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Table of Contents

Abstract

Biorefineries aim at finding sustainable valorization pathways for biomass feedstock. Because of the rich nature of biomass however, the options of processing routes and of final markets are almost endless. Therefore sustainability assessments are key in the development of this sector. In this report, three products are chosen with different applications; first bioenergy produced by anaerobic digestion of energy crops and waste, second biobased PVC and third, biobased alkyd resins for paints. These three different products are assessed by the newly developed PROSUITE assessment framework. In this way, information is gathered on the five endpoints namely human health, natural environment, exhaustible resources, prosperity and social well-being. Furthermore, attention is given to the current status of the technology, but on top of this, it is analyzed what the future impact of these products will be. This is done at a micro-level by considering improvements in efficiency, yields, etc. and at a macro level, by considering the total market penetration and analyzing impact on the whole economy.

In the first case study, bioenergy was produced by anaerobic digestion of silage maize and domestic organic waste. The produced energy was compared with the reference technology, i.e. coal electricity. The functional unit is 387TWh, which is the electricity expected to be produced from coal in 2030 according to the IEA blue map scenario. The assessment shows that electricity production from silage maize scores best on human health, exhaustible resources and prosperity. Electricity from domestic organic waste has a higher impact on these categories, mainly caused by the transport needed for collection of waste and a low stimulation of other economic sectores whereas it scores best for impact on natural environment and impact on social well-being. Within the limitations of land availability (which is rather a policy related question concerning food/feed/fuel/material), bioenergy by anaerobic digestion is therefore a more sustainable alternative compared to coal electricity.

The second case study compares biobased PVC with fossil based PVC. Polyvinyl chloride (PVC) is a thermoplastic produced from ethylene and chlorine. Ethylene is traditionally taken from fossil resources, but can also be produced from ethanol from sugar cane in Brazil. The assessment of these two options, based on a functional unit of 1000kg PVC shows that the prospective technology (biobased PVC) had better results in two of five endpoints (natural environment and exhaustible resources) and the reference technology had better results in two endpoints (social well-being and human health), while in the category prosperity there was a tie.

The third case study focuses on resins which are used as binders in paints. In this study, a sustainability assessment has been conducted for two novel biobased alkyd resins and they are compared to a conventional alkyd resin and two synthetic resins.The functional unit of this study is ‘resin for covering an outdoor-area of 1 m^2 during 4 years. The assessment showed that both biobased resins show better performance compared to the synthetic resins with respect to human health. With respect to impact on natural environment, all biobased resins score higher compared to the synthetic resins as a result of the high contribution of natural land transformation that is caused by the use of fatty acids. Impact on exhaustible resources is lower for the biobased resins compared to the synthetic resins. Impact on prosperity is very similar for all resins due to the magnitude of the number. The same holds for impact on social well-being.

Based on these three case studies, it was concluded that the PROSUITE framework is an operational framework for a more holistic sustainability assessment in different dimensions and at different scales (i.e. micro and macro), especially when using the Condorcet integration methodology. It is therefore a big leap forwards for sustainability assessment in general. It is however obvious that this framework could still be improved, since several aspects are still not straightforward such as the distinction between a ‘functional unit’ and a ‘technology/system level’ approach, the system boundary issues, the normalization of the five endpoints, the difficulty of reliable data-inventories at the different levels, an absolute quantitative integration, etc

General introduction

The world as we know it is rapidly evolving. Industrial revolutions have allowed humanity to grow both in numbers and in standard of living. Basically these evolutions were built on the ability to transform nature in order to increase man's capacities (Kasa, 2009). Better human capacities then allow a faster transformation of nature. Fossil resources play a central role in this progress as they have removed a part of the human constraints; by using coal instead of wood, more land was available for agriculture, allowing a growing food supply and thus growing population (Pomerantz, 2001). The drawback is that at a certain point this cascade evolution overgrows earth's carrying capacity which in its turn has an influence on the social system. Alongside the positive effects, the downsides of fossils such as city smog and working accidents in coal plants were already noticed in the nineteenth century (Kasa, 2009). Furthermore, this source of hydrocarbons was formed by the long term conversion of ancient biogenic material and thus the stock is not endless. Disproportional exploitation rates result in a slowly depleting stock, with price increase as a consequence.

Fossil resources have become a vital part of industry, agriculture, transport and society as a whole (Youngquist, 1999). It is clear that they will keep on taking an important place in our resource supply for the next decades, but it is also clear that a transition to more sustainable sources of material and energy is necessary. Biomass is such an alternative resource, which has a large potential in application range to fulfill demands of society whilst mitigating climate change. It is a rich resource consisting out of different types of molecules, ranging from plant reserves, mainly starches and lipids, to plant structure, mainly lignocelluloses, to proteins and microcomponents such as vitamins and pigments. This means that no biomass molecules can be considered as waste and that different services can be delivered to different markets; from food to biobased materials, to bioenergy. On the other hand, because of limited land availability and the limitation in photosynthesis efficiency, it is uncertain and even quite unlikely that biomass will be able to cover all these demands fully (Fischer et al., 2007; IEA Bioenergy, 2007; Ponton, 2009). The shift to biomass as a renewable resource for different services thus depends directly or indirectly on the process of agriculture with related impact (Figure 1). Therefore, biomass should be used as efficiently and sustainable as possible. This is the principle of biorefining.

Biorefineries are defined by IEA Bioenergy Task 42 (2009) "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". A sustainability assessment of biorefineries should therefore focus on two aspects:

- The supply chain of biomass should be sustainable as it is stated that the major part of the (environmental) impact of biobased products is situated in the agricultural step (Zah et al., 2007).
- The product mix should be sustainable; a smart choice should be made between food, biobased materials and bioenergy

This report investigates these issues in the framework of the PROSUITE project and thus has a double goal:

- Analyze the sustainability of different applications of biomass. For this purpose, this work package of the PROSUITE project has performed three different case studies covering a broad application range and if possible, including the agricultural phase:
    - First the sustainability is analyzed of using different (European) sources of biomass for bioenergy production by anaerobic digestion bioenergy
    - Second, sugarcane from Brazil is converted to a bulk polymer, namely PVC
    - Third, alkyd resins are produced from biomass to be applied in paints
- Whereas most sustainability assessments of biorefineries only consider environmental aspects, this report tests the five endpoint approach developed in PROSUITE, considering also impact on prosperity, social well-being and human health, apart from impact on natural environment and exhaustible resources

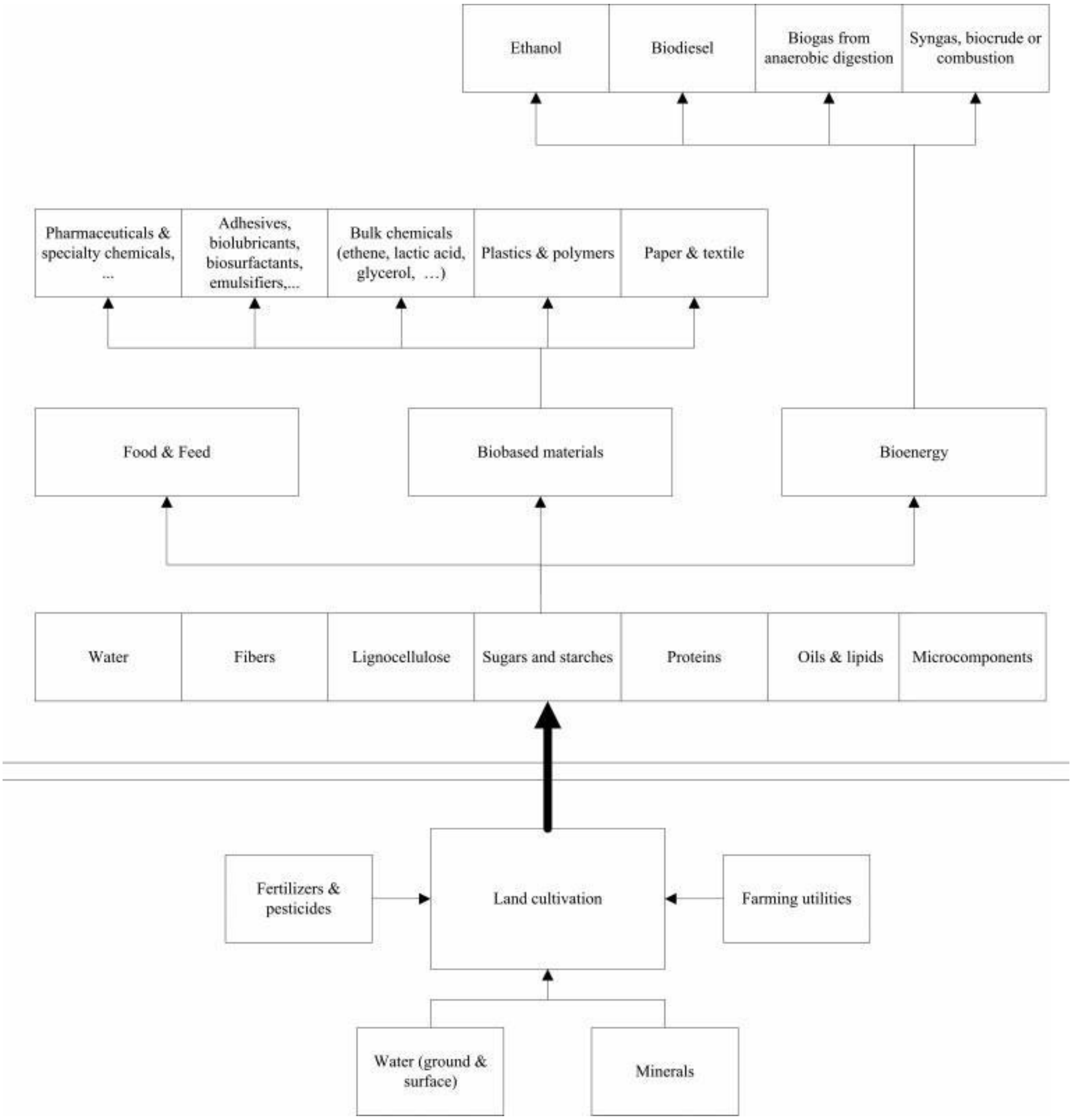

Figure 1: The biomass cascading scheme. Three levels of products can be identified: food and feed, biobased materials and bioenergy. All molecules from the feedstock can be valorized for different applications inducing economic opportunities on the one hand, but creating an extra demand on the other hand.

1 Case Study 1: Bioenergy production by anaerobic digestion of domestic organic waste, farm residues and energy crops

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1.1. Goal and scope of the case study

1.1.1. Scientific background/description of the case

This chapter focuses on the conversion of different sources of biomass to bioenergy by using anaerobic digestion (AD). From a technological perspective, anaerobic digestion is a promising valorization technology as it is able to convert almost all sources of biomass, including different types of organic wastes, slurry and manure to a highly energetic biogas (Holm-Nielsen et al., 2009). Only strongly lignified organic substances such as wood are not suitable for digestion (Weiland, 2010). When using digestable biomass, the different molecules such as carbohydrates, proteins and lipids can be hydrolyzed to soluble sugars, amino acids and long chain fatty acids in order to start the further microbial conversions. Afterwards, during acidogenesis these components are degraded to acetate, hydrogen, carbon dioxide and a number of organic acids, the latter converted further by acetogenesis. Methanogens then convert this mixture to biogas (Gujer and Zehnder, 1983) consisting of approximately 50-70% methane, 30-50 carbon dioxide and smaller amounts of N2, H2O, NH3 and H2S (Petersson and Wellinger, 2009). The remaining fraction in the digester, the digestate, can be further treated and processed to for example stabilized compost, or it can be used directly as a fertilizer. This dual functionality, i.e. the production of energy and fertilizer gives AD a major advantage over composting of biomass which only delivers a fertilizer. It is therefore widely recognized that it is more environmentally sustainable to introduce AD in solid waste management compared to a simple composting process (Haight, 2005). Furthermore, the complex microbiological reaction pathways occurring in AD are a major advantage in comparison to other forms of bioenergy such as bioethanol, where currently Saccharomyces cerevisiae converts only the glucose fraction to ethanol and such as biodiesel, where currently only the oil and fat fractions undergo transesterification. This results in better conversion efficiencies of biomass to biogas compared to other biofuel production alternatives (Börjesson and Tufvesson, 2011) which is an essential parameter in the environmental sustainability of bioenergy. As a result, a better overall energy balance of biogas compared to for example ethanol can be achieved, where extra pre- and post treatment steps might enhance higher yields but do not always have a beneficial effect on the energy balance (Schumacher et al., 2010).

The broad applicability and relatively simple setup of anaerobic digestion, is a major opportunity for the worldwide implementation of this technology as a way to treat waste, i.e. a stabilization of the waste can be achieved and to produce energy simultaneously (Weiland, 2006). It is also implemented more frequently for the digestion of energy crops, by using a large diversity of possible plant materials (Braun et al., 2009), whilst furthermore, digestion is a potential option for (organic) farmers to become energy self-sufficient where digestate application can maintain soil fertility (Oleskowicz-Popiel et al., 2012). In this light, this part of this report aims to be a detailed analysis of the sustainability of using anaerobic digestion for the production of electricity to contribute to renewable energy targets in Europe. A comparison is made between the valorization of domestic organic waste and silage maize as energy crops.

