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Comparative Normative Analysis of Sustainability Measurement methods

DOCTORAL THESIS

MSc

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To

The most Kindhearted Person in my life

Muhammad Ramzan . . . . . My Father

The most Elegant and Respectable Woman ever met

Basheeran Begum . . . . . My Mother

The most Supportive, Inspiring and Motivating Personalities Who are always there to help me whenever needed …. My Siblings

&

The Last but not least the most Dazzling Lady I ever met

Bokhena Zafar . . . . . My Wife.

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Khurram Shahzad
Graz, Austria.

Declaration

This dissertation is submitted to the Institute of Process and Particle Engineering, Graz University of Technology, Graz, Austria, in partial fulfillment of the requirement for the degree of Doctor of Technical Sciences.

The thesis is entitled:

Comparative Normative Analysis of Sustainability Measurement methods

written by Khurram Shahzad and has been approved by the Institute of Process and Particle Engineering, Graz University of Technology, Graz, Austria.

The final copy of this thesis has been examined by the under signed authority, and find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

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Univ.-Prof. Dipl.-Ing. Dr.techn. Michael Narodoslawsky

Date ________________________

ABSTRACT

Sustainability is a well-recognized paradigm influencing future developmental policies and regulations at government as well as intergovernmental level. It is considered as a model consisting of three main pillars of a society, namely economic, environment and social aspects. It is normally represented by three intersecting circles representing each one aspect of sustainability. In other words sustainability means development of human well-being in accordance to the recognition of the fact of one diverse but ultimately finite planet. It is becoming challenging For decision makers, how to fulfil human demand while operating within limits of nature to attain the sustainability. This requires both the effective management of human demands as well as natural capital, while living within its ability to renew itself. In order to achieve this task, reliable measurement tools comparing the supply of natural income with human demand on it are crucial. These tools help decision makers to track progress, set targets and make policies to attain sustainability.

Three objectives will be addressed by evaluation of an industrial process, utilizing four different sustainability measurement methodologies namely Carbon Footprint, Sustainable Process Index (SPI), Emergy accounting and Material Input Per unit Service (MIPS). These objectives include, verification of normative background of these measures, figuring out main environmental factors highlighted by the measure using process case study and investigation, if the results of each method really reflect its normative background.

The motivation of this thesis is to find out similarities and dissimilarities between these methodologies and help decision makers to choose suitable methodology for evaluation. The sustainability of a biopolymer polyhydroxyalkanoate (PHA) production from slaughtering waste residue as a starting material, is evaluated by applying given sustainability methods. The effect of change of energy resources from business as usual (i.e. Electricity mix from the grid and heat provision utilizing natural gas) to different renewable energy resources has also been evaluated.

Abstract

Nachhaltigkeit ist ein weltweit anerkanntes Paradigma das einen starken Einfluss auf zukünftige Entscheidungen von Regierungen sowohl auf nationaler Ebene als auch auf internationaler Ebene hat. Es wird als ein 3 Säulen Modell betrachtet, das sich aus Wirtschaftlichkeit, Umweltverträglichkeit und den sozialen Aspekten der Gesellschaft aufbaut. Diese Bereiche werden normalerweise durch 3 überlappende Kreise definiert, wobei jeder einzelne Kreis einen Aspekt der Nachhaltigkeit repräsentiert. In anderen Worten bedeutet Nachhaltigkeit Entwicklung des menschlichen Wohlbefindens in Betrachtung eines unterschiedlichen aber endlichen Planeten. Für unternehmerisch denkende Weltbürger steigt die Herausforderung, einerseits menschliche Bedürfnisse zu befriedigen und andererseits innerhalb der Nachhaltigkeitskriterien zu operieren. Um die Kriterien zu erfüllen wird sowohl ein effizient, Management der Bedürfnisbefriedigung als auch die natürliche erneuerbare Ressourcen benötigt. Um diese Aufgaben zu erfüllen sind verlässliche Messinstrumente entscheidend die das natürliche Angebot mit der Nachfrage vergleichen können.

Am Beispiel der Evaluierung eines industriellen Prozesses werden die folgende 4 Nachhaltigkeitsmethoden Carbon Footprint, Sustainable Process Index (SPI), Emergy accounting und Material Input Per unit Service (MIPS) diskutiern. Die Ziele der Arbeit inkludieren sowohl die Bestimmung des normgebenden Ursprungs dieser Messinstrumente als auch die Bestimmung der Umweltaspekte die durch Fallstudien hervorgehoben werden.

Die Motivation dieser Doktorarbeit ist die Ermittlung der Gemeinsamkeiten und der Unterschiede dieser Methoden die den Entscheidungsträgern bei ihrer Auswahl helfen sollen. Die Herstellung des Biopolymers Polyhydroxyalkanoat (PHA) aus Schlachtabfällen wird mit den gegebenen Methoden bestimmt. Die Auswirkungen durch die Veränderung alternativer Energiequellen wird ebenfalls evaluiert.

List of Abbreviations

bbl	Barrel
BC	Biocapacity
BSE	Bovine Spongiform Encephalopathy
Cd	Cadmium
CF	Carbon Footprint
CFP	Footprint of products
ELR	Environmental Loading Ratio
ESI	Emergy Sustainability Index
EU	European Union
Ef	Equivalence Factor
EYR	Environmental Yield Ratio
FAE	Fatty acid esters
GFN	Global Footprint Network
gha	Global hectare
GHGs	Greenhouse gases
GWP	Global Warming Potential
Ha	Hectare
HP	High pressure
HCl	Hydrochloric acid
IPPC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standards
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MBM	Meat and Bone Meal
MF	Microfiltration
MWh	Mega Watt Hour
MI	Material input
MIPS	Material Input Per Service unit
MIT	Material Intensity

NGOs	Non-Governmental Organizations
NRR	Non-renewable to renewable ratio
PE-HD	polyethylene high density
PE-LD	Polyethylene low density
PHA	Polyhydroxyalkanoate
SFAE	Saturated fatty acid ester fraction
SPI	Sustainable Process Index
TF	Transformed feed stock
TME	Tallow Methyl Ester
TMR	Total material input required
UEV	Unit Emergy Value
UF	Ultrafiltration
WCED	World Commission on Environment and Development

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1 INTRODUCTION

A general definition introduced by World Commission on Environment and Development (WCED) in its famous report “Our Common Future” is given as ‘Development that meets the needs of the present generation without compromising the ability of futures to meet their own needs’ (WCED, 1987). This definition has been interpreted and used in many different meanings in different disciplines of life.

Sustainability is a well-recognized paradigm influencing future developmental policies and regulations at government as well as intergovernmental level. It is considered as a model consisting of three main pillars of a society, namely economic, environment and social aspects. It is normally represented by three intersecting circles, representing each one aspect of sustainability. In other words sustainability means development of human well-being, in accordance to the recognition of the fact of one diverse but ultimately finite planet. For decision makers it is becoming challenging, how to fulfill human demand while operating within limits of nature, to attain sustainability. This requires both the effective management of human demands as well as natural capital, while living within its ability to renew itself. In order to achieve this task, reliable measurement tools comparing the supply of natural income with human demand on it are crucial. They help decision makers to track progress, set targets and make policies for sustainability (Keiner, 2006).

Sustainability assessment methods range from single issue measures, like Carbon Footprint (Wright et. al. 2011), Water Footprint (Hoekstra and Chapagain, 2008) etc., (measuring exchange of single substance with the environment along the whole life cycle chain of product or service), to direct quantity and quality of energy measures (thermodynamic measures), like Exergy (Wall, 1988) and Emergy Accounting (H. T. Odum, 1996), to more complex aggregated measures like Ecological Footprint (Wackernagel and Rees, 1994), Sustainable Process Index – SPI (Narodoslawsky et al. 1994), The Well Being Index (Prescott-Allen, 2001), The Environmental Sustainability Index (ESI) (Center for International Earth Science Information Network, 2002) and material input efficiency based Material Input Per Service unit (MIPS) (Schmidt-Bleek, 1993), to just name some common measurement categories.

The context of this thesis is to find out normative background of the sustainability measurement methods and make a comparative analysis based on value system behind them. For this purpose four different methods carbon footprint, Sustainable Process Index (SPI), Material input Per Service unit Service (MIPS) and Emergy Accounting Evaluation are selected. The reason to select them is, each of them belongs to a specific normative category, namely single issue problem (carbon footprint), thermodynamic value system (emergy accounting), efficiency oriented evaluation (MIPS) and complex aggregated evaluation system (SPI). A detailed description of the normative backgrounds and methodologies are described in the later chapters.

The motivation of this thesis is to find out similarities and differences between these methodologies and help decision makers to choose suitable methodology for sustainability evaluation. The sustainability of a biopolymer polyhydroxyalkanoate (PHA) production, from slaughtering waste residue as a starting material, is evaluated by applying given sustainability methods. The effect of change of energy resources from business as usual (i.e. Electricity mix from the grid and heat provision utilizing natural gas) to different renewable energy resources has also been evaluated.

2 Problem definition and objectives

The aim of this work is to make a comparison of different sustainability measurement methods based on normative value system behind their development.

2.1 Problem definition

The field of sustainable development is wide and covers three aspects i.e. environmental, economic and social. There are a huge number of sustainability measurement methods available to perform sustainability evaluation. It is quite challenging for engineers to select a method because they are very familiar with the approach of natural laws and technological desighn rules.. They have learned to work with economic assessment tools which provide them useful information how to exploit their design in a better way to increase profit. These economic measures are integrated tools which summarize complex interactions between different economic factors to provide a single target function to maximize (profit) and minimize (material and consumption cost). Both environmental as well as social indicators lack clarity of design as well as convenience of optimization. This situation puts an engineer into a complex confusing situation. This brings us to the source of diversity of sustainable development methodologies. . All of the methodologies are developed based on certain normative value systems. This means they adopt a certain vision of the future, a certain development pathway as “good” and set a particular objective for sustainable development. The decisions made by human beings are oriented according to “better” and “worse”. The values are assigned to open options available to us and require certain normative systems to differentiate between “good and bad” along with orienting themselves according to normative goals which we are trying to achieve through our actions.

The variety of sustainability assessment methods available to engineers to make their decisions according to sustainable development should be loud regarding economy, nature and society. There are different tools available, each having a particular set of normative goals that should be achieved to attain sustainability, competing for attention and dominance. These methodologies therefore are translations of their normative system with the help of science into quantitative or qualitative measures to help and guide in the decision making process. The problems which are faced in these methodologies are:

- Exclusive and commanding, in order to get attention and recognition
- Do not reveal their true normative base behind their development.
- Pretend to be based on pure scientific reasoning.

Sustainability assessment methods range from single issue measure like Carbon Footprint (Wright et. al. 2011), Water Footprint (Hoekstra and Chapagain, 2008) etc., (measuring exchange of single substance with the environment along the whole life cycle chain of product or service), to direct quantity and quality of energy measure, like Exergy (Wall, 1988) and Emergy Accounting (H. T. Odum, 1996), to more complex aggregated measure like Ecological Footprint (Wackernagel and Rees, 1994), Sustainable Process Index – SPI (Narodoslawsky et al. 1994), and Material Input Per Service unit Service (MIPS) (Schmidt-Bleek, 2001), to just name some common measurement categories.

The single issue concern measures focuses on one particular factor in complex environmental problems, like carbon footprint deals with global warming. While thermodynamic measures focus on energy efficiency in both production and consumption. Similarly complex aggregated measures are explicitly developed on normative guiding principles, consisting of wide variety of human-ecosystem interactions and use an overarching normative goal set to make them comparable. Four methods namely Carbon Footprint, Ecological Footprint (Rees and Wackernagel and Sustainable Process Index), Emergy Accounting and MIPS will be compared in detail in this thesis. They have been chosen because each of them belongs to a specific normative category, namely single issue problem (carbon footprint), thermodynamic value system (emergy accounting), efficiency oriented evaluation (MIPS) and complex aggregated evaluation system (SPI).

2.2 Research Objectives

Based on the problem definition following research objectives has been defined.

- Defining normative backgrounds of sustainability measurement methods using SPI, Carbon footprint, Emergy Accounting and MIPS as examples.

- Figuring out main environmental factors highlighted by the measure, using process case study.
- Investigation if the results of each evaluation method really reflects its normative background

3 Life Cycle Assessment and Case Study

Environmental awareness in the society has increased pressure on the Industries to investigate innovative as well as environmentally compatible technologies to provide services. Therefore many companies are investigating ways to minimize their effects on the environment. The companies found it advantageous to explore ways to move beyond compliance by improving their environmental performance, adopting pollution prevention strategies and environmental management systems methodologies. One such approach is life cycle assessment.

3.1 Life Cycle Assessment

Life Cycle Assessment (LCA) studies have gained a vital role in planning and development of processes in industry and community e.g. energy and infrastructure systems (Narodoslawsky and Stoeglehner, 2010). LCA assessments are carried out following ISO14040 norms. Life Cycle Impact Assessment (LCIA) is a fundamental part of LCA. It evaluates the pressure exerted by the process flow on the environment in different steps of life cycle assessment of a product or service. Depending on the goal and context of the studies, wide variety of methods is available (Mayer, 2008). Process industry covers a major part of the interaction between society and environment. In order to decrease environmental pressure arising from this industry, it is needed that environmental assessment becomes an integral part of process designing and optimization (Azapagic and Perdan 2010).

3.1.1 Normative Background

The Life cycle assessment (LCA) approach is used to assess industrial systems from “cradle-to-grave”. The term “cradle-to-grave” refers to gathering materials from the earth to create the product and returning all materials back to the earth at the disposal of specific product. LCA evaluates all stages of a product’s life starting from material collection, manufacturing, usage and disposal, considering that they are interdependent and one operation leads to the next. LCA results consist of cumulative environmental impacts resulting from all stages in the product life cycle. By doing so, it provides a comprehensive view of the environmental aspects of the process or product (SAIC, 2006)

The term “life cycle“ denotes all major activities in the course of products lifespan, including the raw material acquisition required for manufacture of the product, manufacturing process, use and maintenance, till final disposal.

3.1.2 Methodology

LCA is defined and standardized in the ISO 14040 norm (ISO, 2006) by International Organization for Standards (ISO).The LCA is a systematic approach consisting of four modules, namely: goal definition and scoping, inventory analysis, impact assessment and interpretation as shown in Figure 3.1.

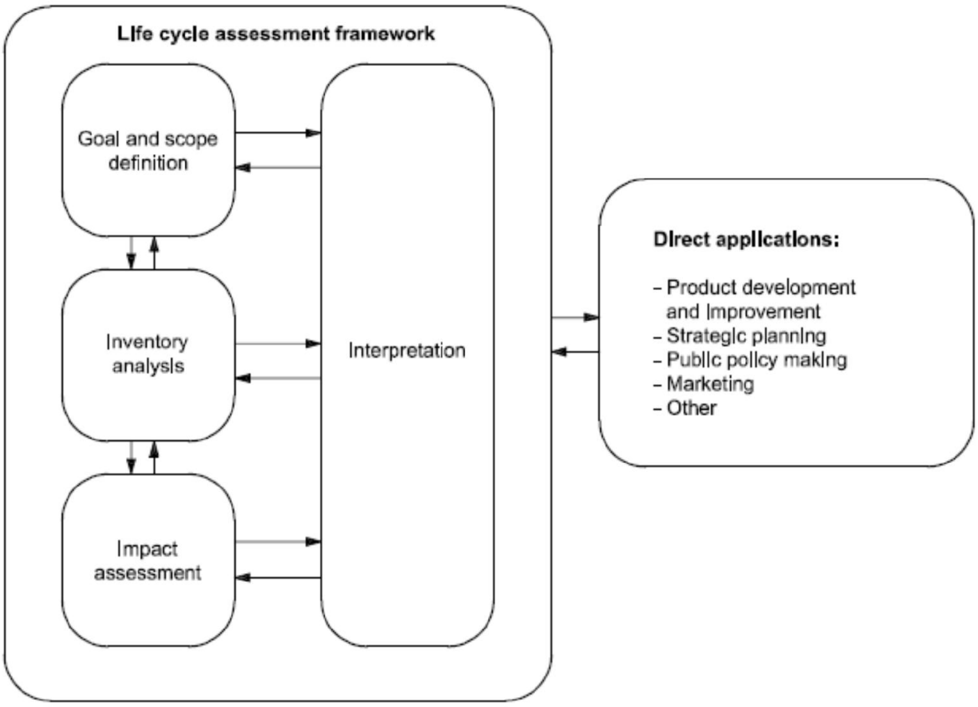

Figure 3.1: Life Cycle Assessment methodology (ISO, 2006).

The brief description of different steps for carrying out LCA is given as follows:

3.1.2.1 Goal Definition and Scoping

It includes definition and description of the product, process or activity along with establishing the context in which the assessment will be carried out. It also includes identification of system boundaries and environmental effects to be reviewed for the assessment.

3.1.2.2 Inventory Analysis

This step deals with identification and quantification of material (water and material usage) and energy (heat and electricity) and environmental releases (e.g. emission to air, solid waste disposal, waste water discharge etc.) during the life cycle of a product, process or activity.

3.1.2.3 Impact Assessment

This step includes assessment of potential human and ecological effects caused by water, energy and material usage and the environmental releases identified in the inventory analysis.

3.1.2.4 Interpretation

This step provides evaluation of the results of the inventory analysis and impact assessment. It helps to select the preferred product, process or service with a clear understanding of the uncertainity and the assumptions used to generate the results.

3.1.2.5 Allocation

If the process provides more than one product, the overall ecological pressure or footprint of the process has to be assigned to different products, in order to reflect their share of ecological pressure on the environment.

1. The whole impacts are allocated to primary products
2. Allocation is based on product mass or energy flows
3. Allocation is in accordance to price or value of respective products, although prices have to be entered manually (Sandholzer and Narodoslawsky, 2007).

3.2 Case Study

In order to find out the answers for the questions raised in chapter 2, a case study dealing with biopolymer production from animal slaughtering waste has been selected. The process design, development and description of the sub-processes have been published in our own publications. A detailed description of the case study taken from Shahzad et al. (2013) given in the annex, is followed as:

"The results presented in this article are based on data from the ANIMPOL project which investigated the utilization of waste streams from the slaughtering, rendering and biodiesel industry. In Europe, 500,000 t/y of waste lipids accrue from the animal processing industry (Titz et al. 2012). Converting these amounts to biodiesel (fatty acid esters, FAE) by means of transesterification would produce about the same quantity regarding the mass (490,000 t/y) of FAE. This FAE contains about 55 % of saturated fatty acid ester fraction (SFAE) that impairs FAEs fuel property due to an elevated cold filter plugging point. Separation of SFAE results in the generation of an excellent biofuel consisting of unsaturated FAE fraction. SFAE can be applied as carbon feedstock for PHA biosynthesis. In addition, about 0.1 t of crude glycerol is generated during the transesterification of 1 t of lipids. Considering the globally increasing biodiesel production, the glycerol market is already strained. Therefore glycerol can be regarded as a low value by-product. Crude glycerol can be utilized as an additional carbon substrate in the ANIMPOL[1] process for cultivation of catalytically active microbial cells and for accumulation of PHA by the cells.

3.2.1 Process development

"Several sub processes were analyzed, from slaughter house waste to PHA production. Fundamental principles of economic and ecologically efficient processes were considered for every decision of process design and development. The process design includes sub processes from slaughtering to PHA purification.

Upstream processing includes hydrolysis, rendering, biodiesel production and fermentation process, while downstream processing includes microfiltration (MF) or ultrafiltration (UF) and high pressure (HP) homogenization and centrifugation for PHA purification. Acid hydrolysis is an innovative addition at pilot scale while rendering, biodiesel production and fermentation process are state of the art processes. A detailed process design flow sheet is shown in Figure 3.2 showing the pathways of the material flows from the slaughter house to the final products MBM, PHA, biogas and high quality biodiesel. For a detailed description of the process design the reader is kindly referred to (Titz et al. 2012). In the current paper the process will only be briefly discussed to provide the base for further discussion.

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[1] Acronym ANIMPOL is used for and Eu project titled "Biotechnological conversion of carbon containing wastes for eco-efficient production of high added value products"

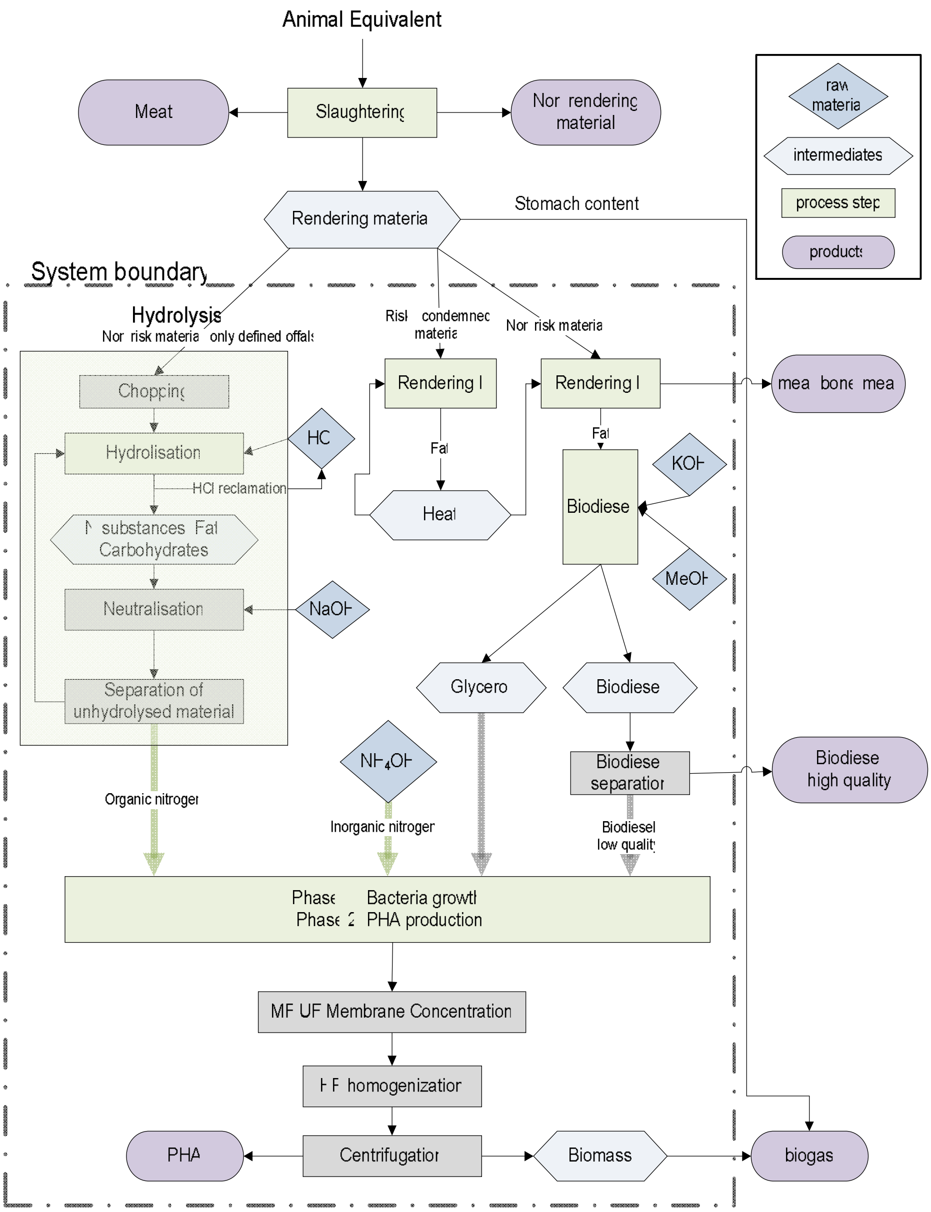

Figure 3.2: Flow sheet of process design for ANIMPOL

3.2.1.1 Hydrolysis

Hydrolysis is the breakdown of larger molecules or compounds into smaller ones by the addition of water molecule in the presence of acid or base acting as a catalyst. In the ANIMPOL-process acid catalyzed offal hydrolysis is carried out using 6 molar (M) hydrochloric acid (HCl), at an *elevated temperature of 120 °C maintained for 6 h (Titz et al. 2012), in order to produce a cheap complex nitrogen source for cell growth. As the fermentation process requires a certain pH value, hydrolyzate is neutralized by using NaOH. The neutralization will result in NaCl production which has no negative effect in the following fermentation process (Pickering and Newton 1990). The life cycle inventory data for 1 t equivalent of organic nitrogen production through offal hydrolysis, based on own group experimental data is given in Table 3.1.*

Table 3.1: Life Cycle Inventory data for 1 t organic nitrogen equivalent hydrolyzate

Input	*Inventory*	*Units*
Transport 28 t Truck	*5951.657*	*tkm*
Grid electricity EU27	*0.957*	*MWh*
Process energy, natural gas	*7.092*	*MWh*
Hydrochloric acid	*46.798*	*t*
Process Water	*31.956*	*m^3*
Sodium hydroxide	*16.902*	*t*

3.2.1.2 Rendering

Slaughter house by-products, mainly fat, blood and bones, constitute the rendering material as shown in Figure 3.2. They find a great variety of application directly or after processing and have added a value to the animals. Protein rich solids are traditionally used in foods, pet food, livestock feeds and as fertilizers. Fats are used in foods, pet foods and feed applications along with transformation into soaps and oleo chemicals. Since the emergence of Bovine Spongiform Encephalopathy (BSE) in the 1990ies, traditional uses have been partly abandoned and new alternative uses as energy or fuel source have been explored in the past decade. Legislative directives have been issued by EU regulating authorities for both fat processing units which is the "Meat product directive" 77/99/EEC (EU, 1977; 1992) and the "Animal by-product regulations" ABPR 1774/2002/EC(EU, 2002) for the rendering sector (Woodgate and Veen 2004).

Animal waste contains high amounts of water and provides a good breeding ground for microbial growth leading to its decomposition and ultimate environmental pollution. The conventional way of handling and stabilizing this material is heat processing known as "rendering". In this process animal by-products are treated at 133 °C and a pressure of 3 bar for at least 20 min to obtain MBM and tallow. The main sub-processes involved in rendering are *grinding, cooking and pressing. As explained in (Titz et al. 2012), there are two distinct processes for rendering in the ANIMPOL process:*

Rendering I sub processes uses condemned material streams from BSE suspected and confirmed animals. The products obtained from this process can only be used for energy purpose according to EU regulations" is given in Table 3.2."

Table 3.2: Life Cycle inventory data for 1 MWh heat production from rendering 1

Inputs	*Inventory*	*Units*
Transport 28t Truck	*43.558*	*tkm*
Net electricity EU25	*0.018*	*MWh*
Process energy, natural gas	*0.267*	*MWh*
Waste Water Treatment	*0.173*	*m3*
Process Water	*0.076*	*m3*

"In the ANIMPOL process, this energy will be used to fulfill a part of energy demand for rendering II sub process, which processes non-risk material. The products of this process are tallow and MBM. Tallow will be used for biodiesel production while MBM will be sold to the market in order to generate revenue. Life Cycle Inventory data for 1 t of tallow production by rendering process based on experimental data (Titz et al. 2012) is given in Table 3.3.

Table 3.3: Life Cycle Inventory data for 1 t fat production

Inputs	***Inventory***	***Units***
Transport 28t Truck	*625*	*tkm*
Grid electricity EU27	*0.25*	*MWh*
Process energy, natural gas	*3.24*	*MWh*
Waste Water Treatment	*2.48*	*m3*
Process Water	*1.08*	*m3*
Heat from Rendering I	*0.30*	*MWh*

3.2.1.3 Biodiesel Production

Biodiesel production using tallow as raw material is a well-developed and optimised process having 96-98 % production yield with respect to the fat input. This form of biodiesel is also known as tallow methyl ester (TME) and is produced by transesterification of tallow with methanol in the presence of KOH as catalyst (Titz et al. 2012).

Life Cycle Inventory data for 1t of biodiesel production based on material and energy flow data obtained by personal communication with Mike Scot serving as Technical Director at "Argent Energy (UK) Ltd" is given in Table 3.4.

Table 3.4: Life Cycle Inventory data for 1 t biodiesel production

Inputs	*Inventory*	*Units*
Tallow from Rendering II	*1.02*	*t*
Potassium Hydroxide	*0.02*	*t*
Sulfuric acid	*0.01*	*t*
Methanol	*0.11*	*t*
Process energy, natural gas	*0.05*	*MWh*
Grid electricity EU27	*0.07*	*MWh*
Waste Water Treatment	*0.10*	*m3*

3.2.1.4 Fermentation Process

The PHA production utilizing microbial fermentation can be distinguished into two phases: In the first phase a high concentration of catalytically active biomass is obtained under optimal nutritional conditions during unrestricted growth. In this phase PHA production is insignificant compared to biomass formation. In the second phase nutritional stress condition for microbes is induced by limited supply of essential nutrients such as phosphate and nitrogen. This results in redirection of carbon flux from pre-dominant biomass production towards PHA accumulation (Titz et al. 2012; Koller et al. 2010a). Downstream processing constitutes a key part of the entire PHA production process. After biosynthesis of the polyester and separation of the bacterial biomass from the fermentation broth, cells are broken up to gain access to intercellular PHA. Choosing an adequate method for separating PHA from residual biomass is dependent on several factors: the microbial production strain, the desired product purity, the in-house availability of chemicals, and the acceptable impact on the molecular mass of PHA (Koller et al. 2010b; Kunasundari and Sudesh 2011).

Life Cycle Inventory data in Table 3.5 is based on information obtained by personal communication (Koller Martin, TU Graz). The hydrolyzate constitutes a source of organic nitrogen and mixture of essential amino acids used in the unrestricted growth phase, while ammonium hydroxide serves as a source of inorganic nitrogen in the PHA production phase and also helps to maintain optimal pH reaction conditions. Biodiesel and glycerol are the main raw materials acting as carbon source for bacteria to produce PHA. Inorganic chemicals are a *mixture of essential chemicals and biochemicals required for the fermentation process. Electricity consumption comprises stirring during fermentation process, pumping of the fermentation media into and out of the reactor, whereas process heat is required for sterilization of media and bioreactor and maintenance of fermentation media temperature at about 37°C. Water is consumed for fermentation media and downstream processing."*

Table 3.5: Life Cycle Inventory data for 1 t PHA production

Inputs	*Inventory*	*Units*
Hydrolyzate	*0.004*	*t*
Ammonium Hydroxide	*0.077*	*t*
Glycerol	*0.237*	*t*
Biodiesel	*1.859*	*t*
Inorganic chemicals SP	*0.078*	*t*
Grid electricity EU27 SP	*0.05*[2]	*MWh*
Waste Water Treatment	*8.118*	*m3*
Process Water	*8.118*	*m3*
Process energy, natural gas	*0.292*	*MWh*

3.2.1.5 Assumptions for Evaluation

Using different methodologies for the evaluation of given production process, the following assumption has been made.

- Animal residue material is considered as waste product coming from slaughter houses. So it is assumed that overall environmental impact, for all methodologies is assigned to main product i.e. meat and residues have zero environmental impact.
- The transportation of the residue material is part of system boundary for the analysis and its environmental impacts are assigned to residues.
- The system boundaries for the production process include mass, material transportation and energy flows of sub-processes within industrial facility.
- Infrastructure of transportation trucks as well as the industrial facility is not included in the system boundary.

[2] Updated input value, including electricity consumption for downstream processing.

- In case of two products from a sub-process (e.g., rendering and biodiesel production), usually mass allocation method is used to allocate the impacts, unless mentioned otherwise.

3.2.1.6 Transportation in Emergy

As explained in the assumptions animal slaughtering residues are considered as waste material and assigned an emergy value of zero. For the transportation of animal slaughtering residues to the rendering facility are taken into account for emergy accounting. The calculations show that 2.43E+05 t/yr animal residues have to be transported for 10,000 t/yr PHA production. It is assumed that animal residues are transported over a mean radius of 75 km resulting in a distance of 150 km/trip. The use of 28 t trucks carries 20 t/trip results in 1.21E+04 trips/yr equal to 1.82E+06 km/yr traveling distance. If one trip requires roughly 3 h for transportation and 0.5 h for loading and unloading of the material and cleaning of the vehicle, annual transportation time is 4.25E+04 h/yr. In accordance to Austrian labor regulation a full time worker works about 1600 h/yr and earns about 29143.75 €/yr (money.oe24.at). It results in 26.6 person/yr as labor input and 29143.75 €/yr labor cost for transportation phase. Frischknecht and Jungbluth (2004) have reported that a 28 t truck requires 1.8 MJ/tkm, which means a sum of 6.56E+13 J/yr of diesel input is required for annual residue transportation. The residue material is considered as waste and has no economic value. The cost of diesel for residue transportation constitutes service and it is equal to 1.74E+06 €/yr.

The evaluations of two products biodiesel and PHA production in the given process as base scenario, using Carbon Footprint, SPI, MIPS and Emergy Accounting methodologies using electricity provision from EU27 mix and fulfilling heat demand from natural gas consumption, are carried out. The comparative analysis is done by evaluating the production of the same products utilizing alternate electricity provision resources, like coal, biogas, hydro power, biomass and wind. In order to highlight importance of heat provision resources another scenario utilizing heat and electricity from biomass has also been calculated.

4 Ecological Footprint Strong Sustainability and Natural Income

According to conventional definition of a process, whatever goes on in a plant, within physical boundary of the plant is termed as a process. This process is connected to the system boundary through raw material, energy, waste and products, labor, authority regulations and prices. Engineers take the responsibility of safety within the plant and quality of the products going out of the plant.

In accordance to economic and environmental aspects of a society, sustainability can be categorized as weak and strong sustainability. According to Pearce and Atkinson (1993) weak sustainability is outcome of neoclassical economic point of view. In accordance to this point of view sustainability of a process can be defined as 'The process in which output of the process has more capital than the input'. The capitals are sum of products of anthropogenic activity (e.g. buildings, infrastructures, machines, railways etc.) and natural capital (e.g. mineral, ore, biodiversity, etc.). This type of sustainability also implies that both types of capitals are interchangeable. Similarly modern economic model does see any fundamental conflict between modernization and environment. It argues that during modernization environmental impacts and economic development may form an inverted U shaped curve (also known as environmental Kuznets curve) as shown in Figure 4.1. After which economic development will help to solve environmental issues (Özdemir et al. 2011).

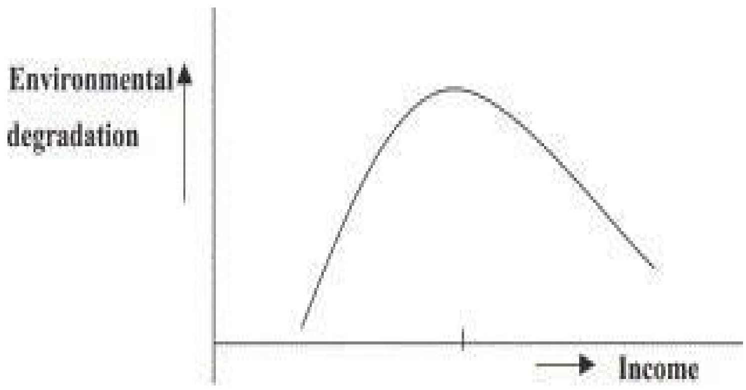

Figure 4.1: Environmental Kuzent curve (taken from: Dinda.2004)

The strong sustainability point of view reveals that social, economic or environmental capitals serve different needs of the society and cannot be interchanged. Thus, each distinct capita should be conserved individually. Similarly political economy perspective can includes in strong sustainability and it opposes economic modernization arguments. It suggests that there is basic contradiction between economic production and ecosystem, which indicates that prospects of the environmental Kuzent curve cannot be considered. The suggested solution lies in "restructuring of societies away from economic expansion and toward ecological sustainability" rather than reorganization oriented policies (Özdemir et al. 2011). The strong sustainability principles are summarized as:

- Sustainable economy is dependent on the natural income i.e. solar and geothermal radiations which are constantly replenished.
- The conservation of natural system´s ability to receive this income and transform it to useful resources for humanoid society must therefore not be put into danger.

4.1 Ecological footprint (Wackernagel and Rees) natural income and fully sustainable

According to Costanza and Daly (1992) societal well-being and economic success is dependent on resources and ecosystem services provision capacity of the planet. Although most current policy decisions were based on the assumption of limitless availability of resources and services, neglecting the fact that the planet has definite boundaries sustainable development cannot be achieved without operating within them (Brucke et al. 2013).

4.1.1 Normative Background

The available published literature reveals that critical limits of planetary-scale transition are approaching as a result of ecological pressure exerted by anthropogenic activities; also tools are needed to evaluate consequences of such pressures on the ecosystem (Barnosky et al. 2012). The ecological footprint developed by Wackernagel and Rees (1996) is one of the potential tools to measure planetary boundaries and the extent human activities are exceeding them.

It assumes that human consumption should be restricted to available limited natural capital (although available for infinite time) and ecosystem services i.e. “ecological budget” (Rees, 2002). It is based on the principle that solar energy is the main source of energy provision and finite volume of earth surface area is required to absorb and transform it into useful resources through compiler ecological system transformation processes to fulfill societal needs. Similarly carbon footprint term is used for carbon emissions (usually represented in tons) caused by a process or activity or organization. Ecological footprint translates carbon dioxide into productive land and sea area required to sequester amount of carbon dioxide emitted by an activity or organization, which represents that almost all energy is provided through renewable resources.

Productive land is used as a proxy for the provision of resource flows and essential life support services by the natural capital. The land area represents the finite character of world and it is roughly proportional to its potential of low entropy biomass production through photosynthesis. While quality of land in a qualitative function of associated ecosystem and their ability of long term production (where long term means more than 100 years or generations while short term means more than 10 years up to few decades). These characteristics are representative of real wealth and are rarely reflected in the money price of land as product (Wackernagel and Rees, 1997).

The equivalence factor (Ef) is a productivity-based scaling factor which converts one hectare of world-average land of a specific land type, e.g. forest and cropland, into an equivalent number of global hectares. These equivalence factors are calculated based on the assessments of relative productivity of land under different land types in a given year.

Yield factors (F) are factors which provide the possibility to compare different areas of same land type to be compared based on common denominator of yield. It is used to rectify the problem of different production yield of given land type, such as crop land which have dramatically different production yields based on factors such as climate, topography and management services. For example comparison of the productivity of average forest in a specific nation to world-average forests, provides national yield factors for that country. These yield factors then convert one hectare of a specific land type such as forest, with in a given nation into an equivalent number of world-average hectares of the same land type. So it can be defined as:

The yield factor for a given land type is the ratio of average yields of that land type, for example forest of a specific country, and world-average yields of that land type.

Biocapacity is the measure of ecological budget or regenerative ability of nature or in other words capacity of land biosphere to produce renewable resources. In contrast to ecological footprint which presents the sum of resources needs to fulfill needs of humanity i.e. demand side, biocapacity is the ability of land to reproduce resources i.e. supply. It is also measured as gha, just as that of ecological footprint. It is calculated according to following equation:

$$BC = S \times F \times Ef \tag{3}$$

In equation 3, BC represents biocapacity of land or territory, S is the area, F is yield factor while Ef is the equivalence factor. The BC of a land is calculated by multiplying certain area (sum of crop land, grazing land and fishing field) with yield factor and equivalence factor of a specific year and the resulted value is expressed in gha. The calculation and comparison of both indicators ecological footprint as well as biocapacity of a region or country provide complete information about the region or country that it is 'ecological lender' or an 'ecological borrower'.

The annual supply and demand for any ecosystem at local, regional, national and global scale can be quantified by means of following two measures (Brucke et al. 2013).

"Ecological Footprint: *a measure of the demand populations and activities place on the biosphere in a given year, given the prevailing technology and resource management of that year.*

Biocapacity: *a measure of the amount of biologically productive land and sea area available to provide the ecosystem services that humanity consumes – our ecological budget or nature's regenerative capacity."*

4.1.2 Methodology

How much of biocapacity is required to support anthropogenic activities? The ecological footprint is envisioned to answer this question. It is a measure of biologically productive land and sea area to support individual, community, regional or national activities and absorb carbon dioxide (CO_2) emission caused by these activities and its comparison to the available land and sea area. There are two distinct types of biologically productive land and sea area:

- Area to fulfill basic demands of food, energy, fiber, timber and infrastructure
- Area required for absorbing CO_2 emissions caused by human economic activities.

Biologically active areas consist of cropland, grazing grounds, forest and fishing grounds, while deserts, open oceans and glaciers are not included. Figure 4.2 represents bio productive areas and their contribution to the economy taken from Global Footprint Network (GFN).

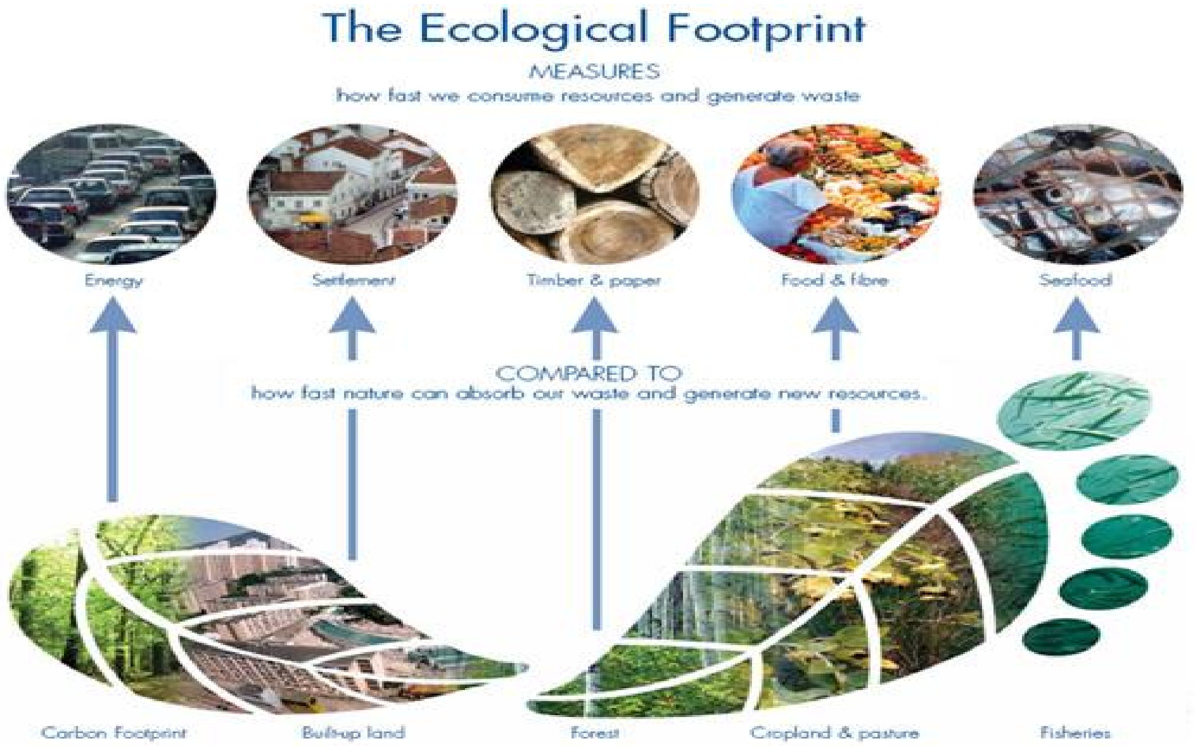

Figure 4.2: Ecological footprint contributions from resource production and waste generation (Global Footprint Network)

The assessment of ecological footprint for an activity, person, population, region, city and world at large, is the measure and sum of areas in these land-use types which are used up to produce resources (for food, housing, transportation, consumer goods and services) and absorb waste. The division of total resource consumption with yield per hectare or dividing amount of emitted waste with absorptive capacity per hectare (ha) gives consumed areas. For example if a population of 100,000 people consumes 10,000 t rice. If the average rice production is 10 t/ha, then ecological footprint of specific population for rice consumption will be 1000 ha. Similarly in case of derived or manufactured products, annual demand is converted to primary product equivalents. For example if consumed product is “wood pulp” then it will be converted into equivalent amount of primary product i.e. “round wood” required to produce this much wood pulp using extraction rates. The energy required for manufacturing processes are also embodied in the consumed areas (Van den Berg and Verbruggen, 1999; Ewing et al. 2008). The formula to calculate consumed area is given as:

Consumed area = Annual demand in tons / Average National yield in annual tons per ha

The average productivity of all the biologically productive land and sea areas in the world in a specific calendar year comprises a global hectare (gha). It allows comparison of different area types using single denominator. The productivity of a crop land ha is different than grazing land as well as fishing ground. Similarly areas of same category e.g. cropland in France and Africa have different per ha productivity. The actual areas of different land types and productivity are converted to common unit of gha using specified equivalent factors and yield factors. Similarly multiplication of average productivity of any specific area with equivalent factor transforms it into global hectare i.e. average global productivity this specific area for the given year. Equivalent factors have identical values for every country and they are calculated for every year. Equivalent factors calculated for different areas for 2005, reported by Ewing et al. (2008) are given in Table 4.1.

Table 4.1: Equivalent factors for different areas for 2005 (Ewing et al. 2008)

Area Type	*Equivalent Factor (gha/ha)*
Primary Cropland	**2.64**
Forest	**1.33**
Grazing Land	**0.50**
Marine	**0.40**
Inland Water	**0.40**
Built-up Land	**2.64**

There is specified particular methodology for ecological footprint calculation because GFN redefines and corrects calculation methodology every year. However general calculations for ecological footprint are made using equations 1 and 2 (Ruževičius, 2011) given as follows:

$$a_i = \frac{c_i}{Y_i} \times F \times Ef \qquad (1)$$

$$F_p = \sum_{i=1}^{n} a_i \qquad (2)$$

Where a_i represents ecological footprint of each element or activity, c_i – is the annual consumption of the element or activity, Y_i is the land productivity or output of each element or activity (kg/ha).

F – is the yield factor ; Ef – equivalence factor ; Fp – represents total footprint of the population.

Equation 1 is used to calculate and translate ecological footprint of each component from land i.e. physical ha to gha by multiplication with yield factor F and equivalence factor Ef. While equation 2 is the sum of all calculated components and provides the total ecological footprint.

4.1.3 Overshoot

Overshoot was identified and defined by William Catton as "growth beyond an area's carrying capacity, leading to crash" (Catton, 1980). There is a difference between ecological overshoot and ecological deficit terms which have been used interchangeably in the past. Now overshoot has been reserved to indicate over use of an ecosystem beyond its sustainable yields. The ecological deficit represents the difference between a population's ecological footprint and the biocapacity available to this population. However, it should be noted that globally the overshoot is equal to the global ecological deficit (Wackernagel et al. 2004). In recent times humanity is using the natural income of 1.5 planets to fulfill its need for resource consumption and waste absorptions. In other words our planet needs one year and six months to assimilate waste and regenerate the required resources.

Figure 4.3 reveals global footprint scenarios based on ecological footprint calculation from 1960-2008 with extrapolation of business as well as rapid reduction in ecological footprint. The business as usual scenario shows a conversion of resources faster than resource regeneration rate has put us in global overshoot and we will require 2 extra planets to fulfill our resources demand.

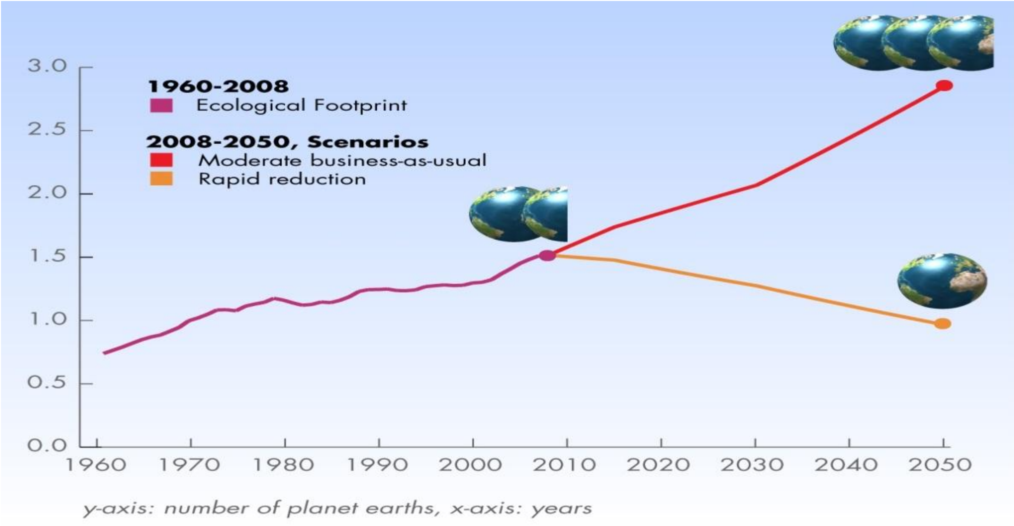

Figure 4.3: Global ecological footprint scenarios (GFN)

4.1.4 Limitations

Ecological footprint analysis has been criticized by a number of researchers due to methodological shortcomings to not correctly account for (McManus and Haughton, 2006; Dietz et al., 2007; Lawn, 2007)

- Deterioration of local biodiversity
- Depletion of non-renewable resources
- Unsustainable activities like release of heavy metals, radioactive materials and persistent organic compounds as well as increased soil salinity from irrigation which could affect future productivity loss.
- Possible loss in bioproductivity due to pollutant emissions to water, air and soil; only greenhouse gases are considered
- Consideration of social and economic aspects of sustainable development
- Almost all energy demand is fulfilled by renewable resources and do not have the ability to distinguish between different energy systems

The ecological footprint is a synthetic indicator which provides guidance to the environmental policy makers, while being easily understood and communicative. Also it has well established footprint standards to ensure scientific reliability of the methodology and robustness of calculations. It is an environmental indicator and does not account social and economic impacts of the activity. In order to have a complete overview of a sustainable development of an activity it should be complemented by other measures.

4.2 Sustainable Process Index (SPI) Natural Income and Eco-Service Function In

The Sustainable Process Index developed by Narodoslawsky and Krotscheck (1995) is one of the members of ecological footprint family. It is a complex and highly aggregated environmental assessment method. It calculates life cycle wide ecological footprint of a product or service delivered by a technology. The outcome of the evaluation is a measure of area that is required to embed the service or product sustainably into the ecosphere, while neither the global material cycles (e.g. global carbon cycle) nor the quality of local compartments (atmosphere, water system or soil) shall be disturbed. All material flow exchanged with the environment (including raw material extraction, emissions or waste extraction) along the life cycle are taken into account. The life cycle assessment methodology of SPI, including embedding of material exchange between ecosphere and anthroposphere, is shown in Figure 4.4.

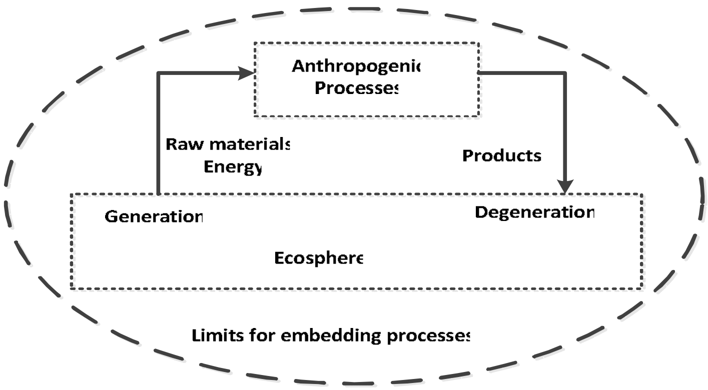

Figure 4.4: Life Cycle Assessment methodology of SPI include embedding of anthropogenic process into ecosphere including both ecosphere and anthroposphere (Krotscheck and Narodoslawsky, 1996)

4.2.1 Normative Background

As conversion of solar radiations into useful goods and services require area, the ecological footprints perceive human as well as natural processes to compete for area in sustainable development. This leads to use area as a proxy measure of sustainability in these assessment methods (Narodoslawsky and Krotscheck, 2004).

Distinct to other ecological footprint methodologies SPI also accounts the natural material cycle as well as quality of environmental compartments. The reason for their inclusion in this measure is to be able to provide assistance to engineers, who not only deal with technology using renewable resources coming directly from natural income or solar radiation, but also utilize fossil resources as well as other non-renewable resources like minerals and metals to fulfill their societal tasks. As any sustainability assessment used by engineers in order to monitor or evaluate sustainability of their process or work should account all materials that are used in their technological practices.

In order to fulfill evaluation criteria compatible with prevailing engineering practices without compromising the normative base of strong sustainability, SPI employs a set of sustainability principles given in (EC, 1996):

- Principle 1. "*Anthropogenic material flows must not exceed the local assimilation capacity and should be smaller than natural fluctuations in geogenic flows*".
- Principle 2 "*Anthropogenic material flows must not alter the quality and the quantity of global material cycles.*".

4.2.2 Material flows and their footprints

In order to make an evaluation in accordance to the basic normative of strong sustainability for an ecological assessment which is also applicable to life cycle assessment and provides needed support to the engineers in their decisions, requires assigning of ecological footprints to the material flows caused by a technical activity. These footprints represent the areas required to embed the activity sustainably into the ecosphere. In accordance to the principles stated above, SPI uses two different approaches (i. areas for material related to global material cycle, ii. areas for all other materials) for this conversion depending on the origin and metabolism of the involved substance. The reference flows for an assessment generated by anthropogenic activity or natural flows are always considered on an annual base.

4.2.3 *Areas for materials related to global material cycles*

SPI evaluates the material flows that are related to global cycles in a way to link them to area requirement of natural processes critical to these cycles. Currently SPI exclusively reports water and carbon cycle according to principle 1.

For water cycle main activity is the transfer of water from atmosphere to land through precipitation. Water is used as resources in the processes or activities therefore footprint area is assigned to catch the specific used amount via precipitation. As water move back to the atmosphere through evapotranspiration, so amount of water that remains on the land is used as reference rate of renewal for the SPI. As rate of precipitation as well as evapotranspiration is dependent of the spatial context, these values also vary accordingly. If an activity or process requires 100,000 m^3 of water per year and precipitation is 0.75 m^3/m^2a, and approximately two third of which is evapotranspired. This flow will have an assigned footprint of 400,000 m^2.

The assessment of carbon cycle is more complex and trickier. It deals differently with renewable carbon resources and fossil carbon resources. For renewable carbon resources a short term sub-cycle is considered. In this cycle CO_2 is fixed through photosynthesis to produce biomass. It requires certain depending on the yield of biomass in question. At the end of life cycle of any product originated from bio-resources, carbon is again released to the atmosphere in the form of CO_2. The amount of this CO_2 is equivalent to CO_2 fixed in the generation of biomass. It closes short term carbon cycle between atmosphere and vegetation. If an activity utilizes 1000 t/maize and the yield of maize is 1 kg/m^2a, in the region where the activity takes place. The footprint assigned to this bio resource or renewable resource flow is 1000,000 m^2 (100 hectares).

The fossil resources are retrieved from long term storage of carbon formed over millions of years and are subject to much slower sub-system of carbon footprint. The SPI methodology focuses on the sedimentation of carbon in the sea bed as a process to close the cycle to long-term (fossil) storage. It is an active process still going on today and long term storage of carbon leading to formation of crude oil and natural gas. SPI calculates sea bed area required to sequester carbon used in an activity as footprint. According to Bolin and Cook (1983) the rate of sedimentation of carbon is 0.002 kg per year per square meter of sea bed. It means that 10 t/a of fossil carbon requires a footprint of 5,000,000 m^2.

4.2.4 Areas for all other materials

All the material flows used by human activity which are not subject to global material cycle are naturally dissipative. These material flows include minerals and metals, which are extracted from point resources, transformed into products and at the end of their life cycle disposed of to the environment. The ecological footprint is the necessary area required to absorb the emitted material flow to the environment, without violating the second principle of sustainability. SPI assesses ecological impact of dissipation of these materials to the environment.

According to principle 1, the approach adopted by SPI methodology to calculate the area to dissipate these material flows consist of two concepts: the natural concentration of these substances in the environmental compartments (particularly water and soil) and natural replenishments of these compartments.

The calculation of footprint for material flow into water compartment is elaborated by supposing an emission of 1 kg/a cadmium (Cd) to water compartment. The replenishment of this compartment will take place through precipitation. In accordance to the data described earlier for water cycle and taking into account evapotranspiration, the replenishment rate will be 0.25 m^3/m^2a. It is considered that this replenished water don't have any contamination of Cd and natural concentration of Cd in this region is 0.005 kg/m^3. If the dissipation of Cd from the specific activity takes place into this replenished water without effecting the natural concentration of the compartment, principle 2 is fulfilled and the quality of the natural water compartment is unchanged. It requires 200 m^3 water for replenishment of ground water which in turn requires 800 m^2 area for sustainable dissipation of Cd from this activity, for replenishment at a rate of 0.25 m^3/m^2a. This is the footprint assigned to this flow.

This approach is also applicable to assess activities that release radioactive substance to water. For example emission of deuterium to the water compartment in case of life cycle assessment of nuclear energy. The amount of deuterium in natural waters is extremely small which serves as reference and emissions of small flows to the environment lead to large ecological footprints. Even if the emissions are well within the legal threshold values.

The dissipation of emissions to the soil compartment also has similar reasoning except the replenishing of this compartment takes place through compost generation. If it is supposed that top soil concentration of Cd in a certain region is 0.001 kg/kg of soil. Also it is assumed that grass has a yield of 0.5 kg/m^2a and 50% of this mass is further lost during composting process. It means that yield of compost is 0.25 kg/m^2a which is the replenishment rate of soil compartment. The sustainable dissipation of 1kg of Cd into soil would require 1,000 kg of soil replenishment and an ecological footprint area of 4,000 m^2.

The air compartment does not have reasonable replenishment rate. In this case SPI methodology compares the rate of exchange $m^2.a$ of flow between natural vegetation and air, in accordance to follow second principle that human activity induced material flows must not alter natural variation in geogenic flows. Bolen and cook (1983) have reported that medium exchange rate of methane between air and land is 0.0045 kg/m^2a. An emission of 1 kg/a of methane will have an assigned footprint of 222.222 m^2.

