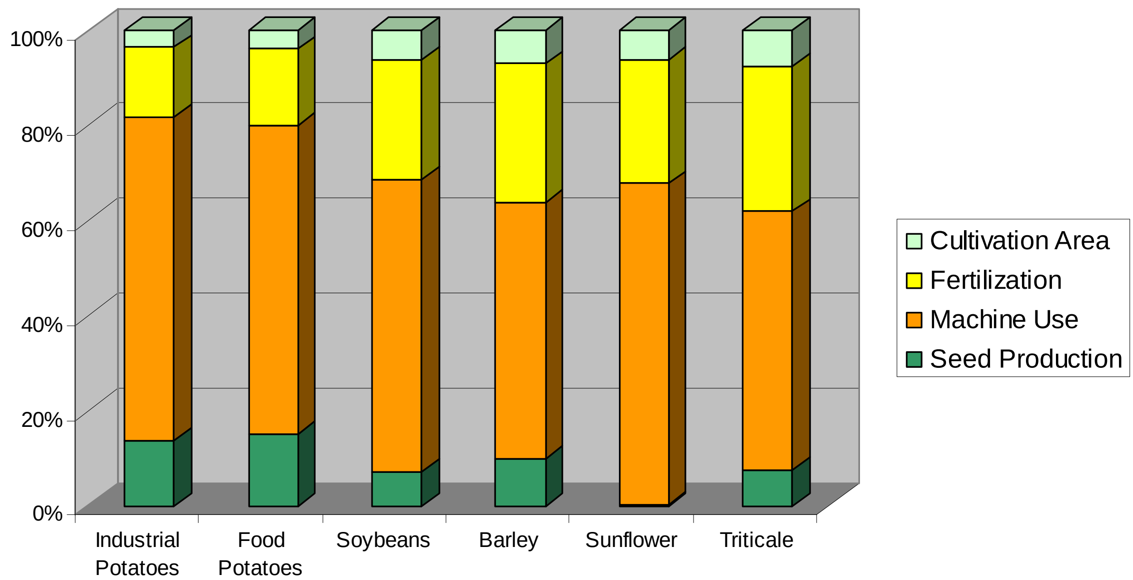


Figure 8-14: Distribution of the ecological footprint along the inputs of organic cultivation 2

The main pressure agricultural machine use exerts on environment is due to the fossil diesel consumption. Therefore, a fuel change would ease the ecological pressure accumulated in agriculture considerably and would benefit especially organic cultivation. To estimate the decrease in the footprint when fossil diesel is replaced in agricultural machines the fuel provision was assumed to be false flax oil. Details for this fuel are described in Chapter 5.7. The change of fuel leads to a decrease of 60% in the area of machine use and therefore, lowers the ecological footprint substantially. Figure 8-15 and Figure 8-16 show the decrease from conventional agriculture to organic agriculture and organic agriculture utilizing false flax oil as feedstock.

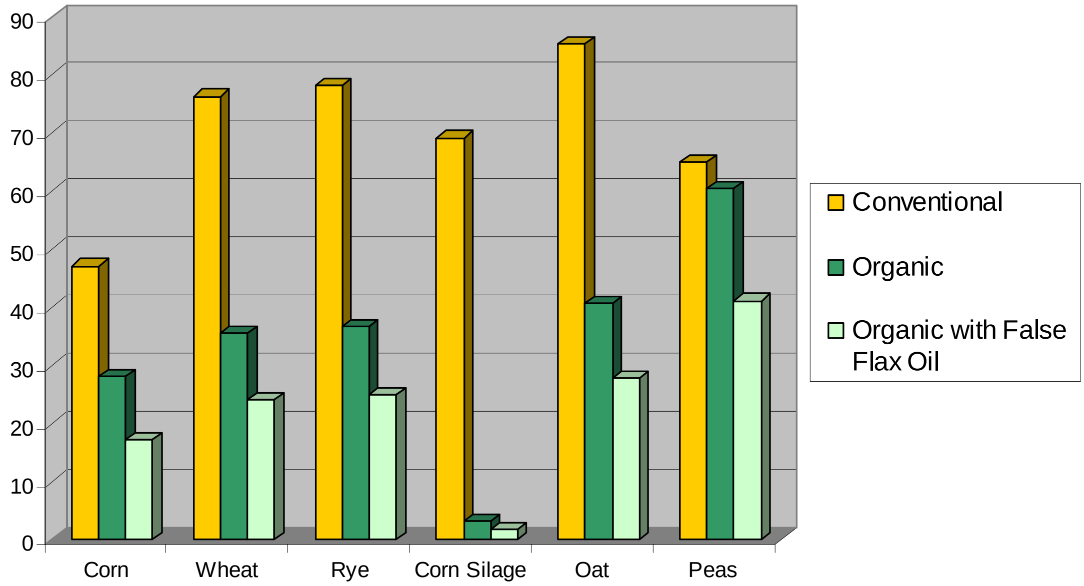


Figure 8-15: Decrease of the ecological footprint utilizing different cultivation methods 1