1.1.2. Functional unit

The original goal of PROSUITE is to assess the sustainability of a technology. Technology is basically a “mean to address some problem” (UNEP, 2012). Figure 2 highlights how difficult it is to generalize a “mean” and assess what we perceive as a complete technology such as anaerobic digestion. The AD process can start from organic waste, in which the main problem is that waste needs to be processed in the most efficient way and therefore it competes in the waste treatment sector. Alternatively AD can process energy crops, in which the main problem is that society is in need of renewable energy and there is competition with food and bioproduct markets. Technologies can solve more than one problem and thus have several functional units. As a result, these problems do not necessarily have a common reference point which makes options hardly comparable or additive. A solution for this problem is leaving the 'waste treatment' problem out of the analysis and considering AD as a mean (technology) producing energy and fertilizer (compost) from a certain feedstock. In this case the reference is the energy and fertilizer market. Doing so actually brings us back to the level of individual products and the 'traditional' functional unit approach. This is of course not a problem, but instead of being able to say "Anaerobic digestion is a good technology", it limits the analysis to more specific conclusions such as "producing product X from feedstock Y with technology Z is more sustainable than producing product X' from feedstock A with technology B". Doing several analyses with a functional unit approach does allow going back to the technology level and allow statements such as "AD should be used for applications X, Y and Z".

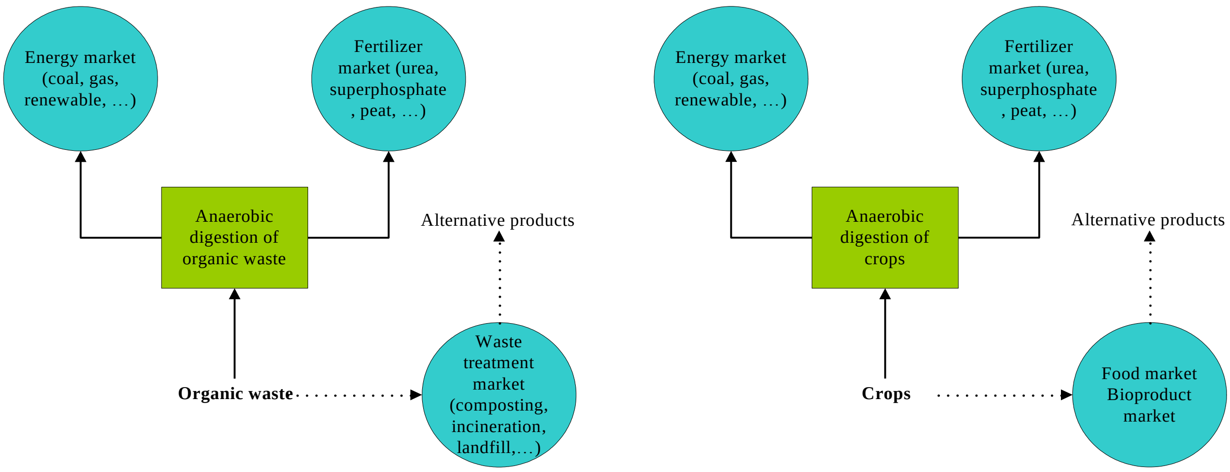

Figure 2: The two applications of anaerobic digestion as a technology; starting from organic waste (left) or from crops (right)

Still, this approach also has methodological issues to be resolved. The most important one is that anaerobic digestion is a technology inherently producing a product basket with two products, i.e. biogas and fertilizer. This means that two markets are penetrated. Whereas the functionality of the energy market is obvious, the functionality of the fertilizer market is less clear. Despite several valuable research efforts such work by Hermann et al. (2011) and VLACO (2009), the functionality and market penetration of compost is a very difficult issue. Traditional calculations start from carbon and nutrient content and identify the displaced products such as peat, urea, superphosphate, etc. If all aspects such as bioavailability, erosion, water balance, etc. are taken into account this might be theoretically correct, but in practice the market might react differently (Andersen et al., 2010). Including the fertilizer market in this study would therefore induce much uncertainty. For this reason, this study uses a (physical) allocation procedure and focusing on the energy market using a functional unit of 1kWh electricity produced from biomass by anaerobic digestion. When valorizing organic waste, the additional functionality of waste treatment is indirectly included by following the zero burden assumption (Ekvall et al., 2007) and by not assigning impact to domestic organic waste 'production'. This micro-scale assessment is followed by a macro-scale assessment by introducing market scenarios and considering the market penetration in which coal power is considered as the displaced and thus reference technology.

Up to now, biomass contributes by 3 to 13% of the energy supply of industrialized countries. Incineration and biodiesel-bioethanol production cover most of this supply, whilst biogas from anaerobic digestion is producing only a small but steadily growing share (Braun et al., 2009). The role of biogas however, can become more substantial. For example in Germany, a leading country in biogas production, anaerobic digestion is considered as a key technology to meet the renewable energy and GHG mitigation targets (Pöschl et al., 2010). On a more international scale, it is stated that up to 18% of primary energy demand can be fulfilled by cultivating energy crops on 30 % of the arable land (Braun et al., 2009). Using 10% of arable land would then yield 4500 petajoules in Europe. This would mean an electricity production of approximately 500 TWh (electric efficiency of 40%) or 16 % of Europe's current production. This calculation excludes the potential of organic waste streams and possible new bioresources such as biodegradable polymers (Guo et al., 2011). It is estimated that 2.5 billion tons of organic waste is generated (Eurostat 2011). It can be assumed that this amount remains relatively constant and exist approximately 37% of organic material. Using the waste-to-electricity conversion rate of this study, this means a potential market supply of 5% of the total electricity production (EU-27) or a production of 151 TWh. It is stated that digestion of livestock production, agro-industrial effluents, sewage treatment and landfill could contribute another 174 TWh (ADNET, 2005).

One of the main limitations for the breakthrough of this technology is therefore the availability of biomass. Not less important is its economic feasibility. Usually, the investment in AD is quite large and energy and digestate prices are relatively low. One of the most important drivers for digesters are the subsidies that are received for the production of renewable energy (Gebrezgabher et al., 2010). The market penetration of this technology is therefore not expected to follow market mechanisms; instead it will depend on regulations and subsidies. The breakthrough of AD is thus a policy question. We therefore assume in our scenario no limitation of biomass availability and assume that policy supports this technology to displace coal. This means that AD will be used to displace 387 TWh electricity, which is the total European supply of coal power in 2030 according to the IEA Blue Map scenario. In this way the potential positive/negative effect for stimulating this technology in Europe is studied.

1.1.3. System boundaries

This study uses a functional unit approach and then investigates the impact of market penetration on the economy. The ILCD handbook describes this as a meso/macro level decision support study. Nevertheless we do not introduce system dynamics, instead our study could also be described as 'accounting' for our functional unit and accounting what happens if this technology gives a (single) shock to the economy. Making a clear distinction between attributional and consequential assessment is not straightforward. It is stated that the modelling principles are the same, but that the difference lies in the inclusion of additional datasets (Zamagni et al., 2012). Zamagni et al. Also argue that this choice is often done inconsistently. In our study for example, we do not include rebound effects due to the difficulty of modelling them. This work is therefore situated somewhere in between attributional and consequential.

Foreground data

The digestion of energy crops and domestic organic waste requires a different setup. Therefore two real plants have been considered in this assessment from which real environmental and economic data is collected in collaboration with OWS. The first case study focuses on a typical setup of digestion in an agricultural context. It is situated in Germany (Bassum, Niedersachsen) and has a capacity of approximately 20,000 tonnes biomass inputs per year. Figure 3 shows pictures of this plant and Figure 4 visualizes the process scheme. The plant is owned by a cooperative of three farmers and run by the farmers themselves. The digester is currently mainly fed by silage maize, supplemented with smaller amounts of rye silage and poultry manure. After storage, biomass is fermented with a residence time of approximately 21 days. The produced biogas is collected in a gas bag, where water is condensed. Afterwards, biogas is converted into electricity and heat in generators of 250kW. The digestate is stored and used as a fertilizer on the surrounding fields. Because of the importance of agriculture in environmental LCA studies, the farming of silage maize was studied more in depth, with a specific focus on the impact of using digestate instead of traditional (organic and mineral) fertilizers. Data of these processes were collected together with the involved farmers and experts. Methane emissions from the digestate storage tank are taken from Liebetrau et al. (2010). Emissions from agriculture are calculated by applying the models used by Nemecec and

Kägi (2007), with more detailed data of metal emissions and of nitrogen leakage taken from Freiermuth (2006) and Svoboda et al. (2011) respectively. Data of diesel consumption was obtained from the involved farmers and the resulting air emissions are taken from EMEP/CORINAIR (2000). Two alternative digester feeds were elaborated for this system in collaboration with involved experts, where all parameters of the inventory can remain constant, except for the agricultural inputs and the energy and digestate output; in the first alternative sugar beet, grass silage and poultry manure, whilst in the second alternative corn stover, cow manure and poultry manure are digested. These last two scenarios are only considered for a fast environmental LCA and not for all impact assessment methods due to the lower data quality.

Figure 3: Pictures of the AD plant in an agricultural context (Bassum, Niedersachsen, Germany)

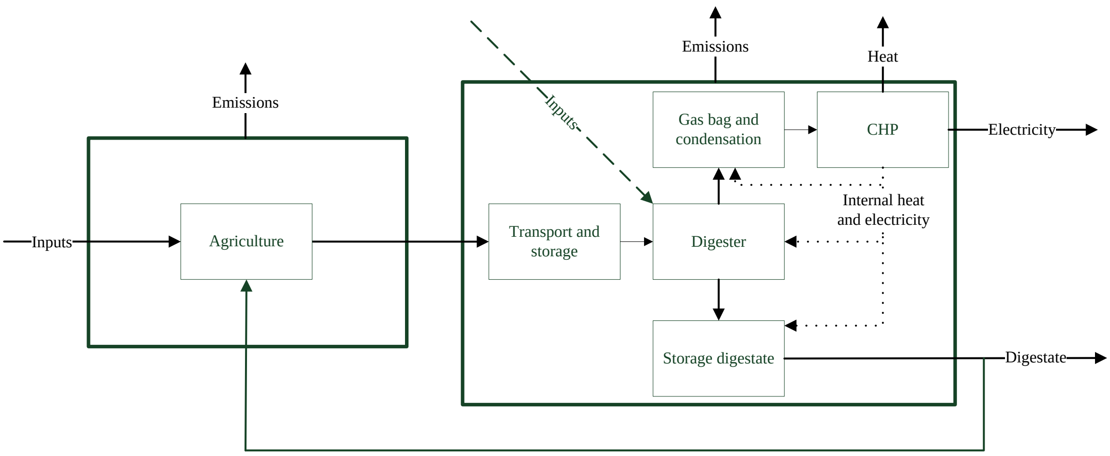

Figure 4: Process scheme of an anaerobic digestion facility in an agricultural context

In the second case study a Belgian production plant owned by a joint authority was studied in which domestic organic waste (±45,000 tonnes per year) is converted into electricity, heat and compost. Figure 5 shows pictures of this plant and Figure 6 visualizes the process scheme. Biomass is collected by selective municipal organic waste collection. The collection in one part of the region is organized by using a temporary waste terminal, whilst the municipal waste collectors in the second part of the region supply the organic waste directly to the facility. The transport distances were collected in collaboration with the involved stakeholders. Because of the diversity of organic waste and contamination due to sometimes careless waste sorting, a specific pretreatment is necessary by means of drum sieves and magnets. Afterwards a piston pump feeds the digester, where the organic fraction is converted to biogas with a residence time of approximately 20 to 25 days. After a water condensation step, the biogas is burned in engines of 625kW to produce electricity and heat. The resulting digestate is post treated by means of a press, centrifuge and sieve, in which the separated heavy fractions are landfilled and the wastewater is treated in a treatment plant. The lighter fraction is further composted in an aerobic composting hall. All processes are in a closed environment from which air is extracted and afterwards filtered in a biofilter. All data of resource use and emissions of this plant, including the composting process and the wastewater treatment is collected based on measurements in the plant and judgement of involved stakeholders and experts. Foreground data is therefore from a relatively high quality.