The synthetic material flows which are produced through anthropogenic activity are alien to ecosphere and have very long resident times in environmental compartments. SPI applies same dissipative methodology to these substances as well, taking into account already measureable amounts of these substances in soil and water. Although it contradicts the basic norm of strong sustainability for SPI, it provides support to the decision makers using realistic or rational approach to estimate the impact of these problematic substances. The production and/use of these substances lead to very large footprint due to very small measureable reference values. It shows the negative impact of their use on the environment.

SPI footprint is assigned to every material flow generated in an anthropogenic activity. The footprint is equivalent to largest calculated area for sustainable dissipation of any substance flow present in the material flow. It is in order to make sure that the ecological pressure for dissipation of all substances is below the assigned limit according to second principle which governs the conservation of quality of local system.

4.2.5 Footprint calculation in SPI

SPI calculates ecological impact as an aggregate of seven different area categories. It includes area needed for resources, energy, manpower, infrastructure (installations) and emissions to air water and soil. Their aggregate provides the ecological footprint of a service or product. It includes delivery of the raw material and energy as well as dispersion of the emissions (Sandholzer and Narodoslawsky, 2007; Gwehenberger and Narodoslawsky, 2007).

The sum of total area A_{tot} i.e. ecological footprint of a process or service, required for sustainable embedding of it into the ecosphere is calculated as:

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \qquad [m^2] \qquad (4)$$

According to equation 1, A_{tot} is the sum of partial areas. A_R, is area required for raw material production. A_E, Area required to provide process energy (heat and electricity). A_I, area required for infrastructure facility or Installations. A_S, area required for staff support and A_P is the area required for sustainable disposal of wastes and emissions to the ecosphere.

The ecological footprint area calculation for the raw materials and sustainable dissipation of waste and emissions include materials subject to global material cycle (water and carbon cycle and substances which are not subject to global material cycle including mineral and metals. The substances subject to global material cycle are assigned specific footprint areas to close the material cycle as explained earlier, upon their extraction, while further footprint accrue along the value chain during production and handling. The minerals and metals have no footprint at the point of extraction while it accumulates along the chain during mining, upgrading, refining and transportation to the factory gate and used in the processes to make products and provide services. These material inputs are assigned dissipative ecological footprint at the end of life cycle of these product, for their release to the ecosphere during metabolic stages of these products. Similarly, recycle materials which complete their life cycle and re-enter into a new cycle as material input (glass and used vegetable oils etc.) do not have any footprint value.

For rough estimation of area required for non-renewable substance (minerals and metals) input flow only energy demand is considered. Normally it is impossible to get precise energy demand per unit mass. In these cases raw material market price is used to calculate energy demand using following equation.

$$ED = CN'' \, 0.95/CE \; (kWh/kg) \qquad (5)$$

In this equation ED represents energy demand for the provision of required material, CN is the price of the material (i.e. market price excluding taxes) and CE is the price of 1 kWh of energy (industrial price excluding taxes). The basic assumption behind this relation is that energy consumption almost exclusively defines price of the basic raw materials. It look like a very rough estimate but its hold true for almost all main products with minor deviation with a factor of 0.95 (Narodoslawsky and Krotscheck, 1995).

The area required for energy provision is equal to area needed to supply 1 kWh of service energy under sustainable prevailing conditions. It depends on the quality of required energy (electricity, mechanical power, or different temperature levels for heat provision etc.). Normally higher area is required for high quality energy service provision.

Area for process installation or infrastructure is the sum of area for direct land use and area needed for the providing buildings and installations. Buildings and installations are products of a life cycle, their total footprint is the sum of footprint accumulated due to the material flow exchange between their production value chain and surrounding environment. The ecological assessment of operating this facility over a reference period of one year (which is time base of SPI calculations), total ecological footprint of facility construction should be depreciated according to its technical life span. The area required directly by the technical processes is considered as direct land use.

In accordance to the concept of natural capital which is equal to the solar radiations coming to the earth surface and human society have to live with in this natural limit. For equitable per capita distribution of natural capital, every human being has to limit ecological footprint of his need of goods and services within the statistical area calculated by dividing the surface of our planet with total number of inhabitants, which is currently around 70,000 m^2. The ecological footprint assigned to staff is equal to the statistical surface area available per person. Generally this aspect has been disregarded in most of the assessments as this footprint is very small as compare to other footprint contributions.

For technological optimization calculation of impact per unit product, good or service is of importance. It is known as the overall footprint of the product a_{tot} and calculated as:

$$a_{tot}\left(\frac{m^2}{unit}\right) = \frac{A_{tot}}{NP} \quad (5)$$

NP represents the number of products or services provided by the process under observation for a reference period. In general practice reference period will be 1 year, based on the availability of yearly natural and engineering flow data (considering bio resource harvesting period) (Krotscheck, 1997). For example ecological footprint calculated per kWh electricity production from hard coal burning is 398 m^2a.

This per service unit area itself is a relative sustainability measure. To make it more prominent it is further divide by available area per inhabitant (a_{in}) in the region which is relevant to the process. It is theoretical mean area (per capita) available per inhabitant for goods and energy supply to each person.

$$\mathrm{SPI} = \frac{\mathrm{a_{tot}}}{\mathrm{a_{in}}}\ \mathrm{cap/unit} \quad (6)$$

SPI helps to design and develop an ecological process by locating hotspots in the process and sub processes. It also provides information about the process steps exerting maximum pressures on the environment. Similarly it also compares alternative technologies to provide products and services with minimum environmental pressures (Narodoslawsky and Krotscheck, 2000). SPI calculations follow ISO 14040 norms and proved their worth in assessing, a number of studies for renewable resource based technologies (Narodoslawsky et al. 2008; Niederl and Narodowsky, 2008). Similarly (Koller et al. 2012) used SPI for calculating ecological impact of Polyhydroxyalkanoate (PHA) production, (Titz at al. 2012) utilized SPI for assessing integrated bio-refinery to evaluate PHA and biodiesel production along others.

4.2.6 SPIonWeb

SPIonWeb is a follow up of excel based tool “SPIonExcel” and it provide more options to evaluate complex processes, including systematic evaluation energy technologies. It is an online web based free software tool, which can be used on any computing device (computer, smartphone or tablet), equipped with a browser regardless of operating system (Windows, Linux, Mac, IOS etc.). Users need only e mail addresses to sign up and use SPIonWeb. Processes information generated within user account are stored on the server and can only be accessible to the respective user. SPIonWeb provides the platform to the users to create life cycle for products or services provided by their specific process, based on energy and mass flows of that certain process. A core central data base containing average default processes (power generation "heat and energy production" base substance and chemicals) has been developed. These processes can be used by the users in their private (user) processes. It helps the user to assess life cycle of a product or service and estimates its SPI footprint, CO_2 emissions and GWP (global warming potential). It's more user friendly and addresses to students, engineers and experts in LCA modelling (Kettl and Narodoslawsky, 2013).

$$a_p = \max(a_{ew}, a_{es}, a_{ea}) \qquad [m^2] \qquad (7)$$

SPIonWeb is built on basic SPI methodology following sustainability principles. The only difference between SPIonExcel and SPIonWeb methodology is calculation of dissipation emission areas. The dissipation areas for emissions into different compartments were used to sum up in SPIonExcel, while SPIonWeb uses eq. 8 to define the dissipation area for emission flow. As shown in eq. 1 a_p represents sustainable dissipation area for emissions to soil water and air. The largest area among these partial dissipation areas is identified as key emission area. It is assumed that if area is provided for the compartment related to the key area, loading of impacts in all other replenished compartments will take place safely below natural concentrations. It is in accordance with principle 2 and reduces SPI footprints calculated by SPIonExcel (Kettl and Narodoslawsky, 2013).

4.2.7 Ecological evaluation of ANIMPOL process

The ecological evaluation carried out by using SPI methodology using inventory data shown in previous chapter follows as:

4.2.7.1 Hydrolysis

The SPI evaluation results for hydrolysis has been shown in Figure 3.2, which shows mineral acid and base are the main contributor having 86% share to the overall footprint of the process. Residues transportation from slaughter house to the facility and electricity provision also has considerable shares. The enormous shares of mineral acid and base are due to their amounts of use and highly energy intensive upstream life cycle production.

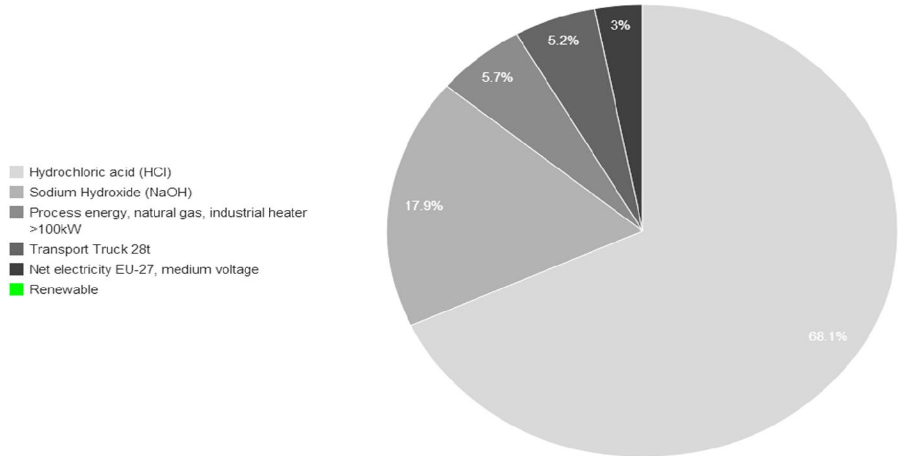

Figure 4.5: Distribution of SPI footprint for hydrolysis process

4.2.7.2 Rendering I

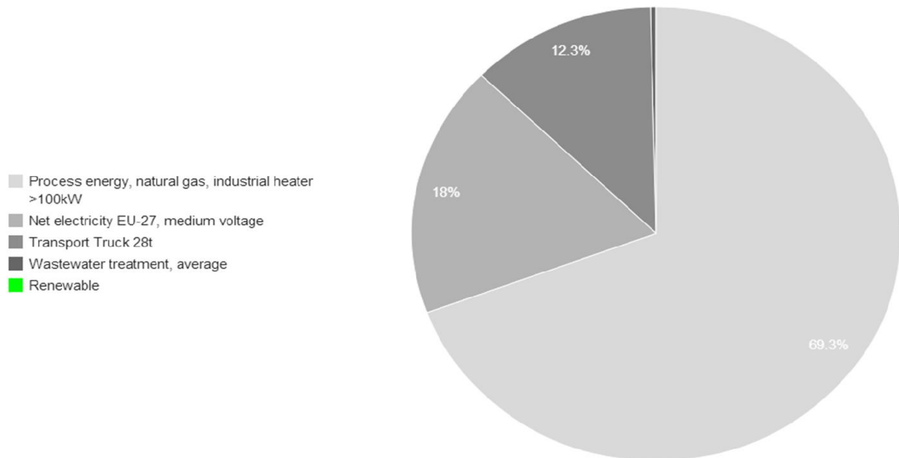

Figure 4.6: Contributions of SPI footprint for rendering I process

Figure 4.6 shows the ecological impact calculated by SPI method in accordance to life cycle inventory data for 1 MWh heat production shown in Table 3.2. It shows that heat, electricity and material transportation are the main contributors having 69%, 18% and 12 % shares to the overall footprint of this process. It indicates the potential of decrease in footprint by utilising energy from renewable energy resources.

4.2.7.3 Rendering II

The life cycle impact assessment using SPI methodology in accordance to data shown in Table 3.3, has been shown Figure 4.7.

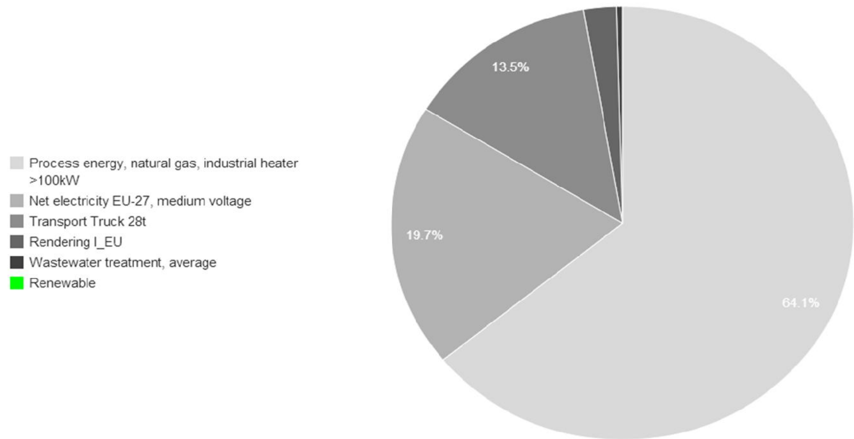

Figure 4.7: Contribution to SPI footprint of rendering II process

It reveals that about 86% footprint is caused by energy input (heat and electricity) including heat from rendering I and 13% by residue transportation. It shows that tallow production is highly energy intensive process. It indicates the potential of ecological optimization by integrating renewable energy inputs.

4.2.7.4 Biodiesel Production

An overview of ecological impact caused by biodiesel production, in accordance to life cycle inventory data shown in Table 3.4, has been shown in Figure 4.8.

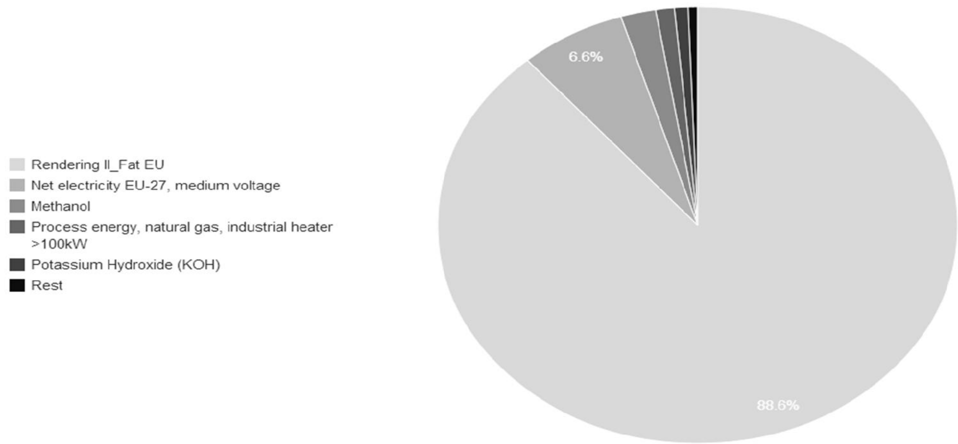

Figure 4.8: Distributions of SPI footprint for biodiesel production process

It reveals that raw materials tallow and methanol along with electricity input are the main contributors to the overall footprint of the process. Tallow is the main material input for biodiesel production i.e. 1.02 t of tallow is required for 1 t of biodiesel production. I has biggest share of footprint causing almost 89% of the overall footprint. The electricity provision is the other prominent contributor having 7% footprint share. As shown in rendering II results, tallow is produced from highly energy intensive process, these results indicate that this process have very high potential for ecological optimization by replacing energy input with more ecofriendly energy resources.

4.2.7.5 Fermentation Process

The ecological assessment results for 1t PHA production have been shown in Figure 4.9. These results are in accordance to life cycle inventory date for 1t PHA production shown in Table 3.1. The results reveal that carbon source (biodiesel) for bacteria to produce PHA is the biggest contributor to the overall impact of the process. It shares almost 68% of the overall impact while electricity provision contributes about 17%. Rest of the footprint is distributed among organic nitrogen source, inorganic chemicals and process energy. Heat provision has very small share in the overall process footprint which is due to heat reclamation using heat integration technology.

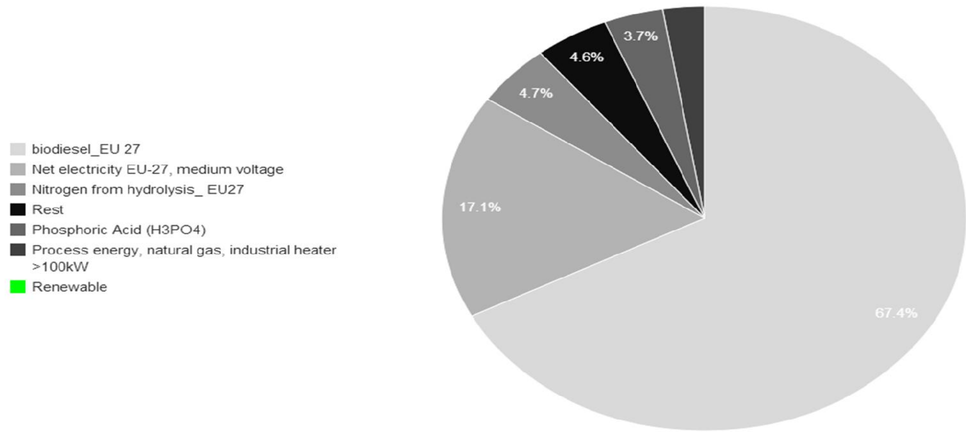

Figure 4.9: Inputs shares of SPI footprint for fermentation process (PHA production)

4.2.8 Effect of change of energy provision resources

The footprint analysis of sub-processes shows that conversion of slaughtering waste residues to a value added product is highly energy intensive process. It indicates potential of ecological optimization by using more eco-friendly energy from renewable energy resources. In order to assess the impact of change of energy from business as usual (electricity from EU mix or national grid and heating with natural gas) to other energy resources, an analysis of biodiesel and PHA production utilizing electricity from coal, hydro power, wind power, biomass and replacement of both electricity and heat from biomass and biogas has been carried out.

4.2.8.1 Comparative analysis of Biodiesel production

The effect of change of energy source on ecological footprint of biodiesel production using SPI has been shown in Figure 4.10. It shows that biodiesel production utilizing electricity form coal has highest footprint but still it has 55% lower footprint than diesel available at regional store. Biodiesel production using electricity from EU27 mix has 61% lower footprint, while biodiesel production using electricity from hydro power, wind power and biomass has 70% lower footprint than diesel. The replacement of electricity as well as heat from biogas has even better impact, having 75% lower footprint. The best scenario for biodiesel production is use of electricity as well as heat from biomass which has 93% lower footprint than diesel. These simulation results along the life cycle of biodiesel production show effectiveness of energy use from different resources.

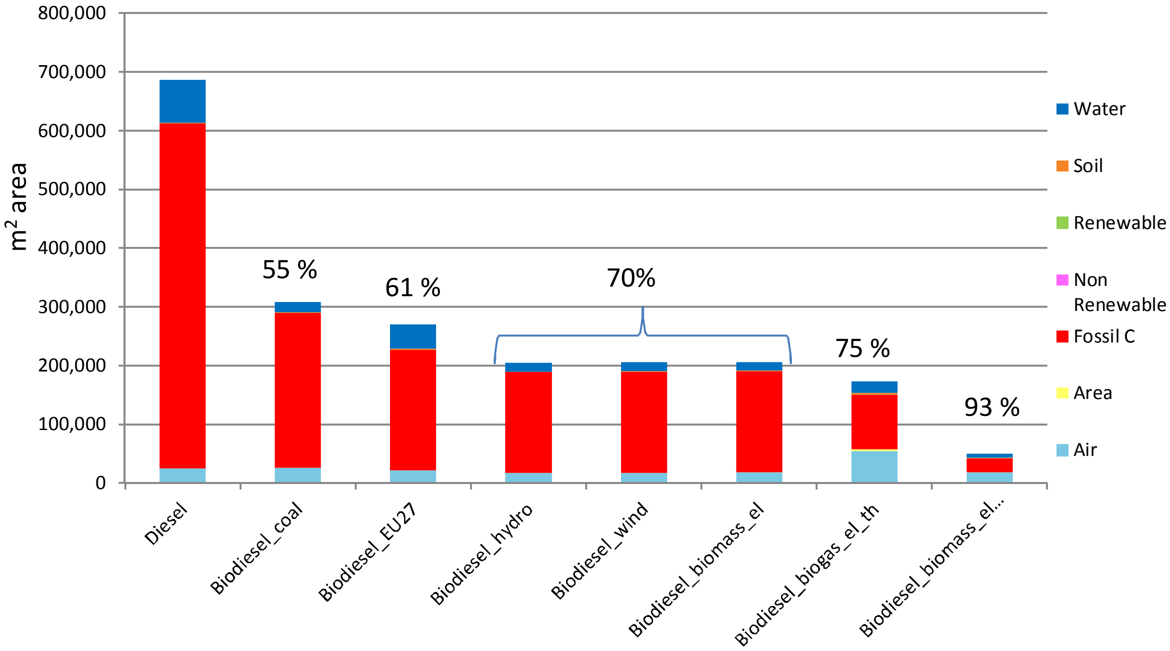

Figure 4.10: comparison of biodiesel production utilizing different energy resources and diesel at ex regional store

4.2.8.2 Comparative analysis of PHA production

The effect of change of energy resources on ecological impact of PHA production along the whole life cycle chain has been shown in Figure 4.11. Among PHA production results, PHA production using electricity from coal has highest SPI footprint. Its footprint value is still 59% less than polyethylene low density (PE-LD)footprint, a fossil based polymer considered as competitor of PHA. The footprint caused by PHA production using electricity form EU27 mix is 65% lower, while PHA production utilising electricity from hydro power, wind power and biomass has 77% lower footprint than PE-LD. The replacement of electricity as well as heat from biogas has slightly lower footprint than electricity from hydro power, wind power, and biomass. The most ecologically optimized scenario for PHA production is use of electricity and heat from biomass. It has 90% lower footprint value than PE-LD.

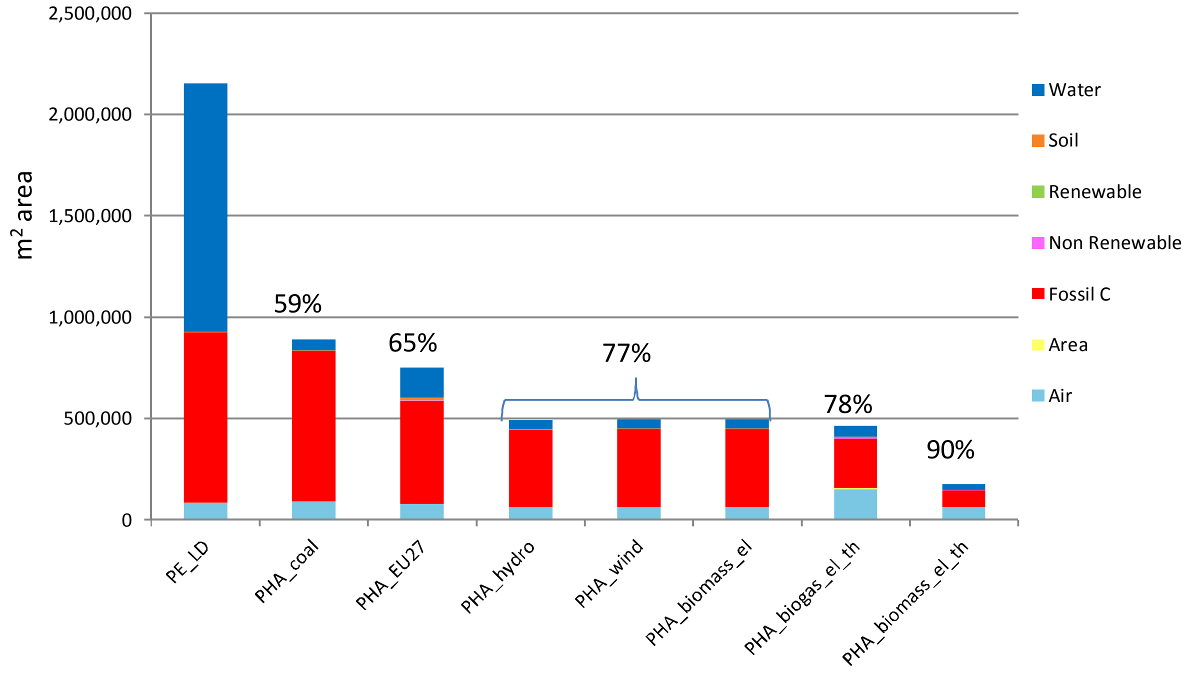

Figure 4.11: comparison of PHA production utilizing different energy resources and Polyethylene low density (PE_LD)

5 Carbon Footprint Avoiding Climate Risk

Climate change due to anthropogenic activities has been identified as one of the biggest challenges for regions, countries, businesses and individuals. In accordance to the Intergovernmental Panel on Climate Change (IPPC) report published in 2007, average global temperature of air and sea water is rising along with extensive melting of polar ice caps resulting in rise of average sea level. Due to which millions of people around the globe are threatened to lose their homes and livelihoods because of anthropogenic CO_2 emissions. It is estimated that in 2010, around 30 million ton of anthropogenic CO_2 was emitted to the atmosphere globally. It is an enormous amount of greenhouse gases (GHGs) released into atmosphere causing global warming (Hirner, 2012). It is causing implications for humans as well as natural systems. According to Meinshausen et al (2009) more than 100 countries have set a goal of GHG mitigation till 2050 compared to preindustrial level to keep average rise in global temperature 2 $^{\circ}$C or below. In order to meet this GHG mitigation target in the earth atmosphere several initiatives at international, national, regional and local level are being developed. One of these initiatives is Carbon Footprint (CF) calculation for regions, countries, businesses, products and services which is a single impact concern and provide assistance to the concern parties to plan their actions for GHG mitigation.

5.1 Normative back ground

The carbon footprint is a single issue measure, which addresses risk of climate change by calculating carbon based emissions e.g., carbon dioxide (CO_2), methane CH_4, etc. in order to attain a set goal of GHG mitigation till 2050, to keep average rise in temperature below 2 ˚C.

The CF of a product or service is the sum of carbon dioxide as well as other greenhouse gas emissions caused by direct or indirect activity along the whole life cycle or production chain stages of the product development. It is represented as kilograms of CO_2 equivalents and may also account for global warming potentials of greenhouse gases. Different definitions for CFP are available in literature. For example it is defined by Carbon Trust (2007) as:

a. "…a methodology to estimate the total emission of greenhouse gases (GHG) in carbon equivalents from a product across its life cycle from the production of raw material used in its manufacture, to disposal of the finished product (excluding in-use emissions)".

b. "…a technique for identifying and measuring the individual greenhouse gas emissions from each activity within a supply chain process step and the framework for attributing, these to each output product (we [The Carbon Trust] will refer to this as the product's carbon footprint)."

Wiedmann and Winx (2008) found several different definitions for carbon footprint in the literature depending on which gases are considered, the system boundaries for the assessment and several other factors. The CF definition put forward by Wiedmann and Winx (2008) is given as:

"*The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product*".

There are enormous number of Non-Governmental Organizations (NGOs) and Public authorities having their own CF software and online calculators but there was no standardized method available to be followed. In order to provide standardized reference methodology for carbon footprint of products (CFP) , (ISO) has developed ISO 14067[3]. It is aimed at providing detailed principles, guidelines and requirements for quantification and communication of calculation of carbon footprint for life cycle of products (CFPs) as well as partial carbon footprint of products (partial CFP) i.e. footprint of product from cradle to gate. It also includes reveals that communication of CFP to the intended audience is based on the CFP study report providing accurate, fair and appropriate representation of CFP (ISO 14067/TS, 2013).

5.2 Methodology

It is expected organizations, countries, communities and other concerned parties will be benefitted by clarity and consistency of quantifying and communication of CFPs. The CFP definition according to Technical Specification is given as:

[3] It is still in the process of development and agreement on its publication cannot be reached. So it is published as published as Technical Specification in accordance to ISO/IEC directives part I.

"Sum of greenhouse gas emissions and removals in a product system expressed as CO_2 equivalents and based on life cycle assessment using the single impact category of climate change".

In accordance to this definition CFP can be calculated using indicators like Global Warming Potential (GWP). The (IPCC) defines GWP as an indicator that reveals potential climate change effect caused by 1 kg of greenhouse gas over a specified time period such as 100 years (GWP100). The GWP of most common greenhouse gases in accordance to IPCC report (2007) are given in Table 5.1. The detailed list of GWP for different emission is provided in APPENDIX II.

Table 5.1: Global warming potential of common greenhouse gases relative to CO_2 (IPPC: 2007)

Type	*Chemical formula*	*GWP100*
Carbon Dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298
HFCs	-	124 -14800
Sulphur Hexafluoride	SF_6	22800
PFCs	-	7390 - 12200

As explained earlier CFP is the sum of GHGs over the whole life cycle of the product including upstream material acquirement, production use and end of life treatment i.e. cradle to grave assessment. It deals with single impact issue regarding climate, while ignoring other issues about environment systems. For example uncontrolled extensive use of biomass to reduce GHGs emissions can ruin biodiversity of the system. It shows that some time mitigation of one environmental impact can lead to adverse effect on other environmental aspect. So where decisions are made on the basis of information gained from single impact issue e.g. CFP, other environmental impacts should also be kept in mind (ISO 14067/TS, 2013).

Other limitations of CFP methodology are similar to ISO 14040 and ISO 14044, which include decision of system boundary condition, functional unit, availability and selection of suitable data, allocation methods, assumptions about transportation of the materials and end-of-life scenarios. Due to these shortcomings in the methodology it is very difficult to compare two different products or services on the same basis until unless both were assessed under same system boundary condition, having same functional unit, following identical assumptions and assessment procedure.

5.3 Footprint calculation for ANIMPOL

The carbon footprint is calculated along the life cycle of the process or product chain during SPI analysis. It is calculated from one of the seven area categories considered by SPI methodology. The fossil C, is calculated along the process chain and provides the opportunity to calculate carbon footprint. It is calculated by using following formula:

Carbon footprint = Fossil C area / 500 * 3.666

According to Bolin and Cook (1983) the rate of sedimentation of carbon is 0.002 kg per year per square meter of sea bed. It means that sedimentation of 1 kg/a fossil carbon requires 500 m^2 footprint area. While factor 3.666 shows that complete combustion of 1 kg fossil carbon yield 3.66 kg CO_2. The carbon footprint calculated for ANIMPOL and its sub-processes is given as follows.

5.3.1 Hydrolysis

The carbon footprint evaluation results according to inventory data shown in Table 3.1 are presented in Figure 5.1. The carbon foot print for 1 t hydrolysate production is 22,189 CO_2 kg equivalents.

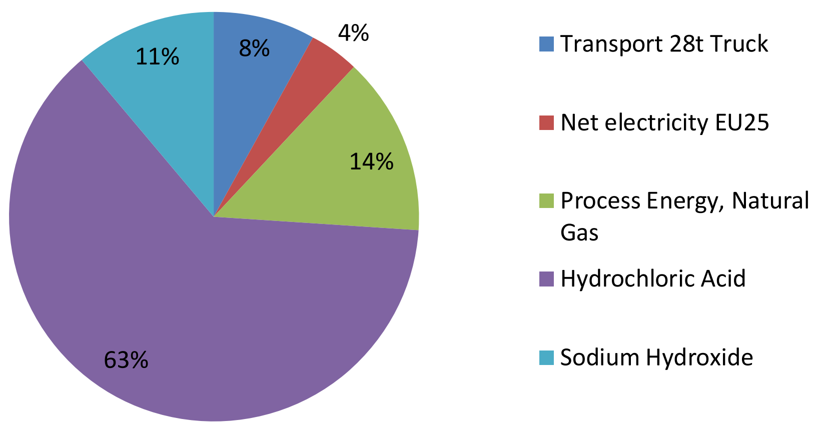

Figure 5.1: Carbon footprint distribution for Hydrolysis

The represented results reveal that hydrochloric acid has the maximum ecological pressure ranging up to 63% of the overall footprint. Other prominent contributors include heat provision 14%, sodium hydroxide 11%, residues transportation 8% and electricity input 4% shares to the overall footprint. These results indicate that mineral acid and base is the main driver of the process contributing almost 75% of the total footprint, while transportation and utilities provide the rest 25% of the footprint.

5.3.2 Rendering

The carbon footprint results for rendering I and rendering II are 147 and 1,889 CO_2 kg equivalent respectively. The contribution from different inputs is presented in Figure 5.2. These results are calculated in accordance to inventory data shown in Table 3.3.

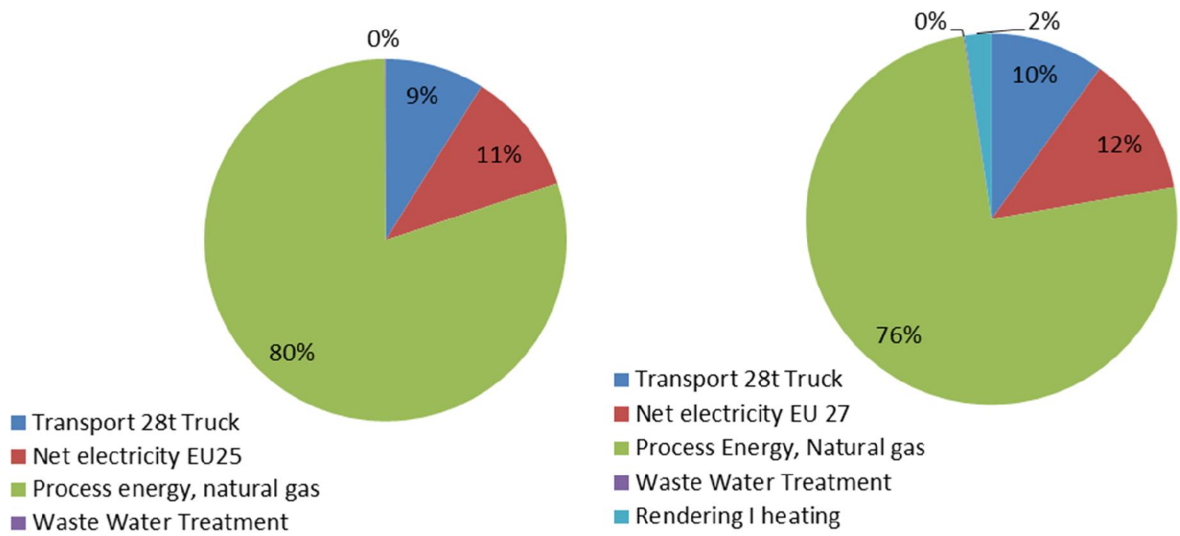

Figure 5.2: Carbon footprint contributions for rendering I (left) and rendering II (right) from different inputs

The results reveal that both process results have similar trends. Heat provision is the main ecological impact contributor with almost 80% contribution in both processes. Electricity provision contributes 11% and 12% for rendering I and rendering II results, while residue transportation contributions are 9% and 10% respectively, to the overall process results. These results indicate that rendering processes are highly energy intensive cooking and milling processes which produce fat and MBM as products.

5.3.3 Biodiesel production

The carbon footprint for 1 t biodiesel production is 1,523 CO_2 kg equivalents. The inventory data used for this calculation has been shown in Table 3.1. The contribution shares of carbon footprint from different inputs are presented in Figure 5.3.

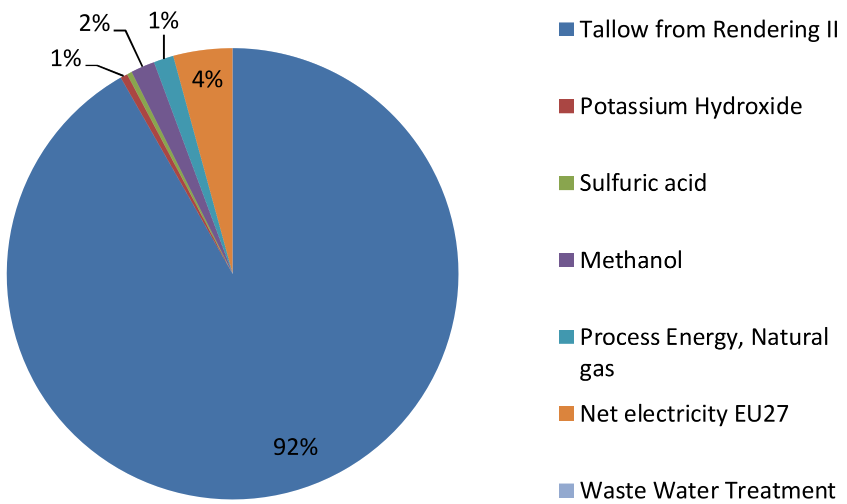

Figure 5.3: Carbon footprint share distribution for biodiesel production

The figure reveals that 92% share is contributed by tallow to the overall footprint of the process. The rest 8% footprint share is contributed by electricity, heat, potassium hydroxide, sulfuric acid, methanol and waste water treatment. Glycerol is produced as a byproduct during biodiesel production. The footprint is allocated to biodiesel and glycerol according to mass allocation method. The high footprint value is due to very high consumption rate of tallow which is obtained through highly energy intensive rendering process.

5.3.4 Fermentation (PHA production)

The inventory data for fermentation process and downstream processing for PHA purification is shown in Table 3.5. The contribution of carbon footprint caused by different inputs has been presented in Figure 5.4 and equals to 3,729 kg CO_2 equivalents.

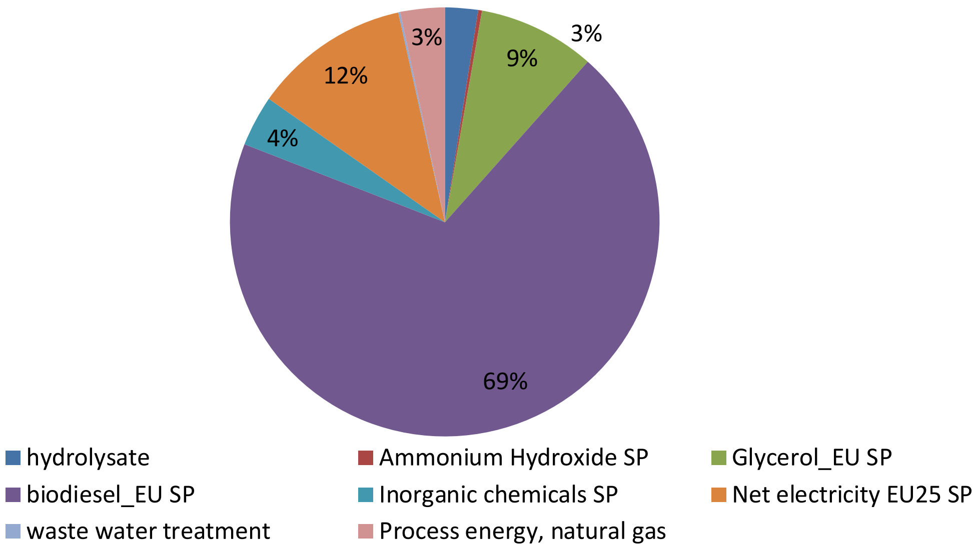

Figure 5.4: Carbon footprint contributions for fermentation process (PHA production)

The results shown in the above figure reveal that about 78% footprints are caused by the carbon input sources (biodiesel and glycerol). Electricity consumption also has considerable 12% contribution, while rest 10% is caused by organic nitrogen source (hydrolysate), heat provision and inorganic chemical inputs. The main drivers for the process are carbon sources and electricity consumption, while others serves as minor contributors.

5.3.5 Effect of change of energy provision resources

As shown by the sub-processes results, the conversion of animal slaughtering residues to PHA, is an energy (electricity and heat) intensive process. In order to ecologically optimize the process, the effect of change of energy provision resources has been studied.

5.3.5.1 Comparative analysis of biodiesel production

The transesterification of tallow with methanol in the presence of potassium hydroxide and sulfuric acid as catalysts results in the formation of tallow methyl ester (TME). The main footprint for this process comes from tallow which is produced from highly energy intensive rendering process. The effect of change of electricity as well as heat provision has been tested. The effect of change of energy along with heat provision has been shown in Figure 5.5. The effect of change of electricity provision from basic scenario i.e. electricity from EU27 with coal, hydro power, wind power and electricity from biomass "PHA_biomass_el" were tested. Along with electricity replacement a couple of scenarios with replacement of electricity as well as heat provision were also carried out, which are "PHA_biomass_el_th" i.e. heat and electricity provision from biomass and "PHA_biogas_el_th" i.e. heat and electricity provision from biogas.

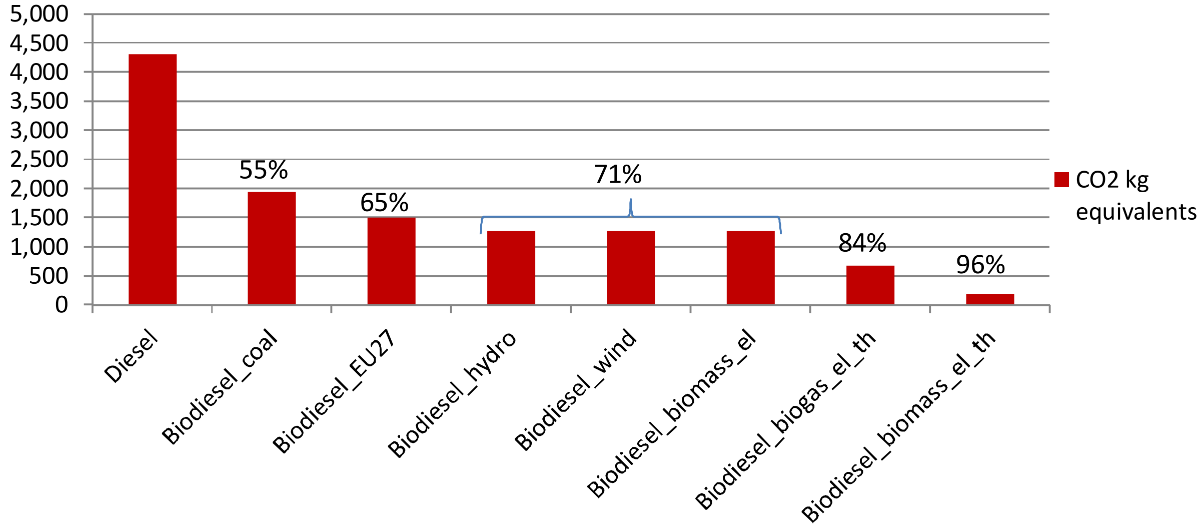

Figure 5.5: Carbon footprint comparison of biodiesel production utilizing different energy resources and diesel at regional distribution store as fossil competitor

The results show that biodiesel production utilizing electricity from coal high footprint value than biodiesel production utilizing electricity from EU27mix. Still biodiesel production using electricity from coal has 55% less footprint than diesel available at ex regional store. Biodiesel production using electricity from EU27mix has 65% lower footprint, while use of electricity from hydro, wind and biomass have 71% lower footprint than diesel. The use of heat and electricity for biodiesel production from biogas has even better result by lowering footprint value up to 84%. The best option for biodiesel production having lowest footprint value is biodiesel production using heat and electricity from biomass. It has 96% lower footprint value than diesel.

5.3.5.2 Comparative analysis of PHA production

PHA production has also been tested by replacing energy provision resources. The simulated results are shown in Figure 5.6. Polyethylene low density (PE-LD) is the considered as the main competitor of PHA. The footprint of PHA production has been compared against polyethylene. . PHA production utilizing electricity from coal has highest footprint value. The results show that it has 12% lower footprint value than PE-LD, while basic scenario (use of electricity from

EU27mix and heat from natural gas) has 39% lower footprint. The use of electricity from hydro, wind and biomass also decreases footprint and its value become 54% lower than PE-LD.

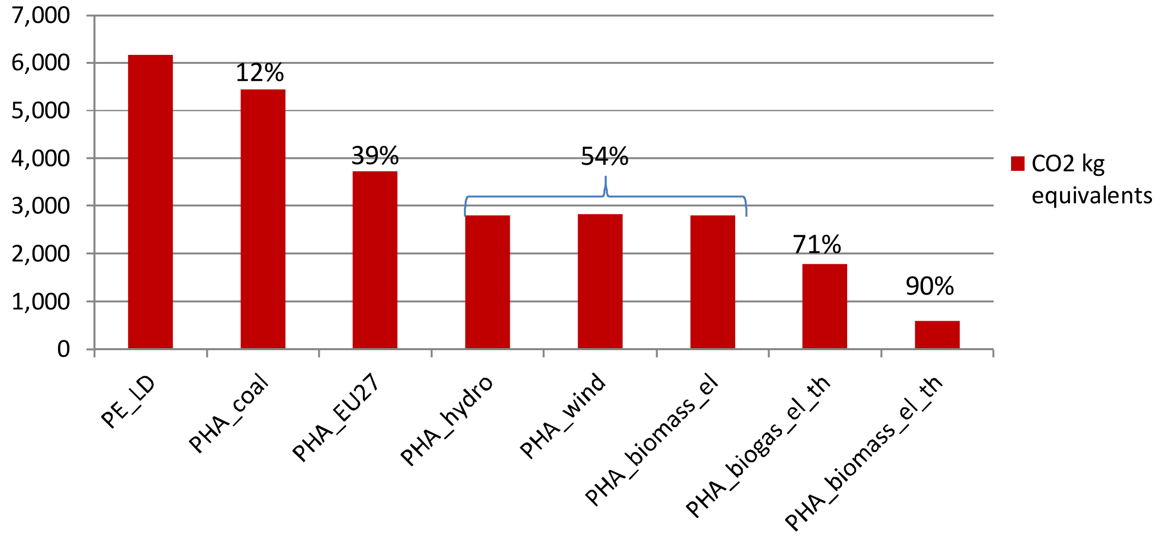

Figure 5.6: Carbon footprint comparison of PHA production utilizing different energy resources and polyethylene low density (PE_LD) as fossil based competitor

Replacements of electricity as well as heat from biogas decreases footprint up to 71% lower than PE-LD. The lowest footprint of PHA production is shown by electricity and heat provision from biomass, having 90% lower footprint value than PE-LD.

6 Emergy Accounting Following Solar Income and Pursuing Autarky

In the 1950's H. T. Odum and his brother have started developing the roots of emergy by realizing the importance of energy to ecology and later energy quality and need to use a "common denominator for energy flows of different kinds" (Hau and Bakshi, 2004).

H. T. Odum (1994) describes the whole planet is a self-organizing system in which resource storages are continuously exhausted and substituted at different rates. The recycling and organization of matter takes place during self-organizational activity driven by solar, geothermal and gravitational energies. Maximization of products and services for growth and support, takes place according to the design principle of self-organization given by Alfred Lotka, also known as maximum power principle. The maximum power principle definition by H. T. Odum is:

"*In time, through the process of trial and error, complex patterns of structure and processes have evolved...the successful ones surviving because they use materials and energies well in their own maintenance, and compete well with other patterns that chance interposes.*"

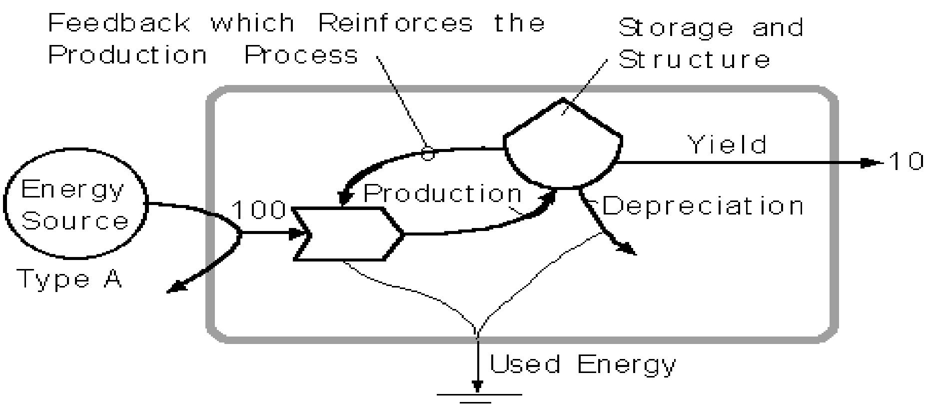

Figure 6.1: Reinforcement of energy transformation, storage and feedback in units self-organized for maximum performance (H. T. Odum, 1998)

The pathways shown in Figure 6.1 illustrate the flows and energy conservation. Tank symbol is used for the storage. The heat sink symbol is used to present the dispersal of available energy from processes and storages following the second law of thermodynamics (H. T. Odum, 1998).

From this concept H. T. Odum derived the basic principle of empower flow and developed the thermodynamic language for energy networks of open systems. He has also developed e.g. energy based common concept of economics and ecosystem sciences integration. The term emergy was first used by David Scienceman in 1983, for **"embodied energies"** described by H. T. Odum, he also termed the units of emergy as emjoules and emcalories to distinguish it from units of available energy (Brown and Ulgiati 2004).

The quality of energy is related to its form and concentration, means high quality is synonymous to higher concentration and provides greater flexibility in its use. For example wood has more concentrated energy than detritus, coal more concentrated than wood and electricity has more concentrated energy than coal. This pattern shows that energy quality increase correspond to increase in energy concentration. Energy quality is measured against a certain reference state, the farther from a reference state, the higher the energy quality, it also varies from system to system. Energy of high quality in one system may not be of same quality in the other system, which may have been optimized following different self-organizing system. For example emergies of solar, coal and electrical energies have different energies which are expressed as solar emergy equivalent joule (seJ) (H. T. Odum, 1998).

There are two different perspectives available for defining material and information quality. First one is "user quality" in which user defines the scale of worth, in accordance to its expectations and utility (energy, material and information) demands. The higher the utility demand the higher the quality. Normally economics defines the value of quality as user quality depending on utility and shortage. In engineering applications energy quality is defined according to the exergy to energy ratio. It is also an example of user defined quality as energy is ranked for its product or service output per unit energy input. The other form of quality definition is "donor-defined quality" which is based on investment in something. The greater the invested value the higher the quality is. Examples of this valuation are parenting, education, working skills etc. the more the effort put into the process the higher the quality of the product (Brown and Ulgiati ch.2, forthcoming).

6.1 Normative Background

Emergy accounting is one of the thermodynamic sustainability measures. The fundamental principle of emergy analysis is based on the consideration that earth is a closed system with solar energy, tidal energy and deep earth heat as main energy inputs and living systems are sustaining each other by energy flow and conversion of one form of energy (low quality) into another (high quality) and degraded heat (Hau and Bakshi, 2004).

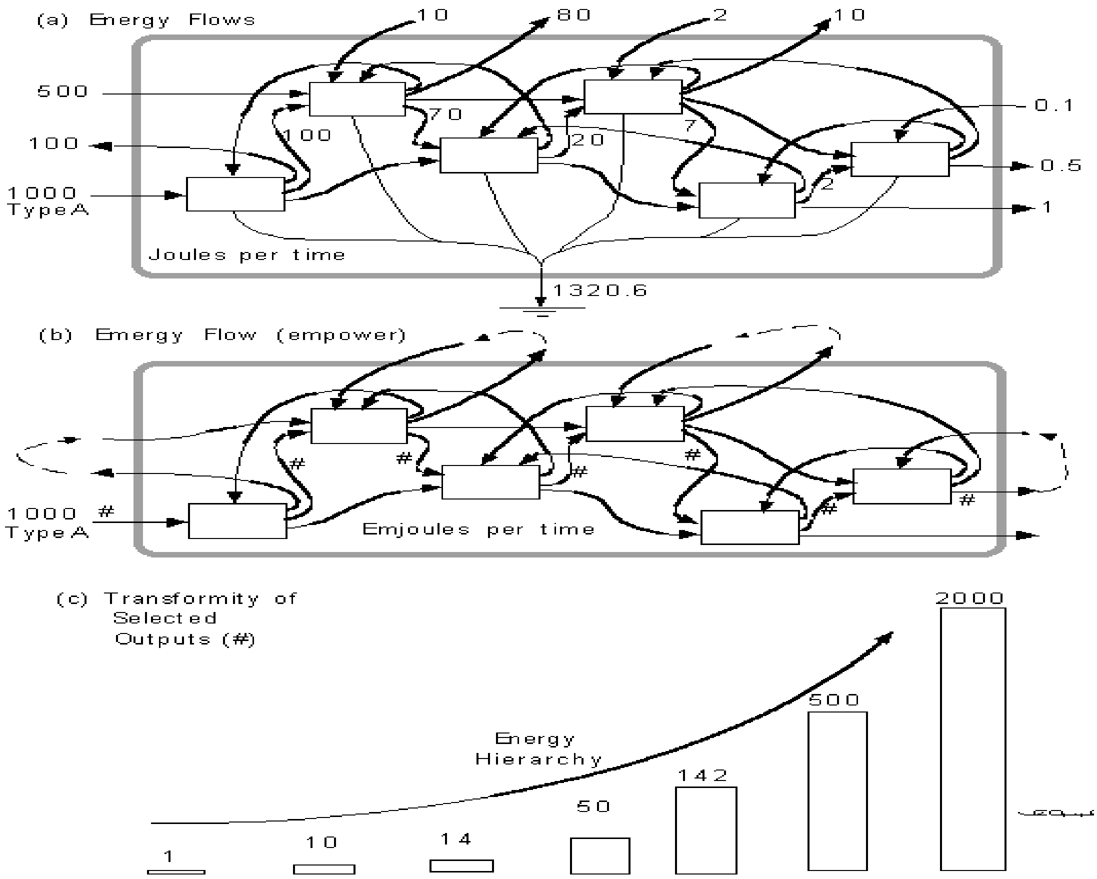

Figure 6.2: System window-wiew of a network representing mutually necessary, energy transformations running on the same source. (H. T. Odum, 1998)

Emergy accounting follows donor-based concept of quality and utilizes thermodynamic basis of material and energy flows to convert them into equivalent of one form of energy, usually sunlight (H. T. Odum 1996). Emergy is the amount of exergy, which is required directly or indirectly to make something. It is the measure of global processes (sun, deep heat and gravitation potential) expressed in the same energy form, required for a process or to make something. Figure 6.2 illustrates single source based network of energy transforming component as shown in Figure 6.1.

The total quantity of energy decrease from left to right but due to more transformations taking place along the path, quality of energy increases from left to right. In is also known as energy hierarchy because each transformation results in convergence of energy flows to make fewer flows of higher energy quality. The energy content decreases from left to right but transformed energy has more ability to reinforce other units of the system. Universal law of energy hierarchy can also be explained by arranging all known process in a series of networks. The examples of universal hierarchy are energy chains of organisms in food web, ecosystem, economies, earth processes and the starts (H. T. Odum, 1998)

It is clear now that more work done to produce something, the higher the quality and more available energy will be transformed and higher the emergy content of the product produced. The total emergy required to make a product or run a process is the measure of self-organizational action of the surrounding environment which is congregated to make that process occur. It is measure of both present and past environmental work necessary to provide the given resource e.g. wood in the forest, oil reservoirs present in the deep soils or any other manufactured goods (Brown and Ulgiati forthcoming).

6.2 Methodology

Ulgiati and Brown (1998) described that the emergy input to a process is the result of all resources and energy input traced back into all processes or chain of processes, used in the process and expressed each in the form of solar energy. Emergy is the measure of value for both energy and material resources at common basis, which is equivalent to biosphere processes required to produce something. The environmental services which are normally free of cost and outside the monetary economy as well as services of humans in the form of labor for processing of the resource are embedded in the emergy value of the resource. So emergy definition by Brown and Ulgiati (H. T. Odum, 1994) is:

"*Emergy is the available energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service*".

The unit of emergy is **emjoule,** which refers to the consumption of available energy in the transformations. For example sunlight, wood, coal, oil and electricity and human services can be transformed into common basis by expressing them in the emjoules of solar energy, required to produce each of them. The value is a unit of solar equivalent energy articulated in solar emjoules which is abbreviated as (seJ).

Thus total emergy input for a process is the sum of all inputs in terms of their solar energy, to obtain the required product or service. The solar emergy of a product is the product of its energy content and solar transformity as shown in the following equation.

$$Em = \sum_i fi * tr_i \qquad i = 1, \ldots \ldots, n \qquad 1$$

Where Em presents the solar emergy (seJ/unit), fi the input flow of ith component and tri is the transformity of the ith flow component. The equation is further translated into calculation or emergy evaluation tables. For emergy calculations renewable inputs (solar radiations, wind, rain potential, geothermal) and non-renewable inputs (soil erosion) for a process, system or region are calculated by utilizing area within boundary conditions of the system under study. The boundary conditions of the system can be selected at plant area, regional area, national level and global level. The renewable as well as local non-renewable (soil erosion) depend on the spatial location of the system. Normally system boundaries are set at national level considering national area for renewable and local non-renewable flow calculations. The calculation of renewable energy flows as well as all other flows is given in APPENDEX III.

Emergy accounting also take into account economic and social impacts of the society. The emergy input per unit of economic product output is termed as emergy unit money. It also provide the amount of emergy one can purchase using certain amount of money in a given country. The purchasing of resources in an economy depends on emergy supporting the economy and the amount of money in circulation. The average money to emergy ratio i.e. emjoules/$ can be calculated by dividing total emergy input of a nation or state by its gross economic product. The emergy/money is valuable for the evaluation of service inputs given in money units e.g prices of the input materials or wages of the labor. For example if current market price of crude oil is $95 / barrel and emergy content in a barrel (bbl) is 8.6E14 seJ (6.1E14 J * 1.41E5 seJ/J), then emergy flow for each dollar (8.6E14 seJ / $95) is approximately 9.05 E12 seJ. This emergy to dollar or currency ratio is known as emprice. Thus emprice of crude oil is 9.05E12 seJ/$ when crude oil price is $95/bbl. Similarly all supplies in the modern economic market have specific emprice which is calculated by dividing their emergy value with their market or economic price.

The value of the solar emergy required for running a process or making a product to the output (in the form of mass, energy, labor or money) of the process or amount of product produced is termed as Unit Emergy Value (UEV). It is the UEVs are calculated to produce a single unit of output e.g. seJ/g, seJ/J or seJ/$ etc, which are compared against the reference emergy flow calculated for the region, country or at large biosphere depending on the system boundary. UEVs gave the same function as that of area (presented as m^2), required in ecological footprint or SPI for sustainable embedding of a process or activity in the earth surface. Some of the common UEVs are explained in more detail as follows:

6.2.1 Transformity

Solar emergy input per unit of available energy (exergy) output is termed as solar transformity. It is represented as seJ/J. If 40,000 emjoules are required to produce 1 joule of wood, then its solar transformity is 40,000 seJ/J. Similarly for oil 310,000 emjoules are required to produce one joule of oil equivalent, its solar transformity is 310,000 seJ/J. The solar transformity of the sunlight is 1.0 by definition and it is the most abundant but dispersed form of energy on earth.