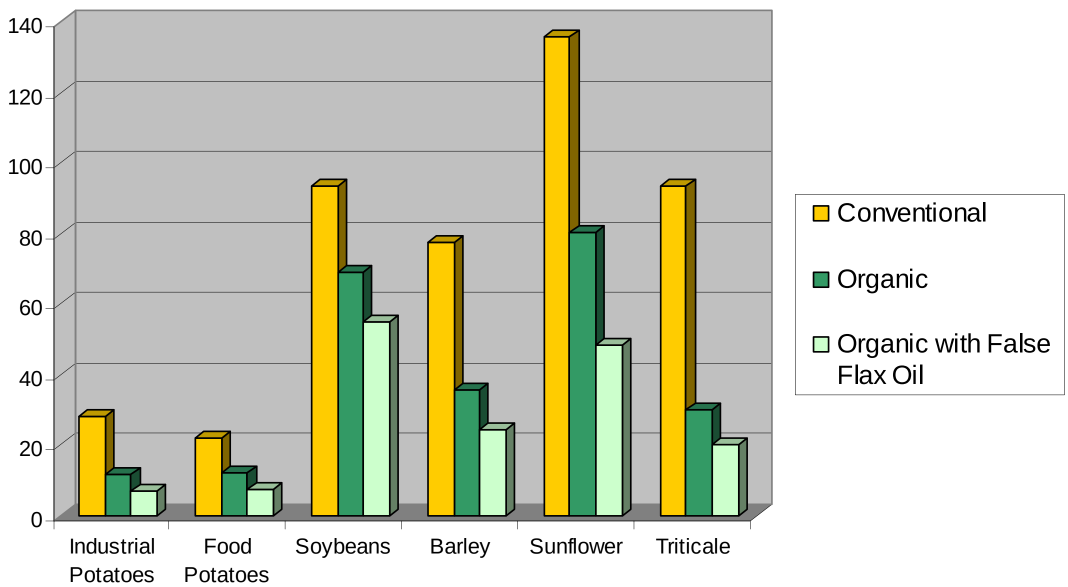


Figure 8-16: Decrease of the ecological footprint utilizing different cultivation methods 2

In some cases this must be calculated in an iterative manner as the product of a process and feedstock production may be linked together. Utilizing organically grown sunflower seed for biodiesel production would lead to a more sustainable biodiesel. Applying this in agriculture would lead to a more sustainable sunflower cultivation and so on.

8.2.B Summary

Agricultural feedstock has a big influence on a process if the feedstock is cultivated solely for the process. Therefore, the selection of this feedstock and its provision has to be done carefully. Preferably organic cultivation should to be chosen or else cultivation with as low fertilizer input as possible.

With cultivation comes a high demand on machine use. This cannot be reduced much even in organic cultivation. What can be done is to apply renewable fuels to agriculture machinery. This could be vegetable oils or biodiesel. However, as has been shown in Chapter 5 Case Study Biodiesel the selection of such a biofuel has to be done carefully.

A further possibility is semi-natural agriculture which does not apply any fertilization and reduces machinery input to a minimum. Further information on this are provided by Braun [55].

8.3 *Chemicals*

Chemicals may be a problematic factor from an ecological point of view. Some processes like the transesterification processes in biodiesel production utilize large amounts of chemicals (in the processes in question methanol). As this methanol is produced from fossil resources which inflict large pressure on environment and is utilized in large amounts the resulting partial footprint has a large influence on the overall footprint.

In such cases the chemical input plays an important role. Here process developers will have to minimize the input need and additionally look for more sustainable alternatives of process chemicals. In case of methanol this could be bio-methanol obtained from fermentation processes or gasification of biomass. Such change in the provision system of chemicals will lead to a decrease that can be substantial and ensure ecological sustainability.

As no data was available for production of bio-methanol assumptions for a comparison have to be made. These assumptions will lead to very rough results but they point out the alteration of the ecological pressure that can be expected of a chemical input change. Therefore, it is assumed that the bio-methanol can be substituted by bio-ethanol for first estimations. The data for bio-ethanol production comes from EdZ [53]. For the energy input biogas was utilized.

The production of bio-ethanol results in a footprint of 206,23$m^2/kg\ a^{-1}$. The ecological footprint of fossil methanol is 543.42$m^2/kg\ a^{-1}$. If bio-ethanol is applied to the transesterification step instead of fossil methanol the overall well to wheel footprint of engine output utilizing biodiesel from rape seed oil decreases to 51.05$m^2/MJ\ a^{-1}$. This is a decrease of 4%.