Figure 5: Pictures of the AD plant valorizing domestic organic waste (Brecht, Belgium)

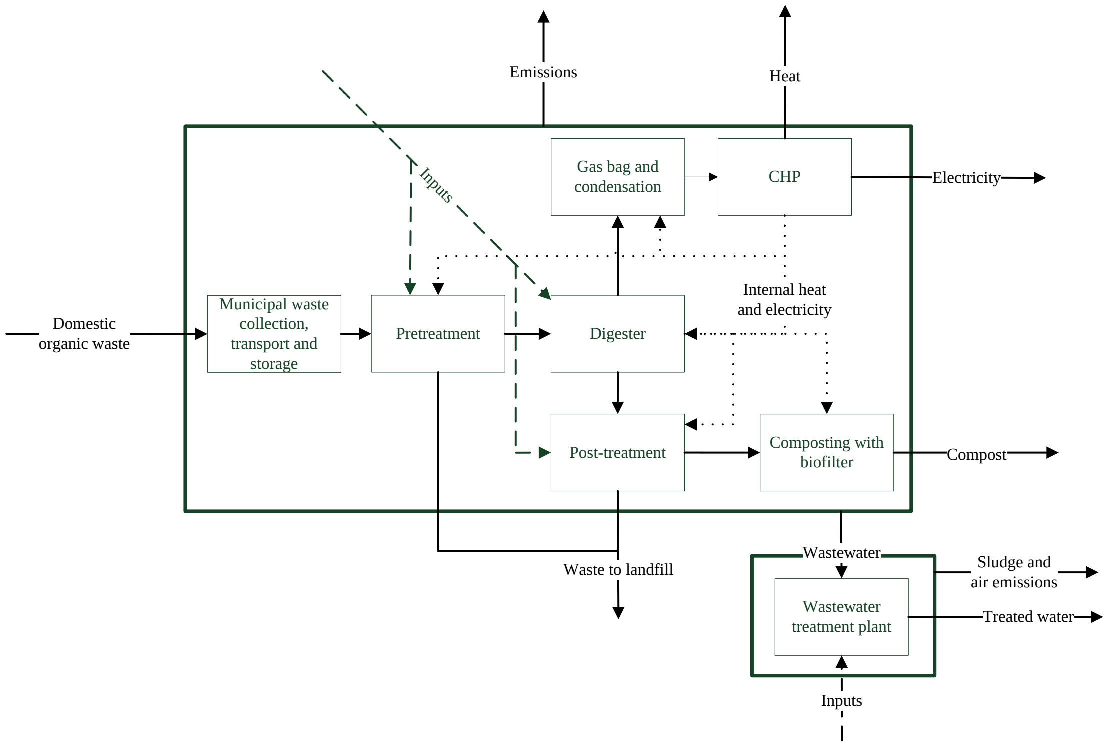

Figure 6: Process scheme of an anaerobic digestion facility valorizing domestic organic waste

Background data

Environmental data of the background system is taken from the ecoinvent database. Macro-economic effects are taken from worldwide input-output tables. Similarly social data is taken from global statistics and therefore the overall system boundary is in a global scale.

Temporal aspect

The analysis is performed for 2010 and 2030. Since making estimations for 2030 is already difficult and highly uncertain, predicting further than 2030 (e.g. 2050) is considered as practically (quantitatively) impossible. In 2010 the aforementioned data sources were used. For the 2030 scenario small modifications were made. In most PROSUITE cases the electricity mix is highly relevant and therefore future electricity mixes were generated. However, AD is an electricity producing technology and the impact of using electricity (in the supply chain) is below 5%. Therefore this case study does not focus on the future electricity mix scenarios. Instead, a discussion panel was set up in collaboration with OWS and it was discussed which improvements could be expected in AD technological efficiency. It was generally agreed that the conversion of biomass to biogas is currently highly efficient. The specific reaction pathway of AD is designed as such that product inhibition is not an important factor; for example fatty acids are formed, but they are fast degraded during acidogenesis. Other inhibition factors can be perfectly controlled. The most significant benefits could come from converting the woody fraction of biomass. Experience has shown however, that in most cases doing so is not economically and environmentally profitable. In most production routes additional pretreatment steps and utilities would be required and the composition and fertilization value of the digestate would change. These aspects are very difficult to model and are thus not included in this study. Our panel agreed that it is most likely that efficiency gains are achieved in the processes surrounding the digester. First of all, equipment such as pumps, sieves, press, conveyors, etc. will become more efficient. Summarizing a study of the IEA (2012), an efficiency gain of 1% per year could be targeted. Following this assumption, we have introduced an efficiency gain of 20% from 2010 (year of data collection) to 2030 allowing the facilities to sell more electricity instead of using it internally. Transport is also subjected to large efficiency gains.

IEA (2010) states that an efficiency gain of 20% can be achieved every 10 years. For 2030 we have therefore introduced a 40% decrease in fuel consumption compared to 2010. This is especially relevant for agriculture, resulting in more efficient use of tractors and in the collection of organic waste. It should be noted that we only introduced these efficiency gains in our foreground system. An additional gain can be achieved in making all equipment more airtight. Our panel estimates that currently 10% of biogas is lost through leaks in equipment (e.g. during conveying of digestate or in pumps during recirculation in the plug-flow reactor). Currently this biogas is lost and lead to the biofilter by ventilation where it is oxidized to CO_2. Efforts to make equipment more airtight could therefore induce an additional energy production of 10% without a change in biomass feed. The last identified improvement is the valorization of produced heat. Currently AD plants are often situated in rural area's far away from heat demand. As a result, electricity is produced and heat is lost in the flue gas. It is however very likely that solutions will be sought to switch from regular generators to combined heat power systems. This can be made possible by:

- Bringing heat demanding technologies closer to AD plants
- Construct biogas grids from digesters to small scale CHP systems
- Upgrade biogas to biomethane and injection in natural gas grid

Our group agreed that at least one of these possibilities will be implemented by 2030.

1.2. Case specific methodology

1.2.1. Impact on human health

At the time of writing this report, the final environmental impact assessment methodologies, mainly from the LC-Impact project, were not yet completely available at endpoint level. When performing an endpoint analysis of coal electricity for example, following results are obtained (Table 1):

Table 1: Results with the PROSUITE environmental assessment method at endpoint level at the time of writing this report

Impact category	Reference unit	Result
Abiotic resource depletion - mineral, fossils and renewables	EUR	3.91E-12
Cancer human health effects	DALY	5.16E-09
Climate change - human health	DALY	1.52E-06
Endpoint fossil rescources in surplus cost - egalitarian	USD2010	0
Endpoint fossil rescources in surplus cost - hierarchist	USD2010	0
Endpoint fossil rescources in surplus cost - individualist	USD2010	0
Endpoint freshwater eutrophication ecosystem damage	day m3	0
Endpoint green house gasses - egalitarian	PDF.m3.yr	3.4E-06
Endpoint green house gasses - hierarchist	PDF.m3.yr	1.39E-08
Endpoint green house gasses - individualist	PDF.m3.yr	2.45E-09
Endpoint human health impact of particular matter	DALY	4.45E-09
Endpoint marine eutrophication ecosystem damage	PAF[m3·d]	0
Endpoint metal rescources in surplus cost - egalitarian	USD2010	8.51E-10
Endpoint metal rescources in surplus cost - hierarchist	USD2010	3.12E-11
Endpoint metal rescources in surplus cost - individualist	USD2010	5.65E-12
Endpoint regional absolute impacts for mammals by landuse	potential loss of non-endemic species	2.42E-14
Endpoint terrestrial acidification ecosystem damage	m2 yr	0.000399
Endpoint Tropospheric ozone human health damage	DALY	4.4E-06
Endpoint water consumption river basins	PDFm3yr	0
Ionizing radiation - human health	DALY	2.52E-10

Land use	Items*a	5.3E-10
Non - cancer human health effects	DALY	1.08E-07
Photochemical ozone creation - human health	DALY	6.48E-12
Tropospheric ozone ecosystem damage	m2.yr	0.000794
Tropospheric ozone ecosystem damage - linear	m2.yr	0.000191

These results are obviously not complete. Furthermore there are currently 9 different units in this result. Deliverable 5.2 presents conversion factors for these categories to convert everything to person equivalent. However, these are not complete and there is a misfit between categories. Therefore it is judged that the approach is still not mature enough to apply in a case study and we have used the readily available Recipe methodology at endpoint level H/A. Macro-economic effects are taken into account in the categories prosperity and social well-being by using the EXIOPOL tables, but not in the environmental assessment. These results per FU can be scaled up to the total market penetration linearly, but this would not yield new relevant information. Therefore the environmental assessment is expressed per functional unit and classified as an *attributional* study.

Occupational health results are taken from WHO data (Concha-Barrientos et al., 2004). The implementation of this data was tested in two ways. First occupational data is coupled to the EXIPOL database relying on economic data of sectors. Next to this we have also tested the methodology by Lex Roes et al., in which the same occupational health data is coupled to physical data of sectors.

1.2.2. Impact on natural environment

Similarly to human health, the Recipe methodology at endpoint level H/A was used.

1.2.3. Impact on exhaustible resources

Similarly to human health and natural environment, the Recipe methodology at endpoint level H/A was used.

1.2.4. Impact on prosperity

The impact on prosperity mainly analyses macro-economic scenarios based on input output databases (in PROSUITE the EXIOPOL database is used). These scenarios are based on micro-economic life cycle costing data. Typically, this information is difficult to gather due to the specificity of processes (concerning capital cost and labor cost, which is not necessarily related to typical LCA procedures considering physical flows) and not in the least due to confidentiality of this information. Therefore, the SCENT tool was developed in the PROSUITE project (WP2.2) to estimate life cycle costing data. In this case study, we gained access to the real economic data under confidentiality and we were therefore able to test the reliability of the developed SCENT tool. The results of this comparison are shown in Figure 7 and Figure 8. The economic life cycle costing data of the anaerobic digestion plant processing organic waste is predicted fairly accurate with a difference of 2% between the real and predicted value. The most important aspect is the capital cost which was predicted with 90% accuracy whereas mainly taxes and insurances were overestimated by the SCENT prediction. The cost of anaerobic digestion on a farm was overestimated with a total difference of 36%. The real capital cost was only 44% of the predicted investment. Other aspects such as labor, taxes and insurances are also overestimated. The main reason for this is that the tool assumes a large scale investment with a large amount of overhead costs. The cost of installed equipment was estimated fairly accurate, however the SCENT tool adds overhead such as contingency, land cost, contractor fee's, construction expenses, etc. In a small scale operation on a farm, these overheads are smaller. For example, land is readily available, and in our case, the farmers helped in construction, resulting in lower labor costs. Furthermore, the SCENT tool does not take into account that money can be available to invest instead of loaning all money from the bank. Nevertheless, the prediction of the costs of the larger scale anaerobic digestion of organic waste was fairly correct and this tool is judged to be a valuable help for use in determination of life cycle costing data.

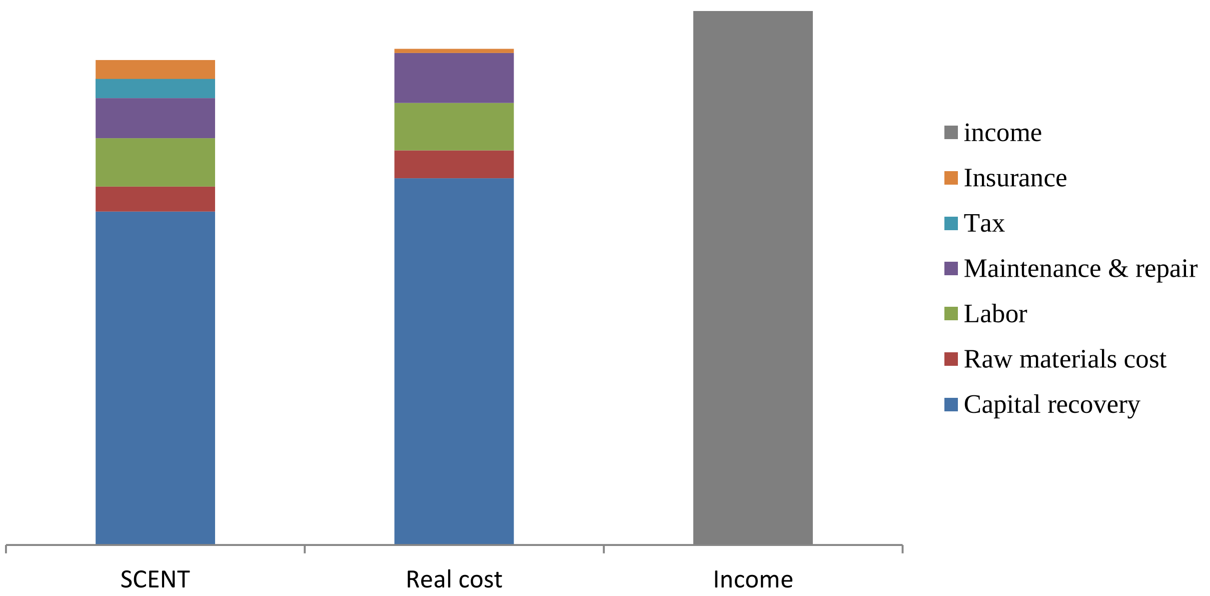

Figure 7: Economic year balance of the anaerobic digestion facility valorizing domestic organic waste comparing real data and modeled data from the SCENT tool. Due to confidentiality, no Y-axis is presented

