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Evaluation of energy technology systems based on renewable resources

DOCTORAL THESIS

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…and last but not least I dedicate this work to Bettina who has been supporting me for many years and who is of utmost importance to me.

Abstract

Serious constraints in the way our economy works like resource depletion and global climate change bring the use of fossil under increasing pressure. Energy production based on renewable resources is therefore increasing continuously. The motivation of this thesis is to give an overview about the ecological impact of different energy technology systems in order to investigate what the change from fossil to renewable resources in our energy provision means for the environment.

Three research objectives will be addressed by presenting results of already published papers. The first objective is to investigate if renewable resource based systems have indeed a lower ecological impact compared to fossil resources based technologies if the whole life cycle is considered. The second objective is to prove that the Sustainable Process Index (SPI) is able to model these systems based on a life cycle approach and discerns strongly between renewable and fossil based technologies in their respective ecological impacts. This methodology, developed in 1995, forms the theoretical background for this thesis. The result of the SPI evaluation of a human activity renders an Ecological Footprint which can be compared for different alternatives.

Within this thesis several software tools using SPI methodology are briefly described to show the versatility of the methodology. In the focus of the thesis however are the application of the SPI on energy technologies and bio based polymer production. Based on the experience of using SPI calculation tools in this thesis is used to improve the current SPIonExcel software to generate a successor, the SPIonWeb, which is also briefly discussed in the thesis in the form of an outlook on further development (third research objective).

Kurzzusammenfassung

Ernstzunehmende Probleme welche unsere Wirtschaftsweise verursacht (Rohstoffausbeutung und globaler Klimawandel), bringen fossile Ressourcen zunehmend unter Druck. Energieerzeugung aus erneuerbaren Ressourcen rückt somit immer mehr in den Vordergrund. Motivation dieser Dissertation ist es einen Überblick über ökologische Einflüsse von verschiedensten Energietechnologien zu geben, um dabei den Wandel von fossilen zu erneuerbaren Energieträgern abzubilden.

Drei Forschungsziele werden durch bereits publizierte Forschungsbeiträge behandelt. Das erste Forschungsziel soll beantworten ob erneuerbare Energieträger einen geringen Einfluss als fossile Energieträger auf die Umwelt haben, unter Berücksichtigung des Lebenszykluses. Forschungsziel 2 soll beweisen dass der Sustainable Process Index (SPI) dazu fähig ist diese Technologien zu modellieren (basierend auf dem Lebenszyklus-Ansatz) und den Unterschied zwischen fossilen und erneuerbaren Technologien darzustellen. Die SPI Methodik, entwickelt 1995, stellt die theoretische Grundlage dieser Dissertation dar. Das Ergebnis der SPI Bewertung einer menschlichen Aktivität ergibt einen Ökologischen Fußabdruck, welcher mit verschiedensten Alternativen verglichen werden kann.

Diese Arbeit beschreibt verschiedenste Softwarepakete welche die SPI Methodik nutzen und kurz beschrieben werden. Im Fokus der Dissertation stehen trotzdem die Anwendung des SPI an Energietechnologien und biologisch basierter Polymerproduktion. Basierend auf der Erfahrung mit bestehenden SPI Softwarepaketen beschreibt diese Arbeit auch kurz die zukünftige Weiterentwicklung des SPIonExcel Werkzeugs zu SPIonWeb (Forschungsziel 3). Dabei wir ein Ausblick auf das noch in Entwicklung befindliche SPIonWeb gegeben.

Index

List of abbrevations

AP	Acidification Potential
CHP	Combined heat and power
CML	Centrum voor Milieukunde in Leiden
CSV	Comma separated values
GWP	Global Warming Potential
kWh	Kilowatt hours
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MIPS	Material Intensity Input Per Service Unit
MJ	Megajoule
ODP	Ozone Depletion Potential
ORC	Organic Rankine Cycle
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PNS	Process Network Synthesis
SPI	Sustainable Process Index

1 Introduction

Energy is a driving force for societal development in developed as well for emerging economies. Ensuring sustainable development is one of the major challenges to our societies.

Two problem areas can be identified which are interconnected, resources and environment. Both are linked through fossil resources. Using fossil resources has an impact to the environment which affects us in many ways, from oil spills in the ocean to global climate change. If the resource base is changed e.g. to biogenic resources however other impacts of different qualities and intensities (e.g. soil degradation, pollution of water bodies with nitrates and pesticides) might affect our environment. The question is if a change in the resource base can fulfill over the whole life cycle the requirement to lower the ecological impacts to nature based. Therefore a change in the resource base is not only a question about global resources and their availability. There is a link between resources used and environmental problems caused by human society. Any dramatic change in the resource base therefore has to be based on careful and realistic assessment of the ecological effects of such a change.

Fossil resources have been the base of our economy for many decades. Almost every daily activity of industries and citizens are involving fossil resources in some way. Currently a gap between production and consumption of crude oil, the most versatile fossil resource, emerges (an effect called "Peak Oil") which in turn causes high exploration costs (as smaller and more remote reserves have to be exploited), higher vulnerability to speculation and in general rising market prices. This means that not only environmental concerns but also hard economic facts conspire against the further use of fossil resources as a base for society. Our society may therefore face a major shift away from a fossil based economy within the 21st century because of limitations to reserves of these resources (Gwehenberger and Narodoslawsky, 2008).

The change from one energy source to another or even a mix of resources implies however changes in the economic structure itself. Renewable resources have different characteristics compared to fossil resources. The way of substituting one resource base by another is complicated by the fact that many different interest groups with different intentions are involved. A huge range of possible renewable resources is available. There is biomass with different energy content, yields in production and local availability, offering storable, material products. Others like wind and solar are non-storable and offer their service only discontinuously. Therefore not only a change in technologies is needed but also a major restructuring in logistics for resources as well as service provision. As we are transitioning from a single source system to a multiple source system regional aspects are becoming more important. Different regions offer different resources which can be transformed into energy and material products. A combination of resource must be applied to substitute fossil resources as bio-resources are limited and other resources like wind and solar radiation are not continuously available. Regional differences in resource availability and raw material qualities open up space for a large number of technologies which can be used for providing energy and other goods.

To compare renewable based with fossil based technologies but also different renewables based technologies among themselves, a reliable method of measurement is needed to quantify the ecological pressures comprehensively. The Sustainable Process Index (SPI) (Krotscheck and Narodoslawsky, 1996) such a measurement tool which offers the possibility to convert material and energy flows as well as emissions into an Ecological Footprint. This measure follows strict sustainability criteria, as described in the following chapters. The use of an ecological evaluation system like the SPI can be used for different ends like measuring the ecological pressure comprehensively, comparison between different alternatives and hot spot identification within the life cycle of a given technology.

Within this thesis the SPI was used to solve questions about ecological feasibility of different technologies and their resources. Results have been published in several journals which are referenced by the main part of the thesis, which will highlight the common base of and links between those publications.

2 Problem definition and objectives

The aim of this work is to compare energy systems based on different resources. This should give more detailed information on how the life cycle impact is changing if the resource base is exchanged.

2.1 Problem definition

Renewable resources are becoming more important and play an increasing role in future of energy generation. A change in resources implies also a change in technologies and logistics. Fossil driven technologies already have their resource logistics installed and many installations are already paid back. A shift to different resources needs also a major shift in terms of raw material provision and technologies. This means that the life cycle attached to a technology is defined by the utilized raw materials. Changing the resource base changes also structures like logistics and storage. These structures are established over decades and may not be replaced within short term. Even if there is the will to change the structure of energy provision several problems are faced if renewable energy technologies are implemented:

- Technology is only a conversion tool. The real decision has to be made on the resource level. Technology is only a result of the chosen resource. Therefore, choosing a resource is difficult if no comparative information to alternative resources is available.
- Many different resources are available within a region. To choose which should play a key role in futures energy strategy is crucial as this decision influences long term investment e.g. in infrastructure. There is a predominance of economic information which does not address to environmental issues in this field.
- There is a lack of adequate measuring methods for decisions makers to compare different life cycles and hence resource utilization pathways on the ecological level.

To overcome the latter problem, an adequate measurement tool is needed. Only a deep look into the whole life cycle is useful to compare technologies based on different resources on the same level. Therefore all impacts (resource use, emissions, etc.) have to be taken into account to provide a specific service. Detailed Life Cycle Inventory (LCI) data is needed which contains all material and energy flows as well as emissions along the life cycle to provide a Life Cycle Impact Assessment (LCIA). This Life Cycle Impact Assessment can be done with many different methods depending on the desired aspects of comparison. It is important to note that each method has its own normative background which means the assessor is responsible to choose an adequate method which fits the given requirements for the assessment problem. The following paragraphs shall give a short overviewjust on "metabolic assessment methods" (that assess the ecological impact of mass and energy flows exchanged between a life cycle and the environment) in order to show this diversity.

The CML method (Heijungs et al., 1992) addresses specific problems (e.g. GWP (IPCC, 1990), ODP (WMO, 1998), AP (Heijungs et al., 1992)) and provides assessment of different factors contributing to these problems. The general approach is to choose a certain reference substance), that is well known to contribute to the problem in question (e.g. CO_2 for global warming. Based on scientific knowledge about a cause effect relationship at the center of the problem in question (e.g. radiation capacities of gases in the case of global warming), factors to compare the effect of the reference substance to other substances are derived (so called "impact factors"). Overall impact is then defined as the sum of mass flows exchanged along the life cycle times the respective impact factors, arriving at a cumulative impact of the life cycle in the particular category. Although this allows comparisons of different factors to a single problem, it is not possible to compare results of different problems to each other (e.g. GWP against ODP).

A particular form of these single issue measures are single substance measures, like the Carbon Footprint. These measures summarize the exchange of a single substance with the environment along the whole life cycle. A well-known representative of this class of measures is the Carbon Footprint (Wiedman and Minx, 2008). The same way of impact assessment is applied for water. In general these assessment methods are even more focused (and incompatible across different problem categories) than the CML method. Shortcomings of this approach in the case of the Water Footprint have been discussed by Stoeglehner et al., 2011.

Another way of impact assessment is to measure mass flows which are induced due to human activities. Material Intensity per Service Unit (MIPS) (Schmidt-Bleek, 1998, Schmidt-Bleek and Bierter, 2000) is the leading methodology in this area which expresses mass flows related to a specific service unit in different categories including abiotic and biotic resources, renewable resources, air and water. The normative background of this assessment method is that it is generally impossible to rightly estimate the danger induced by a certain substance. As a proxy for the real impact the mass moved to provide a certain product is therefore accounted for. The reasoning is that the more mass is moved, the deeper and potentially more harmful is the impact exerted on the environment.

Ecological Footprints form a methodological family which has the same base assumption that the only natural income of earth is solar radiation. Area is needed to transform solar radiation to different kind of energies (e.g. PV) or materials (e.g. biomass). In a truly sustainable society, basically every process on earth is in competition about area (and hence the natural income) which is obviously limited. Therefore area has been chosen to be the reference unit in terms of measurement of environmental impacts. Footprints measure the area necessary to supply an activity with the natural income to support it, they asses how much "nature" is consumed by a certain activity.

The most commonly used Ecological Footprint methodology was developed by Rees and Wackernagel, 1994. This method mainly assesses consumption (in particular energy and food) which is converted in an according Ecological Footprint. A more advanced version addressing energy technologies is the Energy Footprint described by Stoeglehner, 2003.

The SPI methodology extends this approach by including emissions to the environment which are also converted to an equivalent Footprint area to the basically input-driven Ecological Footprint methodology. Within this doctoral thesis SPI Footprints are calculated and used for result interpretation. The methodology will be briefly described below.

2.2 Research objectives

Based on the problem definition three research objectives have been defined:

- Examining if renewable based systems have indeed a lower impact to the environment compared to fossil driven energy technologies if the whole life cycle is considered
- Investigating if the SPI fulfills the given requirements and is able to model processes based on life cycle data, leading to a strong distinction between fossil and renewable based technological systems
- Further development of the SPI calculation tool in the light of the experiences gained in this work and bringing it back to the original SPI methodology, in particular in terms of dissipation area calculation

3 Sustainable Process Index (SPI)

The motivation for developing the SPI was to give engineers a tool which allows them to evaluate processes within their whole life cycle, using information accessible by engineers early on in process development (mainly mass and energy balances). The aim of the SPI was to provide a methodology which allows to evaluate processes under the condition of ecological sustainability.

The SPI methodology is able to model metabolic impacts along a life cycle process chain. A final product is defined by all the resource and emission flows along the life cycle process chain which are needed to produce this final product. Therefore process sharp information is needed. LCI data out of an LCA is needed to model processes in the SPI method.

3.1 Description of the methodology

The ecosystem earth can be seen as a thermodynamically closed system driven by solar radiation as income. Solar energy is the driving force which drives natural as well as anthropogenic processes, be it directly or in stored form (e.g. in case of fossil resources). Two principles are defined which have to be fulfilled if a human activity/process is to be sustainable (SUSTAIN, 1994):

1. *Human activities must not alter long term storage compartments of global material cycles in quality as well as in quantity. If this principle is not adhered to resources will be depleted and substances accumulated in ecosphere, overstraining the natural cycles.*

2. *Flows to local ecosphere have to be kept within the qualitative and quantitative range of natural variations in environmental compartments. If such flows exceed the amount a compartment can integrate the accumulating substances will alter the compartment. This alteration can lead to a local environment that is no longer able to sustain flora and fauna.*

These principles can be used to transfer mass flows into areas. This can be most easily seen with renewable resources. Renewable resources need an area where they are provided. Through resource specific yields the conversion between area and energy/material flow can be realized. In the case of direct solar radiation (PV, solar thermal collectors) dependent technologies this is obvious. For bio- resources the area provided to grow them is also the area necessary to fulfill criterion 1. Mass flows are closed on the field, as e.g. carbon is fixed by photosynthesis (driven by solar radiation) and will be released again when utilizing the resource (e.g. by burning it). This means that when a certain bio-resource is utilized, the area necessary to grow it is the area necessary to close the global carbon cycle sustainably, meaning in a way that global material cycles are not changed in quality (as CO_2 is fixed and CO_2 is released) and quantity (as the same amount of carbon is released by burning the resource as was fixed by photosynthesis to grow the resource).Fossil resources in this methodology can be treated as renewable resources with a very slow regeneration rate. According to the global carbon cycle there are processes which are taking back carbon in long term storage. In particular sedimentation to the sea ground stores carbon for geological time frames, in fact it was one step in the generation of crude oil. To accomplish principle 1 the rate of utilization of fossil resources must not exceed the rate carbon is stored for geologic time frames. So the area for "regeneration" of fossil resources (sedimentation to the seabed) is the area attached to fossil carbon in order not to alter the global carbon cycle.

Non-renewable resources (e.g. metals) are however inherently used in a dissipative way. We extract them from mines and gradually disperse them into the ecosphere.. Therefore non-renewable resources are taken into account according to principle 2, calculating the area necessary to dissipate them sustainably based on local conditions of environmental compartments. Only energy consumption and emissions along the life cycle to provide these resources (e.g. metal extraction, refining, and transport) is calculated on the input side of the SPI.

3.2 Area type definition

As a general rule the SPI method calculates the area necessary to embed a certain life cycle leading to a product or service sustainably into the ecosphere. All areas are based on a time frame of one year (as thus is the common time frame for harvesting bio-resources). Calculation is in most cases done on the base of a certain real world installation (e.g. a biomass Combined Heat and Power generation with a specified capacity in a specified regional context). All life cycle inventory data are then related to this particular installation.

Equation 1 defines this area to embed a human activity into the ecosystem, A_{tot}. This value is expressed in square meter and equal to an Ecological Footprint:

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \qquad [m^2] \qquad (1)$$

A_R = summarizes the areas necessary to provide different raw materials like fossil, renewable and non-renewable resources.

A_E = covers the provisions of energy which takes into account the type and amount of raw materials, raw materials treatment, processing and emissions from energy installations.

A_I = Area for installations summarizes the amount of square meters per year due to land occupation of infrastructure installations. Infrastructure will be taken into account through their process of provision; the yearly area is calculated by dividing the area necessary to produce the infrastructure by its life time.

A_S = Area for staff adds a statistical area per inhabitant per employee working in the process in question. Case studies showed that this part can be seen as negligible in most cases.

A_P = Area for dissipation converts emissions into environmental compartments air, water and soil to respective dissipation area. The rational to calculate this area is that environmental compartments have a natural replenishment rate (e.g. precipitation for water, degradation of biomass to humus for soil). This "new" compartment is built on an area base (as these processes can all be described in rates of "kg/m²a". This compartment is supposed to be free of any material other than the pure compartment. It may be "filled" with a certain substance until the natural concentration of this substance is reached without violating principle 2. If a certain substance has to be dissipated it is necessary to provide so much "fresh compartment" (and hence need so much area) as to ensure that principle 2 is fulfilled and the compartment is only loaded to its natural quality.

A_R, A_E and A_P are the terms which are defining the life cycle character of the final value. A_{tot} gives an Ecological Footprint for the whole activity, if divided by the amount of goods or services (N_P) produced within of the reference time (usually one year, as stated earlier).

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

a_{tot} contains all partial areas related to a specific good or service. Areas from intermediates provided along the life cycle chain are also part of this final value. (Krotscheck, 1995)

Regarding nomenclature the value a_{tot} is equal to the Ecological Footprint. But it may also be called SPI value or SPI Footprint because this clarifies which method was used to achieve the Ecological Footprint.

The method has some interesting advantages when it comes to evaluate human activities using different resource bases.

- It completely relies on natural qualities (e.g. concentration of substances in unpolluted compartments) and rates (e.g. precipitation rates) that may be regionalized. This allows distinguishing finely between different technologies within a regional context or resources from different origins.
- Using only natural, scientifically defined values allows the SPI to evaluate without any influence from (often changeable) societal processes, such as the definition of limit threshold values.
- Treating fossil and renewable resources using the same set of strict sustainability criteria allows comparing human activities regardless of their resource base.

3.3 Interpretation of SPI results

Based on the different area types from the previous chapter seven partial areas have been introduced (Sandholzer, 2006). This shall help the evaluator to distinguish between different kinds of impacts and, which impact along the process chain contributes how much and where to the overall footprint.

- 🟨 Area for area
- 🟪 Area for non-renewable resources
- 🟩 Area for renewable resources
- 🟧 Area for fossil carbon
- 🟦 Area for emissions to water
- 🟨 Area for emissions to soil
- 🟦 Area for emissions to air

These contributions to the overall footprint are of different prominence in varying life cycles. For example "Area for (direct) area" is prominent in bio-resource based processes because of land use for cultivation. In fossil resources based processes "Area for fossil carbon" represents the main impact whereas heavy usage of non-renewable resource usually increases "Area for emissions to water" "- air" or "- soil". This information is available for the whole process as cumulative values however also process sharp information can be extracted for a detailed analysis along the life cycle process chain.

SPI results can be interpreted in different ways. Comparison of a_{tot} helps to compare different ways to provide the same goods and services. Beside that the absolute a_{tot} value can be divided by a statistical available area per inhabitant (a_{in} = 33,604 m²a), which is the overall surface area of the earth (including oceans) divided by the world population (Equation 3). Including the ocean surface is important as sedimentation to seabed is the most important process to close (fossil) carbon cycle. As we are still have a fossil driven society and this area has to be seen as an important part of the natural endowment. Analyzing the total specific area for a good or service allows estimating how much of the "natural budget" of a citizen is used to generate it.

$$\text{SPI index} = \frac{a_{tot}}{a_{in}} \qquad [1] \qquad (3)$$

Summing up all total areas for the goods and services a person consumes finally allows the assessment of life styles. An SPI index above 1 indicates a non-sustainable way of consumption. A value below 1 would indicate a sustainable way of consumption and life style.

4 Family of calculators

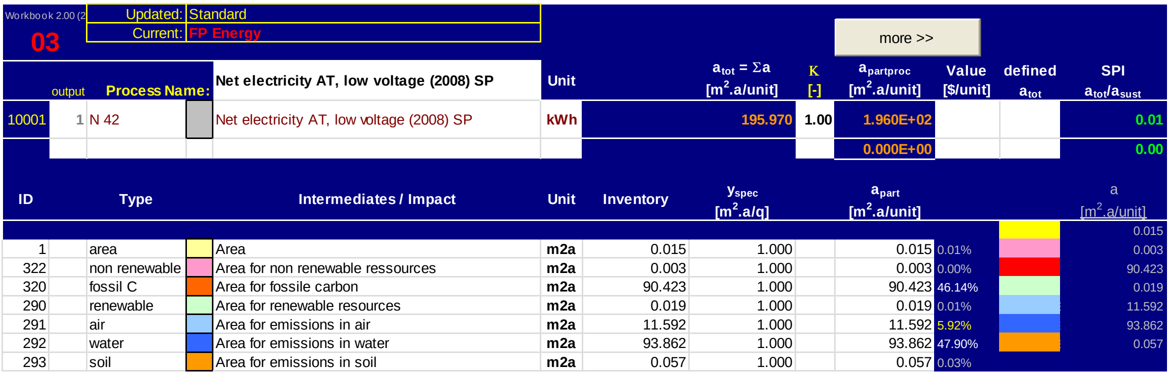
Using sustainability assessment tools usually requires expert knowledge in order to generate the life cycle inventory and to apply evaluation methods correctly. It is however important to provide lay people (at least with regard to LCA) with easy and reliable information about sustainability aspects of their decisions. This is the motivation behind the development of specific SPI-Footprint calculators.

The following chapter should give a short overview about software tools which are available. All of them have the SPI methodology as calculation method in common but are realized in different ways, adapted to the activity/profession they are geared to evaluate. The calculators are always built in a way that takes the knowledge of the respective user into account. Language and program architecture (e.g. logic of on-line questionnaires) are also adapted to the user's are common personal and/or professional environment.

4.1 SPIonExcel

A software tool called SPIonExcel 2.07 is available for free from the SPI homepage (http://spionexcel.tugraz.at) to evaluate processes following the SPI methodology. This program is the root of all other calculators as the footprints used in the other software packages are all calculated using this program and the attached data bank.

The structure of SPIonExcel is a Microsoft Excel® Macro which interacts with underlying Microsoft Access® Databases. A basic database contains frequently used processes in life cycles (e.g. electricity provision, transport, process heat provision, etc.) as already cumulated Footprints according the 7 partial areas. This allows users to start quickly with modeling of processes and to use predefined life cycle process information. These processes are indicated by ending in their name with SP for **S**hort **P**rocess. If more detailed process information or an adjustment of SP processes is needed, **D**eep **P**rocesses (DP) are available. DP allow the user to have a look into every process step which contains all the LCI data as inventory input, in contrast to SP processes which gives users an accumulated SPI results. Figure 1 illustrates a SP screenshot in SPIonExcel.



Workbook 2.00 (2

03

Updated: Standard

Current: FP Energy

	output	Process Name:		Net electricity AT, low voltage (2008) SP	Unit	$a_{tot} = \Sigma a$ [m^2.a/unit]	K [-]	$a_{partproc}$ [m^2.a/unit]	Value [$/unit]	defined a_{tot}	SPI a_{tot}/a_{sust}
10001	1	N 42		Net electricity AT, low voltage (2008) SP	kWh	195.970	1.00	1.960E+02			0.01
								0.000E+00			0.00

ID	Type		Intermediates / Impact	Unit	Inventory	y_{spec} [m^2.a/q]		a_{part} [m^2.a/unit]			a [m^2.a/unit]
										🟨	0.015
1	area	🟨	Area	m2a	0.015	1.000		0.015	0.01%	🟪	0.003
322	non renewable	🟪	Area for non renewable ressources	m2a	0.003	1.000		0.003	0.00%	🟥	90.423
320	fossil C	🟧	Area for fossile carbon	m2a	90.423	1.000		90.423	46.14%	🟩	0.019
290	renewable	🟩	Area for renewable resources	m2a	0.019	1.000		0.019	0.01%	🟦	11.592
291	air	🟦	Area for emissions in air	m2a	11.592	1.000		11.592	5.92%	🟦	93.862
292	water	🟦	Area for emissions in water	m2a	93.862	1.000		93.862	47.90%	🟧	0.057
293	soil	🟧	Area for emissions in soil	m2a	0.057	1.000		0.057	0.03%		

Figure 1: Screenshot – SPIonExcel

New process information is stored in already existing databases or new user defined ones. Based on several predefined SP processes and user defined processes, a complex life cycle process chain can be modeled in SPIonExcel. Visualization of results for a process chain is done by tables and diagrams (Figure 2).

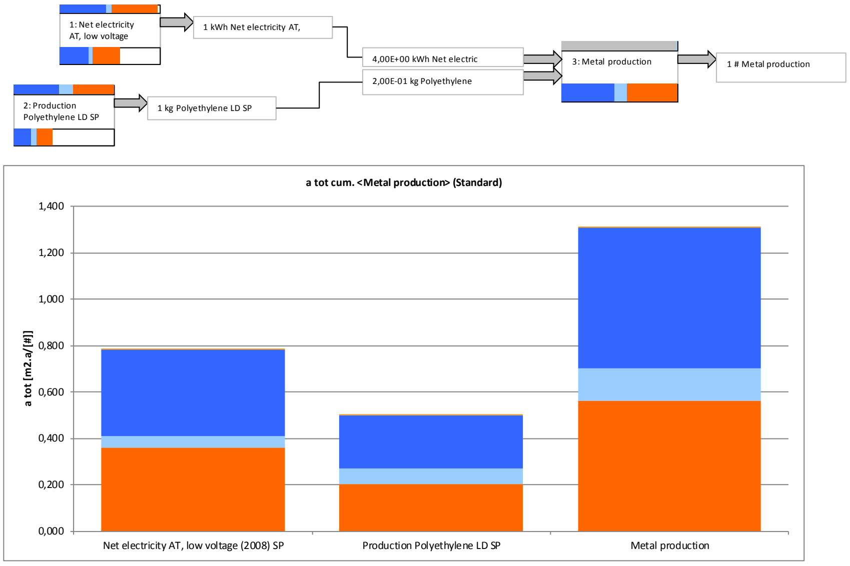


Figure 2: Visualization of results in SPIonExcel

Figure 2 shows an example of how SPIonExcel visualizes process chains. Every box has two bars. The upper bar gives the SPI information for the process itself and the lower bar indicates how much this specific process contributes to the overall SPI result in the final process. Additionally, diagrams can be drawn to visualize the individual contribution of process steps to the final product.

This tool allows experts a quick modeling and has been used for many years. As useful the tool might be, over past years there have been also a demand for calculators for different applications for users who are not completely aware of the whole theoretical background but nevertheless want to obtain quick and reliable information about sustainability issues they are interested in.

4.2 Personal Ecological Footprint Calculator

Every individual is part of the global ecosystem. The "Personal Footprint Calculator" was realized to calculate the individual Ecological Footprint according to the own life style of a person. Accessible via the web address www.fussabdrucksrechner.at everybody has the possibility to evaluate him-/herself. A survey has to be filled by the user to achieve a result. The first part deals with living. Living space, room heating system, hot water preparation, fresh water and electricity consumption are required for the calculation.

The second part addresses mobility separated in work related and leisure mobility. Different means of transportation with mean fuel consumption where appropriate) can be chosen and overall travel distances over a specific time period must be entered.

The last part of the survey is about food consumption to determine how much agricultural effort (production of starchy products, meat, milk,…) and energy consumption (due to cooking) is needed.

Finally, the user gets a result of the overall SPI Footprint which is compared to the average statistical value that is available to every inhabitant. This statistical value is defined by the amount of inhabitants on earth divided by the available surface area of the earth. Additionally the SPI Footprint is divided into different sectors (electricity, heating, mobility, food consumption). On the one hand, this provides the users with a first quick view where his personal ecological hot spot are. On the other hand the calculator is intended to be used as playing tool, which means the users should adjust their survey by going backwards to see how changes in life style impact the results.

4.3 Ecological Footprint Calculator for Schools

This calculator was commissioned by the *Austrian Federal Ministry for Education, Arts and Culture*. The intention was to bring ecologically responsible thinking to students at the age of around 10 to 14. The calculator is accessible by the following web address: www.fussabdrucksrechner.at/schulen (german only). The results will be a SPI footprint for the operation of a school as a whole.

Results contain mainly energy consumption, transportation, waste collection and food provision. After data collection teachers guide their students through the on-line questionnaire of the calculator to reach the Ecological Footprint for their school and explaining how to read the results.

The calculator offers two different modes, a short and long version which differs in the amount of data needed to achieve results. In this calculator the Ecological Footprint is visualized by sectoral Footprints (e.g. electricity, mobility, heating) to get an impression which part of school life contributes to how much to the overall Footprint. Besides that the share of the Footprint according the 7 SPIonExcel categories is also provided. Finally the schools Footprints are compared to the area which should not be exceeded to fulfill the axioms in chapter 3.3.

4.4 Ecological Footprint Calculator for Farmers

"Same idea but quite different realization" – this describes the Calculator for farmers compared to other thematic calculators. The focus was not to give a user-friendly and fancy user interface (like in the Calculator for Schools). The main objective was to provide farmers with the possibility to comprehensively evaluate their operating activities for producing agricultural products. This project was realized in co-operation with *Bio Austria,* a branch of the Chamber of Agriculture*.* The web-based calculator is accessible via: www.fussabdrucksrechner.at/bauern_rechner.

The farmer enters information about energy consumption for machinery, amount of fertilizer and pesticide as well as any additional input to his farm operation. Just as in the Calculator for Schools, two different versions are available. (short and long version). Short version results provide information about the footprint of the whole farm. The long version mode offers the possibility to get detailed results for every agricultural product defined in the calculator however requiring more detailed input.

4.5 ELAS-Calculator

The goal of the ELAS-Calculator is to represent all aspects of a residential area in respect to energy use as a unified parameter. The ELAS-Calculator is available as a free web-based tool (www.elas-calculator.eu) and meant to deliver insight to diverse target groups such as communities, planners, architects and builders as well as interested private persons.

The ELAS-Calculator should permit these target groups to analyse a settlement and/or individual buildings. The calculator may be utilized in "private" or "municipal" mode. The private mode is intended for individuals, who are especially interested in how various factors affect the personal footprint, energy consumption and added value. Simpler questions are asked in comparison to the municipal mode, so that the calculator can be used with less theoretical background. The municipal mode in contrast views a settlement as a whole, defined by building groups.

The ELAS-Calculator serves as a long-term analysis of energy of existing or planned residential areas. Important parameters of settlement projects (e.g. location parameters, existing or planned living space, existing or planned energy supply, existing or expected population, planned technical facilities) have to be provided. Based on this input, the ELAS-Calculator estimates the energy consumption of the residential area for heating, electricity and operation of public infrastructure and mobility. Final results are energy demand, SPI Footprint and CO_2 life-cycle-emissions. Additionally to the ecological results also economic results are given such as turnover, value added, imports and jobs.

For the long-term analysis over 30 years, two pre-assembled scenarios (trend-scenario, green-scenario) are available. Similar as in the private mode, input data regarding residential structural, infrastructural and building-related parameters can be alternated by individual changes of the input data. With this scenarios may be constructed, highlighting how different parameters (like location, residential planning, construction, operation of the buildings and technical infrastructure) affect the energy consumption for construction, heating/cooling, electricity and expected mobility of the residents over a time period of 30 years.

4.6 RegiOpt – Conceptual Planner

Regional **Opt**imizer **C**onceptual **P**lanner (RegiOpt – CP) is intended to combine two different methodologies into one web based program:

- Process Network Synthesis (PNS) to optimize energy technology networks based on a given super structure
- SPI to evaluate the optimum structure from the PNS

PNS (Friedler et al., 1995) was developed by a research group from the University of Pannonia, Hungary. Originally invented for process engineering the methodology is here applied to the optimization of regions (PAPER 1). Based on economic information about energy technologies (investment and operational costs) and raw materials (costs, availability), a "superstructure" is generated which contains every feasible linkage between raw materials, processing technologies and products. PNS gives an optimized structure which represents the solution with the highest "profit".

PNS methodology is realized by the software tool PNSStudio which is available from the homepage www.p-graph.com. Similar to SPIonExcel, PNSStudio is targeted to technical experts and doesn't allow quick results without experience. RegiOpt – CP is targeted to regional development experts and decision makers and fulfills following requirements:

- Providing optimum energy technology network adapted to the given regional setup of resources
- Easy to apply and user friendly for "regional experts" who are not familiar with PNS and SPI
- Visualization and interpretation of results for further communication and discussion

RegiOpt – CP is basically a web page survey which collects data from the user about the region in question (resources, consumption, and existing technical infrastructure) to generate an optimized structure based on a pre-defined superstructure. PNS optimization process itself is invisible to the user and runs in background. Optimized technology network results are presented in tables and diagram and compared to "business as usual". Additionally SPI information based on PNS results are calculated and presented to give an overall picture of economic and ecological potential of a region. RegiOpt – CP is in particular a tool to generate development scenarios for decision makers helping them to find the most advantageous resource utilization pattern for their region.

5 Framework of sustainable technologies on the base of renewable resources

A change in raw material base does not mean different technologies. For fossil resources for instance transport cost and distances have been considered as negligible in the past. For renewable resources this rule is no longer applicable. Low transport density and high water content only allow short transport distances.

Another structural change is the shift from point sources (e.g. oil drilling platforms) to area sources for providing renewable resources (e.g. crops, wood, solar energy) (Gwehenberger and Narodoslawsky, 2008). Networks need to be introduced to collect renewable resources and technologies applied to make them 8or the services generated from them) amenable to long-distance transport.. In terms of non-area based renewable resources like wind and solar, energy storage is becoming important because of their discontinuous availability. This short run-down just illustrates the profound change associated with a shift from fossil to renewable resources.

The following argument applies in particular to biogenic resources. A shift to biogenic resources requires also a rethinking in the how and where these resources are utilized. Centralized, huge capacity power plants based on biogenic resources are less feasible because of the high transport impact for raw material provision. If low grade resources should be transported over long distances, a harvest- site processing step (upgrading) is required. De-centralized and small scale power plants provided with local biogenic resources may however use these low grade resources without conditioning, however requiring smart grids to distribute their services.

Another important argument for localized energy production is the “degree of efficiency”. The usage of biogenic resources in energy technologies always has heat as a by-product. Contrary to electricity, heat cannot be transported over long distances without significant losses. Therefore transport distances for heat (e.g. district heating pipelines) have to be short. This has the effect that energy (in particular electricity) must be produced where heat is required.

Because of this changed setup of raw material provision the factor spatial planning plays a major role if renewable resources are considered. This aspect includes also that much more stake holders are involved in decisions about technological systems (Narodoslawsky and Stoeglehner, 2010) therefore a broader participation and decision support work is needed. Aside from area as a factor in for resource provision, spatial structures are getting into the focus as well. Spatial planning links to energy provision is a matter which is barely addressed although a strong connection between these two sectors is apparent. Spatial planners have to address the necessary social shifts to a renewable based energy provision. PAPER 2 highlights four different archetypes of spatial structures (urban centers, suburban areas, small towns as centers of rural areas and rural areas) which are quite different in their supply and demand situation as well as in their role for resource supply and consumption. Nevertheless these archetypes cannot be treated separately because they are interconnected and need a strong exchange of goods and services between them.

Ecological Footprints are considered as tools to bring scientific and technologic know how about environmental impacts to a higher level of communication. More participants mean more people with different backgrounds. This strengthens the need to present reliable scientific data in a way which is easy to understand for everybody and across disciplines and sectors.

Based on those highlighted points the next chapter presents the outcome of some papers where the SPI was used to address the objectives of this work stated in chapter 2.2.

6 Evaluation of energy technologies and commodity products

Contrary to chapter 4.2 - 4.6 where SPI was used to bring quick results to non-experienced users the following chapters show the practical application of SPI on specific research questions.

Within this chapter energy production, commodity production and combined production of both is discussed because a change to renewable resources must be seen as a profound and encompassing structural evolution step that must not be reduced to either energy or commodity sector. Even today in crude oil refineries energy production (e.g. fuels) and commodity production (e.g. plastics) is happening on the same place. A change in the resource base of energy production of society always has the effect that the commodity production changes as well because of the material sector in terms of non-metal products is much smaller than the energy sector and therefore piggybacks this sector in resources. This will only be re-inforced by the use of renewable resources and therefore energy and commodity production is highly intertwined and cannot be divided clearly.