The concentration of solar emergy through a hierarchy of processes or levels is measured as solar transformity of the specific product output. It is measure of direct or indirect global process support required by a process or product under study from the surrounding environment. So high transformity materials and energy resources require greater environmental energy flows for their production.

As explained in Figure 6.2, transformity increase greatly in going from left to right through energy hierarchy. It is used to locate the position of any energy flow or storage in the universal hierarchy. The transformities have inverse relation to energy flows. General distribution of transformities has been shown in Figure 6.3.

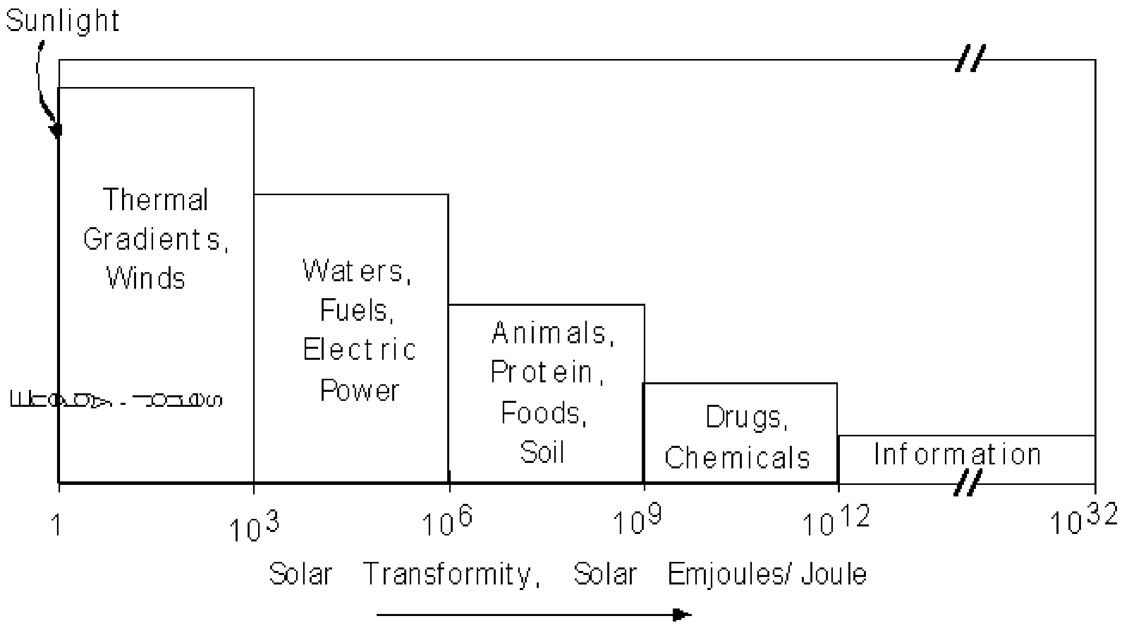

Figure 6.3: Distribution of Transformaties (H. T. Odum, 1998)

The effective use of energy is only possible when it amplifies by interaction with matching energy of lower or higher transformity. It defines an appropriate position and efficient use for each kind of energy with in energy spectrum. Theoretically each and every item has a minimum transformity when it is formed as a result of most efficient formation at the optimal loading for empower. Although for newly developed systems which are either operating at much faster rate than the rate for maximum empower, or otherwise inefficient, the transformity may be much higher than thermodynamic minimum. These minimum and observed large values are useful parameters, one to compare potentials of optimization, the other to evaluate efficiencies of current practices (H. T. Odum, 1998, H. T. Odum, 1996).

6.2.2 Specific Emergy

Solar input per unit mass output is termed specific emergy and expressed as solar emergy per gram (seJ/g). As explained earlier available emergy increases with material concentration, so naturally scarce elements and compounds have higher emergy/mass ratios, when found in the form of concentrated ore, due to more embedded environmental work is required to concentrate them. For example emergy of metals converge to hierarchical centers with concentration and diverge again during their dissipation.

6.2.3 *Emergy cost of labor*

The amount of emergy input required to support one unit of labor directly supplied to a process is known as emergy cost of labor. The workers apply their work on the process and in doing so they invest the whole emergy due to which their labor is possible (food, health, education, training, transportation etc.). Normally this emergy intensity is expressed as emergy per time i.e. seJ/yr or seJ/hr, while emergy per money earned has also been used seJ/$. The indirect labor service for a process to supply the inputs is generally measured as dollar cost of services, that's why emergy intensity of labor is also calculated as seJ/$.

6.3 Value added property of the material flows

In economic terms, value added means difference between sale price and production cost of a product. Similarly value added can also be understood as the price of an item increases with each conversion along the process chain from cradle to grave (in accordance to LCA terminology). This phenomenon of value addition is described by Brown and Ulgiati (ch.5, forthcoming) as shown in Figure 6.4, for a fish swimming in the ocean till a customer eats it in the restaurant. The reported emergy content in fish is 42 E12 seJ (1kg* 50% * 1000 g/kg *5 kcal/g * 1E6 seJ ≈ 10.5 E12 seJ). At each and every step during the chain emergy is added in the form of investment due to fuel and information (labor and service). In the first step (P_1) a transaction of $2 is made to the fisherman, which is used by him to buy energy, goods and labor from the market or economy equivalent to 4.8 E12 seJ. The 2nd transaction (P_2) is equal to $5 which is paid by the whole sale dealer. Out of which $2 goes to the fisherman and rest $3 are used to purchase emergy inputs for energy, goods and labor to the market totaling 5.7 E12 seJ. The next transaction (P_3) of $10 is carried out between the wholesaler and the restaurant owner. Out of this $5 are paid to the market and rest $5 are paid to buy energy, labor and goods of 9.5 E12 seJ. The final transaction (P_4) takes place at the restaurant where the customer pays $25 to the restaurant owner for the fish. Out of this $10 are paid to the wholesaler while $15 are used to purchase energy, goods and labor for the restaurant which is equivalent to 30.0 E12 seJ.

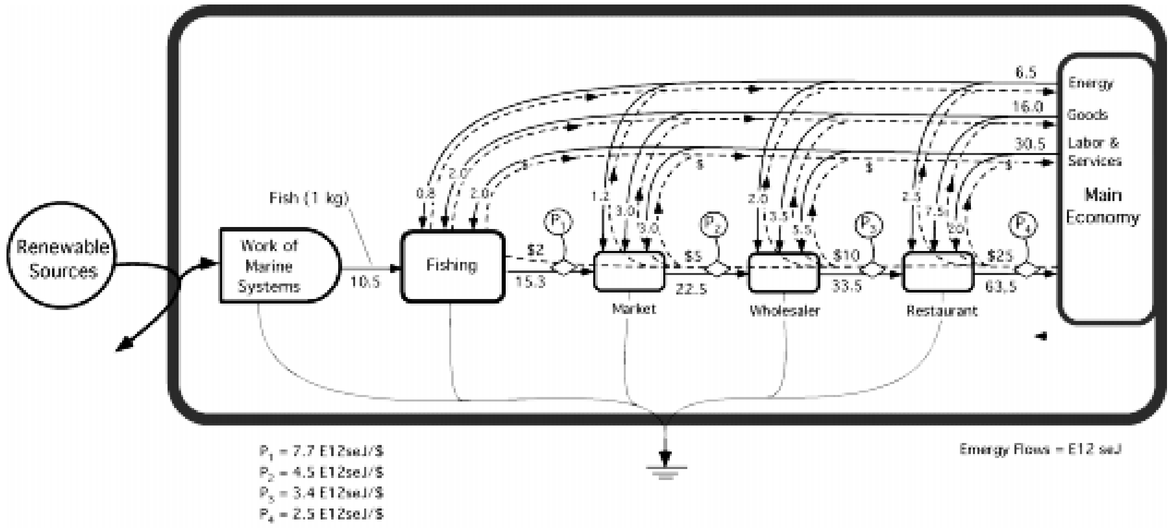

*Figure 6.4: The economic concept of value added using the example of a 1 kg fish. P1 is the price of fish paid to the fisherman, P2 is the price paid at the fish market, P3 is the price paid to the wholesaler, and P4 is the price finally paid by the customer at a restaurant. The emprice at each step in the economic chain decreases. The emergy of the fish (10.5 E12 seJ) is "matched" or "attracts" energy, goods and labor from the main economy totaling 53.0 E12 seJ. . (Emergy of the fish = 1kg * 50% dry weight *5 Kcal/g * 4187 J/Kcal* 1 E6 seJ/J) (Brown and Uljiati, Ch.5, forthcoming).*

With every "transformation" economic value is added to the fish, more and more is paid for the same kg of fish, while money is also paid for energy, fuel, goods and labor at each step. The emergy content of the fish increases from 10.5 E12 seJ/kg to 63.5 E12 seJ/kg, from left to right which is almost 6 times the initial value. The fish has mobilized an emergy investment of almost 5/1 from the main economy in the form of energy, fuel, goods, labor and service.

The fish has highest emprice at the first step when it was sold to the market having highest contribution to the economy, while at the final step when it is consumed by the customer, it does not contribute to the economy anymore. So, in general raw materials have highest potential contributions to the economy in emergy terms, as compared to the finished products. It has been shown by 3 fold decrease in emprice from 7.7 E12 seJ/$ to 2.25 E12 seJ/$, showing an inverse relation to the number of transaction. Greater the number of transactions in a value chain lesser will be the emprice of the product, although overall emergy content. It shows that monetary value of an item is in fact measure of labor and service required to produce it, rather than its emergy value. The price shows the amount of labor and services invested in a product and not its emergy content, because money is always paid to the people and never to the environment (Brown and Ulgiati, 2014).

6.4 Emergy Accounting and Sustainability

Based on the identified input flows and evaluated total emergy which is driving the process, a set of additional indices and ratios can be calculated for measuring sustainability of the process, product or region. Some of the factors which have to be considered for judging sustainability of anthropogenic activity (Brown and Ulgiati, 1997) are:

i) Net yield of the process,
ii) Environmental load of the process
iii) Use of non-renewable inputs

Three main emergy flows which are considered to evaluate a process system in emergy accounting are given as:

- **Renewable flows (R)** are the flows within the system boundary or locally available e.g. sunlight, air and chemical potential of rain falling etc. These are the persistent and reoccurring energy flows of the biosphere. The biological and chemical processes on the earth are carried out by these energy flows and ultimately support the geological processes. Occasionally energy resources (wood and biomass) arising by these resources are regarded as renewable resources. In this case these energy resources must have their production rate equal to their consumption rate, if the consumption rate exceeds the production rate it is accounted as a non-renewable resource.
- **Non-renewable flows (N)** are flows within the system but stock limited and not always locally available e.g. coal, oil, natural gas and ground water, means sources which have faster consumption rates than recharge.
- **The feedback flows (F)** are always stock limited, unavailable locally and imported from the outside boundary of the system like flows of the goods, labor and human services from economy to construct and operate a process or system and maintain its services (Brown and Ulgiati, 2002).

Emergy indices has been defined and explained by a lot of authors (Odum, 1996; Ulgiati et al. 1994; Doherty et al. 1992; Brown and McClanahan, 1996) to discuss different aspects of sustainability.

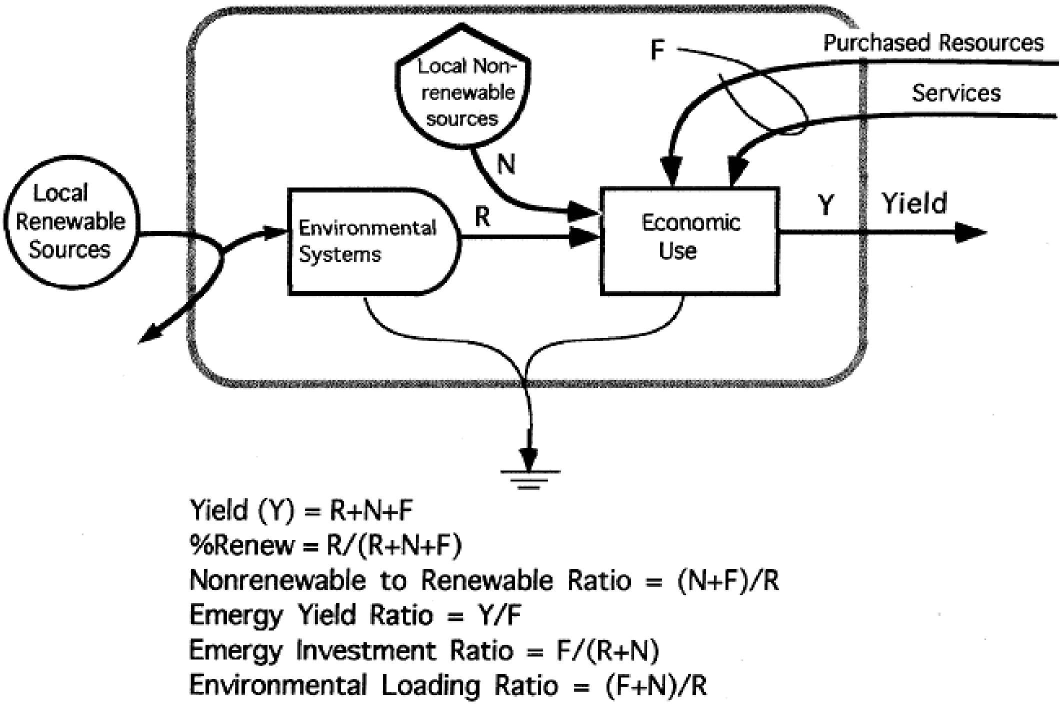

Figure 6.5: Emergy based indices, accounting for local renewable emergy inputs (R), local nonrenewable inputs (N), and purchased inputs from outside the system (F) (Brown and Ulgiati, 1997).

Other flows in emergy evaluation include total emergy content of the process (U), labor (L) and services (S). Some of the indicators defined and explained by Brown and Ulgiati (1997) as shown in Figure 6.5 and emergy flows explained in the above paragraph are given as:

6.4.1 The Environmental Yield Ratio (EYR) EYR = U/(F+L+S)

It is the ratio between product produced and purchased input value (F) entering the system from outside (imports to the system). It describes the ability of the system to utilize local resources during its functioning. It is obtained by dividing output emergy value with imported input value.

In other words it could be defined as a measure of additional resources produced in a process per unit investment or input. It means that it is measure of process efficiency to provide return on investment. It cannot distinguish between renewable and non-renewable flows, but only among investment and return on emergy flows. It compares processes based on their ability to convert invested material into new product or service. Investment means input emergy flows in the form of material or energy (feed stock) entering the process to allow transformation into upgraded material or energy forms. For example in energy production processes investment consists of energy and information (know how, labor, service) provided to the process to execute, while material constitute the feed stock input (crude oil, biomass, natural gas, solar radiations etc.), which are transformed from one form of energy to another. In material transformation processes (e.g. formation of poly ethylene bag from polyethylene), polyethylene is the feed stock while energy input and information are investment. According to above explanation EYR can written in the form of an equation, given as:

$$\mathrm{EYR} = \frac{\mathrm{U}}{\mathrm{I}} = \frac{\mathrm{TF} + \sum_i(\mathrm{R_i} + \mathrm{M_i}) + \sum_i(\mathrm{E_i} + \mathrm{S_i})}{\sum_i(\mathrm{E_i} + \mathrm{S_i})} \qquad 2$$

So net emergy can be written as:

$$\text{Net Emergy} = \mathrm{U} - \mathrm{I} = \mathrm{TF} + \sum_i(\mathrm{R_i} + \mathrm{M_i}) + \sum_i(\mathrm{E_i} + \mathrm{S_i}) - \sum_i(\mathrm{E_i} + \mathrm{S_i}) \qquad 3$$

Where (i) represent the components of material and energy flow under consideration, others follow as:

U = total emergy required to make a product

I = Emergy investment

TF = transformed feed stock

R = Renewable input or resources

M = Material resources

E = non-renewable energy

S = information (labor and services)

U, the sum of emergy of transformed feed stock (TF) i.e. sum of all emergy flows, renewable resources (R) (only those which are recharged faster than their consumption), raw material resources (M), non-renewable energy input (E) and information (S), is the amount of emergy utilized in the process to deliver the product. Similarly (I) is the sum of emergy contribution from non-renewable energy (E) and information (S). It does not include emergy content of material input (M) neither from renewable resources (R). The reason for renewable emergy contribution exclusion from investment is due to the consideration that it is a human controlled process and only intentionally provided inputs are counted. In case of glass bottles production process (U) is the sum of emergy content for silica, fuel, renewable and information while (I) includes emergy content of energy input and information. It has been observed that if a process has higher return on unit investment than another process, it can deliver more yields (more electricity in case of energy production, more polyethylene bags in case of polyethylene bag production process) to the final use as well. It means that efficient processes require less investment to deliver the same product than inefficient processes. In this way efficient processes save resources for the end users to utilize in other process to obtain other requires products or services.

The minimum possible value of EYR is one, which means that whole amount of invested emergy input is used to carry out the process. So, the processes having EYR value one or slightly more than one do not deliver substantial amounts of net emergy to the user and only coverts the provided resources into products. These processes act as consumer processes and so not participate significantly in system development. The EYR values for primary energy sources (coal, crude oil, natural gas, uranium) are usually greater than five. The reason for these high values is production of high emergy flows as a return at the expense of small economic inputs. Similarly secondary energy flows and primary materials provide moderate benefits from investment and their EYR values fall between two and five (Brown and Ulgiati, Ch2, forthcoming).

Similarly societies, regional and national economies exploit locally available as well as imported resources by investing emergy resources. In the economies EYR is not any more a yield ratio, rather it serves as an index of 'locally sustainable production'. In case of economies EYR is calculated by dividing national or regional economic production by imported emergy, which is expressed as production per unit of imports (Brown and Ulgiati, 1997).

6.4.2 The Environmental Loading Ratio (ELR) (ELR) = (F + L + S)/R

It is the ratio of the emergy content of purchased flows F and non-renewable local flow N to the free emergy content of the environment i.e. renewable flow R. It is the measure of pressure exerted on the local ecosystem by the process and is considered as stress on the ecosystem due to the production activity.

This indicator is designed to determine the pressure exerted by the non-renewable resource (imported or purchase and local non-renewable) investment on the indigenous renewable resources utilized by the process or activity. It measures the overall emergy expenses and possible environmental disorder caused by certain development in the region. It has been reported that processes having low ELRs (around two or less) cause relatively low environmental stress or have wider access (means wider system boundary at national or biosphere level which in turn provide access to more renewable flow) to the local environment to 'dilute the load'. Similarly ELRs from three to ten reveal moderate pressure (which could be in case of considering regional area as system boundary). ELR values from 10 to extremely high numbers indicate very high pressure on a small local environment caused by the massive non-renewable emergy flows (in case of considering renewable energy flows accounting for very small system boundary area e.g area of industrial plant having very limited flow of renewable resources). The supply chain of investments may also cause environmental disorder outside the local system boundaries. It does not account any specific local pollution e.g. SO_2, NO_x etc. rather it indicates the stress caused by the invested emergies (Brown and Ulgiati, Ch.2, forthcoming).

6.4.3 Emergy Sustainability Index (ESI) EYR/ELR

Emergy Sustainability Index is the ratio of EYR to ELR and provides information about environmental pressure exerted by the product (Brown and Ulgiati 1997). Lower ESI values indicate that processes or economies consume large share of emergy content from imported or purchased flows (F) and also most of the input emergy content is used in the form of non-renewable input flows. Similarly higher ESI value indicates higher yield value per unit environmental stress. For processes this index can be used in the following ways:

- Comparison of different processes producing same product. The higher the ESI value for a process, the larger will be the global compatibility of this process compared to other process.
- The evaluation of technical and technological innovation of processes. Process yield per unit environmental pressure can be optimized by introducing alternate technologies. This can be achieved by increasing local renewable resource exploitation ability or decreasing the need of non-renewable consumption from outside. The increasing trend of ESI for the specific process shows progress towards environmentally favorable pattern of production.

The sustainability of an economy of a region or nation is dependent on its specific renewable emergy flows, dependence on imports and its load on the indigenous environment. The minimization of imports and dependence on renewable resources are important measures for economic sustainability, which in combination with an index of environmental stress, the ESI, measures long term sustainability of an economy. Higher values of this index reveal that this economy relies heavily on renewable energy resources and minimizes imports and environmental loads. ESI evaluates the regional economies in the following two ways:

- Comparison of different economies in order to assess their persistent global sustainability. The long term economic sustainability of a region can be achieved by increasing renewable emergy flow consumption and declining imported or purchased emergy flow dependency and safety of the its environment.
- The change in index over time indicates the global sustainability trend of an economy. The increase or decrease in sustainable trend depends on the direction of change of index in relation to renewable resource consumption, imports dependence and environmental load (Brown and Ulgiati, 1997).

There are several other ratios or indicators which are also calculated in addition to the three mentioned above, depending upon the type and scale of the system and scope of the studies.

*6.4.4 Percent renewable REN% = 1/(1+ELR) or =R/U*100*

The % Renew is percent of total emergy content which is driving the process or system obtained from the renewable resources (solar, geothermal, tidal) (R/(R+N+M)). The processes having high % Renew value are more sustainable in long run.

6.4.5 The non-renewable to renewable ratio (NRR)

The non-renewable to renewable ratio (NRR) is the ratio between emergy content of the system or process flow coming from non-renewable resources (F+N) and renewable resource distribution (R) i.e. input flow coming from renewable resources. High ratio value means more contribution to emergy content from non-renewable resources leading to less sustainable system.

6.4.6 Areal empower intensity

Areal empower is the ratio of total emergy input (U) to a process to the total available area by the process. Similarly non-renewable and renewable areal intensities are also evaluated by discretely dividing non-renewable and renewable emergies with area.

6.4.7 Emergy per capita

Emergy per capita is the ratio of total emergy consumption in the economy of a region or nation to the total population of the specific area or nation. Emergy per capita also indicate average standard of living for a population, because standard of living depends on per capita available resources.

6.5 Solar baseline

Baselines are important, in order to provide a reference for comparing the impact or disorder caused by a process or activity. The geobiosphere and annual flux of energy driving it is used as a frame of reference in the emergy methodology. Solar baseline (solar equivalents) against which the quality of different forms of energy are measured is also used as another frame of reference in emergy methodology. There are other baselines which can also be used, for example Coal equivalents or a cosmic baseline which starts with the average energy density of the universe. The difficulty in utilizing Coal Equivalents is that lower quality energies have values less than unity (for instance a Joule of sunlight is equivalent to 0.000015 Joules of coal equivalent). Similarly use of background radiation in the universe as the baseline also suffers from too many zeros. So, in order to make calculations easier and less uncertain, the emergy methodology uses the geobiosphere as the frame of reference and solar energy as the base line. The total emergy contribution to the geobiosphere per annum from three driving forces sun, deep heat and gravitation potential is about 15.2 E24 seJ/yr, which is spatially distributed over the planet (Brown and Ulgiati, 2010; Brown and Ulgiati, Ch.4, forthcoming).

6.6 PHA production from slaughtering waste

The conversion of animal slaughtering waste or animal residues involves several sub – processes. These sub – processes are hydrolysis, rendering, biodiesel production and fermentation process.

The detailed description of process design and development has been described in chapter 3. The renewable inputs (sun, wind and rain potential) are calculated and used for Austria. For emergy accounting, material and energy flows for a production capacity of 10,000 t/yr PHA production has been considered and following assumptions has been made:

- Animal slaughtering residues are considered as waste having zero emergy content. Although in reality it does have emergy content because it can only be available when there will be animal production (farming) to produce meat. In this particular study it is assumed that all emergy content is assigned to the main product "meat".
- Only mass and energy flows have been considered for analysis while infrastructure is out of system boundary.
- Out of renewable inputs (sun, wind and rain fall) major input has been accounted in order to avoid double counting, considering that solar radiations are the sole source for wind movement and rain fall.
- It is assumed that water input is a renewable input considering that it is provided from the rain collected water reservoir or alternatively from lake or river.
- Water input has been converted to energy units by multiplying Gibbs free energy content of water.
- For waste water treatment only electricity consumption has been considered in the evaluation.
- The electrical demand is fulfilled using European electricity mix (EU_27) while natural gas has been considered as a source of heat provision.
- For waste water treatment electricity consumption has been considered as an input to the system.

The assumptions for emergy accounting have renewable energy flows as well as water is used as a renewable input, these assumptions differ from basin evaluation assumptions for other methodologies.

A system diagram is required to organize the evaluation, and proper accounting of inputs and outflows from the processes or systems. Figure 6.6 is the system diagram of PHA production process utilizing slaughtering waste as starting material input. It helps to construct evaluation tables of actual flow of material, energy, labor and services. All inputs (energy, material, labor and environmental services) shown in the diagram are evaluated in their common units (J, kg, m^3, $ etc.). Information available in the form of evaluation table data is further processed to calculate different indices for PHA production.

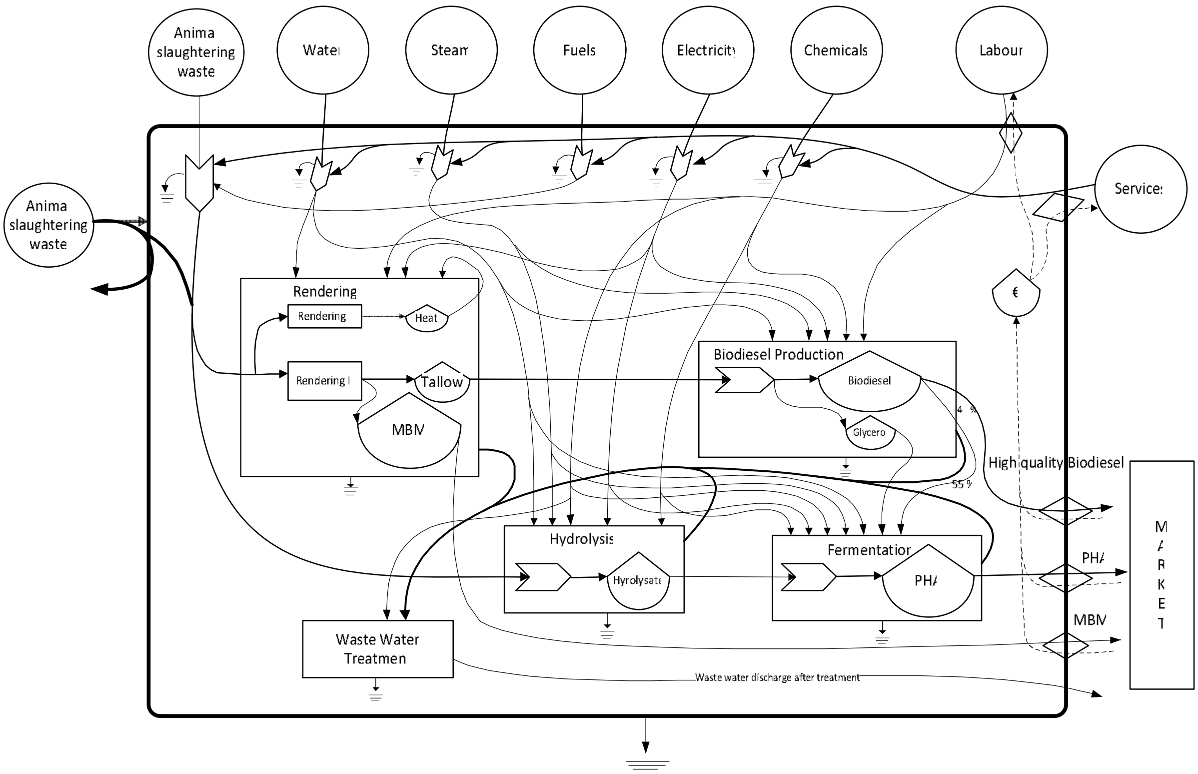

Figure 6.6: Emergy system diagram of PHA production process utilizing slaughtering waste as starting material

6.7 Emergy Accounting for PHA production

The amount of emergy required to produce one unit of each input is called specific emergy (seJ/unit) in case of mass flows and transformity (seJ/J) in case of energy flows. It is a quality factor measuring environmental support intensity provided by the biosphere to the formation of each input (Ulgiati et al 2006). The emergy intensity values for different input flows have been shown in Table 6.1. The reference sources have been written at the end of table as footnote.

Table 6.1: Transformities and other Emergy intensities of material and energy flows

Item	Value	Unit	Reference
All flows are evaluated on a yearly basis. Numbers in the first column refer to calculation procedures .UEV's values are referred to 15.2E+24 baseline (Brown and Ulgiati, 2010)			
Renewable Input (locally available)			
Sun	1.00E+00	0%	[a]

Wind (Kinetic Energy of Wind Used at the Surface)	2.51E+03	0%	[b]
Rainfall (Chemical Potential)	3.05E+04	0%	[b]
Imported Input			
Diesel for transport	1.81E+05	0%	[c]
Electricity	1.20E+05	0%	[d]
Heat (natural gas)	2.76E+05	0%	[c]
Heat (Rendering I products combustion)	1.35E+05	0%	[e]
Biodiesel	3.22E+09	0%	[e]
Glycerol	3.22E+09	0%	[e]
Ammonium Hydroxide (NH4OH)	6.38E+08	0%	[f]
Chemicals	6.38E+08	0%	[f]
Hydrochloric acid (HCl)	6.38E+08	0%	[f]
Sodium Hydroxide (NaOH)	6.38E+08	0%	[f]
Methanol CH3OH	6.38E+08	0%	[f]
Acid (Sulfuric Acid) H2SO4	8.86E+08	0%	[g]
Potassium Hydroxide (KOH)	6.38E+08	0%	[f]
Hydrolysate	6.84E+08	0%	[e]
Fresh water (assumed from natural reservoir or collected rain)	3.05E+04	0%	[b]
Waste water treatment electricity consumption	1.49E+05	0%	[d]
Emergy to money ratio for Austria, 2012	3.38E+11	0%	[h]
Labor	2.00E+17	0%	[h]
Services	3.38E+11	0%	[h]

References for transformities:
[a] By definition
[b] After Odum et al., 2000
[c] Brown et al., 2011.
[d] own calculation after Brown & Ulgiati, 2000, 2002, 2004 and E. Buonocore et al. 2012
[e] own calculation in this study
[f] After Odum et al., 2001
[g] Fahd & Fiorentino 2012
[h] our calculation after NEAD, 2014

6.8 Results and discussion

The results of emergy accounting analysis have been shown in emergy evaluation table for each sub-process one by one as follows:

6.8.1 Transportation Phase

The emergy accounting for transportation phase has been shown in Table 6.2. The emergy content calculated for transportation phase is 1.78E+19 seJ/yr and 1.19E+19 seJ/yr, with (L & S) and without labor and services (L & S) respectively.

Table 6.2: Emergy table of transportation phase

Items	Units	Raw Amounts	Transformity (seJ/Unit)	Ref.	Emergy (seJ/yr)
Slaughtering residues	g/yr	2.43E+11	0.00E+00	[i]	0
Diesel for transport	J/yr	6.56E+13	1.81E+05	[c]	1.19E+19
Labor	working years	2.66E+01	2.00E+17	[h]	5.32E+18
Services	€/yr	1.74E+06	3.38E+11	[h]	5.89E+17
TOTAL EMERGY with Labor and Services					**1.78E+19**
TOTAL EMERGY without Labor and Services					**1.19E+19**

6.8.2 Rendering I

It is assumed that "rendering facility processes 100,000 t/yr and it operates 250 day/yr". This facility requires 3.28E+02 h/yr to process 4.87E+03 t/yr of condemned material in rendering I facility. This time is equivalent to Labor force of 2.05E-01person/yr. The sum of share of transportation service share and utilities cost constitutes the service input for rendering I which is 2.44E+05 €/yr. The inventory input and emergy content calculated for rendering I is given in Table 6.3.

Table 6.3: Emergy table of rendering I

Items	Units	Raw Amounts	Transformity (seJ/Unit)	Ref.	Emergy (seJ/yr)
Slaughtering residues at plant	g/yr	4.87E+09	4.89E+07	[f]	2.38E+17
Electricity EU_27 mix	J/yr	1.07E+12	2.58E+05	[d]	2.35E+17
Heat_natural gas	J/yr	1.61E+13	2.76E+05	[c]	4.45E+18
Fresh water (assumed from natural reservoir or collected rain)	J/yr	6.25E+09	3.05E+04	[b]	1.91E+14
Electricity consumption for waste water treatment	J/yr	2.09E+09	2.58E+05	[d]	5.10E+14
Labor	working years	2.05E-01	2.00E+17	[h]	4.11E+16
Services	€/yr	2.44E+05	3.38E+11	[h]	8.25E+16
TOTAL EMERGY with L & S					5.09E+18
TOTAL EMERGY without L & S					4.97E+18

Total emergy content calculated for rendering I is 5.09E+18 seJ/yr and 4.97E+18 seJ/yr with L & S and without L & S respectively. The emergy content contribution from each input to the total emergy content of the process has been shown in Figure 6.7. In total emergy content with L & S heat provision from natural gas has a maximum share contributing 87%, while services, electricity and slaughtering residues have 2%, 5% and 5% shares. Similarly for total emergy content 90% share is contributed by heat from natural gas and rest 5% from electricity input and 4% from slaughtering residues at plant. It presents that raw material input have almost no comparative contribution to the overall emergy content of the process. Most of the emergy content is provided by the utilities to transform the raw material (waste residue) to a usable product.

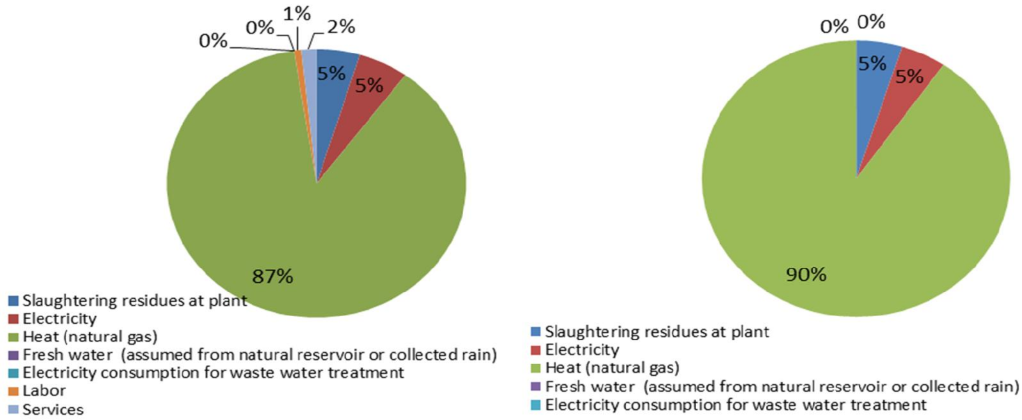

Figure 6.7: Emergy content share contribution of different input flows with and without L & S

6.8.3 Rendering II

Following the same assumption described in rendering I, 1.60E+04h/yr are required for processing of 2.36E+05 t/yr slaughtering residue. It is equivalent to 9.97 person/yr labor force. The sum of share of transportation service share and utilities cost constitutes the service input for rendering I which is 1.21E+07 €/yr. The inventory input and emergy accounting data has been shown in Table 6.4.

Table 6.4: Emergy table of rendering II

Items	Units	Raw Amounts	Transformity (seJ/Unit)	Ref.	Emergy (seJ/yr)
Slaughtering residues	g/yr	2.36E+11	4.89E+07	[f]	1.16E+19
Electricity	J/yr	5.19E+13	2.58E+05	[d]	1.14E+19
Heat (Natural Gas)	J/yr	7.83E+14	2.76E+05	[c]	2.16E+20
Heat from rendering I products burning	J/yr	4.07E+13	1.22E+05	[f]	4.93E+18
Fresh water (assumed from natural reservoir or collected rain)	J/yr	3.04E+11	3.05E+04	[b]	9.26E+15
Electricity consumption for waste water treatment	J/yr	4.76E+05	2.58E+05	[d]	1.05E+11
Labor	working years	9.97E+00	2.00E+17	[h]	1.99E+18
Services	€/yr	1.21E+07	3.38E+11	[h]	4.09E+18
TOTAL EMERGY with L & S					2.50E+20
TOTAL EMERGY without L & S					2.44E+20

Total emergy content for rendering II with L & S is 2.50E+20 seJ/yr, while without L & S it is 2.44E+20 seJ/yr. The emergy content contribution of different input flows for rendering II has been shown in Figure 6.8. In total emergy content with L & S heat provision by natural gas and rendering I have cumulative share of 88%. The rest 12% is contributed by services 2%, electricity 5%, slaughtering residues 4% and labor 1% respectively. The total emergy content without L & S is also contributed mainly by heat provision from natural gas and rendering I. It contributes up to 90% while rest 10% is equally shared between electricity and slaughtering residues. It also shows similar trend as that of shown in Figure 6.8, for transformation of waste raw material input into useable products tallow and MBM. Emergy content of the process is allocated to the products following mass allocation method.

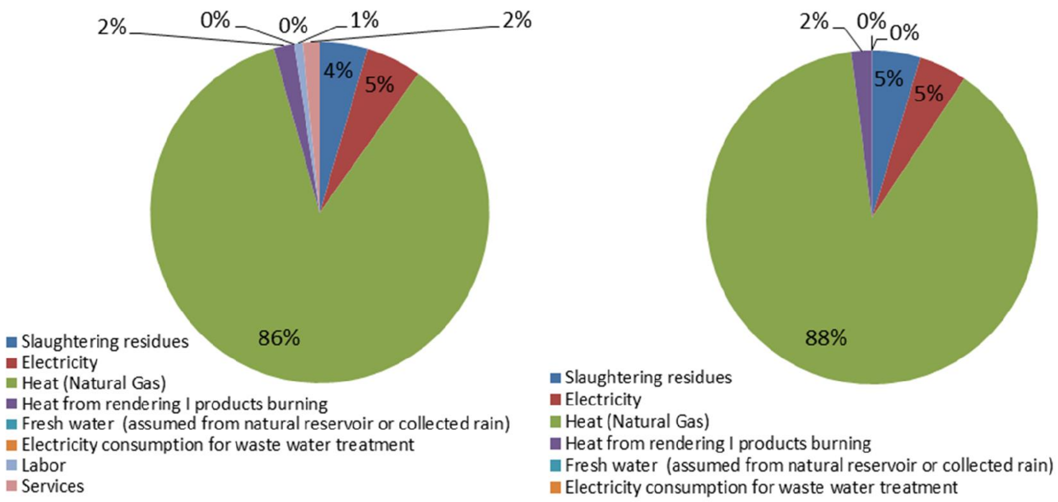

Figure 6.8: Emergy content share contribution of different input flows for Rendering II with and without L & S

6.8.4 Biodiesel Production

In order to calculate labor input, it is assumed that biodiesel production facility have a capacity of 100,000 t/yr and it is operates 250 days/yr. In order to produce 3.31t of biodiesel, it requires 1.95E+3 h/yr which are equivalent to 1.22 person/yr labor force. The sum of cost of raw material, chemicals and utilities constitute services and it is equal to 7.03E+06 €/yr. The inventory data obtained from a project partner and emergy accounting calculations for biodiesel production process with and without L & S has been presented in Table 6.5.

Table 6.5: Emergy table of biodiesel production

Items	Units	Raw Amounts	Transformity (seJ/Unit)	Ref.	Emergy (seJ/yr)
Tallow	g/yr	3.31E+10	2.57E+09	[e]	8.44E+19
Electricity	J/yr	8.46E+12	2.58E+05	[d]	1.86E+18
Heat (natural Gas)	J/yr	4.77E+13	2.76E+05	[c]	1.32E+19
Methanol CH3OH	g/yr	3.61E+09	6.38E+08	[f]	2.30E+18
Acid (Sulfuric Acid) H2SO4	g/yr	4.63E+08	8.86E+08	[g]	4.10E+17
Potassium Hydroxide (KOH)	g/yr	5.96E+05	6.38E+08	[f]	3.80E+14
Fresh water (assumed from natural reservoir or collected rain)	J/yr	1.63E+10	3.05E+04	[b]	4.99E+14
Electricity consumption for waste water treatment	J/yr	2.64E+09	2.58E+05	[d]	5.83E+14
Labor	working years	1.22E+00	2.00E+17	[h]	2.43E+17
Services	€/yr	7.03E+06	3.38E+11	[h]	2.38E+18
TOTAL EMERGY with L & S					1.05E+20
TOTAL EMERGY without L & S					1.02E+20

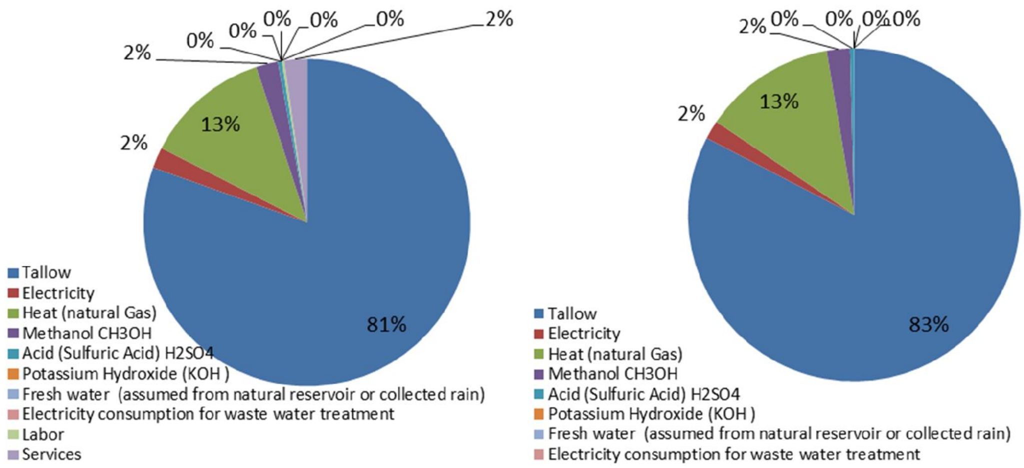

Figure 6.9: Contribution of different input flows for emergy content of Biodiesel production with and without L & S

6.8.5 Hydrolysis

For 10,000 t/yr PHA production, 150 batch/yr are required which in turn needs 1.2E+02 h/yr working time. It is equivalent to 7.5E-01 person/yr labor force. The sum of cost for chemicals and utilities is equal to services for this process i.e. 4.22E+05 €/yr. The inventory input for hydrolysis and emergy content evaluation is shown in Table 6.6.

Table 6.6: Emergy table of hydrolysis

Items	Units	Raw Amounts	Transformity (seJ/Unit)	Ref.	Emergy (seJ/yr)

Slaughtering residues	g/yr	1.73E+09	4.89E+07	[f]	8.44E+16
Electricity	J/yr	1.50E+11	2.58E+05	[d]	3.30E+16
Heat (natural gas)	J/yr	1.11E+12	2.76E+05	[c]	3.07E+17
Hydrochloric acid (HCl)	g/yr	2.04E+09	6.38E+08	[e]	1.30E+18
Sodium Hydroxide (NaOH)	g/yr	7.36E+08	6.38E+08	[e]	4.70E+17
Fresh water (assumed from natural reservoir or collected rain)	J/yr	3.42E+09	3.05E+04	[b]	1.04E+14
Labor	working years	7.50E-01	2.00E+17	[h]	1.50E+17
Services	€/yr	4.22E+05	3.38E+11	[h]	1.43E+17
TOTAL EMERGY with L & S					2.49E+18
TOTAL EMERGY without L & S					2.20E+18

The total emergy content of hydrolysis for both scenario with and without L & S is 2.49E+18 seJ/yr and 2.20E+18 seJ/yr respectively. The emergy content contribution shown in Figure 6.10 reveals that the mineral acid and base are the key contributors in both scenarios.

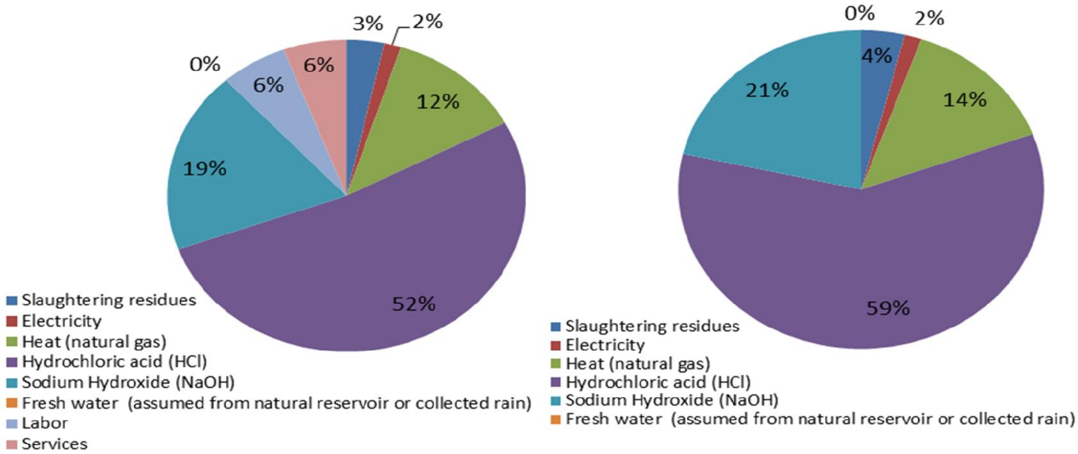

Figure 6.10: Contribution of different input flows for emergy content of hydrolysis with and without L & S

They contribute correspondingly 71% and 80% for emergy content with L & S and without L & S. Heat provision input with 12% and 14% shares is the next prominent contributor in both scenarios. Slaughtering waste has a small contribution of 3% and 4%, while electricity input have equal share of 2% in both scenarios. L & S have a considerable cumulative share of 12% in total emergy content for hydrolysis with L & S.

6.8.6 Fermentation process

The inventory data for fermentation process and emergy evaluation for fermentation process is given in Table 6.7. Based on the data provided by the project partner about fermentation batch duration and handling of downstream processing, it is assumed that fermentation broth requires about 55 h/batch. Also in accordance to own publication about PHA productivity there would be 150 batch/yr , for 10,000 t/yr PHA production (Titz et al. 2012). It results in 8.25E+03 h/yr, which in turn is equivalent to 5.16 person/yr labor force. The sum of cost for chemicals and utilities for fermentation process is 6.31E+08 €/yr which is equivalent to services input.

Table 6.7: Emergy table of fermentation (PHA production) process

Items	Units	Raw Amounts	Transformity (seJ/Unit)	Ref.	Emergy (seJ/yr)
Electricity	g/yr	1.81E+13	2.20E+05	[d]	3.98E+18
Heat (natural gas)	J/yr	1.05E+13	2.76E+05	[c]	2.91E+18
Glycerol	J/yr	3.31E+09	2.93E+09	[f]	9.70E+18
Biodiesel	g/yr	1.78E+10	2.93E+09	[f]	5.23E+19
Hydrolysate	g/yr	3.67E+09	5.98E+08	[f]	2.19E+18
Ammonium Hydroxide (NH4OH)	J/yr	7.67E+08	6.38E+08	[e]	4.89E+17
Chemicals	working years	7.82E+08	6.38E+08	[e]	4.99E+17
Fresh water (assumed from natural reservoir or collected rain)	€/yr	4.17E+11	3.05E+04	[b]	1.27E+16
Electricity consumption for waste water treatment	g/yr	6.74E+10	2.20E+05	[d]	1.48E+16
Labor	J/yr	5.16E+00	2.00E+17	[h]	1.03E+18
Services	€/yr	6.32E+08	3.38E+11	[h]	2.13E+20
TOTAL EMERGY with L & S					2.88E+20
TOTAL EMERGY without L & S					7.34E+19

The emergy content for 10,000 t/yr PHA production with L & S is 2.88E+20seJ/yr, while without L & S it is 7.34E+19 seJ/yr. The distribution of total emergy content for fermentation process with and without L & S into emergy content of input shares is shown in Figure 6.11. The raw material (biodiesel and glycerol) emergy content cumulative contribution to with L & S scenario is 22 %, while in without L & S scenario it is the main input contributor providing almost 85% of the content. For total emergy content with L & S scenario, services are the main contributor having 74% of the overall emergy content, while electricity and hydrolysate contribute about 3%. Similarly, emergy content contribution share for hydrolysate 3%, electricity 6%, heat 4%,while ammonium hydroxide, chemicals and fresh water have cumulative 2% share in total emergy content of fermentation without L & S. It shows that raw material input have significantly high emergy content contribution to fermentation process, while services input dominates the overall emergy content input.

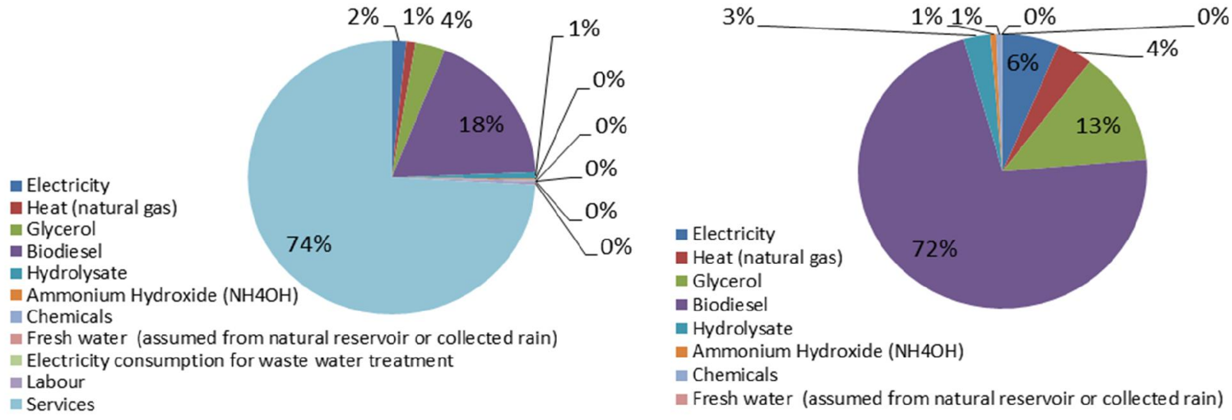

Figure 6.11: Contribution of input flows to the emergy content of fermentation process with and without L & S

6.8.7 Emergy based performance indicators

The emergy based performance indicators calculated for PHA production (overall process involving transportation phase and sub – processes rendering I, rendering II, biodiesel production and fermentation (PHA production process) has been shown in Table 6.8 using system boundary at biosphere level. Emergy indicators calculated using system boundary at industrial unit level (considering renewable energy flows for 1 hectare area in Austria) are shown in APPENDEX III.

Table 6.8: Emergy-base indicators calculated for ANIMPOL bio based PHA production

Emergy Accounting	Value	Unit
Transportation Phase		
Emergy from local renewable resources, R	2.96E+17	seJ/yr
Emergy from imported resources, F	1.19E+19	seJ/yr
Total emergy, U = R + F + L + S	1.78E+19	seJ/yr
Emergy intensity	7.32E+07	seJ/$g_{\text{animal residues transportation}}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	78.12	

Emergy Sustainability Index, EYR/ELR	0.01	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	1.26%	
Rendering I		
Emergy from local renewable resources, R	4.05E+17	seJ/yr
Emergy from imported resources, F	4.97E+18	seJ/yr
Total emergy, U = R + F + L + S	5.09E+18	seJ/yr
Transformity of heat	1.25E+05	seJ/J_{Heat}
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	12.54	
Emergy Sustainability Index, EYR/ELR	0.08	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	7.39%	
Rendering II		
Emergy from local renewable resources, R	2.00E+19	seJ/yr
Emergy from imported resources, F	2.46E+20	seJ/yr
Total emergy, U = R + F + L + S	2.52E+20	seJ/yr
Emergy intensity	2.64E+09	$seJ/g_{(tallow,\ MBM)}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	12.58	
Emergy Sustainability Index, EYR/ELR	0.08	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	7.36%	
Biodiesel Production		
Emergy from local renewable resources, R	7.62E+18	seJ/yr
Emergy from imported resources, F	1.03E+20	seJ/yr
Total emergy, U = R + F + L + S	1.058E+20	seJ/yr

Emergy intensity of biodiesel	2.96E+09	$seJ/g_{(biodiesel,\ glycerol)}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	13.87	
Emergy Sustainability Index, EYR/ELR	0.07	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	6.73%	
Hydrolysis		
Emergy from local renewable resources, R	4.69E+16	seJ/yr
Emergy from imported resources, F	7.05E+19	seJ/yr
Total emergy, U = R + F + L + S	2.49E+18	seJ/yr
Emergy intensity of hydrolysate	6.80E+08	$seJ/g_{(hydrolysate)}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	52.89	
Emergy Sustainability Index, EYR/ELR	0.02	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	1.86%	
Fermentation (PHA production) process		
Emergy from local renewable resources, R	1.59E+19	seJ/yr
Emergy from imported resources, F	7.34E+19	seJ/yr
Total emergy, U = R + F + L + S	2.88E+20	seJ/yr
Emergy intensity of PHA	2.88E+10	seJ/g_{PHA}
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	17.43	
Emergy Sustainability Index, EYR/ELR	0.06	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	5.43%	

The emergy intensities of animal residue transportation, rendering I, rendering II, biodiesel production, hydrolysate and PHA are 7.32E+07 $seJ/g_{animal\ residues\ transportation}$, 1.25E+05 seJ/J_{Heat}, 2.64E+09 $seJ/g_{(tallow,\ MBM)}$, 2.96E+09 $seJ/g_{(biodiesel,\ glycerol)}$, 6.80E+08 $seJ/g_{(hydrolysate)}$, 2.88E+10 seJ/g_{PHA}, respectively. The ratio between emergy content of imported resources (F) and total emergy (U) i.e. "Emergy Yield Ratio" is 1.0 for all sub-processes. This value shows that almost all resources are imported or transported from outside of the system under examination. The values of ELR (which is a ratio between the sum of emergy content of imported input "F", labor "L" and services "S" and renewable input "R") for sub-processes are 78.12 for transportation phase, 12.58 and 12.58 for rendering I and rendering II, 13.87 for biodiesel production, 52.89 for hydrolysis and 17.43 for fermentation process. The values for ESI (ratio between EYR and ELR) are 0.01 for transportation, 0.08 for both rendering I and rendering II, 0.07 for biodiesel production, 0.02 for hydrolysis and 0.06 for PHA production. The renewable fractions for different sub-processes are 1.26 % for transportation phase, 7.39 % for rendering I, 7.36 % for rendering II, 6.73 % for biodiesel production, 1.86 % for hydrolysis and 5.43 % for fermentation process.

6.8.8 Effect of change energy provision resource

A study about electricity production from different resources by Brown and Ulgiati (2002) reveals % renewables from these energy systems. These % renewable values are also integrated as renewable input to the system under study. The reported % renewable content for different energy resources are: wind 86.61 %, geothermal 69.67 %, Hydro 68.84 %, Natural gas (methane) 7.83 % and coal 8.79 %.

6.8.8.1 Comparative analysis of biodiesel production

The performance indicators calculated for biodiesel production process fulfilling energy demand from different energy resources has been shown in Figure 6.12.

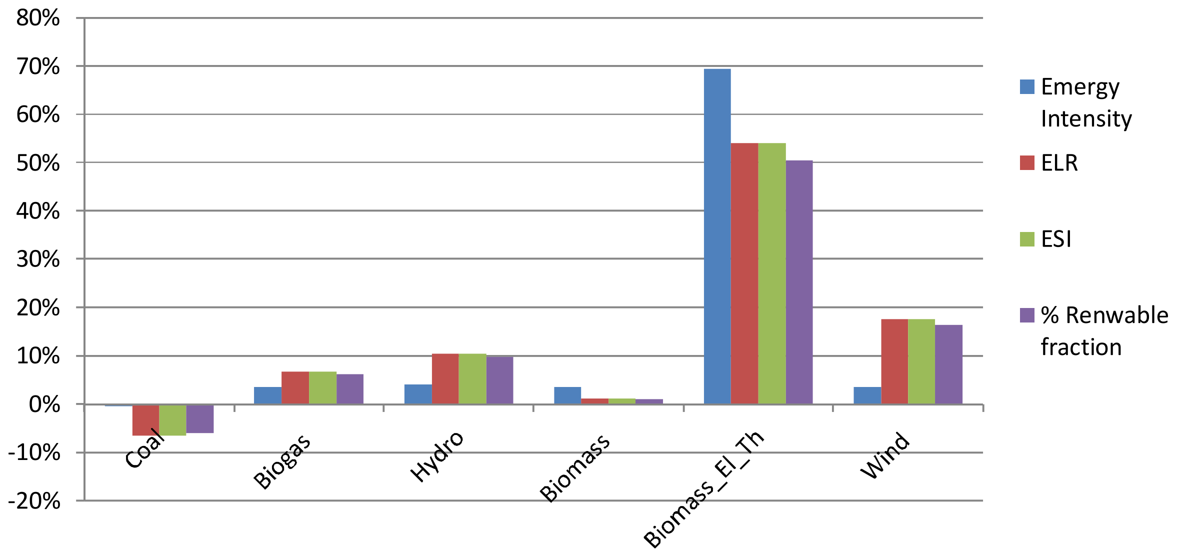

Figure 6.12: comparison of emergy flows and emergy based indicators for Biodiesel production

The change of electricity provision resource shows an impact on different performance indicators. In the current study electricity provision form EU_27mix is considered as basic scenario and results calculated using other electricity provision system is compared with it. The effect of change of resource on emergy intensity of biodiesel production (seJ/g) shows a negative impact for electricity provision from coal, while fulfilling of electricity demand using electricity from biogas, hydro, biomass and wind have slightly positive effect ranging in between 3% to 4%. The provision of electricity as well as heat demand by biomass burning shows about 69% improvement compared to the basic scenario of energy provision from EU electricity mix and natural gas for electricity and heat respectively. The effect of change of energy resources on biodiesel transformity (seJ/J) compared to diesel transformity 1.81E+5 (Brown and Ulgiati, 2011), has a positive impact with 55% to 57% decrease in transformity value for electricity from EU27 mix, coal, hydro power, wind and biomass, while electricity and heat provision from biomass has maximum 87% decrease in transformity value. ELR value also show a positive impact in the range of - 6 % to 17 % by replacing electricity provision from more renewable resources. The change of electricity as well heat provision source with biomass shows about 54% improvement of the process. Similarly ESI and % renewable fractions shows analogous effect as both of these are dependent on ELR values.