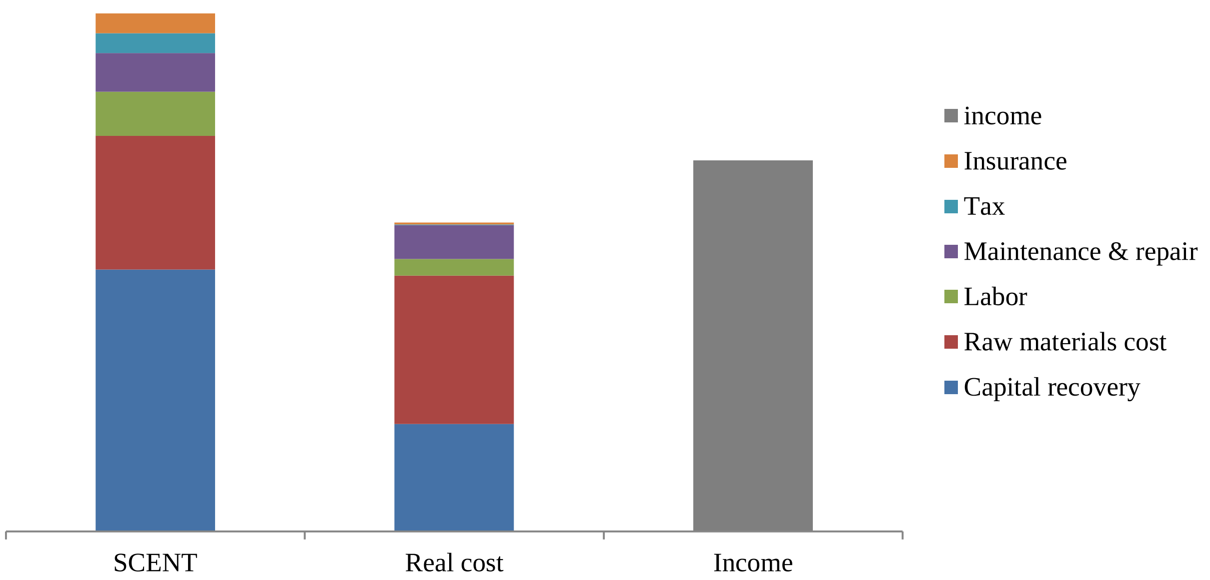

Figure 8: Economic year balance of the anaerobic digestion facility in an agricultural context comparing real data and modeled data from the SCENT tool. Due to confidentiality, no Y-axis is presented

1.3. Results and discussion

Prelude 1: agriculture

In the following points we will focus on the impact of the final product, i.e. electricity. It is however important to realize that the major part of the (environmental) impact of biobased products is situated in the agricultural step (Zah et al., 2007). Due to this relevance we have also collected and analyzed foreground data of maize production, the base product of our bio-energy scenarios from energy crops. This is highly relevant, since the alternative is relying on data available in LCI databases such as ecoinvent. In these databases the cultivation methods for agricultural products are generally limited to intensive (IP) and organic production. In our case study however a combination of the two is used; the farmer uses pesticides and one fertilizer, i.e. diammonium phosphate. On the other hand, the major part of the nutrients is delivered by digestate from the AD process. Therefore we briefly discuss this agricultural cultivation of silage maize with digestate as fertilizer with common practice (IP and organic from ecoinvent) before coming to the assessment of our final product. As a life cycle impact methodology, the Cumulative Exergy Extracted from the Natural Environment (CEENE) (Dewulf et al., 2007) methodology is chosen to construct a resource fingerprint consisting out of seven resource categories: renewable resources (excl. biomass), fossil fuels, nuclear energy, metal ores, minerals, water resources and land occupation (incl. biomass). To account for emissions, six categories are taken from the RECIPE methodology with midpoint indicators and the hierarchist perspective: climate change, ozone depletion, photochemical oxidant formation, terrestrial acidification, freshwater and marine eutrophication (the latter also influenced by emissions from the field). Other categories such as toxicity have not been taken into account due to the requirement of a very detailed and specific inventory. Especially in studies involving agriculture, the emissions of metals and pesticides are determining for life cycle toxicity results. These flows are difficult and very case specific to quantify, and therefore, the authors consider the used models of Nemecek and Kägi (2007) not sufficient for further impact modeling of toxicity. The uncertainty of the results is analyzed by using the most commonly used approach relying on the pedigree matrix followed by a Monte Carlo simulation. In this type of uncertainty quantification it should be considered that only data uncertainty is taken into account, without analyzing the impact of model uncertainty, allocation choices, etc. (Huijbregts, 2011). The results of this assessment are visualized in Figure 9.

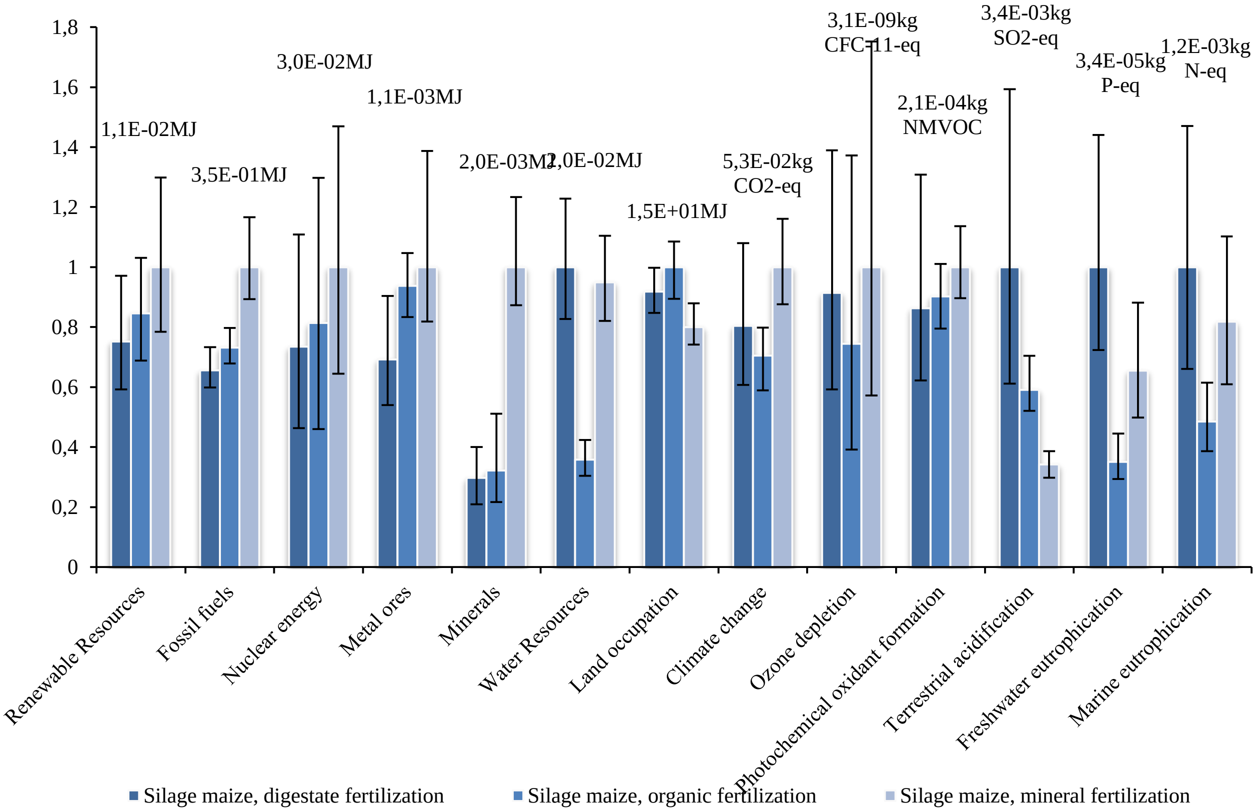

Figure 9: Environmental assessment of alternative ways of producing silage maize cultivation. As impact assessment methods the CEENE and RECIPE methodology are used with uncertainty indication. Internal normalization is used, with maximum value = 1. Absolute values are given on top for the maximum of that impact category.

Concerning yield and resulting land necessity, using digestate as fertilizer scores average compared to the intensive and organic production (not considering region specific aspects of our comparison between Switzerland and Germany). For most other resource categories using digestate scores best. The main reason for this is the replacement of fertilizers by nutrients available in the digestate. This internal use of nutrients is a major advantage compared to the traditional intensive production which needs resource consumption for the production of mineral fertilizers. As such a saving of over 70% minerals and approximately 35% fossils is achieved. The high water use of the silage maize production can be explained by the production of diammonium phosphate, which is added as only fertilizer, but which might be omitted when digestate application practices are improved.

The good performance on a resource basis is linked to a better score in related emissions categories such as climate change, ozone depletion and photochemical oxidant formation. The difference, however, is smaller compared to fossil fuel use in the resource assessment, mainly due to direct emissions from the field such as N2O and CH4. The best performance for ozone depletion is achieved by organic agriculture. This can be explained mainly by the production of pesticides which are applied in both the intensive production and in the digestate fertilization scenario. In contrary to these impact categories, digestate application on the field causes more problems with acidification and eutrophication. Acidification is mainly caused by ammonia emissions during application, while marine eutrophication occurs when nitrate leaks to the groundwater. Freshwater eutrophication is mainly caused by the diammonium phosphate production and could be lowered by omitting this additional mineral fertilizer from the cultivation if digestate application would be sufficient as a nitrogen and phosphorus source.

The environmental impact assessment of digestate application thus shows that digestate is a rich source of nutrients with often a high dry matter content, making it useful as a fertilizer, but also inducing risks of pollution. Whilst the total nitrogen content remains constant before and after the digestion (Lukehurst et al., 2010), the pH of this biological matter is higher, causing high NH_4^+-N concentrations and thus more ammonia emissions during field application (Amon et al., 2006). This was also confirmed by experiments comparing digested with not-digested slurries (Immovilli et al., 2008). Nitrogen leaching could also become a problem, but the quantities are stated to be comparable to cattle slurries (Svoboda et al., 2011). Heavy metal components such as copper (42mg/kg DM) and zinc (217mg/kg DM) measured in the digestate of this study do not exceed concentrations in different types of manure (Lukehurst et al., 2010) and would therefore not require additional precautions. Other risks include the contamination of digestate with pathogens, pesticides, seed residues and other toxic compounds (Lukehurst et al., 2010), especially in digestates obtained after solid waste digestion. Nevertheless, using digestate as a fertilizer can be beneficial for crop growth (e.g. maintaining carbon balance) and saves resources compared to traditional agriculture. It can thus be stated that the benefits exceed the risks, especially if a good agricultural practice is applied (e.g. injection of fertilizer, lowering of pH by acids, timing of application, etc.) (Lukehurst et al., 2010; Holm-Nielsen et al., 2009; Mokry et al., 2008).

For our domestic organic waste scenario we follow the „zero burden assumption" Ekvall et al., (2007) and therefore the life cycle inventory (and thus impact) of the biomass starts with the collection from inhabitants and no prelude is required.

Prelude 2: Some policy considerations for mitigating climate change relying on bioenergy

One of the major drivers for stimulating bioenergy is the mitigation of climate change. Therefore, and because the impact on climate change traditionally weights high in endpoint assessments, we would first like to introduce a short 'traditional' midpoint carbon footprint assessment. This is what is typically done for giving policy advice concerning mitigation of national and international greenhouse gas emissions. In this report, this is afterwards broadened to a complete PROSUITE assessment considering multi-impacts in multi-dimensions. The results of this simplified assessment can be seen in Figure 10.

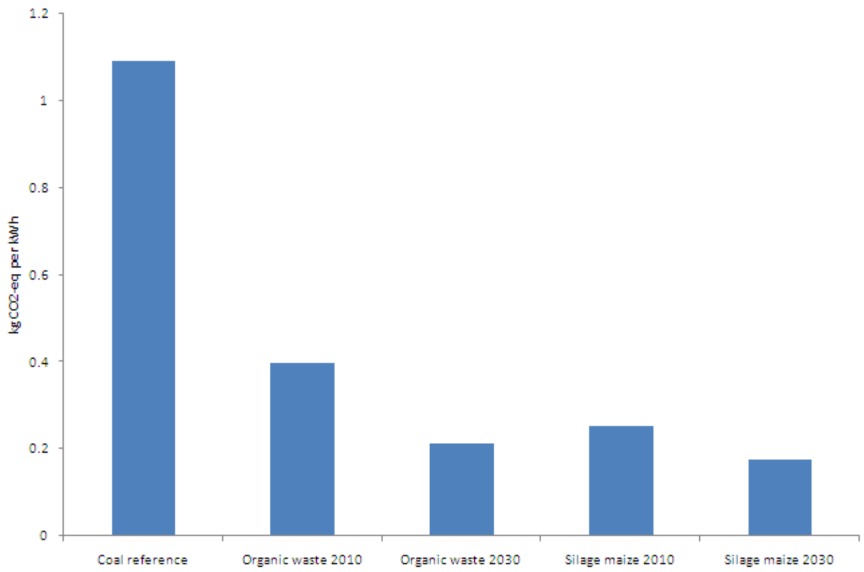

Figure 10: Carbon footprint of the different electricity production scenarios

When considering midpoint level, coal has an impact of 1.09 kg CO_2-eq per kWh (ecoinvent: electricity, hard coal, at power plant (DE) with IPCC 2007 100y) whereas organic waste valorization has an emission of 0.40 and 0.21 kg CO_2-eq per kWh for 2010 and 2030 respectively and electricity from silage maize has an impact of 0.25 and 0.18 kg CO_2-eq per kWh for 2010 and 2030 respectively. The main impact in the organic waste scenario origins from the collection of domestic organic waste and from disposal of residues to landfill), whereas in silage maize digestion approximately 40% of climate impact comes from agricultural processes and over 50% of the impact origins from direct emissions from the plant (leakage of machinery, storage, etc.). Nevertheless for these bioenergy scenarios, a saving of 64 to 84% greenhouse gas emissions is achieved, thus complying with the European Renewable Energy Directive. Replacing total European coal electricity production of 387 TWh in 2030 can save a maximum of 325 Mton CO_2-eq in 2010 and 355 Mton CO_2-eq in 2030. This corresponds to approximately 9% of Europe's greenhouse gas emissions. Organic waste digestion is obviously restricted by the amount of waste available whereas silage maize digestion is restricted by land use. The studied energy crop digestion plant on silage and rye operates at approximately 23 MWh electricity per hectare per year for 2010 and 37 MWh electricity per ha per year in 2030 (notice that land use includes all life cycle land use and that this is also the result of an exergy allocation procedure between electricity and heat; digestate is recirculated). This means that replacing all European coal by energy crop digestion would currently require 47% of all European arable land in 2010, but only 4% in 2030 when taking into account the expected decrease in coal production.