6.1 Energy production

The energy production sector is particularly influenced by the shift to renewable energy sources. Every other sector which is using energy however is influenced automatically when the ecological performance of the energy sector changes. This means a green energy production has the potential to reduce ecological footprints in other economic sectors utilizing energy. Especially for electricity production and transport fuels have the potential to heavily influence the performance of economy as a whole.

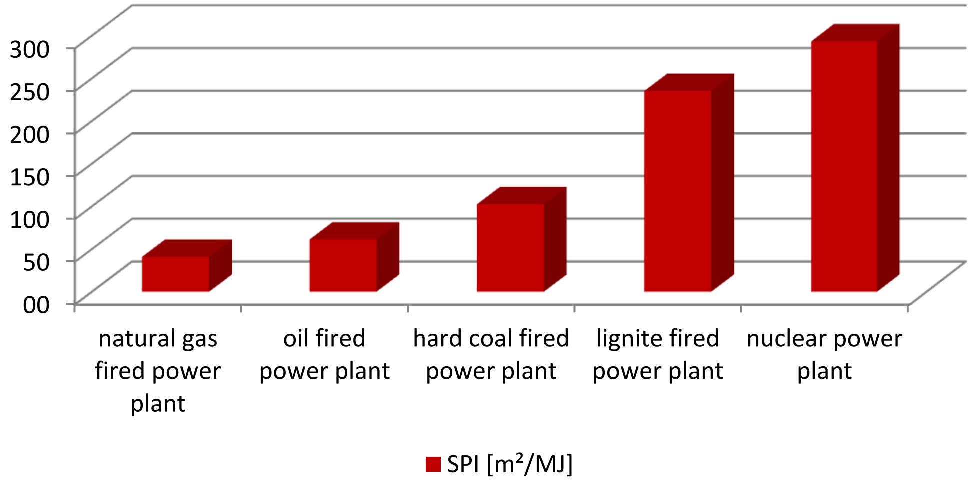


Figure 3: Comparison of fossil based electricity production technologies

Figure 3 illustrates the SPI evaluation results within conventional electricity production technologies. There is a huge bandwidth between nuclear power and a state of the art combined cycle natural gas power plant. Especially nuclear power plants are far from being environmentally friendly although no direct fossil fuel utilization is done. Emissions to the environment of radiation, radionuclides and fossil energy in extraction and refining of uranium however result in a considerable higher Footprint compared even to other conventional fossil driven technologies.

This chapter is intended to look at where renewable driven energy technologies stand compared to conventional energy technologies. Challenges for renewable resources based energy technologies are to apply a systemic approach in evaluation. On the one hand for biomass and biogas technologies logistics and storage have to be taken into account to have comparable results to fossil based technologies. On the other hand discontinuously available resources like wind and solar radiation are defined by their investment in production and the geographical location of operation and in addition require storage (not evaluated here) in order to become part of a comprehensive energy system.

6.1.1 Comparison of different energy technologies

This sub-chapter gives an overview about different renewable resource driven energy technologies. The SPI evaluation here is focused on the life cycle of electricity production. Generalized data was used to get comparative values to fossil driven energy technologies. A more detailed and systemic view in the case of electricity from biogas is provided in the next chapter (6.1.2). PAPER 6 gives an overview of some energy technologies which are providing electricity and heat. Figure 4 indicates some renewable resource based electricity production technologies with blue bars and for comparison the best fossil based technologies with red bars (related to Figure 3).

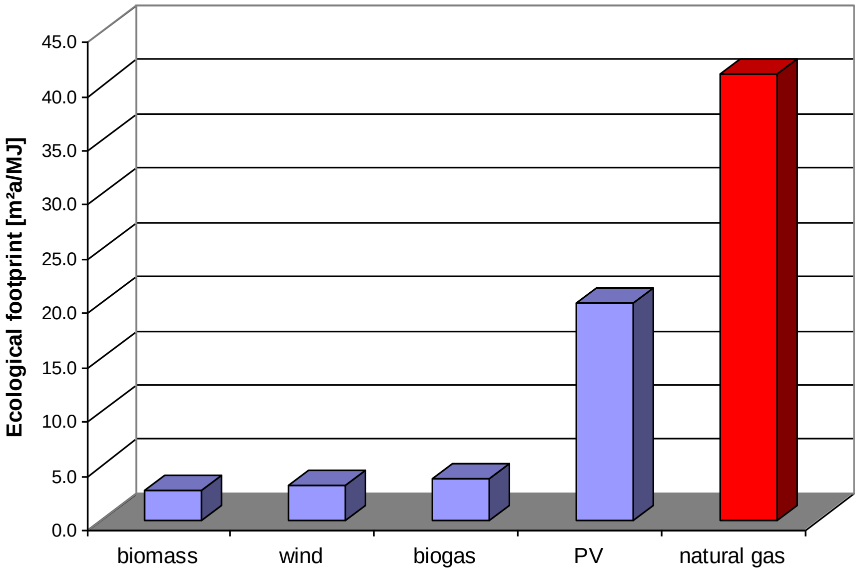


Figure 4: SPI comparison - Electricity production

A natural gas fired power station with a combined cycle technology can be seen as state-of-the-art technology in terms of electrical efficiency (40-45 %). Still the environmental impact is considerably higher compared to renewable based energy technologies. Photovoltaic (PV) turns out to have the highest Footprint within the renewable energy technologies. Energy consumption for panel production (which is fossil based) and low harvest rates result in a high Footprint per MJ. Wind power which relies also on discontinuously available and unpredictable sources has a much lower Footprint because of a less energy intensive process in producing wind power plants. For both PV and wind power the geographic situation and annual run time are crucial which makes it difficult to give precise Footprints for these technologies as they may produce considerable different amounts of electricity in different contexts.

Electricity from biogas is in this specific case based on corn and grass silage, where biogas is burned in a combined heat and power station. Biogas can also be burned in a micro gas turbine particularly for decentralized production. The SPI value is shared between power and heat in both cases according the energy output ratio.

Electricity production out of biomass was evaluated on the base of an Organic Rankine Cycle (ORC) power plant. This technology is intended to produce mainly heat but delivers electricity as a by-product. This is interesting for district heating networks of moderate capacities between 500 KW_{el} to $2MW_{el}$. Wood chips are used to heat an organic working fluid which is driving a turbine connected to a generator for producing electricity.

6.1.2 Biogas production based on intercrops

Biogas is a particularly interesting product because of its broad range of applications. It can be used for electricity and/or heat production or purified to provide biogas in natural gas quality. Purified biogas can be used as biofuel or fed into a natural gas grid. This technology may therefore be either used to provide base-load heat and electricity, bio-fuels or may even stabilize electrical grids by switching from CHP mode to gas purification when needed. Biogas may also be produced from a wide variety of raw materials, from corn and grass silage to manure to biogenic waste. It therefore warrants a closer look at its ecological performance.

Over the last years, subsidies have been provided for electricity from biogas (which is regulated e.g. through the eco feed-in tariff system by the Austrian Government (Ökostromgesetz, 2012)).

Utilization of crops like corn silage for biogas production has come under public scrutiny because of competition between food and energy production. During the nationally funded project Syn-Energy[1] potential intercrops as biogas feedstock were tested in different location in Austria. The aim of Syn-Energy was to investigate intercrop production potentials and their possible utilization for biogas. Bad Zell, a small village in Upper Austria, was focus of a case study. This case study was important for the systemic approach which includes optimization of transport of raw materials as well different locations of electricity production taking into account different options for selling heat within the region. PAPER 7 represents a mid-stage development evaluation and PAPER 8 the final outcome of this case study.

Within this study SPI evaluation achieves two objectives. First it offers an ecological impact assessment about intercrops in combination with main crops. The second objective was the application of PNS to this specific region which gives an optimal production solution. This system is then evaluated based on the SPI. A final comparison discusses if the effort of intercrops is worth implementing when the final Footprint is compared to other ways of producing electricity.

Based on fertilizer and machinery input data for intercrops agricultural production has been evaluated to get a SPI per ton of intercrops. The additional benefit of nitrogen fixation of intercrops which leads to a reduced amount of mineral fertilizer was also addressed.

Intercrops can be planted in combination with main crops and do not affect the main crops in a negative way. The amount of machine hours needed for cultivation is higher because main crop and intercrop needs treatment. To evaluate on a systemic base one

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[1] SynEnergy was funded by the Austrian Energy and Climate Fund (2009-2011)

hectare of agricultural field with main crops only (corn silage) was compare to the same hectare where the main crop is combined with an intercrop.

Table 1 gives a comparison per hectare of agricultural land with different production methods (Chopper and No-Till farming) for harvesting intercrops compared to a conventional production. Import In every case the main crop is not used for energy production. Biogas production out of intercrops represents a surplus benefit which can be achieved on the same area although more machine hours have to be invested.

	maincrop + intercrop		**maincrop only**
	Chopper	**No-till farming**	**conventional**
CH4 yield per t (dry matter) [m³]	300	300	
overall biogas [m³]	1,200	1,200	
intercrop SPI per hectare	119,581	106,934	
main crop SPI per hectare	56,097	37,145	119,924
provision of natural gas	0	0	648,480
biogas purification SPI	48,375	48,375	0
SPI [m² / ha]	**224,053**	**192,454**	**768,404**

Table 1: Biogas production potential based on intercrops vs. natural gas

The intercrops SPI per hectare is quite high (106,000 – 120,000 m²/ha) because of additional machine use. Biogas generated from these intercrops however can be purified to natural gas quality which means it substitutes natural gas. Compared with natural gas, intercrops utilization for methane production shows a much lower SPI value meaning that biogas from intercrops is indeed a more sustainable way to provide methane than from natural gas.

A further objective in this study was to identify an optimal technology network for the concrete case study Bad Zell. For this purpose PNS was used to generate an optimal solution. The challenge here is where to build biogas fermenters, how many and which capacity, considering a large number of local suppliers and necessary transportation.

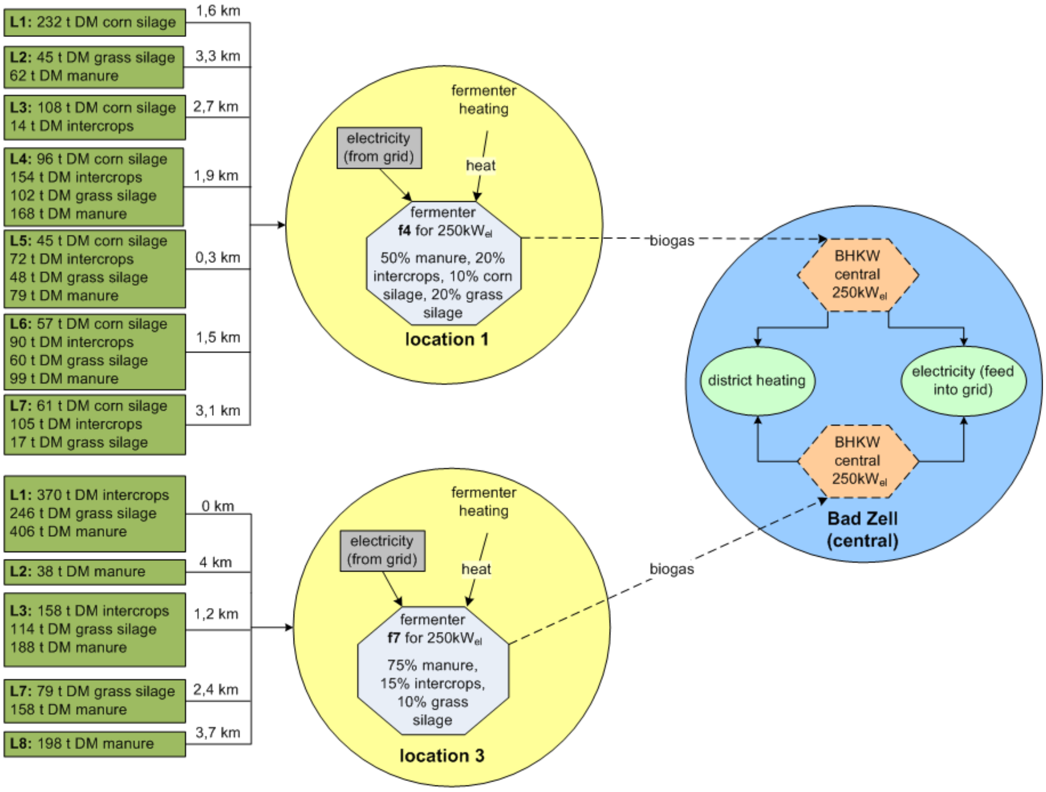

Figure 5: Optimal solution for Bad Zell case study

Figure 5 illustrates different raw material providers with different raw materials and transport distances from possible sites of fermenters which can be connected via biogas pipeline to central CHP units producing electricity for the grid and heat for district heating. SPI evaluation uses PNS optimization results to calculate an Ecological Footprint per MWh of produced electricity. Under the described conditions electricity from biogas would have a SPI value of 21,503 m²/MWh (which is equal to 5.9 m²/MJ) whereas heat would have a SPI value of 2,360 m²/MWh (which is equal to 0.7 m²/MJ) according to a price allocation between electricity and heat.

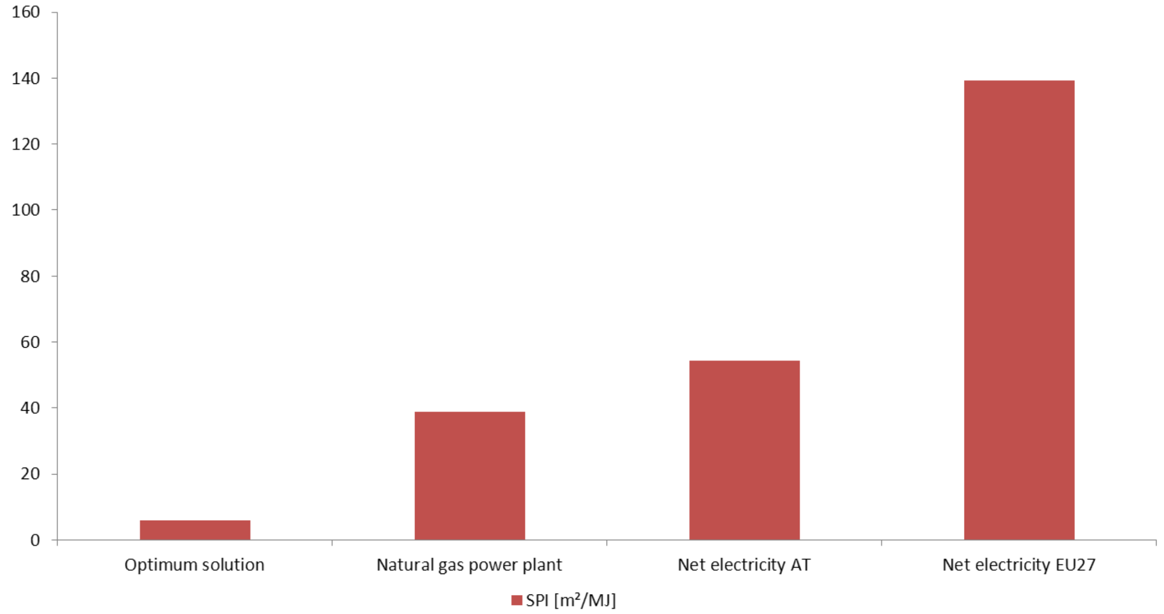

Figure 6: SPI comparison for electricity production

In Figure 6 the SPI value of the optimal solution electricity production is compared to the average electricity mix from EU27 (which can be seen as import electricity Footprint to Austria), Austrian average electricity Footprint and again the natural gas fired power plant already present in Figure 5 and Figure 6. The comparison shows a dramatic decrease of Ecological Footprint per MJ if intercrops are used for electricity provision.

Summarizing chapter 6.1 a clear benefit of renewable resource driven energy technologies can be identified on the production of energy although the ecological pressures of these technologies vary highly depending on their life cycle chain of resources. In a concrete local case study including more detail about transportation logistics and local conditions the results point out a major improvement for energy production from the ecologic point of view.

6.2 Biobased polymer production

Biobased polymers like polyhydroxyalkanoates (PHA) are a possible substitute for Polyethylene. Instead of crude oil renewable raw materials can be processed to PHAs. Fermentation is the main part of PHA production which needs carbon (for the PHA) and nitrogen (for the bacteria growth). Two different raw materials have been addressed in the ecological evaluation, namely sugar cane (PAPER 3) and animal residues (PAPER 4, PAPER

5). In all cases, energy provision is part of the process, highlighting the close interwoveness of commodity product and energy production.

6.2.1 PHB from sugar cane

Polyhydroxybutyrate (PHB) is part of the PHA family and can be produced from sugar cane through fermentation. Based on LCI (Life Cycle Inventory) data from ecoinvent (ecoinvent, n.d.) and Harding et al. (2007), the SPI value for PHB from sugar cane is considerably lower compared to Polyethylene out of crude oil (Figure 7).

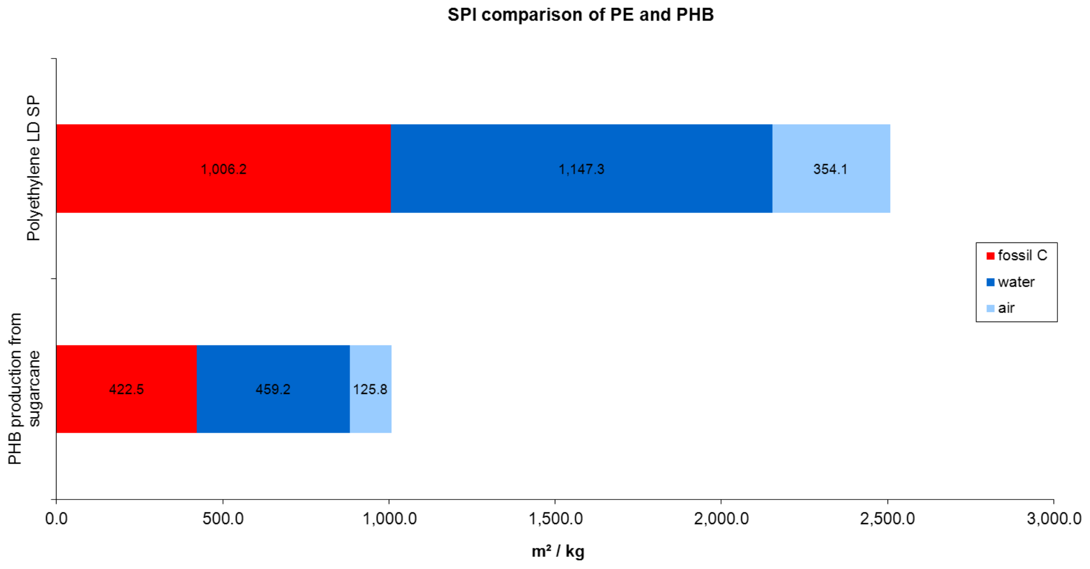

Figure 7: SPI comparison between PE and PHB

Only three main impact categories from SPI are illustrated because others are negligible. It can be seen that fossil C is reduced dramatically because of no crude oil input for polymer production. The main impact is from electricity consumption for the fermentation process itself. Bagasse (as a by-product of sugar production) burning in combined heat and power is taken into account which results in a SPI value of 95 m²/kg for sugar cane. Including fermentation processes the final SPI value is about 1,008 m²/kg PHB. Which is 60% lower compared to Polyethylene (PAPER 3).

Sugar cane utilization for PHB however competes with food production and energy (biofuel) processes, which raises the question if this renewable resource should be brought to this sector of industry.

6.2.2 PHA from animal residues

Instead of relying on primary agricultural products residues may be utilized. ANIMPOL[2], which is an EU funded research project, aims to provide a production scenario for animal residues to a higher value product (up-grading). The main target is to produce PHA from animal residues, generated in slaughterhouses. These residues can be seen as the carbon source for this process. Another goal for ANIMPOL is to substitute inorganic nitrogen (NH_4OH) with organic nitrogen also from the same animal residues, establishing a process utilizing these residues to produce a high value product. Combined with heat integration and closed water cycles a considerably lower SPI Footprint should be achieved compared to fossil based Polyethylene.

In terms of evaluation residues are handled differently compared to other impacts. Multi-output processes give a main product and side-product(s) which requests from the ecological evaluator an allocation. The SPI value for the whole process can be shared between every product according the mass balance or based on the price situation. In this case animal residues are produced as side product to the main product meat. The main intention for raising animals was to produce meat and therefore the whole SPI footprint is assigned to the main product meat. Therefore the impact for animal residues to the PHA production process is 0 m²/unit (this way of allocation does not only apply for animal residues but also for other residues, e.g. straw from wheat). Further treatment of the residue , transport and PHA production are of course part of the evaluation and defines the impact of the whole process on the environment.

PAPER 4 and PAPER 5 show an early stage development of a specific process design which is able to treat animal residues in a way to produce mainly PHA but also meat-and-bone-meal and high quality biodiesel (again highlighting the interrelation between energy and commodity provision). A main feature of this process scheme was the production of organic nitrogen for bacteria growth. Complex nitrogen sources have to be provided to the microorganisms needed to build up bacteria cells. After this first growth phase, fermentation bacteria accumulate PHA within their cell walls (when nitrogen supply is limited), which has to be extracted finally. Figure 8 (PAPER 5) illustrates the process design for the PHA production process which is still preliminary.

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[2] ANIMPOL project is financed by the European Commission within the 7th framework programme (FP7)

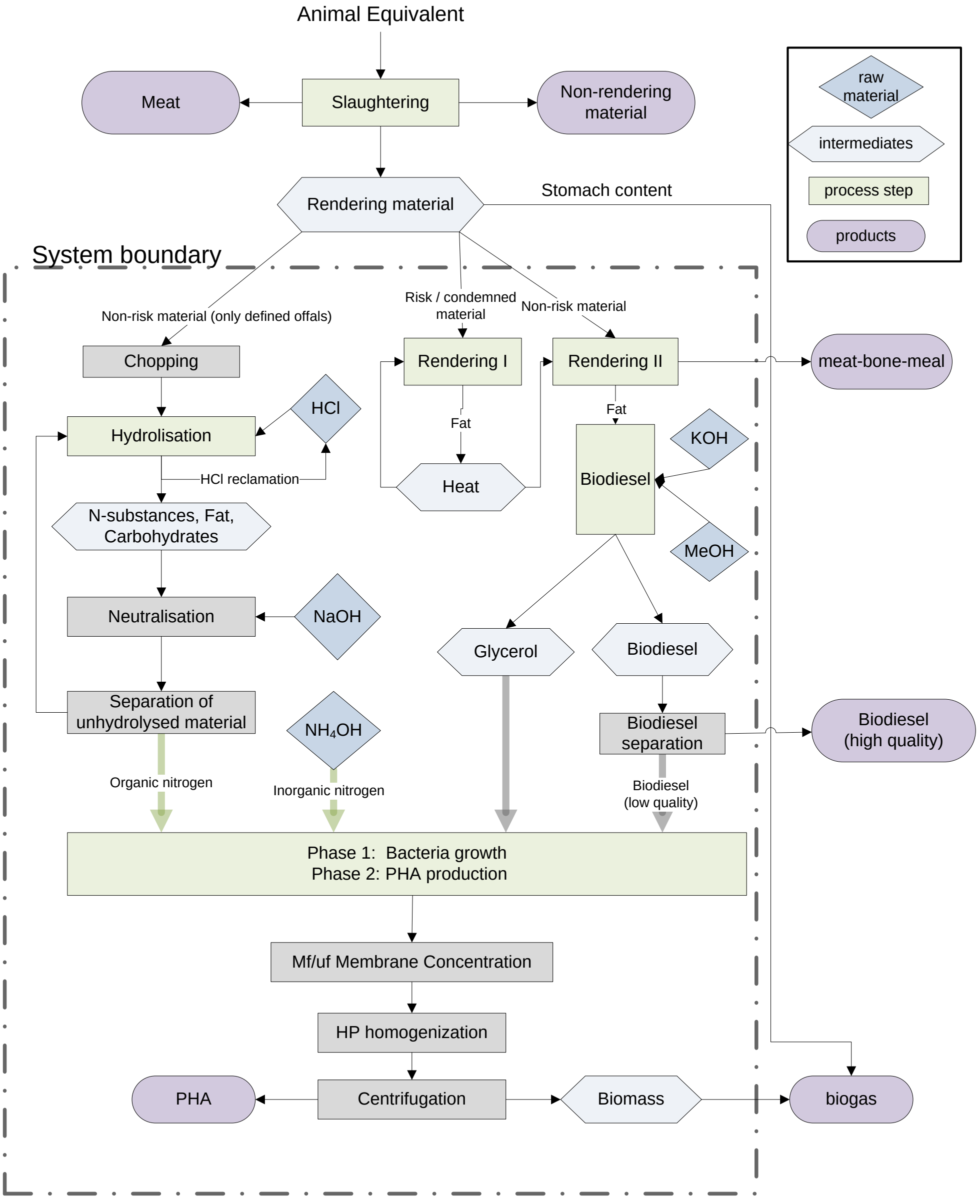


Figure 8: ANIMPOL process design (preliminary)

This upgrading process from residues to multiple high value products needs some input in terms of materials and energy but results in a lower SPI value for PHA compared to Polyethylene as well (1,950 m²/kg PHA compared to 2,500 m²/kg Polyethylene). Compared to sugar cane this value is higher but there are more products which can be gained from animal residues. Aside from that it addresses a raw material which is available without competing with the human food supply. PAPER 5 addresses also economic calculation to point out the feasibility of the whole production scheme. Both cases address process schemes with either integrated renewable energy system and/or provision of energy/energy carriers. These processes will become important when bio-resources have to be utilized to their full potentials. They form a specific category of bio-based processes summarized under the heading of "bio-refineries".

7 Further development of SPI

Experiences from every intensive evaluation work with SPIonExcel show the need for some additional features in the software. One of these requirements is the ability to integrate renewable energy technologies into the life cycle chain of already existing production life cycles. Even life cycle chains of renewable products (e.g. PHA) still contain fossil energy somewhere along the life cycle. SPIonExcel is not able to handle ″nested loops″ (i.e integrating products from downstream in process steps upstream in the life cycle) in its actual software structure. It is therefore not easy to estimate the impact of a more sustainable life cycle, e.g. biodiesel production where agricultural machines use themselves biodiesel, with the existing software. Aside from this major requirement there are some more points which have to be addressed in further developing the SPI software package:

- Process information is stored in local data files. This offers the possibility to disseminate processes easily but does not allow a centralized maintenance of datasets. Additionally it cannot guarantee that every user is working with the same database which can lead to different results for the same processes
- Microsoft Excel® is a continuously changing software base, therefore software maintenance of the Excel macro is constantly needed
- Microsoft Excel® does not allow to dynamically calculate SPI values along the whole life cycle chain for products. This means a change of inputs within a sub-process is not applied automatically to the next level process (which is the major requirement already pointed out above when discussing more sustainable life cycles)
- Visualizing results is complex and tedious
- The limit of 100 process steps does not allow addressing complex processes
- Software crashes related to Microsoft Excel® is pushing the macro to its limits regularly
- Operating System independency (Windows, Mac OS X, Linux,..) is becoming more important
- Software base should be free and Open Source to allow wide dissemination of the program

These weaknesses and lack of user friendly handling options have been identified over the last years of applying SPIonExcel. To address these problems a new software base has been chosen, which is PHP on a web server. **SPIonWeb** stands for a web based successor to SPIonExcel. A centralized MySQL database on Graz University of Technology servers will be set up which will ease maintenance work.

7.1 Dissipation area – Key emission area

Based on the original SPI methodology from Krotscheck and Narodoslawsky, 1996 some changes are introduced in SPIonWeb. Instead of cumulating all emission impacts (which is now done by SPIonExcel) the rule of a "key emission area" is applied. This rule has been part of the original methodology but was not implemented in SPIonExcel, partly because of complexity of programming, partly because of a different pedagogical strategy that put emphasize on highlighting all emission problems caused by a process.

The key emission area approach identifies the largest dissipation area caused by a certain emission flow from a life cycle. According to the original SPI methodology, the same area may then dissipate all other compounds in this flow as the concentrations of these compounds in replenished environmental compartments are safely below their natural concentrations in this compartment, thus fulfilling sustainability principle 2 as described in chapter 3. Therefore the emissions area calculation will be modified as follows:

Within a compartment (air, water or soil) only the largest emission area of an specific flow is considered because the same area is also able to dissipate other emission to the same compartment.

Following this argument from the original SPI methodology, for every emission compartment a key emission area is identified. This is basically done by taking the largest area within a compartment category. The definition of key emission area is extended by a second argument.

The largest dissipation area in any compartment will be chosen as key emission area. It will be assigned to the flow as dissipation area, the compound causing it will be the key emission for this flow and the compartment with the largest dissipation area for the key emission will be the critical dissipation compartment for this flow.

7.2 Dissipation area – Regionalisation of data

Another change that will be introduced in SPIonWeb affects how areas for emissions into water and soil are calculated. Regarding the SPI methodology, "Area for emission to water and soil" are dependent of the local annual precipitation rate respectively soil regeneration rate as well as local/regional concentrations of a compound in question in these compartments. A lower regeneration rate for a compartment results in a higher partial SPI value because of the longer time span which is needed to regenerate the specific compartment. SPIonExcel offered already the possibility to adjust these regional conditions, but only globally, which means adjusting regional conditions affected every user defined process along the chain. Within SPIonWeb every process has its own regional information stored and is therefore handling "Area for emission to water and soil" specifically for the region where this process is located. This offers the possibility to calculate dissipation areas along the life cycle chain more precisely, especially when different process steps are in different location with individual regional conditions.

7.3 Extended results

In addition to SPI values CO_2 life cycle emissions are calculated automatically from the partial area "fossil carbon". Within the database also Global Warming Potential (GWP) factors can be defined for other compounds than CO_2 which offers the possibility to express the GWP as well as the Carbon Footprint of processes, based on the same inventory as the Ecological Footprint.

7.4 Spatial planning options

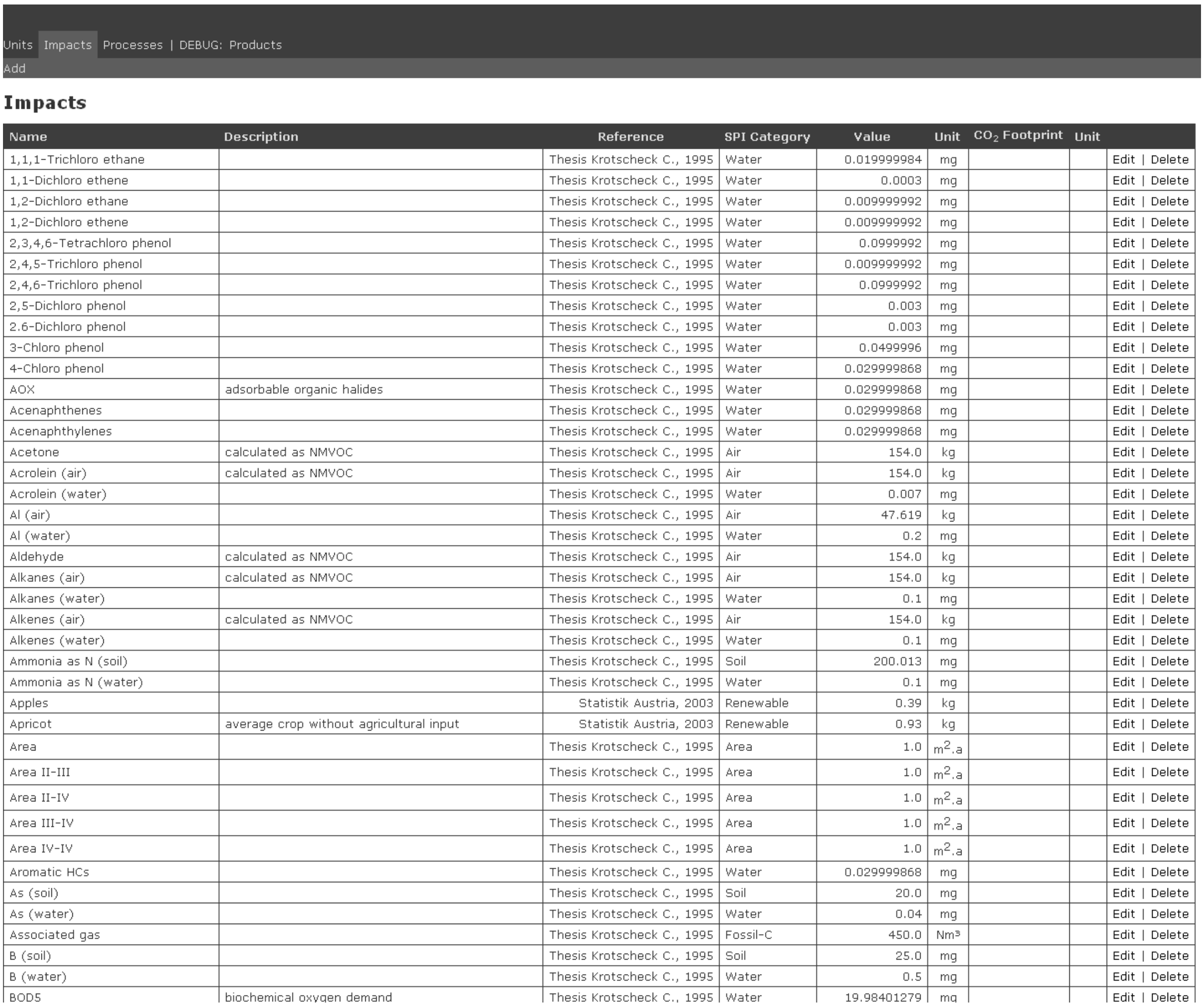
Although Footprint areas are not in direct relation to real land areas because of the conversion rules how mass flows are transferred to areas (e.g. conversion of fossil resources into an equivalent area), SPIonWeb offers more flexible options to evaluate energy related spatial planning. This has been identified as possible useful during the work carried out in PAPER 2. Due to the possibility to calculate dissipation areas based on local conditions, which is not an abstract area, spatial planning related topics can be addresses more easily in the future.

7.5 Software structure

Impacts are part of the central database and are defined by already existing data available in SPIonExcel (Figure 9). For processes a distinction is made between "Core processes" and "User-defined Processes". Core processes are maintained by SPI experts centrally and are provided "read only" to the users. Users are able to embed theses core processes in their own process chains. If adaption is needed users are able to convert core processes to user defined ones, which gives them write access. These processes then are only part of their own project, without changing the core process.

Process details and SPI results are given to the user already during the data input. A detailed tabular output of results will be given to users in the CSV format (comma separated values) which can be further modified and used to draw user defined diagrams.

User administration is done centrally which allows giving different users different access rights to the database. Additionally users have the option to share user defined processes and make them available to others for further use or modification.