6.8.8.1 Comparative analysis of PHA production

The performance indicators calculated for PHA production process providing required energy demand from different energy resources has been shown in Figure 6.13.

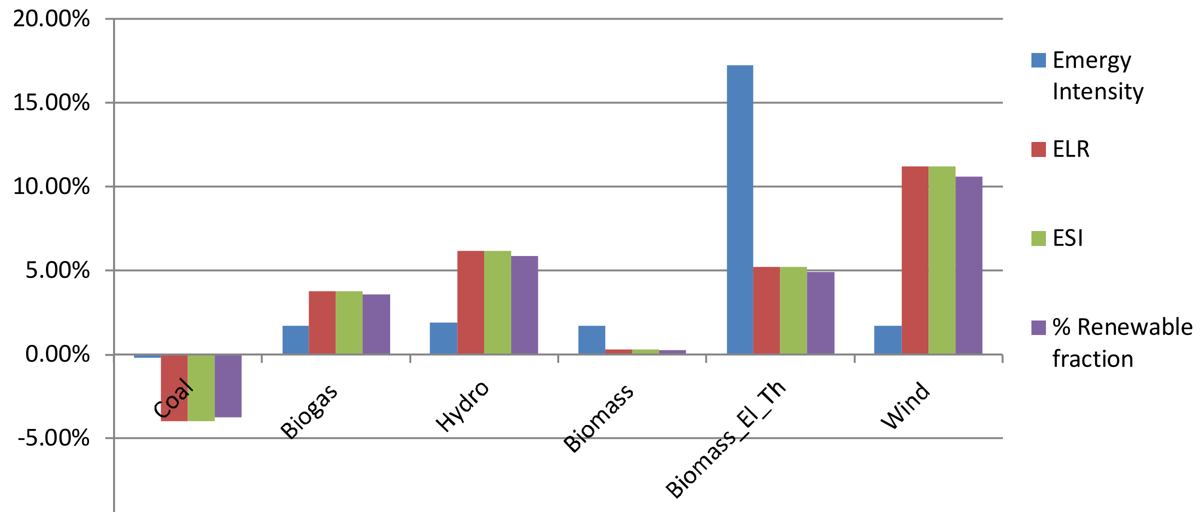

Figure 6.13: comparison of emergy flows and emergy based indicators for PHA production

The replacement of electricity provision with electricity from more renewable resources shows positive impact. The emergy intensity for PHA production (seJ/g) shows very minor improvement ranging in between 1.5% to 2% by changing only electricity provision resource. This impact reaches up to 17% when electricity as well as heat provision resources are replaced with biomass resources. Similarly comparison of emergy intensity for PHA production using electricity EU27 mix, coal, hydro power, wind power and biomass is about 5% to 7% lower than emergy intensity of polyethylene high density (PE-HD)[4], while its value reaches up to 21% lower for electricity and heat provision from biomass. The exchange of electricity resource with electricity from coal shows a negative impact on the overall system making it even less sustainable. The provision of electricity from wind farm represents best available option having highest improvements in the values of ELR 11% as well as ESI 11% and % renewable fraction 10.40%.

[4] Based on emergy accounting value of PE-HD calculated by V. Buranakam (1998)

The ELR must be calculated with reference to the local environment (R only calculated within the hectare of land occupied by the plant) as with reference to the regional scale (where inputs come from, with imported flows split into renewable and nonrenewable fractions). The ELR calculated in the second way compares all the renewable input flows at the larger scale (as renewable fractions of all flows) with the nonrenewable flows at the same scale. In case of system expansion from local to regional scale, the concept of imported flows F becomes irrelevant and non-renewable fraction of F overlaps to non-renewable N. The ELR calculated has a meaning at the larger scale. The values of ELR calculated at the local scale become really huge and simply say that the process has too much loading on the local resources. It shows the process is not sustainable at all, and becomes sustainable only if buffered by the environmental forces available at large scale (this is why power plants and industries need a forest, a respect area, around them. The ELR is linked to the %REN, which therefore is higher in the large scale perspective.

These sorts of choices do not affect the EYR values, because F at the numerator and denominator has the same value, no matter if F is a split into renewable and non-renewable fraction. EYR is an indicator that informs about what extent the process is exploiting the local resources (N and R).

The value of EYR indicator rises in case of exploitation of local resources increases. Otherwise its value is 1, as in current case study and indicates a process that converts resources imported into other resources for export. Similarly ESI is affected as a consequence of its definition as a ratio of EYR and ELR.

7 Material Input Per Unit Service (MIPS) Changing the Existing System by Increasing Efficiency

The present economic set up is incompatible with the sustainable ecosphere. It is based on highly resources intensive processes for food production and other goods and services provision for human activity. It not only causes more and more waste production but also displacement of material during extraction also causes ecological changes (Schmidt-Bleek, 1998). If the material input will continue at the same intensity more than two planet earths would be required to provide necessary material flows to support current western style of living. It will not only increase prices of raw materials (fossil fuels, minerals and metals, etc.) but also poses severe threats to ecologic system (Schmidt-Bleek, 2004).

In this situation the only way approaching to sustainability is systematic and accountable dematerialization of the economic system. The attainable resource productivity depends on the market signal as well as politically devised institutional framework as much as productivity of labor, knowledge and capital (Schmidt-Bleek, 2001). Conversely current resource productivity is far below technical potentials. The production of 1 ton product to serve humanity requires about 30 tons of non-renewable material. Hence in order to reach sustainability, resource productivity has to increase dramatically. It requires fundamental changes in our economic system and way to measure progress (Schmidt-Bleek, 2004).

The global economy not only needs to be brought back in its ecological guard rails but also have to provide sufficient environmental space to "the south". A RIO-Economy i.e. resource input optimized economy, in which goods for end users are replaced by services which are customized to their specific needs. For example by sharing building, vehicles, machines and infrastructure increase the number of service units dramatically, by enhancing the longevity of the goods, without an increase in absolute material input flow of natural materials (Schmidt Bleek, 2001).

For example, by increasing the longevity of goods, by leasing rather than selling a product, and by sharing buildings, infrastructures, vehicles or machines can the total number of service units be improved dramatically, without a corresponding increase in the absolute input of natural raw materials.

In order to calculate the material input of natural resources, all materials and energy consumed to obtain original product or service should be measured from very first dig of the spade onward. For example material input for copper production includes the sum of material movement and energy input during mining as well as all material and energy input during purification process. Development and implementation of possible measures are also required to monitor and improve material flow. One of the tools in practice, to measure and monitor material flows is known as MIPS (Material Input per unit Service) (Hinterberg et al. 1997; Lettenmeier et al. 2009)

7.1 Normative Background

All anthropogenic material flows including transportation processes, energy consumption and land use induce changes in the biosphere. It is impossible to measure quality and quantity and historic background of these changes. Keeping this point in mind, it is not possible to predict a point below which these changes are risk free. In order to stay in the safe territory, *natural systems should be altered by anthropogenic activities as little as possible*. It presents the idea of preventive principle.

MIPS is an input oriented approach which assumes that input and output flows are equivalent in quantitative terms in accordance to mass and energy conservation laws. It means that accounting of material input flows from cradle to grave provide enough information to have preliminary estimation of environmental impacts caused by a product or service (Ritthoff et al. 2002).

The most common environmental protection methodologies are developed to prevent specific dangerous substance arising directly from processes, process effluents, and product use and disposal. Although scientifically it is impossible to observe, simulate, or quantify all possible effects of even single chemical on all possible millions of targets in the environment. This methodology has short comings but still it is serving quite well for addressing important purposes like slowdown of CO_2 emission rates, large scale reduction in chlorofloro carbons (CFC's) emissions as well as improvement of air quality in megacities.

The approach differs from environmental impact regulations which are based on output flows, considering the fact that most of the emissions arising from output flows and their impacts on environment and humans are unknown. There are millions of products in the global economic system causing unaccountable environmental impacts during their production, usage during service provision and end of life disposal. Keeping in mind all these factors the methodology only considers material input flow as environmental impact and assumes that environmental pressure can be reduces by dematerialization. Although it does not exclusively accounts toxicological effect of certain material flows (like mercury, lead and other heavy metals and toxic material flows). It has been argues that substances do show toxic effect for living organisms or humans while they might not have deteriorating effect on the overall ecosystem. This is the consideration behind rating all material flows, having an equal environmental impact (i.e. sand and mercury or lead all have potential weightage). So sum of the material movement starting from material extraction onward to the product development and service delivery or economic activity is equivalent to the generic environmental pressure exerted by the specific product, service or economic activity on the nature (Lettenmeier et al. 2009).

The value system for this approach lies with in old economic paradigm dealing with economic and population growth hands in hands. This methodology explains two basic issues which are technological efficiency and dematerialization of economy considering social justice of material use among developed and developing countries (Schmidt-Bleek, 2001). The question about energy efficiency was:

"*Could technology provide goods and services that offer undiminished end-use satisfaction with substantially less natural resources?"*

The answer to this question is yes. The question is about utilizing engineering intelligence, meaning how much energy and mass flow is needed to generate a certain quantity of product value or utility. Studies reveal that in common practice about 30 kg of non-renewable material and many times more water content is used to produce 1 kg of product. While high tech product production utilizes even ten times more solid nature than average technology require now. The solution to this immense consumption of material resources lies in service oriented knowledge society supported by dematerialized information technology. The wise utilization of brain power can reduce mass and energy input to a great extent. For example, idea of car sharing to fulfill mobility services and development of single workshop containing all mechanical tools for a housing society in order to decrease amounts of products and exploiting maximum potential services out of it. These practices provide the same services without compromising on the standard of living.

"*what is the required reduction in using nature as input into the world wide economy in order to approach sustainability?"*

There are two parts of this question. First one is how much and second one is where and how much reduction in material through put is needed, so that we can attain social justice as well. The ecological pressure caused by an inhabitant of OECD or "North" or the "First" and "Second" world countries is about 15 to 30% more than the inhabitant of "Third World" or developing countries or "South". In accordance to dematerialization principle the inhabitants of these developing countries are not ready to reduce the little they had access to. In relation to the report submitted by a team of scientists in 1980, about reduction in anthropogenic CO_2 and other emissions to biosphere to come away unharmed, which reports that by middle of 21^{st} century the level of CO_2 emitting from human activities should be reduced half and other pollutants even more.

As there is no evidence about the environmental changes induced by material flow over the short or long term; but there is evidence of measurable regional and global biospheric reactions. A reduction of one half of material through put might be a wise idea to stabilize the biosphere.

At present about 20 % of the world population living in the industrialized countries is utilizing about 80% of the material resources. In according to social justice principle, all people have the same right of access to natural resources and there should not be any interference with the economic development of the majority of world's population. The hypothetical corse of decrease of global material flow to 50 % by the middle of next century (Schmidt-Bleek, 1993) is given in Figure 7.1.

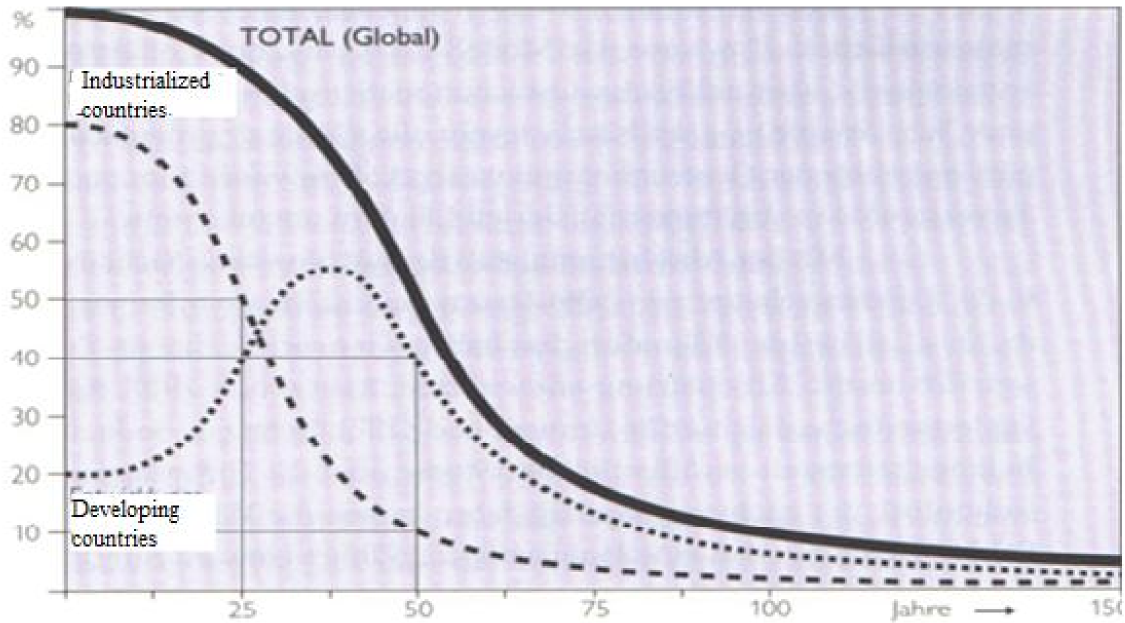

Figure 7.1: The hypothetic course of decrease of global material flow to 50% by middle next century (Schmidt-Bleek, 1993) The steep curve indicates the dematerialization of industrialized economies of countries. The first rising and then falling curve describes ho how to access the rest of the world on natural resources. In order not to make the presentation confusing, the increase was the world's population not included in this time.

It is illustrated in the figure that a goal of 50% reduction of material input for industrialized countries is set in the fifty years' time. The decrease in the material flow is organized in a way that it can support temporary increase and subsequent decrease in material flow for countries of south with in the overall material flow reduction scheme. This dematerialization of the economies is an average value which can vary for certain countries. This dematerialization trend is known as factor 10 and it is defined as:

"*Then the economies of the countries in which, or for which, most of the material flows are presently moved would have to dematerialize by an average factor of ten in order to allow for a reduction in global material flows by fifty percent*".

The idea of **"reduction of resource consumption by a factor of 10"** is not based on natural income. It is based on the calculations made to measure bearable anthropocentric activity (Ritthoff 2002).

The interesting constituents provided by this approach are definition of service unit, decoupling of service unit from material base and introduction of life cycle assessment (LCA) notion i.e. looking at the whole system from cradle to gate.

7.2 Calculation and Methodology

MIPS is the abbreviation of Material Input Per unit of Service and assesses the environmental pressure caused by the products manufacturing or services. It is represented as:

$$\mathrm{MIPS} = \mathrm{MI}/\mathrm{S}$$

The number of units of service (utility) delivered by a product during its life time is equal to its S value, it can also be defined as the total number of expected service units that a product might provide during its life time (Schmidt-Bleek, 1998).

According to the equation MIPS is the reciprocal of resource productivity, indicating the amount of "nature" utilized for the production or consumption of something. Material Input (MI) includes all material and energy flows from natural system to techno-sphere, in mass units. In other words it includes total material input during the whole life cycle of the product i.e. extraction of raw materials, production processes, during usage (operation and maintenance), disposal or recycling phases. In this concept both matter and energy are correlated, as it includes material for energy carriers and technologies. The relative material input per weight, energy or transport unit is called Material Intensity (MIT). Material intensities are calculated for energy carriers, electricity, transport possibilities etc. using units (kg/MWh) or (kg/tkm (Krotscheck 1997, Hinterberg et al. 1997). It also includes the "ecological rucksacks" i.e. the material used directly or indirectly during life cycle of the product. Ecological rucksack is defined as "the material intensity throughput during the whole life cycle of the product i.e. extraction of raw materials, production processes, during usage (operation and maintenance), disposal or recycling phases (Macini et al. 2012).

In MIPS calculation, MI is further divided into 5 different categories: **Abiotic natural resources** include mineral raw materials (such as ores, sand, gravel etc. which are used for extraction), fossil energy carriers (coal, petroleum products) and soil excavation. **Biotic natural resource include** plant biomass obtained from cultivation and uncultivated areas (plants, animals etc.).

Earth Movement in agriculture and silviculture involves earth consumption i.e. erosion and modification of soil through farming or forestry i.e. mechanical earth movement without resource extraction. **Water** consumption is further divided into process and cooling water while surface, ground and deep ground waters are also considered for calculations. **Air** consumption includes aggregate of all air parts which undergo chemical change during combustion (oxygen consumption to produce CO_2), chemical or physical transformation processes. This division is done in accordance to ever increasing national and international statistical analysis of material flow accounting, in order to interconnect the information system at micro as well as macro- levels in order to make comparable with available data (Macini et al. 2012; Ritthoff et al. 2002).

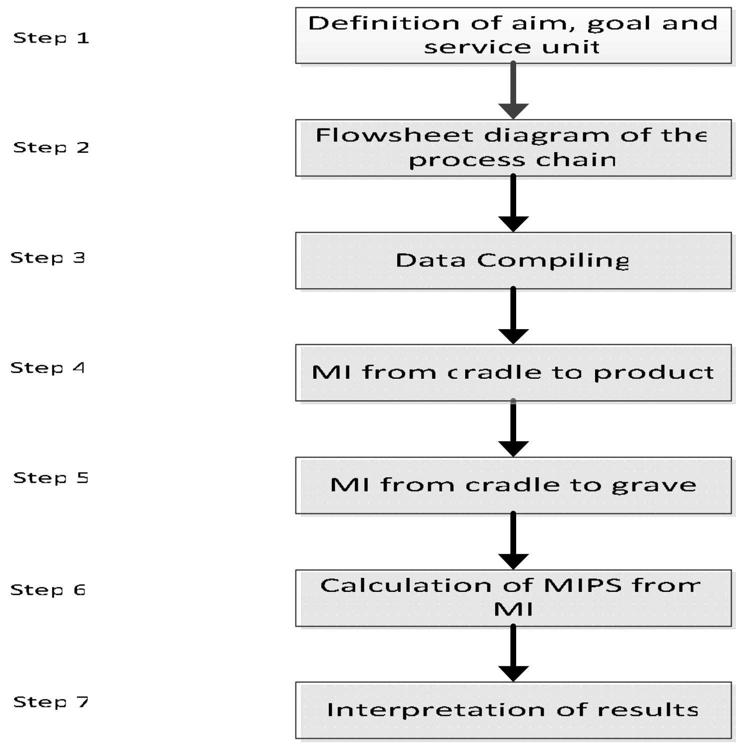

Figure 7.2: Seven steps of MIPS calculation (Ritthoff et al. 2002)

MIPS calculation can be easily divided into seven distinctive steps as shown in Figure 7.2. The first step of analysis is defining aims, goals and basic Service Unit, to which all numerical values will be referred. These steps are common in LCA and MIPS analysis. This approach introduced the concept of LCA notion which is further developed into its present form. It provides the basis for comparison of services and products. Secondly, issue or process life cycle graphic design is presented. It helps to mark input flows, if necessary output flows as well, to gather needed information. Thirdly, gathered data is recorded, using a data-sheet. On the basis of this data Material Input is calculated from "cradle to product" (step 4) which is a distinct in MIPS while in LCA we use cradle to gate or cradle to grave, by connecting this data with the MI factors. Thereafter in the 5th step Material Input is calculated from "cradle to grave" by including data from life cycle phases of "use" and "recycling/disposal".

In the later steps Material Input Per unit of Service (MIPS), can be calculated from Material Input "from cradle to grave" i.e. (result obtained in step 5) and an interpretation of the results is made respectively (Ritthoff et al. 2002).

In order to attain relation between material input and service unit i.e. MIPS calculation is done by dividing the total material input for the whole life cycle by total number of services. The results are greatly influenced by the number of service units, so they must be defined carefully and in realistic way. For example if total service performance of a car is assumed 200,000 or 300,000 kilometers it really makes a difference in material input per unit service.

Useful example of MIPS calculation for a T-shirt is described in detail by Lettenmeier et al. (2009). It has been explained in detail how unit service selection effects the final assessment of a product or service. It is assumed that one wearing-cycle of the T-shirt is a service unit and it has a life cycle of 100 wearing cycles. The total material input for T-shirt is equal to the sum of material input for T-shirt production and material input for used phase (T-shirt use phase = 100* washing + 100 * ironing). The value of MIPS will be obtained by dividing total material input with 100, as shown in Table 7.1.

Table 7.1: MIPS values of the specific T-shirt (kg/wearing cycle) 5

Material Inputs amounts	Unit (kg/wearing cycle)
Abiotic material	0.42
Biotic material	0.001
Water	37
Air	0.003
Erosion	0.001

With these results provide an opportunity to compare T-shirts on a basis of life span wearing cycles. Service unit can be further intensified by considering the life span of the T-shirt. For example if the same shirt is being clothed for 5 years and it is considered as the service unit. Then

[5] This table has been reproduced from "The 7 steps for designing eco-innovative products" by Lettenmeier et al. 2009.

it provides the opportunity to compare durability of T-shirts. The factor that has to be kept in mind and considered for calculation is: "long life" T-shirt has only one production process while "short life" T-shirts needs to be produced several time for usage over the same time, while the usage expenses (i.e. washing, ironing etc.) will remain the same. Material flow accounting (MFA) statistical date can also be use differentiate and indicate the domestic and foreign resource requirements of an economy in a quantitative manner (EUROSTAT 2001).

7.3 Ecological rucksack

In the early 1990ies, "ecological rucksack" was used as metaphor by Schmidt-Bleek[6] to demonstrate the fact that creation of every object in the industry requires more material then contained in its final form. It means that according to MIPS concept it denotes the "value lost" from ecological perspective. It is reported that the rucksack of industrial products is usually more than 10 kg nature per kg of product. It depicts that more than 90 % of the natural capital mobilized and used is waste on the way to the market. Similarly water consumption for each kg of food or industrial goods production exceeds 100 or 1000 kg. Thus "ecological rucksack" is hidden material flow burden or total material input from nature essential for a product or service "from the cradle to the point of sale". The products normally require additional material and energy inputs i.e. utility costs, in order to deliver benefit or service. For example material input required for electric bulb production from cradle to the point of sale is its rucksack. It requires electricity to lighten up which is its service. Thus MIPS is a measure of cradle to cradle material input for a unit service or benefit (Lettenmeier et al. 2009).

In MIPS concept defining the ecological rucksack of the products or services available in the market, allows the measurement and comparison of their environmental impacts. Rucksacks provide the norms and quantifiable roots for eco-innovation in the development of future products and services (Hinterberg et al. 1997). The metaphors footprint and rucksack are closely related and it can be said that "material footprint" of a product is its ecological rucksack. Similarly "material footprint" of a benefit or service is the total material input i.e. material input (MI) in MIPS, needed to deliver the required service or benefit. Normally material input in different categories i.e. abiotic, biotic, air, water and soil erosion are considered separately. While

[6] Friedrich Bio Schmidt-Bleek, Factor 10 Institute, Carnoules/Provence, www.factor10-institute.org

in practice sum of biotic and abiotic material input along with erosion (i.e. total material input required TMR) in the agricultural product, provides reasonable approximations in relation to material input for similar product in the region (Macini et al. 2012, Lettenmeier et al. 2009).

7.4 MIPS and Sustainability

The economy can only be sustainable if it can provide services of equal quality to all, while being residing within natural boundaries. It calls for most efficient consumption of natural resources. Waste and emissions of our economy are reasons for abnormal behavior of the climate, leading to natural disasters costing billions of Euros every year.

MIPS as a sustainability index, through very simple conversion of inventory to an aggregated mass flow, provide an insight in current level of input. It considers all material inputs equally undesirable, regardless of their nature and toxicity e.g. natural gas, coal, fuel, water etc. Due to this consideration it may provide awkward results by replacing non-toxic high volume inputs with highly environmentally hazardous low volume inputs (Hertwich et al. 1996). The reason behind this assumption is that the hazardous substances effect only living organisms while their deteriorating impact on the overall system is unknown. Based on this assumption all material inputs are considered to have equal impact on the environment. Still in case of known hazardous substances their usage should be avoided at the first place, if not then their flow should be reduced as much as possible using available preventive measures.

In order to attain sustainability, a high resource efficiency and reduction of material flow by a factor of 10 is required. It means doubling of worldwide prosperity, by allowing cut in material flow by half i.e. an increase of resource productivity by a factor of four.

7.5 Disadvantages

The disadvantage of the methodology is given as:

- Does not take into account “surface use” for industrial, agricultural as well as forestry purposes although available surface area of the earth is limited.
- Do take into account specific environmental toxicity of the material flows
- MIPS concept does not make any direct reference to biodiversity

7.6 Evaluation of PHA production from Slaughtering waste

A detailed description of the case study has been discussed in chapter 3. While conversion of material and energy input into equivalent mass units follow same assumptions which are assumed for emergy accounting. The material intensity (MI) factors based on data obtained from published literature for different inputs are shown in Table 7.2. The references used for data acquisition are provided as footnote at the end of Table 7.2.

Table 7.2: Material intensity factors per unit of products

Material Intensity factors per unit of product					
Item	**abiotic**	**water**	**air**	**unit**	**Reference**
Diesel for transport	1.36E+00	9.70E+00	3.22E+00	g/g	[a]
Electricity	4.31E-04	1.85E-02	1.49E-04	g/J	[a]
Heat (natural gas)	2.98E-05	1.22E-05	8.88E-05	g/J	[a]
Heat (Rendering I products combustion)	2.41E-05	5.40E-04	6.50E-05	g/J	[b]
Tallow	5.07E-01	1.14E+01	8.82E-01	g/g	[b]
Meat and Bone Meal (MBM)	5.07E-01	1.14E+01	8.82E-01	g/g	[b]
Biodiesel	7.83E-01	1.55E+01	1.37E+00	g/g	[b]
Glycerol	7.83E-01	1.55E+01	1.37E+00	g/g	[b]
Ammonium Hydroxide (NH4OH)	1.93E+00	3.49E+01	1.50E+00	g/g	[c]
Chemicals	1.93E+00	3.49E+01	1.50E+00	g/g	[c]
Hydrochloric acid (HCl)	3.03E+00	4.07E+01	3.80E-01	g/g	[a]
Sodium Hydroxide (NaOH)	2.76E+00	9.03E+01	1.06E+00	g/g	[a]
Methanol CH3OH	1.67E+00	4.46E+00	3.87E+00	g/g	[a]
Acid (Sulfuric Acid) H2SO4	2.50E-01	4.10E+00	7.00E-01	g/g	[a]
Potassium Hydroxide (KOH)	1.93E+00	3.49E+01	1.50E+00	g/g	[c]
Hydrolysate	2.27E+00	4.17E+01	4.66E-01	g/g	[b]
Fresh water (assumed from natural reservoir or collected rain)		1.30E+00		g/g	[a]
Waste water treatment electricity consumption	4.31E-04	1.85E-02	1.49E-04	g/J	[a]

References:

a. Wuppertal Institute, 2014

b. Own calculations in this study

c. own calculation after Wuppertal Institute, 2014

7.7 Results and discussion

The material intensities calculated for different sub-processes have been explained in the following paragraphs.

7.8.1 Residue transportation

The material intensity calculation for transportation phase includes material input required for diesel provision only, which is 1.46E+06 kg/yr. The material intensity evaluation for transportation phase is shown in Table 7.3.

Table 7.3: Material intensity evaluation of transportation phase

Mass balance (local scale)			**MFA = material flow accounting (global scale)**		
Description of flow	Units	Mass	Mass abiotic g/unit	Mass water (g/unit	Mass air g/unit
Diesel for transport	g/yr	1.46E+09	1.99E+09	1.42E+10	4.72E+09
Working years	-	-			
Output					
Slaughtering residues	g/yr	2.43E+11	8.20E-03	5.85E-02	1.94E-02

The ratio between material intensity for transportation phase and residue mass to be transported gives material intensity values for slaughtering residues. These material intensities of slaughtering residues have been used in material intensity evaluation of other sub-processes.

7.8.2 Rendering I

The calculation shows that rendering I processes 4.87E+09 g/yr of condemned materials producing 4.07E+13 J/yr heat equivalent. Table 7.4 reveals inventory data and material intensity evaluation of rendering I.

Table 7.4: Material intensity evaluation of Rendering I

Mass balance (local scale)			**MFA = material flow accounting (global scale)**		
Description of flow	Units	Mass	Mass abiotic g/unit	Mass water (g/unit	Mass air g/unit
Slaughtering residues	g/yr	4.87E+09	3.99E+07	2.84E+08	9.44E+07
Electricity	J/yr	1.07E+12	4.6E+08	1.98E+10	1.59E+08
Heat (natural gas)	J/yr	1.61E+13	4.79E+08	1.96E+08	2.39E+09
Fresh water (assumed from natural reservoir or collected	g/yr	1.27E+09	0	1.64E+09	0

rain)					
Electricity consumption for waste water treatment	J/yr	2.31E+09	996281	42891504	343877.6
Labor	-				
Total input	g/yr		9.8E+08	2.2E+10	2.65E+09
OUTPUT					
Energy content of heat	J/yr	4.07E+13			
	g/J		2.41E-05	0.00054	6.5E-05

The evaluation results for abiotic and water inputs have been presented in Figure 7.3. The graphical presentation shows that 51% abiotic material is contributed by electricity provision both for the process as well as waste water treatment. The rest 49% of abiotic material input is contributed by heat demand delivery. For overall water input almost 91% share is contributed by electricity provision, while direct water provision accounts for 7.5% of the overall input. Heat demand and slaughtering residues share a cumulative 2% share.

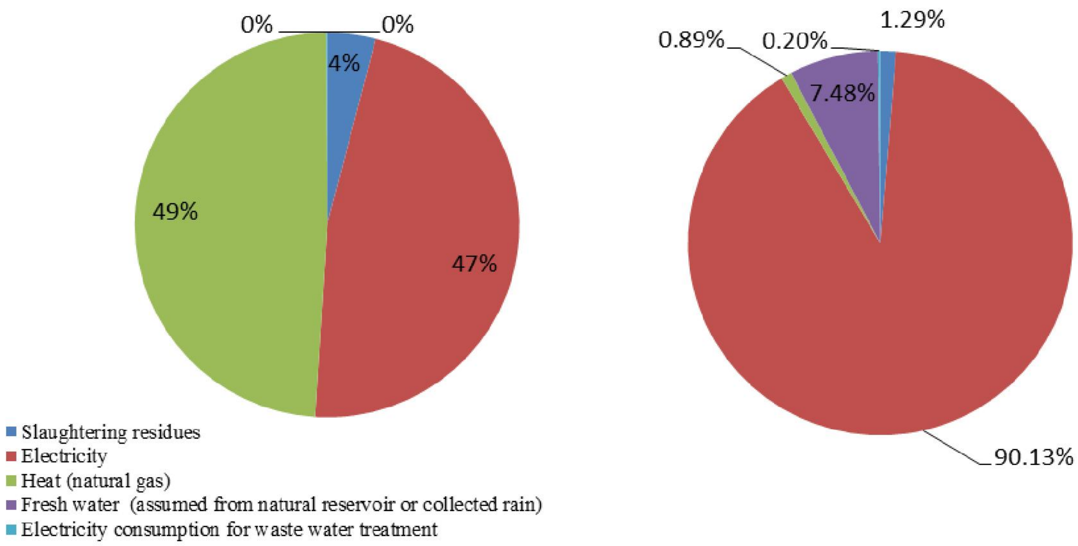

Figure 7.3: Material input shares of abiotic material (left) and water input (right) for rendering I

7.8.3 Rendering II

The calculations result reveals that 2.36E+11 g/yr animal residues are processed in rendering II unit. The inventory data and material intensity evaluation has been given in Table 7.5.

Table 7.5: Material intensity evaluation of rendering II

Mass balance (local scale)			MFA = material flow accounting (global scale)		
Description of flow	Units	Mass	Mass abiotic g/unit	Mass water (g/unit	Mass air g/unit

Slaughtering residues	g/yr	2.36E+11	1.94E+09	1.38E+10	4.59E+09
Electricity	J/yr	5.19E+13	2.23E+10	9.62E+11	7.71E+09
Heat (Natural Gas)	J/yr	7.83E+14	2.33E+10	9.54E+09	6.95E+10
Heat from rendering I products burning	J/yr	4.07E+13	9.80E+08	2.20E+10	2.65E+09
Fresh water (assumed from natural reservoir or collected rain)	g/yr	6.15E+10	0.00E+00	7.99E+10	0.00E+00
Electricity consumption for waste water treatment	J/yr	4.76E+08	2.05E+05	8.82E+06	7.07E+04
Labor	-				
Total Input	g/yr		4.86E+10	1.09E+12	8.44E+10
Products					
Tallow	g/yr	3.31E+10			
	g/g		5.07E-01	1.14E+01	8.82E-01
Meat and Bone Meal (MBM)	g/yr	6.26E+10			
	g/g		5.07E-01	1.14E+01	8.82E-01

The evaluation results shown in Figure 7.4 reveal that heat and electricity provision are the biggest contributors for abiotic material input having 50% (cumulative for natural gas and heat from rendering I products) and 46 % contributions respectively. Raw material input i.e. slaughtering residues contributes about 4 % of the overall input. For water input electricity has the maximum input covering 89% of the over all, while direct water input to the process has 7% contribution. The contribution from heat provision is 3% and slaughtering residues 1%. The overall for the process results show that it is highly energy intensive process which converts raw material into usable products.

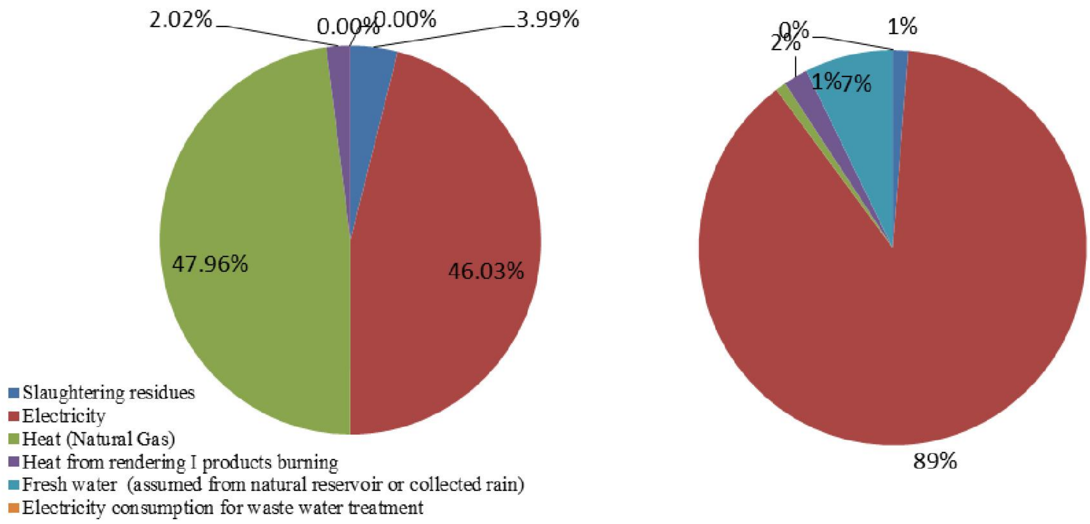

Figure 7.4: Material input shares of abiotic material (left) and water input (right) for rendering II

7.8.4 Biodiesel Production

The material intensity assessment per unit biodiesel production is shown in Table 7.6.

Table 7.6: Material intensity evaluation of biodiesel production process

Mass balance (local scale)			**MFA = material flow accounting (global scale)**		
Description of flow	Units	Mass	Mass abiotic g/unit	Mass water (g/unit	Mass air g/unit
Tallow	g/yr	3.31E+10	1.68E+10	3.76E+11	2.92E+10
Electricity	J/yr	8.46E+12	3.64E+09	1.57E+11	1.26E+09
Heat (natural Gas)	J/yr	4.77E+13	1.42E+09	5.81E+08	4.23E+09
Methanol CH_3OH	g/yr	3.61E+09	6.02E+09	1.61E+10	1.4E+10
Acid (Sulfuric Acid) H_2SO_4	g/yr	4.63E+08	1.16E+08	1.9E+09	3.24E+08
Potassium Hydroxide (KOH)	g/yr	595670	1148154	20778459	894994.2
Fresh water (assumed from natural reservoir or collected rain)	g/yr	3.31E+09	0	4.3E+09	0
Electricity consumption for waste water treatment	J/yr	2.64E+09	1138721	49023782	393042.5
Labor	-				
Total Input	g/yr		2.8E+10	5.56E+11	4.9E+10
OUTPUT					
Biodiesel	g/yr	3.24E+10			
	g/g		7.83E-01	1.55E+01	1.37E+00
Glycerol	g/yr	3.31E+09			
	g/g		7.83E-01	1.55E+01	1.37E+00

Per unit evaluation of biodiesel production results shown in Figure 7.5, reveal that raw material i.e. tallow is the main contributor with 60% and 68% contributions for both abiotic material input as well as water input to the overall process. Methanol consumption and energy demand (electricity and heat) are the other main contributors for abiotic material input. Methanol contributes 22%, electricity 13% and heat 5% to the overall process abiotic input. For water input electricity and methanol are the two significance contributors after raw material. Electricity 28%, methanol 3 % and all other inputs have less than 1% contributions after tallow. It shows that this process is energy intensive as well as has significant input of fossil chemicals.

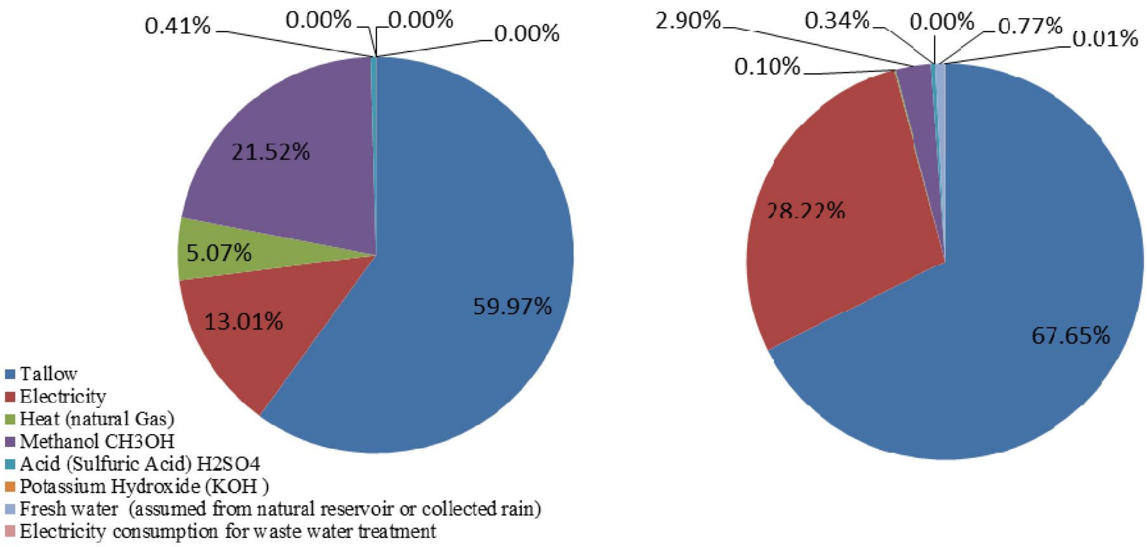

Figure 7.5: Material input shares of abiotic material (left) and water input (right) for biodiesel production

7.8.5 Hydrolysis

The material intensity evaluation of unit hydrolysate is shown in Table 7.7.

Table 7.7: Material intensity evaluation of hydrolysis process

Mass balance (local scale)			**MFA = material flow accounting (global scale)**		
Description of flow	Units	Mass	Mass abiotic g/unit	Mass water (g/unit	Mass air g/unit
Slaughtering residues	g/yr	1.73E+09	1.42E+07	1.01E+08	3.35E+07
Electricity	J/yr	1.50E+11	6.45E+07	2.78E+09	2.23E+07
Heat (natural gas)	J/yr	1.11E+12	3.31E+07	1.36E+07	9.87E+07
Hydrochloric acid (HCl)	g/yr	2.04E+09	6.17E+09	8.28E+10	7.74E+08
Sodium Hydroxide (NaOH)	g/yr	7.36E+08	2.03E+09	6.64E+10	7.80E+08
Fresh water (assumed from natural reservoir or collected rain)	g/yr	6.93E+08	0.00E+00	9.01E+08	0.00E+00
Labor	-				
Total Input	g/yr		8.31E+09	1.53E+11	1.71E+09
OUTPUT					
Hydrolysate	g/yr	3.67E+09			
	g/g	0	2.27E+00	4.17E+01	4.66E-01

The calculated results shown in Figure 7.6, depicts that mineral acid and bases are the main contributors both abiotic material input as well water input. Hydrochloric acid causes almost 74 % of abiotic material input along with 24% caused by sodium hydroxide input. Remaining input shares less than 2 % of abiotic input contribution among them. For water input for hydrolysis hydrochloric acid 54% and sodium hydroxide 43% are the main contributors and accounts for 97% of overall water input to the process. The energy provision (heat and electricity) fresh water and slaughtering residues covers only 3% of the water input.

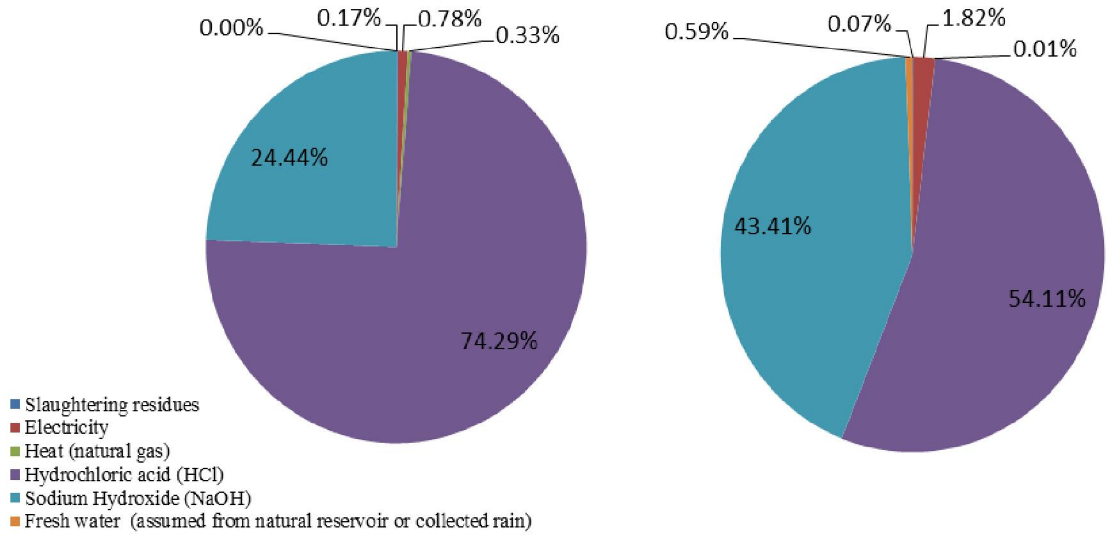

Figure 7.6: Material input shares of abiotic material (left) and water input (right) for hydrolysis

7.8.6 Fermentation (PHA production)

The inventory data and material input evaluation of unit PHA production is given in Table 7.8.

Table 7.8: Material intensity evaluation of fermentation process

Mass balance (local scale)			MFA = material flow accounting (global scale)		
Description of flow	Units	Mass	Mass abiotic g/unit	Mass water (g/unit	Mass air g/unit
Electricity	J/yr	1.81E+13	7.77E+09	3.35E+11	2.68E+09
Heat consumption	J/yr	1.05E+09	31279.61	12819.51	93326.05
Glycerol	g/yr	3.31E+09	2.59E+09	5.14E+10	4.53E+09
Biodiesel (LQ)	g/yr	1.78E+10	1.4E+10	2.77E+11	2.44E+10
Hydrolysate	g/yr	3.67E+09	8.31E+09	1.53E+11	1.71E+09
Ammonium Hydroxide (NH_4OH)	g/yr	7.67E+08	1.48E+09	2.67E+10	1.15E+09
Chemicals	g/yr	7.82E+08	1.51E+09	2.73E+10	1.17E+09
Fresh water (assumed from natural reservoir or collected rain)	g/yr	8.43E+10	0	1.1E+11	0
Electricity consumption for waste water treatment	J/yr	6.74E+10	2.90E+07	1.25E+09	1.00E+07
Labor	-				

Total Input	g/yr		3.57E+10	9.81E+11	3.57E+10
Output					
PHA the Main product	g/yr	1E+10			
	g/g		3.57E+00	9.81E+01	3.57E+00

Material intensity from Wuppertal institute

The raw materials for this process i.e. biodiesel and glycerol contributes about 46% of the abiotic material input as shown in Figure 7.7. Hydrolysate and electricity consumption contributes 23 and 21% respectively while ammonium hydroxide and chemicals contribute about 4% each. Similarly for water input per unit PHA production raw material input and heat demand has significantly lower contribution while electricity provision input contribution is significantly higher than abiotic material inputs. The main contribution of water input are 34% electricity, 33% raw material, 15% heat, 11 % fresh water and 3% each for chemicals and ammonium hydroxide. The energy input has significant contribution in both abiotic as well as water input per unit PHA production.

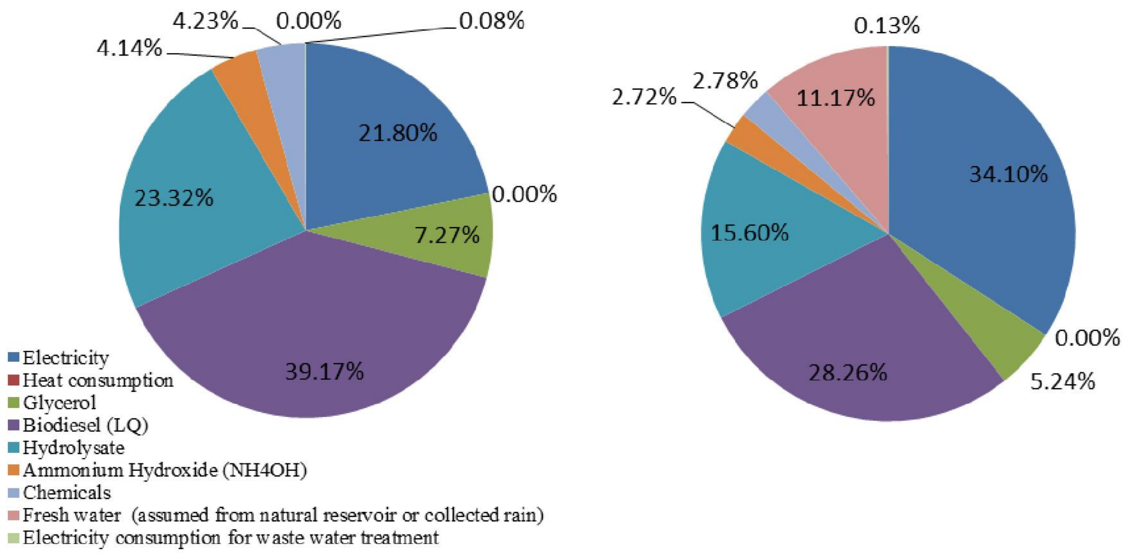

Figure 7.7: Material input shares of abiotic material (left) and water input (right) for fermentation (PHA production) process

7.8.7 Effect of change of energy provision resource

The energy (electricity and heat) input has shown significant contribution in both abiotic as well as water input in all sub-processes, throughout the overall PHA production process. It provides the opportunity to have a look at the system behaviour by fulfilling electricity demand from different energy provision systems. The effect of change of electricity provision source for biodiesel production and PHA production has been studied.

7.8.7.1 Comparative analysis of biodiesel production

The abiotic material input and water input for biodiesel production is compared with global values of abiotic material input and water input for diesel production. The comparison of biodiesel production utilizing electricity from EU-27 gird mix, hard coal, wind and biogas has been shown in Figure 7.8, detailed calculations are given in APPENDIX IV. Material input per unit of biodiesel production shows reduction of material input in the range of EU-27 mix 42%, hard coal 18%, wind 65% and biogas 57%. Similarly water input also shows significant variation depending on the energy provision resource. The provision of electricity from EU-27 mix and hard coal uses 60 and 44 % more water consumption than diesel, while electricity provision from wind and biogas have 81% and 79 % lower water input than diesel. In case of biogas there is an extra input of biotic material which is not the case in EU-27 mix, hard coal and wind. The comparison shows that biodiesel production process using electricity from wind has least impact on the environment.

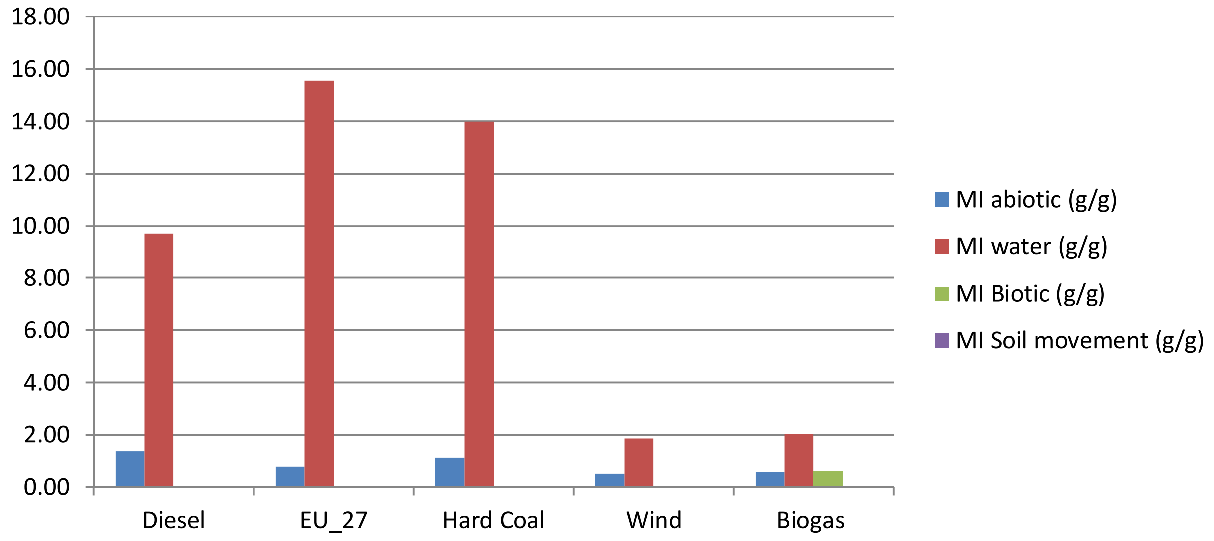

Figure 7.8: Effect of change of energy provision from different resources on biodiesel production

7.8.7.1 Comparative analysis of PHA production

The comparison of abiotic and water input results for PHA production utilizing electricity from different resources is compared with abiotic and water input values for low density polyethylene (LDPE) as shown Figure 7.9. The results reveal that abiotic material input has variable impact trend while water input has significantly lower values. The abiotic material input for PHA production is almost double for hard coal compared to LPDE. Similarly it is 43% and 7% higher for EU-27 mix and biogas than abiotic material input for LDPE. The water input shows a decreasing trend from EU-27 mix to wind. The water input reduction for different electricity resources are: 20% for EU-27 mix, 25% hard coal, 71% wind and 70% for biogas. The most environment friendly option is to use electricity from wind farm to produce PHA. Biogas is the 2nd best option but it has extra input of abiotic materials as well.

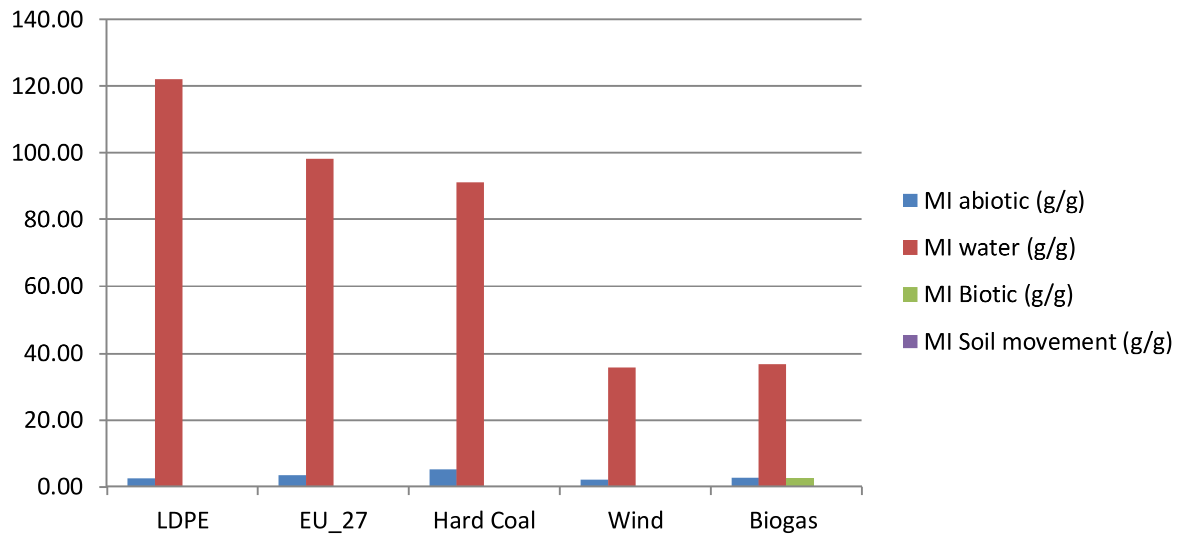

Figure 7.9: Effect of change of energy provision from different resources on PHA production

8 Discussion

The results obtained from evaluation of PHA production utilizing animal slaughtering waste as a starting material using different assessment methodologies has been shown in the previous chapters. In order to find out major driving factors of the process, detailed comparative analysis has been carried out. The comparative analysis revealing contribution of different input material and energy resources to each sub-process is described as follows.

8.1 Hydrolysis

The contributions of ecological pressure exerted by inventory inputs of hydrolysis shown in Table 3.1, calculated by different assessment methods has been compared and shown in Figure 8.1.

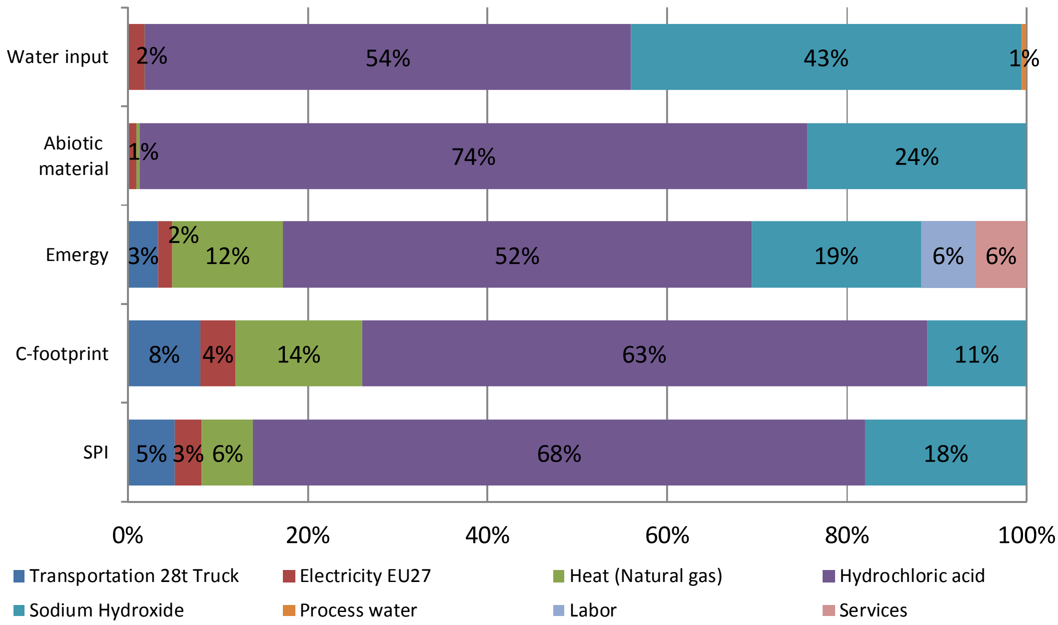

Figure 8.1: Comparative analysis of ecological pressure calculated by different methodologies

It reveals that mineral acid and base consumption is the main driving factor for this sub-process. Material input methodology have calculated maximum shares of 98% and 97% for "abiotic material" and "water input" categories, while electricity has a very small share of 1% and 2%

respectively. According to emery accounting evaluation mineral acid and base are the main contributors having 71% share, while heat provision 12%, labor and services 6% each, residues transportation 3% and electricity provision contributes about 2%. Carbon footprint results have 74% for mineral acid and base, 14% for heat provision, 8% for transportation and 4% for electricity, contributions respectively. Similarly SPI results show 86% contribution from mineral acid and base and rest 14% is distributed among heat 6%, transportation 5% and electricity provision 3%. These results disclose that mineral acid and base consumption has been figured out as the main driving factor for this process by all assessment methods. Other important contributions are heat electricity and material transportation, while emergy accounting evaluation has a prominent contribution from labor and services. Material intensity results are distinctively different than other methodologies, which are indicating the fact that both are products of highly energy intensive process and high material intensities. Also these inputs have large material flows.

8.2 Rendering

The ecological evaluation results for rendering I, calculated by different assessment methodologies have been shown in fig.