Within its restrictions bioenergy from anaerobic digestion can thus contribute significantly to the increase in renewable energy. In what follows we would like to highlight that there are many other important aspects that should

1.3.1. Impact on human health

Figure 11 shows the results of the human health impact caused by emissions of the different electricity production pathways in DALY per kWh. It can be clearly seen that the coal reference has a higher impact, mainly caused by climate change, which is traditionally an important factor in environmental assessments, human toxicity and particulate matter formation. The impact on climate change is indeed 2.7 to 4.3 times higher than the 2010 bioenergy options and 5.2 to 6.2 times higher compared to the 2030 bioenergy options. The best option is silage maize digestion, followed by organic waste valorization. This higher impact of this option is mainly caused by transport induced during collection of waste.

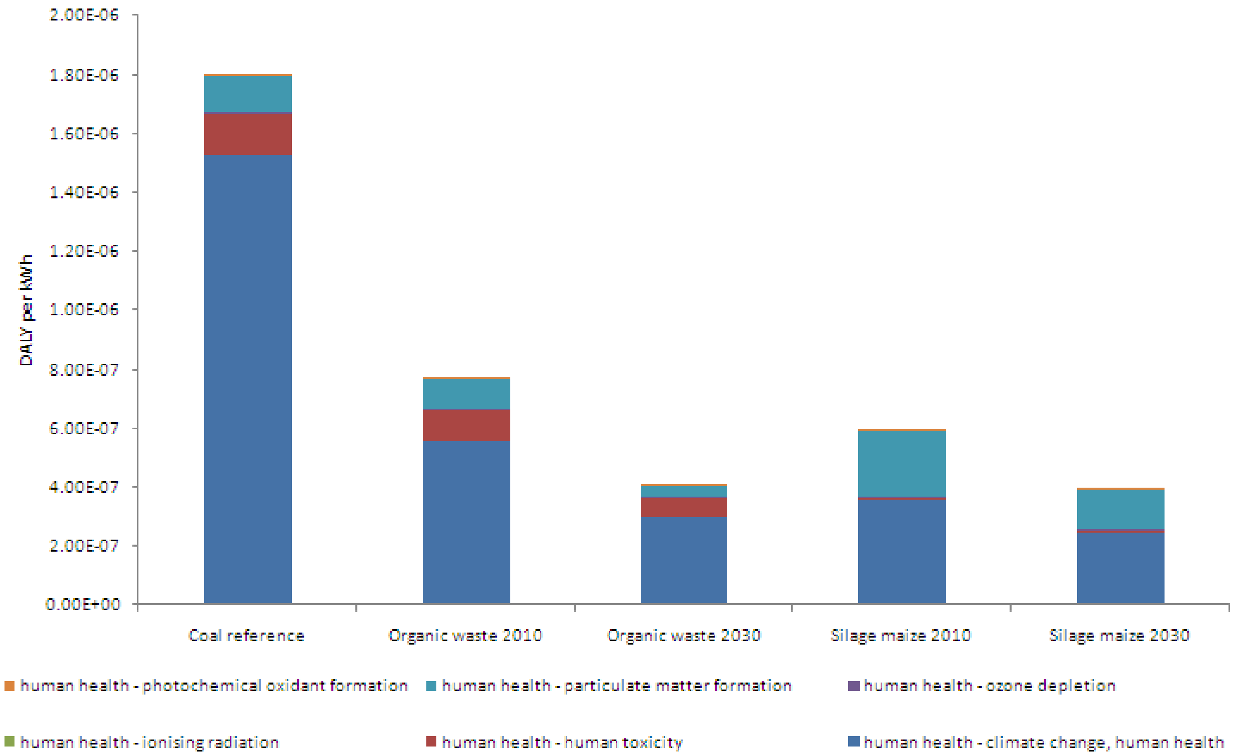

Figure 11: Human health impact caused by emissions

The results in Figure 11 exclude occupational health impact. This is included in Figure 12, but the influence is limited to an impact of 1 to maximally 3 %. Figure 13 gives more details on the occupational health impacts. It can be seen that coal has the largest impact, mainly due to asthmatic aspects, probably caused by particulates emissions, and noise impact. Occupational health from organic waste treatment by anaerobic digestion has several types of occupational health impact, with as main contributor injuries during the processing of the waste. Similarly impact on occupational health by silage maize digestion is mainly caused by injuries of which almost 50% are caused by the agriculture of maize itself.

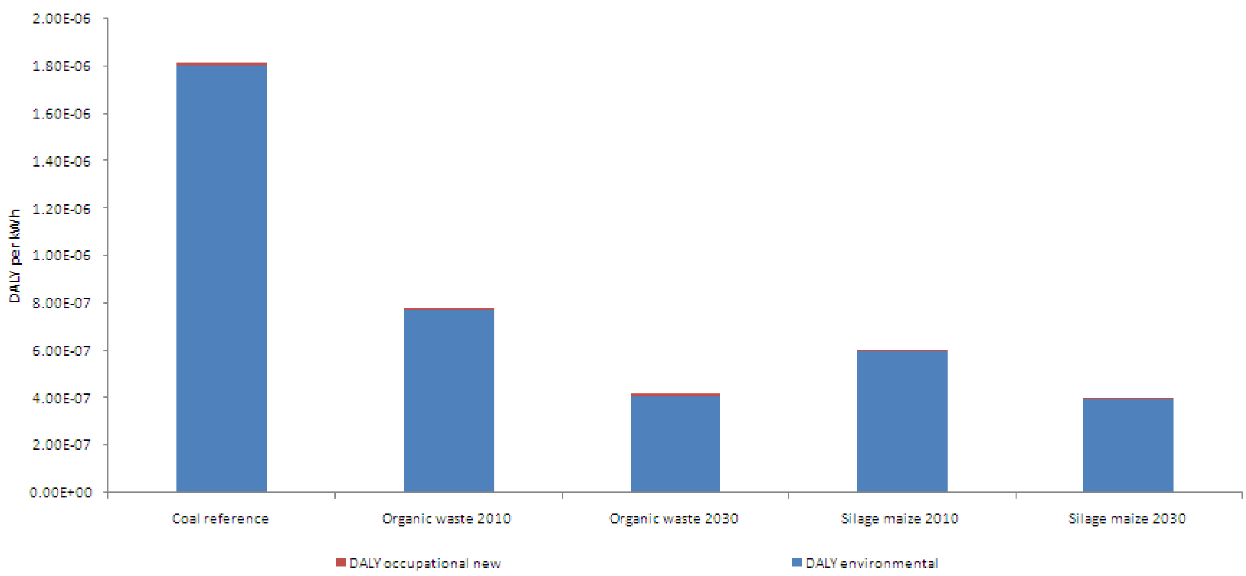

Figure 12: Human health impact including occupational health with the final PROSUITE methodology

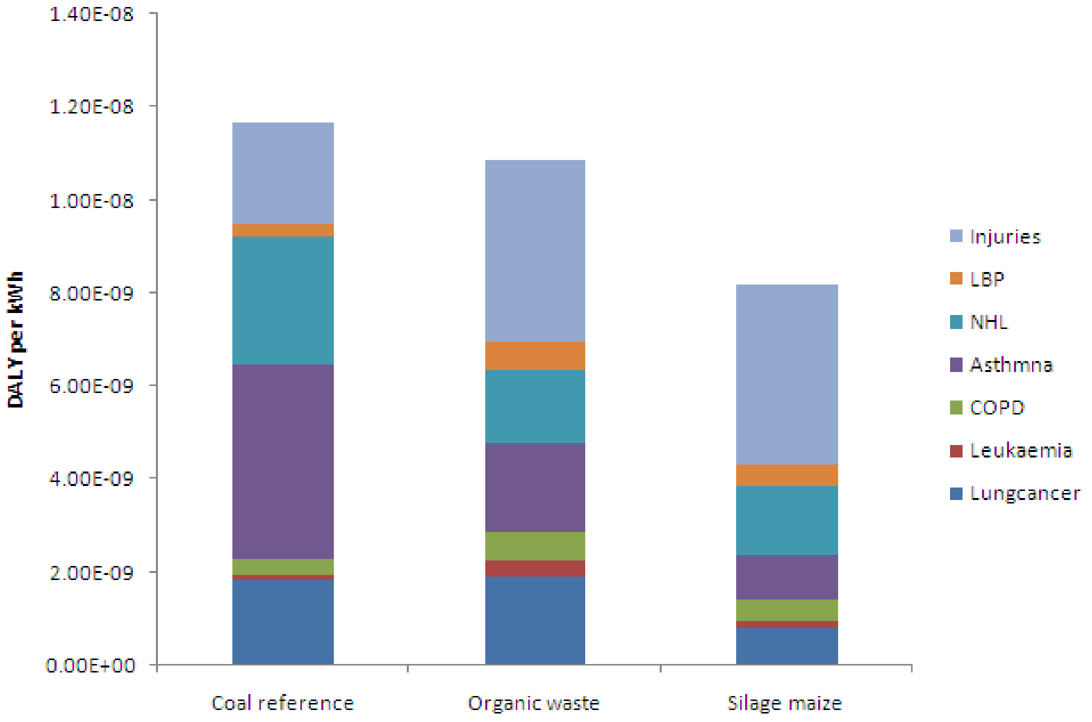

Figure 13: Detailed results of occupational health impact

From the current PROSUITE approach to account for occupational health, it could be concluded that human health impact caused by occupational hazards is not that important. However, whereas the current methodology uses the EXIOPOL tables, linking occupational health effects to economic values, the initial approach was based on physical production numbers of sectors. The results of the initial assessment are presented in Figure 14. In this case the relative impact of occupational health effects ranges from 8 to 42%. The potential injuries during the agricultural phase therefore become very important. In our opinion it is thus too early to conclude that occupational health impact is not important.

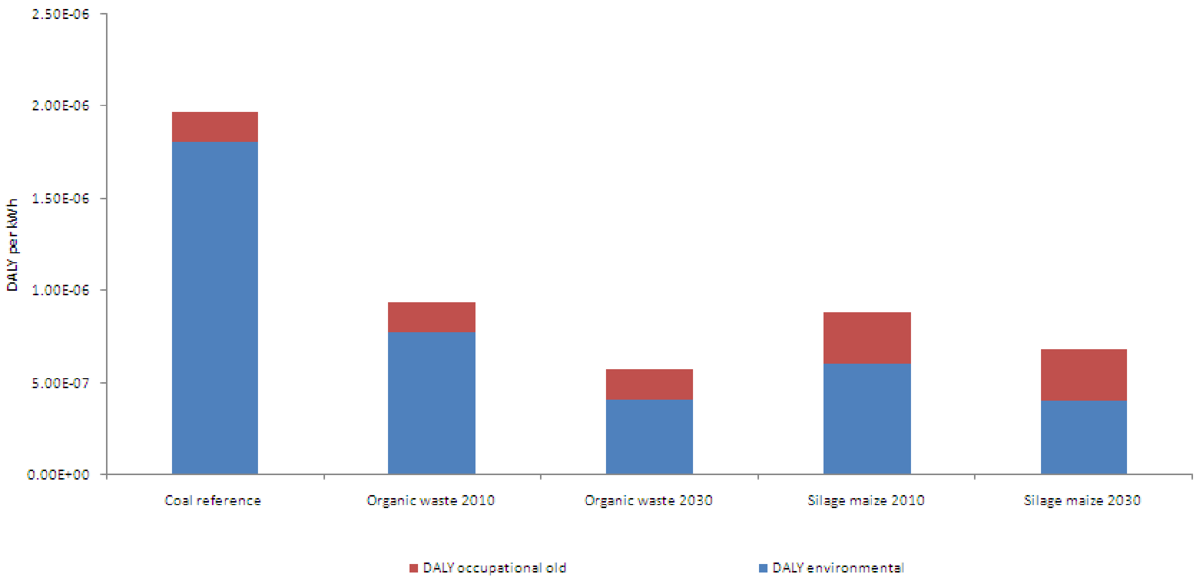

Figure 14: Human health impact including occupational health with the initial PROSUITE methodology

1.3.2. *Impact on natural environment*

The results of the assessment of impact on natural environment are shown in Figure 15. Climate change is also a determining impact category for impact on the natural environment and therefore coal clearly has the largest impact. Second, the collection of organic waste induces transport and related emissions. Due to an increase in transport efficiency however, this impact will drop. Furthermore, the collection domestic waste is also a service to society, which is attributed to the energy production in this study, but which could also be attributed to the function 'waste treatment', which is not included in this work as described above. Silage maize electricity has the highest impact on the natural environment, mainly caused by land use which is required for the cultivation of energy crops.