Impacts

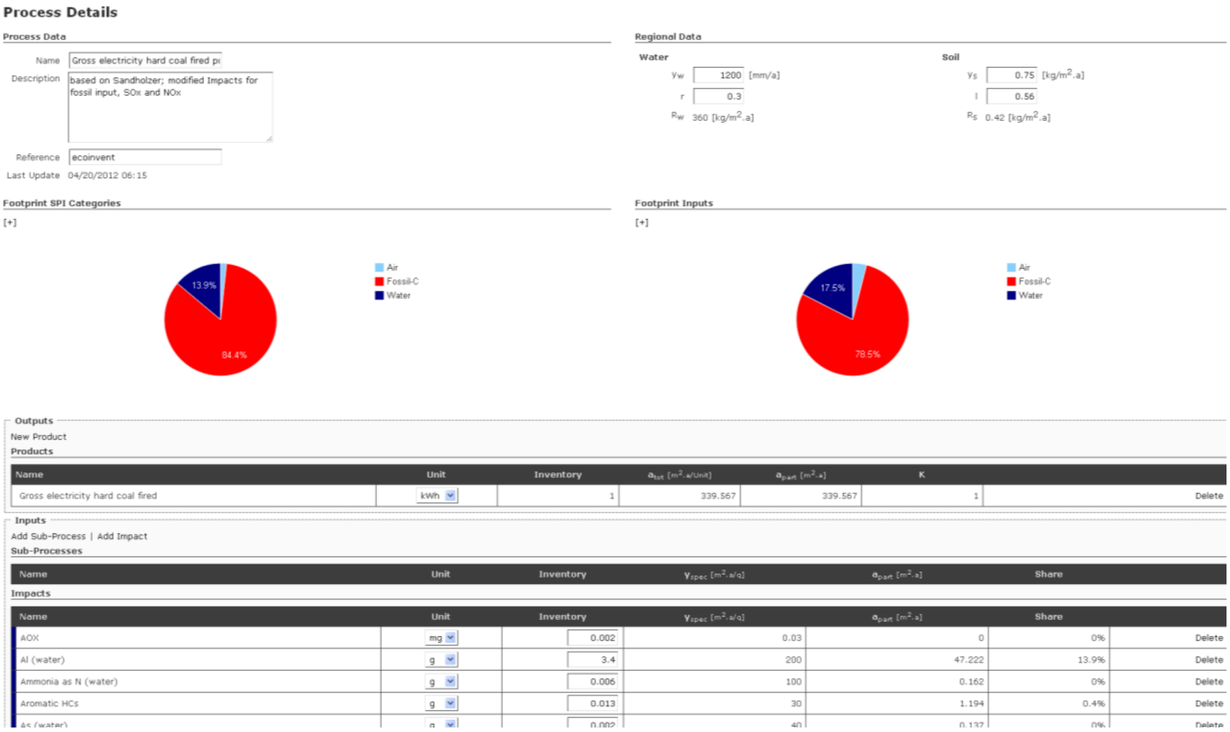
Name	Description	Reference	SPI Category	Value	Unit	CO_2 Footprint	Unit	
1,1,1-Trichloro ethane		Thesis Krotscheck C., 1995	Water	0.019999984	mg			Edit | Delete
1,1-Dichloro ethene		Thesis Krotscheck C., 1995	Water	0.0003	mg			Edit | Delete
1,2-Dichloro ethane		Thesis Krotscheck C., 1995	Water	0.009999992	mg			Edit | Delete
1,2-Dichloro ethene		Thesis Krotscheck C., 1995	Water	0.009999992	mg			Edit | Delete
2,3,4,6-Tetrachloro phenol		Thesis Krotscheck C., 1995	Water	0.0999992	mg			Edit | Delete
2,4,5-Trichloro phenol		Thesis Krotscheck C., 1995	Water	0.009999992	mg			Edit | Delete
2,4,6-Trichloro phenol		Thesis Krotscheck C., 1995	Water	0.0999992	mg			Edit | Delete
2,5-Dichloro phenol		Thesis Krotscheck C., 1995	Water	0.003	mg			Edit | Delete
2.6-Dichloro phenol		Thesis Krotscheck C., 1995	Water	0.003	mg			Edit | Delete
3-Chloro phenol		Thesis Krotscheck C., 1995	Water	0.0499996	mg			Edit | Delete
4-Chloro phenol		Thesis Krotscheck C., 1995	Water	0.029999868	mg			Edit | Delete
AOX	adsorbable organic halides	Thesis Krotscheck C., 1995	Water	0.029999868	mg			Edit | Delete
Acenaphthenes		Thesis Krotscheck C., 1995	Water	0.029999868	mg			Edit | Delete
Acenaphthylenes		Thesis Krotscheck C., 1995	Water	0.029999868	mg			Edit | Delete
Acetone	calculated as NMVOC	Thesis Krotscheck C., 1995	Air	154.0	kg			Edit | Delete
Acrolein (air)	calculated as NMVOC	Thesis Krotscheck C., 1995	Air	154.0	kg			Edit | Delete
Acrolein (water)		Thesis Krotscheck C., 1995	Water	0.007	mg			Edit | Delete
Al (air)		Thesis Krotscheck C., 1995	Air	47.619	kg			Edit | Delete
Al (water)		Thesis Krotscheck C., 1995	Water	0.2	mg			Edit | Delete
Aldehyde	calculated as NMVOC	Thesis Krotscheck C., 1995	Air	154.0	kg			Edit | Delete
Alkanes (air)	calculated as NMVOC	Thesis Krotscheck C., 1995	Air	154.0	kg			Edit | Delete
Alkanes (water)		Thesis Krotscheck C., 1995	Water	0.1	mg			Edit | Delete
Alkenes (air)	calculated as NMVOC	Thesis Krotscheck C., 1995	Air	154.0	kg			Edit | Delete
Alkenes (water)		Thesis Krotscheck C., 1995	Water	0.1	mg			Edit | Delete
Ammonia as N (soil)		Thesis Krotscheck C., 1995	Soil	200.013	mg			Edit | Delete
Ammonia as N (water)		Thesis Krotscheck C., 1995	Water	0.1	mg			Edit | Delete
Apples		Statistik Austria, 2003	Renewable	0.39	kg			Edit | Delete
Apricot	average crop without agricultural input	Statistik Austria, 2003	Renewable	0.93	kg			Edit | Delete
Area		Thesis Krotscheck C., 1995	Area	1.0	$m^2.a$			Edit | Delete
Area II-III		Thesis Krotscheck C., 1995	Area	1.0	$m^2.a$			Edit | Delete
Area II-IV		Thesis Krotscheck C., 1995	Area	1.0	$m^2.a$			Edit | Delete
Area III-IV		Thesis Krotscheck C., 1995	Area	1.0	$m^2.a$			Edit | Delete
Area IV-IV		Thesis Krotscheck C., 1995	Area	1.0	$m^2.a$			Edit | Delete
Aromatic HCs		Thesis Krotscheck C., 1995	Water	0.029999868	mg			Edit | Delete
As (soil)		Thesis Krotscheck C., 1995	Soil	20.0	mg			Edit | Delete
As (water)		Thesis Krotscheck C., 1995	Water	0.04	mg			Edit | Delete
Associated gas		Thesis Krotscheck C., 1995	Fossil-C	450.0	Nm^3			Edit | Delete
B (soil)		Thesis Krotscheck C., 1995	Soil	25.0	mg			Edit | Delete
B (water)		Thesis Krotscheck C., 1995	Water	0.5	mg			Edit | Delete
BOD5	biochemical oxygen demand	Thesis Krotscheck C., 1995	Water	19.98401279	mg			Edit | Delete

Figure 9: SPIonWeb - Impacts

7.6 User interface

The main interface for users will be the process section where every single process step within the life cycle can be defined with the according LCI input data (Figure 10). Beside descriptive information about the process it is now possible to specify individual dissipation parameters for every process. This influences the two partial areas "Area for emission to water" and "Area for emission to soil". Different locations have different dissipation parameters. On the one hand this is the local regeneration rate of the compartment water (mainly through precipitation) and on the other hand the local regeneration rate of soil based on local humus production.

A graphical representation of the SPI Footprint is given for the process.



Process Details

Process Data

Name: Gross electricity hard coal fired pc

Description: based on Sandholzer; modified Impacts for fossil input, SOx and NOx

Reference: ecoinvent

Last Update: 04/20/2012 06:15

Regional Data

Water

y_w: 1200 [mm/a]

r: 0.3

R_w: 360 [kg/m^2.a]

Soil

y_s: 0.75 [kg/m^2.a]

l: 0.56

R_s: 0.42 [kg/m^2.a]

Footprint SPI Categories

[+]

Footprint Inputs

[+]

Outputs

New Product

Products

Name	Unit	Inventory	a_{tot} [m^2.a/Unit]	a_{part} [m^2.a]	K	
Gross electricity hard coal fired	kWh	1	339.567	339.567	1	Delete

Inputs

Add Sub-Process | Add Impact

Sub-Processes

Name	Unit	Inventory	y_{spec} [m^2.a/q]	a_{part} [m^2.a]	Share

Impacts

Name	Unit	Inventory	y_{spec} [m^2.a/q]	a_{part} [m^2.a]	Share	
AOX	mg	0.002	0.03	0	0%	Delete
Al (water)	g	3.4	200	47.222	13.9%	Delete
Ammonia as N (water)	g	0.006	100	0.162	0%	Delete
Aromatic HCs	g	0.013	30	1.194	0.4%	Delete
As (water)	g	0.002	40	0.137	0%	Delete

Figure 10: SPIonWeb - Process details

SPIonWeb is still under development, therefore not every feature is described here in detail. The final version is scheduled to come on-line in late summer 2012.

8 Conclusions

Based on the three research objectives defined in chapter 2.2 that the following conclusions may be drawn:

- The SPI is able to give life cycle data based results to aid the ecological evaluation of energy technology systems.
- The differences between fossil and renewable resources are pointed out clearly by this evaluation.
- Further development of the SPI software orients itself on the original SPI methodology in terms of key emission area. This is an important step for a more systemic argumentation of the emission part within SPI results. The extension of processes by regional condition data prepares the SPIonWeb for the future to address a global economy much better.

Finally three main aspects can be identified that make the Sustainable Process Index methodology particularly useful.

The first aspect is about **limited natural income** of the globe combined with a continuously increasing human economy. SPI is useful to address this problem as it bases its evaluation on area (necessary to convert solar radiation to useful services and products). Besides its methodological merits area is a value system well known to the lay people, which is important if results have to be presented to non-experts.

The second aspect is about **process analysis** which can be done by using SPI. Due to the process step sharp setup procedure in SPIonExcel (as well as in SPIonWeb) ecological hotspots within a life cycle can be identified easily, both in terms of in which step they occur and what particular impact is critical. This information is useful if life cycle optimization is needed.

The third aspect is about **ecological comparison** of different kinds of goods and services. Because of the generalized measure unit [m^2a] different activities (e.g. 1 kWh of electricity compared to 1 kg of meat production) are comparable on the same level. This might be useful to get a feeling for ecological impacts in general. It may also be used to prioritize action, if several activities are compared and the most relevant can be addressed first.

Regarding renewable resource based systems as a focus of the evaluation in this work it may be said that renewable resource based technologies have been identified to have a major benefit compared to fossil resource based energy technologies and of course nuclear energy systems.

It must however be pointed out that in terms of evaluating renewable resource utilization a systemic approach becomes more important, due to the fact that for area based renewable resources transport logistics becomes a key part for comprehensive life cycles.

An interesting aspect particularly for renewable energy technologies is the difference between technologies regarding their ecological impact. For some technologies the input resource are crucial (e.g. biogenic resources based technologies) while for others the impacts during production of equipment (e.g. for photovoltaic, wind power) is more important.

Aside from the outcome about renewable energy technologies some practical things in SPI evaluations have also been identified. Due to the development of renewable energy technologies over the past years, SPIonExcel does not fulfill all requirements for versatile evaluation software anymore. Including renewable resource energy technologies into other life cycle is needed to get reliable results in a situation where more and more sustainable energy systems are implemented.

SPIonWeb as a follow-up to SPIonExcel should provide much more possibilities in evaluation of complex processes. Along with the need of a systemic evaluation of energy technologies which increases the amount of processes, SPIonWeb will also be able to handle more complex processes spanning different sites in different regions in the future.

In addition to SPIonWeb other thematic calculators are part of future development to extend the dissemination possibilities in order to bring the SPI methodology to interested people without the expert knowledge necessary to provide a full scale life cycle inventory and to evaluate comprehensive life cycles ecologically.

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10 PAPER 1

Regional Optimizer (RegiOpt) - Sustainable energy technology network solutions for regions

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10.1 Contribution to PAPER 1

Increasing efforts in combining PNS and SPI methodology led to the idea of RegiOpt. Contribution to this paper was to present the idea from a general point of view. Within this paper a short overview about the efforts in developing RegiOpt are given.

Regional Optimizer (RegiOpt) – Sustainable energy technology network solutions for regions

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Abstract

Developing energy strategies for the future is an important strategic task for regions and municipalities. Renewable based technologies and decentralized energy supply based on regional resources have the potential to locally and regionally increase added value, provide new jobs, decrease the dependency on limited fossil resources as well as on external energy providers and may have a positive impact on ecological stability.
Regional Optimizer (RegiOpt) software tool is based on the concept of Process Network Synthesis (PNS) (Friedler et. al, 1995 and Halasz et. al, 2005) and of the Sustainable Process Index (SPI) (Kotscheck et. al., 1996 and Sandholzer et. al., 2005). Both methodologies are combined in RegiOpt to enable the user to create economically optimal sustainable energy technology networks and at the same time evaluate them with respect to environmental sustainability.
Inputs to the software are (renewable) resources (e.g. amount of crops available for energetic use, biowaste, waste heat, etc.) and regional energy demand profiles. Both resource provision and energy demand can be provided in time dependent form. On top of that the user may supply contextual information like costs and prices of particular resources and services.
Result of the calculation with RegiOpt is the economically optimized technology network that fulfils the energy needs defined by the user and renders the highest regional added value. RegiOpt also provides the ecological footprint according to the SPI methodology. The user is able to calculate different scenarios based on different input data. RegiOpt software tool will be provided in two versions. Web based "Conceptual Planner" as a simple analysis for regional stakeholders and an "Advanced Designer" for a more detailed technology network scenario generation meant for expert use.

Keywords: Process Network Synthesis, PNS, Sustainable Process Index, SPI, Regions, energy production, electricity, heat, ecological footprint

Introduction

Local and regional stakeholders are increasingly interested in energy supply based on regionally available resources. Utilizing these resources increases the local or regional added value reduces economic dependencies and may also reduce ecological pressures, in particular green house gas emissions. Local economic is supported and new jobs are provided.
Every region however differs in terms of their available resources as well as their energy demand and market opportunities. Therefore RegiOpt. should help local stakeholders and decision makers to generate feasible future scenarios for their region. The user of RegiOpt gets an optimal renewable resource based technology network in accordance with the economical context of the region that is evaluated with the ecological footprint. By varying key parameters (e.g. prices for crops or conventional energy sources, availability of renewable resources and prices for energy services and products) a user will be able to generate scenarios that render a comprehensive picture of feasible development pathways for the region in question.

RegiOpt – A software tool for regions

RegiOpt combines two well established methodologies for process network analysis and evaluation of ecological sustainability. Process Network Synthesis (PNS) [Z,Y] is used to generate optimized technology networks using of a predefined set of available technologies provided within the software. In this set only technologies are considered that have proven their feasibility and that have been implemented at least on pilot scale. The PNS routine will select suitable technologies for any given region depending on availability of resources and the

structure of the energy demand. Economic optimization will then render the most optimal technology network that links available resources with regional demand (possibly including necessary imports and indicating surplus production). The user may define restrictions for the scenarios (e.g. demand that have to be strictly met, upper limits for market capacity to absorb certain products, etc.) as well as time profiles for demand and resource provision (at least when applying the “Advanced Designer”).
This optimized technology network is evaluated in terms of environmental pressures with the Sustainable Process Index (SPI) [X,W] method. The final result provides a potential economic output (annual profit) and an ecological footprint for any given scenario.

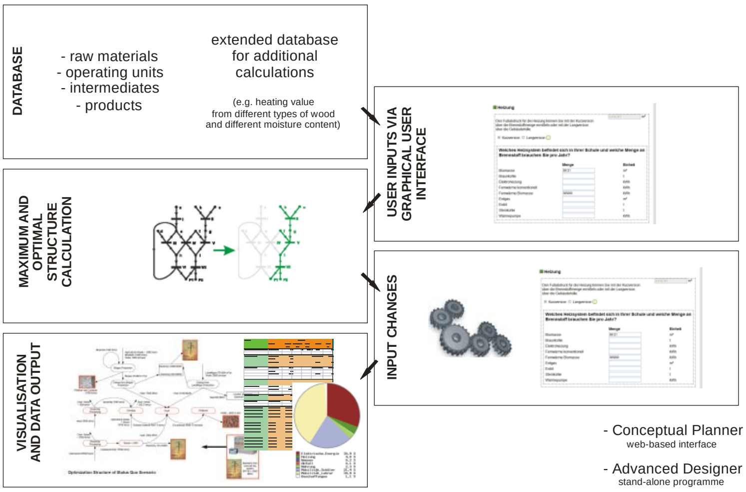

Figure 1: RegiOpt Macrostructure

The result is based on a predefined renewable energy technology list which is stored in a background database and will be up-dated in terms of performance and costs of technologies in regular intervals. Combined with contextual inputs given by the user following an input protocol the calculation is performed according to the architecture depicted in Figure 1.
Two different versions of RegiOpt will be available: a web based “Conceptual Planner” (CP) and a stand-alone program called “Advanced Designer” (AD). Both are using the same database but differ in graphical user interface. Conceptual Planner is meant for regional stakeholders and decision makers and will provide them with the ability to generate an optimized technology network based on a simple input protocol requiring non-expert knowledge on a website. AD version is dedicated for expert use only and will require more specific and detailed information of the region and will provide encompassing information taking spatial resource distribution and temporal profiles for resource provision and demand into consideration. AD and CP however are based on the same RegiOpt - Solver.

Database

A major feature of RegiOpt is an encompassing database. It includes
raw materials (renewable resources)
intermediates (e.g. biogas)
products (e.g. electricity)
operating units (technologies)
and provides basic data for each item like yields for different renewable resources, composition of materials and current prices for resources, products and energy services as well as mass and energy balances for conversion technologies and basic economic data like operating costs and investment costs (in most cases for different scales of any given technology). This list is compiled from real world projects as well as from literature data and information from technology providers. This list represent a “maximum structure” with regard to process synthesis.
For CP the database (and hence the maximum structure) is fixed and cannot be modified. AD provides the user however with the possibility to add, deleted or modify existing datasets.

Conceptual Planner CP

The CP operates as a webpage and enables users to calculate an optimized technology network for their regions based on non-expert knowledge. The user follows an input protocol that shortens the list of technologies in the

maximum structure based on regionally available resources and demands. The user is asked for available areas in different qualities (crop land, forests, grassland and possible areas for solar energy technologies).
Figure 2 illustrates how the amount of available resources is deduced from this input. Forest areas are interesting for energy wood that in turn is a possible input for different technologies (e.g. biomass burner, wood pellets production, biomass based combined heat and power (CHP) plants, etc.). The user has to define how much wood is already used (e.g. timber, wood products like furniture, energy wood for existing energy supply). Any excess biomass it will be used for as a resource for the generation of the optimised technology network generated by RegiOpt. Crop land can be used for energy crops where RegiOpt adapts the set of possible crops to the climatic zone where the region is located. Acreage necessary for food and fodder production is subtracted and the rest can be used for energy crops with RegiOpt taking care of possible competition between different crop productions.
Grassland can be used to provide input for a number of technologies, e.g. biogas production. Again acreage used by ruminants will be subtracted and the rest can be used for providing raw material to the technology network.

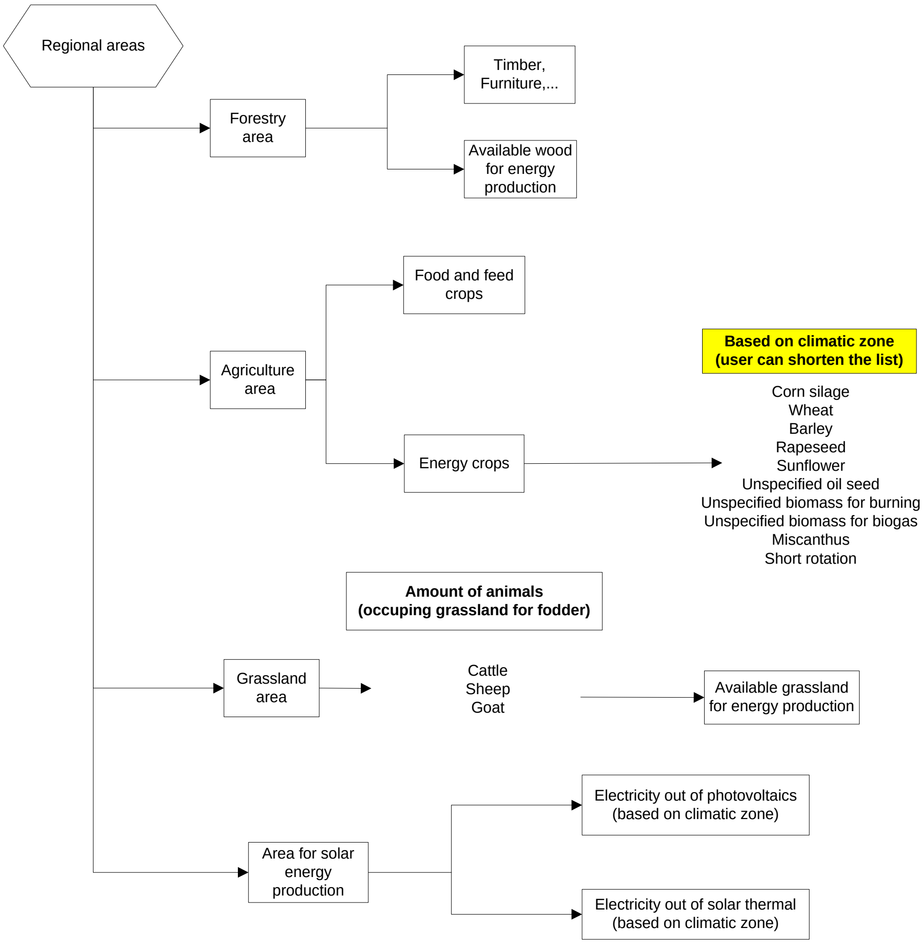

Figure 2: RegiOpt – CP; Area conversion methodology

The focus of the CP lies on providing a “quick and reliable” first analysis of the potential for a given region. It should be seen as a valuable starting point for a planning process, providing local and regional stakeholders with a solid base for discourse..

Advanced Designer AD

Detailed regional planning for future pathways towards sustainable energy systems will be supported by the AD. Although the basic database and the RegiOpt – Solver is the same for CP and AD, AD will provide expert user with a broad possibility to contextualize the data and to include time profiles as well as a first order spatial differentiation of demand and resource provision within a region. Results from the AD will therefore provide the user with additional information, in particular about the location, size and operational characteristics of the technologies involved in the regional sustainable energy system.

Results

RegiOpt-Solver (both for CP and AD) generates an optimal technology network for a sustainable energy system for any given region, using local and regional resources and fulfilling local and regional demand. The result for a given scenario based on the contextual data provided by the user will show the annual profit for the whole network as well as necessary investment costs and operating costs for the technologies involved. In addition an ecological footprint is calculated for the scenario, providing insight into possible ecological risks and highlighting benefits. Results can be stored for comparison with further scenarios, using different contextual frameworks.

Conclusion/Outlook

RegiOpt will be a powerful tool to support local and regional decision makers as well as energy experts in planning of sustainable local and regional energy systems. The web based CP part of RegiOpt will give non-expert local and regional stakeholders with a solid base for their initial discourse by providing them with a comprehensive first analysis of their chances for using local resources and meeting local demand. It also provides them with a versatile tool to develop a feasible vision for their energy future and with information about necessary co-operation between different sectors and stakeholders.
The AD part of the software will enable experts to build on the energy vision defined by non-expert stakeholders and optimize the technology network to accommodate time profiles for resource provision and demand as well as to decide about the best spatial distribution of the elements of the technology network.

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11 PAPER 2

Spatial dimension of sustainable energy systems: new visions for integrated spatial and energy planning

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11.1 Contribution to PAPER 2

During the research project PlanVision (funded by the Austrian Climate and Energy Fund) a matrix was developed which contains 34 elements interlinked to each other. These elements represent spatial planning and technological conditions which have more or less influence to the whole spatial system. Main contribution was to identify critical, active, passive and inactive elements. Another contribution to this paper was to fill out the matrix from an ecological evaluator point of view and to interpret these results.

Spatial dimensions of sustainable energy systems - *New visions for integrated spatial and energy planning*

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Abstract

The turn to sustainable energy system is a mayor societal goal at the global level. In this paper we argue that this radical shift in energy provision towards increased energy efficiency and the use of renewable resources can only be achieved if its spatial dimensions are taken into consideration. Spatial structures have considerable influence on different aspects of the energy demand, and with spatial planning the resource availability and use is influenced. Further, we propose that different spatial types need different strategies for the implementation of sustainable energy systems and that integrated spatial and energy planning is needed to support this change. Visions for four types of spatial structures, the city, the suburban area, the small town as well as the rural areas define their roles in the "space-resource-planning continuum", which are the foundation to shape an integrated spatial and energy planning system.

Keywords

Spatial planning, rural development, energy, renewable resources

Background

As energy systems are key infrastructures of society they are also an important issue of spatial planning. So far, the link between spatial planning and energy systems is mainly dealing with the problem that the energy provision of the built environment is guaranteed, may it be for residential, commercial or industrial development. Energy is a "hard" factor for zoning, especially for commercial and industrial areas [1]. Besides the fact, that energy has to be provided – which is usually no strong restriction because of the possibility to use easily available and readily transportable fossil energy – the link between spatial planning and energy planning is underdeveloped. We propose to look at spatial planning and energy planning not as distinct "two sides of a coin" but as a continuum so that intellectual separation and sectoral analysis leads to sub-optimal solutions. In the project PlanVision[3] an analysis of the interactions between spatial planning and energy planning was carried out. This is the base for this paper.

As can be derived from previous studies, there are substantial contributions spatial planning can make in shaping sustainable energy systems. Spatial planning sets frameworks for energy consumption, production and distribution [2], no matter if this is done consciously in planning processes or accidentally – often with negative effects concerning energy efficiency and environmental pressure.

Spatial planning decisions have mayor impacts on the energy demand of the built environment as well as mobility connected with the spatial structures (see e.g. [3]-[7]). Several initiatives of urban planning point out, that energy efficient settlement structures also lead to a high quality of life and have several features in common like decentralised concentration, multi-functionality, nearness within walking and/or biking distances as well as certain densities (see e.g. [8]-[16]). Although these relations between settlement structures and energy demand are well known, real developments more often do not comply with these concepts which leads to an increase of energy demand even in spite of more energy efficient buildings, appliances and vehicles (see for Austria e.g. [17]-[19]). Besides spatial organisation spatial planning decisions also influence energy demand by choosing sites with a certain topography and exposition as well as by framing the built structures in building schemes (see e.g. [5] [20]-[24]).

Research has also been done on spatial dimensions of energy conversion and distribution as energy provision (especially in the case of bio-based energy carriers) causes land demand and, therefore, calls for core issues of spatial planning like zoning, securing of land uses and resources as well as minimisation of spatial conflicts. Several studies have contributed to questions which spatial developments, land use conflicts and/or impacts of the utilisation of

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[3] Stöglehner, G., Narodoslawsky, M., Steinmüller, H., Steininger, K., Weiss, M., Mitter, H., Neugebauer G.C., Weber, G., Niemetz, N., Kettl, K.-H., Eder, M., Sandor, N., Pflüglmayer, B., Markl, B., Kollmann, A., Friedl, C., Lindorfer, J., Luger, M., Kulmer, V. (2011): PlanVision – Visionen für eine energieoptimierte Raumplanung. Projektendbericht. Gefördert aus Mitteln des Klima- und Energie-fonds. Wien. [not published yet].

specific renewable resources might arise (see e.g. [1] [25]-[28]). Furthermore, process designs for energy planning on the local and regional level have been elaborated. (see e.g. [29]-[42]). Within the project PlanVision an in-depth system analyisis of the spatial-resource-planning continuum was carried out identifying four elements (out of 34), namely multi-functionality, density, siting as well as resources that dominate the system.

The aim of this article is to examine in detail which implications the use of renewable resources for energy supply has for spatial planning. We also include the assumption in our considerations that in the long term also industry might switch to renewable resources and, therefore, additional pressures on limited renewable resources, especially biomass, will arise. Therefore, we will discuss spatial planning implications of an extensive sustainable use of renewable energy and introduce a new vision for the spatial organisation of energy and resource supply under sustainable conditions. Finally, we make a proposal for shaping integrated spatial and energy planning.

Methods

We develop the train of argument in the following way: First, we define spatial dimensions of sustainable energy systems. From these dimensions we develop a generic vision for spatial development considering a spatial-resource-planning continuum. Within this continuum we ascribe functions to four archetypes of spatial structures urban areas, suburban areas, small towns as centres of rural areas as well as rural areas based on the characteristics of different products and services. Furthermore, implications of the vision concerning the four dominating system elements are derived for the four spatial archetypes leading to specific objectives that should guide future planning. Finally, we deduce integrated spatial and energy planning instruments to achieve these objectives.

Spatial dimensions of sustainable energy systems

Sustainable energy systems, their generation as well as their utilisation are intrinsically linked to spatial management. Contrary to a society based on fossil resources to meet its energy and material demand, a sustainable society based on renewable resources will have to draw on space as its ultimate fundament for wealth. The reason for this prominence of space is that almost all renewable resources, solar radiation, wind and hydro power as well as bio-resources may be tracked back to our ultimate sustainable natural income, solar energy.

Solar energy is the quintessential area dependent resource. It can only be "harvested" from earths surface or by harnessing processes, such as wind and water power, that emanate from interaction between solar radiation and earth's surface. This makes spatial management and planning tantamount to resource and energy planning in a sustainable society.

Another aspect of renewable resources is of importance when analysing the link between spatial planning and resource provision: renewable resources are notoriously de-centralised resources. This is of course a logical result of their dependency on space for their generation. Contrary to all fossil (and nuclear) resources that emanate from point resources like mines and wells, renewable resources emerge on every square meter of earth's surface in the form of solar radiation and/or bio-resources.

Needless to say that this increased importance of space as the ultimate resource for sustaining life and economic activity of mankind has major implications for spatial planning. Spatial planning and energy planning cannot be separated anymore. From the point of view of planning, the reliance on sustainable energy sources creates a "spatial-resource-planning continuum" that can only be approached in an integrated way.

One particular consequence is the need to guide spatial planning and development according to the functionality of the space involved: the double role of space as the ultimate resource provider as well as habitat for society requires a more differentiated look on different spatial categories and their particular role and development framework.

This is in marked difference to the current situation of a fossil based society. As these resources are point resources (exploited usually far from areas of intensive human settlement), all spatial elements away from the singular exploitation areas (mines, wells, etc.) have comparable access to external resources. This in turn leads logically to the postulate of equal development opportunities for every location as there are only minor functional requirements in terms of resource management on a spatial level. Economic development is mainly driven by resources that have no immediate link to the space subjected to planning and hence spatial planning (with very few exemptions) is not linked to resource management. From a resource point of view in a fossil society, spatial planning deals with a mostly amorphous, unstructured matter.

A differentiated framework for spatial planning from the resource point of view must take into account

- the main characteristics of renewable resources;
- the structure of the distribution pathways for different qualities of energy in particular;
- archetypical categories for spatial development and their functionality within the spatial-resource-planning continuum.

Main characteristics of renewable resources

Solar radiation is an abundant resource that lacks however the high energy concentration of fossil resources. Harvesting this everlasting energy form therefore requires relatively large areas. A society based on renewable resources will thus have to manage its spatial resources in the most careful way.

Besides requiring space renewable resources by and large show in some cases (solar energy) cyclical and in other cases (wind power) erratic time dependency in their emergence. This requires storage to align energy provision with energy demand. In any case storage is costly, either in terms of money (e.g. for batteries) or in required area (when biomass is used to "store" solar energy). The imperative to provide storable energy for stabilising energy provision as well as for particular applications (namely mobility) assigns biomass in its various forms a privileged role among other sustainable energy forms. This in turn increases the spatial requirements considerably, because biomass has a much lower yield compared to other sustainable energy forms such as thermal solar energy, PV or wind power. The utilisation of arable land as well as forests and hence spatial planning becomes much more intricate in a society based on renewable resources as a result of the intrinsic need for energy from biomass.

Finally logistical considerations become central to the energy system. Many renewable resources (in particular low grade biomass like grass, wood chips or straw) have low transport densities, in some cases (e.g. wood chips, grass) paired with high humidity. This restricts feasible transport distances considerably, requiring de-central conditioning and/or utilisation of such resources.

Structure of distribution pathways for sustainable energy

Besides the characteristics of sustainable energy resources the structure of distribution pathways is an important factor in the spatial-resource-planning continuum. Different energy qualities such as electricity, heat/cooling energy, gas and oil are distributed via large scale infra structures and show widely different ranges and distribution densities. On top of that energy qualities may be transformed into each other following restrictions defined by laws of nature: electricity may readily be transformed to heat/cooling energy, gas and oil may be partly transformed into electricity but always render heat as a by-product in this transformation, low temperature heat can only be transformed into cooling energy.

Table 1 shows the characteristics of different distribution grids. This table already assumes that these grids are "smart" in the way that they accommodate feed-in from different providers than central sources where appropriate.

Generic visions for spatial development within the spatial-resource- planning continuum

A sustainable energy based society requires highly efficient management of the space as the ultimate resource. Efficient management however entails differentiation between spatial elements and insight into the functionality of these elements. A generic categorization of spatial elements within the spatial-resource-planning continuum renders the following four archetypes:

- Urban centres
- Suburban areas
- Small towns as centres of rural areas
- Rural areas

Table 1: Characteristics of different energy distribution pathways

Energy form		Density	Range	Feed-in	Utilisation
Electricity	Low voltage	Very high	10 km	Everywhere	Everywhere
	Medium voltage	high	50 km	Everywhere	Everywhere
	High voltage	medium	500 km	International, Urban centre Suburban Small city	Urban centre Suburban area Small town
Gas	Low pressure	Very high	20 km	Urban centre, Suburban, Small town Selectively in rural areas	Urban centre Suburban area Small city
	High pressure	Very low density	1.000 km	International, Urban centre	Urban centre
Heat		Very high	10 km	Everywhere	Everywhere
Oil		Very low density	1.000km	International, Urban centre	Urban centre

These archetypes are assigned vital and widely different functionalities within the spatial-resource-planning continuum. From a resource/product point of view the generic visions – independent from the state of development of the four archetypes and the gap between state and vision – may be described as follows:

Urban centres are the main consumers of energy in all forms. Conversely they are the main providers of complex (industrial) goods (e.g. electronic devices, machinery, cars etc.) and services.

Suburban areas form the spatial reserve for urban centres and take over a major supply function for them, namely the supply with fresh products of daily consumption (e.g. high quality food).

Small towns as centres of rural areas have the function to convert in particular bio-resources into easily transportable commodities and form crucial nodes in the distribution grids for energy, linking them and shifting energy from one to the other (e.g. by using biomass to generate electricity and heat or to generate (bio-)gas that may be distributed via the grid).

Rural areas are the ultimate provider for crucial bio-resources, both for sustenance as well as storable energy carriers.

In order to obtain a clearer picture on the interaction between these archetypes, at least on the level of material products, table 2 provides an overview on what type supplies what product to society.

Table 2: Matrix of provision and consumption among archetypical space categories

Product type	Consumer	Provider
Fresh products of daily consumption	Urban centre	Suburban area
	Suburban area	Suburban area
	Small town /rural centre	Rural area
	Rural area	Rural area
Commodoties	all	Small town/rural centre
Bio-resources for commodities	Small town/rural centre	Rural area
Complex industrial goods	all	Urban centre

The nature of the spatial-resource-planning continuum however requires not only to take energy aspects into consideration but to match them with the basic functions the described archetypes have to provide from the social and economic point of view. Taken together these different functions can then be used to provide a comprehensive set of planning goals for sustainable spatial development. Table 3 provides this overview.

In the following sub-chapters the visions for the spatial types are described in more detail along the dominating system elements multi-functionality, density, siting as well as resources as base for the production and distribution of sustainable energy.

Urban centres

As urban centres are the main user of energy and resources and production areas for primary production are limited, questions regarding the generation of energy take a backseat to those concerning efficiency (including energy saving by structural, technical and behavioural change), distribution and transport. Efficiency is the highest premises for sustainable urban development in order to reduce material and energy input in the first place. This requires also conscious material management, including collection and transport of waste combined with recycling of materials and thermal use which might substantially contribute to the energy supply of the city. In addition to waste a city’s resource portfolio may also include solar energy utilisation.