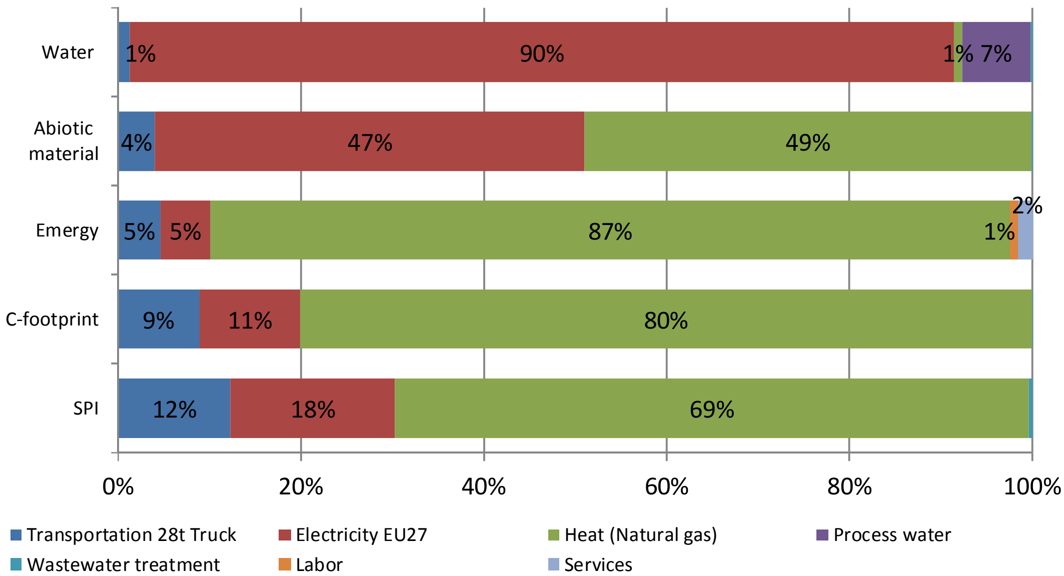

Figure 8.2: Comparative ecological assessment results for rendering I, using different assessment methodologies

The results reveal that MIPS methodology has distinctively different results which are in accordance very high value of material input per kWh, while material input per kWh of heat is almost half, of electricity value. For water input about 90% shares comes from electricity provision, while 7% out of the rest 10% is contributed by direct water input or process water. Similarly abiotic material input have 47% contribution from electricity provision and 49% from heat provision, while rest 4% is contributed by transportation. Emergy accounting, carbon footprint and SPI results show somewhat similar trends. Emergy accounting evaluation has 87% contribution from heat provision, 5% each from electricity and residue transportation, 2 % from services and 1% from labor respectively. Carbon footprint results distribution shows 80% for heat, 11 % for electricity and 9% for residue transportation respectively. Similarly SPI results reveal that heat provision is responsible for 69% environmental pressure while rest is mainly contributed by electricity about 18% and transportation which is about 12%. According to above mentioned results heat provision and electricity are the main driving factor for rendering I. Also transportation of residues has significant contribution to the overall process.

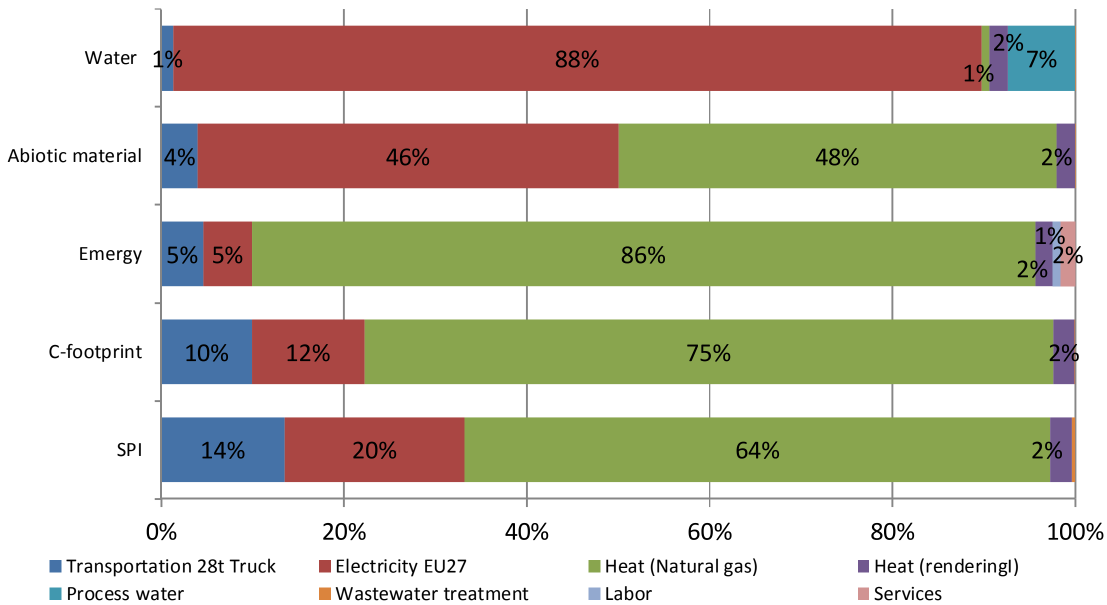

Figure 8.3: Ecological assessment results for rendering II, using different assessment methodologies

The evaluation results of rendering II have been shown in Figure 8.3. The results reveal similar trend as that of rendering I process, which is because of being duplicate of rendering I process.

The only inclusion is heat provision from rendering I, which contributes about 2% each in all results. The main driving factors for rendering II are electricity and heat input along with transportation to a minor extent.

8.3 Biodiesel Production

The calculated evaluation results for biodiesel production using different assessment methodologies are displayed in Figure 8.4.

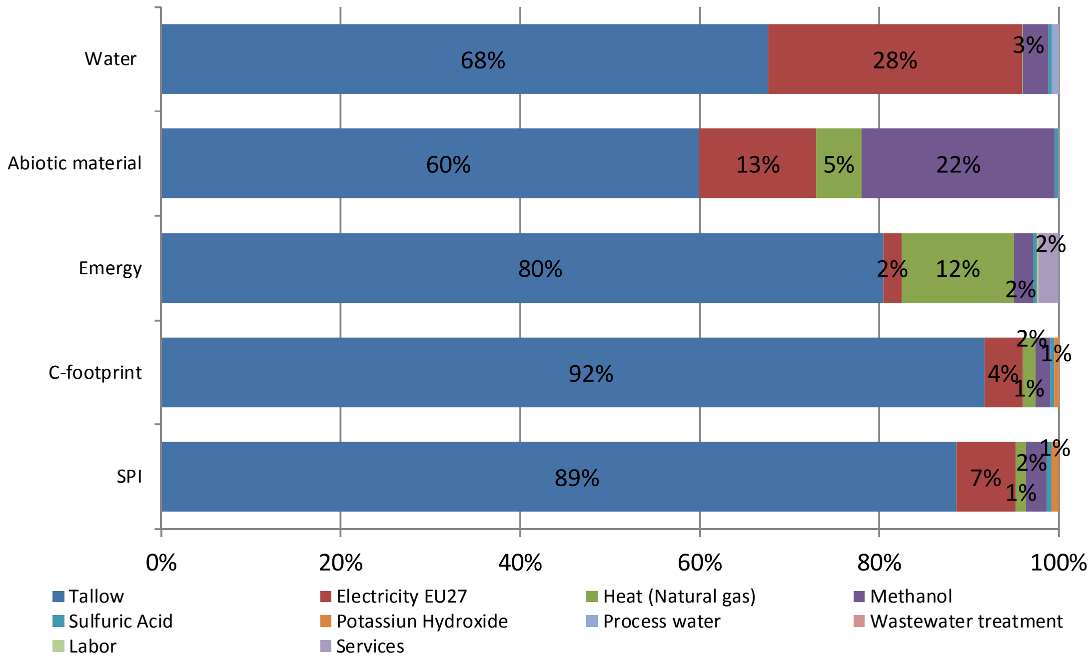

Figure 8.4: Ecological assessment results obtained by different methodologies for biodiesel production

The results showed in the above figure reveals that tallow input shares the main contribution to all results. For material input methodology, water input results have 68% share while electricity and methanol have 28% and 3% contributions respectively. Abiotic material input results have 60% tallow, 13% electricity, 5% heat and 22% methanol contributions respectively. Emergy accounting evaluation results show 80% tallow, 12% heat and 2% each electricity, methanol and services contributions respectively. Carbon footprint evaluation results contain 92% tallow, 4% electricity, 2% methanol and about 1% each for potassium hydroxide and heat input contributions. Similarly SPI results comprise 89% tallow, 7% electricity, 2% methanol and about

1% each for heat and potassium hydroxide shares respectively. The results from all methodologies reveal that main driving factors for this process are tallow and electricity, while heat provision shows a significant share in emergy evaluation results. In these results methanol contribution is very high compare to the results of other methodologies. It is in agreement with hydrolysis results, indicating consumption of highly material intensive chemical product.

8.4 Fermentation Process

The results for fermentation process evaluation using four different assessment methodologies are shown in Figure 8.5.

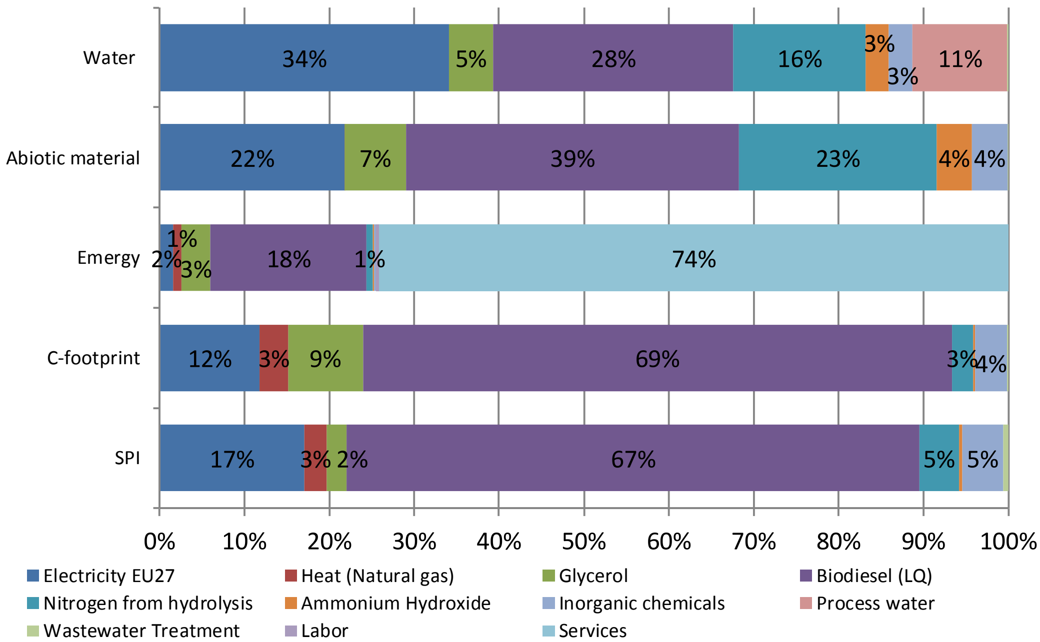

Figure 8.5: Ecological evaluation results for fermentation process, calculated by different methodologies

These results show completely different trend than those of previous processes. The material input methodology results for water input constitute 34% electricity, 33% carbon source input (biodiesel and glycerol), 16% organic nitrogen source (hydrolysate), 11% process water and 3% each for ammonium hydroxide and inorganic chemical inputs. Abiotic material input results contain 46% carbon source, 22% electricity, 23% hydrolysate and 4% each for ammonium hydroxide and inorganic chemicals. Emergy accounting evaluation results show distinguishing trend having 74% share from services, 21% from carbon sources and all other inputs have 5%

representation. Carbon footprint and SPI results share somewhat similar trend, both having about 70% contributions from carbon resources. Carbon footprint result is comprised of 68% biodiesel, 9% glycerol, 12 % electricity, 3% heat and hydrolysate, while rest 4% is shared among all other inputs. Similarly SPI results are constituted by 67% biodiesel, 2% glycerol, 17% electricity, 3 % heat provision and 5% each by ammonium hydroxide and inorganic chemicals inputs.

SPI evaluation results shows that mineral acid and base consumption is the main driving factor in hydrolysis. This is due to highly energy intensive life cycle production of both mineral acid and base. Heat and transportation also show minor impact with respect to overall impact of the sub-process. For rendering process heat and electricity are the main driving factors along with minor impact caused by slaughtering residue material transportation. It is highly energy intensive process because it involves cooking at high pressure (3 bar) and mechanical squeezing of the material to obtain tallow and MBM. Main driving factors for biodiesel production process are tallow input and electricity provision. It can also be considered as an energy intensive process because of tallow input. 1 ton of biodiesel production requires 1.02 t of tallow which is produced from highly energy intensive process. Electricity provision has a small impact compares to tallow input and it is used for continuous stirring to provide maximum surface interaction for transesterification reaction and pumping in and out of the materials. The main driving factors for fermentation process are mainly raw material inputs (biodiesel, glycerol and hydrolysate) and electricity provision. Biodiesel and glycerol serve as carbon source for bacteria to produce PHA, while hydrolysate serves as a source of organic nitrogen for catalytically active biomass production in the first phase of fermentation process.

Carbon foot evaluation results discussed above reveal that mineral acid and base consumption is the main driving force for this process, while heat and transportation are the minor contributors. The highest contribution from acid and base consumption is due to their energy intensive life cycle production as well as emission to air. For rendering processes main driving factor is heat provision for cooking of the slaughtering residues, while electricity consumption for mechanical activity i.e. pressing or squeezing of the cooked material and transportation of the residue material also minor contributions. For biodiesel production tallow input accounts for almost 92% of the overall footprint, it is produced through highly energy intensive rendering process. Electricity consumption has a small contribution of only 4% while other inputs have even lesser shares. For fermentation process carbon source i.e. biodiesel and glycerol are the main driving factor along with electricity provision.

Emergy accounting evaluation results reveal that for hydrolysis main driving factors are acid and base inputs while heat provision also has a significant to the total emergy content of the process. Similarly labor and services also have minor contributions to the total emergy content of the processes. The main contributing factor for rendering processes is heat provision while residue transportation and electricity are minor contributors to the total emergy content of the process. For biodiesel production main contributor of emergy content is tallow, while heat provision is the minor contributor to the overall emergy content of the process. Tallow being a product of highly energy intensive rendering process and one of the main contributors of biodiesel production indicates the possible potential of ecological optimization by utilizing energy from different resources. Similarly emergy accounting evaluation for fermentation process shows that main contributor of total emergy content of this process is services, while biodiesel and glycerol also have significant contribution.

Material input methodology results shows that mineral acid and base are the deciding factors for hydrolysis while heat electricity and transportation are the key factors in rendering process. In biodiesel production process tallow consumption, electricity provision and methanol consumption are important factors to drive the whole process. Similarly in fermentation process biodiesel, glycerol and hydrolysate (raw materials), electricity and water consumption are key factors controlling the whole process. Material input results also indicate potential of ecological optimization using different energy sources with a little exception. For example methanol consumption in biodiesel production contributes significance share as well as hydrolysate input has substantial contribution to fermentation process results. Also use of process water in fermentation process has consider contribution to the overall process results.

8.5 Comparative analysis using different energy resources

Electricity consumption shows a significant share in the overall footprint result which is used for pumping in and out of fermentation media, continuous stirring of the media to stabilize and maintain required conditions. As explained earlier biodiesel, glycerol and hydrolysate are products of highly energy intensive processes. This process also indicates the potential of ecological optimization by replacing energy provision resources. In accordance to the findings of these preliminary results, comparative analysis for biodiesel as well as PHA production has been carried out utilizing energy from different resources as shown in Figure 4.10 and Figure 4.11 respectively. The results reveal that energy use from renewable resources decrease ecological pressure to a great extent. For example diesel available at the regional store and biodiesel production from slaughtering waste using electricity from coal and heat provision from natural gas have 14 and 6 folds higher footprint respectively than biodiesel production using electricity and heat from biomass. Similarly PE-LD and PHA production using electricity from coal and heat from natural gas have 12 and 5 folds higher footprint respectively than PHA production utilizing electricity and heat from biomass.

Carbon footprint evaluation results show similar trend as that of shown by SPI evaluation results and show the potential of ecological optimization by utilizing energy from more environmental friendly resources. The comparative analysis of biodiesel and PHA production utilizing energy from different resources is carried out in the light of preliminary results are shown in Figure 5.5 and Figure 5.6 respectively. This analysis has shown immense potential of ecological optimization with exchange of energy resources for biodiesel as well as PHA production. Diesel and biodiesel produced by utilizing electricity from coal and heat from natural gas has 25 and 11 folds higher carbon footprint than biodiesel production utilizing electricity and heat from biomass. Similarly production of PE-LD and PHA production using electricity from coal and heat from natural gas has 10 and 9 fold higher carbon foot print than PHA production using electricity and heat from biomass.

The effect of change of energy provision resource on in emergy evaluation of biodiesel and PHA production are given in Figure 6.12 and Figure 6.13 respectively. The emergy intensity of biodiesel production (seJ/g) shows a negative impact for electricity provision from coal, while fulfilling of electricity demand using electricity from biogas, hydro, biomass and wind have slightly positive effect ranging in between 3% to 4%. The provision of electricity as well as heat demand by biomass burning shows about 69% improvement compared to the basic scenario of energy provision from EU electricity mix and natural gas for electricity and heat respectively. Similarly effect of change of energy resources on biodiesel transformity (seJ/J) compared to diesel transformity 1.81E+5 (Brown and Ulgiati, 2011), has a positive impact with 55% to 57% decrease in transformity value for electricity from EU27 mix, coal, hydro power, wind and biomass, while electricity and heat provision from biomass has maximum 87% decrease in transformity value. The emergy intensity for PHA production (seJ/g) shows very minor improvement ranging in between 1.5% to 2% by changing only electricity provision resource. This impact reaches up to 17% when electricity as well as heat provision resources are replaced with biomass resources. Similarly comparison of emergy intensity for PHA production using electricity EU27 mix, coal, hydro power, wind power and biomass is about 5% to 7% lower than emergy intensity of polyethylene high density (PE-HD), while its value reaches up to 21% lower for electricity and heat provision from biomass.

The comparison of biodiesel and PHA production utilizing electricity from EU-27 mix grid energy, hard coal, wind and biogas has been shown in Figure 7.8 and Figure 7.9 respectively. Material input per unit of biodiesel production shows reduction of material input in the range of EU-27 mix 42%, hard coal 18%, wind 65% and biogas 57%. Similarly water input also shows significant variation depending on the energy provision resource. The provision of electricity from EU-27 mix and hard coal uses 60 and 44 % more water consumption than diesel, while electricity provision from wind and biogas have 81% and 79 % lower water input than diesel. In case of biogas there is an extra input of biotic material which is not the case in EU-27 mix, hard coal and wind. Similarly comparison of abiotic and water input results for PHA production utilizing electricity from different resources is compared with abiotic and water input values for low density polyethylene (LDPE) as shown. The results reveal that biotic material input has mixed impact while water input has significantly lower values. The abiotic material input for PHA production is almost double for hard coal compared to LPDE. Similarly it is 43% and 7% higher for EU-27 mix and biogas than abiotic material input for LDPE. The water input shows a decreasing trend from EU-27 mix to wind. The water input reduction for different electricity resources are: 20% for EU-27 mix, 25% hard coal, 71% wind and 70% for biogas. The most environment friendly option is to use electricity from wind farm to produce biodiesel as well as PHA.

SPI and carbon footprint show similar behaviour in their results. It might be due to the fact that carbon footprint results are induced from life cycle fossil carbon emission category, which accounts for use of fossil carbon along the life cycle chain of the product, including life cycle chains of material and energy provision for the production of the product. Carbon footprint can have more prominent results, considering it will be calculated using normal LCA methodology in use for its calculation, compare to SPI methodology which have distinctive way of handling emissions. In general almost 80 % of carbon footprint of a product or service, account for energy consumptions during the process.

8.6 Labour and services

The inclusion of labour and services are additional emergy inputs which are added to the analysed process. These include fraction of renewables that support the economy at national level along with welfare of a given society. The highest impact in emergy evaluation fermentation process (PHA production) is contributed by labor and services. The comparison of emergy indicators with and without labor and services also reveal that the inclusion of socio-economic flows remarkably decrease renewability and sustainability of the systems (as shown in APPENDIX III). It shows there is a linkage between emergy evaluation as an environmental assessment and economic analysis. This high percentage suggests that PHA preproduction (industrial process) is mainly based on indirect contributions from the society, which is typical for industrial products. Every provider of (indirect) labor (an economic agent) is supported by a social network of activities (like, food, health, education, security, transportation, hobbies etc.), which are paid by the money, earned in a process. So, emergy that supports fermentation process is actually emergy that supports a quality of life for labor, paid for by their monetary revenue.

The labor and services represents the emergy required to support direct and indirect human labor (i.e. whole socio-economic network) and is directly associated to its economic cost, determined by wider economic system. It indicates the fact that industrial processes have little ability to affect their own sustainability. This problem of high labor cost cannot be solved by reducing labor wages and quality of life, but instead improving societal dynamics. It requires decrease in resources use, reduction is luxuries and waste production, which in turn require less emergy to support the economy. Ultimately a decrease in emergy per capita and emergy value of money (Emergy/GDP; seJ/€), will decrease emergy share of labor and services, but without reduction in societal welfare.

8.7 Evaluation of waste

SPI evaluation accounts both input and output material flows and it calculates the area required to embed the whole process sustainably into the ecosphere. It uses dissipative measurement method to calculate area, for emissions related to output flows, into their respective compartments (air, soil, water). In carbon footprint which is a single measure issue methodology, only CO2 or GHGs are measured to address climate change and global warming. In MIPS, output flows are not considered and it only focuses on dematerialization of input flows.

The emergy evaluation is carried out utilising local, regional, national and biospheric boundary conditions which define available renewable inputs to the system under consideration. Emergy dealing at a biosphere perspective have different meaning for anthropogenic waste terminology, as it argues no flow is a waste because every flow or residue from a process becomes an input to another process. In principle any flow coming out as residue from a process is either nutrient or toxin, have an impact on the surrounding environment leading to system evolution, by favouring some and effecting negatively to others. Similarly Brown and Ulgiati argued (2010) "*effect can be both positive and negative: Transformity does not suggest the outcome that might result from the interaction of a stressor with in an ecosystem, only that with high transformity the effect is greater. Where empower density of a stressor is significantly higher than the average empower density of the ecosystem it is released into, one can expect significant changes in ecosystem function*". Similarly transformity of a product or service only explains efficiencies of the current practices along with comparison of optimisation potentials.

9 Conclusion

The evaluation results of case study, utilizing carbon footprint, SPI, Emergy accounting and Material Input Per unit Service methodologies, reveal that all methodologies rate the evaluation process in accordance to the value system behind their development. This confirms our third research question about reflection of normative background in the results. For example coal has higher footprint values for SPI and carbon footprint as well as higher UEV and MIPS value. The reason behind is long-term environmental investment during its formation and high emissions during combustion process.

Cross examination of the results show that most of the trends are similar except few exceptions. These results include exceptionally high impact share of mineral acid and base consumption in hydrolysis as well as higher impact of methanol consumption in biodiesel production, for MIPS methodology. It indicates the fact of having very high material input values for chemicals derived from minerals, under highly energy intensive life cycle chain processes. Similarly labor and services input share in fermentation process shows discrete behavior for emergy accounting results. This high percentage suggests that PHA preproduction (industrial process) is mainly based on indirect contributions from the society, which is typical for industrial products. Every provider of (indirect) labor (an economic agent) is supported by a social network of activities (like, food, health, education, security, transportation, hobbies etc.), which are paid by the money, earned in a process. So, emergy that supports fermentation process is actually emergy that supports a quality of life for labor, paid for by their monetary revenue. The high share represents that very little emergy is directly invested in fermentation process – larger portion is invested in the social welfare of the labor. Excluding these results, all other results from all methodologies show similar trend.

All methodologies have the potential to rate the energy technology and in this study exchange of energy provision from business as usual (EU mix grid electricity and natural gas for heating) to biomass for both heat and electricity represents the most environment friendly option. This is in accordance to completion of short term carbon cycle, including fixation of CO_2 by photosynthesis and release of same amount of CO_2 in the combustion process. Similarly in emergy accounting wood or biomass also accounted as renewable sources, fulfilling the fact that their replacement time is as fast as their use rate.

In general, it can be said that all methodologies have certain strong points (e.g. relative inclusion of social and economic aspects in emergy accounting), while carbon footprint, SPI and MIPS do not address these aspects. Similarly emergy accounting and MIPS do not explain emissions based on output flows. Carbon footprint uses single measure base to partly address this issue while on the other hand SPI explains it more exclusively, using material dissipation approach. Having these, entire plus and minuses, it can be said that all methodologies are important and playing their role to attain global sustainability. It's up to the decision makers (engineers in technology development especially) to have a look at their system boundary and select the suitable measurement methodology according to their need. If I will be the person to decide, which sustainable measurement methodology is suitable for evaluation of a certain process or system? I will prioritize them according to the nature of the system in study and evaluation requirements like, SPI for process design and development studies, carbon footprint will be appropriate measure for addressing climate change and global warming, in case of pure scientific work involving thermodynamics emergy evaluation will be a good option to choose. I will avoid using MIPS, because it does not show any sound scientific base nor it uses any reference concerning biodiversity.

10 References

Azapagic, A. & Perdan, S. 2010, "Sustainability of Nuclear Power" in Sustainable Development in Practice John Wiley & Sons, Ltd, , pp. 211-260.

Barnosky, A.D., Hadly, E.A., Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P.A., Martinez, N.D., Mooers, A., Roopnarine, P., Vermeij. G., Williams, J.W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D.P., Revilla, E. & Smith, A.B. 2012, "Approaching a state shift in Earth's biosphere", Nature, vol. 486, pp. 52-58.

Bolin, B. & Cook, R.B. 1983, "The major biochemical cycles and their interactions. SCOPE series 21. ", John Wiley & Sons, Hoboken/U.S.A.

Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, C.J., Wackernagel, M. & Galli, A. 2013, " Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework", Ecological Indicators, vol. 24, pp. 518-533-ISSN 1470-160X.

Brown, M.T. & McClanahan, T.R. 1996, "Emergy analysis perspectives of Thailand and Mekong River dam proposals", Ecological Modelling, vol. 91, no. 1–3, pp. 105-130.

Brown, M.T. & Ulgiati, S. 1997, "Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation", Ecological Engineering, vol. 9, no. 1–2, pp. 51-69.

Brown, M.T. & Ulgiati, S. 2001, "The role of environmental services in electricity production processes ", Journal of Cleaner Production, vol. 10, pp. 321–334.

Brown, M.T. & Ulgiati, S. 2002, "Emergy evaluations and environmental loading of electricity production systems", Journal of Cleaner Production, vol. 10, no. 4, pp. 321-334.

Brown, M.T. & Ulgiati, S. 2004, "Energy quality, emergy and transformity: H.T. Odum's contributions to quantifying and understanding systems", Ecological modeling, vol. 178, pp. 201-213.

Brown, M.T. & Ulgiati, S. 2010, "Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline", Ecological Modelling, vol. 221, no. 20, pp. 2501-2508.

Brown, M.T., Protano, G. & Ulgiati, S. 2011, "Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas", Ecological Modelling, vol. 222, no. 3, pp. 879-887.

Brown, M.T. & Ulgiati, S. 2014, " Emergy Systems: Coupling Humanity and Nature ", Springer, forthcoming.

Buonocore, E., Franzese, P.P. & Ulgiati, S. 2012, "Assessing the environmental performance and sustainability of bioenergy production in Sweden: A life cycle assessment perspective", Energy, vol. 37, no. 1, pp. 69-78.

Buranakam, V. 1998, "Evaluation of recycling and reuse of building materials using the emergy analysis method. ", Ph.D Dissertation, Department of Architeture, University of Florida. Gainesville, FL.

Carbon Trust 2007, "Carbon Footprint measurement Methodology, Version 1.3. ", The Carbon Trust, London, UK.

Catton, W. 1980, "Overshoot: The Ecological Basis of Revolutionary Change. ", Champaign, IL, University of Illinois Press.

Center for International Earth Science Information Network, 2002 " Environmental Sustainability Index (ESI). Available at: http://sedac.ciesin.columbia.edu/es/esi/ESI2002_21MAR02tot.pdf last accessed [15.06.2014]

Costanza, R. & Daly, H.E. 1992, "Natural capital and sustainable development. ", Conservation Biology, vol. 6, no. 37, pp. 46.

Demirel, Y. (2012), Energy, Green Energy and Technology, Springer-Verlag London Limited. 2012. DOI: 10.1007/978-1-4471-2372-9_2,

Denafas, G., Buineviþius, K., Urniežaitơ, I., Puškorius, R. & Rekašius, J. 2004, "1. Meat and Bone Meal Incineration in Terms of Industrial and Energetic Infrastructure in Lithuania: Energetic and Environmental Aspects. ", Environmental research, engineering and management, vol. 4, no. 30, pp. 36-48-ISSN 1392-1649.

Dietz, T., Rosa, E.A. & York, R. 2007, " Driving the human ecological footprint. Front Ecol Environ ", vol. 5, pp. 13–8.

Dinda, S. 2004, "Environmental Kuznets Curve Hypothesis: A Survey", Ecological Economics, vol. 49, pp. 431 - 455.

Doherty, S.J., Brown, M.T. & Murphy, R.C. 1992, "Emergy analysis and public policy perspectives for Papua New Guinea. ", A Research Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville, FL.

European Commission 1996, "Operational Indicators for progress towards sustainability. ", Project nr. EV5V – CT94, pp. 0374.

Eurostat 2001, "1. Economy-Wide Material Flow Accounts and Derived Indicators: a Methodological Guide", Eurostat, Luxembourg.

Ewing, B., Goldfinger, S., Wackernagel, M., Stechbart, M., Rizk, S.M., Reed, A. & Kitzes, J. 2008, " The Ecological Footprint Atlas 2008", Global Footprint Network, Oakland., .

Fahd, S., Fiorentino, G., Mellino, S. & Ulgiati, S. 2012, "Cropping bioenergy and biomaterials in marginal land: The added value of the biorefinery concept", Energy, vol. 37, no. 1, pp. 79-93.

Frischknecht, R., Jungbluth, N., Althaus, H., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G. & Spielmann, M. 2004, " The ecoinvent Database: Overview and Methodological Framework ", The International Journal of Life Cycle Assessment, vol. 10, no. 1, pp. 3-9.

Global Footprint Network (GFN) "Global Footprint Network (GFN)", Available at: http://www.footprintnetwork.org/en/index.php/GFN/ , pp. [last accessed: 4 June 2014].

GREET, 2010, The Greenhouse Gases, Regulated Emissions, and Energy Use In Transportation Model, GREET 1.8d.1, developed by Argonne National Laboratory, Argonne, IL, released August 26, 2010. http://greet.es.anl.gov/ accessesd at: http://cta.ornl.gov/bedb/appendix_a/Lower_and_Higher_Heating_Values_of_Gas_Liquid_and_Solid_Fuels.pdf [accessed date: 04.02.2014]

Gwehenberger, G., Narodoslawsky, M., Liebmann, B. & Friedl A 2007, " Ecology of scale versus economy of scale for bioethanol production", Biofuels, bioproducts and Biorefining, vol. 1, no. 4, pp. 264-269.

Hau, J.L. & Bakhshi, B. 2004, " Promise and Problems of emergy analysis. ", Ecological Modeling, vol. 178, pp. 215-225.

Hertwich, E.G., Pease, W.S. & Koshland, C.P. 1997, "Evaluating the environmental impact of products and production processes: a comparison of six methods", Science of The Total Environment, vol. 196, no. 1, pp. 13-29.

Hirner, H. 2012, "Greenhouse gas emissions - ISO 14067 to enable worldwide comparability of carbon footprint data. ", pp. [last accessed: 03 June 2014].

Hinterberger, F., Luks, F. & Schmidt-Bleek, F. 1997, "Methods Material flows vs. ‚Natural capiotal‘ What makes and economy sustainable? ", Ecological Economics, vol. 23, pp. 1-14.

Hoekstra, A.Y. & Chapagain, A.K. 2008, "Globalization of water: Sharing the planet's freshwater resources,",Blackwell Publishing, Oxford, UK .

IPCC 2007, "Climate Change: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)]. ", IPCC, Geneva, Switzerland, pp. 104 pp.

ISO 2006, "1Environmental Management - Life Cycle Assessment - Principles and Framework , ", ISO 14040ISO 14067/TS.

ISO/TS 14067 2013, "Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification and communication. The British Standards Institution. ", Published by BSI Standards Limited.

Keiner, M. 2006, "1. The future of sustainability.", Springer: Dordrecht.

Kettl, K. & Narodoslawsky, M. 2013, "SPIonWeb – Dynamic Life Cycle Impact Assessment (LCIA) process modelling based on Sustainable Process Index (Ecological Footprint) ", Journal of Environmental Accounting and Management, vol. 1, no. 1, pp. 1-12.

Koller, M., Atlić, A., Dias, M., Reiterer, A. & Braunegg, G. 2010a, "Microbial PHA Production from Waste Raw Materials, in: G.-Q. Chen, A. Steinbüchel (Eds.), Plastics from bacteria. ", Natural functions and applications. Springer Berlin Heidelberg, , no. 14, pp. 85-119.

Koller, M., Salerno, A., Miranda, de Sousa. D. M., Reiterer, A. & Braunegg, G. 2010b, "Modern biotechnological polymer synthesis: a review", Food Technology and Biotechnology, vol. 3, no. 48, pp. 255- 269.

Koller, M., 2012, Graz University of Technology, "Institute of Biotechnology and Biochemical Engineering", , pp. martin.koller@tugraz.at.

Krotscheck, C. & Narodoslawsky, M. 1996, "The Sustainable Process Index; a new dimension in ecological evaluation.", Ecological Engineering, vol. 4, no. 6, pp. 241-258.

Krotscheck, C. 1997, "How to measure sustainability? Comparison of flow based mass and/or energy highly aggregated indicators for eco-compatibility. ", EnvironMetrics, vol. 8, no. 661, pp. 81.

Krotscheck, C., KoÈnig, F. & Obernberger, I. 2000, "Ecological assessment of integrated bioenergy systems using the Sustainable Process Index", Biomass and Bioenergy, vol. 18, pp. 341-368.

Kunasundari, B. & Sudesh, K. 2011, "Isolation and recovery of microbial Polyhydroxyalkanoates. ", eXPRESS Polymer Letters, vol. 5, no. 7, pp. 620–634.

Lawn, P. 2007, " A stock-take of green national accounting initiatives", Soc Indic Res, vol. 80, pp. 427–60.

Lettenmeier, M., Rohn, H., Liedtke, C. & Schmidt-Bleek, F. 2009, "Resource Productivity in 7 steps: How to develop eco-innovative products and services and improve their material footprint", Wuppertal Institute for Climate,Environment and Energy, , no. ISBN 978-3-929944-80-8.

Macini, L., Lettenmeier, M., Rohn, H. & Liedtke , C. 2012, "Application of the MIPS method for assessing the sustainability of production –consumption systems of food", Journal of economic behavior and organization, vol. 81, no. 3, pp. 779-793.

Mayer, A.L. 2008, "Strengths and weaknesses of common sustainability indices for multidimensional systems ", Environment International, vol. 2, no. 34, pp. 277–291.

McManus, P. & Haughton, G. 2006, " Planning with ecological footprints: a sympathetic critique of theory and practice", Environ Urban, vol. 18, pp. 113–27.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, C.B.S., Frieler, K., Knutti, R., Frame, J.D. & Allen, R.M. 2009, "Greenhouse-gas emission targets for limiting global warming to 2 °C. ", Nature, , no. 458, pp. 1158-1162.

Michael, F. & Ashby, K.J. 2013, "Materials and Design: The Art and Science of Material Selection in Product Design ",Edition 3 Publisher Butterworth-Heinemann, , pp. ISBN 0080982824, 9780080982823.

Narodoslawsky, M., Krotscheck, Ch. & Sage, J. (1994). The Sustainable Process Index (SPI) – A Measure for Process Industries. In: Proceedings AFCET, International Symposium: Models of Sustainable Development. Exclusive or Complementary Approaches of Sustainability? Volume II, March 16-18, Paris

Narodoslawsky, M. & Krotscheck, C. 1995, " The Sustainable Process Index (SPI): evaluating processes according to environmental compatibility", J Hazard Mater, vol. 2-3, no. 41, pp. 383–397.

Narodoslawsky, M. & Krotscheck, C. 2000, "Integrated ecological optimization of processes with the sustainable process index ", Waste Management, vol. 20, pp. 599-603.

Narodoslawsky, M. & Krotscheck, C. 2004, "What can we learn from ecological valuation of processes with the sustainable process index (SPI) - the case study of energy production systems " J. of Cleaner Prod, vol. 12, pp. 111-115.

Narodoslawsky, M., Niederl-Schmidinger, A. & Halasz, L. 2008, "utilising renewable resources economically: new challenges and chances for process development. Journal of Cleaner Production ", Journal of Cleaner Production, vol. 16, pp. 164-170.

Narodoslawsky, M. & Stoeglehner, G. 2010, "Planning for Local and Regional Energy Strategies with the Ecological Footprint", Journal of Environmental Policy & Planning, vol. 4, no. 12, pp. 363–379.

NEAD 2014, "National Environmental Accounting data base." Available at: http://www.cep.ees.ufl.edu/emergy/nead.shtml

Ness, B., Urbel-Piirsalu, E., Anderberg, S. & Olsson, L. 2007, "Categorising tools for sustainability assessment. Ecological Economics", vol. 3, no. 60, pp. 498-508.

Niederl-Schmidinger, A. & Narodoslawsky, M. 2008, "Life Cycle Assessment as an engineer's tool? ", Journal of Cleaner Production, , no. 16, pp. 245-252.

Odum, H. T., 1994. Ecological and general systems, University of Colorado Press, Niwot, Colorado, 644 pp.

Odum, H.T. 1996, "Environmental Accounting. EMERGY and Environmental Decision Making.", John Wiley & Sons, Toronto.

Odum, H.T. 1998, "Emergy Evaluation.", Minnesotans For Sustainability.

Odum, H.T., Brown, M.T. & Brandt-Williams, S. 2000, "Introduction and Global Budget". Handbook of Emergy Evaluations, Folio #2. Center for Environmental Policy, P.O. Box 116450, University of Florida, Gainesville, FL 32611.

Özdemir, E.D., Härdtlein, M., Jenssen, T., Zech, D. & Eltrop, L. 2011, "A confusion of tongues or the art of aggregating indicators—Reflections on four projective methodologies on sustainability measurement", Renewable and Sustainable Energy Reviews, vol. 15, no. 5, pp. 2385-2396.

Pearce, D.W. & Atkinson, G.D. 1993, "Capital theory and the measurement of sustainable development: an indicator of "weak" sustainability", Ecological Economics, vol. 8, no. 2, pp. 103-108.

Pickering, M.V. & Newton, P. 1990, "Amino acid hydrolysis: Old problems, new solutions", Bio.Separations, , no. LC/GC 8(10), pp. 778-81.

Prescott-Allen, R. 2001, "The Wellbeing of Nations. A Country-by Country Index of Quality of Life and the Environment. ", Island Press, Washington.Center for International Earth Science Information Network .

Rees, W.E. 2002, "An ecological economics perspective on sustainability and prospects for ending poverty.", Popul Environ, vol. 24, no. 15, pp. 46.

Ritthoff, M., Rohn, H. & Liedtke, C. 2002, "Calculating MIPS "Resource productivity of products and services". . I", Wuppertal Institute for Climate,Environment and Energy at the Science Centre North Rhine-Westphalia, , no. ISBN 3-929944-56-1e.

Ruževičius, J. 2011, "Ecological footprint: evaluation methodology and international enchmarking. ", Verslo ir teisės aktualijos / Current Issues of Business and Law, vol. 6, no. 1, pp. 11–30-ISSN 1822-9530 print / ISSN 2029-574X.

SAIC 2006, "1. LIFE CYCLE ASSESSMENT: PRINCIPLES AND PRACTICE", Scientific Applications International Corporation (SAIC) ,11251 Roger Bacon Drive ,Reston, VA 20190. pp. EPA/600/R-06/060.

Sandholzer, D. & Narodoslawsky, M. 2007, "SPIonExcel-Fast and easy calculation of the Sustainable Process Index via Computer", J Resources, Conservation and Recycling, vol. 50, pp. 130-142.

Schmidt-Bleek, F. 1993", - „Wieviel Umwelt braucht der Mensch – mips, das ökologische Mass zum Wirtschqften“, Birkhäuser, " Basel, Boston, Berlin, 1993; appeared in Japanese (4th edition, pringer Tokyo), Chinese and Finnish. English version in www.factor10-institute.org under the title “The Fossil Makers.

Schmidt-Bleek, F. 1998, "1.Das MIPS-Konzept: weniger Naturverbrauch - mehr Lebensqualität durch Faktor 10."Droemer, München.

Schmidt-Bleek, F. 2001, "1. EcoDesign 2001", 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing Date: 12-15 December 2001, Venue: Tokyo Big Site, Japan. BUSINESS CENTER FOR ACADEMIC SOCIETIES JAPAN.

Schmidt-Bleek, F. 2004, "TowardsSustainable Futures– Tools and Strategies", International Conference Tampere, Finland.

Shahzad, K., Kettl, K.-., Titz, M., Koller, M., Schnitzer, H. & Narodoslawsky, M. 2013, "Comparison of ecological footprint for biobased PHA production from animal residues utilizing different energy resources, " Clean Techn Environ Policy.

Titz, M., Kettl, K., Shazhad, K., Koller, M., Schnitzer, H. & Narodoslawsky, M. 2012, "Process optimization for efficient biomediated PHA production from animal-based waste streams. "Clean. Technol. Environ. Policy, vol. 3, no. 14, pp. 495-503.

Ulgiati, S., Odum, H.T. & Bastianoni, S. 1994, " Emergy use, environmental loading and sustainability: an emergy analysis of Italy ", Ecol. Modelling, vol. 73, pp. pp. 215–268.

Ulgiati, S. & Brown, M.T. 1998, "Monitoring patterns of sustainability in natural and man-made ecosystems", Ecological Modelling, vol. 108, no. 1–3, pp. 23-36

Ulgiati, S., Raugei, M. & Bargigli, S. 2006, "Overcoming the inadequency of single-criterion approaches to Life Cycle Assessment", Ecological Modelling, vol. 190, pp. 432-422.

United Nations 2003., "1. Economic and social commission for western asia, 2003, ", Waste water treatment Technologies: A General review, United Nations.

Wackernagel, M. & Rees.W. E. 1994, "The Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning toward Sustainability. ", University of British Columbia School of Community and Regional Planning, Vancover (1994) Unpublished PhD Thesis

Wackernagel, M. & Rees, W.E. 1996, "Our Ecological Footprint: Reducing Human Impact on the Earth. ", New Society Publishers, Gabriola Island, BC.

Wackernagel, M. & Rees, W.E. 1997, "Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective", Ecological Economics, vol. 20, no. 1, pp. 3-24.

Wackernagel, M., Monfreda, C., Niels, B., Schulz, B.N., Erb, K., Haberl, H. & Krausmann, F. 2004, "Calculating national and global ecological footprint time series: Resolving conceptual challenges." Land Use Policy, vol. 3, no. 21, pp. 271-278.

Wall, G. 1988, "1. Exergy Flows in Industrial Processes", Energy, vol. 13, no. 2, pp. 197-208.

WCED 1987, "Our Common Future", Oxford University Press,Oxford.

Wiedmann, T. & Minx, J. 2008, "A Definition of 'Carbon Footprint'. In: C. C. Pertsova, Ecological Economics Research Trends: Chapter 1.", Nova Science Publishers, Hauppauge NY, USA., , pp. 1-11.

Woodgate, S. & Van der Veen, J. 2004, " The role of fat processing and rendering in the European Union animal production industry", Biotechnol. Agron. Soc. Environ, , no. 8, pp. 283-294.

Wright, L., Kemp, S. & Williams, I. "1. Carbon footprinting': towards a universally accepted definition", Carbon Management, vol. 2, no. 1, pp. 61–72.

Wuppertal institute for climate, Environment and Energy 2014, "1. Material Intensity of materials, fuels, transport services, food".

Websites used

http://weatherspark.com/history/32356/2014/Vienna-Niederosterreich-Austria

http://www.icpdr.org/main/danube-basin/austria

www.theaa.com , fuel price on 22nd April 2012

http://money.oe24.at/Service/Gehaltscheck-So-viel-verdient-Oesterreich/785437

http://www.energy.eu/

http://www.unitconversion.org/

http://www.holding-graz.at/wasserwirtschaft/gebuehrenentgelte-preise/wasserpreise.html

www.icispricing.com

http://ed.icheme.org/costchem.html

http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

http://ecoinvent.org/

APPENDIX I

11 Paper I

Process Design and Evaluation of Biobased Polyhydroxyalkanoates (PHA) Production

Karl-Heinz Kettl, Michaela Titz, Martin Koller, Khurram Shahzad, Hans Schnitzer, Michael Narodoslawsky

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11.1 Contribution to the paper

The contribution to this paper includes preliminary process design with the help of project partners for bio-based bio-degradable polymer production through bacterial fermentation of lipids. The raw material is the waste residue coming from slaughter houses. Preliminary results from SPI analysis provided important results about key parts of process design, which have to be in the focus of interest. Intermediate results of process design and related SPI results have been presented at the PRES 2011, Conference in Florence, Italy.

Process Design and Evaluation of Biobased Polyhydroxyalkanoates (PHA) Production

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Conventional plastic products are made of crude oil components through polymerization. Aim of the project ANIMPOL is to convert lipids into polyhydroxyalkanoates (PHA) which constitute a group of biobased and biodegradable polyesters. Replacing fossil based plastics with biobased alternatives can help reducing dependence on crude oil and decrease greenhouse gas emissions.

As substrate material waste streams from slaughtering cattle, pig or poultry are taken into account. Lipids from rendering site are used for biodiesel production. Slaughtering waste streams may also be hydrolyzed to achieve higher lipid yield. Biodiesel can be separated into a high and low quality fraction. High quality meets requirements for market sale as fuel and low quality can be used for PHA production. This provides the carbon source for PHA production. Nitrogen source for bacteria reproduction is available from hydrolyzed waste streams or can be added separately. Selected microbial strains are used to produce PHA from this substrate.

An optimized process design will minimize waste streams and energy losses through recycling. Ecological evaluation of the process design will be done through footprint calculation according to Sustainable Process Index methodology (Sandholzer et. al, 2005; Narodoslawsky and Krotscheck, 1995).

Introduction

Plastics are very frequently used products which are produced from crude oil. Many products are based on plastic and therefore are also fossil based. Polyhydroxyalkanoates (PHA) or Poly-β-hydroxybutyric acid (PHB) added value products”), funded by the European Commission within the 7th Framework program, is to produce biobased plastics (PHA) out of animal waste streams.

Especially waste from slaughtering industry can be used as source for lipids and nitrogen. Both are needed for PHA production. Starting from rendering products like tallow, biodiesel can be produced chemically via transesterification. Two different qualities of biodiesel are available. A high quality unsaturated biodiesel fraction for the fuel market and a low quality biodiesel fraction containing mainly saturated fatty acids. Low quality biodiesel can be used for PHA production.

are biologically based polymers which are now produced mostly from sugar cane or molasses (Harding et. al., 2007). Aim of the ANIMPOL project (“Biotechnological conversion of carbon containing wastes for eco-efficient production of high Process Design and Assessment

To get the highest efficiency for the PHA production, Cleaner Production Studies will be done to build a process design. Through Process Intensification (PI) technologies, energy demands will be decreased to a minimum level. The design also implements the objectives of cleaner production. After optimizing the design in terms of specific technologies, an ecological footprint will be calculated according to the Sustainable Process Index (SPI) methodology.

Process Intensification (PI)

PI is a paradigm shift in process design. The focus concretes on minimization of the plant size and the reduction of energy intensive structures, as well as the use of internal gains. In the 1970s Colin Ramshaw and his co-workers at The Imperial Chemical Industries lead the development of this concept. Process Intensification was defined as a “reduction in plant size by at least several orders of magnitude” (Doble and Kruthiventi, 2007).

There aren’t any clear boundaries between the concepts of Process Intensification and the general approaches of process optimization. Only the way on how the main goals of reduction - energy as well as resources and consequently also Greenhouse gas emissions- could be achieved, is different. Unlike process optimization, which focuses on the improvement of established systems, Process Intensification creates new processes and structures. Therefore, reachable efficiency potentials, especially in concepts with Gordian process structures, are not only geared on the development of new technologies, but on the development of new processes and structures using existing technologies. Solutions which are accomplished by Process Intensification are tailored to particular needs. Because of the given reason, it is possible to improve the energy efficiency in a sustainable way by setting defined objectives (Moulijn et. al., 2008).

Sustainable Process Index (SPI)

To measure the ecological impact of the PHA production an ecological footprint is used. This value allows comparing different products in terms of their environmental burden. Production processes for conventional fossil based plastics can be compared with the ANIMPOL, PHA production process via the ecological footprint methodology.

SPI methodology (Sandholzer et. al, 2005; Narodoslawsky and Krotscheck, 1995) uses areas as references and is part of the ecological footprint family. Material and energy consumption is taken into account and expressed in an equivalent area of different categories (area for infrastructure, area for renewables, area for non-renewables and area for fossil carbon). Also emissions into the three ecological compartments air, water and soil are part of the overall ecological footprint for the final product. This methodology is well known and already used in other publications (e.g. Eder et. al., 2009 and Gwehenberger et. al., 2007).

Meat production is an energy and material intensive process. Fertilizer and fodder production are using much of energy, regarding to the fact that only 36 wt% from a cattle are sold on the food market in Austria (Niederl and Narodoslawsky, 2004). Waste streams (excluding inwards) from slaughterhouses are used now for rendering to produce meat and bone meal and tallow. Meat and bone meal is sold to the market and tallow can be used as substrate for biodiesel production.

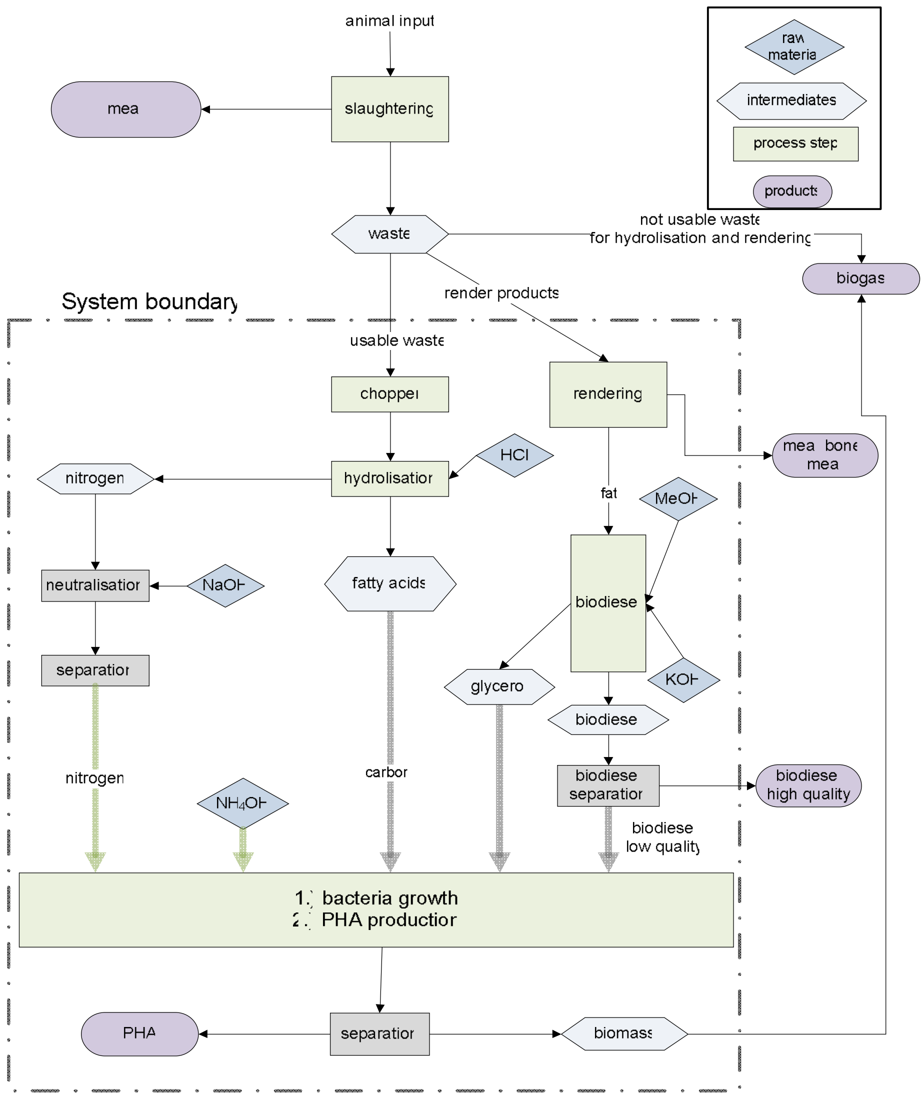

Figure 11.1: Process flowchart

Slaughtering Waste Utilization for Bio-based Polyester Production

Figure 1 illustrates a flow sheet how waste stream could be utilized in an alternative, value-creating way. There are some key process steps which are described in detail.

Rendering

Waste fat undergoes rendering which produces meat and bone meal and tallow for biodiesel production. The conventional way of rendering uses every waste stream with the exception of hides and inwards. In our approach a part of the slaughterhouse waste (e.g. hearts, livers, lungs,…) can be used for hydrolysis instead of rendering.

Hydrolysis

Hydrolysis can be done using a strong acid like hydrochloric acid. This step produces nitrogen compounds (amino acids and their low molecular mass oligomers) from the proteins which can easily be used for microbial growth prior to the PHA production step. The carbon fraction (mainly odd-numbered fatty acids) will also be used for the growth of bacteria in the first step of the bioprocess and as carbon source in the second step, where the intracellular carbon flux is directed towards PHA accumulation due to the limitation of an essential growth component such as nitrogen- or phosphate source.

Biodiesel

Biodiesel or in that case TME (tallow methyl ester) is made out of the tallow stream from the rendering process. Methanol is used for transesterification which is catalyzed by KOH. Biodiesel as main product contains a mixture of saturated and unsaturated fatty acids. A higher content of unsaturated fatty acids results in a higher quality of biodiesel. Therefore high quality biodiesel is sold to the market and low quality biodiesel (which contains a high amount of saturated fatty acids) is a substrate for PHA production.

PHA Production

Nitrogen from the hydrolysis step and carbon is used to produce high concentrations of catalytically active microbial biomass. After the desired concentration of biomass is reached, the nutritional conditions in the bioreactor are changed towards surplus of carbon source. Together with the limitation of another essential growth component the bacteria are performing the intracellular accumulation of the final product polyhydroxyalkanoate. This polyester is biodegradable and can be used to substitute plastics out of crude oil. After the downstream processing, PHA- free biomass components remain as side-product.

Biogas

To reduce waste stream for the whole process and to supply energy a biogas power plant could be part of the whole process flow sheet. In Figure 1 the biogas unit is outside of the system boundary because it is not a key technology for the PHA production itself. As option the utilization of the

PHA-free biomass waste stream after the PHA isolation step is taken into account. Heat from a combined heat and power unit could be used internally for the PHA production and electricity for selling to the market. This can improve economic feasibility and reduce the ecological impact.

Conclusions

Taking into account the possible enhancement of each process step in the production of PHA starting from animal-derived residues, one can make considerable progress towards the designing of a cost-efficient and ecologically benign technology. Modern tools of Life cycle assessment and Cleaner production studies provide precious tools to quantify the sustainability and efficiency of the novel bioprocess to be developed. What is needed for an industrial implementation of the promising research results is the narrow cooperation of the experts in the special scientific fields of microbiology, genetic engineering, biotechnology, chemical engineering and polymer science. The successful translation of the project into industry will provide benefit for the industrial sectors of rendering, slaughtering, biodiesel and polymer industry.

References

Doble M. and Kruthiventi A. K., 2007, Green Chemistry and Engineering, Academic Press. California, USA.

Eder M., Sandor N., Kettl K.-H. and Narodoslawsky M., 2009, Ecological impact of renewable resource based energy technologies, Chemical Engineering Transactions, Volume 18, 611-616.

Gwehenberger G., Narodoslawsky M., Liebmann B. and Friedl A., 2007, Ecology of scale versus economy of scale for bioethanol production, Biofuels, Bioproducts and Biorefining, Volume 1, Issue 4, 264-269.

Harding K.G., Dennis J.S., von Blottnitz H. and Harrison S.T.L., 2007, Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly-β-hydroxybutyric acid using life cycle analysis, Journal of Biotechnology, 130, 57-66.

Koller M., Salerno A., Dias M., Reiterer A. and Braunegg G., 2010, Modern Biotechnological Polymer Synthesis: A Review, Food Technol. Biotechnol., 48, (3), 255–269.

Narodoslawsky M. and Krotscheck Ch., 1995, The sustainable process index (SPI): evaluating processes according to environmental compatibility, Journal of Hazardous Materials, 41, 383-397.

Niederl A. and Narodoslawsky M., 2004, Life cycle assessment of the production of biodiesel from tallow and used vegetable oil, ACS National Meeting Book of Abstracts, 227, (1), CELL-162.

Sandholzer D., Niederl A. and Narodoslawsky M., 2005, SPIonExcel – fast and easy calculation of the Sustainable Process Index via computer, Chemical Engineering Transactions, 7, (2), 443-446.

Moulijn J.A., Stankiewicz A., Grievink J. and Górak A., 2008, Process intensification and process systems engineering: A friendly symbiosis, Computers and Chemical Engineering 32, 3–11.

12 Paper II

Process Optimization for Efficient Biomediated PHA Production from Animal-Based Waste Streams

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12.1 Contribution to the paper

The paper addresses three main aspects of ANIMPOL process design and development. First one is process design for fermentation process utilising different PHA productivity scenarios. The second aspect deals with ecological evaluation utilising SPIonExcel program, while 3rd aspect deals with economic evaluation to estimate investment and operations costs. Contributions include process design and development after rigorous discussions with in whole group as well as discussions with industrial partners involved in the consortium. Data collection and SPI evaluation of PHA production as final product, but evaluations of all key parts were also carried out to address the latter two aspects with in this paper.