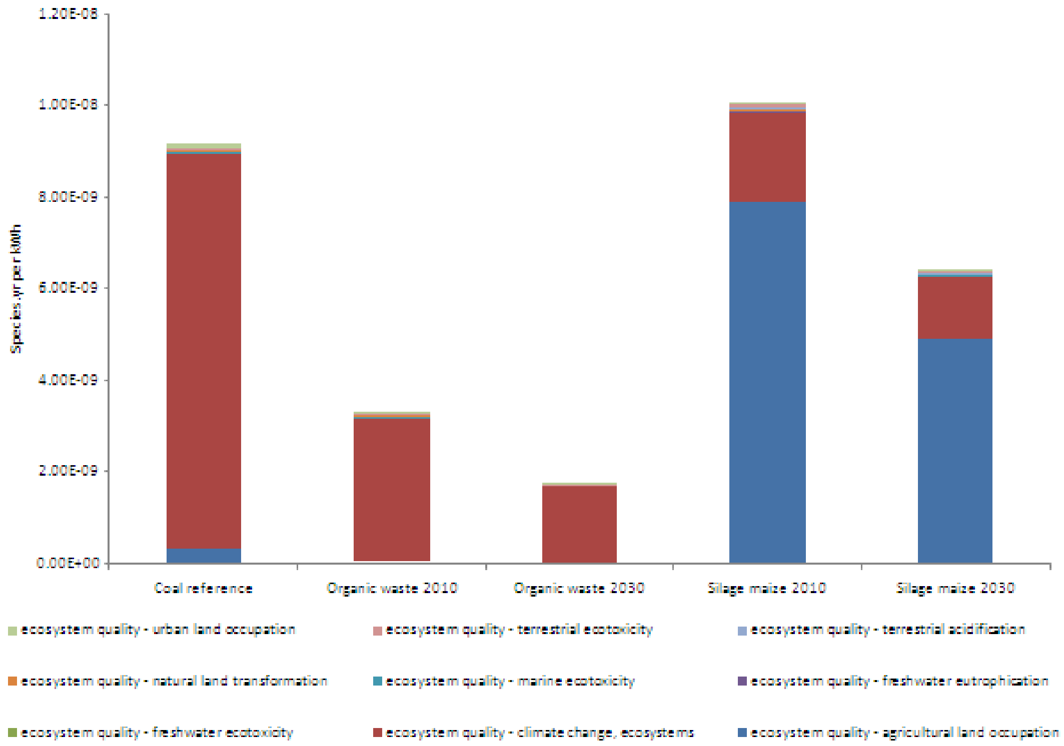

Figure 15: Impact on the natural environment by the different energy generation technologies

A major advantage on anaerobic digestion is that it can be operated with local resources and therefore the impact is also expected to be local. This is shown in Figure 16 and Figure 17 generated from OpenLCA highlighting the location of impacts on the natural environment. It should be noticed however that these maps will be very relevant in the future, but that they are currently limited because the elementary flows taken from ecoinvent are not yet regionalized in the used version of the database (v2.1). As such, the impact of coal is also visualized in Europe by using current assessment practices, whereas it is known that the most important reserves of coal are found in the USA, Russia, India and China (World Coal Association, 2012).

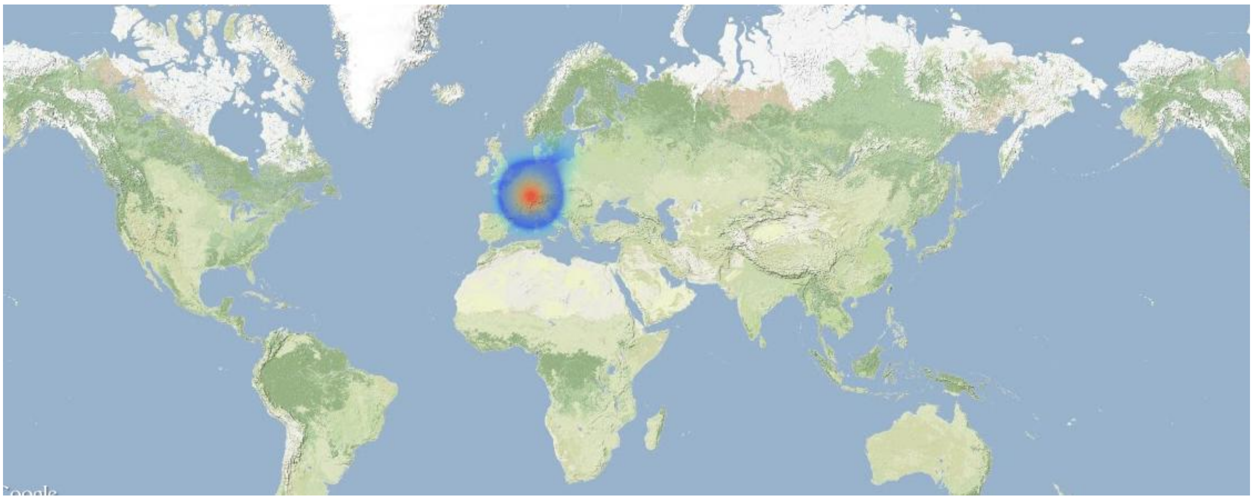

Figure 16: Map of environmental impact of AD of organic waste (2010)

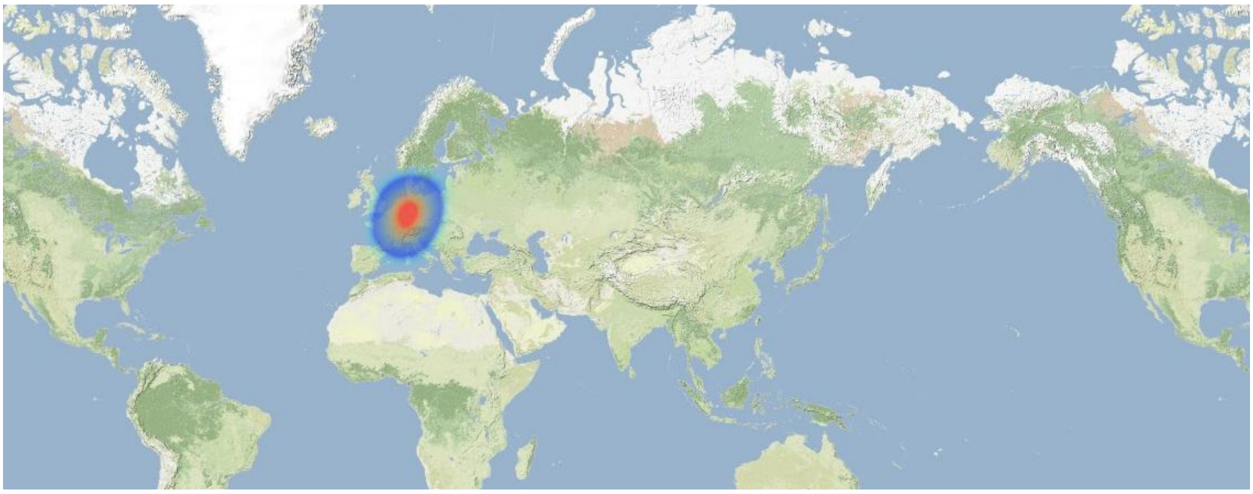

Figure 17: Map of environmental impact of AD of silage maize (2010)

1.3.3. Impact on exhaustible resources

Impact on exhaustible resources is dominated by fossil depletion, whereas metal depletion has a much lower impact (only 0.2% of the total impact). Since all fossils are burned in this case study (i.e. no fixation in a material such as plastic), the impact on fossil depletion shows similar trends to the impact on climate change as discussed in the endpoints human health and natural environment. Coal has the highest impact, followed by organic waste valorization and silage maize digestion.

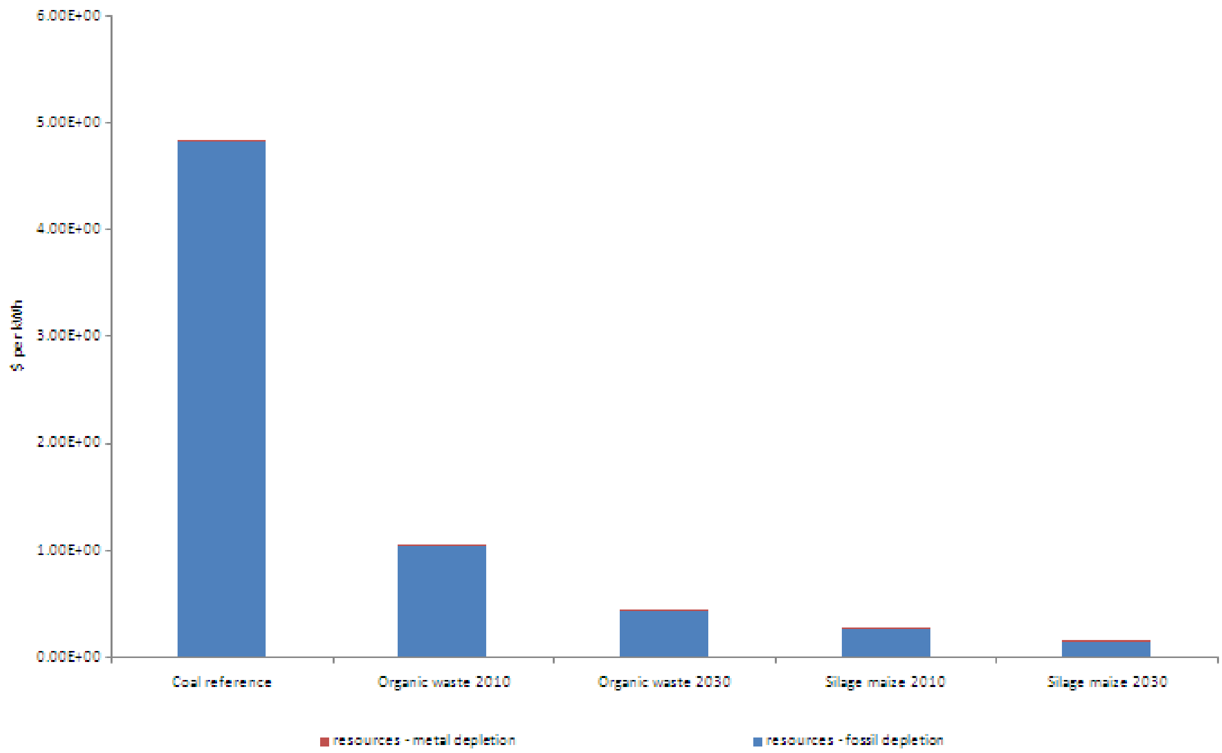

Figure 18: Impact on exhaustible resources

1.3.4. Impact on prosperity

The results of the impact on prosperity for the reference and prospective technologies are shown in Table 2. These numbers include subsidies given by governments for the production of renewable electricity. Without these subsidies, electricity from AD would currently not be competitive, nor profitable. On the other hand, from the Life Cycle Costing Data it can be concluded that silage maize digestion has the lowest financial risk, mainly because it has the lowest capital investment per kWh. The digestion of a pure agricultural stream can be done in a relatively simple setup, which limits capital costs significantly. Current risk assessment however is only based on capital expenses and not on the availability and price of biomass, amount of subsidies, etc. which are probably the biggest risks when investing in energy from crops. Organic waste valorization requires a more complex setup with pre- and post-treatment with a lower electricity production and therefore has the highest capital cost related risk. On the other hand, it depends on a local resource (domestic waste) and therefore has a low import dependency. From these results, the import dependency of coal is lower than the import dependency of silage maize. This is because coal was modeled as a European resource. In reality, the import dependency for coal will be higher since the main coal reserves are situated outside Europe.

Since GDP numbers are high, the influence of the studied technology is small and not visible incTable 2. Figure 19 gives a more detailed view on the macro-economic result. It can be seen that silage maize electricity induces most economic activity both in Europe and worldwide. Whereas coal origins from ancient carbon, current cultivation of crops (biogenic carbon) requires much more inputs from our current economy. Replacing fossil energy by cultivated biomass therefore induces more economic activity. In contrary, the valorization of organic waste is less beneficial for the economy because there is no need for additional supply chains. This case study therefore shows that GDP might be a sound indicator for economics, but on the other hand, the fact that using a resource more efficiently is not economically sound is somehow pervert from a 'sustainability' perspective. On the other hand, the positive effect of efficient waste valorization is already shown in other endpoints.