Multifunctional, densely populated areas are an important precondition to guarantee for the efficiency of complex infrastructures like energy supply, public transport, high quality social infrastructures as well as for economic advantages. Multifunctional and dense areas are also an important precondition for the levelling out of dynamics between consumption and production as well as cascade use of energy over time. Concerning siting and zoning of different land uses on the system level multifunctionality and at least medium dense agglomeration are key to ensure energy efficiency, both from the mobility point of view as well as according to the preconditions for energy (and resource) cascades. In particular heat cascading needs short distances (as heat losses in grids are considerable) and diversity in heat quality demand (provided by multifunctionality) to utilise energy in the most efficient way with energy intensive industries at the top of the cascades and residential heat and cool at its bottom. Details like local climate conditions or urban design questions might just lower energy demand and might contribute to fulfil the efficiency paradigm.

Table 3: Generic visions – elements for spatial categories

Urban centre		Suburban area		Small town/rural centre		Rural area	
Basic function	goal	Basic function	goal	Basic function	goal	Basic function	goal
Living space for majority of people	Highes quality of living	Spatial reserve for urban centre	Highest logistic efficiency for people and goods	Attractive living space for de-centralised industrial society	High quality of living	Sufficient population density for primary production and sustainance	Basic provision of • goods (daily consumption) • education (primary level) • social services • cultural services
	Sufficient leisure time opportunities				Excellent leisure time opportunities		
	High environmental quality		High environmental quality		Highest environmental quality		
	Comprehensive provision of • goods • education (up to tertiary level) • social services (health/ care) • cultural services • research		Basic provision of • goods (daily consumption) • education (primary level) • social services • cultural services		Advanced provision of: • Goods • education (up to secondary level) • social services (health/ care)l • cultural services • research	Recreational space	Highest environmental quality
							Sufficient touristic infrastructure
Main energy/resource consumer	Highest efficiency of use		Highest utilisation efficiency	Resource conversion	Lowest pressure in resource conversion /utilisation	Sustainable resource provision	Highest efficiency in space utilisation
	Lowest pressure in energy provision/utilisation		Lowest pressure in energy provision/utilisation				Max. long term yield per area
	Lowest resource consumption		Lowest resource consumption		Highest conversion efficiency		Stable eco systems
Provider of complex (industrial) goods and services	Highest resource conversion efficiency	Space reserve for provision of complex goods	Highest resource conversion efficiency		Linking the distribution grids		Highest logistical efficiency for renewable resources and by-products of conversion processes
	Strong societal interaction	Provision of fresh goods for urban centre	Highest efficiency in space utilisation				
	International interconnectedness		Max. long term yield per area				No ressource import

Suburban areas

In this vision presented here, suburban areas are perceived as spatial reserve for urban areas dedicated to the following functions: primary production of fresh goods with maximum production within environmental capacity limits. Furthermore, suburban regions will provide space for "spill-over" complex goods production close to urban centres adhering the high efficiency principle like in urban centres.

In our vision just basic supply should be covered in suburban areas whereas for more specialised supply demands the suburban area shall be oriented to the urban centre. Suburban shopping centres or hypermarkets do not comply with our vision as they clearly violate the highest efficiency principle postulated for urban regions (mainly because of the necessary individual mobility induced by them as well as the sealing of productive areas) as well as the necessary multi-functionality in cities by concentrating commerce.

This concept calls for high logistic efficiency for people and goods which means orientation of siting and zoning for the built environment in medium dense mixed use areas located on high-capacity public transport lines as well as siting industrial and commercial facilities for complex products on regional and supra-regional distribution grids (electricity, gas, heat, transport) complying with ideas of decentralised concentration.

Suburban areas are important locations to produce fresh products for the urban centres (again against the backdrop of highest efficiency for the provision of urban centres) and may as well be the location of autonomous production of energy (especially drawing on solar energy technologies and the wastes from the production of fresh products for cities), whereas suburban areas have little importance for large scale commodity production.

In this spatial archetype the restructuring process according to this vision requires the most intense changes of actual developments as suburban areas are arguable the farthest from sustainability considering the spatial-resource-planning continuum.

Small towns as centres of rural areas

Rural small towns are designated to a completely new role in a renewable resource economy. They become the platform of resource processing for commodities which lies in the nature of renewable resources: as they often have little durability and low transport densities, transport distances have to be kept short from the harvesting area to the sites of transformation into commodities. This is dictated by the need to mitigate land deprivation (by returning nutrients from by-products of biogenic raw material conversion to the land) and to high energy demand for transport of biogenic raw materials and wastes from processing them, usually featuring either low transport densities or high water content or both. In this sense the utilisation of a renewable resource base means to find an optimum between an "economy of scale" – which means the bigger the commodity production plant is, the more efficient is the resource conversion – and the "ecology of scale" – the smaller the plant is the more efficient is transport logistics [43]. In order to find this optimum in a generic way, we suggest that medium sized commodity production in small towns might best fulfil this task.

To efficiently produce commodities, rural small towns will become nodes between different grids like information, electricity, transport, district heating. They have labour and supply functions for the regional population (in contrary to suburban areas which are oriented towards the urban centres in most of these aspects). Furthermore, innovation capacity in research in development concerning commodity production has to be built up. As resources differ in different regions, there will be considerable differences in the means and ways commodities are offered. Concerning energy conversion rural small towns will have to be treated similar to urban centres, meaning that mainly solar energy and thermal energy recovery of waste materials from the commodity production will be the main sources of energy.

Following this vision, rural small towns might become an attractive living environment of a decentralised industrial society. Efficiency principles apply in particular to resource conversion and optimal management of supply grids, e.g. for the utilisation of material and energy residues from the commodity production. Again, multi-functionality and density are important features to establish to ensure efficiency in energy use like short supply grids for district heating and to sustainable transport. Because of nearness in small towns transport will often include walking and biking, whereas public transport is mainly important to reach urban centres as well as the surrounding rural villages. The role of siting and zoning can be argued in the line with urban centres.

Rural areas

In this vision rural areas have the task of supplying resources for society as supply area of all other spatial types. This is accompanied by securing of daily supply (e.g. food, schools, childcare) as well as by the function as recreation area. The long-term securing of biological productivity and stabile ecosystems includes mixed-functions of primary production within environmental capacity limits as well as re-introducing of materials and nutrients from conversion processes and from harvest. In order to utilise "economy of scales", to guarantee efficiency of transport logistics and to utilise waste heat in energy grids the processing of raw materials on rural sites is not desired in this vision but is concentrated in small towns as centres of rural regions.

Concerning settlements that means providing living space mainly for the population needed to keep up primary production, basic supply and recreational uses. Density for settlements is important in order not to waste bioproductive land and secure ecological compensation areas as well as for organising efficient public transport to small towns and urban centres and other supply infrastructures. It would even be desirable to increase bioproductive areas at the cost of underused sprawl settlements and infrastructures.

Results and discussion

The generic vision presented above may not only guide planning decisions or provide additional backup of long desired planning visions like multifunctional settlements, decentralised concentration, density, nearness etc. as presented in the introduction section. This vision also adds further notions to terms used in spatial planning. For instance, the concept of multi-functionality is normally addressed to the seven basic spatial functions housing, working, nourishing, recreation, supply and disposal, transport as well as communication [15]. Considering resource use, supply and disposal has to be more specified along the production chain of renewable resources – commodities – convenience products and further re-feeding of residues to production sites. Further notions of multi-functionality or density or zoning are added by the fact that in order to utilise energy most efficiently, the loss of waste heat has to be minimised, which means that energy cascading has to be exhausted. Therefore, district heating is very important which is most efficient in multi-functional and dense areas as reasoned above.

Many aspects to implement the vision presented here can be covered within existing planning schemes especially when it comes to energy efficient and energy saving settlement design. Most design principles to reduce energy demand are state of the art in the planning discourse but far from state of the art in planning practice. Dependent on the current status of the planning regulations of a specific country additional planning instruments might be useful to be introduced like legally binding planning objectives for "structural" energy efficiency of settlements, coordination of regional planning, zoning, subsidies, tax payments, possibilities to influence real estate markets, legally binding frames for building schemes like minimum (and maximum) densities etc.

Additionally, we propose holistic, spatially differentiated energy and resource planning on national, regional and local levels that has to spatially assign resource utilisation and environmental protection measures. Such integrated energy and resource plans should comprise at least the following contents:

- energy efficiency and energy saving targets;
- renewable material and energy utilisation targets under consideration of environmental capacity limits, environmentally friendly production techniques and non-use of ecological compensation areas;
- spatially differentiated area based material flows in order to enforce re-introduction of nutrients into primary production areas;
- determination of the demand for energy conversion and distribution facilities.

The demand question for energy conversion and distribution facilities operates on the system level, where necessities, size and technological options are clarified before specific sites are designated and projects developed. In this model the development consent for energy supply facilities could only be approved if the demand for a certain plant or grid can be derived from the integrated spatial and energy plan. Furthermore, also existing spatial plans like regional plans or local spatial development strategies would be feasible to secure renewable resources by zoning respective areas, whereas the main contents of the integrated energy and resource plans sets the frame for spatial planning and goes beyond its competence.

Conclusions

The turn towards a renewable resource and energy base of society will introduce new challenges not only for the affected infrastructure systems, but also for spatial planning. These impacts are causes by the nature of renewable, especially biomass based resources which are characterised, inter alia by low transportation density and short durability if unprocessed. Designing viable supply chains around biomass resources means to structure spatial organisation in a different way with implications for urban and regional planning way beyond the supply infrastructures.

Taking spatial dimensions of the transition to sustainable energy systems into account, mayor challenges arise, inter alia, (1) in cutting back energy demand by re-designing cities, towns and villages as well as related infrastructures in order to achieve, inter alia, multifunctional, dense and structurally energy efficient units that allow for energy efficient individual lifestyles; (2) in enhancing sustainable energy and material resource production by securing sufficient areas and keeping them free of land uses that compromise resource production and utilisation, e.g. by preventing urban sprawl; (3) in guaranteeing for energy and resource production within environmental capacity limits; (4) in a spatial differentiation of energy and resource production and processing according to natural production conditions; (5) in coordinating energy and resource planning and spatial planning to reach optimal exploitation of already conversed energy by cascading and the connection of different grids.

With the visions for the spatial-resource-planning continuum we draft a potential future for managing this transition to a renewable resource base and to sustainable energy systems. The inevitable transition to a sustainable resource base, with resources that are both limited and linked to spatial conditions, requires profound change in planning practice as resource constraints might become dominating guardrails for human development. Spatial structures set effective frameworks for resource systems both on the demand and the supply side, which at the moment often do not comply with resource efficiency. Spatial structures are, although not unchangeable, persisting over time, so that a re-direction of practiced planning paradigms towards more sustainable spatial development is pivotal for society.

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12 PAPER 3

SUGARCANE AS FEEDSTOCK FOR BIOMEDIATED POLYMER PRODUCTION

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Contribution to book:

Sugarcane: Production, Cultivation and Uses

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12.1 Contribution to PAPER 3

Within PAPER 3 the SPI evaluation of PHB production has been the main contribution. Because of sugar cane as resource a life cycle evaluation of sugar cane was needed to get a SPI Footprint for the final product. This offered the possibility to compare PHB to conventional fossil based Polyethylene.

Chapter

Sugarcane as Feedstock for Biomediated Polymer Production

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Abstract

The availability of fossil resources for production of various goods like plastics causes increasing preoccupation for numerous industrial branches. Not least due to miscellaneous political developments in several petrol exporting countries, the unpredictably fluctuating price of petrol constitutes a factor of immense uncertainty, especially for the highly petrol-dependent polymer industry.

Nowadays, switching from fossil to renewable resources as starting materials for polymer production is generally considered as a promising strategy to overcome these problems, especially in combination with industrial waste treatment.

In order to make biobased and biodegradable polymers like polyhydroxyalkanoates (PHAs) economically more competitive with common resistant plastics from fossil resources, their production has to be reduced considerably. *Inter alia*, the selection of suitable renewable resources as carbon feedstock for PHA production is one of the major cost decisive factors in the entire PHA production chain. Sucrose from sugarcane, together with its high significance for nutrition purposes, constitutes a powerful renewable feedstock for the biomediated production of polymers like PHAs and other goods required by mankind such as biofuels. Beside the selection of a suitable carbon source, potential microbial production strains guaranteeing fast growth, high product formation rates and robustness have to be chosen. Such organisms are found among

Gram-negative and Gram-positive bacteria and even among extremophilic representatives of the archaea.

The integration of PHA production into a sugar and ethanol factory starting from the raw material sugarcane is realized on semi-industrial scale in Brazil. This integration makes it possible to achieve an economically competitive production price for the biopolyester when compared to other PHA production processes on a larger scale. This cost reduction is enabled by an efficient utilization of by-products of the sugarcane plant, especially the lignocellulosic waste bagasse, and by the utilization of additional in-house waste streams for the biopolymer isolation from bacterial cells. In this process, bagasse is burned for generation of steam and electrical energy required for several process steps in PHA production. Further, the price advantage to be obtained is caused by the availability of the substrate sucrose in high quantities. Together with the combustion of the sucrose-stemming ethanol as a “first generation biofuel”, CO_2 emissions from the production plant return to the sugarcane fields via photosynthetic fixation by sugarcane, resulting in a carbon balance of nearby zero. This way, major drawbacks in profitability and environmental embedding of PHA production are solved by a future-oriented, integrated process. In addition, the production of biobased polyethylene starting from sugar cane is discussed in the work.

The article points out the ecological and economical aspects of biopolymer production starting from sugarcane and its by-products such as molasses and hydrolyzed bagasse. It is demonstrated that the application of Life Cycle Analysis and the strategies of Cleaner Production provide precious tools for quantifying the ecological footprint of sugarcane based polymer production. Further, potential improvements of the process by a number of recently investigated microbial production strains are highlighted.

Introduction

Plastic materials for numerous applications are indispensible for the modern human society. This is owing to their desirable chemical and mechanical properties allowing them to replace traditional basic materials like wood and metals. Among these properties, versatility of properties, low density, tensile strength, imperviousness to water, non-rusting and high resistance to natural degradation processes have to be underlined[1].

At the end of 2010, the global overall production volume of plastics made from fossil resources reached over 250 million tons which is in huge contrast to the values valid only 20 years before, where the entire plastic production amounted to 100 million tons, or even 60 years, when only 1,5 million tons of plastic were produced [2,3]. This indicates that, without exaggeration, mankind nowadays lives in the “plastic age”. As a consequence, our planet is literally covered with highly resistant polymeric materials mainly due to their lacking accessibility to natural degradation, the insufficient performance of recycling systems and the risks connected to thermal conversion of plastics by incineration [4]. These facts, together with the strongly fluctuating prices for fossil resources, provoke an increasing awareness of industrial decision-makers to switch to novel strategies for polymer production based on renewable resources.

In contrast to plastics from fossil resources as discussed above, polyhydroxyalkanoates (PHAs) represent a class of polyesters that are *biobased* regarding the feed stocks, further, they are *produced by living microorganisms*, and, finally, they are *biocompatible* and *biodegradable* according to standardized norms and certificates as explained later. In addition to these favorable attributes, PHAs and its follow-up products can be processed to create a broad range of marketable products for a multiplicity of applications such as simple packaging materials, starting materials for fine chemicals, products for medical purposes and surgery (monomeric PHA building blocks active as drugs, drug delivery carriers, or biomedical implant materials) [5], and, more recently, even for production of biofuels [6]. This variety of potential applications is due to the possible fine tuning of the monomer composition of PHAs during their biosynthesis by providing the microbes with special co-substrates, resulting in the intracellular accumulation of co- and terpolyesters. This PHA composition is mainly responsible for the material properties like crystallinity, thermodynamic behavior and mechanical characteristics. It has to be emphasized that the processing of PHAs, e.g. via injection molding, can be accomplished using the same processing devices as used for converting classical plastics like polyethylene (PE), polypropylene (PP), polyethylene terephtalate (PET) and many others [4].

In nature, PHA accumulation occurs in a broad range of Gram-positive and Gram-negative eubacterial species and in several representatives of the domain of the archaea. Estimation exists that about 30% of all soil-inhabiting prokaryotic species are able to accumulate PHA [7]. For PHA harboring prokaryotic cells, these inclusions mainly serve as storage materials for carbon and energy, providing them an advantage for survival under starvation conditions. Beside this, PHAs play crucial metabolic roles for different microbial species for sporulation, cyste formation, germination, and control of exopolysaccharide excretion. Further, PHAs enhance the cell´s endurance under environmental stress factors such as UV irradiation, high salinity, thermal and oxidative stress, desiccation, or osmotic shock. In addition, they are important for balanced use of available intracellular energy and distribution of carbon reserves, the energy flow for cell motility, and, looking at diazotrophic species, for the energy flow during nitrogen fixation. Under conditions of starvation these reserve materials are catabolized again by the cells [8,9]. Figure 1 shows an electron microscopic picture of cells of *Cupriavidus necator*, a well-known Gram-negative eubacterial strain that is able to produce PHA from various renewable resources such as the hydrolysis products of sucrose. In Figure 1, PHA granules are well visible as refractive intracellular inclusions.

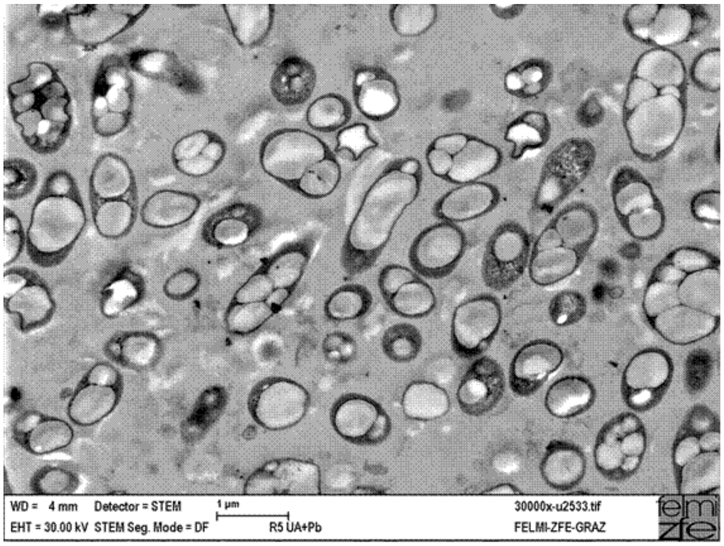


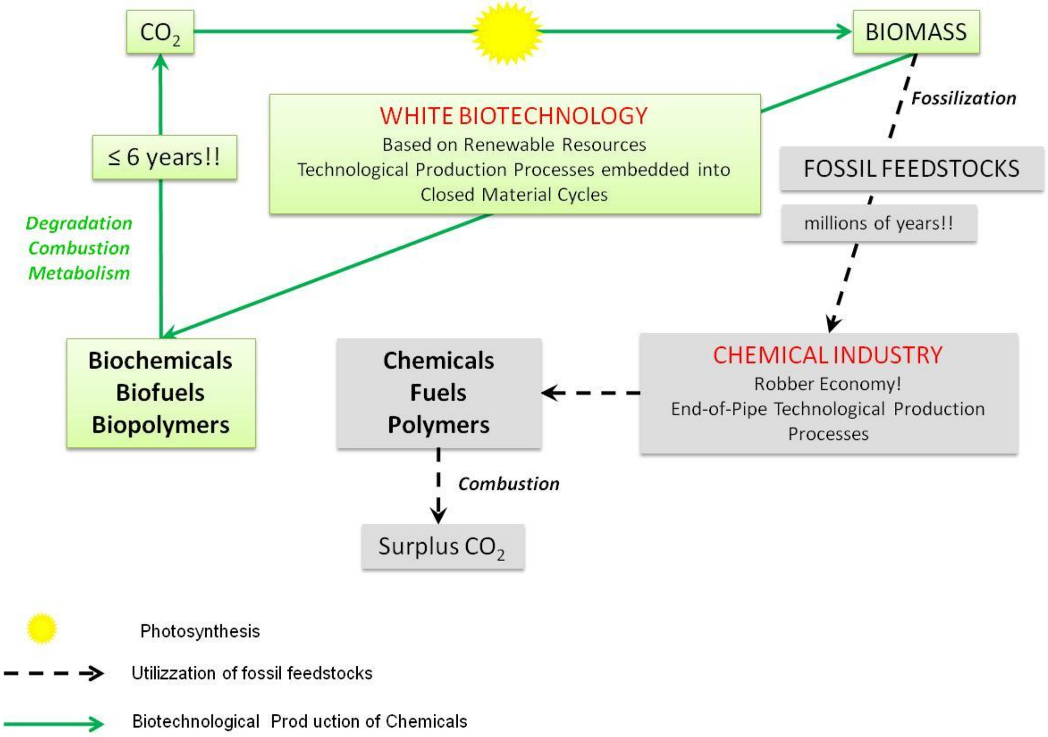
Figure 1. Electron microscopic picture of PHA-rich cells of *Cupriavidus necator*; magnification 1/30000. The percentage of PHA in CDM amounts to 70%.

In general, PHA accumulation is favoured by adequate availability of a suitable carbon source together with a limited supply of macro-elements like nitrogen, phosphate or oxygen or limitation of certain micro-components like sulphur, potassium, iron, tin, or magnesium. A high intracellular energy charge, characterized by a high pool of ATP, NADH, NADPH, or acetyl-CoA, favours the formation of PHA.

If plastic items made of PHAs are disposed in a composting plant, they are completely degraded to water, CO_2 and cell biomass as the final products of their oxidative conversion. Here, it has to be emphasized that water and CO_2 are the starting materials for the photosynthetic re-generation of carbohydrates by green plants and other phototrophic organisms; these carbohydrates can be utilized again by microorganisms for PHA accumulation. This demonstrates that, in contrast to petrol-based plastics, PHAs are perfectly integrated into the natural closed loop of carbon cycle. Underlined by this fact, the application of PHAs instead of common end-of-pipe plastics based on full carbon backbone polymers from fossil feedstocks clearly contributes to sustainable economic development.

Figure 2 visualizes the contrast of the life cycle of biopolymers like PHA and classical plastics based on PE, PP, and other mass polymers. In addition, the life cycle of biofuels and biochemicals is also integrated into the graphic and compared to the fate of fossil feedstock based fuels and chemicals. As illustrated, the photosynthetic fixation of CO_2 by the action of phototrophic organisms (green plants, algae, phototrophic prokaryotes) results in the formation of the so called “primary biomass” or “phytomass” of plants, algae and phototrophic prokaryotes (cyanobacteria). Based on the nutritional chain, this “primary biomass” is converted by animals, forming the so called “zoomass”, and by chemoheterotrophic microbes. Hence, the expression “biomass” encompasses all living organisms and also dead biomass like straw, deadwood or dead zoomass. The entire mass of living organisms on earth can be estimated at $1{,}8 * 10^{12}$ t; the amount of carbon present in the entire (living and dead) biomass on this planet is estimated at $5{,}6 * 10^{12}$ t. Annually, about $1{,}7 * 10^{9}$ t of biomass are produced via photosynthesis. Considering the organic compounds, biomass is mainly composed of polysaccharides (including cellulosics, lignocellulosics, and sugars), proteins, lipids, and nucleotides. Although fossil feedstocks like mineral oil originate from chemical and geological processes that converted biomass millions of years ago, they are not classified as “biomass” anymore. Classical technological production processes based on fossil feedstocks result in the formation of surplus CO_2. This can easily be understood by the fact that fossil feedstocks contain carbon that was fixed in earth´s interior for millions of years. Hence, combusting materials based on fossil feedstocks leads to the oxidation of this carbon to CO_2, thus resulting in an unbalancing problem regarding the GHG effect. In the case of polymers based on fossil feedstocks, the disposal in landfills as alternative to combustion results in increasing piles of waste due to the high durability of these materials. But this unbalancing problem can be faced and eventually appropriate solutions can be identified. Among the modern approaches aimed at finding viable solutions to plastic waste, reengineering of full carbon backbone polymers convertible to plastic items, eventually susceptible to degradation and biodegradation, is a way under scrutiny and application worldwide [10,11]. Regarding the example of production of PHA or bioethanol from sugarcane, it is clear that conversion of these final products by combustion or degradation results in the formation of CO_2 containing merely carbon that was fixed in the sugarcane plant until a short time before. Soon, this CO_2 is photosynthetically fixed again by sugarcane plants, thus closing the loop carbon cycle.

Today, the industrial implementation of living organisms for production of biofuels (e.g.: biodiesel, bioethanol from sugarcane), biopolymers (e.g.: PHA production from sugarcane) or biochemicals is also known as "White Biotechnology" which is characterized by the utilization of renewable resources as feedstocks and the embedding of the production processes into closed material cycles. The significance of the strategy to switch to renewable either as an alternative to fossil feed-stocks or a complimentary option to the reengineered plastic items is impressively underlined by the current development of the crude oil price that amounted to more than 100 US-$ per barrel in the Summer of 2011, but nearby three times the price of January 2009, when less than 40 US-$ had to be paid per barrel. [12, 13].



Based on [8].

Figure 2. Global carbon cycle comparing different industrial approaches. In biotechnological production of chemicals, fuels and polymers, called "White Biotechnology", the mass stream for carbon is balanced. In contrast, when utilizing fossil feedstocks, carbon fixed in the bowels of the earth is finally converted to surplus CO_2 causing an unbalancing problem.

What Characterizes a "Green Plastic"?

A broad range of various polymeric materials exists for which the stylish and fashionable attribute "*green* plastic" is claimed by the manufactures. In many cases, the *de facto* properties of such commercialized materials do not really match the strict definitions that are prescribed for classifying plastics as "*biobased*", "*biodegradable*", "*compostable*" or "*biocompatible*" (CEN/TR 15391, CEN/TR15932), thus making them "*green*". Such attributes do only apply to plastics if they fulfill the strict requirements defined by standardized norms and certificates. For instance, the norm regarding the plastic packaging through composting (EN-13432) postulates that a (plastic) material is "*biodegradable*", if 90% of its carbon is metabolized within 180 days, and "*compostable*", if not more than 10% of the material remains in a sieve of 2mm pore size after 180 days of composting. The classification „*biocompatible*" refers to the fact that, using standardized methods for assessing the ecotoxicity of the (plastic) material, it must not feature any negative impact on living organisms or the involved environment as described in the certification according to a standardized norm (ISO 10993). Biodegradability is of special significance for *in vivo* applications of polymers such as implants for surgery or other medical applications. In addition, a polymer can be classified as „*biobased*", if the production of the building block monomeric units is based on renewable resources; here, the polymerization of the monomers may occur chemically (e.g.: polymerization of fermentative produced lactic acid to polylactic acid [PLA]) or biotechnologically (e.g.: *in vivo* polymerization of hydroxyacyl-CoAs by PHA synthases towards PHA).

Important examples for commercially available biodegradable plastic materials are *Ecoflex*® (BASF SE, Germany) and *Materbi*® (Novamont S.P.A., Italy)[2]. *Ecoflex*® constitutes a *biodegradable* and *compostable* product based on fossil feedstocks. The properties of *Ecoflex*® can be fine tuned according to the envisaged application by making blends and composites with it by using polysaccharide fibers like PHAs or PLA. It can be processed via injection molding or film blowing and is especially suitable for application as film for food packaging or agricultural mulching films. The main disadvantage in the presented case of *Ecoflex*® is the need of fossil raw materials; hence, it cannot be classified as „*biobased*". This is in contrast to the „*biobased*" material *Materbi*®. Here, the production is based on corn starch as a renewable resource, also the biodegradability under composting conditions of *Materbi*® is certificated. *Materbi*® can undergo injection molding, melt extrusion, film blowing or foaming.

In some areas of the world, bioethanol constitutes a source for polymer production. A prerequisite for this is that ethanol can be produced for a low price and consuming low quantities of energy others than from renewable resources. An example for this is the BRASKEM process in Brazil, where PE is produced from bioethanol as obtained stemming from sugarcane sucrose fermentation. The energy needed for the fermentation, the distillation and the production of absolute ethanol is provided by combusting sugarcane bagasse. The company BRASKEM produces high-density PE at a plant capacity of around 200 kt that

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[2] CEN/TR 15351- Plastics - Guide for vocabulary in the field of degradable and biodegradable polymers and plastic items

CEN-TR15932- Plastics- Recommendation for terminology and characterization of bioplastics

EN-13432 Requirements for Packaging Recoverable through Composting and Biodegradation. Test-Scheme and Evaluation Criteria for the Final Acceptance of Packaging

ISO 10993- Biological evaluation of medical devices already provides enough material for commercial application; nevertheless, with respect to almost the 10 Mt of PE based on fossil fuel feedstock it can be considered as a drop of water in the Mediterranean sea. The polymer can be classified as "*biobased*" due to the fact that sugarcane sucrose acts as the raw material for the fermentative generation of bioethanol. The generation of ethylene by dehydration and the subsequent polymerization of this monomer towards PE are accomplished according to the well established petrochemically based processes. The finally obtained PE is neither *biodegradable* nor *compostable,* hence, the final fate of plastic products made of BRASKEM PE does not differ from petrol-based PE; in both cases, the spent plastic has to be disposed off in landfills or has to be incinerated. In contrast to petrol-based PE, incineration of BRASKEM PE does not result in a negative carbon balance due to the fact that the produced CO_2 was part of the natural carbon cycle only a short time span before. As mentioned earlier, PE production based on energy demanding steps like fermentative and distillative bioethanol production is only reasonable if the supply of energy and of the raw material is ascertained as it is the case at the BRASKEM process. In most countries of the world, the realization of similar processes appears rather doubtful due to the high energy requirements. It is also worth mentioning that usually convertible ethanol is industrially obtained and catalyzed by hydration of ethylene whereas the opposite reaction (ethanol dehydration) is thermodynamically unfavoured.

Polylactic acid (PLA) constitutes another *biobased* polymeric material with properties of typical thermoplastic items. The commercial production of its monomer, lactic acid, *via* chemical means is based on acidic hydrolysis of lactonitrile, which is classically generated by the conversion of acetaldehyde with hydrogen cyanide. Today, the biotechnological production of lactic acid from different renewable resources by the action of different lactobacilli is gaining importance [14]. Lactic acid cannot be directly polymerized to PLA, because each condensation step is accompanied by the elimination of one molecule of water, which is impeding the achievement of high molar mass PLA. Instead, lactic acid is oligomerized and then catalytically dimerized to cyclic lactides. Although dimerization also generates water, it can be separated prior to polymerization. PLA of high molecular mass is produced from the lactide monomer by ring-opening polymerization (ROP) using either metal containing or metal- free chemical catalysts. The process for the production of PLA is more or less optimized and commercialized in moderately large scale under the trademark of Nature Works by Cargill Co and nowadays is used for the production of various plastic items; hence, they might be favourable for being utilized as 'simple' plastic materials in many fields [15]. In any case, it has to be considered that PLA typically needs high temperatures to initiate hydrolytic degradation. Highly crystalline PLA is reported not to be biodegradable at all in soil. The materials are rather crystalline with a melting temperature of 155–165 °C and are suitable for processing steps such as injection moulding, film-blowing and melt extrusion [14].

A lot of research activity has been accomplished during the last couple of years at the University of Münster in the field of polythioesters (PTE) like poly(3-mercaptopropionate) (PMP). These materials are biotechnologically accessible by recombinant bacteria by providing them mercaptoalkanoic acids like 3-mercaptopropionate (3MP) as carbon substrates; these substrates however do not constitute renewable materials [16,17]. Hence, although the production of PTE is biomediated, they cannot be considered as biobased due to the raw material situation. Comparison among PTE and their oxo-analogues (PHAs) shows PTE is characterized by lower crystallinity and often also higher thermal stability. These characters are attracting interest for different potential applications, where durable and resistant plastic items based on a heteropolymer are required. Nevertheless, the preparation of a monomeric building block like 3MP is fairly expensive, making an economical feasible production of PTE on a larger scale rather doubtful [18]. In addition, despite many attempts, no degradation of PTE by enzymes or whole cells is reported until today, only copolyesters of 3HB and mercaptoalkanoates like poly(3HB-*co*-3MP) are accessible to degradation by natural depolymerases; this is due to the high specifity of such enzymes for oxo-esters. Hence, at the moment the positive economical and ecological impact of a broad implementation of these materials appears rather doubtful [19].

The combination of the characteristics „*biobased*“, *“biodegradable”, “compostable”* and “*biocompatible*” is justified for materials consisting of microbially produced PHA, underlining their suitability for replacing polymeric materials based on fossil feedstocks in the production of marketable plastic items.

In table 1, information on the polymeric materials as discussed above are summarized with specific reference to the producers and their features including origin, biocompatibility and biodegrability.

Table 1. Characteristics of different "green plastics"

Material	**Manufacturer (today and past)**	**Monomer**	**Production of the monomers**	**Polymer-ization of the monomers**	**Bio-based**	**Bio-compatible**	**Bio-degradable**	**compostable**	**Accessible from sucrose as starting material**
PHA	e.g.: PHBISA; ICI-Marlborough; Lhemie Linz; Telles Metabolix Inc. and Archer Daniels Midland; Monsanto; Tianan; Shandong and others	Hydroxyalkanoic acids	in vivo in microbial cells	in vivo in microbial cells	+	+	+	+	+
PLA	e.g.: NatureWorks LLC, Biopearls, Guangzhou Bright China, Hisun Biomaterials, Kingfa Science & Tech., Nantong,	L- or D-Lactic acid	in vivo excretion by microbial cells	Chemically	+	(+)[1]	(+)[2]	(+)[2]	+
PTE	Laboratory scale at University of Münster	Mercaptoalkanoic acids	Chemically	in vivo in microbial cells	-	-	-	-	-
Ecoflex®	BASF SE	Aliphatic and aromatic compounds of petrochemical origin	Chemically	Chemically	-	+	+	+	-
Materbi®	Novamont S.P.A.	Glucose (as monomer of starch)	Photosynthetic production of carbohydrates	in vivo polymerization to starch by plants	+	+	+	+	-
Biobased PE	BRASKEM	Biobased ethene	chemically from biobased ethanol	chemically	+	-	-	-	+

1: *in vivo* degradation of PLA can cause inflammatory response; *2*: total degradation of highly crystalline PLA doubtful

The Need for Cost-Efficient Carbon Feedstocks for PHA Production

The implementation of White Biotechnology, as visualized in Figure 2, can be regarded as really promising for sustainable development, although for a range of industrial products, especially bulk-products, biotechnological production strategies still have not yet passed the threshold for economic feasibility. This is mainly caused by the expenses of the raw materials. Here, a viable solution can be the utilization of a broad range of waste- and surplus materials upgraded to the role of feedstocks for the bio-mediated production of desired end-products. Such materials are mainly produced in agriculture and such industrial branches that are closely related to agriculture [20, 21, 22, 23]. Especially the economics of PHA production is to a high extent, namely up to 50% of the entire production costs, defined by costs met for the supply of raw materials. This can easily be understood by considering the fact that PHA accumulation occurs under aerobic conditions, resulting in high losses of carbon substrate by intracellular respiration. Hence, mainly due to a considerable loss of carbon by CO_2-formation, only a maximum amount below 50% of the carbon source is directed towards cell biomass growth and PHA accumulation. The utilization of waste materials as feedstocks for PHA biosynthesis constitutes a viable strategy for cost-efficient biopolymer production and supports various agro-industrial branches to overcome existing waste disposal problems.

In many regions of the world, the industrial realization of value-added conversion of low-cost agricultural feedstocks can provide a certain degree of geopolitical independence for several countries. This means that the required import of fossil reserves can be omitted by replacing fossil feedstocks by efficient implementation of renewable resources available in the respective countries. The selection of the appropriate waste stream as feedstock for biotechnological purposes mainly depends on the global region where a production plant will be constructed. In order to save costs for transportation, facilities for the production of biopolymers, biofuels and biochemicals should be integrated into existing production lines, where the feedstocks directly accrue as waste streams. In addition, the availability of convertible feedstocks all over the year has to be ascertained. This rises up problems like the material´s appropriateness of long-term storage; this is of special importance for lignocellulosic materials during the off-season where no harvest takes place.

In Europe and North America, enormous amounts of excess whey are available in dairies and cheese factories. Beside various growth-enhancing components such as minerals, vitamins and protein residues, whey contains the disaccharide lactose as the main carbon-containing ingredient. Instead of being disposed off into waste water treatment plant as it is realized at many dairy industries, whey lactose can be biotechnologically applied for the production of lactic acid, polylactic acid (PLA), PHA [24,25,26,27,28,29], bioethanol [30], biogas and biohydrogen [31]. In addition, biochemicals like antibiotics [32], lactobionic acid, emulsifiers and surfactants [33] are reported to be accessible starting from whey lactose by the action of microbial production strains.