Process Optimization for Efficient Biomediated PHA Production from Animal-Based Waste Streams

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Conventional polymers are made of crude oil components through chemical polymerization. The aim of the project ANIMPOL is to produce biopolymers by converting lipids into polyhydroxyalkanoate (PHA) in a novel process scheme in order to reduce dependence on crude oil and decrease greenhouse gas emissions. PHA constitutes a group of biobased and biodegradable polyesters that may substitute fossil based polymers in a wide range of applications.

Waste streams from slaughtering cattle will be used as substrate material. Lipids from rendering are used in this process scheme for biodiesel production. Slaughtering waste streams may also be hydrolyzed to achieve higher lipid yield. Biodiesel then is separated into a high and low quality fraction. High quality biodiesel meets requirements for sale as fuel and low quality is used for PHA production as carbon source. Selected offal material is used for acid hydrolysis and serves as a source of organic nitrogen as well as carbon source for PHA-free biomass with high production rate in fermentation process. Nitrogen is a limiting factor to control PHA production during the fermentation process. It will be available for bacterial growth from hydrolyzed waste streams as well as added separately as NH4OH solution. Selected microbial strains are used to produce PHA from this substrate.

The focus of the paper is about an overview of the whole process with main focus on hydrolysis, to look for a possibility of using offal hydrolysis as an organic nitrogen substitute. The process design will be optimized by minimizing waste streams and energy losses through cleaner production. Ecological evaluation of the process design will be done through footprint calculation according to Sustainable Process Index methodology.

Keywords: PHA, biopolymers, hydrolysis, animal residues, Sustainable Process Index

Introduction

General: the exigency for novel technologies in polymer production

The implementation of living organisms for production of chemical biopolymers like polyhydroxyalkanoate (PHAs) on an industrial scale constitutes part of “White Biotechnology”, characterized by the utilization of renewable resources as feedstock and the embedding of the production processes into closed material cycles. The use of renewable resources as an alternative to fossil feed-stocks becomes interesting for the chemical sector against the backdrop of rising oil prices underlined by the current development of the crude oil price that amounted to more than 100 USD/barrel (for Brent Crude Oil) in the Summer of 2011, which is more than double the price of January 2009, when less than 50 USD/barrel had to be paid (OPEC, 2009). Political developments in several petrol exporting countries, as well as the approaching production maximum of crude oil production add to market uncertainty, especially for the highly petrol-dependent polymer industry.

Besides increasing market uncertainty environmental considerations and in particular reduction of greenhouse gas emissions have to be taken into account for any new process providing commodity products. Although processes based on renewable resources, especially when using waste streams from other industries, have a clear advantage in this respect, process development has to take necessary steps to guarantee sustainability of production. Using tools like Life Cycle Assessment (LCA) and Cleaner Production methods, the reduction of environmental impact for production of polymeric materials has therefore to be part of any new process development (Sudesh and Iwata, 2008).

PHA biopolyesters and economic challenges in their production

Chemically, PHAs are polyoxoesters of hydroxyalkanoic acids (HAs). In nature, PHA accumulation occurs by a broad range of Gram-positive and Gram-negative eubacterial species and in several representatives of the domain of the archaea from renewable resources like carbohydrates, lipids, alcohols or organic acids; this accumulation classically occurs under unfavorable growth conditions due to imbalanced nutrient supply. For PHA harboring microbial cells, these inclusions mainly serve as reserve materials for carbon and energy, providing them an advantage for survival under starvation conditions, and enhance the cell´s endurance under environmental stress factors. Under conditions of starvation PHAs are catabolized again by the cells (Chen, 2010; Koller et al, 2011).

PHAs attract more and more interest due to the fact that they feature material properties similar to petrochemical thermoplastics and/or elastomers. In contrast to petrochemical plastics, PHAs combine the characteristics “biobased”, “biodegradable”, and “compostable” and “biocompatible”, hence they can be classified as real “green polymers”. If items made of PHAs are composted, they are completely degraded to water and CO2 as the final oxidation products. Here it has to be emphasized that these final oxidation products are the starting materials for the photosynthetic re-generation of carbohydrates by green plants. This demonstrates that, in contrast to petrol-based plastics, PHAs are perfectly embedded into natures closed cycle of carbon, underlining their suitability for replacing polymeric materials based on fossil feed stocks needed for the production of marketable plastic items (Koller et al, 2010).

In order to make biobased and biodegradable polymers like PHAs economically more competitive with common resistant plastics from fossil resources, their production costs have to be reduced significantly. Most of all, the selection of suitable renewable resources as carbon feedstock for PHA production is the major cost decisive factor in the entire PHA production chain, amounting up to 50 % of the entire production costs (Choi a. Lee, 1999). Here, a viable solution is identified, in the utilization of waste and surplus materials upgraded to the role of feedstocks for the bio-mediated polymer production. Such materials are mainly produced in agriculture and such industrial branches that are closely related to agriculture (Braunegg et al, 1998; Khanna a. Srivastava, 2005; Koller et al, 2005 a; Solaiman et al, 2006; Khardenavis et al, 2007).

Objectives and strategies of the ANIMPOL project

The ANIMPOL project, financed by the European Commission within the 7th framework programme (FP7), aims at the sustainable and value-added conversion of waste from slaughterhouses, rendering industry, and waste fractions of the biodiesel production. Lipids from slaughterhouse waste are converted to fatty acid esters (FAEs, biodiesel). FAEs consisting of saturated fatty acids generally constitute a fuel that has an elevated cold filter plugging point (CFPP) which can be somewhat limiting in blends that exceed 20 % (v/v) FAEs. In the ANIMPOL project, these saturated fractions are biotechnologically converted towards high-value added biopolymers. As a by-product of the transesterification of lipids to FAEs, crude glycerol phase (CGP) accrues in high quantities. CGP is also available as carbon source for the production of catalytically active biomass and the production of low molecular mass biopolymers. This brings together waste producers from the animal processing industry with meat & bone meal

(MBM) producers (rendering industry), the bio-fuel industry, and polymer producing industry, resulting in value creation for all players.

According to personal communication with project partner, the entire amounts of animal lipids from the slaughtering process can be quantified with more than 500,000 ton/year (y). This lipid content is potential raw material for 490,000 t/y biodiesel production, containing about 55% saturated biodiesel fraction. This saturated fraction is potential substrate for PHA production. . From the saturated biodiesel fraction, the amount of PHA biopolyesters can theoretically be calculated with a conversion yield of 0.7 g/g (Choi and Lee 1999). The annual CGP production in 2008 from biodiesel production has been reported 700,000 tons (Stelmachowski, 2011). If this glycerol is applied for production of catalytically active biomass, about 0.4 g biomass per g of glycerol may be obtained.

The ANIMPOL project develops an integrated process, comprising the scientific fields of microbiology, genetic engineering, biotechnology, fermentation technology, chemistry, chemical engineering, polymer chemistry & processing, LCA and cleaner production studies, combined with feasibility studies for the marketing of the final products. This is done in close cooperation of academic and industrial partners. The project aims at solving local waste problems which affect the entire European Union; the solutions are meant to be applied to the entire EU.

Process design development

From the slaughterhouse-waste to the PHA, several sub processes were analysed. Every decision in the process design is influenced by the fundamental principle to create an ecological and economic efficient process to use the residual streams for the production of PHA.

In the current process design as shown in Figure 12.1, rendering, hydrolysis, biodiesel and PHA production are key parts. A closer look at the flow sheet of the process design reveals that slaughtering of the animals produces three main streams meat, non-rendering material and rendering material. Meat is directly sold to the market. Non rendering material contains manure, digestive tract content, milk and colostrum etc. Rendering material contains all body parts of the animal not to be consumed by humans.

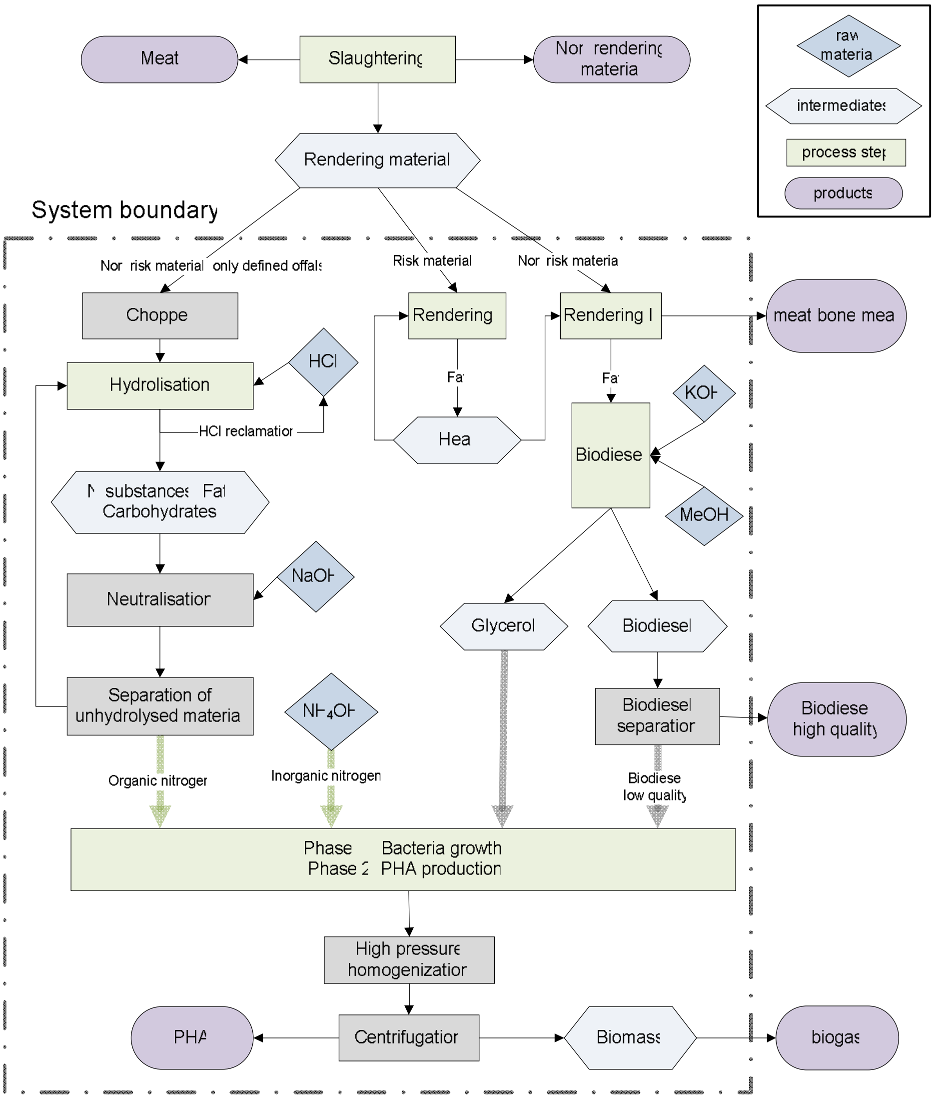

Figure 12.1: Flow sheet of process design for ANIMPOL

According to the Regulation No 1774/2002 from European Union (European Union, 2002) rendering material is categorized as risk and non- risk material.

Risk material comprise of all body parts, hides and skins from Transmissible Spongiform Encephalopathy (TSE) suspected and TSE confirmed animals, pets, animals from zoo and wild animals suspected of being infected with communicable disease. Rendering products obtained by this material can only be used for the production of heat. Tallow is used as direct combustion fuel and MBM is incinerated in an approved incineration plant.

Non-risk material contains all body parts, offal, blood, hides, skin, feather, wool, horns and fur from animals neither having TSE nor suspected of being infected by it. A portion of the non-risk material (selected offal) will be used for hydrolysis to produce necessary organic nitrogen source. Rest of the non-risk rendering material will be processed to rendering products.

In the rendering process, animal by-products are treated at 133 ˚C and 3 bar for at least 20 min to obtain MBM and also tallow extract. There are several rendering products like MBM, tallow, blood flour, feather flour and their classification is based on the input material.

For the process design presented here a rendering process with the output of 21 % tallow, 24 % MBM and 55 % water is taken into account (Niederl and Narodoslawsky 2004). The Tallow will be utilized to produce biodiesel and the MBM will be sold.

The Biodiesel process has an already well developed design. For the process design in this project the variation of the feedstock to tallow was considered. According to data from an existing industrial facility producing biodiesel using tallow as feedstock, biodiesel production yields are 96 to 98 %. Biodiesel is tallow methyl ester (TME) produced from tallow provided by a rendering process, through a transesterification reaction with Methanol using KOH as catalyst. Following Cunha et al, (2009), 1kg biodiesel and 100 g of glycerol are produced from 1kg of tallow using 1:6 molar ratio of methanol to tallow.

TME contains a mixture of saturated and unsaturated fatty acids. The content of unsaturated fatty acids defines the quality of the biodiesel, which is measurable with the Cold Filter Plugging Point (CFFP). Own analysis shows, that the representative TME contains 45% of high quality biodiesel fraction. Low quality biodiesel, which contain a high amount of saturated fatty acids, will be separated using a crystallization step. The low quality biodiesel fraction is used as a carbon source in the PHA- production while the high quality fraction will be sold directly. Acid hydrolysis of offal provides a complex nitrogen source for the fermentation process instead of (more costly) casamino acids.

On an industrial scale, PHA production occurs under controlled conditions in bioreactors, enabling the maintenance of constant process parameters (pH value, temperature, dissolved oxygen concentration) and the operation under mono-septic conditions.

Normally, the PHA production process encompasses two easily distinguishable phases: first, a desired concentration of catalytically active biomass is produced under balanced growth conditions by providing all substrates required by the microbes for unrestricted growth. In this phase, the production of PHA is insignificant if compared to biomass formation. In a second phase, the supply of an essential nutrient such as nitrogen, phosphate or minor components is restricted, causing nutritional stress conditions for the microbes. This provokes the redirection of the carbon flux from biomass production towards predominant PHA accumulation (Koller et al, 2008; Koller et al, 2010).

Different operation modes are known for biotechnological PHA production; among them, fed-batch strategies are most widely used on pilot- and industrial scale (Nonato et al, 2001). Here, all substrates are re-feed to the system according to their consumption by the production strain. In this case, cell harvest occurs only at the end of the fermentation batch after pasteurizing the cells in situ in the bioreactor. Fed-batch processes for PHA production are generally stable and highly reproducible as soon as reliable fermentation protocols for the production processes are available. In contrast, the continuous mode is the one that should enable high productivities and constant product quality (Zinn et al, 2003; Sun et al, 2007). Here, the concentration of active biomass, PHA and of all substrates is kept constant as soon as steady-state conditions are reached; under these conditions, cell harvest also occurs continuously. Although not yet widely applied in biotechnological industrial praxis because of a higher complexity of the technical set-up and a higher risk for microbial contamination, continuous fermentation strategies are considered to have a huge potential, also for PHA production. In addition, multistage systems provide different cultivation conditions in each stage and thereby approximate the characteristics of a continuous plug flow tubular reactors (CPFR). It is described that a cascade with at least five reactors in series can be used as a process-engineering substitute for a CPFR (Moser, 1988; Braunegg et al, 1995). Most recently, the highly efficient production of PHA using a five-stage continuous bioreactor cascade was successfully demonstrated (Atlić et al, 2011).

Hydrolysis and PHA productivity scenarios

For the optimization of the hydrolysis process, 3 different scenarios, based on PHA productivity were considered. The aim was to figure out the hydrolysate demand and the effects on the process design (i.e. usable waste streams).

It is assumed that the annual PHA production target will be 10,000 t. According to an optimal fermentation time of 48 hours, this leads to 150 batches with 67 t per batch.

Scenario I is based on average values from current laboratory experiments. This scenario forms the baseline for comparison.

Scenario II is based on optimal fermentation conditions, assuming that produced Cell Dry Mass [7](CDM) contains 80 % PHA and 20 % residual biomass. *Scenario III* is based on the results of other projects using different bacterial strains and feedstock (Nonato et al, 2001). This scenario represents the upper bound for possible improvement of the process optimization within the ongoing project. All the information to develop these scenarios was generated by the authors and project partners. *Table 12.1* summarizes the performance parameters for these scenarios.

Table 12.1: PHA productivity parameters referring to fermentation media (FM)

	units	scenario I	scenario II	scenario III
PHA	[kg dm / m^3 FM]	30.2	62.8	114.5
residual biomass	[kg dm / m^3 FM]	15.4	15.4	28.1
CDM	[kg dm/ m^3 FM]	45.6	78.2	142.6
CDM	[%w]	4.56	7.82	14.26
PHA productivity	[kg dm / m^3 FM* h]	0.63	1.63	2.4

In *Scenario I* 45.6 kg/m³ CDM are produced containing 30.2 kg PHA (dm) and 15.4 kg residual biomass (dm). Only 4.56 %w CDM are produced, PHA productivity is 0.63 kg/m³h PHA, assuming a fermentation time of 48h.

The biomass matter remains constant in *Scenario II however* the PHA content rises to 62.8 kg /m^3 FM. The PHA productivity rises accordingly to 1.63 kg/m^3 FM*h^{-1}.

[7] total biomass (dry matter (dm)) produced in the fermentation process (PHA + residual biomass)

Scenario III shows nearly double the PHA output, namely 114.5 kg /m^3 FM. The CDM content and PHA productivity rises with the PHA productivity reaching 2.4 kg/m^3 FM*h^{-1}.

For a rough estimate of the fermenter size the best case scenario, with 114.5 kg of PHA per m^3 FM, was used. This leads to a fermenter size of 582 m^3. This size was used to calculate the required amount of hydrolysate for the fermentation.

The incentive for the using hydrolysis is to substitute the casamino acid needed as complex nitrogen source for the fermentation process. *Table 12.2* shows the composition of the selected offal for the hydrolysis (Neto 2006). There are different fractions like proteinaceous materials (N-substances), carbohydrates, and fat available, which can be used in the fermentation process by the micro-organisms.

Table 12.2: Chemical composition of offal

Offal	water [%]	N-substances [%]	fat [%]	carbohydrates [%]	ash [%]
lung	79.9	15.2	2.5	0.6	1.9
kidney	75.5	18.4	4.5	0.4	1.2
spleen	75.5	17.8	4.2	1.0	1.6
liver	71.5	19.9	3.6	3.3	1.6
heart	71.1	17.5	10.1	0.3	1.0
average	**74.7**	**17.8**	**5.0**	**1.1**	**1.4**

Based on the results of Neto, 2006, the maximum concentration of complex nitrogen source generated via hydrolysis) in the prepared fermentation broth is 5g/l (dry mass) (Neto, 2006). Derived from this data, the required dry mass from hydrolysation per batch is 2.9 t, which will result in annual consumption of 437 t of offal dry mass. The average dry mass content of offal is 25.3 % leading to an annual demand of offal fresh material of 1,727 t (Neto, 2006).

f offal material is 15,495 t/y.

Table 12.3 shows the mass flow of different organs in the offal used to provide hydrolysate for PHA fermentation. The ratio of these mass flows is according to the ratio provided by the slaughterhouse process. The demand for hydrolysation is contrasted with the offer from a rendering facility with a capacity of 130,000 t /y. The rendering material is about 21.6 % of an animal, using this value calculated animal equivalent is 601,935 t /y. As can be seen in *Table 12.3* calculated offer of offal material is 15,495 t/y.

Table 12.3: Offal offer based on 130.000 t/y rendering plant size and offal demand for the hydrolysis

offal	weight per animal equivalent[8] [kg]	weight per animal animal equivalent wt. [%]	Available material wt. [t/y]	demand for hydrolysis [t/y]
lung	4.1	0.7	4,212	469
heart	2.3	0.4	2,388	266
liver	6.4	1.1	6,600	736
spleen	1.0	0.2	1,066	119
kidney	1.2	0.2	1,230	137
total	**15.1**	**2.6**	**15,495**	**1,727**

Different fractions of usable (meat, tradable offal etc.) and waste (stomach content, condemned material) are assumed according to (Riedl, 2003). Animal equivalent is the total animal slaughtering input which is calculated by using the input for hydrolysation of the residual material will be carried out with 6 M HCl at 120 ˚C using concentration 100 kg/m³of offal dry mass for 6 hours (Neto, 2006), followed by neutralization using NaOH. Assuming 150 batches per year and necessary offal dry mass of 437 t/y, leading to 4,370 m³ of 6 M HCl.

Equal moles of base will be required to neutralize the solution because the acid concentration remains constant after the hydrolysis leading to an annual demand of 1,330 t solid NaOH in the neutralization step, which generates 1,556 t of neutralization product NaCl. In the FM the NaCl concentration is limited with 5 g/l, which is equivalent to 0.07 m^3 of hydrolysate.

Process design evaluation

Carbon and nitrogen balance

The carbon and nitrogen are liked to each other in a specific ratio. It has been explained in the following description. Considering theoretical values for conversion rates (Y) of substrate to biomass or PHA in fermentation step, the input of carbon source into the system boundary to be

[8] standard cow: weight 587 kg

finally converted by the production strain in the bioreactor can be roughly balanced. Theoretical conversion rate values are given as: Biodiesel: Y = 0.6; Glycerol: Y = 0.48; Carbohydrates: Y = 0.48; Fat: Y = 0.6; and N-Substance (considered as carbon source): Y = 0.48 (Choi a. Lee, 1999; Koller et al, 2005a; Koller et al, 2012). Production of biomass and PHA from different substrates can be seen from *Table 12.4*.

Table 12.4: Chemical composition of offal in ANIMPOL

offal	mass [t/y]	water [m^3/y]	dry mass [t/y]	N-substances [t/y]	fat [t/y]	carbohydrates [t/y]	ash [t/y]
lung	469	375	94	71	12	3	9
kidney	137	104	34	25	6	1	2
spleen	119	90	29	21	5	1	2
liver	736	526	209	147	27	24	11
heart	266	189	77	47	27	1	3
total	**1,727**	**1,284**	**443**	**311**	**76**	**30**	**26**

During the offal hydrolysis proteins are hydrolysed to amino acids. These amino acids are termed as N-Substances and it is assumed that N-substances obtained by offal hydrolysis contain 14 % pure nitrogen. Theoretical annual available nitrogen from hydrolysis is therefore about 44 t, based on 311 t/y of N-substances (see *Table 12.5*). PHA free biomass and PHA production is calculated by using the following assumption:

"1 kg of nitrogen theoretically corresponds to 7.14 kg of PHA free biomass providing 28.56 kg of PHA considering a PHA content of 80 % in the entire cell biomass".

According to this assumption, the available organic nitrogen is sufficient for 1,243 t of PHA production. This process will produce 13,024 t of biomass containing 10,419 t of PHA. In fermentation process nitrogen acts as the growth limiting factor provoking PHA production. According to own experimental evidence, the ratio between organic nitrogen and inorganic nitrogen is fixed. The available 44 t of organic nitrogen is sufficient to produce 311 t of PHA free biomass. The rest of the PHA free biomass which is 2,294 t requires 321 t of nitrogen. This required amount of nitrogen is provided by inorganic source of nitrogen i.e. NH4OH. It is used to control the reaction conditions as 25% NH4OH (wt/wt) solution. The calculated 25 % (wt/wt) NH4OH consumption is therefore 3,213 t/y containing 321 t of nitrogen.

Table 12.5: Carbon balance according to the flow sheet

fractions	input [t/y]	biomass yield [%]	biomass [t/y]	PHA yield [%]	PHA [t/y]
biodiesel (low quality)	18,598	60	11,159	80	8,927
glycerol	3,45	48	1,656	80	1,325
carbohydrates	30	48	14	80	11
fat	76	60	46	80	37
N-Substances	311	48	149	80	119
Total biomass and PHA			**13,024**		**10,419**

Sustainable Process Index (SPI)

SPI is a life cycle impact assessment (LCIA) methodology which offers the possibility to calculate ecological footprint for processes (Narodoslawsky and Krotscheck, 1995) and has been used for many different applications (e.g. Gwehenberger and Narodoslawsky, 2008). For footprint calculation the freeware program SPIonExcel (Sandholzer and Narodoslawsky, 2007) was used. This methodology can be applied for any good and services (e.g. Kettl et al, 2011).

SPI evaluation of PHA production

Based on material and energy flows for the production of PHA according to Table 12.6 an ecological footprint was calculated.

Table 12.6: Life Cycle Inventory (LCI) data for 1 kg of PHA

Input	Inventory	Unit
Process water	8.7	kg
Ammonium hydroxide	0.08	kg
Biodiesel (low quality)	1.74	kg
Net electricity EU27	0.32	kWh
Wastewater treatment	0.01	m^3
Hydrolysate	0.49	kg
Glycerol	0.32	kg

Sub-processes like separation of the low quality fraction of biodiesel, hydrolysate production and biodiesel conversion are calculated within SPIonExcel and linked to the main process of PHA production. Net electricity was assumed to be a European average mix based on the International Energy Agency energy statistics (IEA 2008).

The overall SPI value per kg of PHA is about 1,950 m² which is lower as compared to Polyethylene LD (2,500 m²/kg). This SPI value for PHA can be lowered during further process design optimization. Figure 12.2 illustrates the share of the footprint between input streams for c

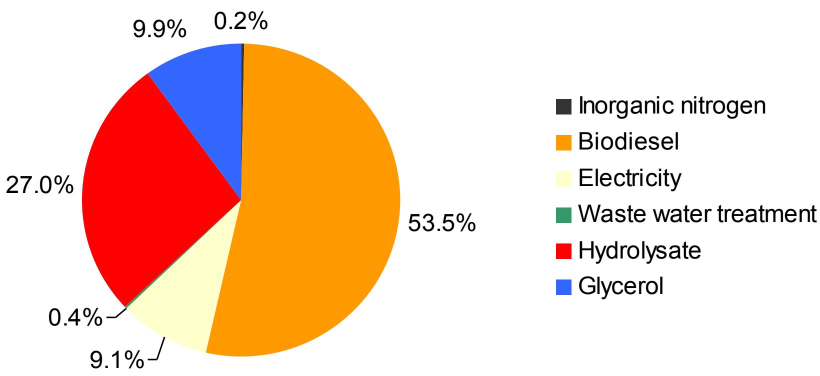

Figure 12.2: SPI results for 1 kg of PHA production in percent shares of input

The main part of the footprint for the PHA production derives from the usage of biodiesel (low quality) as carbon source. This is due to the fact that biodiesel is produced from fat by an energy intensive rendering process. Another main impact to the ecological assessment is displayed by the hydrolysis of the offal material which uses a high amount of acidic catalyst. The reduction and/or recovery of the required catalyst is therefore of major importance and has to be focused in the further process development. The same holds for the biodiesel production, where the footprint reduction potential is high under if heat integration is considered. This reduction would directly and effectively influence the foot print for the whole PHA production process.

Economic analysis for hydrolysis

Beside the ecological evaluation an economical calculation is mandatory to bring the project from lab to industrial scale. Especially investment and operating costs have to be estimated to get an idea about the feasibility for PHA against conventional plastics production but also for every key part in the process design.

At this stage of development priority has to be laid on the evaluation of the hydrolysis process in order to decide if this will be a feasible part of the process concept. Ecological considerations already point out the importance of acid recovery in this step. Here nitrogen production costs are compared to the price for inorganic nitrogen available from the market. Price are obtained from (Pitt M, n.d.) for NaOH, (ICIS, n.d.) for HCl and (European Energy Portal, n.d.) for electricity. The following Table 12.7 represents the production costs for organic nitrogen via hydrolysis.

Table 12.7: Nitrogen production costs per year

Inputs	**unit**	**quantities**	**price [€/unit]**	**annual costs [€/y]**
HCl	[t/y]	2,530	70	177,125
NaOH	[t/y]	1,064	339	360,659
Heating	[kWh/y]	315,954	0.038	12,133
Electricity	[kWh/y]	34,085	0.099	3,381
Total nitrogen production cost	[€/y]			553,299
Total nitrogen production	[t/y]	44		
Total nitrogen production cost per ton				12,693

It can be said that nitrogen obtained from the organic source (offal) is quite expensive as compared to inorganic source of nitrogen (NH4OH) which costs 500 €/t compared to 12,693 €/t nitrogen. It is therefore clear that offal cannot be used as sole nitrogen source in the process. Hydrolysis however provides a high quality, complex nitrogen source for fermentation, which would otherwise be supplied by high cost substances like casamino acid and grass silage juice which costs 928,989.64 €/t nitrogen and 720,505.49 €/t nitrogen respectively and thus considerably more than nitrogen from offal.

Further optimization scenarios have been taken into account to improve the cost effectiveness of offal hydrolysis. .Different HCl reclamation will lower the production costs considerably. Beside that a possible alternative hydrolysis agent (H_2SO_4) has been taken into account. Prices for H_2SO_4

and $Ca(OH)_2$ are obtained from (Pitt M, n.d.). Table 12.8 shows the annual nitrogen costs using HCl reclamation and as alternative H_2SO_4.

Table 12.8: Comparison of nitrogen of annual production costs using HCl reclamation and H2SO4 for hydrolysis

Inputs	HCl [€/y]	NaOH [€/y]	heat [€/y]	electricity [€/y]	costs [€/y]	nitrogen production costs [€/t]
no reclamation	177,125	360,660	12,133	3,381	553,299	12,693
50 % reclamation	88,563	180,330	12,133	3,381	284,406	6,524
70 % reclamation	53,138	108,198	12,133	3,381	176,849	4,057

Hydrolysis with H_2SO_4

H_2SO_4 [€/y]	$Ca(OH)_2$ [€/y]	heat [€/y]	electricity [€/y]	cost [€/y]	N production [€/t]
82,625	244,925	12,133	3,381	340,839	7,746

The bandwidth for the costs of hydrolysis are hugely dependent from the rate of reclamation but remain much higher compared to inorganic nitrogen while the advantage compared to other complex nitrogen sources becomes even more pronounced. Offal hydrolysis is therefore a sensible strategy to lower overall production costs however acid reclamation in this process step is a condition sine qua non from ecological as well as economical points of view.

Conclusions

The paper presented a process concept to generate PHA and biodiesel from waste flows resulting from slaughter houses and rendering of animal residuals. Using selected offal via hydrolysis as a complex nitrogen source as well as glycerol and low grade biodiesel as a carbon source are innovative features of this integrated scheme to utilize waste from meat production.

Economic evaluation reveals that the pathway of offal utilization provides a complex nitrogen source that is considerably more costly than mineral nitrogen sources but is however cheaper than comparable other complex nitrogen sources. The use of this material is therefore limited to providing the necessary complex nitrogen sources for fermentation. The use of inorganic nitrogen is still indispensable due to the microbial requirements. Considering the positive effect of hydrolysate on microbial cultivation during balanced growth, it may only be replaced by other agricultural sources (e.g. silage juice) to shorten the lag time (Koller et al, 2005 b), but at considerably higher costs.

Ecological evaluation showed two particular sub-processes to be crucial with regard to the overall ecologic performance of the PHA and biodiesel production: the hydrolysis step of offal and the rendering process providing lipids for the biodiesel production. Focus for further process development, besides increasing the PHA yield, will therefore be laid on acid reclamation in the hydrolysis process and heat integration in the rendering step.

The overall process performance at this stage of development clearly indicates the potential of this concept. Using waste material from meat production to provide bio-degradable, versatile plastics as well as high quality biofuel will serve the goal of reducing the ecological footprint of society in general and in particular the reduction of greenhouse gas emissions at competitive costs.

References

Atlić A, Koller M, Scherzer D, Kutschera C, Grillo Fernandes E, Horvat P, Chiellini E, Braunegg G (2012) Continuous Production of Poly([(R]-3-hydroxybutyrate) by *Cupriavidus necator* in a Multistage Bioreactor Cascade. Appl Microbiol and Biotechnol 91:295 – 304. doi: 10.1007/s00253-011-3260-0.

Braunegg G, Lefebvre G, Renner G, Zeiser A, Haage G, Loidl-Lanthaler K (1995) Kinetics as a tool for polyhydroxyalkanoate production optimization. Canadian Journal of Microbiology 41:239-248, doi:10.1139/m95-192.

Braunegg G, Lefebvre G, Genser KF (1998) Polyhydroxyalkanoates, biopolyesters from renewable resources: Physiological and engineering aspects. Journal of Biotechnology 65:127-161. doi: 10.1016/S0168-1656(98)00126-6.

Chen G-Q (2010) Plastics completely synthesized by bacteria: polyhydroxyalkanoates. In: Guo-Qiang Chen (ed) Plastics from bacteria: natural functions and applications, Microbiology monographs Vol. 14. pp 17-37, Springer, Berlin Heidelberg, Germany. doi: 10.1007/978-3-642-03287-5_2.

Choi J, Lee SY (1999) Factors affecting the economics of polyhydroxyalkanoateproduction by bacterial fermentation. Appl Microbiol Biotechnol 51:13–21. doi:10.1007/s002530051357.

Cunha ME, Krause LC, Moraes MSA, Faccini CS, Jacques RA, Almeida SR, Rodrigues MRA, Caramão EB (2009) Beef tallow biodiesel produced in a pilot scale. Fuel Processing Technology 90:570–575. doi: 10.1016/j.fuproc.2009.01.001.

EUROPE'S ENERGY PORTAL, (n.d.), www.energy.eu/, last accessed 08.06.2011.

European Union (2002), Regulation (EC) No 1774/2002 of the European parliament and of the council of 2002 laying down health rules concerning animal by-products not intended for human consumption, Official journal of the European Communities L273:1-95.

Gwehenberger G, Narodoslawsky M (2008) Sustainable Processes – The challenge of the 21st century for chemical engineering. Process Safety Environmental Protection 8:321-327. doi: 10.1016/j.psep.2008.03.004.

ICIS , (n.d.), Chemical prices and chemical industry trends from ICIS pricing, www.icispricing.com/il_shared/Samples/SubPage110.asp, last accessed 08.06.2011.

IEA (2008) International Energy Agency, Energy Statistics, www.iea.org/stats/index.asp, last accessed 08.06.2011.

Kettl K-H, Niemetz N, Sandor N, Narodoslawsky M (2011) Ecological Impact of Renewable Resource-Based Energy Technologies, Journal of Fundamentals of Renewable Energy and Applications 1:1-5. doi: 10.4303/jfrea/R101101.

Khanna S, Srivastava AK (2005) Recent advances in microbial polyhydroxyalkanoates. Process Biochemistry 40:607-619. doi: 10.1016/j.procbio.2004.01.053.

Khardenavis AA, Kumar MS, Mudliar SN, Chakrabarti T (2007) Biotechnological conversion of agro-industrial wastewaters into biodegradable plastic, poly –ßhydroxybutyrate. Bioresource Technology 98:3579-3584. doi: 10.1016/j.biortech.2006.11.024.

Koller M, Braunegg G, Bona R, Hermann C, Horvat P, Martinz J, Neto J, Pereira L, Varila P, Kroutil M (2005a) Production of polyhydroxyalkanoates from agricultural waste and surplus materials. Biomacromolecules 6:561-565. doi: 10.1021/bm049478b.

Koller M, Bona R, Hermann C, Horvat P, Martinz J, Neto J, Pereira L, Varila P, Braunegg G (2005b) Biotechnological production of poly (3- hydroxybutyrate) with *Wautersia eutropha* by application of green grass juice and silage juice as additional complex substrates. Biocatalysis and biotransformations 23 (5):329-337. doi: 10.1080/10242420500292252.

Koller M, Bona R, Chiellini E, Grillo FE, Horvat P, Kutschera C, Hesse PJ, Braunegg G (2008) Polyhydroxyalkanoate production from whey by *Pseudomonas hydrogenovora*. Bioresource Technology 99:4854 – 4863. doi: 10.1016/j.biortech.2007.09.049.

Koller M, Salerno A, Sousa Dias M, Reiterer A, Braunegg G (2010) Modern Biotechnological Polymer Synthesis: A Review. Food technology and biotechnology 48(3): 255 – 269.

Koller M, Gasser I, Schmid F, Berg G (2011a) Linking ecology with economy: insights into PHA producing microorganisms. Engineering in Life Sciences 11:222-237. doi: 10.1002/elsc.201000190.

Koller M, Salerno A, Reiterer A, Malli H, Malli K, Kettl KH, Narodoslawsky M, Schnitzer H, Chiellini E, Braunegg G (2012) sugar cane as feedstock for biomediated polymer production. Sugarcane: Production, Cultivation and Uses. Nova Science Pub Inc.

Moser A (1988) Bioprocess Technology: Kinetics and Reactors. Springer-Verlag, New York, United States of America.

Narodoslawsky M, Krotscheck Ch (1995) The Sustainable Process Index (SPI): evaluating processes according to environmental compatibility. Journal of Hazardous Materials 41:383-397. doi: 10.1016/0304-3894(94)00114-V.

Neto J (2006) New strategies in the production of polyhydroxyalkanoates from glycerol and meat and bone meal. Ph.D Thesis, Graz University of Technology, Graz, Austria.

Niederl- A, Narodoslawsky M (2004) Life Cycle assessment – study of Biodiesel from Tallow and Used Vegetable Oil, Graz University of Technology, Graz, last accessed 08.06.2011.

Niederl A, Narodoslawsky M (2008) Life Cycle Assessment as an engineer's tool?. Journal of Cleaner Production 16:245-252. doi: 10.1016/j.jclepro.2006.08.024.

Nonato RV, Mantelatto PE, Rossell CE (2001) Integrated production of biodegradable plastic, sugar and ethanol. Appl Microbiol Biotechnol 57:1-5. doi: 10.1007/s002530100732.

OPEC (2009)*Monthly Oil Market Report January 2009.* Organization of Petroleum Exporting Countries. www.opec.org/opec_web/static_files_project/media/downloads/publications/MR012009.pdf, last accessed 25.10.2011.

Pitt M , (n.d.), Chemicals cost guide, ed.icheme.org/costchem.html, last accessed 08.06.2011.

Riedl Ch (2003) Stoffstromanalyse in Schlachthöfen. MSc Thesis, Graz University of Technology, Graz, Austria.

Sandholzer D, Narodoslawsky M, (2007) SPIonExcel – fast and easy calculation of the Sustainable Process Index via computer. Resources, Conservation and Recycling 50 (2):130-142. doi: 10.1016/j.resconrec.2006.06.012.

Solaiman DKY, Ashby RD, Foglia TA, Marmer WN (2006) Conversion of agricultural feedstock and coproducts into poly(hydroxyalkanoates). Appl Microbiol and Biotechnol 71:783-789. doi: 10.1007/s00253-006-0451-1.

Stelmachowski M (2011) Utilization of glycerol, a by-product of the transesterification process of vegetable oils: a review, Ecological Chemistry and Engineering's, vol. 18, no. 1, pp. 9-30.

Sudesh K, Iwata T (2008) Sustainability of biobased and biodegradable plastics. Clean - Soil,Air,Water 36:433-442. doi: 10.1002/clen.200700183.

Sun Z, Ramsay JA, Guay M, Ramsay BA (2007) Fermentation process development for the production of medium-chain-length poly-3-hydroxyalkanoates. Appl Microbiol Biotechnol 75:475-485. doi: 10.1007/s00253-007-0857-4.

Zinn M, Weilenmann HU, Hany R, Schmid M, Egli T (2003) Tailored synthesis of poly([R]-3-hydroxybutyrate-co-3-hydroxyvalerate) (PHB/HV) in Ralstonia eutropha DSM 428. Acta Biotechnologica 23:309-316, doi:10.1002/abio.200390039.

13 Paper III

Ecological Footprint Comparison of Biobased PHA Production from Animal Residues

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13.1 Contribution to the paper

The contributions to this paper include process design and evaluation of PHA production in ANIMPOL project. It addresses measurement of ecological optimization potential for PHA production utilizing energy (electricity and heat) from business as usual (electricity from grid and heat from natural gas) and provision of energy input from renewable resource i.e. biomass burning. A comparative analysis is made between PHA production from business as usual, using renewal energy (PHA_R) and evaluation results of polyethylene low density production (PE_LD).

Ecological Footprint Comparison of Biobased PHA Production from Animal Residues

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Utilization of waste streams is gaining more and more importance to reduce costs at the input side of a process. This affects not only costs, as environmental impacts can be minimized due to utilization of recovered waste streams too. ANIMPOL is an EU funded research project which is focused on the production of biopolymers from animal residues. This report compares conventional plastic production against fermentation of animal residues to polyhydroxyalkanoates (PHA) which constitutes a group of biobased and biodegradable polyesters. Beside PHA high quality biodiesel and meat and bone meal are produced which improves the economic feasibility of the whole process design. Through hydrolysis of specific residues the substitution of inorganic nitrogen can be achieved (Kettl et al., 2011a).

For comparison of different production scenarios Ecological Footprint evaluation, according to the Sustainable Process Index methodology (Sandholzer et. al., 2005; Narodoslawsky and Krotscheck, 1995) was applied. Sub-process sharp information is available to figure out ecological hotspots within every process step. Ecological optimization potentials as well as production cost reduction are pointed out to address cleaner production already in the process designing phase.

Introduction

Polymeric material is most commonly used as a packing material to ensure safe and efficient distribution of goods. This ever increasing production and packing, has made waste disposal an emergency for several countries. The waste disposal problem and regulations for safe and cleaner environment has served as driving force to stimulate increased research for the potential solutions like bio based and biodegradable polymers or other more sustainable materials.

This need have provided incentive for research and development of novel production techniques based on renewable resources. “White biotechnology” has been used for sustainable production of polymers, fine chemicals and fuels by utilising microorganisms or enzymes. Polyhydroxyalkanoates (PHAs) are one of the potential value-added products which are produced by certain bacteria from carbonaceous substrates (like carbohydrates, lipids, alcohols or organic acids) as carbon and energy reserves under unfavourable growth conditions due to imbalanced nutrient supply (M. Koller et al., 2010; J. Yu et al., 2008).

The biodegradable and biocompatible properties of make this potential substitute for some conventional plastics. The potential applications of PHA range from rigid plastics to ductile elastics make them interesting for various industries and medical applications. Nevertheless a major drawback of PHA production has been high production cost. In order to reduce the PHA production cost, substantial efforts has been made through efficient bacterial strain development, optimization of fermentation and downstream processing for PHA recovery. Keeping in mind that carbon substrate is the major cost factor in PHA production, selection of the carbon source is a critical factor in determining the cost of overall PHA production (Yu et al., 2008; J. Y. Chee et al., 2010).

Agriculture and food processing industries have enormous amount of waste discharge per annum which is a potential renewable carbon source for bio based PHA production. The utilization of these resources not only decrease carbon substrate cost but also solve waste disposal problem. Aim of the ANIMPOL project ("Biotechnological conversion of carbon containing waste for eco efficient production of high value added products"), financed under 7th frame work program by the European union, is to produce biobased plastics (PHA) utilizing slaughtering waste streams.

Process Design Development

According to the flow sheet there are three main streams originating from the slaughtering process. Meat, non-rendering material (manure, digestive tract material, colostrum etc.) and rendering material (mainly fat, bones and blood). Meat and non-rendering materials are direct products which are consumed in the market while rest of the material is utilized as input for the sub processes. Main parts of the process design are hydrolysis, rendering, biodiesel, PHA production which are elaborated in the previous publications (M. Titz et al., 2012 and Kettl at al., 2011a). The downstream processing of the PHA production includes fermentation media concentration using micro or ultra-filtration membranes, high pressure homogenization and centrifugation and washing.

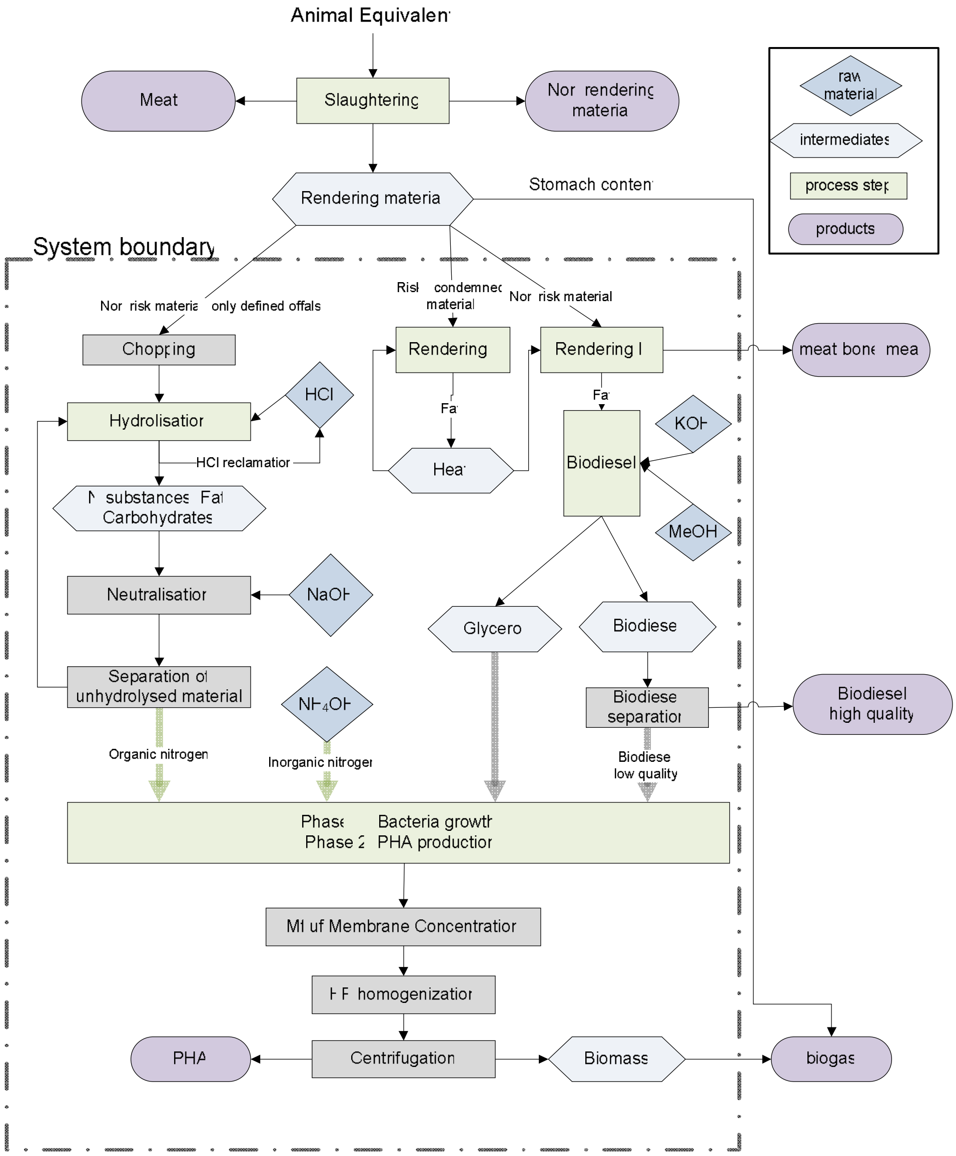

Figure: Flow sheet of process design for ANIMPOL

Ecological Assessment

In this study SPI methodology was used as LCIA method. It results in an ecological footprint, calculating the area necessary to embed the whole life cycle to provide products or services sustainably in the ecosphere. The Sustainable Process Index (SPI) developed by Krotscheck and Narodoslawsky (1995) is based on the assumption that the only income of our planet is solar energy. This income drives all natural processes and global material cycles (e.g. the global carbon cycle). The key resource to transform this income into utilisable material (e.g. biomass) or energy is area, e.g. Productive land, air and water have to be retained in a condition that allows them to remain the key production factors in a sustainable economy, therefore all emissions into the three compartments air, water, and soil are considered for the ecological footprint calculation following the principles that global material cycles must not be changed and that the local qualities of these compartments must not be changed either. Therefore the SPI value is a sum of seven different sub-areas which are area for infrastructure, non-renewable material, renewable material, fossil carbon, emissions to water, emissions to soil and emission to air. These areas are indicated by different colours and sum of all areas to provide raw materials, energy and to absorb emissions is the ecological footprint of the life cycle of the product or service.

The SPI may be used to compare different technologies (Kettl et al., 2011b), optimize the environmental performance of a single product (ecodesign) or to optimize the environmental performance of a company (Gwehenberger et al., 2007). The SPI as a tool looks at the whole product–service chain of PHA production and provides concrete and encompassing information about the environmental impacts of the processes in question.

SPI Calculations for different process

The ecological footprint (SPI value) for the final PHA product according to the process design accumulates evolved of every process key step is evaluated separately and cumulated to a final PHA footprint. Therefore base of evaluation for every key part is production of 1 t of PHA.

Animal residues or waste

Waste materials from slaughterhouses are considered with an SPI value of 0 m²/ton. The transportation of the waste material to the rendering plant is taken into account. For 1 t of PHA production 13.64 t of waste material will be transported within 75 km radius causing 150 km distance per trip. Total freight transportation is 2,046 tkm/ton of PHA production. SPI value for transportation using 28 t transportation trucks is 173,855 m^2.

Hydrolysis

SPI for offal hydrolysis is the sum of calculated SPI values for offal transportation, electricity consumption for chopping, acid reclamation, heat consumption for heating, acid consumption and base consumption for neutralization. As explained in the previous publication (M. Titz et al., 2012) offal hydrolysis is the source of complex organic nitrogen to be used in the fermentation process. Available amount of complex organic nitrogen is 0.0044 ton/ton of PHA production. SPI value for hydrolysis is 9,338,949 m^2/ton of complex organic nitrogen.

Rendering

SPI calculations for rendering process are divided into two parts depending on material to be processed. Products from condemned waste material are only used for heat production, (Rendering II in this particular case). In contrast to Rendering II processes the main part of the waste stream produces meat and bone meal (MBM) and tallow.

Rendering I

As explained in (M. Titz et al., 2012) input material will be condemned material (all body parts from TSE suspected and confirmed animals) which is not allowed for the processing of tallow. SPI for Rendering I is the sum of calculated SPI values for condemned material transportation, electricity consumption, heat consumption, waste water treatment and process water. The outcome of rendering I is about 0.7 MWh of process heat with an SPI value of 32,507 m^2/MWh which will be used for heating purposes in Rendering II.

Rendering II

This is the main rendering process processing extra fat, bones and animal viscera to produce tallow and MBM. Tallow is further utilized to produce biodiesel while MBM will be sold to the market. In Rendering II inputs for SPI calculations are waste transportation, electricity (EU27-mix), heat (produced from Rendering I), heat from natural gas, waste water treatment and process water. This process is a multi-output process because the main product is tallow and as secondary product we get MBM for selling to the market. Thus SPI value is allocated to both products according to production mass ratio. SPI for products is 231,498 m2/ton of tallow/MBM. This value of SPI for tallow production is used in SPI calculation for biodiesel production.

Biodiesel

Biodiesel is produced by transesterification of fat with methanol in 1:6. Other inputs during biodiesel production are KOH, H_2SO_4 and heat. The cumulative SPI value is 658,360 m2/ton of biodiesel production. This SPI value is a cumulative value allocated by applying mass allocation between biodiesel and glycerol.

SPI value for biodiesel as well as glycerol is 284,774 m^2/ton. Crude biodiesel will be further processed to low and high quality biodiesel fraction. Low quality is about 55% of crude biodiesel which will be used in PHA production and rest 45% high quality biodiesel (biodiesel HQ) will be sold in the market according to project outline. Biodiesel separation process is not fixed yet, so energy and chemical input data is missing. Due to this reason the SPI value per ton of biodiesel LQ and HQ are the same as for crude biodiesel.

PHA production and downstream processing

PHA production and downstream processing is comprised of fermentation process, PHA separation and purification process. The following table represents SPI the inventory data which comprises nitrogen input from the offal hydrolysis, NH_4OH as an inorganic nitrogen source, glycerol and biodiesel as carbon sources, chemicals according to fermentation media requirements, energy and water inputs. Table 13.1 represents inventory inputs for PHA production calculated according to mass flow calculations. The calculated SPI value is 1,085,298 m^2/t of PHA production.

Table 13.1: PHA Production Inventory Data

PHA production inventory data		
input	inventory	units
Organic nitrogen	0.0044	t
Ammonium Hydroxide	0.0767	t
Glycerol	0.2371	t
biodiesl	1.8588	t
Inorganic chemicals	0.0782	t
Net electricity EU27 mix	0.3214	MWh
waste water treatment	8.1178	m^3

Process Water	8.1178	m^3
Process energy, natural gas	2.8980	MWh

Results and discussion

The footprint distribution for different inputs has been shown in Figure 13.1. It shows that maximum footprint which accounts for 54% is produced by the carbon source (biodiesel (LQ) and glycerol). The other two most prominent factors are net electricity EU-27 mix and steam consumption (from natural gas), sharing 17% and 19% of overall foot print respectively. Although organic nitrogen mix from hydrolysis is very low, it has significant share in the overall footprint. The reason for high footprint of this process is high energy and inorganic acid and base consumption.

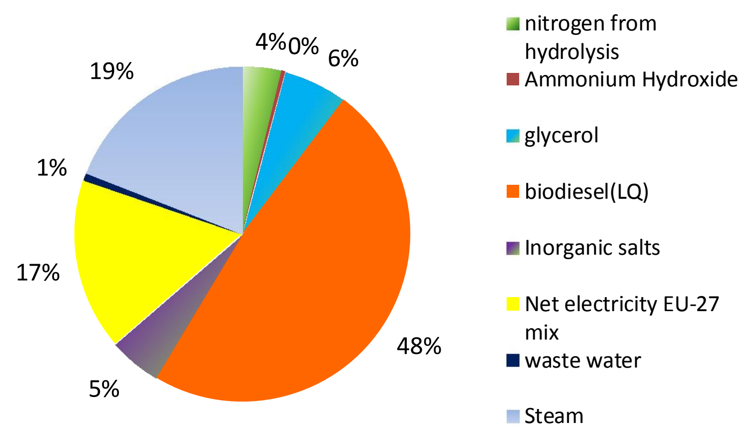

Figure 13.1: PHA production footprint distribution

The above results show the current progress in the PHA production using EU-27 electricity mix and natural gas as energy resources. Figure 13.2 represents the PHA-R production (PHA production using renewable energy source) fulfilling energy demands from completely renewable resources. For these calculations "net electricity biomass fired power station" and heat production from wood chips has been used as energy sources. The distribution of footprint is very different as compared to the conventional scenario. In this scenario carbon input source have even bigger share which is about 63% while other important inputs are inorganic salts, complex organic nitrogen from hydrolysate and steam consumption respectively.

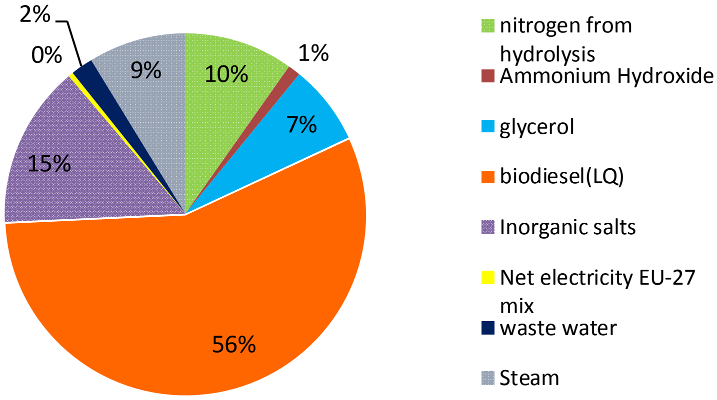

Figure 13.2: PHA-R production footprint distribution

Figure 13.3 compares the footprint per ton of PHA production, PHA-R production, based on the ANIMPOL process with a conventional Polyethylene low-density (PE-LD) production process. The overall footprint values per ton production of PHA, PHA-R and PE-LD are 1,085,298 m^2, 372,950 m^2 and 2,508,409 m^2 respectively. PHA production in the current scenario has 57% lower footprint than PE-LD while PHA-R production scenario has 66% and 85% lower SPI value compared to PHA and PE-LD respectively. Although some data about energy consumption in biodiesel separation process is missing but results are very promising to compare ecological footprint bandwidth and relation between different products.

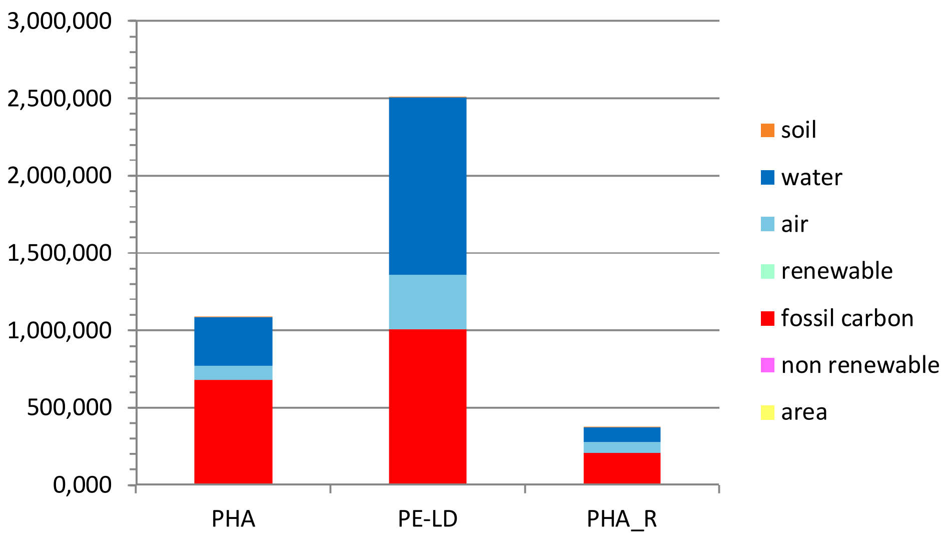

Figure 13.3: Comparison of overall footprint for PHA, PE-LD and PHA-R

Out of the sub-category “Area for fossil carbon” the life-cycle CO_2 emissions can be calculated which would be 3.9 t CO_2 per ton PHA, 1.5 ton CO_2 per ton PHA_R and 7.4 t CO_2 per t Polyethylene LD.