Table 2: Results of the impact on prosperity of the reference and prospective scenarios

	Reference System	Prospective System - silage maize	Prospective System - Domestic organic waste
Production Volume (Monetary)	5.83E+07	4.33E+06	7.29E+07
Production Volume - functional units	3.87E+08	3.87E+08	3.87E+08
Total Price (€ per FU)	0.15	0.01	0.19
Direct Capital Requirements (€ per FU)	0.02	0.00	0.06
Direct Compensation of Employees (€ per FU)	0.01	0.03	0.06
Total Compensation of Employees (€ per FU)	0.04	0.05	0.12
Import Dependency - FU - %	5%	7%	5%
Fincancial Risk - FU Capital Cost/Total Cost	16%	3%	31%
Total Compensation of Employees - Economy Wide	5.51E+13	5.51E+13	5.51E+13
Total Capital Compensation - Economy Wide	1.72E+13	1.72E+13	1.72E+13
Import Dependency - Economy Wide - €	1.60E+12	1.60E+12	1.60E+12
BW linkages - Economy Wide	2.03	1.84	3.71
FW linkages - Economy Wide	2.73	1.37	2.84
Structural index - Economy Wide	467.81	467.81	467.81
Capital Productivity - €/€	6.74	6.74	6.74
Labour Productivity - €/€	2.10	2.10	2.10
Labour Productivity - €/hours	15,361,701.88	15,361,696.21	15,361,700.75
Resource Productivity	796667.71	796668.54	796669.24
Novelty			
Domestic GDP - Economy Wide - €	2.14E+13	2.14E+13	2.14E+13
Global GDP - Economy Wide - €	1.16E+14	1.16E+14	1.16E+14

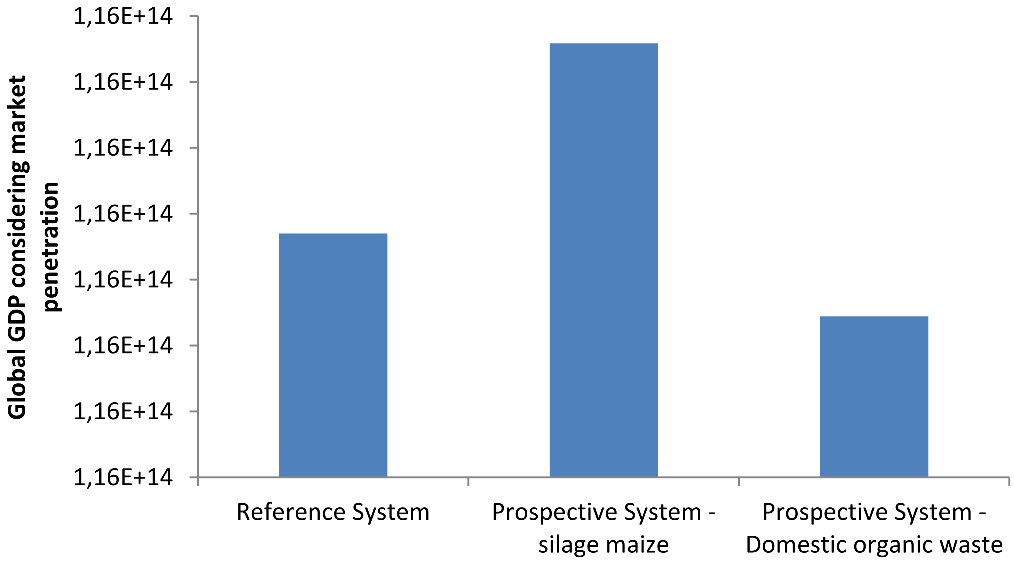

Figure 19: impact on prosperity by analysing the global GDP of the reference system and the two prospective options

The Impacts on social well-being were analyzed based on six quantitative indicators (knowledge-intensive jobs, total employment, global income inequalities, regional income inequalities, child labour, and forced labour), and five qualitative

indicators (change in risk perception, possibility of misuse, trust in risk information, stakeholder involvement, long-term control functions). Table 3 shows the results of the quantitative assessment expressed per functional unit and

Table 4 shows the economy wide results. The results for total labour and skilled labour indicate that organic waste digestion requires most labor, this is mainly because of the high amount of jobs in sector p40.11.e of the EXIOPOL tables, namely electricity from biomass and waste. The valorization of organic waste indeed requires both engineers and operators for the different processes of pre- and post-treatment steps such as wastewater treatment, composting, transport by tractor, etc. The agricultural setup has a lower requirement of both total and skilled labour because of the small scale of the reactor and the fact that the farmers operate the facility themselves. It is however difficult to analyze how these results are obtained because of the 'black box' economic tables. Distortion from the subsidies is possible. Child labor occurs most in the biobased energy scenarios; the main impact on child labour for silage maize digestion is situated in the agricultural process (over 50%), whereas for organic waste this is situated in the collection of waste and in coal electricity this is situated in the coal mines. Forced labor has the same sources and occurs most in energy crop digestion due to agriculture. Whereas for world markets, these results would probably be true, these results shows the disadvantage of working with generic data; in our case study, we know exactly where maize was produced and who collected the waste. In our cases, no child or forced labor was involved in these foreground processes. We therefore suggest for future work to combine foreground data, if available, with the exiopol data.

Concerning regional inequalities, silage maize has the lowest GDP increase in non OECD countries, whereas coal and organic waste valorization have a more significant contribution from non OECD countries. For coal electricity, this seems reasonable, but for organic waste valorization, this is a strange result. Due to the black box nature of the input-output tables, we are not able to check these results. Figure 20 shows a more detailed view on the GINI result focusing on global inequalities. The GINI result for organic waste valorization is highest, which means that this scenario induces most inequalities, followed by the silage maize digestion and the coal electricity. In general however, for the social well-being, most economy-wide results show only small differences, meaning that effects on the total economy are almost negligible. This makes the assessment of the endpoint social well-being not straightforward.

Table 3: Results of the impact on social well-being expressed per functional unit

	Reference System	Prospective System - silage maize	Prospective System - Domestic organic waste
Labour (hours per FU)	0.00379	0.003625	0.008157
Labour high skilled (hours per FU)	0.000669	0.000659	0.00165
Child Labour Total (hours per fu)	4.19E-05	9.47E-05	9.62E-05
Child Labour Hazardous activities (hours per fu)	3.01E-05	7.56E-05	7.36E-05
Forced Labour Total (hours per fu)	3.03E-06	5.12E-06	4.88E-06
ΔGDP OECD-non OECD (€ per fu)	-0.14657	-0.00057	-0.17786

Table 4: Results of the impact on social well-being expressed for the full market penetration

	Reference System	Prospective System - silage maize	Prospective System - Domestic organic waste
Labour Economy Wide (hours)	7.53309E+12	7.53E+12	7.53E+12
Labour high skilled - Economy Wide (hours)	1.63418E+12	1.63E+12	1.63E+12
Child Labour Total - Economy Wide (hours)	2.80066E+11	2.8E+11	2.8E+11
Forced Labour Total - Economy Wide(hours)	19508090748	1.95E+10	1.95E+10
ΔGDP OECD-non OECD (€ per fu)	-1.41532E+12	-1.4E+12	-1.4E+12
Global Income inequality (GINI)	0.653699619	0.6537	0.6537

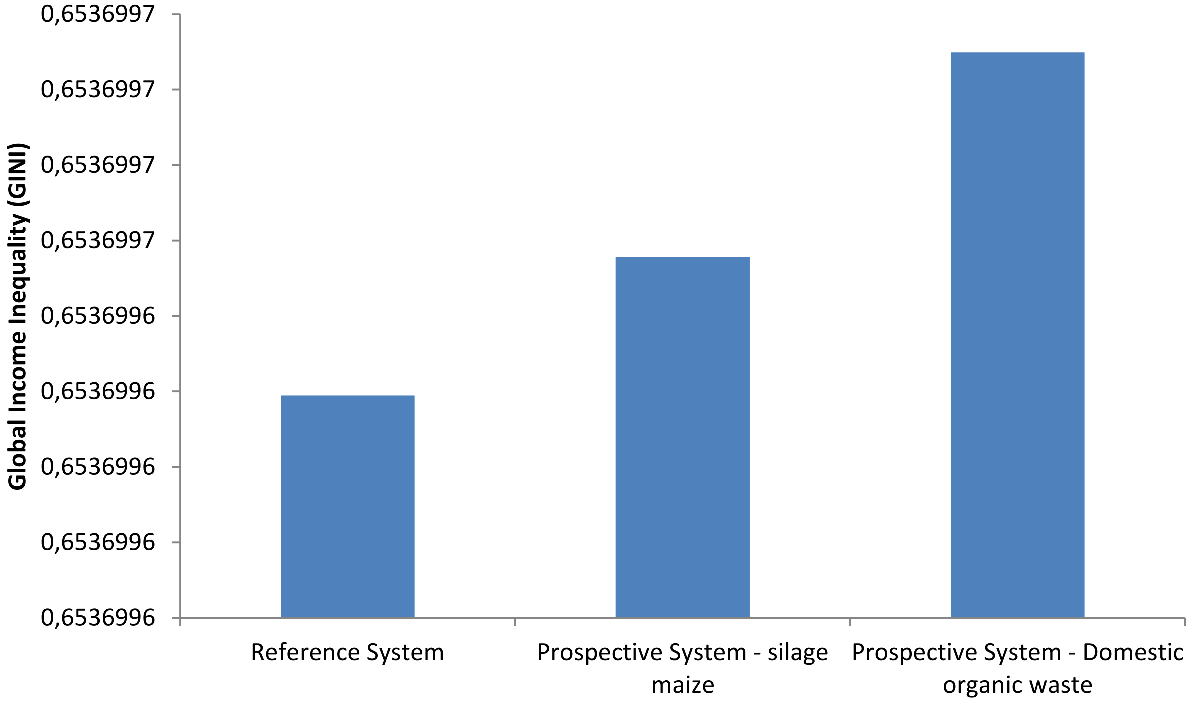

Figure 20: Results of the GINI assessment

Table 5 shows the absolute economy wide difference of impact on social well-being between the reference and prospective technologies. By doing so, the relative difference is always smaller than 0.00% and therefore the proposed Likert scale cannot be used.

Table 5: Absolute difference between the reference and prospective technologies

	Prospective System - silage maize	Prospective System - Domestic organic waste
Labour Economy Wide (hours)	-977223.0947	2195534.289
Labour high skilled - Economy Wide (hours)	-170088.6772	481570.6365
Child Labour Total - Economy Wide (hours)	-3446.228943	26947.92157
Forced Labour Total - Economy Wide(hours)	-481.3509407	1017.170364
ΔGDP OECD-non OECD (€ per fu)	56644233.33	-23129235.86
Global Income inequality (GINI)	3.67276E-08	9.09016E-08

Therefore, in order to make one assessment of the social well-being endpoint, it is required to integrate these results by using normalization and weighting for which following equation is used with weighting and normalization factors presented in Table 6:

$$S_{wb} = \frac{\sum_{i=1}^{6} W_{a,i} \times \left(\frac{I_i}{N_i}\right)}{6}$$

In which:

W_i = weighting factor for indicator i

I_i = the value of indicator i

N_i = the normalization factor for indicator i

Table 6: Normalization and weighting factors used in the assessment of social well-being

	Normalization factor	Unit	Weighting factor	Positive/negative
Total employment	8.98E+02	Hours	1	Positive
Knowledge-intensive jobs	1.95E+02	Hours	1	Positive
Regional inequalities	-2.19E+03	€	1	Negative
Income inequalities (GINI)	9.13E-11	N/A	1	Negative
Children in hazardous labour	1.96E+01	Hours	1	Negative
Forced labour	2.22E+00	Hours	1	Negative

To account for the fact that some categories need be high and others low, the categories with a positive impact (higher is better; i.e. labour and regional inequality) are multiplied with -1 in this equation. In this way, the lower the total impact on social well-being is, the better. The final results are visualized in Figure 21 and indicate that silage maize has the lowest impact and organic waste valorization the highest. This is mainly caused by the fact that the category ΔGDP OECD-non OECD becomes more important by the used normalization factor and silage maize scores best (lowest) in this category.

Table 7: The summary of impact on social well-being

	Reference System	Prospective System - silage maize	Prospective System - Domestic organic waste
Labour Economy Wide (hours)	-8.39E+09	-8.39E+09	-8.39E+09
Labour high skilled - Economy Wide (hours)	-8.38E+09	-8.38E+09	-8.38E+09
Child Labour Total - Economy Wide (hours)	1.43E+10	1.43E+10	1.43E+10
Forced Labour Total - Economy Wide(hours)	8.79E+09	8.79E+09	8.79E+09
ΔGDP OECD-non OECD (€ per fu)	-6.46E+08	-6.46E+08	-6.46E+08
Global Income inequality (GINI)	7.16E+09	7.16E+09	7.16E+09
Total impact on social well-being	**2.14E+09**	**2.14E+09**	**2.14E+09**

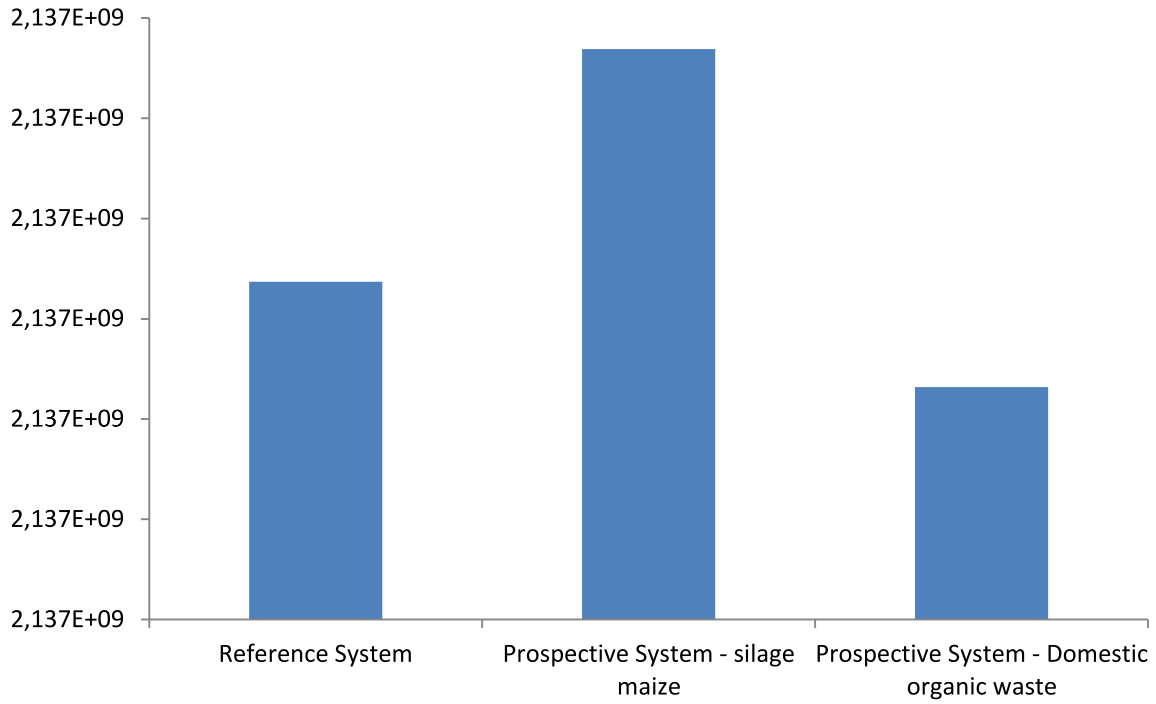

Figure 21: Final normalized impact on social well-being

1.4. Conclusions

Integration

In this case study, the impact on five endpoints is first calculated separately and will now be integrated by using two methodologies, as proposed in WP5, namely by making a weighted sum and through Condorcet methodology.