Caused by new legislative situation in Europe that compulsorily requires the addition of biofuels to common fuels, the increasing production of biodiesel in Europe generates enormous amounts of its major side stream, namely glycerol. Glycerol constitutes a precious starting material for the production of PHA, lactic acid, PLA, biogas, or 1,3-propanediol, a starting substance for the chemical production of polymers.

The occurrence of waste lipids available for bioconversion is versatile: waste cooking oil, different plant oils, lipids of meat-and-bone meal or waste water from the olive oil (alpechìn) and palm oil production are available. A novel field of interest might also be the application of oils from microalgae that is accessible by cultivation of these phototrophic organisms with CO_2 from industrial exhaust gases as sole carbon source. For some species, this carbon supply can be supported by the co-feeding of nutrient-rich wastewater sewage. Such microalgal oils often contain multiple unsaturated fatty acids that constitute potential precursors for unsaturated PHA building blocks. In addition, yields for PHA production from oils are in many cases significantly higher than from sugars. In all cases, the triacylglycerides can either be directly utilized as carbon source, or, after hydrolysis to glycerol and fatty acids, or after transesterification with production of biodiesel and glycerol as by-product.

In other areas of the world, waste from sugar industry (molasses), starch, waste lipids, alcohols like methanol [34] and especially lignocellulosic feedstocks are available in quantities that are appropriate for the demands in industrial process.

Lignocellulosic (consisting of cellulosic and hemicellulosic fibres that are strongly linked to lignin by ester and ether bonds) and cellulosic materials provide feedstocks globally available in relatively high quantities. Industrial branches generating the major shares of this waste are wood-processing, paper and agriculture industry. In the case of agriculture, one must not forget the enormous amounts of rice straw that are produced annually in several global regions like in China, Indochina or in the Maghreb. Nowadays a lot of effort is dedicated worldwide to develop bio-refinery plants for the conversion of lignocellulosic and cellulosic waste to raw materials for biotechnological production of bioethanol, biopolymers and a range of fine chemicals. The optimization of methods for energetically practicable digestion of lignocellulosics and the development of effective biocatalysts for the breakdown of cellulose and hemicellulose into microbial convertible sugars (hexoses and pentoses) are the prerequisite for an efficient biotechnological conversion of these promising raw materials into desired end-products. The potential applications of sugarcane bagasse for production of biofuels, biopolymers and its composites are illustrated in Figure 3.

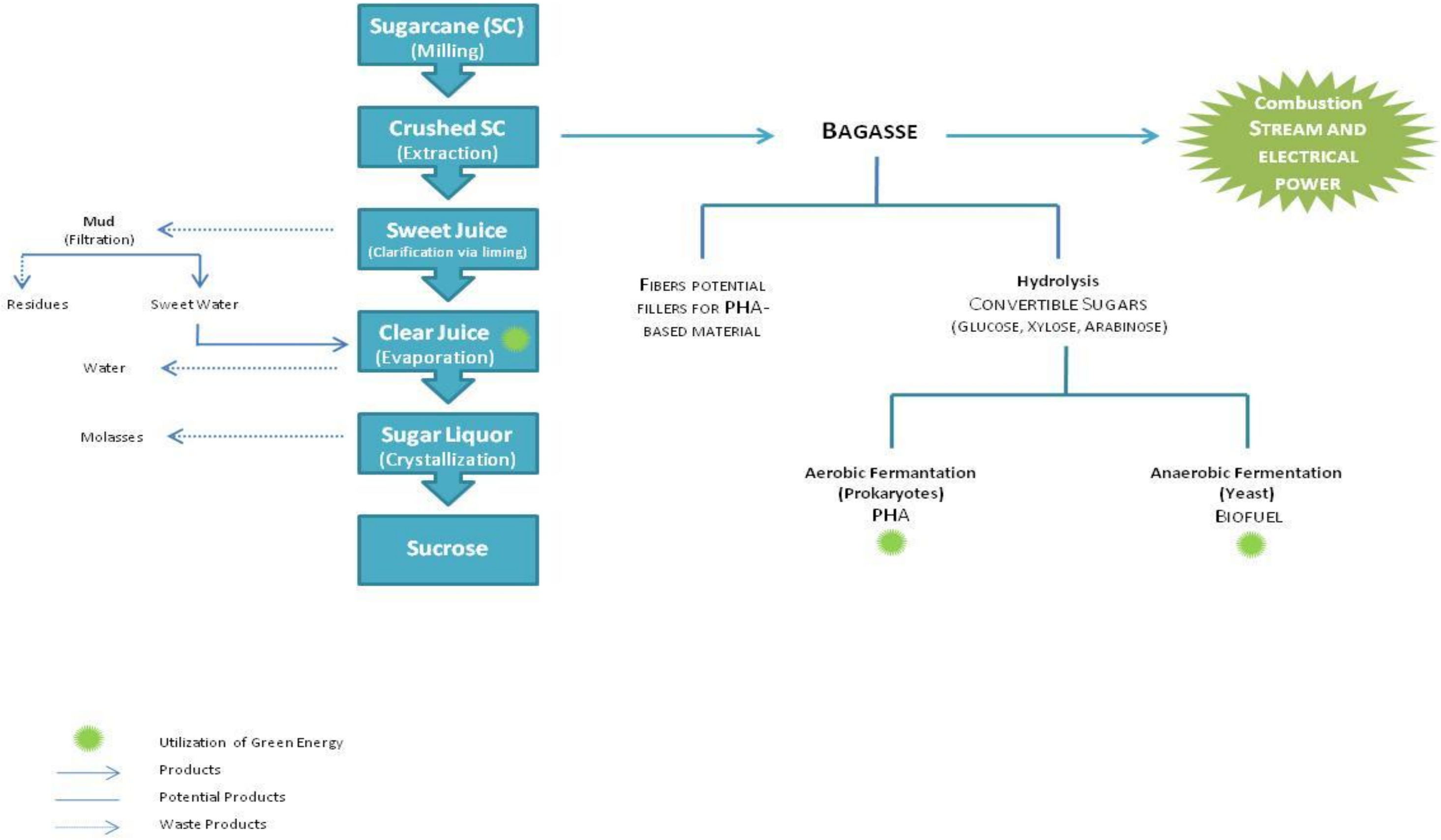


Figure 3. Utilization of bagasse from sugarcane.

Utilization of sucrose in biotechnology that constitutes the core-part of this book chapter has to be strictly distinguished from the conversion of the waste streams mentioned above. Of course, sucrose constitutes a material of high nutritional value and has a considerable market price. Nevertheless, conversion of sucrose into biopolyesters can be economically feasible by the integration of biopolymer production into an existing sugar cane mill as it is realized on pilot scale at the company PHB Industrial S/A (PHBISA) in Brazil. Here, the obtained sucrose is biotechnologically converted to bioethanol and partly to PHA. In this scenario, the required energy for bioethanol and biopolymer production is generated by burning the surplus biomass from the sugarcane plant, namely bagasse. The fusel oil fraction of the bioethanol distillation is applied as extraction solvents for PHA isolation from microbial biomass [35].

The Suitability of Sugarcane Sucrose for Biomediated PHA Production

A huge number of PHA producing microorganisms is able to metabolize sucrose (*2-β-D-fructofuranosyl-1-α-D-glucopyranoside*) or at least its hydrolysis products, namely equimolar mixtures of glucose and fructose. This is in huge contrast to the utilization of other disaccharides like lactose that also occurs in large quantities as an industrial by-product, but, in contrast to sucrose, is only converted by a rather restricted number of PHA producing microorganisms [36].

In principle, industrially relevant PHA producers from sucrose can be divided into two distinct groups: the first directly hydrolyzes sucrose by existing intra- or extracellular enzymes (activity of invertase, *β-fructofuranosidase*, EC 3.2.1.26) and converts the hydrolysis products glucose and fructose for generation of catalytically active cell mass and PHA. This is the case for the outstanding PHA producers *Burkholderia sp*. [37] or *Haloferax mediterranei* [38]. The second group encompasses those microbial strains able to convert the monomeric sugars glucose and fructose, but do not possess the metabolic prerequisites for sucrose hydrolysis; in this case, enzymatic or chemical hydrolysis of sucrose prior to the bioprocess is required (e.g. this is required for the best investigated PHA producer *Cupriavidus necator* that is used for PHA production at PHBISA). It is of crucial importance for economic viability that both monomeric sugars are converted by the production strain in order not to lose half of the carbon source. A schematic representation for the basic metabolic routes encompassing key enzymes and intermediate compounds for PHA production and mobilization starting from sucrose is provided in Figure 4.

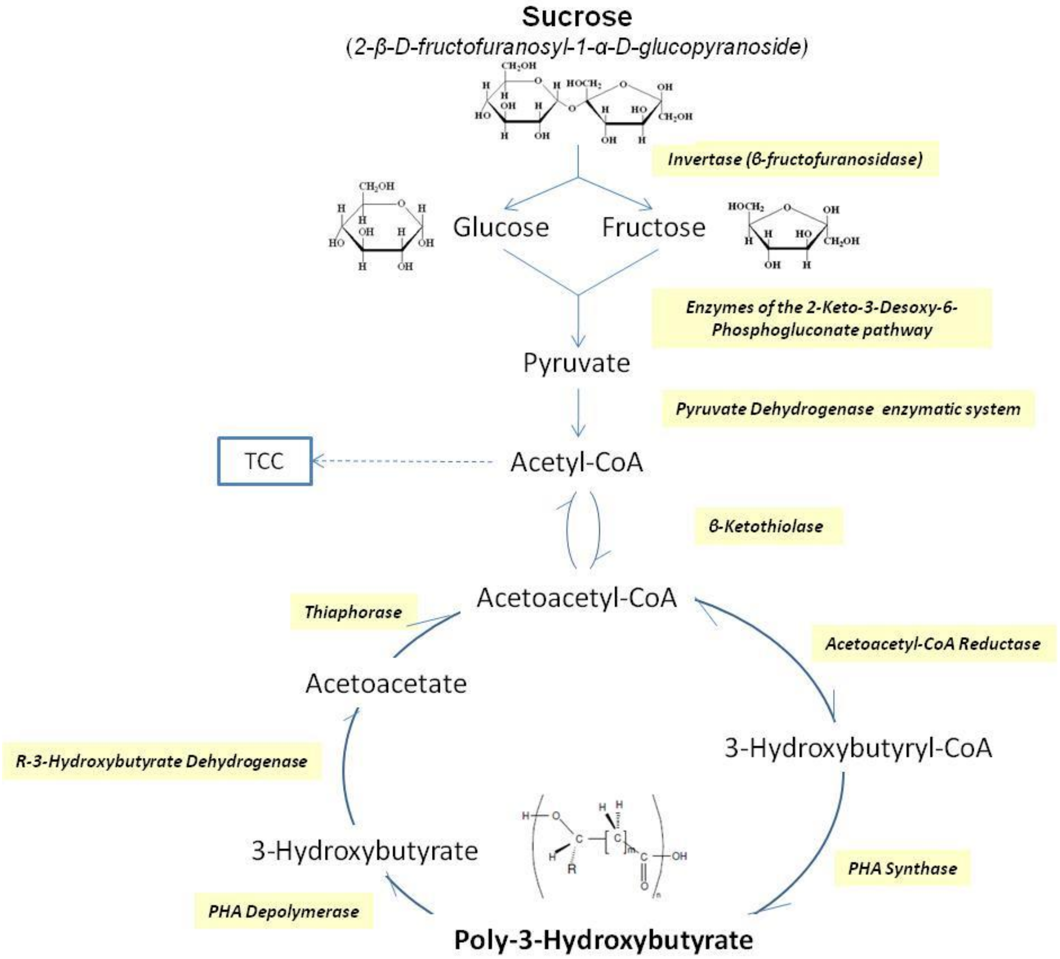


Figure 4. Basic metabolic route from sugarcane-based sucrose to PHB. Acetyl-CoA acts as the central metabolite that can enter the tricarboxylic acid cycle (TCC) under balanced nutritional conditions, or be shifted towards PHA biopolyester production under nutritional stress.

Industrial Utilization of Sugarcane at Phbisa, Brazil

A novel approach for PHA production is provided by the utilization of carbon sources that feature a considerable market value and do not constitute waste materials, but are produced within a process integrating the fabrication of the carbon substrate and PHA. As mentioned before, this is implemented in pilot scale by the bioplastic manufacturing company PHB Industrial S/A (PHBISA) at Modra, São Paulo State, Brazil. Starting from sugar cane, the company produces saccharose and bioethanol. The waste streams from the sugar fabrication (bagasse) and the generation of bioethanol (fusel alcohols) are used for running the PHA production and making it economically competitive. The PHA produced is on the one hand the homopolyester poly-3-hydroxybutyrate (PHB) and, on the other hand, the copolyester poly-(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV). The latter is produced by co-feeding the 3-hydroxyvalerate precursor propionic acid together with hydrolyzed sucrose during the PHA accumulation phase. Both types of PHA are commercialized under the trade mark "BIOCYCLE^{TM}" by the company and can be processed via melt extrusion or injection moulding and be applied for packaging of food, cosmetics and pesticides, manufacturing of agricultural seedling pots, and for biomedical applications. Hence, the company operates an "optimized biorefinery plant" that shows lower environmental impacts and higher economic efficiency if compared to classical scenarios such as autonomous or annexed plants.

Starting from cane sugar, about 3 kg of sucrose is needed to produce 1 kg PHB using *Cupriavidus necator* DSM 545 as production strain. The electrical power needed is generated by high-pressure steam as derived from bagasse combustion, the major by-product of the sugar cane production. Low-pressure steam that is additionally needed for heating and sterilization is also provided from bagasse combustion [35]. Figure 5 provides a schematic representation indicating the closed cycles of material streams used for the production of sucrose, bio-ethanol and PHA at PHBISA. This illustration also indicates the potential utilization of different waste streams for the process. The recycling of residual PHA free biomass after hydrolysis as a carbon and nitrogen source should be assessed and compared to alternative applications like the utilization as fertilizer for sugar cane cultivation or the generation of methane as fuel for energy production via anaerobic digestion of the biomass hydrolysate in biogas plants.

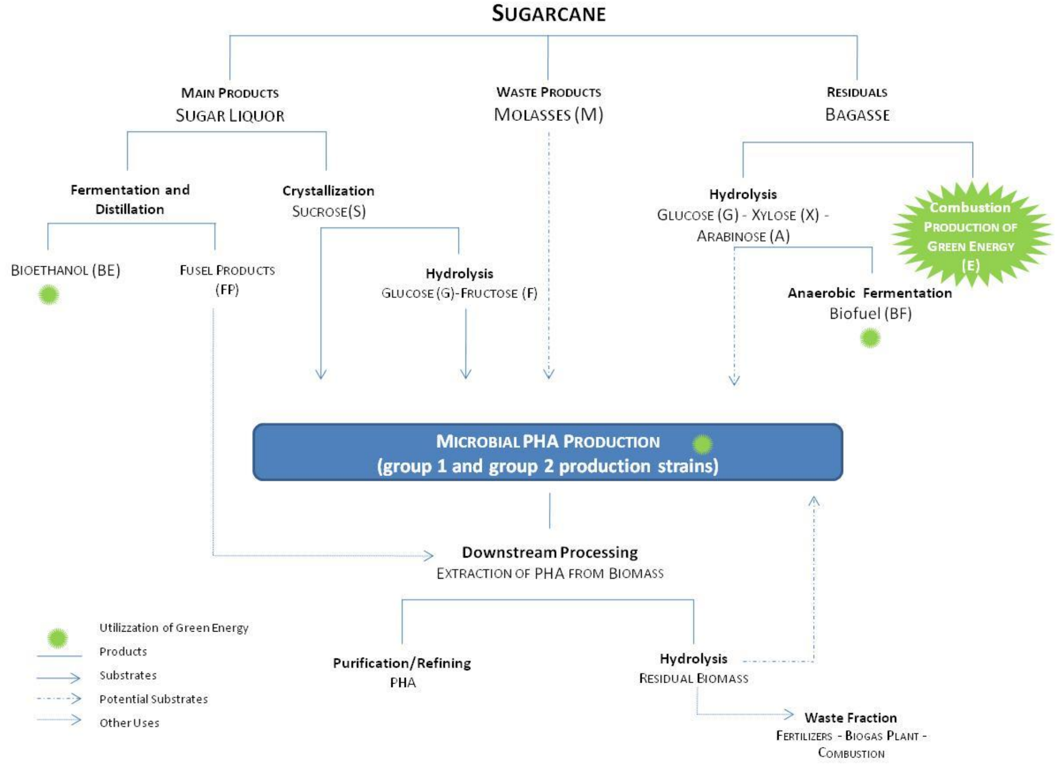


Figure 5. Process flow sheet of the entire process including actual and potential utilization of waste streams.

After fermentation and biomass separation from the aqueous supernatant, normally via centrifugation, flocculation or filtration, PHA recovery from biomass constitutes another not negligible cost factor, especially in large scale production. The described PHA production process is embedded in an ethanol production plant and can therefore gives rise to the fusel alcohols, mainly iso-pentanol, from the distillery step. The application of the fusel alcohols as extracting solvents combines two important advantages. Firstly, these compounds normally constitute a waste stream without any market value and, when used as extraction solvent, the costs for alternative solvents are saved. Secondly, this extraction solvent is less harmful to handle than chloroform that is taken as the classical extraction solvent. Further, the extraction yields (95%), remaining molecular mass (250 to 400 kDa) and product purity (higher than 98%) of the biopolyesters isolated by this method are high enough for the subsequent polymer processing [35].

Due to in-house energy supply and availability of the carbon source sucrose, the production costs per kilogram PHB are estimated with less than 3 US$ [39,35,40]. Figure 6 provides the production cost generation for the PHA biopolymer production [35] One has however to consider that the market prices for sugar as for bagasse are directly related to the prices for crude oil! Figure 7 illustrates the single process steps making the presented process economically feasible.

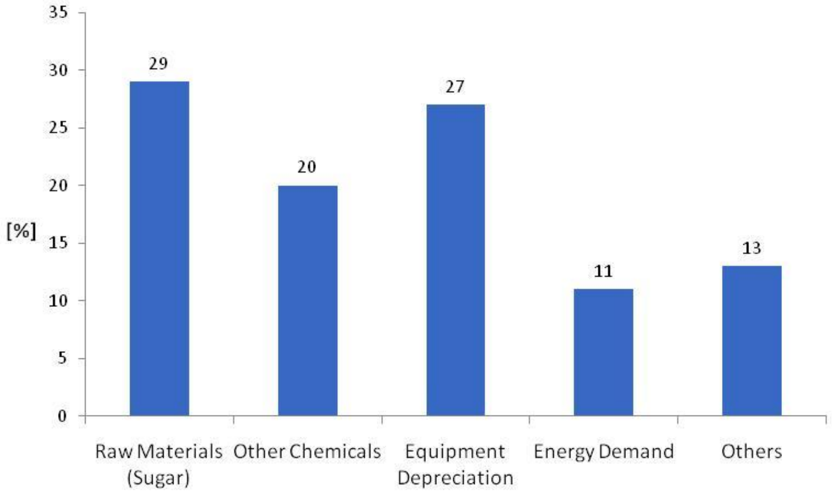
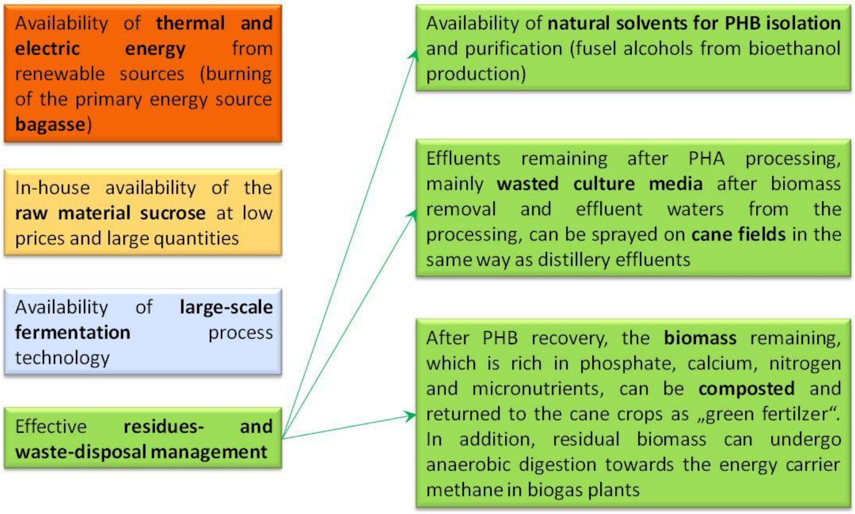


Figure 6. Cost composition for PHA production at PHB Industrial S/A. Based on [35].



Availability of **thermal and electric energy** from renewable sources (burning of the primary energy source **bagasse**)

In-house availability of the **raw material sucrose** at low prices and large quantities

Availability of **large-scale fermentation** process technology

Effective **residues- and waste-disposal management**

Availability of **natural solvents for PHB isolation** and purification (fusel alcohols from bioethanol production)

Effluents remaining after PHA processing, mainly **wasted culture media** after biomass removal and effluent waters from the processing, can be sprayed on **cane fields** in the same way as distillery effluents

After PHB recovery, the **biomass** remaining, which is rich in phosphate, calcium, nitrogen and micronutrients, can be **composted** and returned to the cane crops as „green fertilzer“. In addition, residual biomass can undergo anaerobic digestion towards the energy carrier methane in biogas plants

Figure 7. What makes the PHB Industrial S/A (PHBISA) process economically feasible? Based on [35].

Additional Microbial PHA Producers from Sugarcane

Haloferax mediterranei was originally isolated at the Mediterranean coast of the Iberian peninsula [41] and nowadays is considered as the industrially most promising PHA producer among all known archaea [42,43]. Within the phylum of the Euryarcheota, this microorganism belongs to the class of halobacteria, the extremely halophilic branch within the “Archaea” domain. This strain does not only tolerate high salinity conditions, but even requires sodium chloride concentrations of 2-5 mol L^{-1} for growth. The genus Haloferax is of special interest due to the faster growth compared to related organisms and features a broader substrate spectrum: it is known to convert several mono-, di- and polysaccharides [38]. Among the investigated sugars, sucrose is directly converted by *H. mediterranei*.

By the authors of this book chapter, the organism was tested for its growth on the following substrates. Cultivation on sucrose from Brazil was compared with the monosaccharides glucose and fructose (hydrolysis products of sucrose), equimolar mixtures of glucose and fructose (Figure 8), and, as reference, the strain was also cultivated on yeast extract as the sole nitrogen-, carbon and phosphate source (data not shown).

Figure 8 provides the amounts of PHA produced during 68 hours of cultivations. The amounts of produced PHA and the volumetric PHA productivity are in a similar range between 1,4 g/L (0,021 g/L·h) for sucrose and 1,56 g/L (0,023 g/L·h) for molasses. The reference substrate consisting of equimolar mixtures of glucose and fructose resulted in 1,66 g/L PHA (0,024 g/L·h). Detailed results of these experiments are collected in Table 2. It has to be emphasized that, in all cases, the produced biopolyesters contained about 10% of 3HV in the matrix of PHB without the addition of a 3HV-related co-substrate such as propionic or valeric acid. This attribute, together with its high robustness and genetic stability, makes the organism especially interesting for industrial-scale production of high-quality PHA copolyesters. The high salinity of the nutritional medium further results in a high osmotic pressure inside the cells. This high osmotic pressure inside the cells opens the door for a simple and cost-effective method to separate PHA from residual cell mass. By exposure of the cells to hypotonic medium (distilled water), the PHA granules are set free and can be separated from the cell debris by centrifugation [38,44,45]. Beside sucrose, a broad range of additional carbon-rich waste streams was also tested on bioreactor scale using this archeon, such as whey lactose [46,36], glycerol phase from the biodiesel production [46], or starchy residues [47,38].

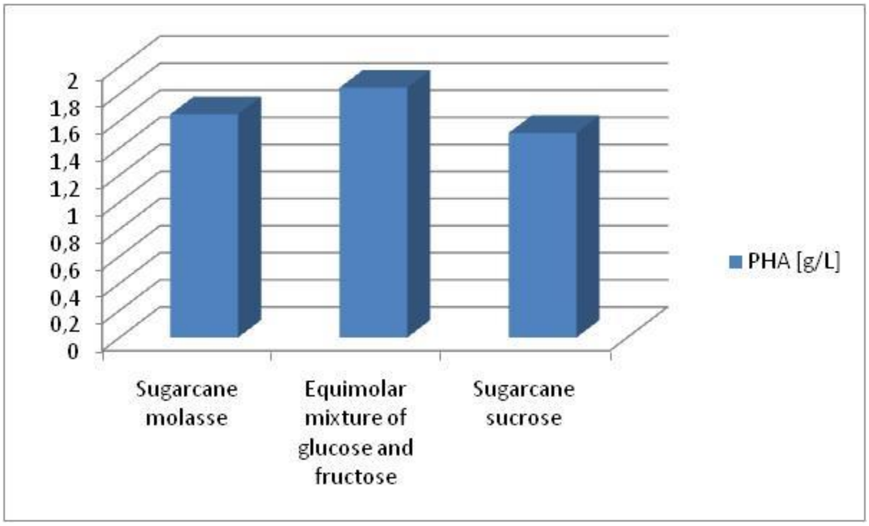


Figure 8. PHA production by *Haloferax mediterranei* on laboratory scale using sugarcane molasse, equimolar mixtures of the sucrose hydrolysis products glucose and fructose, and sugarcane sucrose.

Molasses, a by-Product of the Sugarcane Industry, as Substrate for PHA Production

Molasses constitute a common side stream of sugarcane industry that remains after the removal of crystalline sucrose from the sugar liquor (see Figure 5). Molasses can be commercialized at up to half of the price of pure sugars like glucose [48]. They contain sucrose as the major carbohydrate beside other sugars and additional components like various B-vitamins (Thiamine, Riboflavin, Niacin, Pyridoxine, Biotin and Folic acid) and numerous minerals (potassium, phosphate, calcium, magnesium, cupper, and iron) that can act as promoters for microbial growth.

The first investigation of molasses as substrates for PHA production described in literature was done by the group of Page [49]. The authors report a production of 2.5 g/L

PHA on shaking flask scale after 24 hours of cultivation using a mutant strain of *Azotobacter vinelandii* UWD on a medium based on molasses as carbon substrate. The production of PHA from molasses by sucrose-utilizing recombinant organisms, namely *Escherichia coli*, *Klebsiella oxytoca* and *Klebsiella aerogenes*, harbouring plasmids with the PHA synthesis genes of *Cupriavidus necator*, was investigated by Zhang and co-workers [48]. The scientists describe the accumulation of about 3 g/L of PHA on shaking flask scale after 37 hours of cultivation, corresponding to PHA contents in CDM of approximately 50% and a volumetric productivity of 0,08 g/L h. Due to the fact that the inserted plasmids only contained the PHA synthesis genes, but lacked the information for PHA degradation, the PHA produced by the recombinant organisms showed considerably high molecular masses of 1 to 2 MDa. Years later, even better results were obtained by an Indian group that combined the utilization of molasses with the addition of the complex substrate corn-steep liquor. The utilized organism, *Azotobacter beijerinckii*, produced 3.7 g/L PHB after 24 hours of cultivation, corresponding to a volumetric productivity of 0,15 g/L·h. Additionally, the study encompasses detailed investigations of the beneficial effect of several minor compounds like metals contained in untreated molasses, but not in refined sugar, on microbial growth und PHB production [50].

A rather complex three-stage process was developed by Albuquerque and colleagues for the production of PHA from sugarcane molasses. The process consists in the first step of a fermentative conversion of molasses by acidogenic organism towards acetic, propionic, butyric and valeric acid. Further, PHA-accumulating organisms were selected which, in a second step, finally converted the fermentatively produced organic acids towards PHA. It turned out that the pH-value in the first, fermentative step has a major impact on the organic acids profile and hence polymer productivity and structural features of the obtained polymer. At higher pH values, acetic and propionic acids were the main products, while lower pH values resulted in the formation of butyric and valeric acid. The PHA accumulation using fermented molasses was investigated with two different microbial cultures. The authors report a carbon conversion of up to 50% of the supplied organic acids towards PHA. The type of organic acids present in fermented molasses was decisive for the composition of the finally produced polymer; a higher amount of odd-numbered organic acids (propionic and valeric acid) increase the percentage of 3-hydroxyvalerate in the obtained PHA. In addition, the limitation of the growth component nitrogen further increased the carbon conversion from organic acids towards PHA to up to 62%. In addition, enrichment strategies for optimum operation of the bioreactor to select suitable PHA-accumulating cultures on fermented molasses were developed [51].

The application of sugarcane molasses as growth enhancer was investigated by Beaulieu and co-workers [52]. Here, *Cupriavidus necator* was used as production strain on shaking flask scale on glucose as the main carbon source. As described before, this organism is not able to directly convert the sucrose present in molasses without a prior hydrolysis, but it can benefit from the numerous additional ingredients of molasses. Testing supplementations of sugarcane molasses in quantities of 0; 0,1; 0,3 and 0,5 % (v/v), the authors found out that best results can be obtained using a molasses' addition of 0,3 % (v/v), resulting in a final PHB concentration of 9,0 g/L, a CDM of 23,1 g/L, a percentage of PHB in CDM of 39%, and a yield of PHB from the main carbon source glucose of 25% (g/g).

The detailed results of the described experiments using sugarcane molasses for PHA production are collected in Table 2.

Alternative “Sweet” Substrates for PHA Production

In addition to sugarcane molasses, a range of additional “sweet” materials is available that are rich in convertible sucrose. Among these materials, date syrup, sugar beet molasses, green syrup, and soy molasses were already successfully tested for microbial conversion towards PHA.

Omar and co-workers report the production of PHA by a wild type strain of *Bacillus megaterium* on a range of “sweet” substrates such as date syrup, sugar beet molasses and the corresponding pure carbohydrates in defined media. In each case the authors noticed positive impacts of the inexpensive, complex substrates on microbial growth due to additional compounds included in these feedstocks. Cultivation of the organism under controlled conditions was also accomplished using a 42 litre bioreactor. Here, maximum productivities were reported after 14 hours of cultivation (0,06 g/L h). In the later stage of the experiment, productivity decreased due to formation of endospores by the microorganism which in this phase is a concomitant, carbon consuming process to PHA accumulation [53]. This carbon-consuming sporulation is an economically unacceptable loss of substrate. A solution for this problem could be the utilization of non-spore forming mutants like the strain *Bacillus megaterium* KM. The significance of this study can be understood by the enormous number of date palm trees cultivated in different countries, especially on the Arabian Peninsula. In Saudi Arabia, for example, the quantity of dates surmounts 500 000 tons annually [54].

On a 10 litre bioreactor scale, Braunegg and colleagues [55] report PHA production from green syrup and sugar beet molasses by two different wild type strains of *Alcaligenes latus* (strains DSM 1123 and 1124; up-to-date nomenclature: *Azohydromonas lata*;). Also in this case, the results were compared with those obtained with the pure sugars glucose and sucrose. Although specific rates for growth and product formation were significantly lower, when complex substrates where used, production yields of biomass and PHA from the carbon source were in the same range for pure and complex substrates. In addition, the authors noticed that the use of sucrose, when compared with glucose as the main carbon source, gave a higher PHA accumulation during balanced microbial growth by the applied *Alcaligenes latus* strains.

The first report on medium-chain-length PHA (*mcl*-PHA) production from soy molasses was provided by Solaiman and co-workers [21]. In this study, *Pseudomonas corrugata* 383 was selected for the conversion of soy molasses into *mcl*-PHA. The authors report yields of up to 3,4 g CDM per litre culture using a soy molasses based growth medium. The concentration of PHA amounted to up to 17% of the CDM. The obtained *mcl*-PHA biopolyesters harboured different saturated and unsaturated building blocks like 3-hydroxyhexanoate, 3-hydroxyoctanoate, 3-hydroxydecanoate, 3-hydroxydodecanoate, 3-hydroxydodecenoate, 3-hydroxytetradecanoate, and 3-hydroxytetradecenoate.

The detailed results of the described experiments using different sweet substrates for PHA production are collected in Table 2.

Utilization of the Sugarcane by-Product Bagasse for PHA Production

Considering the fact that a lot more bagasse is available than needed for the energy production as described before for PHBISA, it is reasonable to assess possibilities for further value-added utilization of this material. As an example, hemicellulose and cellulose fractions of bagasse can be hydrolyzed and utilized by suitable microbial strains for PHA biosynthesis. This was successfully demonstrated by Silva *et al.* [56] for strains of *Burkholderia sacchari* IPT 101 and *Burkholderia cepacia* IPT 048. On laboratory scale, hydrolyzed bagasse was investigated as carbon source for PHA biosynthesis, and its performance as substrate was directly compared to pure sugars occurring in hemicelluloses and cellulose, namely the pentose xylose and the hexose glucose. The authors report excellent results on bioreactor scale using *B. sacchari* IPT 101 on hydrolyzed bagasse; 62% of PHA in CDM was reached at a conversion yield of 0.39 g/g; these results were considerably better than obtained with pure sugars, but lower cell densities with respect to those detected with to pure substrates. In the case of *B. cepacia* IPT 048 on hydrolyzed bagasse, PHA in CDM reached 53% at a conversion yield of 0.29 g/g The detailed results of utilization of hydrolyzed sugarcane bagasse for PHA production by *B. cepacia* IPT 048 and *B. sacchari* IPT 101 are collected in table 2. Felipe *et al.* [57] mention the formation of toxic aldehyde compounds such as furfural or hydroxymethylfurfural (HMF) during acidic hydrolysis of bagasse. Procedures have to be developed for removal of these components. Silva *et al.* (2004) have compared different processes for detoxification of the acidic hydrolyzed sugar cane bagasse. Treatment with active charcoal turned out to be a feasible and effective method to significantly lower the concentration of aldehydes. Additionally, powdered bagasse might also be an interesting filler material for PHA-based composites [58]. Figure 9 illustrates the potential applications of sugarcane bagasse for energy production, and the application of the hydrolysis products for biopolyester and biofuels production.

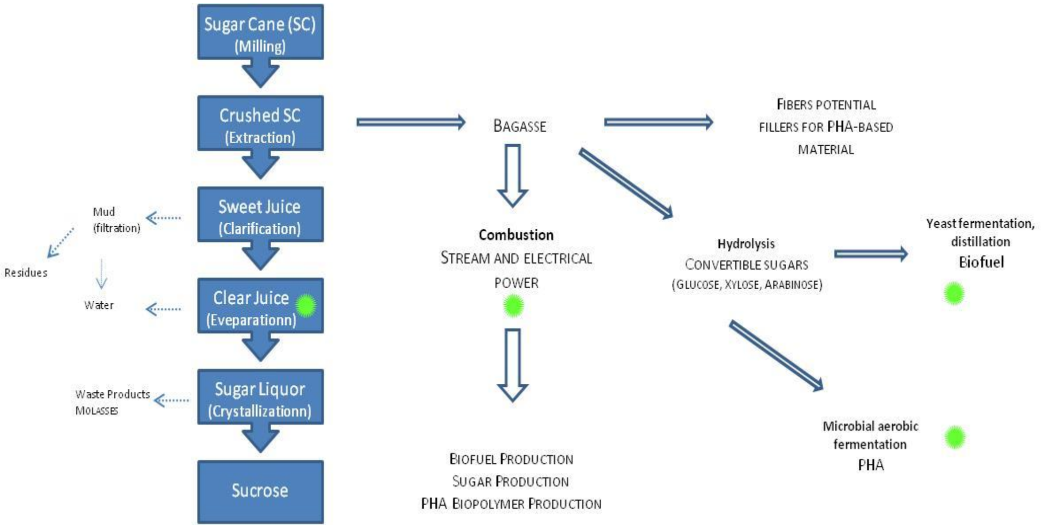


Figure 9. Potential applications of sugarcane bagasse.