Conclusion and outlook

The paper represents the ecological footprint analysis of PHA production utilising waste streams from slaughtering industry. The results clearly indicate that major footprint shareholders are carbon source for PHA production and energy consumption. Keeping in mind that starting material is a waste stream and carbon source for PHA production is produced through highly energy intensive rendering process and biodiesel production process. The footprint for carbon source can be reduced by process optimization, heat integration and using maximum renewable energy. The 2nd scenario PHA_R production shows possible achievable footprint and CO2 emission reductions. The process is in further optimization stage using heat integration and cleaner production studies. Furthermore economic analysis is also carried out side by side in order to assess the economic feasibility of the process.

References

Chee J. Y., Yoga S., Lau N., Ling S., Raeid M., Abed M., Sudesh K (2010) Bacterially produced polyhydroxyalkanoate (PHA): Converting renewable resources into bioplastics. Current research, technology and education topics in applied microbiology and microbial biotechnology. A Mendez-vilas edition, Formatex

Gwehenberger G., Narodoslawsky M., Liebmann B., Friedl A (2007), Ecology of scale versus economy of scale for bioethanol production. Biofuels, bioproducts and Biorefining, 1(4), 264-269. doi: 10.1002/bbb.35

Kettl K.-H., Titz M., Koller M., Shahzad K., Schnitzer H., Narodoslawsky, M. (2011a) Process design and evaluation of biobased polyhydroxyalkanoates (PHA) production, Chemical Engineering Transactions, 25, 983-988.

Kettl K.-H., Niemetz N., Sandor N., Narodoslawsky M (2011b) Ecological Impact of Renewable Resource-Based Energy Technologies, Journal of Fundamentals of Renewable Energy and Applications, 1, 1-5. doi: 10.4303/jfrea/R101101

Koller M., Salermo A., Dias M., Reiterer A and Braunegg G (2010) Modern biotechnological polymer synthesis. Food Technol Biotechnol 48 (3), 255-269.

Narodoslawsky M. and Krotscheck Ch (1995) The sustainable process index (SPI): evaluating processes according to environmental compatibility, Journal of Hazardous Materials, 41, 383-397. doi: 10.1016/0304-3894(94)00114-V

Sandholzer D., Niederl A. and Narodoslawsky M (2005) SPIonExcel – fast and easy calculation of the Sustainable Process Index via computer, Chemical Engineering Transactions, 7, (2), 443-446.

Titz M, Kettl K-H, Shazhad K, Koller M, Schnitzer H, Narodoslawsky M (2012) Process optimization for efficient biomediated PHA production from animal-based waste streams. Clean Technol Environ Policy. doi:10.1007/s10098-012-0464-7

Yu J., Chen L X L (2008) Greenhouse gas emissions and fossil energy requirement of bioplastics from cradle to gate of a biomass refinery. Environ Sci Technol 42, 6961-6966. Doi: 10.1021/es7032235

14 Paper IV

Comparison of Ecological Footprint for Biobased PHA Production from Animal Residues Utilizing Different Energy Resources

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14.1 Contribution to the Paper

The contributions to this paper include ecological optimization of process design developed for bio-based, biopolymer polyhydroxyalkanoate (PHA) production from animal residues. It addresses "Impact of geographical context and energy provision on the ecological pressure" of PHA production utilising electricity mix from countries representing different continents.

Comparison of Ecological Footprint for Biobased PHA Production from Animal Residues Utilizing Different Energy Resources

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Keywords: PHA, Biopolymers, Animal Residues, Energy Resources, Sustainable Process Index, Ecological Footprint

Abstract

Realizing a sustainable development of our planet requires a reduction of waste production, harmful emissions and higher energy efficiency as well as utilisation of renewable energy sources. One pathway to this end is the design of sustainable biorefinery concepts. Utilizing waste streams as raw material is gaining great importance in this respect. This reduces environmental burden and may at the same time contribute to economic performance of biorefineries. This paper investigates the utilization of slaughtering waste to produce biodegradable polyesters, polyhydroxyalkanoate (PHA), *via* bioconversion. PHA is the target product while production of high quality biodiesel along with meat and bone meal (MBM) as by-products improves the economic performance of the process.

The paper focuses on ecological comparison of different production scenarios and the effect of geographical location of production plants taking different energy production technologies and resources into account; Ecological Footprint evaluation using Sustainable Process Index (SPI) methodology was applied. Keeping in mind that the carbon source for PHA production is produced from waste through energy intensive rendering process, the effect of available energy mixes in different countries becomes significant. Ecological Footprint results from the current study shows a bandwidth from 372,950 to 956,060 m^2/t PHA production, depending on the energy mix used in the process which is compared to 2,508,409 m^2/t for low density polyethylene (PE-LD).

Introduction

Polymers produced by petro-chemical industry are omnipresent in our society; published data report a current annual production of 250 Mt worldwide with a strongly increasing trend (Koller et al. 2013). Polymers are broadly used due to their low density, high versatility of material properties, resistance to chemical and natural degradation and simple and well-established production technologies. Negative impacts arising from exhaustive utilization of polymers include the fact that these materials are based on limited fossil feedstocks, and that the often desired resistance to degradation results in tremendous piles of plastic waste. The conversion of spent polymers in incineration bears the risk of generation of toxic compounds, such as hydrochloric acid in the case of polyvinylchloride. Generally, thermal conversion of all petrochemical polymers releases CO_2 into the atmosphere contributing to global warming. Laudable strategies like recycling systems as implemented in many regions do not function to a degree that really offers a solution for the polymers waste problem; in addition, each recycling cycle results in a decrease of the polymers material performance (Braunegg et al. 2004).

Today, we notice an increasing public sensibility about the need to switch to renewable resources for generation of energy and goods like polymers (Koller et al. 2012a). Biopolymers are frequently discussed in public media, by the scientific community and representatives of involved industrial branches as future-oriented alternatives to common polymers from petro-industry (Keshavarz and Roy 2010). Here, two crucial barriers have to be pointed out, why biopolymers cannot yet be regarded as a universal cure for the plastic situation and currently amount to no more than 5 % of the entire global plastic market:

a) Production of biopolymers still is not cost competitive due to high energy requirements, low conversion yields of carbon substrates to biopolymers caused by the production of side-products such as CO_2, by the costs of the carbon source itself, and by productivities that are usually lower in the case of bioprocesses than in optimized chemical processes (Koller et al. 2005).

b) Material performance, in many cases, does not yet meet the benchmark of their petro-chemical competitors. For this reason, strong efforts are currently devoted to creating composites and blends of various biopolymers together with compatible organic or inorganic additives and filler materials; here, especially nano-composites may result in enhanced material characteristics (Chiellini et al. 2004; Patel et al. 2005). In addition, post-synthetic modification of biopolymer by chemical or enzymatic means provides a viable strategy to improve and fine-tune the material quality and performance for a defined application (Hany et al. 2004; Rupp et al. 2008).

A remedy for high cost biopolymer production is the utilization of carbon rich waste streams stemming from various industrial branches. Upgrading them to feeds stocks for biotechnological production of value-added products like biopolymers, saves costs for expensive substrates and reduces competition with the food sector as no “fresh” bio-resources like carbohydrates from cereals or valuable lipids from oil seeds have to be supplied. At the same time using waste flows provides industry with a strategy to utilize their by-products in a reasonable way (Solaiman et al. 2006; Khardenavis et al. 2007). Selecting the adequate feedstocks for bio-polymer production is mainly dependent on the region where the polymer production takes place. Hence, locally available waste streams shall be applied for biopolymer production in order to minimize transportation distances between the site where the raw material is generated and the polymer production plant (Koller et al. 2010a).

The expression “green plastic” nowadays is exhaustively used by the manufacturers of such products. Many of these materials however do not meet the strict requirements to allow their classification as “green plastic”. Generally, a “green plastic” has to be based on renewable resources instead of fossil feedstocks. In addition, it has to be “bio-compatible”, as it must not negatively impact its biological environment, and, finally, the material has to degrade according to strict norms and within defined time frames (being either “biodegradable” or “compostable” (Koller et al. 2012b).

Polyhydroxyalkanoates (PHA) are regarded as a family of biopolymers addressing all the attributes mentioned in the prior paragraph. They are produced as carbon- and energy storage materials by prokaryotic microorganisms starting from renewable carbon substrates like sugars, organic acids, alcohols or lipids. They are well known as biodegradable, compostable materials that can also be applied *in vivo*, e.g. as implants or surgical sutures due to their high biocompatibility (Zinn et al. 2001). Together with these biologically favourable attributes, their material characteristics resemble those of petro-chemical elastomers, rubbers or latexes. The exact material properties are dependent on the composition of the PHA on the molecular level that in turn is a result of the carbon substrate used and the selected microbial production strain (Steinbüchel and Valentin 1995). This opens the door for applying PHA in various fields, starting from simple packaging materials to carriers for controlled release of fertilizers and pesticides in agriculture to the application in the medical field (reviews by Chen 2010; Koller et al. 2010b). For PHA production the costs are highly determined by the expenses for the carbon substrates.

This is due to the fact that microbial cell growths as well as conversion of carbon source to PHA are aerobic processes. This means that a huge share of the carbon source undergoes the respiration process towards CO_2. Normally, only about the third part of the supplied carbon is finally found in the accumulated bioplastic, the rest is fixed in the non-PHA part of biomass or released as CO_2 or side-products excreted into the cultivation medium (Koller et al. 2005). The production of PHAs based on industrial waste streams is currently a field of intensive research. Important examples are the utilization of whey lactose, molasses from sugar industry, side streams from plant oil production or (ligno) cellulosic materials as carbon source (Sudesh and Iwata 2008; Shrivastav et al. 2010).

This study is based on a process design developed for 10,000 t/y of PHA production using slaughtering waste as raw material. A full mass and energy balance has been considered for 1 t/y PHA production, utilizing real experimental data (Titz et al. 2012).

The ANIMPOL process

The results presented in this article are based on data from the ANIMPOL project which investigated the utilization of waste streams from the slaughtering, rendering and biodiesel industry. In Europe, 500,000 t/y of waste lipids accrue from the animal processing industry (Titz et al. 2012). Converting these amounts to biodiesel (fatty acid esters, FAE) by means of transesterification would produce about the same quantity regarding the mass (490,000 t/y) of FAE. This FAE contains about 55 % of saturated fatty acid ester fraction (SFAE) that impairs FAEs fuel property due to an elevated cold filter plugging point. Separation of SFAE results in the generation of an excellent biofuel consisting of unsaturated FAE fraction. SFAE can be applied as carbon feedstock for PHA biosynthesis. In addition, about 0.1 t of crude glycerol is generated during the transesterification of 1 t of lipids. Considering the globally increasing biodiesel production, the glycerol market is already strained. Therefore glycerol can be regarded as a low value by-product. Crude glycerol can be utilised as an additional carbon substrate in the ANIMPOL process for cultivation of catalytically active microbial cells and for accumulation of PHA by the cells.

Several sub processes were analysed, from slaughter house waste to PHA production. Fundamental principles of economic and ecologically efficient process were considered for every decision of process design and development. The process design includes sub processes from slaughtering to PHA purification.

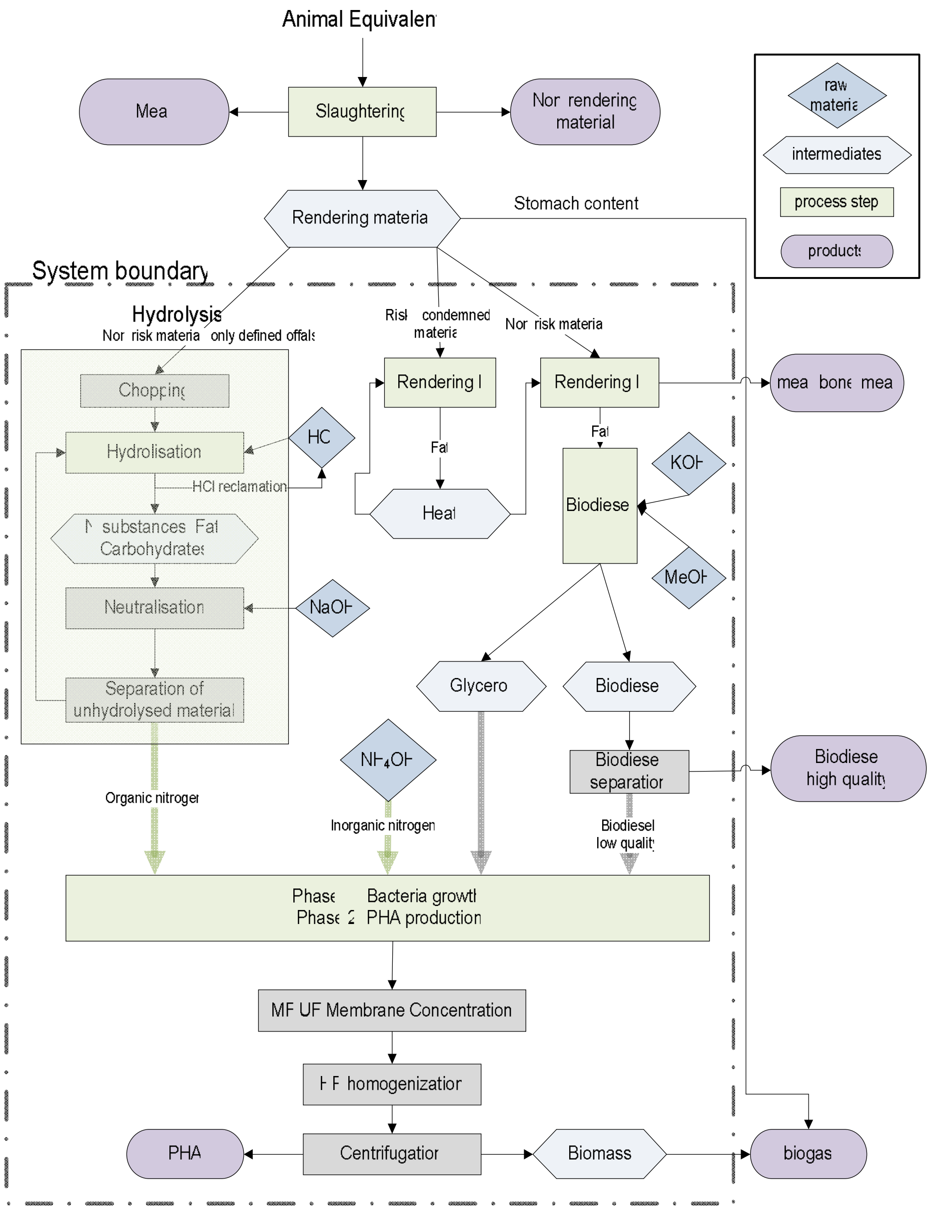

Figure 14.1: Flow sheet of process design for ANIMPOL

Upstream processing includes hydrolysis, rendering, biodiesel production and fermentation process, while downstream processing includes microfiltration (MF) or ultrafiltration (UF) and high pressure (HP) homogenization and centrifugation for PHA purification. Acid hydrolysis is an innovative addition at pilot scale while rendering, biodiesel production and fermentation process are state of the art processes. A detailed process design flow sheet is shown in Figure

14.1 showing the pathways of the material flows from the slaughter house to the final products MBM, PHA, biogas and high quality biodiesel. For a detailed description of the process design the reader is kindly referred to (Titz et al. 2012). In the current paper the process will only be briefly discussed to provide the base for further discussion.

i. Hydrolysis

Hydrolysis is the breakdown of larger molecules or compounds into smaller ones by the addition of water molecule in the presence of acid or base acting as a catalyst. In the ANIMPOL-process acid catalysed offal hydrolysis is carried out using 6 molar (M) hydrochloric acid (HCl), at an elevated temperature of 120 °C maintained for 6 h (Titz et al. 2012), in order to produce a cheap complex nitrogen source for cell growth. As the fermentation process requires a certain pH value, hydrolysate is neutralised by using NaOH. The neutralisation will result in NaCl production which has no negative effect in the following fermentation process (Pickering and Newton 1990). The life cycle inventory data for 1 t equivalent of organic nitrogen production through offal hydrolysis, based on own group experimental data is given in Table 14.1.

Table 14.1: Life Cycle Inventory data for 1 t organic nitrogen equivalent hydrolysate

Input	Inventory	Units
Transport 28 t Truck	5951.657	tkm
Grid electricity EU27	0.957	MWh
Process energy, natural gas	7.092	MWh
Hydrochloric acid	46.798	t
Process Water	31.956	m^3
Sodium hydroxide	16.902	t

ii. Rendering

Slaughter house by-products, mainly fat, blood and bones, constitute the rendering material as shown in Figure 14.1. They find a great variety of application directly or after processing and have added a value to the animals. Protein rich solids are traditionally used in foods, pet food, livestock feeds and as fertilizers. Fats are used in foods, pet foods and feed applications along with transformation into soaps and oleo chemicals. Since the emergence of Bovine Spongiform Encephalopathy (BSE) in the 1990ies, traditional uses have been partly abandoned and new alternative uses as energy or fuel source have been explored in the past decade. Legislative directives have been issued by EU regulating authorities for both fat processing units which is the "Meat product directive" 77/99/EEC (EU, 1977; 1992) and the "Animal by-product regulations" ABPR 1774/2002/EC(EU, 2002) for the rendering sector (Woodgate and Veen 2004).

Animal waste contains high amounts of water and provides a good breeding ground for microbial growth leading to its decomposition and ultimate environmental pollution. The conventional way of handling and stabilizing this material is heat processing known as "rendering". In this process animal by-products are treated at 133 °C and a pressure of 3 bar for at least 20 min to obtain MBM and tallow. The main sub-processes involved in rendering are grinding, cooking and pressing. As explained in (Titz et al. 2012), there are two distinct processes for rendering in the ANIMPOL process:

Rendering I sub processes uses condemned material streams from BSE suspected and confirmed animals. The products obtained from this process can only be used for energy purpose according to EU regulations. In the ANIMPOL process, this energy will be used to fulfill a part of energy demand for rendering II sub process, which processes non-risk material. The products of this process are tallow and MBM. Tallow will be used for biodiesel production while MBM will be sold to the market in order to generate revenue. Life Cycle Inventory data for 1 t of tallow production by rendering process based on experimental data (Titz et al. 2012) is given in Table 14.2.

Table 14.2: Life Cycle Inventory data for 1 t fat production

Inputs	**Inventory**	**Units**
Transport 28t Truck	625	tkm
Grid electricity EU27	0.25	MWh
Process energy, natural gas	3.24	MWh
Waste Water Treatment	2.48	m^3
Process Water	1.08	m^3
Heat from Rendering I	0.30	MWh

iii. Biodiesel

Biodiesel production using tallow as raw material is a well-developed and optimised process having 96-98 % production yield with respect to the fat input. This form of biodiesel is also known as tallow methyl ester (TME) and is produced by transesterification of tallow with methanol in the presence of KOH as catalyst (Titz et al. 2012).

Life Cycle Inventory data for 1t of biodiesel production based on material and energy flow data obtained by personal communication with Mike Scot serving as Technical Director at "Argent Energy (UK) Ltd" is given in Table 14.3.

Table 14.3: Life Cycle Inventory data for 1 t biodiesel production

Inputs	Inventory	Units
Tallow from Rendering II	1.02	t
Potassium Hydroxide	0.02	t
Sulfuric acid	0.01	t
Methanol	0.11	t
Process energy, natural gas	0.05	MWh
Grid electricity EU27	0.07	MWh
Waste Water Treatment	0.10	m^3

iv. PHA production

The PHA production utilizing microbial fermentation can be distinguished into two phases:

In the first phase a high concentration of catalytically active biomass is obtained under optimal nutritional conditions during unrestricted growth. In this phase PHA production is insignificant compared to biomass formation. In the second phase nutritional stress condition for microbes is induced by limited supply of essential nutrients such as phosphate and nitrogen. This results in redirection of carbon flux from pre-dominant biomass production towards PHA accumulation (Titz et al. 2012; Koller et al. 2010a). Downstream processing constitutes a key part of the entire

PHA production process. After biosynthesis of the polyester and separation of the bacterial biomass from the fermentation broth, cells are broken up to gain access to intercellular PHA. Choosing an adequate method for separating PHA from residual biomass is dependent on several factors: the microbial production strain, the desired product purity, the in-house availability of chemicals, and the acceptable impact on the molecular mass of PHA (Koller et al. 2010b; Kunasundari and Sudesh 2011).

Life Cycle Inventory data in Table 14.4 is based on information obtained by personal communication (Koller Martin, TU Graz). The hydrolysate constitutes a source of organic nitrogen and mixture of essential amino acids used in the unrestricted growth phase, while ammonium hydroxide serves as a source of inorganic nitrogen in the PHA production phase and also helps to maintain optimal pH reaction conditions. Biodiesel and glycerol are the main raw materials acting as carbon source for bacteria to produce PHA. Inorganic chemicals are a mixture of essential chemicals and biochemicals required for the fermentation process. Electricity consumption comprises stirring during fermentation process, pumping of the fermentation media into and out of the reactor, whereas process heat is required for sterilization of media and bioreactor and maintenance of fermentation media temperature at about 37 °C. Water is consumed for fermentation media and downstream processing.

Table 14.4: Life Cycle Inventory data for 1 t PHA production

Inputs	**Inventory**	**Units**
Hydrolysate	0.004	t
Ammonium Hydroxide	0.077	t
Glycerol	0.237	t
Biodiesel	1.859	t
Inorganic chemicals SP	0.078	t
Grid electricity EU27 SP	0.321	MWh
Waste Water Treatment	8.118	m^3
Process Water	8.118	m^3
Process energy, natural gas	0.292	MWh

Ecological evaluation with the Sustainable Process Index (SPI)

In this study ecological assessment is carried out using SPI methodology. The SPI is a member of the Ecological Footprint family and measures the footprint as cumulative area to embed the whole life cycle of an industrial process sustainably into the biosphere. It was developed by Krotscheck and Narodoslawsky (1995) based on the assumption of all ecological footprint measures (e-g. Rees and Wackernagel, 1996, Čuček et al. 2012) that sustainable economy is dependent on the solar radiations as sole natural income for our planet driving all natural flows and material cycles. The SPI method compares the mass and energy flows generated in a technological process to the natural flows using strict ecological sustainability principles (Krotscheck and Narodoslawsky 1996). It provides an aggregate measure of the ecological pressures incurred by provision of raw material and infra-structure as well as emissions along the Life Cycle and thus allows comparison of technologies as well as the identification of ecological hot spots within the Life Cycle of an industrial process. The consideration of all these environmental impacts and total area required for sustainable embedding of the overall process in the ecosphere is given by:

$$A_{tot} = A_R + A_E + A_I + A_S + A_D$$

Where A_R presents area required for the raw material extraction, A_E area for energy, A_I area for infrastructure or physical installations, A_S area to support the staff and A_D area for sustainable dissipation of waste and emissions to the ecosphere. Atot is overall area for the process producing services or goods. The area per unit or service a_{tot} is given as:

$$a_{tot} = A_{tot} / N_P$$

N_P presents the number of goods or services produced by the specific process e.g kWh of energy produced in a specific energy process (Narodoslawsky and Krotscheck 2004).

The calculated SPI footprint may be split corresponding to different aspects of the ecological pressure: fossil resources, non-renewable resources, renewable resources, land occupation as well as emissions to water, air and soil. (Sandholzer and Narodoslawsky 2007; Gwehenberger and Narodoslawsky 2007). This allows the identification of the particular aspect causing the ecological footprint of a process step SPI value for 1 t of PHA production using available LCI data is calculated by using SPIonExcel software (spionexcel.tugraz.at). Starting material for the

ANIMPOL process is a waste collected from slaughtering houses. It is assumed that average distance for waste collection is in radius of 75 km, means 150 km will be travelled per trip of waste collection. The unit of freight transport is ton kilometre (tkm) which is defined as: "A unit of measure of goods transport which represents the transport of one ton by road over one kilometre" (OECD 2002). For 10,000 t PHA production transportation under the assumed set-up is equal to 20,466,756 tkm. It is allocated to offal and rendering material using mass allocation method. The system boundary assumes rendering material as a waste flow with no ecological pressure assigned to it and covers the process from waste transportation to PHA production as a pure product. SPI value for sub processes hydrolysis, rendering, biodiesel production and PHA production including fermentation and down streaming processes is calculated to find out the ecological hotspots within this process.

In these calculations grid electricity is assumed to be medium voltage European average mix based on International Energy Agency (IEA) statistics as shown in Table 14.5 (IEA 2009; Fig 1; Stoeglehner et al. 2011). For heating, process energy is derived from natural gas using industrial heaters. For comparison of footprint in different countries energy provision mixes for specified countries were used. Natural gas is considered as a source for heat provision in all cases, while heat production from biomass is considered for "renewable energy case". In the latter case a technology mix for renewable electricity includes 43 % from biomass, 48 % wind power, 4 % geothermal and 5 % solar energy (IEA 2009, Eurostat 2009). The environmental pressure for energy provision technologies varies depending on different resources and technological structures (Kettl et al. 2011). Energy provision system and its environmental impacts changes between countries, due to variation of available resources and technological systems for energy production. The effect of change of geographical location on the overall process and product's environmental pressure is also considered in the current study.

Ecological evaluation of sub-processes

The SPI for hydrolysis is shown in Figure 14.2 which reveals that mineral acid and base are the key factors of the footprint and contribute about 83 % to the overall footprint of the sub process, while transportation (of the part of slaughter house by-product used for hydrolysis) and energy provision have significant shares, too. The large share of mineral acid and base footprint is due to their highly energy intensive up-stream Life Cycle.

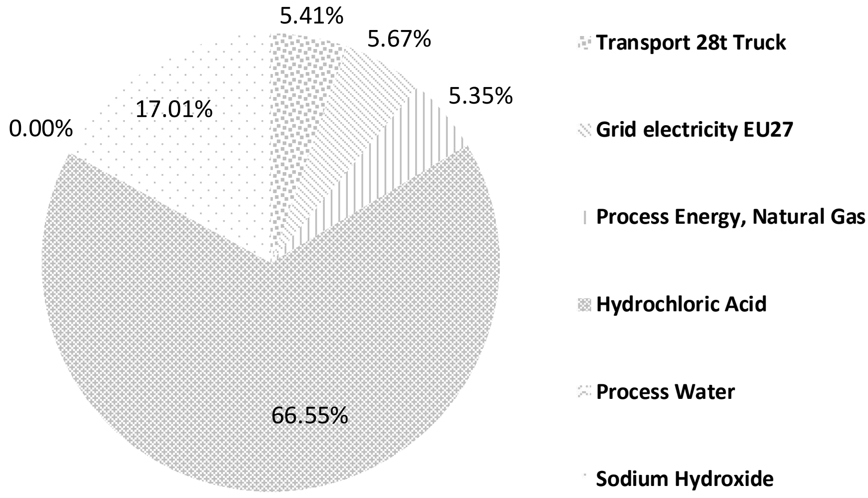

Figure 14.2: Ecological Assessment of Hydrolysis

Figure 14.3 Figure 14.3Figure 14.3evaluates the impact of rendering according to the Life Cycle Inventory in Table 14.2. It reveals that energy (electricity and heat) and transportation are the main contributors with 87 % and 12 % of the overall ecological footprint. This indicates the potential to minimize the footprint by utilizing energy produced from renewable sources.

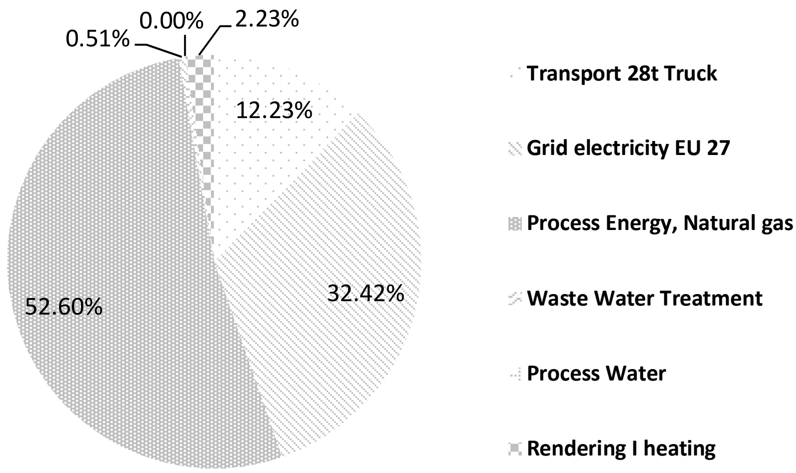

Figure 14.3: Ecological assessment chart for rendering process

Figure 14.4Figure 14.4 provides an overview of the ecological impact according to inventory data given in Table 14.3 for the biodiesel production step. It can be seen that raw material (tallow from rendering process) along with methanol and electricity are the main contributors to the overall footprint of the process. Tallow production is a highly energy intensive process as shown in Figure 14.3; it is the main material input for biodiesel production process requiring 1.02 t fat per t biodiesel. It is responsible for about 69 % of total footprint along with 17 % for methanol and 11 % of electricity. Heating has a small share of about 1 % because heating is provided to a great extent by utilising heavy glycerol material obtained during biodiesel distillation with a calorific value equivalent to heavy fuel oil.

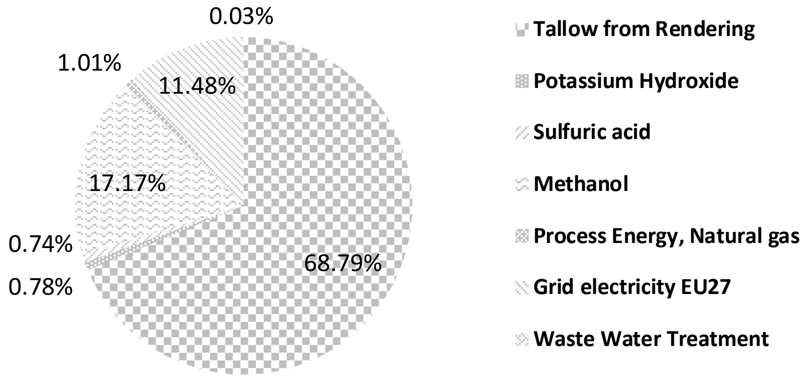

Figure 14.4: Graphical representation of ecological footprint for Biodiesel production

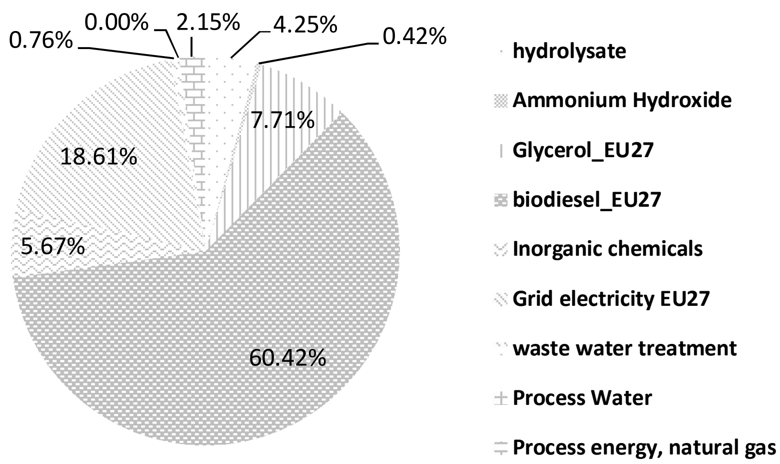

Figure 14.5: Graphical diagram of ecological footprint of PHA production

Figure 14.5 shows the footprint distribution of producing 1 t PHA. The raw material (biodiesel and glycerol) are the major footprint contributors along with electricity consumption; they contribute about 68 % and 19 % to the overall footprint. Process energy has a small share because it is provided by utilizing heat from high energy sub processes through heat integration.

Impact of geographical context and energy provision on the ecological pressure

The footprint analysis of the sub processes reveals that conversion of slaughter house waste material into a value added marketable material constitutes a highly energy intensive process. This means in turn that the ecological performance of the process depends on the national context depending on the prevailing energy provision technology mix in a national economy. In order to highlight this fact, a comparison of biodiesel as well as PHA production using electricity mixes as shown in Table 14.5, from different countries in Europe (AT, PL, DE, DK, NO, IT and FR) along with People's Republic of China and USA is presented.

Table 14.5: Electricity mix for different countries (%) and average SPI/kWh per technology and country

Technologies	*SPI [m²/kWh]*	*EU27*	*AT*	*DE*	*NO*	*DK*	*FR*	*IT*	*PL*	*USA*	*CN*
coal	368.8	26.46	5.25	43.40	0.07	48.64	5.30	14.84	88.78	45.19	78.82
oil	208.1	2.99	1.19	1.63	0.02	3.23	1.14	8.87	1.79	1.20	0.45
gas	140.0	22.62	12.87	13.31	3.19	18.52	3.88	50.32	3.16	22.68	1.37
biomass	12.2	2.86	4.18	4.38	0.13	6.29	0.39	2.06	3.45	1.19	0.06
waste	5.0	1.02	0.83	1.63	0.08	4.77	0.73	1.16	0.16	0.54	0.00
nuclear	1,056.3	27.86	0.00	22.77	0.00	0.00	75.59	0.00	0.00	19.82	1.90
hydro	1.4	11.19	45.56	4.17	95.70	0.05	11.42	18.26	1.96	7.12	16.66
geothermal	13.2	0.17	0.00	0.00	0.00	0.00	0.00	1.83	0.00	0.41	0.00
PV	63.2	0.44	0.04	1.11	0.00	0.01	0.03	0.23	0.00	0.06	0.01
wind	8.8	4.13	2.05	6.52	0.74	18.48	1.46	2.24	0.71	1.77	0.73
other/biogas	13.7	0.26	0.02	1.07	0.06	0.00	0.07	0.21	0.00	0.02	0.00
Country mix [m²/kWh]		**436.5**	**195.9**	**495.7**	**21.1**	**281.3**	**899.2**	**238.9**	**575.1**	**460.4**	**255.9**

The countries in Europe are selected based on their well-established husbandry industry and significantly different energy provisions systems while People's Republic of China and USA are included being the two biggest world economies. Figure 14.6 shows the comparison of ecological footprint calculated by SPI methodology for fossil diesel and biodiesel production using electricity mixes from different countries (IEA 2009) natural gas to fulfil heat requirements, as well as a process using renewable energy (biodiesel-RE). In renewable energy (RE) scenario electricity provision comprises of renewable energy mix for EU27 (Eurostat 2009), while heat demand is fulfilled by biomass burning. In biodiesel renewable electricity + natural gas (biodiesel-REl+NG) electricity consumption if fulfilled by renewable electricity (REl) and natural gas (NG) is used for heating. It can be seen that fossil diesel production has the highest footprint 715,469 m^2/t among all while biodiesel-RE has the lowest value of footprint 310,771 m^2/t.

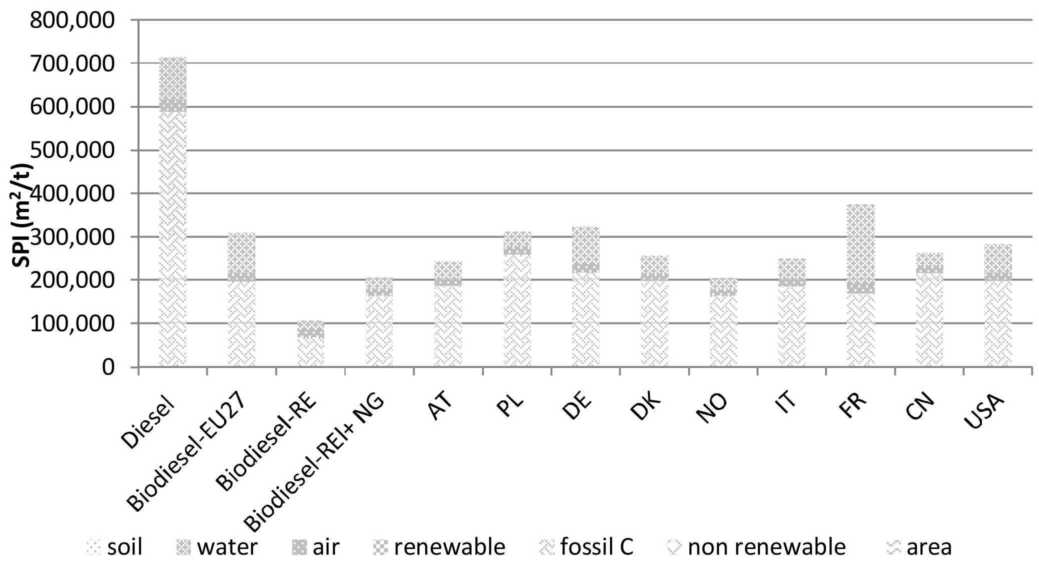

Figure 14.6: Footprint of biodiesel production using energy mix from different countries

The differences in the footprint value for different countries are based on energy mix composition; the greater the share of renewable energy production, the lower will be the footprint value of the product or service. The analysis shows the overall ecological impact for energy provision systems in different countries as well as distribution of it in different impact categories.

Out of seven categories "area for fossil carbon C, emission to water and air" are the most prominent ones, while others categories have negligible effect. "Area for fossil C" represents the impact on the global carbon cycle occupies more than 75 % of total footprint area except for France where emissions to water are also high. These high emissions to water are due to a high share of nuclear power generation of 72 % in grid electricity mix for France. The highest share of "area for fossil carbon" is shown in the case of Polish energy mix with a share of 84 % coal powered electricity production.

Figure 14.7 shows the footprint comparison per t PHA production again using energy mix for different countries, the EU 27 energy mix, and the RE mix defined for the biodiesel case. These values are compared to a fossil based polymer competitor PE-LD. It can be seen that PE-LD features the highest footprint value 2,508,409 m^2/t, while PHA-RE shows the lowest footprint value 372,950 m^2/t.

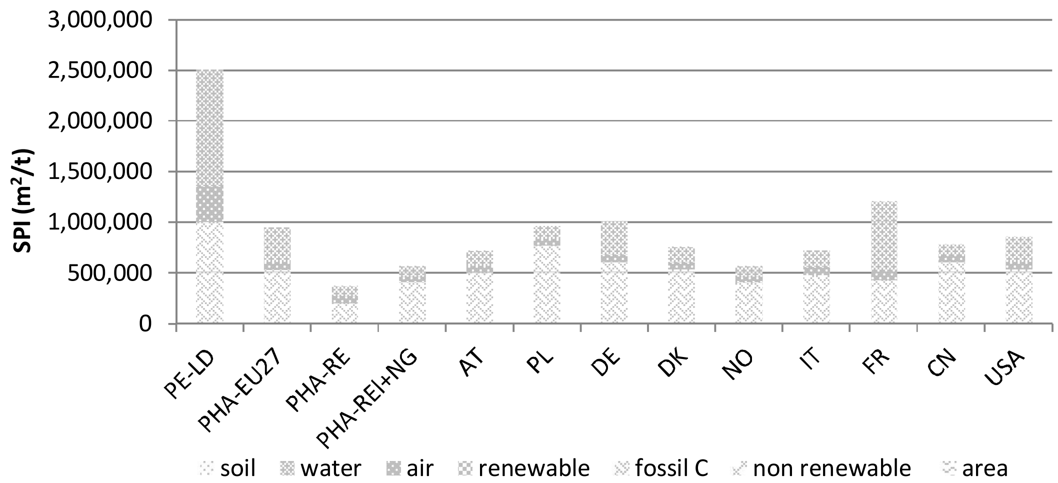

Figure 14.7: Comparison of footprint for PHA production using energy mix from different countries

Norway features a significantly lower footprint for PHA production (567,393 m^2/t), almost equal to the "RE+NG" case (566,962 m^2/t), because more than 91 % of the power in Norway is generated utilizing hydropower production system.

In the category "PHA production emissions to water" values for PE-LD and PHA production in France increased to a higher extent. This is due to higher emissions of heat and chemicals to water in case of PE-LD while in the French case the use of nuclear electricity generation is responsible for these emissions. This is due to the large Life Cycle emissions of nuclear power to water, especially from the reprocessing of used nuclear fuel.

The life cycle CO_2 emissions for different scenarios have been calculated on the base of the same Life Cycle Inventory data as the SPI calculations. The comparison of CO_2 emissions per t of PHA production is presented in Figure 14.8.

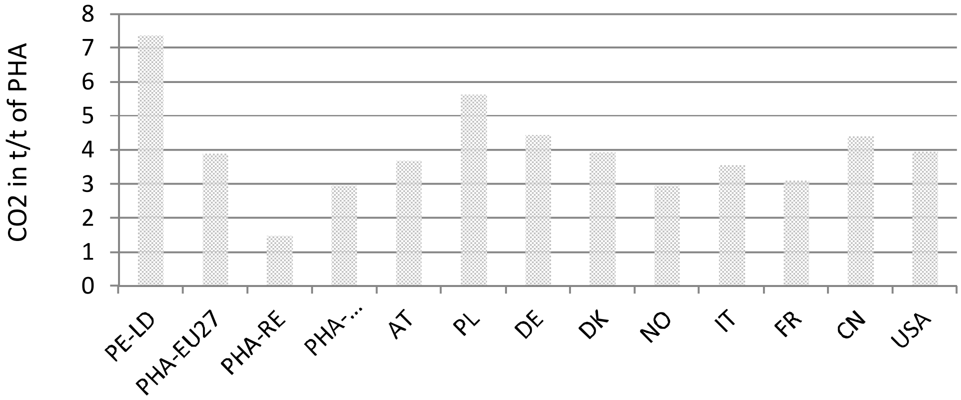

Figure 14.8: CO2 emissions for PHA production using energy mix from different countries

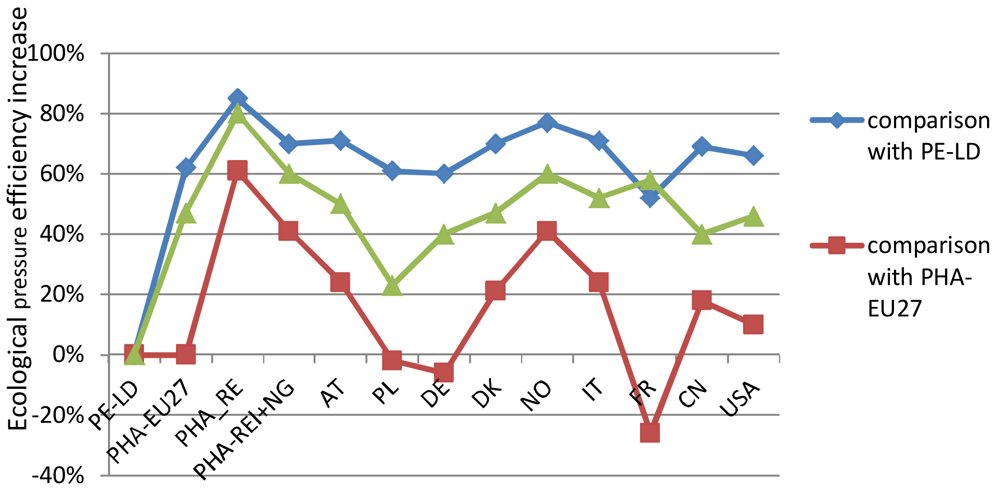

Figure 14.9: Comparison of ecological pressure efficiency

As expected PE-LD has the highest CO_2 emissions (7.4 t) compared to the renewable energy scenario's 1.5 t CO_2 emissions per t of PHA production. Poland has significantly higher (5.6 t)

CO_2 emissions compared to other countries, especially Norway with 2.97 t CO_2 emissions, while REl+NG have quite high CO_2 emissions caused by natural gas consumption as well as use of fossil fuel in the production of solar photovoltaic and biomass burning. Germany and the People´s Republic of China also have moderately high CO_2 emissions, 4.41 t and 4.45 t, respectively. This is due to their large share of coal fired power generation. Figure 14.9 shows ecological pressure reduction efficiency of different scenarios with reference to PE-LD and PHA-EU27.

It reveals that PHA-EU27 scenario has 62 % less footprint compared to PE-LD while PHA-RE scenario has 85 % and 62 % lower footprint compared to PE-LD and PHA-EU27 scenario, respectively. Similarly REl+ NG scenario has 70 % lower footprint than PE-LD and 41 % lower than EU energy mix scenario. In this case lower ecological reduction efficiency is caused by different heat provision technology. Among countries Norway has the highest ecological efficiency having more than 90% electricity produced from hydro power plants with least environmental impacts. Austria, Denmark, Italy and People's Republic of China also have very good ecological pressure reduction efficiency compared to PE-LD as well as PHA–EU27. Poland and Germany presents slightly inefficient cases compared to PHA-EU27 as results of electricity provision from coal and nuclear technologies. France shows the worst scenario compared to PHA-EU27. This inefficiency of ecological pressure reduction is due to very high emissions to water caused by nuclear technology.

PHA-RE is the most efficient CO_2 emission reduction case with 80% efficiency compared to fossil based PE-LD. Among the countries Norway with 60% CO_2 emission reduction is the best, while Poland with 20 % CO_2 emission efficiency presents the least efficient scenario. Germany and Poland show different CO_2 reduction efficiencies although they showed similar ecological pressure reduction efficiency. This contrast in CO_2 reduction efficiency for Germany and very high CO_2 reduction efficiency shown by France is caused by electricity provision using nuclear technology. Nuclear technology has extremely high emissions to water but have lower CO_2 emission compared to fossil fuels. The band width of ecological pressure reduction efficiency varies from 60 % for PHA-RE to blow zero in case of Poland, Germany and France. In case of CO_2 emissions reduction efficiency band width varies from 80 % in PHA-RE to 20% for Poland compared to PE-LD.

This analysis shows the impact of energy provision technologies on the overall process. In the designing and development of a sustainable process, utilization of renewable resources as raw material and production of bio or compostable materials is not the only criteria. Factors like fuel used for transportation of the raw material and source and technologies of utilities provisions are also important parameters to be considered. Fossil based energy and fuel production technologies have much higher environmental impacts than renewable based energy technologies and products (Kettl 2011). Consideration of these factors reduces environmental pressure and makes the overall process and products obtained much more environment friendly and greener.

Conclusions

Ecological footprint evaluation of a polymer based on renewables reveal that environmental pressure of a process or product is highly dependent on the available energy systems. Ecological foot print of electricity provision vary widely with Norway, featuring more than 90 % hydro power, coming out with the lowest footprint and France featuring the highest footprint because of its high share of nuclear energy. Fossil and renewable resource based production technologies differ from each other by factors. This has been highlighted by results of life cycle for PE-LD and PHA production using renewable energy sources. Effect of fossil and nuclear based energy systems become worst when applied to highly energy intensive processes e.g. production of tallow and biodiesel in the current study. In the light of evaluations performed, a switch to renewable resource based energy systems would dramatically decrease process impacts for biopolymers. This will make biopolymers even more environmentally efficient compared to fossil competitors when the energy system for heat and electricity becomes “greener”.

Using waste material from other industries as raw material for biopolymer production is attractive in the ecological as well as economic sense. Converting by-products from slaughter houses into raw materials for the biopolymer process like fat and hydrolysate require however energy intensive process steps. Energy integration in the design phase therefore becomes a prerogative for processes utilising low grade bio-resources.

Nomenclature:

AT	Austria
A_R	Area for resources

A_E	Area for energy consumption
A_I	Area for installations
A_S	Area for services
A_D	Area for dissipation
A_{tot}	Total area
$a_{tot} = A_{tot} / N_P$	Total area per service unit
CN	Canada
DE	Germany
DK	Denmark
IT	Italy
FR	France
NO	Norway
PL	Poland
USA	United States of America

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References

Braunegg G, Bona R, Koller M (2004) Sustainable Polymer Production. Polymer Plast Tech Eng 43(6):1779-1974. doi:10.1081/PPT-200040130

Chen (2010) Plastics completely synthesized by bacteria: Polyhydroxyalkanoates, in Chen GQ, Steinbüchel A (2010) (Eds.), Plastics from bacteria. Natural functions and applications, Springer-verlag Berlin Heidelberg, pp 17-38

Chiellini E, Cinelli P, Chiellini F, Imam SH (2004) Environmentally Degradable Bio-Based Polymeric Blends and Composites. Macromolecular Biosciences 4(3):218-231. doi:10.1002/mabi.200300126

Čuček L, Klemeš J J, Kravanja Z (2012) A review of footprint analysis tools for monitoring impacts on sustainabaility. J Cleaner Prod. 34:9-20. doi:10.1016/j.jclepro.2012.02.036

Eurostat (2009) Panorama of energy. Energy statistics to support EU policies and solutions. ISBN 978-92-79-11151-8, ISSN 1831-3256, doi:10.2785/26846, Cat. No. KS-GH-09-001-EN-C

Gwehenberger G, Narodoslawsky M (2007) The ecological impact of the sugar sector- Aspects of the change of a key industrial sector in Europe. Computer Aided Chemical Engineering 24:1029-1034. doi:10.1016/S1570-7946(07)80196-9

Hany R, Bohlen C, Geiger T, Schmid M, Zinn M (2004) Toward non-toxic antifouling: synthesis of hydroxy-, cinnamic acid-, sulfate-, and zosteric acid-labeled poly[3-hydroxyalkanoates]. Biomacromolecules 5:1452-1456. doi:10.1021/bm049962e

International Energy Agency (IEA), World Energy Outlook (2009) Organization for Economic Cooperation and Development. www.iea.org/stats/index.asp: last accesses on: 14.Jan 2013

Kettl K H, Niemetz N, Sandor N, Eder M, Narodoslawsky M (2011) Ecological Impact of Renewable Resource-Based Energy Technologies. Journal of Fundamentals of Renewable Energy and Applications. doi:10.4303/jfrea/R101101

Keshavarz T, Roy I (2010) Polyhydroxyalkanoates: bioplastics with a green agenda. Current Opinion in Microbiology 13(3)321-326. doi:10.1016/j.mib.2010.02.006

Khardenavis A A, Kumar M S, Mudliar S N, Chakrabarti T (2007) Biotechnological conversion of agro-industrial wastewaters into biodegradable plastic, poly–ß-hydroxybutyrate. Bioresource Technology 98:3579-3584. doi:10.1016/j.biortech.2006.11.024

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Koller M, Bona R, Braunegg G, Hermann C, Horvat P, Kroutil M, Martinz J, Neto J, Varila P, Pereira L (2005) Production of Polyhydroxyalkanoates from Agricultural Waste and Surplus Materials. Biomacromolecules 6:561-565. doi:10.1021/bm049478b

Koller M, Atlić A, Dias M, Reiterer A, Braunegg G (2010a) Microbial PHA Production from Waste Raw Materials, in: G.-Q. Chen, A. Steinbüchel (Eds.), Plastics from bacteria. Natural functions and applications. Springer Berlin Heidelberg 14: 85-119. doi:10.1007/978-3-642-03287-5_5

Koller M, Salerno A, Miranda de Sousa D M, Reiterer A, Braunegg G (2010b) Modern biotechnological polymer synthesis: a review, Food Technology and Biotechnology, 48(3):255-269

Koller M, Salerno A, Tuffner P, Koinigg M, Böchzelt H, Schober S, Pieber S, Schnitzer H, Mittelbach M, Braunegg G (2012a) Characteristics and potential of microalgal cultivation strategies. J Cleaner Prod. 37:377-388. doi:10.1016/j.jclepro.2012.07.044

Koller M, Salerno A, Muhr A, Reiterer A, Chiellini E, Casella, S, Horvat P, Braunegg G (2012b) Whey Lactose as a Raw Material for Microbial Production of Biodegradable Polyesters. Polyester.pp 51-92. doi:10.5772/48737

Koller M, Salerno A, Muhr A, Reiterer A, Braunegg G (2013) Polyhydroxyalkanoates: Biodegradable Polymeric Materials from Renewable Resources. Materiali in tehnologije = Mater and technol. 47. doi: 10.1016/j.jbiotec.2013.02.003

Krotscheck C, Narodoslawsky M (1996) The Sustainable Process Index; a new dimension in ecological evaluation. Ecological Engineering 6(4):241-258. doi:10.1016/0925-8574(95)00060-7

Kunasundari B, Sudesh K (2011) Isolation and recovery of microbial Polyhydroxyalkanoates. eXPRESS Polymer Letters 5(7):620–634. doi: 10.3144/expresspolymlett.2011.6d

Narodoslawsky M, Krotscheck C (1995) The Sustainable Process Index (SPI): evaluating processes according to environmental compatibility. J Hazard Mater 41(2-3):383–397. doi:10.1016/0304-3894(94)00114-V

Narodoslawsky M, Krotscheck C (2004) What can we learn from ecological valuation of processes with the sustainable process index (SPI) – the case study of energy production systems. J Cleaner Prod 12:111-115. doi:10.1016/S0959-6526(02)00184-1

OECD, 2002. Glossary of Statistical Terms. [online] available at: stats.oecd.org/glossary/detail.asp?ID=4097. Last accessed 14 Jan 2013.

Patel MK, Bastioli C, Marini L, Wurdinger GE (2005) Life-cycle Assessment of Bio-based Polymers and Natural Fiber Composites Environmental Assessment of Bio-based Polymers and Natural Fibres. Biopolymers online. Willey, Online Library. doi:10.1002/3527600035.bpola014

Pickering MV, Newton P (1990) Amino acid hydrolysis: Old problems, new solutions. Bio.Separations. LC/GC 8(10):778-81

Rees W, Wackernagel M (1996) Urban ecological footprints: why cities cannot be sustainable – and why they are a key to sustainability. Environ Impact Assess Rev 16:223-248

Rupp B, Ebner C, Rossegger E, Slugovc C, Stelzer F, Wiesbrock F (2010)

UV-induced Crosslinking of the Biopolyester Poly(3-hydroxybutyrate)-co-(3-hydroxyvalerate). Green Chem 12:1796-1802. doi:10.1039/C0GC00066C

Sandholzer D, Narodoslawsky M (2007) SPIonExcel-Fast and easy calculation of the Sustainable Process Index via Computer. Resources, Conservation and Recycling 50:130-142. doi:10.1016/j.resconrec.2006.06.012

Shrivastav A, Mishra SK, Shethia B, Pancha I, Jain D, Mishra S (2010) Isolation of promising bacterial strains from soil and marine environment for polyhydroxyalkanoates (PHAs) production utilizing Jatropha biodiesel byproduct. International Journal of Biological Macromolecules. 47(2): 283–287. doi:10.1016/j.ijbiomac.2010.04.007

Solaiman DKY, Ashby RD, Foglia TA, Marmer WN (2006) Conversion of agricultural feedstock and co-products into poly(hydroxyalkanoates). Appl. Microbiol. Biotechnol. 71: 783-789. doi:10.1007/s00253-006-0451-1

Steinbüchel A, Valentin HE (1995) Diversity of bacterial polyhydroxyalkanoic acids. FEMS Microbiology Letters 3:219–228. doi:10.1111/j.1574-6968.1995.tb07528.x

Stoeglehner G, Niemetz N, Kettl KH (2011) Spatial dimensions of sustainable energy systems: new visions for integrated spatial and energy planning. Energy, Sustainability and Society 1:2. doi:10.1186/2192-0567-1-2

Sudesh K, Iwata T (2008) Sustainability of biobased and biodegradable plastics. Clean-Soil, Air, Water 36 (5-6) 433-442. doi: 10.1002/clen.200700183

Titz M, Kettl K-H, Shazhad K, Koller M, Schnitzer H, Narodoslawsky M (2012) Process optimization for efficient biomediated PHA production from animal-based waste streams. Clean. Technol. Environ. Policy 14(3):495-503 doi:10.1007/s10098-012-0464-7

Woodgate S, Van der Veen J (2004) The role of fat processing and rendering in the European Union animal production industry. Biotechnol. Agron. Soc. Environ. 8:283-294

Zinn M, Witholt B, Egli T (2001) Occurrence, synthesis and medical application of bacterial polyhydroxyalkanoate. Adv. Drug Deliv. Rev. 53:5-21. doi:10.1016/S0169-409X(01)00218-6

15 Paper V

SPIonWEB – Ecological process evaluation with the Sustainable Process Index (SPI)

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15.1 Paper contribution

The contribution to the paper includes ecological evaluation of PHA production from animal slaughtering waste utilizing SpionWeb. A basic scenario (PHA_EU27) was executed producing PHA utilising conventional energy resource (electricity EU27 mix and natural gas for process energy). In the next scenario (PHA_biogas_conventional), energy (electricity and process energy) is provided by burning conventional biomethane (produced from 50 % mixture of conventional corn and manure) in the combined heat and power (CHP) unit. In the final scenario (PHA_biogas loop) biomethane produced from biomass (50 % mixture of biological corn silage and manure) cultivated using purified biogas as fuel in the agricultural machinery.

SPIonWEB – Ecological process evaluation with the Sustainable Process Index (SPI)

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Abstract

Chemical engineers however need quick and reliable cradle-to-grave evaluations, conforming to the ISO norm 14040, already at the design stage in order to assess the ecological performance of their design compared to design alternatives as well as to identify ecological hot spots in order to decrease the ecological impact of the process in question.

The Sustainable Process Index methodology has been particularly developed for this purpose and has been widely applied to the measurement of the ecological performance in production systems. Ecological performance is expressed in aggregate form as Ecological Footprint per service unit, thus allowing the engineer to take decisions. De-aggregation into different environmental pressure categories that this methodology allows as well helps the engineer to understand, what causes the engineer to pinpoint the process steps that are critical to the overall performance of the ecological pressure in a certain process step. For the modelling of these problems the software tool SPIonExcel has been in use in the last decade.

SPIonWeb is a web browser based software tool substituting SPIonExcel, which allows to model industrial processes on a thoroughly revised data base and a still more encompassing methodological base. Basic processes like electricity, transport, base chemical production chains are provided in a life cycle based database. Dynamic modelling allows creating process loops which allows simulating changes in the final product ecological performance if sub-process modification are assumed. Besides the Ecological Footprint (calculated with the SPI method) the program also features process visualization, detailed material balance for inputs and emissions, CO_2 and GWP life cycle emissions.

The paper provides examples of ecological process evaluation for different chemical engineering applications, in particular processes providing energy from different renewable sources and bio-chemical processes, e-g. bio-plastic production. Analysing these thoroughly different process

chains will be used to highlight the information that can be gleaned from ecological process evaluation during chemical engineering design.