This shows that the change as well as an optimization of the chemical input of a process will not lead to a reduction of the footprint on the same scale as the energy and feedstock inputs.

8.4 *Conclusions*

Three major factors contribute to the ecological pressure of processes from renewable resources. These are energy, agricultural feedstock and chemicals.

Of these three chemicals usually have the smallest influence. A change in chemicals may lead to a decrease of the overall ecological footprint of the obtained product. However, this decrease tends to be small.

Agricultural feedstock has a much larger influence on the sustainability of a process. The kind of cultivation plays a major role. In conventional agriculture the input of fertilizer and the extensive use of agricultural machines exert a high pressure in the supply chain of the process feedstock. This pressure can be decreased by applying alternative cultivation methods like organic or semi-natural farming. Additionally the commonly used synthetic fertilizers can be substituted by organic ones. A further step towards sustainable cultivation is the substitution of fossil fuel used by agricultural machines. Vegetable oils can be utilized leading to a still lower footprint.

Energy is the most prominent of the three factors from an ecological point of view. Especially electricity provision is presently unsustainable. The potential decrease of the ecological footprint of almost all processes (even those utilizing fossil resources) by sustainable electricity provision is tremendous. Due to these facts engineers are required to optimize the energy consumptions of processes early in development. However, the increase of sustainability engineers are able to achieve in this area is limited as they depend on the provision systems.

8.5 *Heuristics*

Summarizing the work done in this thesis the following heuristics regarding process development for renewable resources can be stated:

- Processes from renewable resources are not inherently more sustainable than their fossil counterparts. Therefore, a process has to be assessed already during development phase.
- Energy consumption, especially electricity need, is a major factor for sustainability of the process. This factor is not only related to the amount of energy utilized by the process but also by the manner of its provision. The more sustainable energy is provided the less influence this input will have.

- Feedstock has to be chosen carefully as it may shift a process from superiority compared to fossil alternatives to inferiority from a sustainable viewpoint. If possible the feedstock should be a waste or surplus material. Such utilization will not only increase sustainability of the process but of the whole system as waste materials are reintegrated in anthropogenic material cycles and processed to value products.
- If the feedstock is from agriculture it is preferable to cultivate it organically or even semi-natural. Conventionally grown feedstock inflicts large environmental pressures already by its provision and will burden each following process step.
- The role of chemicals for sustainability varies from process to process. If chemicals can be derived from renewable resources they should be favored. Other issues like energy optimization and careful selection of the feedstock should be treated first by process developers.
- Processes from renewable resources exert most ecological benefit when embedded in sustainable systems (e.g. for energy provision) as the contribution of the process itself in reaching sustainability is limited by its industrial surroundings.

9 Review of the Working Hypotheses

In this chapter the working hypotheses have to be reviewed in the light of the results obtained.

- ***Hypothesis 1:*** *Processes from renewable resources are inherently more sustainable than processes from fossil ones.*
  As has been seen in the case studies in the current thesis as well as published by others [14] processes from renewable resources are not inherently more sustainable. Sustainability depends on many different factors which are not always optimal for such processes, especially when they constitute from new technologies. Ecological assessment can identify ecological problematic aspects and dead ends for a process utilizing renewable resources and help to ensure its sustainability.
- ***Hypothesis 2:*** *Switching from fossil to renewable feedstock without further changing the structure of economy will lead to sustainable industry.*
  The change of feedstock may decrease the environmental pressure exerted by industries. This may not be the case for all processes as hypothesis one does not hold true. Nonetheless a decrease may be accomplished. However, the goal of reaching sustainable industry will not be achieved if only feedstock of industrial processes is changed. This can only be realized by changing the whole economic system that industry is based on. An important factor in this plays energy provision, especially electricity production. Without including these industrial sectors in the change sustainability will not occur.
- ***Hypothesis 3:*** *Process development plays a major role in ensuring the sustainability of processes from renewable resources.*
  Process developers are in a key position regarding the sustainability of the process itself. They are able to ensure that a process exerts as small as possible a pressure on the environment. This can be done by choosing more sustainable process alternatives and optimizing the process from an ecological point of view already during development phase. However, process developers are dependent from the provision systems available. As these provision systems are mostly not sustainable engineers will be limited in developing sustainable processes.

- ***Hypothesis 4:*** *Ecological assessment during process development is the perfect tool to ensure sustainable processes.*

  With rough mass and energy balances which are available already in an early development stage ecological assessment can be carried out. This phase is optimal for changes in process design from an ecological point of view. Processes can be changed most easily during development phase as the effort of time and money for these changes is lowest. As has been shown in this thesis ecological assessment is able to identify problematic aspects that exert pressure on environment. Process developers may then change processes accordingly. When ecological evaluation is done not until the process is already on the market the costs for change almost always outbalance ecological concerns.

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