Survey of Eco-Balances for PHA Production from Sugarcane

A number of Life Cycle Assessments (LCA) and Cleaner Production studies attempt to quantify the environmental impact and feasibility of processes for microbial PHA production [59]. A LCA, also known as 'ecobalance', 'cradle-to-gate analysis' or 'cradle-to-grave analysis' is the investigation and evaluation of the environmental impacts of a given product or service caused or necessitated by its provision. The term 'life cycle' refers to the notion that a holistic assessment has to include raw material production, processing, manufacturing, distribution, application and disposal of any product including all intervening transportation steps [60]. LCA in a narrower sense of the word is a methodology to report on the evaluation of ecological impacts following the standards laid down in the ISO –Standards (ISO, 1996). Such reports feature several compulsory parts in particular Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation of results. Goal and Scope of a LCA study defines the system boundary and provides important information for readers about considered data and assumptions. Material and energy balance data along the whole life cycle are collected in the LCI. Based on these data a LCIA will quantify the ecological impacts incurred by the provision of a specific product or service. A variety of LCIA methods are available in literature, e.g. MIPS [61], CML [62], CED [63] and Sustainable Process Index (SPI) [64]. Every LCIA method delivers different results depending on the focus of the methodology.

Some papers quantify the environmental impact of PHA production via LCIA tools within an LCA study, mainly focusing on isolated aspects of the production. They assess the polymer production itself or look solely on CO_2 emissions or energy demand [65, 66]. These studies render inconclusive results regarding the ecological impact of PHA production.

An interesting, comprehensive and complete “cradle to gate” LCA study was elaborated for the PHA production process by PHBISA in Brazil. It compared PHA to the petrochemical plastics PE and PP [67]. The LCA presented in the study encompasses the net CO_2 production and all major parts of the production cycles. As a conclusion, PHA from the “Brazilian process” turned out to be superior to PP and PE in all major CML-LCIA categories such as ozone layer depletion, human toxicity and marine, fresh water and terrestrial ecotoxicity [67].

Another comparative LCA has been performed by an Italian group in order to assess the environmental impact of replacing of conventional petrochemical plastics by PHA-based composites prepared by a melt-mixing technique using sugarcane bagasse or organophilic montmorillonite as filler materials [58]. A conventional high-impact polystyrene cathode ray tube monitor housing (CRTMH) and glass-fibers-filled polypropylene internal panels (GFPIP) of an average car have been chosen as reference products. Energy use based on fossil feed stocks and the perspective for global warming over a period of one century has been selected as indicators for the environmental impact. It turned out that the relatively low Young´s modulus and high density for PHA-based composites compared to conventional plastics are a drawback for their environmental performance, but substantial environmental benefits can be obtained due to the saving inputs in the PHA production process. On a `cradle-to-gate` basis, all PHA-based composites appear to be environmentally superior to conventional polymers used for the two chosen applications. When the system boundaries are extended to a ´cradle-to-grave´ analysis (including the application phase and the follow-up treatment such as waste incineration with energy recovery), PHA-based composites are still advantageous only for CRTMH. In the case of GFPIP, the mass of the functional unit becomes overriding, and no substantial savings were observed. Finally, regardless of the system boundaries, composites of PHA and sugarcane bagasse show lower impact values than the composites of PHB and organophilic montmorillonite, and natural fibers seem to be the most promising filler in order to further improve the environmental performances of PHB composites [58].

The Sustainable Process Index (SPI) developed by Krotscheck and Narodoslawsky [64] can be considered the preferred one for LCA method and 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 SPI is based on the assumption that the only income of our planet is solar energy and 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 an area, using e.g. techniques like photovoltaics, thermal solar energy or the indirect utilization of solar energy via conversion of biomass [68,69]. 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 as follows:

Area for area (e.g. land occupation)
Area for non-renewable material
Area for renewable material
Area for fossil carbon
Area for emission to water

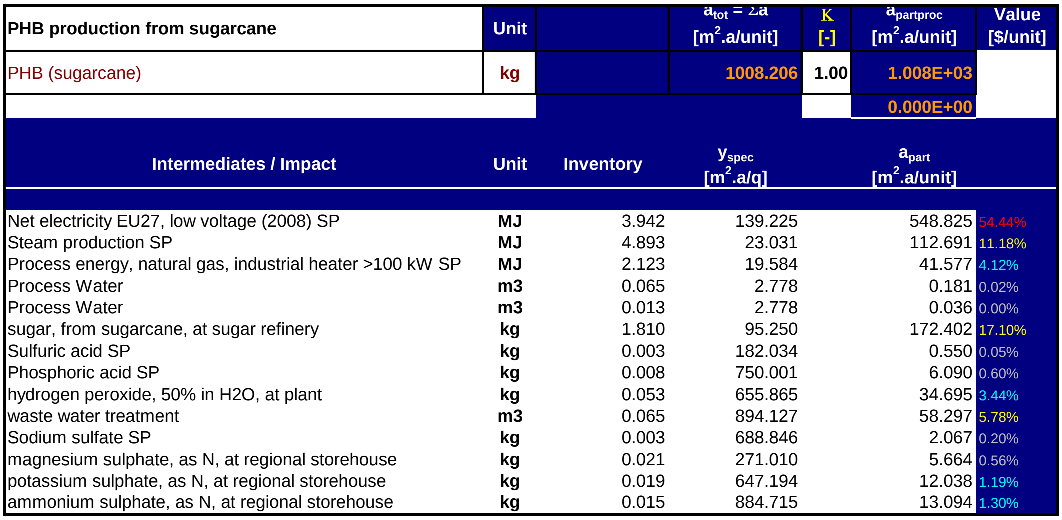
Area for emission to soil
Area for emission to air

The 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 [70], optimize the environmental performance of a single product (ecodesign) [71] or to optimize the environmental performance of a company [72,73]. Especially the latter is of importance in the case of utilizing energy from bagasse for PHA production from sugarcane. 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.

A particular tool to minimize waste and emissions during the PHA production process based on environmental assessment and to maximize the product output can be identified in the strategy of Cleaner Production. Cleaner Production is a preventive ecological protection methodology that may be applied to a particular company and product. Cleaner Production helps a company to intelligently selecting adequate materials, save energy and to avoid waste streams, waste water generation, gaseous emissions, noise and unused heat. Cleaner Production is also based on the strong belief that solar energy has to be applied wherever possible [68, 74].

In this study the SPI methodology was used to calculate the ecological footprint for sugarcane and PHB. Based on ecoinvent data (information: Ecoinvent, Swiss Centre for Life Cycle Inventory, Switzerland), the footprint for the cultivation of sugarcane and refining to sugar (including combined heat and power energy provision from bagasse) is 95.25 m²/kg. Further processing to PHB based on the LCI data of Harding et al. [67] results in 1,008.21 m² per kg PHB (Figure 10).



PHB production from sugarcane	Unit		$a_{tot} = \Sigma a$ [m^2.a/unit]	K [-]	$a_{partproc}$ [m^2.a/unit]	Value [$/unit]
PHB (sugarcane)	kg		1008.206	1.00	1.008E+03	
					0.000E+00	

Intermediates / Impact	Unit	Inventory	y_{spec} [m^2.a/q]	a_{part} [m^2.a/unit]	
Net electricity EU27, low voltage (2008) SP	MJ	3.942	139.225	548.825	54.44%
Steam production SP	MJ	4.893	23.031	112.691	11.18%
Process energy, natural gas, industrial heater >100 kW SP	MJ	2.123	19.584	41.577	4.12%
Process Water	m3	0.065	2.778	0.181	0.02%
Process Water	m3	0.013	2.778	0.036	0.00%
sugar, from sugarcane, at sugar refinery	kg	1.810	95.250	172.402	17.10%
Sulfuric acid SP	kg	0.003	182.034	0.550	0.05%
Phosphoric acid SP	kg	0.008	750.001	6.090	0.60%
hydrogen peroxide, 50% in H2O, at plant	kg	0.053	655.865	34.695	3.44%
waste water treatment	m3	0.065	894.127	58.297	5.78%
Sodium sulfate SP	kg	0.003	688.846	2.067	0.20%
magnesium sulphate, as N, at regional storehouse	kg	0.021	271.010	5.664	0.56%
potassium sulphate, as N, at regional storehouse	kg	0.019	647.194	12.038	1.19%
ammonium sulphate, as N, at regional storehouse	kg	0.015	884.715	13.094	1.30%

Figure 10. LCI data for SPI calculation.

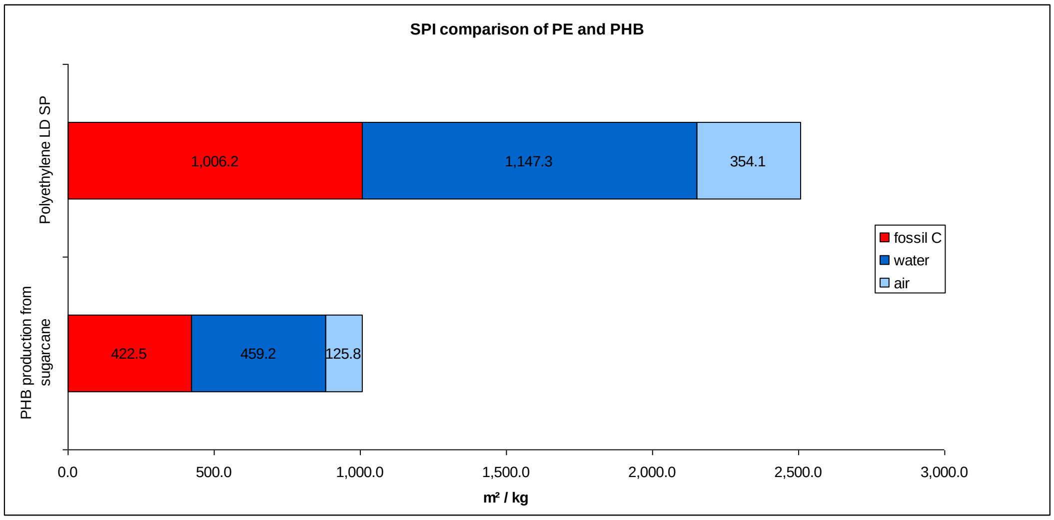


Figure 11. SPI comparison between Polyethylene and PHB.

Results shown in Figure 11 illustrate in which category the footprint occurs but negligible categories are discarded. High emissions to water are because of using net electricity from the grid (european average mix) which is strongly driven by nuclear power, which results in high emissions to water. Therefore the location of production and locally provided energy affects the result strongly. Compared to low density polyethylene (LDPE) from crude oil, which has a footprint of 2,508.41 m²/kg, this would point out a saving of ecological pressures of about 60 %. Out of the sub-area 'fossil C' which is equivalent to CO_2-emission over the whole life cycle 3.1 kg CO_2 per kg PHB are emitted. Compared to 7.4 kg CO_2 per kg of LDPE it is considerably lower. SPI results in higher CO_2 emissions compared to Harding et al., 2007 (1.96 kg CO_2 e.g. per kg PHB) although only carbon dioxide was considered as one of the greenhouse gases. Nevertheless this value points to a reduction of 58 % of CO_2 emissions compared to LDPE.

Conclusion

Despite the enormous efforts devoted during the last four decades on the production, structural characterization and processing on laboratory and pilot scale of microbial PHAs starting from renewable feedstocks, the market penetration of PHA, so far, has not yet taken off. Some actions undertaken in the 1980ies by ICI-Marlborough (United Kingdom), Chemie Linz (Austria), and, more recently, by Monasanto (USA) and at the present by a joint venture between Telles Metabolix Inc. and Archer Daniels Midland (USA) and others like Tianan or Shandong (People's Republic of China) constitute encouraging and laudable exceptions.

As demonstrated in the text, industrial PHA production should be integrated into the existing structures of the waste or raw material generating industrial unit to minimize production costs due to synergistic effects. A prime example for this strategy is implemented by the presented integration of a PHA production pilot plant into a sugar mill combined with ethanol production in Brazil (PHBISA). In this scenario, the in-house product sucrose acts as carbon source and is available in huge quantities, the total process energy is generated from combusting surplus bagasse as a primary energy source, and the PHA-extraction solvent is also available in-house as a waste stream of the ethanol distillation unit. The PHBISA process demonstrates a viable strategy for other agro-industrial production companies in different global regions to utilize their waste streams for biopolymer production such as whey from dairy productions, glycerol from biodiesel production, lipid wastes from plants or animals, (ligno)cellulosics and other polysaccharide components. Also for Europe, similar concepts based on regionally arising waste- and surplus materials appear very reasonable and should be forcefully imposed.

The sugarcane-based PHA production process can be further optimized in order to achieve additional economical benefit. The application of novel production strains that directly convert sucrose without prior hydrolysis towards glucose and fructose would save the costs for sucrose hydrolysis. In addition, costs for cooling of the bioreactor can be saved using a microbial production strain with a higher temperature optimum for cultivation.

Uniting the potential enhancements of each process step, one can definitely make substantial progress towards a cost-efficient technology. This appears possible by the selection of extremophilic production strains like *Haloferax mediterranei* which are capable to accumulate high value copolyesters directly from non-hydrolyzed sucrose without the need of co-substrate supply. These attractive attributes go together with minor sterility precautions and cheap and convenient methods for biopolyester isolation by using simple cell disintegration in hypotonic aqueous environment.

In any case, the development of really efficient biopolymer production processes starting from diverse waste streams needs an integrated vision and the strict cooperation of experts with different scientific backgrounds. Chemical engineers, microbiologists, enzymologists, polymer scientists, medical researchers, genetic engineers and experts in the fields of LCA and Cleaner Production have to concentrate their special expertise and know-how in order to close the existing gaps between the promising data from the laboratory scale and the industrial realization.

In future, biopolymer production from sugarcane has the potential to contribute to socioeconomic benefit by job creation directly in sugar producing factories which are mainly located in developing and emerging countries. Hence, biopolymer production in the existing production lines can become a strong economic pillar for sugar industry in the future. An additional number of qualified employees can be expected globally in research institutions, where further developments on laboratory scale have to take place in order to optimize the promising strategy to generate bioplastics from available renewable resources on industrial scale.

Parallel to this approach, strategic efforts should be also focused on the use of by-products or wastes generated both in small-medium enterprises as well as in big industries as a source for the production of PHA downstream to their processes. This should help to end up with holistic zero-waste processes and with a positive economical contribution bound to the production of added-value commercially marketable and environmentally friendly materials.

Table 2. Overview of PHA from sugarcane sucrose, hydrolyzed sugarcane sucrose, or hydrolyzed bagasse by different microbial production strains as reported in literature

Microbial production strain	**Scale**	**Substrate**	**Productivity of PHA [g/L h]**	**Specific productivity of PHA [g/g h]**	**Biomass [g/L]**	**PHA [g/L]**	**Type of PHA produced**	**PHA / biomass [%]**	**Yield [g PHA / g substrate]**	**Reference**
Cupriavidus necator DSM 545	Industrial scale bioreactor (m³)	hydrolyzed sucrose	1,44	0,036	120-150	78-105	PHB (PHBHV only after addition of propionic acid)	65-70	0,31	[30, 40]
Azotobacter vinelandii UWD	Laboratory bioreactor (2,5 liter)	Beet molasses	1,4	0,117	35	23	PHB (PHBHV produced in parallel set-ups by additions of valerate)	66	0,36	[44]
Azohydromonas lata DSM 1123	Laboratory bioreactor (10 liter)	green syrup	0,22	0,051	7,6	3,3	PHB	43	0,22	[50]
Azohydromonas lata DSM 1124	Laboratory bioreactor (10 liter)	beet molasses	0,21	0,033	9,1	2,8	PHB	31	0,30	[50]
Haloferax mediterranei ATTC 1411	Shaking flask scale	sucrose plus yeast extract	0,021	0,126	1,57	1,40	PHBHV	71	0,07	this work
Bacillus megaterium	Shaking flask scale	date syrup	0,04	0,025	3,3	1,7	PHB	52	n. r.	[48]

Bacillus megaterium	Shaking flask scale	beet molasses	0,04	0,021	3,7	1,8	PHB	50	n. r.	[48]
Bacillus megaterium	Shaking flask scale	sucrose	0,0005	0,001	0,5	0,025	PHB	5	n. r.	[48]
Bacillus megaterium	Laboratory bioreactor (42 liter)	date syrup	0,06	0,024	3,4	0,85	PHB	25	13	[48]
rec. Klebsiella aerogenes	Laboratory bioreactor (10 liter)	molasses	0,75	0,075	34	24	PHB	70	n.r.	[43]
Azotobacter beijerinckii	Shaking flask scale	molasses and corn steep liquor	0,155	0,028	19,2	3,73	PHB	20	n.r.	[45]
Haloferax mediterranei ATTC 1411	Shaking flask scale	molasses plus yeast extract	0,023	0,110	1,77	1,56	PHBHV	88	0,08	this work
Haloferax mediterranei ATTC 1411	Shaking flask scale	equimolar mixtures of glucose and fructose plus yeast extract	0,026	0,015	3,46	1,76	PHBHV	51	0,09	this work
Burkholderia sacchari IPT 101	Laboratory bioreactor (10 liter)	hydrolyzed sugarcane bagasse	0,11	0,041	4,4	7,1	PHB	62	0,39	[51]
Burkholderia cepacia IPT 048	Laboratory bioreactor (10 liter)	hydrolyzed sugarcane bagasse	0,09	0,043	4,4	2,3	PHB	53	0,29	[51]
Pseudomonas corrugate		soy molasses	0,003	0,003	1,5	0,26	*mcl*-PHAs consisting of	17	n.r.	[16]

388							3HHx, 3-HO, 3-HD, 3-HDD, 3-HDDe, 3-HTD, and 3-HTDe			
Cupriavidus necator	Shaking flask scale	glucose plus sugarcane molasses as growth enhancer	0,12	0,008	23,06	9,00	PHB	39	0,25	[47]

n.r.: not reported
3-HHx: 3-hydroxyhexanoate
3-HO: 3-hydroxyoctanoate
3-HD: 3-hydroxydecanoate
3-HDD: 3-hydroxydodecanoate
3-HDDe: 3-hydroxydodecenoate
3-HTD: 3-hydroxytetradecanoate
3-HTDe: 3-hydroxytetradecenoate

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13 PAPER 4

Process design and evaluation of biobased polyhydroxyalkanoates (PHA) production

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13.1 Contribution to PAPER 4

First steps on process design development have been done in conjunction with the partners who are experts at the PHA fermentation part. A first SPI evaluation gave some initial information about key parts of the process design which have to be in the focus of interest. Intermediate 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 greenhous 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. Aim of the ANIMPOL project ("Biotechnological conversion of carbon containing wastes for eco-efficient production of high added value products"), funded by the European Comission within the 7th Framework program, is to produce biobased plastics 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.

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 leaded the development of this concept. Process Intensification was defined as a "reduction in plant size by at least several orders of magnitude" by them (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.
(Senter Novem, 2007)

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 via the ecological footprint.
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)

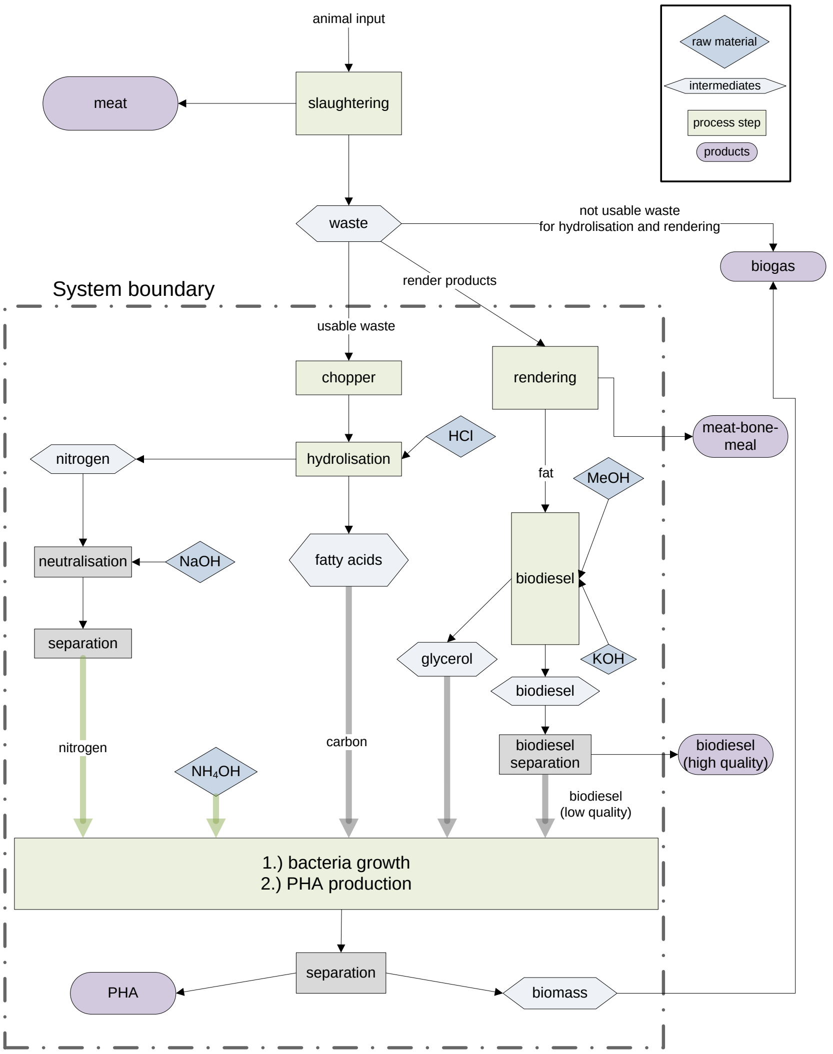

Figure 11: Process flowchart

Slaughtering waste utilisation for biobased polyester production

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 offals) 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 1 illustrates a flowsheet 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 offals. In our approach a part of the slaughterhouse waste (e.g. hearts, livers, lungs,…) can be used for hydrolysis instead of rendering this parts.

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 componet, the bacteria are performing the intracellular accumulation of the final product polyhydroxyalkanoate. This biopolyester is biodegradable and can be used to sustitute 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 an 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 production PHA 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 economical 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, genetical 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.

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14 PAPER 5

Process Optimization for efficient biomediated PHA production from animal-based waste streams

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14.1 Contribution to PAPER 5

This paper addresses three main aspects out of the ANIMPOL project. First is the process design for an industrial scale PHA production process scenario. Second aspect was the ecological evaluation with the SPIonExcel program and third aspect an economic evaluation to estimate the investment and operation costs. Contributions are the process design which was developed in lots of discussion within the whole group. Data collection and SPI evaluation for the PHA production as final product. But also key parts of the process design development have been carried out to address the latter two aspects within 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 polyhydroxyalkanoates (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 NH_4OH 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 polyhydroxyalkanoates (PHAs) on an industrial scale constitutes part of "White Biotechnology", characterized by the utilization of renewable resources as feedstocks 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 unfavourable growth conditions due to imbalanced nutrient supply. For PHA harbouring 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 catabolised 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 CO_2 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 feedstocks 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.

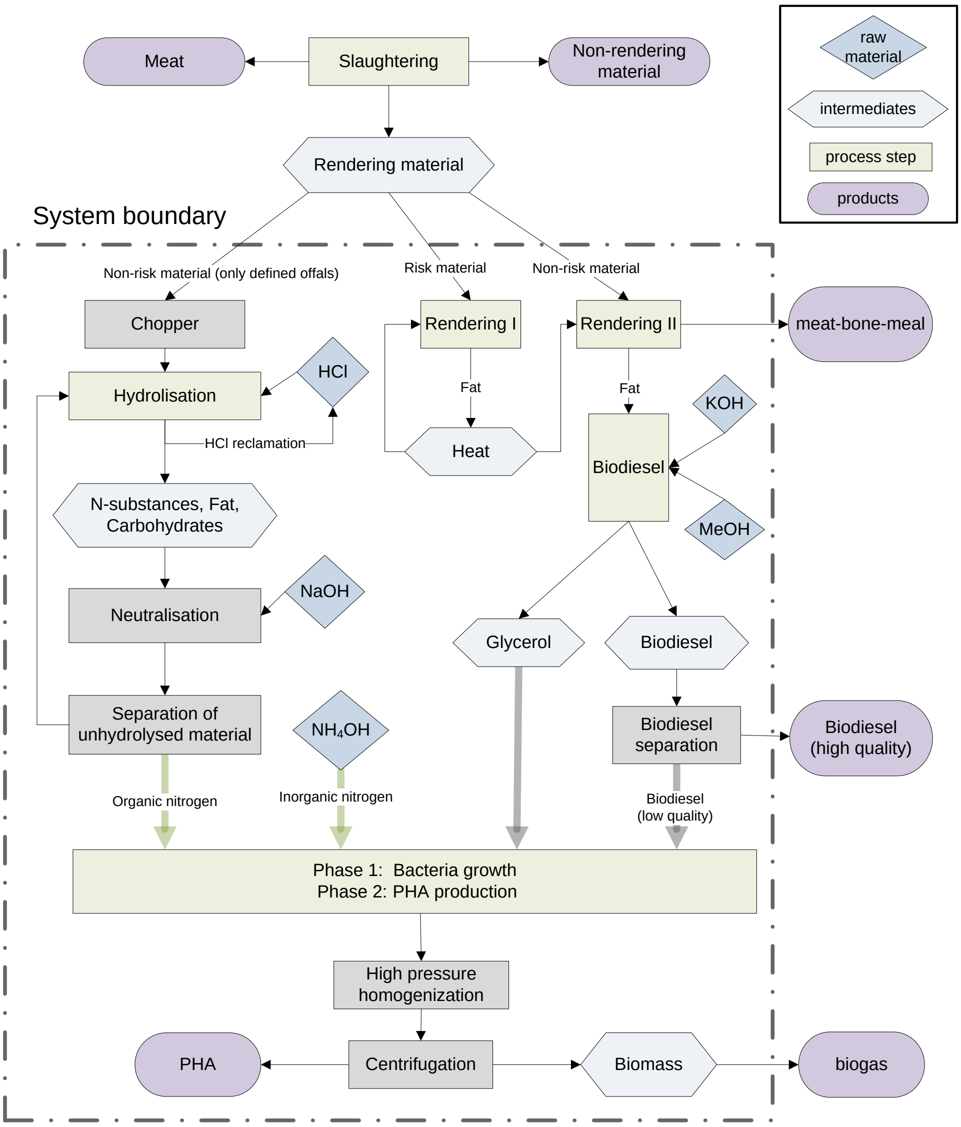
According to personal communication with project partner, the entire amounts of animal lipids from the slaughtering process can be quantified with more than 500,000 ton/year (y). This lipid content is potential raw material for 490,000 t/y biodiesel production, containing about 55% saturated biodiesel 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.

Figure 1: Flow sheet of process design for ANIMPOL



In the current process design 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.

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 monoseptic 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 [6](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 1 summarizes the performance parameters for these scenarios.

Table 2: 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

---

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

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}.

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 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 3: Chemical composition of 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).

Table 4 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 3 calculated offer of offal material is 15,495 t/y.

Table 4: Offal offer based on 130.000 t/y rendering plant size and offal demand for the hydrolysis

offal	weight per animal equivalent[7] [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

Table 5: 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**

Hydrolization of the residual material will be carried out with 6 M HCl at 120 °C using concentration 100 kg/$m^3$of 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 m^3 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.

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[7] standard cow: weight 587 kg

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 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 6.

Table 6: 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**

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 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. NH_4OH. It is used to control the reaction conditions as 25% NH_4OH (wt/wt) solution. The calculated 25 % (wt/wt) NH_4OH consumption is therefore 3,213 t/y containing 321 t of nitrogen.

Ecological evaluation

Based on the mass and energy flows from the process design a first ecological evaluation was carried out Instead of calculating the footprint after the process design is finished, here ecological evaluation is used a decision criteria during the process development. This provides the possibility to focus on those parts of the process design that are ecological hotspots. In this process scheme particular interest will be laid on the contribution of the hydrolysis step to the ecological pressure as this step is distinctively new in the technology concept. The evaluation will be carried out with the Sustainable Process Index in order to cover a broad range of ecological impacts.

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 aand Narodoslawsky, 2008). For footprint calculation the freeware program SPIonExcel (Sandholzer aand 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

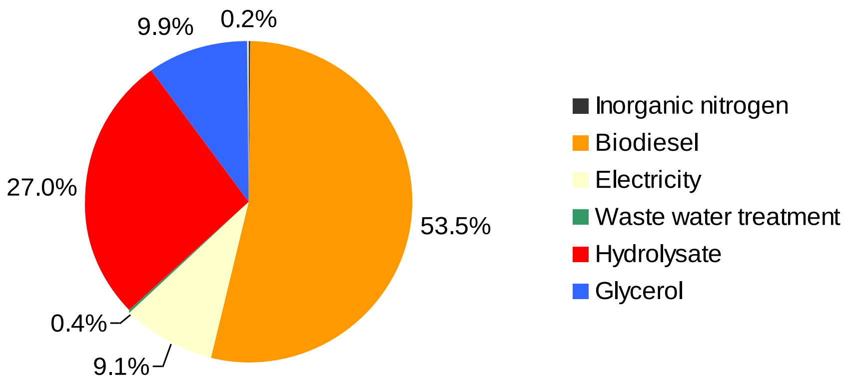
Based on material and energy flows for the production of PHA according to Table 7 an ecological footprint was calculated.

Table 7: 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 2 illustrates the share of the footprint between input streams for different sub-processes respectively.

Figure 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 represents the production costs for organic nitrogen via hydrolysis.

Table 7: Nitrogen production costs per year

	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 (NH_4OH) 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 shows the annual nitrogen costs using HCl reclamation and as alternative H_2SO_4.

Table 8: Comparison of nitrogen of annual production costs using HCl reclamation and H_2SO_4 for hydrolysis

Hydrolysis with HCl

	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.

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15 PAPER 6

Ecological Impact of renewable resource-based energy technologies

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15.1 Contribution to PAPER 6

This paper addresses few different renewable and fossil energy technologies but with a quite different life cycle chain behind each technology. For those Footprints a huge amount of life cycle data was needed to achieve a result for every specific energy technology. The whole paper is based on this evaluation and interpretation results.

Ecological impact of renewable resource based energy technologies

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ABSTRACT

Renewable resources based energy technologies are currently gaining strong interest, particularly in the light of global climate change and volatile energy markets. A major argument for their use is their ecological advantage. The paper will compare the ecological impact of various biofuel technologies, technologies providing electricity and heat on the base of different resources, both biogenic and direct as well as indirect solar energy. It will compare these technologies with on the base of the Sustainable Process Index (SPI), a comprehensive and sensitive ecological measure addressing resource provision as well as emissions and global warming with a consistent methodology. The paper will analyse different aspects of the ecological impacts of energy technologies and bio-fuels. On the base of this analysis conclusions will be drawn regarding the most important factors influencing ecological performance as well as unresolved questions for a solid evaluation for these technologies.

KEY WORDS

Sustainable Process Index, ecological footprint, energy technologies, biofuels

1 Introduction

The quest for an energy provision that will mitigate human caused climate change and the necessity to brace for the decline in the availability of fossil energy resources like crude oil and natural gas (Schindler and Zittel [1]; IEA [2]) have increased interest in alternative energy technologies considerably since the turn of the century. There is a general consensus that energy technologies on the base of renewable sources such as solar radiation, wind power and biomass will not only achieve a sea change in terms of global warming but will be inherently friendly to the environment too. Recent studies (Heedegard et. al. [3]) however challenge these assumptions at cost for biofuels and call for a more careful analysis of ecological impact of energy technologies over the whole life cycle.

There is a methodological challenge in comparing different energy technologies that is caused by the fact that they are based on widely different sources and techniques to exploit these sources. Conventional energy technologies are mostly based on fossil resources like coal, crude oil and natural gas. These technologies usually exhibit their largest pressure on the environment during operation by emitting CO_2 into the atmosphere and thus changing the global carbon flow systems with grave consequences for the global climate.

Technologies based on biofuels and biomass in general exert quite different pressures on the environment. For these technologies the pressures caused by agriculture as well as transport become important, as do pressures caused by pollutants like NO_x produced during burning biogenic energy carriers. Especially fossil fuel which is commonly used in mechanised agriculture is a very important factor for the ecological footprint for biofuels. Another main factor on the emission side of agricultural crop production is the production of N_2O from the usage of mineral fertilizers (Kendall and Chang [4]). CO_2 emissions during operation however have almost no importance for those technologies as biogenic resources per se do not change global carbon flows. In general a detailed view on the substrates, co-products and transport emissions during the life cycle is necessary.

Finally there is a group of energy technologies that do not cause appreciable environmental pressure during operation such as wind power, solar heat and photovoltaic and to a lesser extent hydro power. For these technologies the main environmental pressure is linked to the construction and installation of the equipment like PV panels, wind turbines and solar collectors. The task of comparing these different energy technologies in terms of their environmental pressures requires a tool that must take into account different qualities of environmental impacts yet still leads to a meaningful evaluation of the overall environmental performance of the technique.

There are several methodologies available for evaluating environmental impacts like MIPS (material input per service unit, (Schmidt-Bleek and Bierter [5])), CML-Method (Centrum voor Milieukunde Leiden, (Heijungs et. al. [6]), CED (cumulative energy demand, (Ökoinstitut e.V. [7])), Energy footprint (Stöglehner [8]) and even more as Fijal [9] and Finnveden et. al. [10] are describing in their work. For a complete environmental impact assessment an analysis tool is needed which can evaluate material flows, energy flows and emissions. This calls for a measure that is highly aggregated (to allow comparison) but evaluates different impacts in a transparent scientifically based way. The Sustainable Process Index (SPI) (Narodoslawsky and Kroteschek [11]) is such a measure which follows the rules of the ISO 14040 norm. The SPI has already proved its usefulness in a number of studies involving renewable resource based technologies (Narodoslawsky et al. [12]; Narodoslawsky and Niederl [13];

Niederl and Narodoslawsky [14]) and is freely available on the internet (Sandholzer et al. [15]) via the website http://spionexcel.tugraz.at.

The SPI is a member of the ecological footprint family and measures the area that is necessary to embed a human activity sustainably into the ecosphere, taking resource provision, energy use, waste and emissions into account. By referring the environmental pressures incurred by manufacturing and construction of equipment to the economic life time of the installation, the environmental impact of infrastructure can also be considered.

2 Differing environmental pressures for different technologies

Energy provision technologies offer an opportunity to investigate the environmental profiles of technologies based on widely different resources and technological structures. There are many ways to provide heat, electricity and fuel but there is a product that is very comparable, namely the energy output in MJ. Evaluating the impact of different technologies with the SPI is therefore not only interesting from the point of view which technology provides the needed energy while causing the lowest impact on nature. It is also interesting from the point of view of what particular impact a certain technology causes as this may be the starting point for optimisation as well as supporting strategic planning against the background of changing structures in the resource base of society in the 21st century. The following figures show that “renewable resource based energy technologies” represent a very diverse range of technologies with large differences in both their overall pressure as well as the distribution of this pressure into different impact categories. For better overview the information rendered by the SPIonExcel program has been condensed in seven categories, the use of fossil-carbon, non-renewable and renewable resources (whereas the amount of fossil-carbon represents the impact on global carbon cycle), area utilisation and emissions to air, soil and water. Despite of these 7 categories only 3 of them (fossil-carbon resource, emissions to air and to water) are considered in this report (e.g. Figure 2 and 5) because the rest are in that case negligible. All comparative values of footprints refer to the impact incurred by providing 1 MJ of the energy form in question at the point of distribution.

2.1 Electricity provision technologies

Figure 1 shows the comparison between five different technologies to supply electricity. The unit m²a/MJ from Figure 1 to 5 means footprint area per year of production and produced MJ.

Part of the diagram is a wind turbine based on data from a Vestas 3 MW turbine (Vestas [16]), a monocristalline photovoltaic panel based on data from ecoInvent (Jungbluth and Tuchschmid [17]), a biogas unit (producing heat and power through a micro gas turbine, based on a mix of grass-,corn- and clover silage), a biomass ORC (organic rankine cycle) unit powered by wood chips (Bauer [18]) and a high performance natural gas combined heat and power system (with a 90 % overall efficiency and a 45 % electricity efficiency with respect to the gas input).