Keywords: Ecological Footprint, Ecological Performance, Sustainable Process Index on Web, Dynamic Lifecycle Impact Assessment

Introduction

A wide variety of assessments methods are available, depending on the goal and context of the studies (Mayer, 2008). The ultimate need to measure the pressure exerted by humanity on the environment required an appropriate set of indicators. Similarly increased awareness about environmental issues, life cycle impact assessment has become an important issue for access to consumer as well as international market. As a result processes that provide products or service has to be ecologically optimized (Sandholzer and Narodoslawsky, 2007). Life cycle assessment (LCA) is an important assessment method which helps to successful execution of product or process development under environmental sustainability framework. It is an assessment technique which measures environmental performance of a process, product or service unit along its life cycle (Khan et al., 2004), including resources extraction until waste handling (Harst and Potting 2013). In the recent times footprint indicators have become important tools for researchers, consultants and policy makers, in order to assess different aspects of sustainability (Fang et al. 2014). The SPI is a member of the ecological footprint family and is compatible with the procedure of the life cycle analyses described in the EN ISO 14,000. It provides the opportunity to describe the relevant ecological pressures of a process including process chain and product usage and disposal.

Methodology

Sustainable Process Index (SPI)

The Sustainable Process Index (SPI) is a tool for the evaluation of environmental impacts of processes. It was developed by Krotscheck and Narodoslawsky based on the assumption that a sustainable economy builds only on solar radiation as natural income (Krotscheck and Narodoslawsky, 1995). The Sustainable Process Index is calculated by using material and energy flows of a product or service extracted from and dissipated to the ecosphere and compares them to natural flows. The sum of total area A_{tot} i.e. ecological footprint of a process or service, required for sustainable embedding of it into the ecosphere is calculated as:

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \qquad [m^2] \qquad (1)$$

According to equation 1, A_{tot} is the sum of partial areas. A_R, is area required for raw material production. A_E, Area required to provide process energy (heat and electricity). A_I, area required for infrastructure facility or Installations. A_S, area required for staff support and A_P is the area required for sustainable disposal of wastes and emissions to the ecosphere (Gwehenberger and Narodoslawsky, 2007). For technological optimization calculation of impact per unit product, good or service is of importance. It is known as the overall footprint of the product a_{tot} and calculated as:

$$a_{tot} \left(\frac{m^2}{unit}\right) = A_{tot}/NP \qquad (2)$$

NP represents the number of products or services provided by the process under observation for a reference period, which is 1 year in general, practice. This per service unit area itself is a relative sustainability measure. To make it more prominent it is further divide by available area per inhabitant (a_{in}) in the region which is relevant to the process. It is theoretical mean area (per capita) available per inhabitant for goods and energy supply to each person.

$$SPI = \frac{a_{tot}}{a_{in}} \text{ cap/unit} \qquad (3)$$

SPIonWeb is built on basic SPI methodology following sustainability principles. The only difference between SPIonExcel and SPIonWeb methodology is calculation of dissipation emission areas. The dissipation areas for emissions into different compartments were used to sum up in SPIonExcel, while SPIonWeb uses eq. 4 to define the dissipation area for emission flow. The largest area among these partial dissipation areas is identified as key emission area and it is assumed that if area is provided for the key area, loading of impacts in all other replenished compartments will take place safely below natural concentrations.

$$a_p = \max(a_{ew}, a_{es}, a_{ea}) \qquad [m^2] \qquad (4)$$

SPIonWeb is an online web based free software tool, which can be used on any computing device (computer, smartphone or tablet), equipped with a browser regardless of operating system (windows, Linux, Mac, IOS etc.). It helps the user to assess life cycle of a product or service and estimates its SPI footprint, life cycle CO_2 emissions and GWP (global warming potential). It provides the opportunity of making quick scenarios for comparison and evaluation of recycled material (making loops). It's more user friendly and addresses to students, engineers and experts in LCA modelling.

This paper deals with ecological evaluation of PHA production from animal slaughtering waste utilizing SpionWeb. A basic scenario (PHA_EU27) was executed producing PHA utilising conventional energy resource (electricity EU27 mix and natural gas for process energy). In the next scenario (PHA_biogas_conventional), energy (electricity and process energy) is provided by burning conventional biomethane (produced from 50 % mixture of conventional corn and manure) in the combined heat and power (CHP) unit. In the final scenario (PHA_biogas loop) biomethane produced from biomass (50 % mixture of biological corn silage and manure) cultivated using purified biogas as fuel in the agricultural machinery (Kettl and Narodoslawsky, 2013).

Biopolymer Polyhydroxyalkanoate (PHA)

The results discussed in this study are based on the data acquired during ANIMPOL project, it studies production of biopolymers "polyhydroxyalkonates (PHA)", utilising slaughtering waste as starting material. The overall process consists of following sub-process: hydrolysis, rendering, biodiesel production and fermentation process. The process inventory data for 1 Ton (t) PHA production, obtained from different project partners is shown in Table 15.1 (Shahzad et al., 2013).

Table 15.1: Inventory inputs for PHA_EU27_natural gas process

Input	*Unit*	*Inventory*
Ammonium Hydroxide	t	0.0770
Glycerol production	t	0.2370
Inorganic Chemicals	t	0.0060
Iron Sulfate	t	0.0001
Net electricity EU-27, medium voltage	MWh	0.3214
Phosphoric acid (H3PO4)	t	0.0524

Process energy, natural gas, industrial heater > 100 kW	MWh	0.2921
Sodium Chloride	t	0.0002
Sodium Sulfate	t	0.0192
Waste water treatment, average	m^3	8.1178
Biodiesel_EU27	t	1.8588
Nitrogen from hydrolysis_EU27	t	0.0043
Process water (Europe) m3	m^3	8.1178

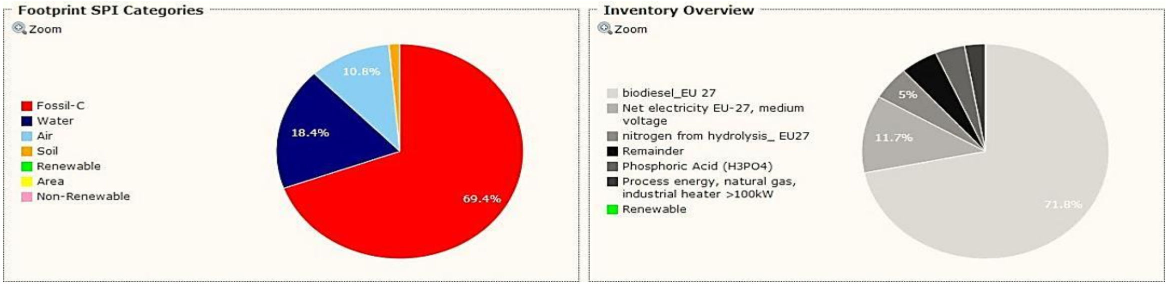


Figure 15.1: Screen snapshot of graphical inventory overview of PHA_EU27_natural gas process

The electricity consumption (Net electricity EU27, medium voltage) includes stirring, transfer of media and downstream processing. The process energy (process energy, natural gas, industrial heater > 100 Kw) consumption constitutes sterilisation of the media and maintenance of media temperature at 37 ˚C (Shahzad et al., 2013).

Figure 15.1 is a snapshot of automatically generated graph, which shows the distribution of foot print in SPI categories and share of different inventory Inputs.

The SPIonWeb also automatically generates process hotspots to figure out optimisation potentials as shown in Figure 15.2. In the current study, optimisation potential are in electricity consumption, biodiesel production, process heat consumption and PHA production (fermentation process). Biodiesel production has shown the highest potential, due to highly energy intensive production from tallow and maximum consumption as a raw material in the fermentation process.

In the light of hotspot results it is decided to evaluate the whole process using renewable energy resources. In PHA_biogas_conventional scenario, energy system is replaced with electricity and heat produced from conventional biogas using combined heat and power (CHP) unit. In PHA_biogas loop scenario, energy provision in the PHA production process is replaced with energy obtained from biogas produced using mixture of 50 % biological corn silage and manure.

In this case biomass is produced using biogas fuelled machinery in agricultural practice (for ploughing, harvesting and transportation), creating a loop of biogas and purified biogas used in the machinery (Kettl and Narodoslawsky, 2013).

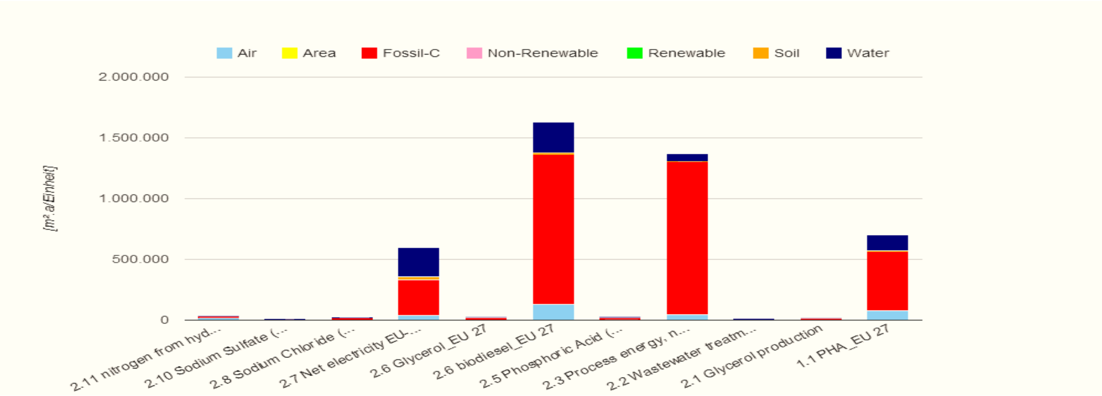


Figure 15.2: Screen shot of SPI hot spot graph for PHA_EU27_natural gas

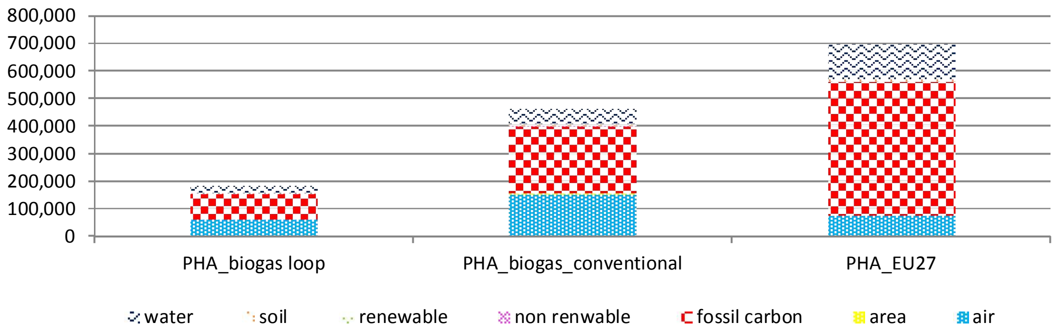


Figure 15.3: Comparison of overall SPI footprint in different scenarios

In the light of hotspot results it is decided to evaluate the whole process using renewable energy resources. In PHA_biogas_conventional scenario, energy system is replaced with electricity and heat produced from conventional biogas using combined heat and power (CHP) unit. In PHA_biogas loop scenario, energy provision in the PHA production process is replaced with energy obtained from biogas produced using mixture of 50 % biological corn silage and manure. In this case biomass is produced using biogas fuelled machinery in agricultural practice (for ploughing, harvesting and transportation), creating a loop of biogas and purified biogas used in the machinery (Kettl and Narodoslawsky, 2013).

Figure 15.3 represents the comparison of SPI footprints for 1 (t) of PHA production in different scenarios based on ANIMPOL process. SPIonWeb also calculates SPI footprint, CO2 life cycle emissions out of fossil carbon category, as well as global warming potential (GWP) as shown in

Table 15.2. PHA_biogas_conventional scenario has 33 % lower ecological pressure than PHA_EU27 (normal industrial practice) production scenario, while PHA_biogas loop scenario has 73 % reduction in ecological pressure. Similarly life cycle CO2 emissions comparison show a maximum reduction of 81 % for PHA_biogas loop scenario and 50 % reduction for PHA_biogas_conventional scenario. The GWP results show similar trend for PHA_EU27 and PHA_biogas loop scenarios while PHA_biogas_conventional have highest GWP. The higher GWP values are related to NO_X (nitrogen oxides) emissions in the agricultral practises. The highest GWP value for PHA_biogas_conventional is due to the usage of diesel fuel in the agricultural machinery input and application of synthetic fertilizers and pesticides in conventional agriculture.

Table 15.2: Comparison of footprint, CO2 emissions and GWP in PHA production processes

Comparison of footprint, CO_2 emissions and GWP			
	Footprint (m^2)	CO_2 emissions (kg)	GWP (kg CO_2 e.)
PHA_EU27	697,769	3,556	63,323
PHA_biogas_conventional	462,269	1,766	101,373
PHA_biogas_biogas loop	184,207	671	61,856

1. Conclusions

SPI provides the opportunity to include ecological assessment in technology selection as well as planning of regional development. It can be computed utilising basic input-output flow (mass and energy balances, prices for installations and raw material) data. It computes clear, understandable and meaningful results which allow comparative analysis of alternative technologies in the process industry and regional optimization. Similarly it is very useful tool for process design, development and optimisation, using early stage ecological assessment for decision making.

References

A. Niederl-Schmidinger, M. Narodoslawsky (2008), Life Cycle Assessment as an engineer's tool? Journal of Cleaner Production 16, 245-252. doi:10.1016/j.jclepro.2006.08.024

A. L. Mayer, (2008), Strengths and weaknesses of common sustainability indices for multidimensional systems, Environment International, 34 (2), 277–29.

D. Sandholzer, M. Narodoslawsky, (2007), SPIonExcel-Fast and easy calculation of the Sustainable Process Index via Computer, J Resources, Conservation and Recycling, 50,130-142.

E. van der Harst and J. Potting (2013), A critical comparison of ten disposable cup LCAs. Environmental Impact Assessment Review 43, 86–96. doi: 10.1016/j.eiar.2013.06.006

G. Gwehenberger, M. Narodoslawsky, B. Liebmann, A. Friedl (2007), Ecology of scale versus economy of scale for bioethanol production, Biofuels, Bioproducts and Biorefining, 1 (4), 264 – 269.

K. Fang, R. Heijungs, G. R. de Snoo (2014), Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: Overview of a footprint family. Ecological Indicators 36, 508–518. doi: 10.1016/j.ecolind.2013.08.017

F.I. Khan, R. Sadiq, B. Veitch (2004), Life cycle iNdeX (LInX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production 12, 59–76.

K.-H. Kettl, M. Narodoslawsky (2013), SPIonWeb – Dynamic Life Cycle Impact Assessment (LCIA) process modelling based on Sustainable Process Index (Ecological Footprint), Journal of Environmental Accounting and Management 1(1), 1-5. doi:10.1016/j.resconrec.2013.02.006.

K. Shahzad, K.-H. Kettl, M. Titz, M. Koller, H. Schnitzer, M. Narodoslawsky (2013), Comparison of ecological footprint for biobased PHA production from animal residues utilizing different energy resources, Clean Techn Environ Policy, doi 10.1007/s10098-013-0608-4

M. Narodoslawsky, C. Krotscheck (1995), The sustainable process index (SPI): evaluating processes according to environmental compatibility. Journal of Hazardous Materials 41(2-3) 383-397.

APPENDIX II

SPI and carbon Footprint supporting data

		Diesel	Biodiesel_co	Biodiesel_EU27	Biodiesel_hydro	Biodiesel_wind	Biodiesel_biom	Biodiesel_biogas	Biodiesel_biomass_el_th
	air	24,535	25,198	21,658	17,160	17,227	18,332	54,526	17933.1224
	area	197	43	47	40	39	39	2,785	17.6394
	fossil C	587,748	264,652	204,476	172,368	172,937	172,309	93,052	24851.6788
	non renewable	4	6	6	5	8	5	575	4.1934
	renewable	19	52	29	18	18	62	23	226.0047
	soil	1,141	968	3,087	829	835	826	2,415	317.7317
	water	72,630	16,681	41,216	14,283	14,401	14,253	19,387	6858.5091
SPI footprint		**686,275**	**307,600**	**270518**	**204,704**	**205,466**	**205,826**	**172763**	**50,209**
Carbon footprint		**4309**	**1940**	**1499**	**1264**	**1268**	**1263**	**682**	**182**

APPENDIX II 1: SPI and carbon footprint results using different energy sources

		PE_LD	PHA_coal	PHA_EU27	PHA_hydro	PHA_wind	PHA_biomass_el	PHA_biogas_el	PHA_biomass_el_th
	air	85,723	92,226	78,515	61,095	61,355	65,632	151,066	64,812
	area	225	102	1,190	92	88	89	6,596	44
	fossil C	840,203	741,596	508,534	384,181	386,384	383,952	242,115	80,848
	non renewable	4	16	1,821	12	26	12	1,362	11
	renewable	34	232	143	103	101	271	115	608
	soil	3,255	2,950	11,158	2,411	2,436	2,400	6,305	1,355
	water	1,223,607	52,633	147,656	43,345	43,801	43,230	57,509	28,030
SPI results		**2,153,050**	**889,755**	**749016**	**491,239**	**494,190**	**495,585**	**465069**	**175,708**
Carbon footprint		**6,160**	**5,438**	**3,729**	**2,817**	**2,833**	**2,816**	**1,775**	**593**

APPENDIX II 2: SPI and carbon footprint results for PHA production

APPENDIX II 3: GWPs relative to CO2. For ozone-depleting substances and their replacements (copied from IPCC[9])

Industrial Designation or Common Name	Chemical Formula	GWP at 100 years' time horizon (100-yr)
Carbon dioxide	CO_2	*1*
Methane	CH_4	*25*
Nitrous oxide	N_2O	*298*
CFC-11	CCl_3F	*4,750*
CFC-12	CCl_2F_2	*10,900*
CFC-13	$CClF_3$	*14,400*
CFC-113	CCl_2FCClF_2	*6,130*
CFC-114	$CClF_2CClF_2$	*10,000*
CFC-115	$CClF_2CF_3$	*7,370*
Halon-1301	$CBrF_3$	*7,140*
Halon-1211	$CBrClF_2$	*1,890*
Halon-2402	$CBrF_2CBrF_2$	*1,640*
Carbon tetrachloride	CCl_4	*1,400*
Methyl bromide	CH_3Br	*5*
Methyl chloroform	CH_3CCl_3	*146*
HCFC-22	$CHClF_2$	*1,810*
HCFC-123	$CHCl_2CF_3$	*77*
HCFC-124	$CHClFCF_3$	*609*
HCFC-141b	CH_3CCl_2F	*725*
HCFC-142b	CH_3CClF_2	*2,310*
HCFC-225ca	$CHCl_2CF_2CF_3$	*122*
HCFC-225cb	$CHClFCF_2CClF_2$	*595*
HFC-23	CHF_3	*14,800*
HFC-32	CH_2F_2	*675*
HFC-125	CHF_2CF_3	*3,500*
HFC-134a	CH_2FCF_3	*1,430*
HFC-143a	CH_3CF_3	*4,470*
HFC-152a	CH_3CHF_2	*124*
HFC-227ea	CF_3CHFCF_3	*3,220*
HFC-236fa	$CF_3CH_2CF_3$	*9,810*
HFC-245fa	$CHF_2CH_2CF_3$	*1030*
HFC-365mfc	$CH_3CF_2CH_2CF_3$	*794*
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	*1,640*

9 Available at: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html#table-2-14

Sulphur hexafluoride	SF_6	*22,800*
Nitrogen trifluoride	NF_3	*17,200*
PFC-14	CF_4	*7,390*
PFC-116	C_2F_6	*12,200*
Perfluorinated compounds (continued)		
PFC-218		*8,830*
PFC-318		*10,300*
PFC-3-1-10		*8,860*
PFC-4-1-12		*9,160*
PFC-5-1-14		*9,300*
PFC-9-1-18		*>7,500*
trifluoromethyl sulphur pentafluoride		*17,700*
Fluorinated ethers		
HFE-125		*14,900*
HFE-134		*6,320*
HFE-143a		*756*
HCFE-235da2		*350*
HFE-245cb2		*708*
HFE-245fa2		*659*
HFE-254cb2		*359*
HFE-347mcc3		*575*
HFE-347pcf2		*580*
HFE-356pcc3		*110*
HFE-449sl (HFE-7100)		*297*
HFE-569sf2 (HFE-7200)		*59*
HFE-43-10pccc124 (H-Galden 1040x)		*1,870*
HFE-236ca12 (HG-10)		*2,800*
HFE-338pcc13 (HG-01)		*1,500*
Perfluoropolyethers		
PFPMIE		*10,300*
Hydrocarbons and other compounds – Direct Effects		
Dimethylether		*1*
Methylene chloride		*8.7*
Methyl chloride		*13*

16 APPENDIX III

Supporting data for Emergy Evaluation

APPENDIX II 4: Emergy indicator calculations for transportation with and without labor and services

Indicators	***Slaughtering residues***	
Emergy demand for environmental support	With L & S	Without L & S
Specific emergy (seJ/g)	7.32E+07	4.89E+07
Transformity (seJ/J)	-	-
Emergy money ratio (seJ/€)	-	-
EYR= U/(F+L+S)	1.00	1.00
ELR= (F+L+S)/R	78.12	40.17
ESI= EYR/ELR	0.01	0.02
% Renewable = 1/(1+ELR) or =R/U*100	1.26%	2.43%

APPENDIX II 5: Emergy indicator calculations for rendering I with and without labor and services

Indicators	***Heat from rendering I***	
Emergy demand for environmental support	With L & S	Without L & S
Specific emergy (seJ/g)	-	-
Transformity (seJ/J)	1.25E+05	1.22E+05
Emergy money ratio (seJ/€)	-	-
EYR= U/(F+L+S)	1.00	1.00
ELR= (F+L+S)/R	12.54	12.25
ESI= EYR/ELR	0.080	0.082
% Renewable = 1/(1+ELR) or =R/U*100	7.39%	7.55%

APPENDIX II 6: Emergy indicator calculations for rendering I with and without labor and services

Indicators	***Tallow***		***Meat and Bone Meal***	
Emergy demand for environmental support	With L & S	Without L & S	With L & S	Without L & S
Specific emergy (seJ/g)	2.64E+09	2.57E+09	2.64E+09	2.57E+09
Transformity (seJ/J)	1.09E+05	1.06E+05	1.09E+05	1.06E+05
Emergy money ratio (seJ/€)	5.08E+12	4.95E+12	5.08E+12	4.95E+12
EYR= U/(F+L+S)	1.00	1.00	1.00	1.00
ELR= (F+L+S)/R	12.58	12.29	12.58	12.29
ESI= EYR/ELR	0.08	0.08	0.08	0.08
% Renewable = 1/(1+ELR) or =R/U*100	7.36%	7.52%	7.36%	7.52%

APPENDIX II 7: Emergy indicator calculations for biodiesel production with and without labor and services

Indicators	**Biodiesel**		**Glycerol**	
Emergy demand for environmental support	With L & S	Without L & S	With L & S	Without L & S
Specific emergy (seJ/g)	2.96E+09	2.89E+09	2.96E+09	2.89E+09
Transformity (seJ/J)	8.27E+04	8.06E+04	8.27E+04	8.06E+04
Emergy money ratio (seJ/€)	3.18E+12	3.10E+12	3.18E+12	3.10E+12
EYR= U/(F+L+S)	1.00	1.00	1.00	1.00
ELR= (F+L+S)/R	13.87	13.54	13.87	13.54
ESI= EYR/ELR	0.07	0.07	0.07	0.07
% Renewable = 1/(1+ELR) or =R/U*100	6.73%	6.88%	6.73%	6.88%

APPENDIX II 8: Emergy indicator calculations for hydrolysis with and without labor and services

Indicators	**Hydrolysate**	
Emergy demand for environmental support	With L & S	Without L & S
Specific emergy (seJ/g)	6.80E+08	6.00E+08
Transformity (seJ/J)	-	-
Emergy money ratio (seJ/€)	6.09E+12	5.38E+12
EYR= U/(F+L+S)	1.0000	1.0000
ELR= (F+L+S)/R	52.8887	46.9565
ESI= EYR/ELR	0.0189	0.0213
% Renewable = 1/(1+ELR) or =R/U*100	1.86%	2.09%

APPENDIX II 9: Emergy indicator calculations for fermentation process with and without labor and services

Indicators	**PHA production**	
Emergy demand for environmental support	With L & S	Without L & S
Specific emergy (seJ/g)	2.81E+10	7.34E+09
Transformity (seJ/J)	5.11E+05	1.33E+05
Emergy money ratio (seJ/€)	6.91E+12	1.80E+12
EYR= U/(F+L+S)	1.00	1.00
ELR= (F+L+S)/R	17.39	4.71
ESI= EYR/ELR	0.06	0.21
% Renewable = 1/(1+ELR) or =R/U*100	5.44%	17.50%

APPENDIX II 10: Emergy-base indicators calculated for ANIMPOL biobased PHA production using facility area as system boundary

Emergy Accounting	Value	Unit
Transportation Phase		
Emergy from local renewable resources, R	4.34E+14	seJ/yr
Emergy from imported resources, F	1.19E+19	seJ/yr
Total emergy, U = R + F + L + S	1.78E+19	seJ/yr

Emergy intensity	7.32E+07	seJ/$g_{animal\ residues}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	40956.33	
Emergy Sustainability Index, EYR/ELR	0.00002	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	0.0024%	
Rendering I		
Emergy from local renewable resources, R	4.34E+14	seJ/yr
Emergy from imported resources, F	4.82E+18	seJ/yr
Total emergy, U = R + F + L + S	4.94E+18	seJ/yr
Transformity of heat	1.21E+05	seJ/J_{Heat}
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	11382.85	
Emergy Sustainability Index, EYR/ELR	0.000002	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	0.0088%	
Rendering II		
Emergy from local renewable resources, R	4.34E+14	seJ/yr
Emergy from imported resources, F	2.39E+20	seJ/yr
Total emergy, U = R + F + L + S	2.45E+20	seJ/yr
Emergy intensity	2.56E+09	seJ/$g_{(tallow,\ MBM)}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	235228.24	
Emergy Sustainability Index, EYR/ELR	0.000002	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	0.00018%	
Biodiesel Production		
Emergy from local renewable resources, R	4.34E+14	seJ/yr
Emergy from imported resources, F	9.95E+19	seJ/yr
Total emergy, U = R + F + L + S	1.021E+20	seJ/yr
Emergy intensity	2.86E+09	seJ/$g_{(biodiesel,\ glycerol)}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	235228.24	
Emergy Sustainability Index, EYR/ELR	0.0000043	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	0.00043%	
Hydrolysis		
Emergy from local renewable resources, R	4.34E+14	seJ/yr
Emergy from imported resources, F	2.18E+18	seJ/yr
Total emergy, U = R + F + L + S	2.47E+18	seJ/yr
Emergy intensity of hydrolysate	6.74E+08	seJ/$g_{(hydrolysate)}$
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	5695.91	
Emergy Sustainability Index, EYR/ELR	0.00018	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	0.018%	
Fermentation (PHA production) process		

Emergy from local renewable resources, R	4.34E+14	seJ/yr
Emergy from imported resources, F	6.58E+19	seJ/yr
Total emergy, U = R + F + L + S	2.80E+20	seJ/yr
Emergy intensity of PHA	2.80E+10	seJ/g_{PHA}
Environmental yield ratio, EYR = U/(F+L+S)	1.00	
Environmental Loading Ratio, (ELR) = (F + L + S)/R	645481.24	
Emergy Sustainability Index, EYR/ELR	0.0000015	
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	0.00015%	

APPENDIX II 11: comparison of emergy flows and emergy based indicators for Biodiesel production

Indicators	EU_27	Coal	Biogas	Hydro	Biomass	Biomass_El_Th	Wind
Emergy from local renewable resources, R	7.62E+18	7.18E+18	7.88E+18	8.17E+18	7.44E+18	5.06E+18	8.92E+18
Emergy from imported resources, F	1.03E+20	1.04E+20	9.95E+19	9.90E+19	9.95E+19	2.98E+19	9.95E+19
Total emergy, U = R + F + L + S	1.06E+20	1.06E+20	1.02E+20	1.02E+20	1.02E+20	3.24E+19	1.02E+20
Emergy intensity	2.96E+09	2.97E+09	2.86E+09	2.84E+09	2.86E+09	9.06E+08	2.86E+09
Environmental yield ratio, EYR = U/(F+L+S)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Environmental Loading Ratio, (ELR) = (F + L + S)/R	13.87	14.77	12.94	12.42	13.71	6.37	11.43
Emergy Sustainability Index, EYR/ELR	0.072	0.068	0.077	0.081	0.073	0.157	0.087
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	6.73%	6.34%	7.17%	7.45%	6.80%	13.56%	8.05%
Percentage deviations:							
Emergy intensity		-0.39%	3.50%	3.95%	3.50%	69.40%	3.50%
ELR		-6.51%	6.68%	10.45%	1.17%	54.03%	17.58%
ESI = EYR/ELR		-6.51%	6.68%	10.45%	1.17%	54.03%	17.58%
% Renewable fraction		-6.08%	6.23%	9.75%	1.09%	50.40%	16.40%

Reference: Brown and Ulgiati 2002

APPENDIX II 12: comparison of emergy flows and emergy based indicators for PHA production

Indicators	EU_27	Coal	Biogas	Hydro	Biomass	Biomass_El_Th	Wind
Emergy from local renewable resources, R	1.59E+19	1.53E+19	1.62E+19	1.66E+19	1.57E+19	1.38E+19	1.76E+19
Emergy from imported resources, F	7.34E+19	7.39E+19	6.87E+19	6.81E+19	6.87E+19	2.49E+19	6.87E+19
Total emergy, U = R + F + L + S	2.88E+20	2.88E+20	2.83E+20	2.83E+20	2.83E+20	2.39E+20	2.83E+20
Emergy intensity	2.88E+10	2.88E+10	2.83E+10	2.83E+10	2.83E+10	2.39E+10	2.83E+10
Environmental yield ratio, EYR = U/(F+L+S)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Environmental Loading Ratio, (ELR) = (F + L + S)/R	17.43	18.11	16.78	16.37	17.38	16.55	15.51
Emergy Sustainability Index, EYR/ELR	0.057	0.055	0.060	0.061	0.058	0.060	0.064
Renewable fraction, REN% = 1/(1+ELR) or =R/U*100	5.43%	5.23%	5.62%	5.76%	5.44%	5.70%	6.06%
Percentage deviation:							
Emergy intensity		-0.18%	1.64%	1.85%	1.64%	16.84%	1.64%
ELR		-3.89%	3.70%	6.08%	0.27%	5.05%	11.00%
ESI = EYR/ELR		-3.89%	3.70%	6.08%	0.27%	5.05%	11.00%
% Renewable fraction		-3.68%	3.50%	5.75%	0.25%	4.78%	10.40%

Reference: Brown and Ulgiati 2002

Basis Calculations for emergy analysis

All data refer to Chemical plant build in Austria for PHA production utilizing slaughtering waste as the starting material.

Total Area used=	1.00E+00	ha/yr	References
	1.00E+04	m^2	[a]

Renewable Input (locally available)

1 Sun insolation

Solar energy received = (avg. Insolation, J/m2/yr)(area, m2)= 4.63E+13 J/yr

Albedo 0.20

Solar energy received =	3.70E+13	J/yr	

2 Wind

Wind energy = (air density, kg/m^3)*(drag coeff.)*(geostrophic wind velocity, $m/s)^3$*(area, m^2)*(sec/year)=

Air density =	1.3	kg/m^3	
Wind velocity (average 2005) =	3.85	m/s	[b]
Geostrophic wind =	5.2	m/s	
Drag coeff.	3.00E-03		
Time frame	3.15E+07		
Wind energy on land	1.73E+11	J/yr	

3 Rainfall

Rain (average temperate areas)	1.09	m/yr	[c]
Water density	1.00E+06	g/m^3	

Mass of rainfall water	1.09E+10	g/yr	
Fraction of water that is evapotranspired	0.50		
Evapotranspired rain water	0.55	m/yr	
Mass of evapotranspired water	5.45E+09	g/yr	

Free energy of water= (evapotranspired water, g/ha/yr)*(Gibbs free energy per gram of water, J/g)

Gibbs free energy of water	4.94	J/g	[d]
Energy of evapotranspired rain water	2.69E+10	J/yr	

Indirect Environmental inputs

Assumption:

1. It is assumed that plant is situated near a river or lake and almost 100 water input is renewable.

Fresh water input	1.44E+11	g/yr
Gibbs free energy of water	4.94	J/g
Energy of fresh water	7.13E+11	J/yr

2. As electricity mix for Austria have about 65 % hydroelectricity share so roughly 10 % share of electricity is contributed by the renewable energy.

Total Electricity input	7.96E+13	J/yr
Renewable share	7.96E+12	J/yr

3. It is assumed labor input induces about 5% renewable energy share to the system.

Nonrenewable Input (locally available)

Imported Input

Transportation phase

	Truck transport			
	Steel for transport			
4	**Animal Waste**	2.43E+05	t/yr	[e]
5	**Diesel for transport**			
	Diesel	1.46E+06	kg/yr	[f]
	density	8.21E-01	kg/L	
	Diesel	1.20E+06	L/yr	
		1.46E+09	g/yr	
	High Heat Value	4.48E+01	MJ/kg	[g]
		4.48E+04	J/g	
	Diesel energy	6.56E+13	J/yr	
	Diesel price	1.45E+00	€/L	[h]
	Annual economic value	1.74E+06	€/yr	
6	**Labor**			

Assumption: It is assumed that animal slaughtering waste is collected over an area 75 Km radius. So considering the outer boundary of the system, one trip of waste collection requires 150 km of transportation.

Loading, downloading and cleaning of the truck take about 30 minutes i.e.. 0.5 h

Traveling time per trip	3	h	
Total time for one trip	3.5	h	
Average loading of heavy truck	2.00E+01	t/trip	[i]
Number of trips	1.21E+04	trip/yr	

	Distance per trip	1.50E+02	km/trip	
	Total transportation time	4.25E+04	h/yr	
		1.82E+06	km/yr	
	Normal working hours	8	h/day	
	Average working hours per person in Austria	1600	h/yr	[j]
	Number of person per year	2.66E+01	persons	
	Working years	2.66E+01	person/yr	
	Average salary	29143.75	€/yr	[j]
	Total cost of Labor	7.74E+05	€/yr	
	Services			
	Total services measured by economic cost of inputs	**1.74E+06**	**€/yr**	
7	**Output**			
	Slaughtering residues	2.43E+05	t/yr	
		2.43E+11	g/yr	
Rendering 1				
8	**Slaughtering residues**	4.87E+03	t/yr	
		4.87E+09	g/yr	
9	**Electricity**	2.97E+05	kWh/yr	[e]
		1.07E+12	J/yr	
	Price	1.02E-01	€/kwh	[k]
	Electricity cost	1.77E+05	€/yr	
10	**Heat (natural gas)**	1.61E+07	MJ/yr	

		4.48E+06	kWh/yr	[l]
		1.61E+13	J/yr	
	Price	3.95E-02	€/kWh	
	Economic cost for heating	1.77E+06	€/yr	
11	**Fresh water** (assumed from natural reservoir or collected rain)			
	Water used	1.27E+03	m^3/yr	
	Density of water	1	kg/l	
	Mass of water used	1.27E+06	kg/yr	[e]
		1.27E+09	g/yr	
	Gibbs free energy of water	4.94	J/g	[d]
	Total energy in fresh water	6.25E+09	J/yr	
	Water price	1.72E+00	€/m^3	[m]
	Water cost	2.17E+03	€/yr	
12	**Waste water Treatment**			
	Waste water	2.90E+03	m^3/yr	
	Density of water	1	kg/l	
	Mass of water used	2.90E+06	kg/yr	[e]
		2.90E+09	g/yr	
	Electricity consumption for waste water treatment	0.222	kwh/m^3	[n]
		7.99E-01	J/g	
		2.31E+09	J/yr	
	Price	4.87E-03	€/m^3	[o]

Water total cost	1.41E+01	€/yr	

13 Labor

Assumption: It is assumed that rendering facility processes 100,000 t/yr and it operates 250 days per year.

Rendering facility operation capacity	1.00E+05	t/yr	
Facility operation days	2.50E+02	days/yr	
Waste processes per day	4.00E+02	t/day	
Waste processed per hour	1.48E+01	t/hr	
Waste input for rendering I	4.87E+03	t/yr	
Processing time	3.28E+02	hrs/yr	
Average working hours per person	1.60E+03	hr/yr	
Working years	2.05E-01	person/yr	
Average salary	2.91E+04	€/yr	[j]
Total cost of Labor	5.98E+03	€/yr	

Services

Total services measured by economic cost of inputs	**2.09E+05**	**€/yr**	
Service share from slaughtering residue transportation	**3.49E+04**	**€/yr**	

14 OUTPUT

Heat from rendering I products burning	1.13E+07	kWh /yr	
Energy content of heat	4.07E+13	J/yr	
Equivalent to natural gas	2.57E+15	m^3/yr	[k]

	HHV	2.13E+04	Btu/lb	
		4.99E+04	J/g	
		8.16E+08	g/yr	
	Price of natural gas	3.95E-02	€/kWh	
	Economic value	4.47E+05	€/yr	

<u>Rendering II</u>

15	**Slaughtering residues**	2.36E+05	t/yr	
		2.36E+11	g/yr	
16	**Electricity**	1.44E+07	kWh/yr	[e]
		5.19E+13	J/yr	
	Price	1.02E-01	€/kwh	[k]
	Electricity cost	1.46E+06	€/yr	
17	**Heat (Natural Gas)**	7.83E+08	MJ/yr	
		2.18E+08	kWh/yr	[l]
		7.83E+14	J/yr	
	Price	3.95E-02	€/kWh	[k]
	Economic cost of heating	8.59E+06	€/yr	
19	**Fresh water (assumed from natural reservoir or collected rain)**			
	Water used	6.15E+04	m^3	
	Density of water	1	kg/l	
	Mass of water used	6.15E+07	kg/yr	[e]
		6.15E+10	g/yr	

Gibbs free energy of water	4.94	J/g	[d]
Total energy in fresh water	3.04E+11	J/yr	
Price	1.72E+00	€/m³	[m]
Water total cost	1.05E+05	€/yr	

20 Waste water Treatment

Waste water	5.96E-01	t/yr	
Density of water	1	kg/l	
Mass of water	5.96E+02	kg/yr	[e]
	5.96E+05	g/yr	
Electricity consumption for waste water treatment	0.222	kWh/m³	[n]
	7.99E-01	J/g	
	4.76E+05	J/yr	
Price	4.87E-06	€/kg	[o]
Water total cost	2.90E-03	€/yr	

21 Labor

Assumption: It is assumed that rendering facility processes 100,000 t/yr and it operates 250 days per year.

Rendering facility operation capacity	1.00E+05	t/yr
Facility operation days	2.50E+02	days/yr
Waste processes per day	4.00E+02	t/day
Waste processed per hour	1.48E+01	t/h

Waste input for rendering II	2.36E+05	t/yr	
Processing time	1.60E+04	h/yr	
Average working hours per person	1.60E+03	h/yr	
Working years	9.97E+00	person/yr	
Average salary	2.91E+04	€/yr	[j]
Total cost of Labor	2.91E+05	€/yr	
Services			
Total services measured by economic cost of inputs	1.02E+07	**€/yr**	
Service share from slaughtering residue transportation	**1.70E+06**	**€/yr**	
Service share from rendering I	**2.44E+05**	**€/yr**	

22 Products

Tallow			
Mass of Tallow	3.31E+04	t/yr	
	3.31E+10	g/yr	
Energy content of tallow	3.56E+04	J/g	[p]
	1.18E+15	J/yr	
Economic value of Tallow	6.5E+2	€/t	
Annual economic value	2.15E+07	€/yr	
Meat and Bone Meal (MBM)			
Mass of MBM	6.26E+04	t/yr	
	6.26E+10	g/yr	
Energy content of MBM	1.83E+04	J/g	[p]

		1.15E+15	J/yr	
	Economic value of MBM	4.5E+02	€/t	
	Total economic income of MBM	2.82E+07	€/yr	
	Mass Allocation			
	Total mass production	9.57E+10	g/yr	
	Tallow	35%		
	MBM	65%		
	Energy content Allocation			
	Total energy content	2.33E+15	J/yr	
	Tallow	51%		
	MBM	49%		
	Economic Allocation			
	Total economic value	4.97E+07	€/yr	
	Tallow	43.28%		
	MBM	56.72%		
Biodiesel production				
23	**Tallow**	3.31E+04	t/yr	
		3.31E+10	g/yr	
24	**Electricity**	2.35E+06	kWh/yr	[e]
		8.46E+12	J/yr	
	Price	1.02E-01	€/kwh	[k]
	Electricity cost	2.38E+05	€/yr	

25	**Heat (natural Gas)**	1.32E+07	kWh/yr	
		4.77E+13	J/yr	
	Price	3.95E-02	€/kWh	[k]
	Natural gas cost	5.23E+05	€/yr	
26	**Methanol CH_3OH**			
	CH_3OH	3.61E+03	t/yr	[e]
		3.61E+09	g/yr	
	Price	1.90E+02	€/t	[q]
	CH_3OH cost	6.85E+05	€/yr	
27	**Acid (Sulfuric Acid) H_2SO_4**			
	H_2SO_4	4.63E+02	t/yr	[e]
		4.63E+08	g/yr	
	Price	1.00E+02	€/t	[r]
	H_2SO_4 cost	4.63E+04	€/yr	
28	**Potassium Hydroxide (KOH)**			
	KOH	5.96E-01	t/yr	
		5.96E+05	g/yr	
	Price	4.94E+02	€/t	
	KOH cost	2.94E+02	€/yr	
29	**Fresh water (assumed from natural reservoir or collected rain)**			
	Water used	3.31E+03	m^3/yr	
	Density of water	1	kg/l	

Mass of water used	3.31E+06	kg/yr	[e]
	3.31E+09	g/yr	
Gibbs free energy of water	4.94	J/g	[d]
Total energy in fresh water	1.63E+10	J/yr	
Price	1.72E+00	€/kg	[m]
Water total cost	5.68E+03	€/yr	

30 Waste water Treatment

Waste water	3.31E+03	m^3/yr	
Density of water	1	kg/l	
Mass of water	3.31E+06	kg/yr	[e]
	3.31E+09	g/yr	
Electricity consumption for waste water treatment	0.222	kWh/m^3	[n]
	7.99E-01	J/g	
	2.64E+09	J/yr	
Price	4.87E-03	€/m^3	[o]
Water total cost	1.61E+01	€/yr	

31 Labor

Assumption: It is assumed that Biodiesel production facility has a production capacity of 100,000 t/yr and it operates 250 days per year.

Facility operation capacity	1.00E+05	t/yr
Facility operation days	2.50E+02	days/yr

Biodiesel production per day	4.00E+02	t/day	
Biodiesel production per hour	1.67E+01	t/hr	
Biodiesel production	3.24E+04	t/yr	
Processing time	1.95E+03	h/yr	
Average working hours per person	1.60E+03	h/yr	
Working years	1.22E+00	person/yr	
Average salary	2.91E+04	€/yr	
Total cost of Labor	3.54E+04	€/yr	
Services			
Total services measured by economic cost of inputs	**1.79E+06**	**€/yr**	
Service share from Rendering II for Tallow	5.24E+06	€/yr	

32 OUTPUT

Biodiesel			
Mass of Biodiesel	3.24E+04	t/yr	
	3.24E+10	g/yr	
Biodiesel (saturated Hydrocarbons)	1.46E+10	g/yr	
Biodiesel (unsaturated Hydrocarbons)	1.78E+10	g/yr	
Energy content of Biodiesel (LHV)	3.75E+04	J/g	[s]
	1.22E+15	J/yr	
Economic value of Biodiesel	9.7E+02	€/t	
Total economic price	3.15E+07	€/yr	
Glycerol			

	Mass of Glycerol	3.31E+03	t/yr	
		3.31E+09	g/yr	
	Energy content of Glycerol	1.90E+04	J/g	[t]
		6.29E+13	J/yr	
	Economic value of Glycerol	5.4E+02	€/t	
	Total economic income of Glycerol	1.79E+06	€/yr	
	Mass Allocation			
	Total mass	3.57E+10	g/yr	
	Biodiesel	91%		
	Glycerol	9%		
	Allocation using energy content			
	Total energy content	1.28E+15	J/yr	
	Biodiesel	95%		
	Glycerol	5%		
	Economic Allocation			
	Total economic value	3.32E+07	€/yr	
	Biodiesel	94.62%		
	Glycerol	5.38%		
<u>Hydrolysis</u>				
33	**Slaughtering residues**	1.73E+03	t/yr	
		1.73E+09	g/yr	
34	**Electricity**	4.16E+04	kWh/yr	[e]

		1.50E+11	J/yr	
	Price	1.02E-01	€/kwh	[k]
	Electricity cost	4.23E+03	€/yr	
35	**Heat (natural gas)**	3.09E+05	kWh/yr	
	kWh	2.78E-01	MJ	
		1.11E+12	J/yr	
	Price	3.95E-01	€/kWh	[k]
	Natural gas cost	1.22E+04	€/yr	
36	**Hydrochloric acid (HCl)**			
	HCl	2.04E+03	t/yr	[e]
		2.04E+09	g/yr	
	Price	7.00E+01	€/t	
	HCl cost	1.43E+05	€/yr	
37	**Sodium Hydroxide (NaOH)**			
	NaOH	7.36E+02	t/yr	[e]
		7.36E+08	g/yr	
	Price	3.39E+02	€/t	[q]
	NaOH cost	2.49E+05	€/yr	
38	**Fresh water (assumed from natural reservoir or collected rain)**			
	Water used	6.93E+02	m^3/yr	
	Density of water	1	kg/l	
	Mass of water used	6.93E+05	kg/yr	

	6.93E+08	g/yr	
Gibbs free energy of water	4.94	J/g	[d]
Total energy in fresh water	3.42E+09	J/yr	
Price =	1.72E+00	€/m³	[j]
Water total cost	1.19E+03	€/yr	

39 Labor

Assumption: There are 150 PHA production batches per year. The production of hydrolysate per batch requires about 8 hours including chopping, hydrolysis, acid reclamation and sieving.

No. of batch	1.5E+02	batch /year	
Labor time per batch	8	hrs/batch	
Total Labor time	1.2E+3	hrs/yr	
Average working hours in Austria	1.6E+3	hrs/yr	[j]
Working years	7.50E-01	person/year	
Average salary	2.91E+04	€/yr	[j]
Total Labor cost	2.19E+04	€/yr	
Services			
Total services measured by economic cost of inputs	**4.10E+05**	**€/yr**	
Service share from slaughtering residue transportation	**1.24E+04**	**€/yr**	

40 Output

Hydrolysate

Amount of hydrolysate	3.67E+03	t/yr	[e]

		3.67E+09	g/yr	
	Economic value of hydrolysate	1.12E+02	€/t	
	Economic value of Hydrolysate	4.09E+05	€/yr	
Fermentation (PHA production)				
41	**Electricity**	5.02E+06	kWh/yr	
		1.81E+13	J/yr	
	Price	1.02E-01	€/kwh	[k]
	Electricity cost	5.09E+05	€/yr	
42	**Heat consumption**	2.92E+06	kWh/yr	
	Natural gas	1.05E+13	J/yr	
	Price	3.95E-02	€/kWh	[k]
	Natural gas cost	1.15E+05	€/yr	
43	**Glycerol**			
	Glycerol	3.31E+03	t/yr	[e]
		3.31E+09	g/yr	
	Price	5.40E+02	€/t	[q]
	Glycerol cost	1.79E+06	€/yr	
44	**Biodiesel (LQ)**			
	Biodiesel	1.78E+04	t/yr	[e]
		1.78E+10	g/yr	
	Price	9.70E+02	€/t	
	Biodiesel cost	1.73E+07	€/yr	

45	**Hydrolysate**			
	hydrolysate	3.67E+03	t/yr	[e]
		3.67E+09	g/yr	
	Price	1.12E+02	€/t	[q]
	Nitrogen Cost	4.09E+05	€/yr	
46	**Ammonium Hydroxide (NH4OH)**			
	NH_4OH	7.67E+02	t/yr	
		7.67E+08	g/yr	
	Price	3.39E+02	€/t	[q]
	NH_4OH cost	2.60E+05	€/yr	
47	**Chemicals**			
	Chemicals	7.82E+02	t/yr	
		7.82E+08	g/yr	
	Chemicals price	7.76E+05	€/yr	
	Chemicals cost	6.07E+08	€/yr	
48	**Fresh water (assumed from natural reservoir or collected rain)**			
	water used	8.43E+04	m^3/yr	
	Density of water	1	kg/l	
	Mass of water used	8.43E+07	kg/yr	[e]
		8.43E+10	g/yr	
	Gibbs free energy of water	4.94	J/g	[d]
	Total energy in fresh water	4.17E+11	J/yr	

Price	1.72E+00	€/t	[m]
Water total cost	1.45E+05	€/yr	

49 **Waste water Treatment**

Waste water	8.43E+04	m^3/yr	
Density of water	1	kg/l	
Mass of water	8.43E+07	kg/yr	[e]
	8.43E+10	g/yr	
Electricity consumption for waste water treatment	0.222	kwh/m^3	[n]
	7.99E-01	J/g	
	6.74E+10	J/yr	
Waste water treatment cost	4.87E-03	€/m^3	[o]
Water treatment total cost	4.11E+02	€/yr	

50 **Labor**

Assumption: There are 150 production batches and each batch needs roughly 55 h including fermentation and downstream processing.

Time needed for 1 batch	5.50E+01	h	
Batch	1.50E+02	batch/yr	
Working hours	8.25E+03	h/yr	
Average working hours in Austria	1.60E+03	h/yr	[j]
Working years	5.16E+00	person/yr	
Average salary	29143.75	€/yr	[j]
Total cost of Labor	1.50E+05	€/yr	

Services

Total services measured by economic cost of inputs	6.27E+08	€/yr	
Services share for Hydrolysate production	4.22E+05	€/yr	
Services share from Biodiesel Production for Biodiesel input	3.66E+06	€/yr	
Service share from Biodiesel Production for Glycerol input	3.78E+05	€/yr	

51 **Products**

PHA

Mass of PHA	1.00E+04	t/yr	
	1.00E+10	g/yr	
Energy content of PHA	5.50E+04	J/g	[u]
	5.50E+14	J/yr	
Economic value of PHA	4.07E+03	€/t	
Total economic price	4.07E+07	€/yr	

References:

[a] Own assumption for the plant size

[b] http://weatherspark.com/history/32356/2014/Vienna-Niederosterreich-Austria

[c] http://www.icpdr.org/main/danube-basin/austria

[d] [Odum, 1996]

[e] own calculations based on the data provided by the partners

[f] own calculations after Frischknecht and Jungbluth (2004)

[g] [Demirel, 2012]

[h] www.theaa.com , fuel price on 22nd April 2012

[i] own assumption 75 km radius.

[j] http://money.oe24.at/Service/Gehaltscheck-So-viel-verdient-Oesterreich/785437

[k] http://www.energy.eu/ (2012)

[l] http://www.unitconversion.org/

[m] http://www.holding-graz.at/wasserwirtschaft/gebuehrenentgelte-preise/wasserpreise.html

[n] Eco invent data 2010.

[o] Economic and social commission for western asia, 2003, Waste water treatment Technologies: A General review, United Nations, 2003.

[p] Denafas G. Et al. 2004.

[q] [average value from www.icispricing.com]

[r] http://ed.icheme.org/costchem.html

[s] GREET. 2010

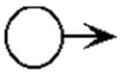
[t] http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

[u] Michael F. et al: 2013

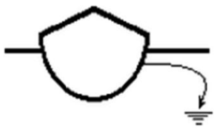
Energy system symbols (Odum, 1996)

<u>Use of Energy System Symbols</u>
(From: Odum, H. T., 1996. "Environmental Accounting". J. Willey.)

Energy circuit: A pathway whose flow is proportional to the quantity in the storage or source upstream.

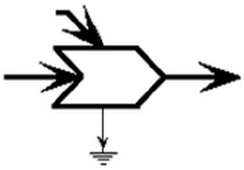


Source: Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

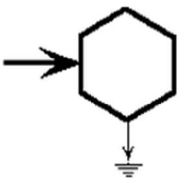


Tank: A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

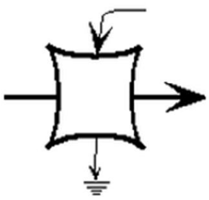
Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.



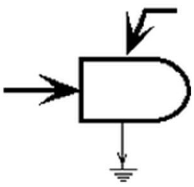
Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both;control action of one flow on another; limiting factor action;work gate.



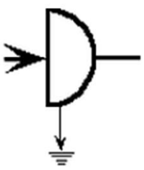
Consumer: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.



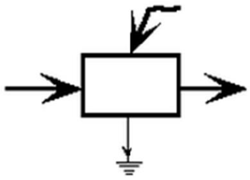
Switching action: A symbol that indicates one or more switching actions.



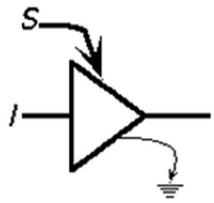
Producer: Unit that collects and transforms low-quality energy under control interactions of high-quality flows.



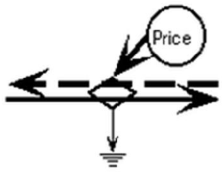
Self-limiting energy receiver: A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.



Box: Miscellaneous symbol to use for whatever unit or function is labeled.



Constant-gain amplifier: A unit that delivers an output in proportion to the input I but is changed by a constant factor as long as the energy source S is sufficient.



Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Definitions of terms

Available Energy- Potential energy capable of doing work and being degraded in the process (units: kilocalories, Joules, etc.)

Useful Energy- Available energy used to increase system production and efficiency Power- Useful energy flow per unit time

Emergy- Available energy (exergy) of one kind previously required directly and indirectly to make a product or service (units: emjoules, emkilocalories, etc.)

Empower- emergy flow per unit time (units: emjoules per unit time) Transformity- emergy per unit available energy (units: emjoule per joule)

Solar emergy- Solar energy required directly and indirectly to make a product or service (units: solar emjoules)

Solar Empower- Solar emergy flow per unit time (units: solar emjoules per unit time)

Emergy Intensity - Emergy of one kind required to produce a product or service per unit of output of the product or service. There are two types of EIs: transformity and specific emergy

Solar Transformity- Solar emergy per unit available energy (units: solar emjoules per Joule)

Specific Emergy (solar) – Solar emergy per mass of a product (units: solar emjoules per gram)

Emdollars, (Em$)- Dollars of gross economic product due to an emergy contribution's proportion of the national empower

(after Odum, 1996).

17 APPENDIX IV

Electricity EU_27							
Indicators	Slaughtering residues	Heat from rendering I products burning	Tallow	Meat and Bone Meal (MBM)	Biodiesel	Glycerol	Total Input
Material resource depletion							
MI abiotic (g/g)	8.20E-03	2.41E-05	5.07E-01	5.07E-01	7.83E-01	7.83E-01	3.57E+00
MI water (g/g)	5.85E-02	5.40E-04	1.14E+01	1.14E+01	1.55E+01	1.55E+01	9.81E+01
Electricity_hard Coal							
Indicators	Slaughtering residues	Heat from rendering I products burning	Tallow	Meat and Bone Meal (MBM)	Biodiesel	Glycerol	Total Input
Material resource depletion							
MI abiotic (g/g)	8.20E-03	3.57E-05	7.52E-01	7.52E-01	1.11E+00	1.11E+00	5.07E+00
MI water (g/g)	5.85E-02	4.86E-04	1.02E+01	1.02E+01	1.40E+01	1.40E+01	9.11E+01
Electricity_wind farm							
Indicators	Slaughtering residues	Heat from rendering I products burning	Tallow	Meat and Bone Meal (MBM)	Biodiesel	Glycerol	Total Input
Material resource depletion							
MI abiotic (g/g)	8.20E-03	1.35E-05	2.84E-01	2.84E-01	4.81E-01	4.81E-01	2.19E+00
MI water (g/g)	5.85E-02	5.87E-05	1.24E+00	1.24E+00	1.84E+00	1.84E+00	3.57E+01
Electricity_Biogas							
Indicators	Slaughtering residues	Heat from rendering I products burning	Tallow	Meat and Bone Meal (MBM)	Biodiesel	Glycerol	Total Input
Material resource depletion							
MI abiotic (g/g)	8.20E-03	1.71E-05	3.61E-01	3.61E-01	5.85E-01	5.85E-01	2.67E+00
MI water (g/g)	5.85E-02	6.50E-05	1.37E+00	1.37E+00	2.02E+00	2.02E+00	3.67E+01
MI Biotic		2.16E-05	4.57E-01	4.57E-01	6.18E-01	6.18E-01	2.80E+00
MI Soil movement		2.55E-06	1.09E-03	1.09E-03	1.02E-03	1.02E-03	2.18E-03

APPENDIX IV 1: Material Input calculation for sub-processes using electricity from EU-27 mix from grid and natural gas as heat provision source

Indicators for Biodiesel Production					
Indicators					
Material resource depletion	Diesel	EU_27	Hard Coal	Wind	Biogas
MI abiotic (g/g)	1.36	0.78	1.11	0.48	0.59
MI water (g/g)	9.70	15.55	14.01	1.84	2.02
MI Biotic					0.62
MI Soil movement					0.00

APPENDIX IV 2: Effect of change of electricity provision resources on material input for biodiesel production

Indicatords for PHA production					
Material resource depletion	LDPE	EU_27	Hard Coal	Wind	Biogas
MI abiotic (g/g)	2.49	3.57	5.07	2.19	2.67
MI water (g/g)	122.20	98.14	91.12	35.74	36.68
MI Biotic					2.80
MI Soil movement					0.00
MI Biotic		1.4321	2.04E+00	8.80E-01	1.07E+00

APPENDIX IV 3: Effect of change of electricity provision resources on material input for biodiesel production