It goes without saying that the value for the biogas unit can only be seen as one value within a range of ecological footprints for this technology as the impact on the environment is critically dependent on the raw material, fossil fuel usage for machinery and application of mineral fertilizers. The calculation for the biogas unit assumes that biogas manure is used as biological fertilizer on the fields to substitute mineral fertilizers. Footprints may become considerably higher (by a factor of three at least) if biogas production is based on conventionally produced crops.

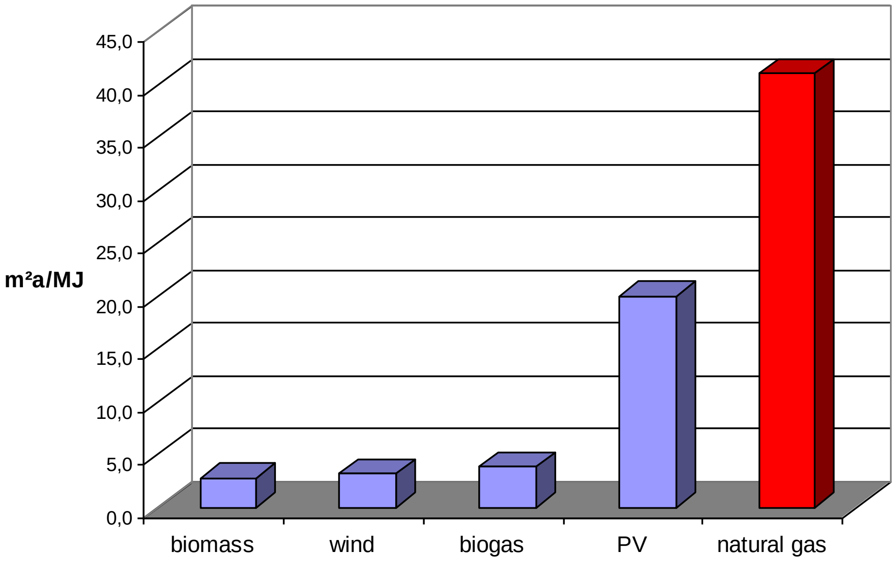

Fig. 1: Comparison of ecological footprints for different electricity provision technologies

From this figure it becomes clear that even a “clean” fossil based technology as natural gas turbines exert a higher pressure than all renewable resource based alternatives. The difference here is not just percent points but factors, with natural gas derived electricity (with 41.0 m^2a/MJ) exerting 10.8 times the impact of the biogas technology (with 3.8 m^2a/MJ) and still two times the impact of the “worst” renewable based technology photovoltaics (PV with 19.9 m^2a/MJ).

It is however interesting to look at the different impact profiles of the technologies. Figure 2 shows a comparison of these pressures for biomass, biogas, wind turbine, PV and natural gas. Analysing these it is obvious that the pressure on climate (represented by the fossil C contributes representing CO_2-emissions) is strong in all technologies. It is clear that this pressure category dominates the natural gas technology however it is interesting that it is also a strong influence in renewable resources based technologies. The reason is that our current energy system is still mostly fossil based and any energy input to production and manufacturing of equipment is also causing pressures in this category.

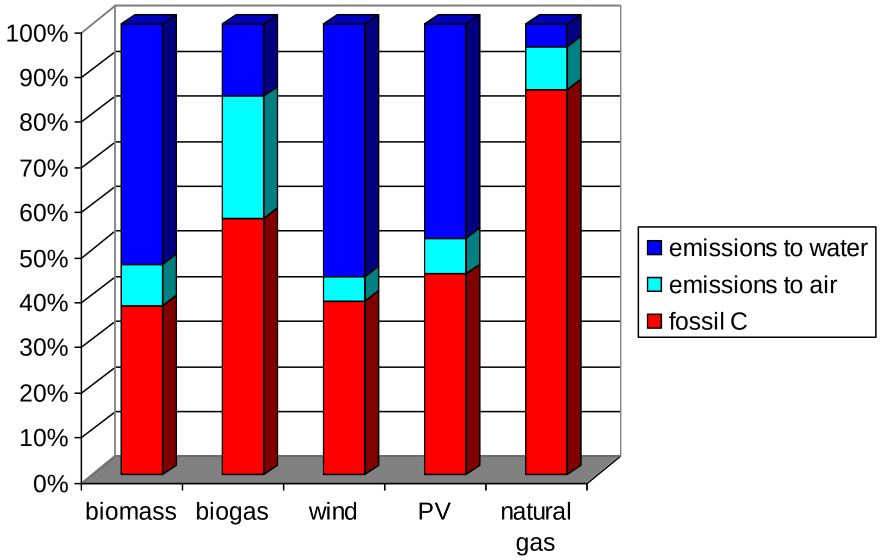

Fig. 2: Environmental pressure distribution for electricity generating technologies

Another interesting result is the difference in the profile between photovoltaic panels and wind turbines. A comparison reveals that the fossil carbon pressure dominates the wind turbine, reflecting the fossil contribution to steel processing. This cannot be reduced unless fossil coal is replaced by a renewable based alternative (like charcoal) in iron smelting, a change that has a low probability of realisation in this century.

In photovoltaic panel production the emissions (especially to water) are prominent, as a result of the complex chemical process employed to produce the semiconductor wafers. This points to the necessity to have a sharp eye on the emissions from this process. Moreover it is interesting that the carbon emission pressure predominantly comes from the frames of the panels (which are made from metals), caused by the energy intensive production processes of these materials. By and large the contribution from the raw material itself as well as the direct area use is negligible.

2.2 Heat generation processes

Figure 3 presents the comparison between three different heat providing processes. Combined heat and power technologies from chapter 2.1 (biogas unit, biomass ORC unit and natural gas turbine) are sharing the ecological footprint with the electricity production part rated to their amount of output in MJ. The comparison shows a similar picture than in electricity generation, with renewable based technologies coming out on top with regard to environmental pressures.

Difference between the worst (natural gas turbine which has 19.6 m²a/MJ) and the best technology (biomass ORC unit with 2.7 m²a/MJ) results in a 7.3 times higher footprint for the natural gas turbine. Which is not such a big difference as in Figure 2 but again the fossil carbon technology is much worse compared to renewable based technologies.

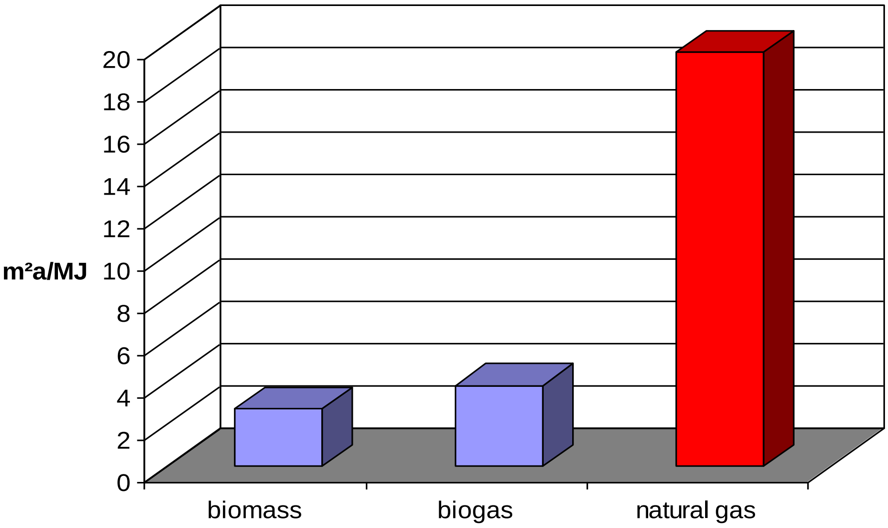

Fig. 3: Comparison of ecological footprints for different heat provision technologies

2.3 Biofuel systems

A particularly interesting picture arises with fuels. Figure 4 compares different biofuel systems based on renewable as well as fossil resources.

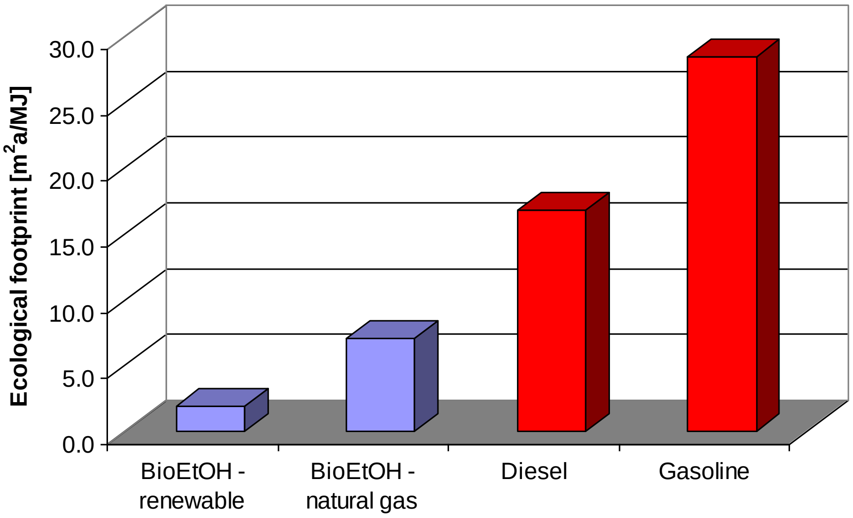

Fig. 4: Comparison of ecological footprints for different fuel systems

The two left hand columns in this figure represent the ecological pressure of bioethanol, with the first column on the left side showing the value for a production of ethanol from corn, using biomass for the provision of electricity and heat for the process. The column to the right shows the pressure exerted by ethanol from a process that uses natural gas as a source of process energy and again corn as substrate. The comparison shows that the energy source for the process decides about the impact of two otherwise similar ways to produce fuel.

Ethanol from corn is according to this calculation environmentally advantageous compared to fossil gasoline. As Reijnders and Huijbregts [19] show, this effect can be even increased if sugar cane is used as a resource.

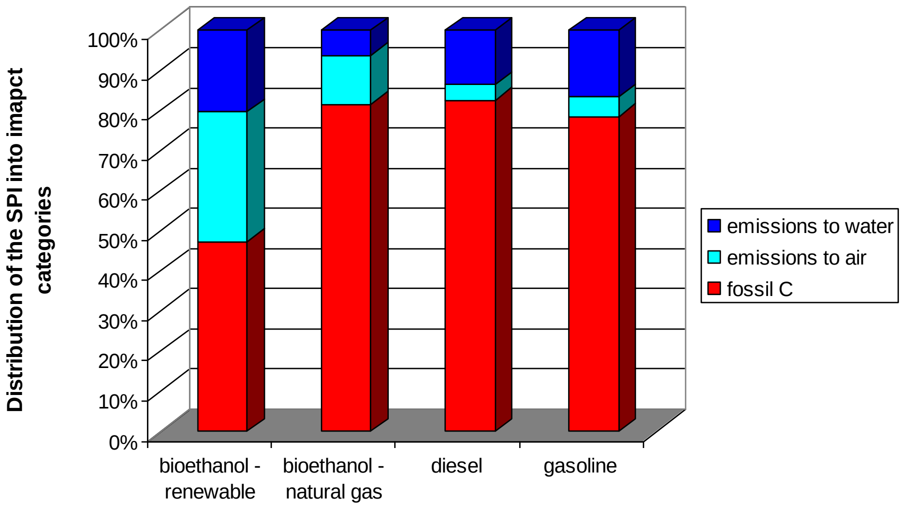

Fig. 5: Environmental pressure distribution for biofuel systems

The comparison of the impact profiles is shown in Figure 5 for the two bioethanol alternatives, gasoline and diesel. The main pressure for bioethanol from corn using natural gas as process energy source is clearly dominated by the fossil carbon impact. Even in the case of the bioethanol production using biomass as process energy source fossil carbon is an important environmental factor. The absolute size of the impact however is much lower and the origin is different. Whereas in the former case fossil carbon (and thus carbon dioxide emissions) is linked to the energy provision of the process, in the latter case the impact results from agriculture, especially the fossil energy to generate fertiliser and the fuel for machines. The large fraction of fossil carbon impact for diesel and gasoline is however not surprising. The fossil carbon part in biofules can be decreased by using biofuels for agriculture machinery and transport systems by Ometto and Roma [20].

3 Conclusion

Comparing different energy technologies with the SPI reveals some interesting insights:

- The environmental pressure of fossil based technologies and fuels are indeed much larger than that of comparable technologies and products on the base of renewable resources. The impact of fossil technologies is by factors larger than that of renewable resource based technologies.

- Fossil carbon plays a major role in the pressure even of renewable resources based technologies. This is linked to the fossil orientation of our current resource system as coal, fossil oil and gas dominate the energy provision of industry as well as transport and energy provision for society.

- Using fossil energy in processes based on renewable resources inevitably raises the ecological impact considerably as is evidenced by the bioethanol case.

- There are large differences in between different technologies/products based on renewable resources regarding their environmental pressure. Just using a renewable source does not qualify a technology or product to become overall sustainable.

- Technologies which exhibit high pressures stemming from energy provision (like photovoltaic panels) will become more attractive the more the overall energy system becomes more sustainable.

In general the evaluation confirms that a switch towards renewable resource based technology systems is indeed capable of reducing human pressure on the environment dramatically. This is mainly true because these technologies shift the environmental pressure away from fossil carbon impacts that currently dominate environmental considerations.

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16 PAPER 7

Ecological evaluation of biogas feedstock from intercrops

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16.1 Contribution to PAPER 7

Ecological SPI evaluation of the case study “Bad Zell” was the main contribution which was also presented on the PRES 2010 Conference in Prague, Czech Republic. This paper represents an early development phase of the Syn-Energy project. Although it points already out that the PNS optimum structure und these conditions seem to be ecologically feasible nad is utilizing intercrops.

Ecological evaluation of biogas feedstock from intercrops

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The production of biogas from renewable resources is a common technology for combined heat and power provision. Small scale plants represent de-centralized energy supply for communities and are an important part of regional development and de-central usage of renewable resources.

To avoid conflicts with the food- and feedstock provision the usage of main crops as main source for biogas production should be avoided. Intercrops are planted on agricultural fields between the periods for main crops and may be used to provide biogas feedstock fields besides main crops. This biogas can be used in decentralized biogas units to produce electricity and heat. Beside the energetic usage of intercrops possible positive side effects are analysed. The usage of intercrops instead of mulching has a potential to decrease emissions of nitrates to water and nitrous oxide to air. Especially emission reduction of nitrous dioxide, a potent greenhouse gas, is part of the analysis.

For the calculation of environmental effects of agriculture with intercrops the ecological evaluation method of the Sustainable Process Index (SPI) is used (Narodoslawsky et. al., 2008).

Introduction

Intercrops are planted beside main crops e.g. wheat, corn or triticale between the main crop periods. Intercrops however can also be used to increase yield per hectare besides improving soil quality. Intercrops have the potential to increase biological nitrogen fixation and rebuilding of humus. This would decrease usage of mineral fertilizers which results in a lower ecological pressure. Taking intercrops from the field may decrease this positive effect. This has to be balanced with the potential positive impact of providing energy from intercrops, if they are to be used as substrate for biogas production. For an economic analysis of different possible biogas production scenarios the well known method of the process network synthesis (PNS) (Friedler et. al., 1995; Halasz et. al., 2005) is used. PNS is able to calculate different concepts of using fields most efficiently and also indicate if biogas should be used centralized or decentralized based on economical values.

Process Network Synthesis (PNS)

Process Network Synthesis is a method to find an optimal technology pathway out of a complex technology network (maximum structure). The main aim is to find a network consisting operations of processes technologies to transform raw materials into products (including energy). This method allows the optimisation of process structures as well as energy and material flows. Time dependencies like resource availability (e.g. harvesting of renewable resources) as well as product or service demand (e.g. varying heat demand for district heating over the year) are part of the optimisation. The input necessary for this optimisation includes mass and energy balances, investment and operating costs for the technologies considered, costs for resources and utilities, prices for products and services as well as constraints regarding resource supply and product/service demand.

Intercrops

To get raw data about soil effects a set of intercrops combined with common main crops are planted on 3 different locations in Austria. Climatic differences between the locations are used to get specific yield data for planting different kind of intercrops. One target is to increase economic output per hectare and simultaneously improve soil quality through intercrops.

Typical planting rotation is to grow the winter type of main crops (e.g. wheat, rape, etc.) and after harvesting the regeneration period starts. This period is used to plant intercrops. Decreasing effects of soil erosion, loss of nitrate and simultaneously increased yield per hectare and year are an argument for planting intercrops. After the intercrop period the main crop period starts again instead of taking a break between the main crop phases without planting anything on the acre.

Case study

First step of analysis was a PNS network with all possible biogas feedstock from regional providers. Several locations for biogas plants are chosen and virtually interlinked with the PNS-Solver. Transport distances are taken into account through slightly different raw material prices for each provider group of substrates.
Second step was the calculation of an ecological footprint through SPI out of the optimal solution from PNS.

Economic evaluation - PNS

Figure 1 illustrates the maximum structure from PNS of a case study from Bad Zell in Upper Austria. Every possible connection between substrates, production technology and products are illustrated. This results in a very complex maximum structure for optimisation. Detailed information about the maximum structure is listed below:

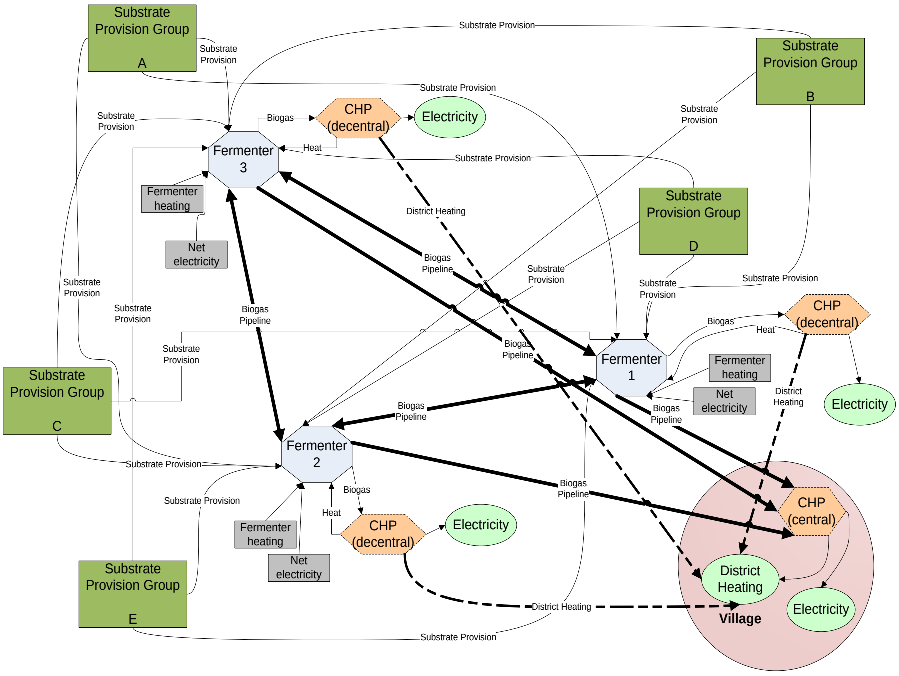

Figure 1: PNS - Maximum Structure

I. There are many small farmers in Bad Zell who can provide different substrates. These providers of main crops, intercrops and manure are grouped to simplify transport situations. Each provider group has a specific transport distance to each fermenter and they are able to supply every fermenter every possible substrates (corn, grass silage, intercrops and manure).

II. Three possible locations for a biogas fermenter are chosen. For every location also three different sizes are available (80KW$_{el}$, 160KW$_{el}$ and 250KW$_{el}$).
    - A biogas fermenter including a combined heat and power unit (CHP) could be possible. It can sell electricity to the grid, provide heat for the fermenter (for free) and additionally selling heat for the central district heating grid (DHG). To sell heat to DHG additional pipelines would be required which increases investment costs.
    - Another option for PNS would be to install a biogas fermenter excluding a CHP unit with the possibility to transport the biogas (through a biogas pipeline) to one of the others including a CHP unit or transporting it to the central CHP unit. In this case investment

costs are lower for a fermenter but an additional heating for the fermenter is required (in this case a wood chip burner)

III. Because of high priced DHG-pipelines there is also the possibility to transport biogas to a centralized CHP unit (with a higher capacity) which produces electricity (for the grid) and heat (for DHG). An advantage of transporting the biogas is the low price for biogas pipelines.

All available scenarios are part of the maximum structure. PNS is used to get an optimized structure out of Figure 1 with the highest revenue. Transport situation (e.g. distances between provider groups) is taken into account through different transport prices for each route.
Out of the maximum structure PNS calculates several possibilities how to link these production options. Figure 2 illustrates which provider groups and how many substrates are taken for the optimal solution. Not every provider group is part of the final solution due to different transport distances. Only one fermenter (biggest size) excluding CHP chosen and biogas is transported through biogas pipelines to a centralised CHP. Because heat can be sold to villages DHG it increases the overall revenue although biogas pipelines are needed. Although main crops (corn) are used, intercrops are part of the optimal structure. Therefore it makes sense for farmers to plant intercrops on their fields.

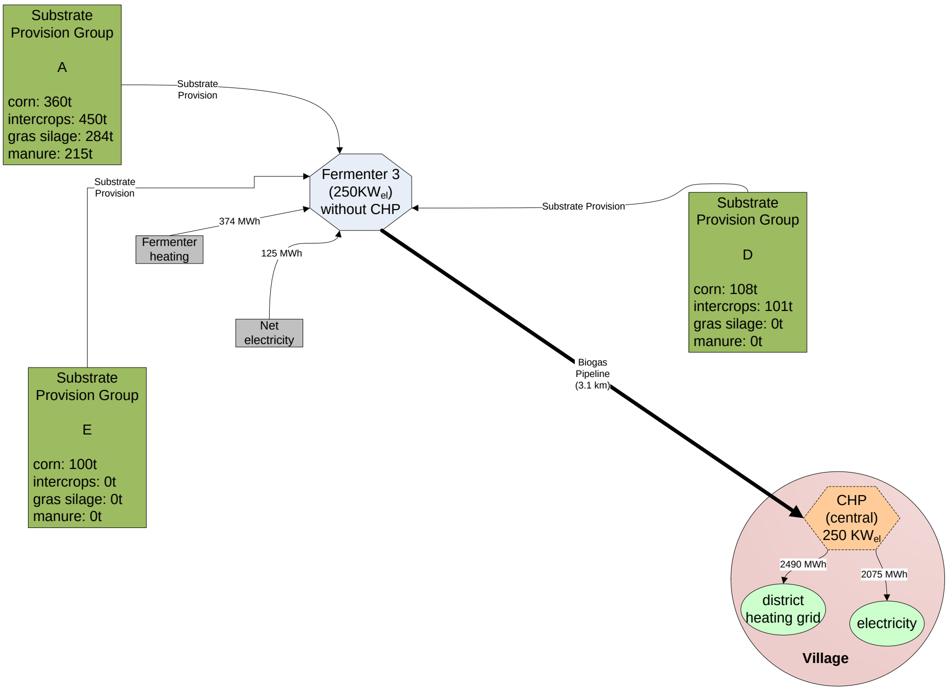

Figure 2: PNS - Optimum Structure

Ecological evaluation - SPI

Chapter 4.1 figured out how a biogas production can look like with the emphasis of highest revenue for the overall system. To rate the environmental effects of the optimal solution an ecological footprint was calculated. Due to lack of data environmental impact for biogas pipeline infrastructure is not taken into account.
Figure 3 illustrates the Process Chain for the production of electricity and heat from biogas feedstock.

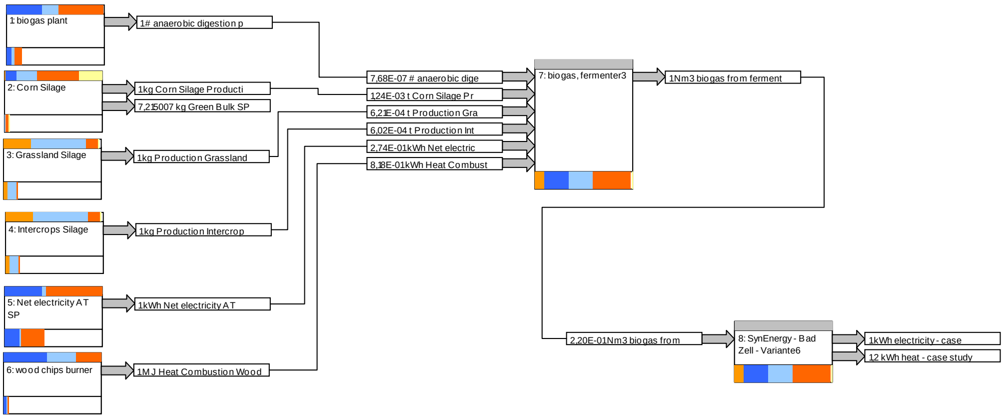

Figure 3: SPI – Process Chain

This results in a footprint of **14.35 m²a / kWh** per year. According to this result **40.7 g** of CO_2 is emitted to atmosphere per kWh of electricity or heat.

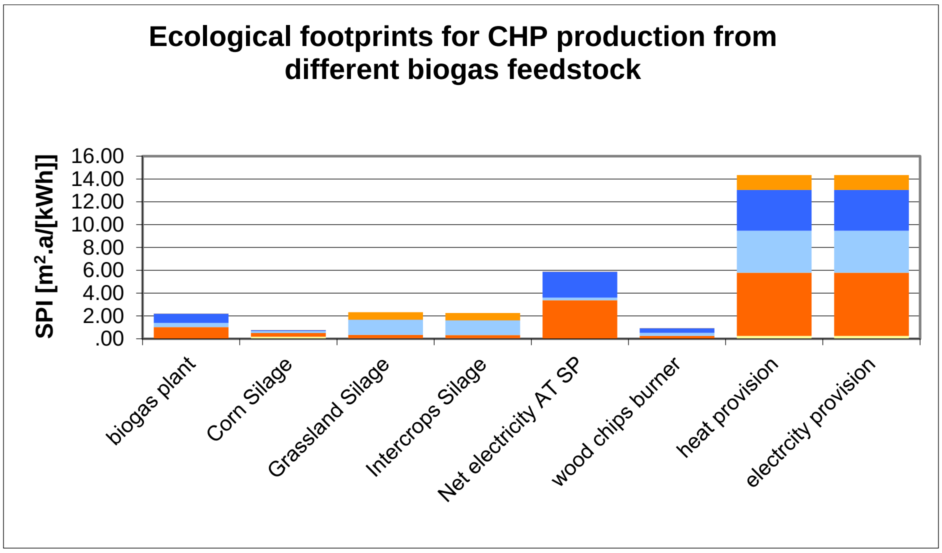

Figure 4: SPI – Process Chain Report

Figure 4 illustrates the specific footprints for different substrates, infrastructure, fermenter heating and net electricity. It is obvious that the usage of net electricity increases the footprint dramatically. From the economic point of view it makes more sense to sell electricity from biogas to the grid than using it internally.
Each footprint is shared into different SPI categories which are the different colours (orange = area for emissions to soil, dark blue = area for emissions to water, light blue = area for emissions to air, red = area for usage of fossil carbon and yellow = area for infrastructure).

Conclusions

Focus of the optimisation is not to identify a pathway through a huge set of different technologies which are producing heat or electricity. PNS was used in this case study to proof if the usage of intercrops is economic feasible. Main crops like corn are still used because of a high biogas yield but also intercrops are part of the optimal structure. Planting of intercrops requires a rethinking of farmers and needs subsidies for a wide introduction.
SPI evaluation gives a view on the ecological footprint and carbon dioxide emission through the whole process chain.

Outlook

Transport distances are a key factor for PNS optimisation. Because of this importance future work is to include transport based on time consumption and not distances. Loading and unloading to biogas plants are time intensive which results in higher costs than a kilometre of road transport. Manure transportation with flexible tubes will be part of future maximum structure for PNS.
Ecological footprint evaluation will be stressed until a more detailed PNS optimisation is available.

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17 PAPER 8

Economic and Ecological Potential Assessment for Biogas Production Based on Intercrops

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17.1 Contribution to PAPER 8

A much more detailed outcome from the project Syn-Energy was part of this paper. A detailed SPI evaluation of conditions for growing intercrops was made to have an initial SPI value for evaluation the PNS optimum structure. PNS superstructure development in conjunction with Nora Niemetz (who made the PNS optimization itself) represents another contribution to this chapter within the book "Biogas".

Chapter 9

Economic and Ecological Potential Assessment for biogas production based on intercrops

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1. Introduction

Biogas production is discussed controversially, because biogas plants with substantial production capacity and considerable demand for feedstock were built in recent years. As a consequence, in most cases corn becomes the dominating crop in the surrounding and the competition on arable land is intensified. Therefore biogas production is blamed to raise environmental risks (e. g. erosion, nitrate leaching, etc.). Furthermore it is still discussed, that a significant increase of biogas production could threaten the security of food supply. The way out of this dilemma is simply straight forward but also challenging: to use preferably biogenous feedstock for biogas production which is not in competition with food or feed production (e. g. intercrops, manure, feedstock from unused grassland, agro-wastes, etc.). However, the use of intercrops for biogas production is not that attractive since current biogas technology from harvest up to the digestion is optimized for corn. Additionally current reimbursement schemes do neither take the physiological advantages and higher competitiveness of corn into account nor compensate lower yield potentials of intercrops which are growing in late summer or early spring. Higher feed-in tariffs for biogas from intercrop feedstock, as they are provided for the use of manure in smaller biogas systems, would not only be justified, as shown below, but also stimulating. Beyond that, the plant species used as intercrops as well as the agronomic measures and machinery used for their growing seem to provide lots of opportunities for optimization to increase achievable yields. Moreover, adaptations of biogas production systems, as discussed in this chapter, facilitate biogas production from intercrops.

Further advantages of intercrops growing are that they contribute to a better soil quality as well as humus content and reduce the risk of nitrous oxide emissions. Simultaneously intercrops allow a decrease of the amount of chemical fertilizer input, because the risk of nitrate leaching is reduced and if leguminosae are integrated in intercrop-mixtures, atmospheric nitrogen is fixed. This is important, because conventional agriculture for food and feed production utilizes considerable amounts of mineral fertilizers. Due to the fact that the production of mineral nitrogen fertilizers is based on fossil resources, it makes economically and ecologically sense to reduce the fertilizers demand.

In the case study, a spa town in Upper Austria, the set-up of the supply chain is seen as key parameter. An important issue in this case are more decentralized networks for biogas production. This can be achieved e.g. with several separated decentralized biogas fermenters which are linked by biogas pipelines to a centralized combined heat and power plant.

2. Methodologies

Process Network Synthesis (PNS) was used as a tool for economic decisions to get an optimal technology solution for biogas production with particular consideration of feedstock which is not in competition with food or feed production. Ecological evaluation of the resulting optimal PNS solution through footprint calculation was based on the Sustainable Process Index (SPI). These calculations are based on the data, which was gathered in three field tests, and the practical experiences, that were gained in the growing and harvesting of intercrops on more than 50 hectares of arable land. Besides the determination of dry matter yields of different kinds of intercrops and intercrop mixtures the effects on ground water, soil and nutrient management were investigated in the field experiments with time-domain-reflectometry, soil water and mineral nitrogen content measurement. Additionally, the potential biogas production was measured by means of biogas fermenter lab scale experiments.

2.1 Process Network Synthesis (PNS)

Process Network Synthesis (PNS) (Friedler et. al., 1995) uses the p-graph method and works through energy and material flows. Available raw materials are turned into feasible products and services, while in- and outputs are unequivocally given by each implemented technology. Time dependencies like resource availability (e.g. harvesting of renewable resources) as well as product or service demand (e.g. varying heat demand for district heating over the year) are part of the optimization.

The necessary input for this optimization includes mass and energy balances, investment and operating costs for the technologies considered, costs for resources and utilities, prices for products and services as well as constraints regarding resource supply and product/service demand. For the case study all data were provided from project partners and are specific for the considered region. First the so called maximum structure is generated linking resources with demands. From this starting point the optimization is carried out resulting in an optimum solution structure representing the most economical network.

2.2 Sustainable Process Index (SPI)

Sustainable Process Index (SPI) was developed by Krotscheck and Narodoslawsky in the year 1995 and is part of the ecological footprint family. The SPI represents as a result the area which is required to embed all human activities needed to supply products or services into the ecosphere, following strict sustainability criteria. Based on life cycle input (LCI) data from a life cycle assessment (LCA) study, SPI can be used to cover the life cycle impact assessment (LCIA) part. LCA studies are standardized and described by the ISO norm 14040 (ISO, 2006). Within the methodology there are seven impact categories defined which are indicated by different colors:

- 🟨 Area for area
- 🟪 Area for non-renewable resources
- 🟩 Area for renewable resources
- 🟧 Area for fossil carbon
- 🟦 Area for emissions to water
- 🟨 Area for emissions to soil
- 🟦 Area for emissions to air

A high footprint is equal to a high environmental impact!

The freeware tool SPIonExcel (Sandholzer et. al., 2005) was used to calculate the ecological footprint (Graz University of Technology, n.d.) This offers the possibility to measure not only the economical performance of the PNS scenarios.

To assess the sustainability of biogas production from intercrops it is necessary to consider the whole crop rotation and the effects of intercrop on main crops. A direct comparison of biogas feedstock from main crops (e. g. corn) and intercrops is not possible, because inter crops grow with lower temperatures and less hours of sunshine. Therefore one of the systems compared, was corn as main crop, commonly cultivated with plow, and an intercrop cultivated with conservation tillage and harvested with a chopper for biogas production. It was assumed, that biogas was processed to natural gas quality. In the second system with intercrops corn was cultivated with conservation tillage whereas the intercrop was grown with direct drilling and harvested with a self-loading trailer instead of a chopper. Since a late harvest of a winter intercrop with high yields would reduce corn yields, an early harvest with an average intercrop yield of only 4 tons dry matter was assumed. In the reference system corn was grown without intercrop and the biogas produced in the intercrop systems was substituted by natural gas. The yield of the main crop corn was equal in all systems (15 tons dry matter of the whole plants per hectare for silage).

	common intercrop system		improved intercrop system		reference system without intercrop
position in crop rotation	main crop	intercrop	main crop	intercrop	main crop
tillage	plow	conservation tillage	conservation tillage	direct drilling	plow
harvest	chopper	chopper	chopper	self-loading trailer	chopper

Table 8: Systems compared with the Sustainable Process Index (SPI)

3. Intercrops

In temperate climate zones, allowing only the cultivation of one main crop per year, intercrops are planted after the harvest of the main crops (e.g. wheat, corn or triticale) or as undersown crops, while the main crop is still growing. Summer intercrops are harvested in September or October as long as the trafficability of fields is sufficient. Achievable yields of summer intercrops are higher, the earlier main crops are harvested and intercrops are sown. The variety of plant species, suitable for biogas production from summer intercrops is very high and reaches from different kinds of millet, over grainlegumes, clover, sun flowers to cruciferae or other plants, adequate for regional conditions and the specific crop rotation of the fields. If cultivated as undersown crops, the variety of usable plant species (e. g. specific types of clover and grass) is restricted to those, not growing too fast and capable to resist a long period with shadow from the main crops.

Winter intercrops (e. g. feeding rye, triticale, different types of clover or rape) are sown in autumn and reaped before the cultivation of summer main crops (e. g. corn or soybean). The later winter intercrops are harvested, the higher are the achievable intercrop yields but the higher is also the risk of diminishing yields of the main crop. For example, output cuts of corn may be higher than additional yields of the intercrop, if intercrops are harvested in the middle of May or later. Therefore, the harvest of the intercrop at exactly the right moment with immediate subsequent cultivation of the main crop is crucial for the overall outcome of this type of crop rotation.

Dry matter yields, achievable with intercrops, vary to a higher extent than those of main crops, because they grow at the edges of the growing season and have less opportunities to compensate unfavourable conditions for growing. Furthermore, there are only a few farmers with experience and appropriate machinery for cultivation and harvesting of intercrops for biogas production at present.

Dry matter yields of summer intercrops in own field experiments in the years 2009 and 2010 averaged out at about 3 tons per hectare. After early cultivation with adequate machinery yields achieved 5 tons and more in some cases. However, intercrops did not achieve yields worthy for harvest in other cases, because of late harvest of main crops in the middle of august in connection with high precipitation and low temperatures in august and September. Under these conditions undersown summer intercrops (e. g. red clover under wheat and spelt) were advantageous and reached yields of almost 5 tons in the middle of September.

The yields of winter intercrops depend mainly on the time of harvest and the average temperature in March and April. If harvested at the end of April or the beginning of May, yields of about 4 tons dry matter were achieved with feeding rye or mixtures of rye or triticale with winter pea or rape. Yields of the following corn were equal or at maximum 10 percent lower than corn without preceding intercrop, if the intercrop was sufficiently manured with biogas digestate. A comparison with average yields found by other authors is compiled in Table 9.

	summer intercrops	winter intercrops
	dry matter yields in tons per hectare	
Own experiments	3	4 (without reduction of corn yields)
Neff, 2007	5	
Aigner/Sticksel/Hartmann, 2008	3	4,9 (middle of April) 7,5 (5. Mai)
Laurenz, 2009	4,5	6 (with a reduction of corn yield of 2,5)
Koch, 2009	5	

Table 9: Average yields of summer and winter intercrops

Methane yields per hectare, achievable with winter intercrops, average out at about 1100 cubic meter with a methane content per kg organic dry matter of 310 liter. The methane yields of summer intercrops are lower and achieved 800 cubic meter per hectare in average. The methane content amounts in average 290 liter methane per kg organic dry matter. Therefore, between 4 and 6 hectare of intercrops are required to substitute one hectare of corn as biogas feedstock. This may seem little at the first glance. Considering the fact, that only rates of 10 or 20 percent of arable land should be used for biogas production at maximum, if the security of food supply should not be threatened, it becomes a considerable dimension, since intercrops for biogas production may be cultivated on 60 up to 90 percent of the arable land, if crop rotations are designed accordingly. Therefore the overall biogas potential of intercrops is comparable with the potential of corn.

However, the realization of these potentials requires adaptations of farmers' conditions for biogas production, as current reimbursement schemes and common technical equipment for tillage, drilling, harvest and biogas production make the use of intercrops profitable, only if farmers also apply for agro-environmental payments. Since these payments are only available in certain countries and are not guaranteed for the same period as biogas plants have to be operated, the risk for specific investments is considerable. To stimulate biogas production from intercrops, the physiological advantages and higher competitiveness of corn should be taken into account in the design of reimbursement schemes and tariffs should compensate lower yield potentials of intercrops. Higher feed-in tariffs for biogas from intercrop feedstock, as they are already provided for the use of manure in smaller biogas systems, would also encourage the optimization of agronomic practices (e. g. plant species used as intercrops, tillage, drilling) and technical equipment. In this way, the amount and reliability of intercrop yields would be increased additionally.

3.1 Ecological evaluation of intercrops

Based on input data for the production of main crops with and without intercrops several ecological footprints were calculated. Corn silage as main crop has a yield of 15 ton per hectare (dry matter) and 4 t (dry matter) per hectare of intercrop. SPI calculation includes machinery working hours, fertilizers, pesticides, agricultural area, and nitrogen fixation by leguminosae and seeds. Input data for the footprint calculation is listed in Table 10 which is derived from (KTBL, n.d.).

		chopper+plow	**conservation tillage + self-loading trailer**	**chopper+plow**	**conservation tillage + self-loading trailer**	**conventional**
		intercrop	**intercrop**	**main crop**	**main crop**	**main crop (no intercrops)**
	LCI input data	**workings hours per ton (dry matter)**				
machinery input	Tractor (<45 kW), light workload	0,40	0,23	0,04	0,04	0,04
	Tractor (<45 kW), normal workload	0,18	0,18			
	Tractor (<70 kW), normal workload	0,88	0,44	0,55	0,52	0,55
	Tractor (<70 kW), heavy workload			0,13		0,13
	Tractor (70-110 kW), light workload	0,24	0,24			
	Tractor (70-110 kW), normal workload	0,36	0,24	0,20	0,28	0,20
		kg per ton (dry matter)				
fertilizer	Application of N-Fertiliser	0,01				0,03
	Application of P-Fertiliser	0,01				0,01
	Application of K-Fertilisation	0,03				0,03
	Application of Ca-Fertiliser	0,04				0,04
		g per ton (dry matter)				
pesticides	Herbicide Phenmediapham	0,02				0,02

Table 10: LCI data

In terms of nitrogen fertilizer demand the use of leguminosae in intercrop mixtures reduces the demand of mineral nitrogen fertilizer through nitrogen fixation. Based on these data the ecological footprint results are listed in Table 11.

	SPI results [m² per ton (dry matter)]		
	Chopper	**No-till farming**	**Conventional**
main crop	7.972,1	7.128,9	7.994,9
intercrop	14.024,3	9.286,3	--------

Table 11: LCIA results

These footprints are per ton dry matter of intercrop or main crop. In general the lower machinery input for reduced tillage results in an accordingly lower footprint which points out the advantage of this method. This effect becomes more important as the yield of the crop decreases. The yields of intercrops are inevitably lower than of main crops, because of lower temperatures and less sunshine hours. Therefore, the footprint of intercrops sown with direct drilling and harvested with self-loading trailer is 34 % lower than of intercrops grown with conservation tillage and harvested with chopper. The amount of fertilizer for the main crops can be reduced with leguminosae intercrops. For this reason the footprint of the main crop in the reference system is higher than in the first system with intercrops with common tillage. If the effect of reduced nitrogen leaching or nitrous oxide emissions would be considered in the SPI-calculation, the difference would become even bigger.

For an overall assessment of the three systems, biogas produced in the systems with intercrops was processed to natural gas quality and substituted with natural gas in the system without intercrop. With processing the average methane content of biogas from about 60 % is increased to 96 % CH_4. Of course, biogas from intercrops can also be used in combined heat and power plants (CHP). Its processing is only obligatory for the comparison with natural gas. Although the footprint per ton dry matter of intercrops, even if they are sown with direct drilling, is bigger than the footprint of main crops, it is much smaller than the footprint of natural gas, it may substitute.

Table 12 illustrates this overall balance per hectare of agriculture area. Biogas purification SPI relies on life cycle data from ecoinvent database (Ecoinvent, n.d.). This balance can be seen as a rough estimation of the footprint reduction potential, if not only agriculture but also natural gas consumption is considered.

	with intercrops		**Conventional**
	Chopper	**No-till farming**	
CH_4 yield per t (dry matter) [m^3]	300	300	
overall biogas [m^3]	**1.200**	**1.200**	
intercrop SPI per hectare	119.581	106.934	119.924
main crop SPI per hectare	56.097	37.145	0
provision of natural gas	0	0	648.480
biogas purification SPI	48.375	48.375	0
SPI [m^2 / ha]	**224.053**	**192.454**	**768.404**

Table 12: Energy balance per hectare

Table 12 points out an advantage for intercrop cultivation with direct seeding and harvesting with self-loading trailer in comparison with intercrops grown with conservation tillage and harvest with chopper. The footprint of intercrops used for green fertilizing to increase soil quality, was not calculated in detail. Nevertheless it can be assumed that the footprint is worse than the footprints of intercrops for biogas production, because the efforts for drilling are the same and instead of harvesting energy is needed for their incorporation into the soil. For natural gas the SPI value is 540.4 m^2/Nm^3. Although further biogas purification is needed the whole balance points out a footprint reduction potential of 70 – 75 %.

4. PNS Optimization

A case study, as part of the so called Syn-Energy[8] project, was carried out in a spa town in Upper Austria wherein the set-up of the supply chain was seen as one of the key parameters. Beside detailed analyses of intercrops (e.g. biogas content, yields) a main focus was to find a network in respect of a higher degree of decentralization for biogas production. This can be achieved e.g. with several separated decentralized fermenters that are linked by biogas pipelines to a single combined heat and power plant. The specific data for intercrops were used to carry out the evaluations. Of note was to show how intercrops can affect networks from an ecological and economical point of view.

4.1 Case study

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[8] Syn-Energy „Klima- und Wasserschutz durch synergetische Biomassenutzung – Biogas aus Zwischenfrüchten, Rest- und Abfallstoffen ohne Verschärfung der Flächenkonkurrenz"; programme responsibility: Klima- und Energiefonds; programme management: Österreichische Forschungsförderungsgesellschaft mbH (FFG), report not published yet

Figure 12 shows three potential decentralized locations for biogas production. As there is a spa town located in the considered region it was not possible to contemplate a fourth, central location for a fermenter as it would infringe with the touristy activity there. There is already an existing district heating network in town that should be extended. The heat needed could be either generated by a centrally placed CHP with biogas transported via pipelines or heat produced with decentralized CHPs could be used for fermenter heating and/or transported via long –distance heat pipelines to the town. In the first case, with central CHP, fermenter heating is provided by wood chip furnace.

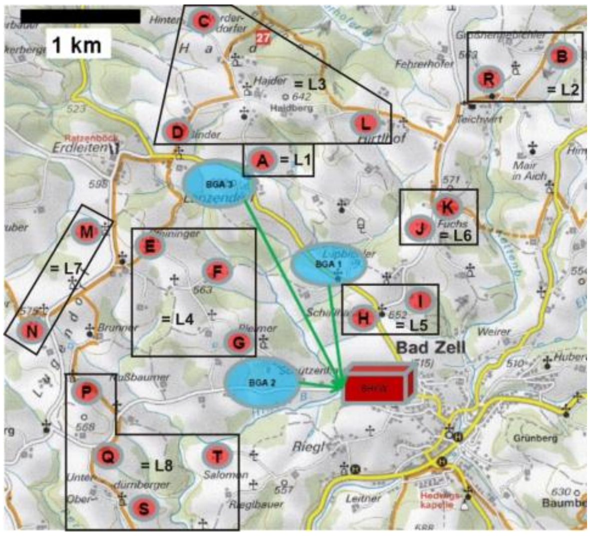

Figure 12: Substrate providers (A-T) and possible fermenter locations (BGA1-3)

The fermentation could work with different feedstock types to find out the most lucrative way of using intercrops, manure, grass silage and corn silage. Corn as additional feedstock was taken into consideration for economic reasons, because it is favored under current economic conditions. For the optimization it was assumed that proportional to the availability of manure biomass in an amount of 34 % intercrops, 18 % grass silage and 16 % corn silage (referring to fresh weight) per livestock unit can be supplied. As there are several farmers in and around the considered region eight provider groups (1-8 according to Table 13 and black bordered providers in Figure 12) were defined. The substrate costs were the same for each group.

The providers differed in the amount of available resources as well as in the distance to each possible fermenter location, which directly correlates with transport distances and costs. Transport costs included fix costs for loading and unloading and variable costs depending on the distance (including unloaded runs). For solid substrates fixed costs of 2 €/t fresh weight were taken into account. Similarly, the conversion was made for the variable costs, which were assumed with 0.49 €/km. Fixed transport costs for manure were defined with 20 €/t dry mass with variable costs of 5 €/t dry mass per kilometer. For grass and corn silage a storage was taken into account. As it is not possible to bring the investment costs down to one number because they are highly depending on the local basic conditions a fix investment of 150,000 € for a silage storage was taken into account. As soon as a location is chosen by the PNS a storage has to be included there. Two locations mean two times investment costs to store the silage that is used for biogas production.

Transportation of heat and biogas could be achieved via pipeline networks. Network energy demands as well as losses caused by transporting were included. Regarding heat it was assumed that the total produced heat amount could be used for district heating. As location 1 and 3 are in one line to the spa town one biogas pipeline could be used for both locations to transport biogas to the central CHP. Therefore no additional costs arise for a biogas pipeline from location 1, if location 3, which is farther away, supplies the center with biogas.

Provider Group	Distances in km to		
	Location 1	Location 2	Location 3
1 (A)	1.6	3.4	0
2 (B, R)	3.3	4.7	4
3 (C, D, L)	2.7	4.6	1.2
4 (E, F, G)	1.9	1.4	3.3
5 (H, I)	0.3	2.1	2.1
6 (J, K)	1.5	2.9	3
7 (M, N)	3.1	3	2.4
8 (P, Q, S, T)	3.8	1.9	3.7

Table 13: Transport distances for substrate provision

Because of different transport distances the PNS could decide which provision group and amount of substrate should be used to get the most economical optimum solution. The fermentation could run with various substrate feeds. Dependent on them fermenter sizes, costs and exposure times differed. Seven different fermenters were part of the PNS to find the most lucrative way of substrate input. The feeds are shown in Table 14.

Feed [%]	Manure	Inter-crops	Grass silage	Corn silage
1	30	0	0	70
2	30	70	0	0
3	50	50	0	0
4	50	20	10	20
5	75	0	0	25
6	75	25	0	0
7	75	15	10	0

Table 14: Substrate feeds for fermentation

In Table 15 the substrate parameters are described. The optimization was based on two different cost situations (maximum and minimum) concerning substrate provision.

* decided by project partners	Manure	Corn silage	Intercrops	Grass silage
Dry Mass Content [%]	9	33	24	30
Substrate Costs* min. [€/t DM]	5	65	50	50
Substrate Costs* max. [€/t DM]	10	110	80	80
CH$_4$-output [m^3/ t DM]	200	340	300	300

Table 15: Substrate parameters and costs in € per ton dry matter and cubic meter methane per ton dry matter

Figure 13 shows the so called maximum structure for the PNS optimization, which includes all input and output materials with energy and material flows with economic parameters like investment or operating costs and prices. For the optimization three fermenter sizes (up to a capacity that serves a 250 kW$_{el}$ CHP) were available for biogas production. Four combined heat and power plant capacities (up to 500 kW$_{el}$) were involved in the maximum structure. The fermenters could be heated by decentralized CHPs or with a wood chip furnace on site in case the biogas is transported to a central CHP.

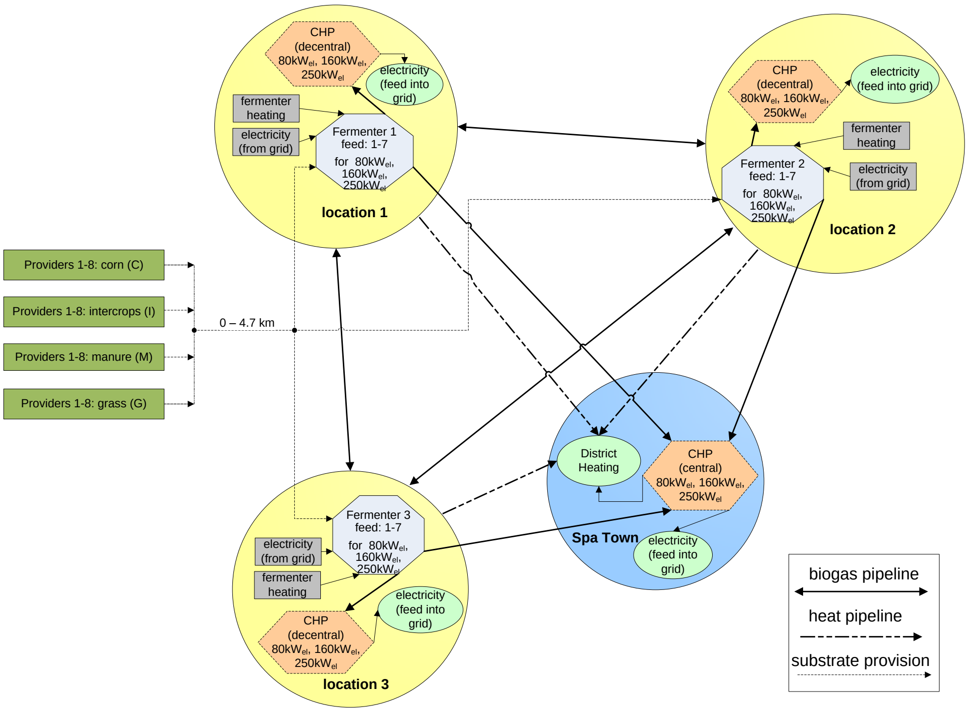

Figure 13: Maximum structure for PNS Optimization

The biomass furnace that could be a choice to provide fermenter heating was not implemented as separate technology in PNS' maximum structure, but a price of 5 ct/kWh heat was assumed (Wagner, 2008). Produced electricity could be fed into electricity providers' grid, thus benefiting from feed-in tariffs according to Austrian's Eco-Electricity Act (RIS, n.d.).

4.2 PNS optimum solution

The PNS optimization shows that the technology network providing the most benefit for the region includes two different locations (1 and 3) for biogas generation. At location 3 biogas is produced with substrate feed 4, a mixture consisting of manure, intercrops, grass and corn silage. The fermenter runs 7.800 full load hours and is able to provide a 250 kW_{el} CHP with biogas. At location 1 the set up includes a fermenter with same capacity but different load. Substrate mixture 7 is used for biogas production which contains manure, intercrops and grass silage. Both fermenters are heated with a biomass furnace on site. All provider groups can supply the fermenters with at least one substrate. The optimal technology network includes two central 250 kW_{el} CHPs supplied via biogas pipelines with biogas from both locations. For the pipeline coming from location 1 no additional costs have to be incurred because the pipeline would be part of the routing from location 3 to the center. The produced heat covers the central heat demand for a price of 2.25 ct/kWh. The electricity is fed into the grid and feed-in tariffs of 20.5 ct/kWh can be gained. Figure 14 depicts the optimum structure for a situation with maximum substrate costs as listed in Table 15.

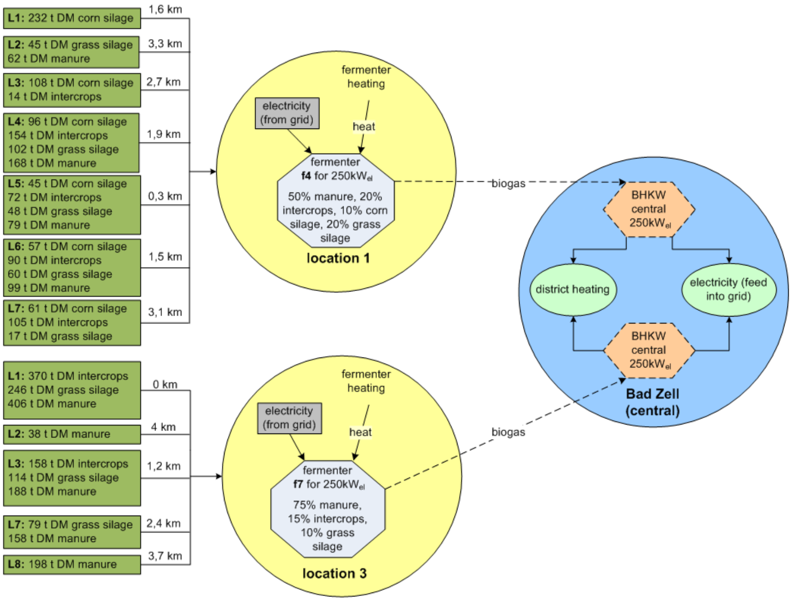

Figure 14: Optimum structure of a technology network generated with PNS

With this technology network and 15 years payout period a total annual profit of around 196,350 € can be achieved (interest rates are not included). The total material costs including electricity consumed from the grid and costs for fermenter heating add up to approx. 438,000 €/yr with additionally 60,300 € per year for transportation. The total investment costs for this solution would be around 2,895,000 € including district heating and biogas network as well as the costs for fermenters and CHPs.

With minimal substrate costs (see Table 15) there is no change in the optimal structure, but the revenue is higher commensurate to the lower substrate costs (one-third reduction). The revenue for the structure with minimal substrate costs excluding interest accounts for a yearly amount of about 280,400 €.

4.3 Scenarios

To prove plausibility of the optimum PNS structure two scenarios were carried out, both for minimum as well as for maximum substrate cost situations. In the first case the maximum structure was reduced by taking away corn availability. With that only five substrate mixtures could be used for biogas production. The second scenario was set up to get an idea how feed-in tariffs can influence the outcome of an optimization. Therefore it was not allowed that a network set-up results e.g. in two 250 kW$_{el}$ CHPs if a 500 kW$_{el}$ instead could be taken.

4.3.1 Scenario I – No corn silage

As already mentioned in the beginning corn is currently a dominating substrate for biogas production. To show the potential of intercrops no corn is available in this scenario. Not to lose the comparability the amount of corn was compensated with an additional availability of intercrops. The calculation was based on the CH_4-outputs and adds up to additionally 904 t intercrops. With that 2,170 t/yr intercrops, about 1.7 times more than in the basic maximum structure shown in Figure 13, are available in the maximum structure of this scenario. Under these conditions PNS could choose between five different substrate feeds.

The optimization results in a technology network including two locations using the whole amount of available intercrops as shown in Figure 15.

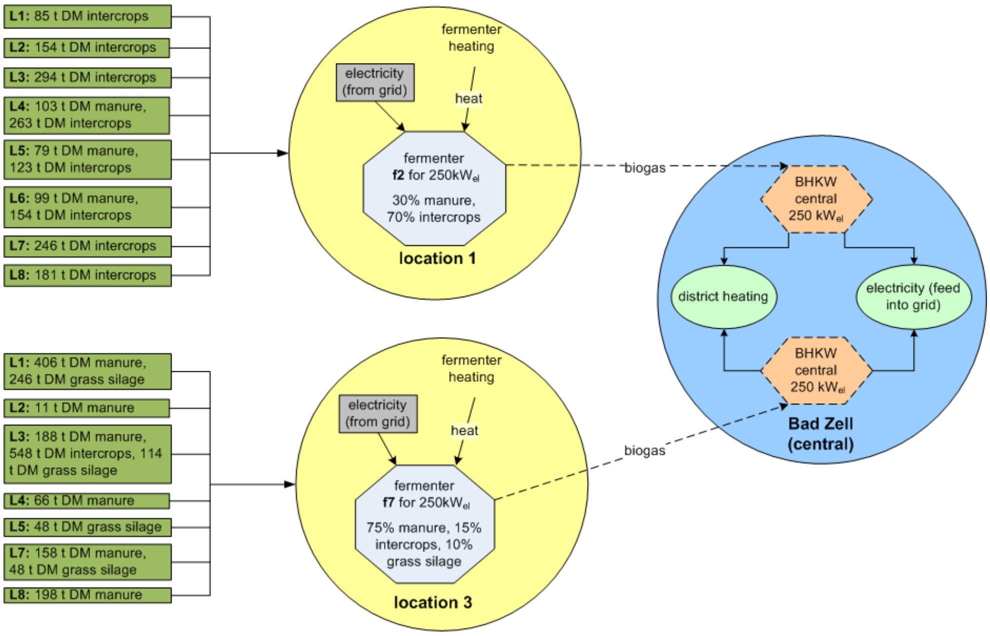

Figure 15: PNS optimum structure for scenario 1 without corn silage availability

At location 3 a fermenter processing substrate feed 7 with a capacity to produce biogas to supply a 250 kW_{el} CHP runs 7,800 full load hours a year. A second fermenter placed on location 1 and with same efficiency is supplied with substrate feed 2 consisting of 70 % intercrops and 30 % manure. It turned out that with this structure the outcome has yearly revenue of approx. 208,000 €. Compared to the optimum structure it is higher, but the basic conditions are different. Therefore this solution did not come up in the optimization of the maximum structure in the beginning. But it clearly shows that intercrops have a great potential to produce electricity and heat within a highly profitable biogas network without being in competition with food or feed production. But the precondition would be that in the case study a higher amount of intercrops is available as feedstock.

4.3.2 Scenario II – 500 kW_{el} CHP unit

Operating a 500 kW_{el} CHP goes along with reduced feed-in tariffs of 20 €/MWh according to Austrian's Eco-Electricity Act. The positive effect of lower investment and operating costs for larger capacities is therefore narrowed by less revenue for produced electricity. If is forbidden to use two CHPs with same capacity at one location in the maximum structure to gain higher feed-in tariffs the next larger CHP capacity has to be taken although this would go along with shortened revenue. With this precondition the optimization of the maximum structure presented in Figure 13 but with only one central 500 kW_{el} CHP unit whereas the rest of the optimum structure (Figure 14) stays the same.

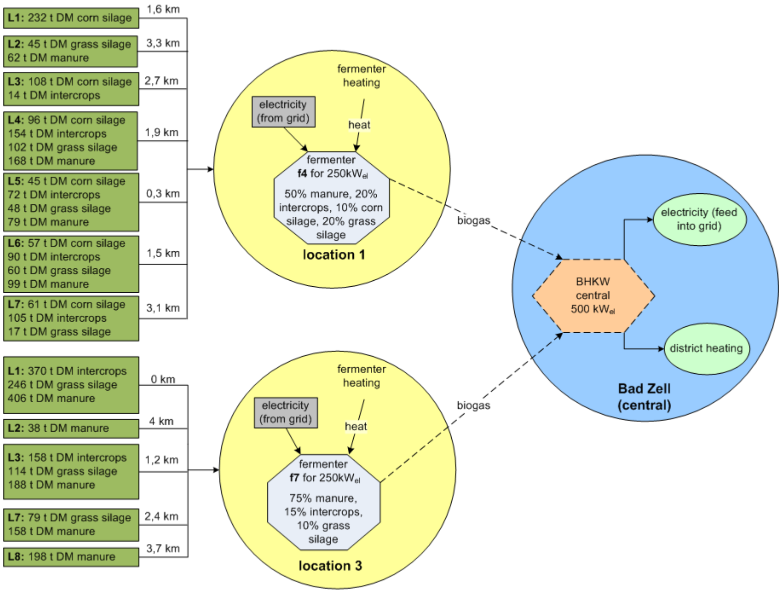

Figure 16: PNS optimum structure with a central 500 kW_{el} CHP

The revenue is narrowed but not as much as it was in scenario 1. To use a 500 kW_{el} central CHP would cause a revenue reduction of yearly 50,000 € within a payout period of 15 years.

4.3.3 Comparison of PNS' optimum solution and the scenarios

Table 16 overviews the results of the three optimizations described before.

	Optimum Structure		Scenario 1		Scenario 2	
Substrate costs	max.	min.	max.	min.	max.	min.
Investment costs [€]						
Total investment costs	2,894,519	2,894,519	2,894,519	2,894,519	2,824,519	2,824,519
Products [MWh / yr] and Revenues [€/yr]						
Total produced electricity	3,826	3,826	3,900	3,900	3,826	3,826
Total produced heat	4,591	4,591	4,680	4,680	4,591	4,591
Revenue for electricity fed in (205 € / MWh)	784,281	784,281	799,500	799,500	707,766	707,766
Revenue for district heating (22,5 € / MWh)	103,296	103,296	105,300	105,300	103,296	103,296
Total revenue [€/yr]	887,576	887,576	904,800	904,800	811,062	811,062
Operating Costs [€/yr]						
Fermentation	114,423	114,423	116,390	116,390	114,423	114,423
CHPs	75,556	75,556	75,556	75,556	51,346	51,346
Transport	60,286	60,286	64,121	64,121	60,286	60,286
Substrates	213,561	129,488	213,400	131,740	213,561	129,488
Electricity	34,432	34,432	35,100	35,100	34,432	34,432
Total operating costs [€/yr]	498,258	414,185	504,267	422,607	474,048	389,975
Operating result without depreciation	389,319	473,392	400,534	482,194	337,015	421,088
Depreciation for 15 years*	192,968	192,968	192,968	192,968	188,301	188,301
Operating result with depreciation*	196,351	280,424	207,566	289,226	148,714	232,787

Table 16: PNS results summary

It turned out that the profitability of a fermenter on location 2 is lower than on the other locations. It was never preferred in any optimum structure. The other locations have one advantage – the shared usage of biogas pipelines whereas no additional costs for location 1 have to be born. There are never heating pipelines from the different locations to the center considered in the optimum technology networks. Just the biogas is transported; heat is produced centrally and distributed within a district heating network, although additional biomass furnaces are required. In scenario 1 the missing corn silage availability was compensated by a higher amount of intercrops, referring to the CH_4 content, and it shows the best revenue, because of higher plant utilization and higher revenue for electricity and heat production. Although in the optimal scenario the amount of corn relating to the total feedstock was not even 17 % of the total (dry matter) the compensation for corn with intercrops results in higher revenue. For more corn that intercrops compensate in the input the impact would be even higher. Therefore it is obvious that intercrops can be a profitable feedstock to run a biogas plant. For the case study the availability of intercrops would have to be raised as described before which would lead to the best technology network for the region.The system has two limiting factors; on the one hand the distances between the fermenter locations and the feedstock providers accompanying different transport costs and on the other hand the limited resource availability. It could be shown that it is not lucrative to run a central CHP with higher capacity (500 kW_{el}) as feed-in tariffs are lower and less revenue can be gained. Nevertheless, from the point of view of sustainability, it would be preferable to substitute two smaller CHPs with a bigger one. An adaptation of reimbursement schemes to the solutions presented is recommended.

5. SPI Evaluation

Based on the economic results of the PNS optimization and previous SPI evaluation of different intercrops, a footprint for the PNS results was calculated. The evaluation includes every substrate, transport, net electricity and infrastructure for fermenters and CHP units. SPIonExcel already provides a huge database of LCIA datasets which can be used for modeling the scenarios. In case of intercrops substrate the SPI value for conservation tillage + self-loading trailer from Table 11 was used.

SPI evaluation results					
		electricity		heat	
	overall SPI [km²]	production [MWh / a]	SPI [m² / MWh]	production [MWh / a]	SPI [m² / MWh]
Optimum solution	93.08	3,825	21,503	4,591	2,360
Scenario 1 - No corn	89.32	3,900	20,236	4,680	2,221
Scenario 2 - 500KW_{el} BHKW	91.51	3,825	20,876	4,591	2,539

Table 17: LCIA results based on PNS scenarios

The overall footprint points out the environmental impact for one year of production. In case of the optimum solution it would need 96.6 km² of area which has to be reserved to embed the production sustainably into nature. The overall footprint is shared between both products according the amount of output and the price per MWh (electricity: 205 €/MWh; heat: 22.5 €/MWh). Price allocation of the footprint leads to a higher footprint for the higher valued product.

Scenario 1 has a benefit from the ecological point of view but it goes herein with lower revenue according to Table 16. For scenario 2 there is only a slightly difference to the optimum solution which points out that the footprint reduction for having one higher capacity CHP unit instead of two small ones, is negligible.

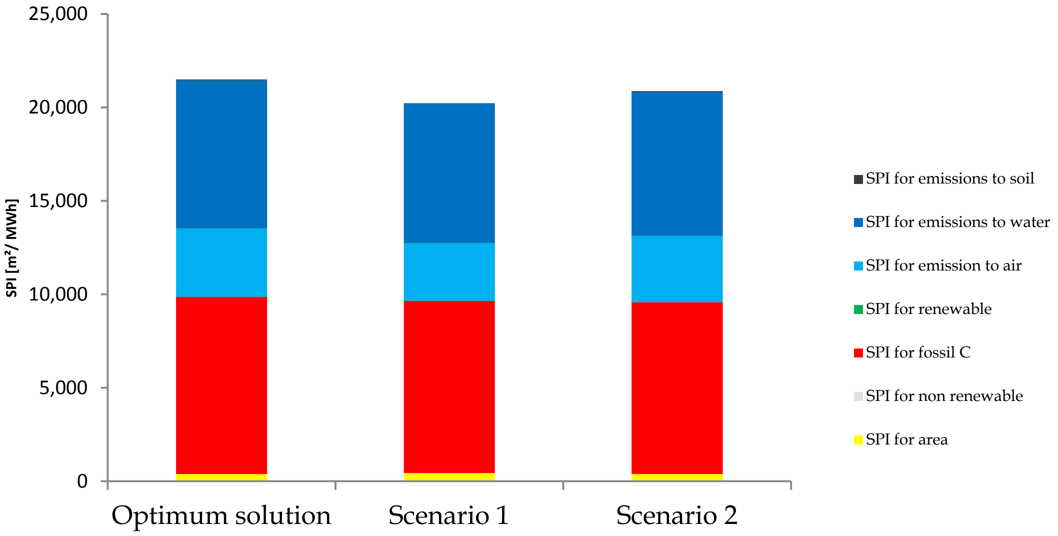

Figure 17: SPI category comparison

Main impact categories are in every case 'fossil carbon', 'emissions to water' and 'air'. This mainly derives from the utilization of net electricity which contributes around 45 % to the whole footprint. Main contribution to this categories stemming from net electricity and machinery input in agriculture which are still mainly fossil based. This is also the main optimization potential for a further decrease of the footprint.

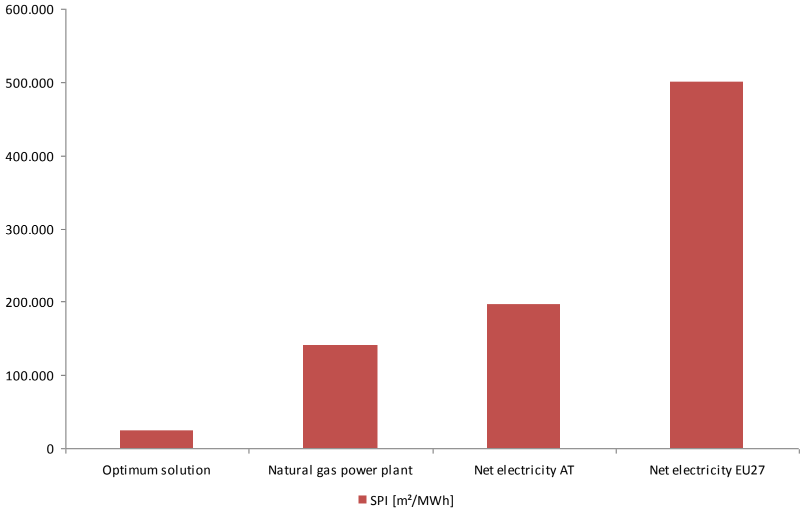

Figure 18: Comparison of electricity production

Compared to other electricity provision system the optimum solution from the PNS has an ecological benefit in footprint ranging from 61 to 96 % which is pointed out in Figure 18. Although the footprint of the optimum solution could be optimized by using the produced electricity for itself and not selling to the grid (which has economic reasons because of high feed-in tariffs) the ecological benefit compared to other sources is obvious. Every contribution to a greener net infects simultaneously all net participants.

6. Conclusion

The three pillar principle of sustainability serves as conceptual framework to conclude this study. Not only economic and ecological factors are important to implement innovative structures. Often we forget about the social component, the third pillar of sustainability. Not to do so farmers' opinion about intercrops where taken into account. It turned out that intercrops production also abuts on farmers' psychological barriers and the need of intensive cooperation among farmers in the surrounding of a biogas plant. In conjunction with economic risk and high investments, determining farm management for at least 15 years it becomes obvious, that well-considered decisions are to be made. Therefore, it is not astonishing that farmers hesitate, if economic benefits do not clearly compensate social an managerial risks of biogas production from intercrops. Furthermore, the situation that biogas production from corn is favorable regarding profitability and practicability in comparison to biogas production from intercrops, reduces farmers motivation to decide for the latter. But even the growing and harvesting of intercrops requires additional work and the strict time frame to cultivate fields, the risk of soil compaction through harvest and potential lower yields of main crops after winter intercrops are counter-arguments to cooperate with farmers already running biogas plants. Higher feed-in tariffs for biogas from intercrops seem to be inevitable and sensitization of decision makers and farmers is needed to emphasize that the planting of intercrops holds many advantages and that intercrops reduce the ecological footprint decisively. Although a higher energy input for agricultural machines is required because of the additional workload for intercrops. In summary the energy balance per hectare including biogas production points out an benefit. In times of green taxes a reduction of CO_2 emissions can diminish production costs. More biogas output per hectare raises the income beside minimized mineral fertilizer demand reduces costs and lowers the ecological footprint. Furthermore, biogas production from intercrops contributes to a reduction of nitrate leaching and nitrous oxide emissions from agriculture. With the transport optimization in-between the network the ecological footprint decreases caused by intelligent fermenter set-up going along with less transport kilometers and fuel demand. A farmer association running an optimal network described before lowers the investment risk and ensures continuous operation and stable substrate availability. On the other hand an association has the potential to strengthen the community and the social cohesion of regions. Some of the advantages mentioned before effect the regional value added positively. On closer examination it could be shown that intercrops can play an important role in sustainable agriculture for the future by running a social and ecological acceptable network and still being lucrative for the operators and the region. Finally biogas production from intercrops does not affect the security of food supply. On the contrary it may even increase productivity in the case of stockless organic farming.

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