First we summarize all results at endpoint level, which can be found at a technology wide (i.e. 387 TWh) and economy wide (i.e. including all sectors) level in $V_j = \sum_{i=1}^{n} v_{i,j} \times w_i$

$$\sum_{i=1}^{n} w_i = 1$$

In which:

V_j = the aggregated score for alternative j

$V_{i,j}$ = the normalized score for endpoint indicator I for alternative technology j

w_i = the weight assigned to endpoint indicator i

n = the number of endpoint indictors (=5)

Table 8. From the impact categories human health, natural environment and exhaustible resources, we will only take the 2030 scenario's, because the 2010 values are missing for the endpoints prosperity and social well-being. Afterwards, a weighted sum is made by using following equation and normalization and weighting factors presented in Table 9 (notice that social-wellbeing was already normalized in the assessment of the endpoint separately):

$$V_j = \sum_{i=1}^{n} v_{i,j} \times w_i$$

$$\sum_{i=1}^{n} w_i = 1$$

In which:

V_j = the aggregated score for alternative j

$V_{i,j}$ = the normalized score for endpoint indicator I for alternative technology j

w_i = the weight assigned to endpoint indicator i

n = the number of endpoint indictors (=5)

Table 8: A summary of results at endpoint level.

	Reference System	Prospective System - silage maize	Prospective System - Domestic organic waste	unit
Impact on human health	7.02E+05	1.56E+05	1.62E+05	DALY
Impact on natural environment	3.56E+03	2.49E+03	6.75E+02	Species yr
Impact on exhaustible resources	1.87E+12	6.69E+10	1.78E+11	$
Impact on prosperity	1.16E+14	1.16E+14	1.16E+14	€
Impact on social well being	2.14E+09	2.14E+09	2.14E+09	/

Table 9: Normalization and weighting factors used for the 5 endpoints in the PROSUITE project

	Normalization factor	Unit	Weighting factor
Impact on human health	2.54E-02	DALY/person	0.3
Impact on natural environment	7.30E-05	Species.yr/person	0.25

Impact on exhaustible resources	7.90E+01	$/person	0.1
Impact on prosperity	9.24E+03	€/person	0.1
Impact on social well-being	N/A		0.25

Table 10 shows the final results of the weighted sum approach. Prosperity should be as high as possible, whereas the other impacts should be as low as possible. It can be seen that the impact on prosperity and the impact on social wellbeing dominate the complete assessment and that especially impact on human health and natural environment is negligible (<1%). The reason for this is that the impact on social well-being and prosperity is analyzed economy-wide and the impact on human health, natural environment and exhaustible resources is analyzed technology wide considering only the total market penetration (i.e. 387 TWh) and not the reaction of the while economy. Obviously there are many differences between the traditional LCA practice and the use of input-output tables. Aspects such as system boundary and functional units were thoroughly discussed in the project. However, no 'final' solution was found. As such, it seems difficult to apply a weighting sum at the current state of the art of the assessments.

Table 10: Final weighted and normalized result of the reference and prospective technologies

	Reference System	Prospective System - silage maize	Prospective System - Domestic organic waste
Impact on human health	8.30E+06	1.85E+06	1.91E+06
Impact on natural environment	1.22E+07	8.52E+06	2.31E+06
Impact on exhaustible resources	2.37E+09	8.47E+07	2.25E+08
Impact on prosperity	-1.25E+09	-1.25E+09	-1.25E+09
Impact on social well being	2.14E+09	2.14E+09	2.14E+09
Final assessment score	3.27E+09	9.79E+08	1.11E+09

To avoid the difficulty of integration related discussions concerning system boundary, positive and negative results, etc. we also use the Condorcet rule, which allows a comparison per endpoint category. Because we have 3 options, scores are given from 0 to 2. in which the best technology receives the highest score. The result of this integration methodology is visualized in Figure 22. By using this methodology, it can be seen that electricity from silage maize has the best score, followed by electricity from organic waste. The reference electricity from coal scores worst.

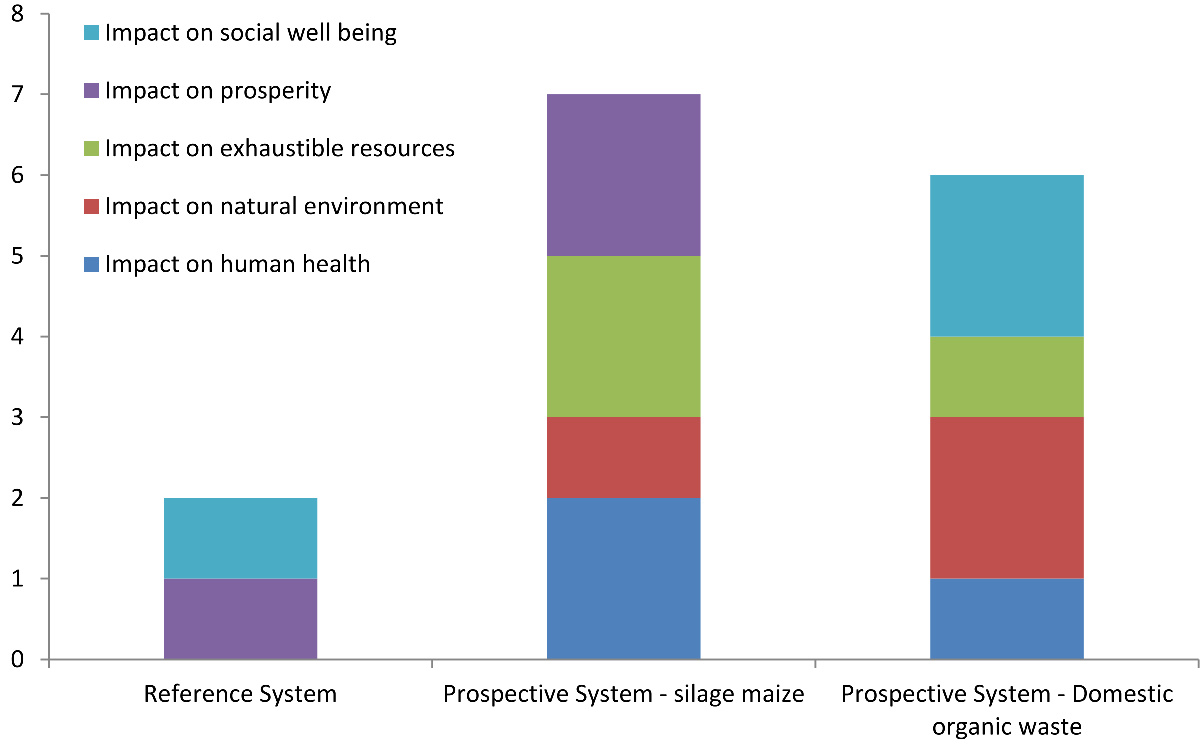

Figure 22: Integration of the PROSUITE assessment by using the CONDORCET methodology

Overall conclusions

In this sustainability assessment we have compared three types of electricity; first the reference was established, which is electricity from coal. Second, electricity from energy crops; in this case silage maize, and third, electricity from domestic organic waste are considered. Our assessment shows that silage maize electricity scores best for the endpoints human health, exhaustible resources, prosperity and social well-being when using the Condorcet methodology. Electricity from domestic organic waste digestion scores best for the impact on the natural environment. Whereas this result is interesting as such, probably the most important realization of this project is that it is a major attempt to integrate the previously named 'three dimensions of sustainability'. The project has brought people together, gathered interesting, multidisciplinary insights and is a good basis for further work. The positive and negative aspects are clearly shown in this case study and the impression of the authors of this part of the report is summarized below:

- New endpoints are constructed; instead of using the traditional three pillar approach, 5 more tangible endpoints are developed. This allows a more interdisciplinary assessment (e.g. human health impacts from social and environmental causes). More discussions could follow this new step; for example if there is a need to separate the human well-being into socio-economic impacts and more qualitative social impacts related to happiness. Another example is the inclusion of GDP as an indicator for prosperity. In our case study, a better valorization of organic waste performs bad, because it does not induce more economic activity. In general, efficiency gains score low on GDP whereas bad things such as accidents or wars can score good.
- The functional unit approach is criticized because it only focuses on micro-economic aspects. This is true, and things such as the Jevons paradox (if there are a lot of slightly better things, the overall impact can still be higher due to macro-economic effects such as growth) indeed suggest that considering only small scale issues in assessments misses essential impacts. However, this project shows that a macro-scale assessment has its own challenges. For example the impact on GDP of all technologies is marginal. More research is needed on how the assessment and interpretation of results can be improved is necessary.

- The integration of micro-scale with macro-scale assessments is not straightforward. Integration of a functional unit in the total economy and the other way around requires needs more research.
- Whereas the impact assessment is a very important thing, also the collection of reliable data inventories should gain more focus. For example the environmental assessment of agriculture is still very uncertain. Several emissions are estimated with a high error margin. A macro-scale assessment is even more difficult. It increases uncertainty by aggregating all results. Furthermore these tables can only be made every few years and are therefore fast outdated.
- As discussed in this project, a flagging system could be elaborated (i.e. I do not want child labor in my product)
- Silage maize electricity scores best in this assessment. This is mainly because of the fact that the shortage of land is not yet included in sustainability assessments. Similarly, more work could be done on the use of scarce metals (depletion)

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2. Case study 2: Biobased PVC from sugarcane bioethanol

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2.1. Goal and scope of the case study (partially redrafted from Alvarenga et al. (2013))

2.1.1. Scientific background/description of the case

Polyvinyl chloride (PVC) is a thermoplastic that has been produced in industrial scale since the first half of the 20th century and, thanks to its versatility, found applications in many economic sectors (e.g. construction and packaging). The global demand for PVC exceeded 30 million metric tonnes in 2009 and it is in constant growth (+5% on global average), especially in developing countries (http://www.pvc.org/en/). Ethylene and chlorine are the two main feedstocks needed to manufacture PVC. While the supply of chlorine is virtually inexhaustible, the availability of fossil-based ethylene is limited to the end of the petrochemical era.

In this sense, and in addition to society's pressure on environmental impacts related to climate change and resource depletion, new technologies are being developed to manufacture ethylene from renewable raw materials, such as converting bioethanol into (bio)ethylene by dehydration (Martinz et al. 2008; Morschbacker et al. 2009). Bioethanol may come from different biomass sources, but sugarcane is the main raw material for this commodity in Brazil, one of the biggest producers in the world (Cerqueira Leite et al. 2009; Goldemberg and Guardabassi 2010). Its production is projected to grow even more in the future, induced by increasing internal and external demands (UNICA (www.unica.com.br) and CTBE (http://www.bioetanol.org.br/)). Bioethanol has been used as source of fuel in Brazil for more than 30 years and its efficiency and environmental impacts have been extensively discussed in literature (Seabra et al. 2011; Cavalett et al. 2011; Cavalett et al. 2013; Ometto et al. 2009; Brehmer et al. 2009; Macedo et al. 2008). Due to legislation and governmental-industry agreements (UNICA 2007; Governo do Estado de Sao Paulo 2002), the harvest of sugarcane involving burning techniques will be gradually reduced in the upcoming years, decreasing the environmental impacts as well (De Figueiredo and La scala Jr 2011; Gullet et al. 2006; Maioli et al. 2009; Silva et al. 2010; Garbiate et al. 2011).

In this case study we compared the fossil-based PVC (reference scenario) with the bioethanol-based PVC (prospective scenario):

- The PVC from the reference scenario is manufactured from ethylene of fossil origin, i.e. the feedstock is crude oil and/or natural gas, that is converted into ethylene through cracking;
- The PVC from the prospective scenario is manufactured from ethylene of biological origin, i.e., the

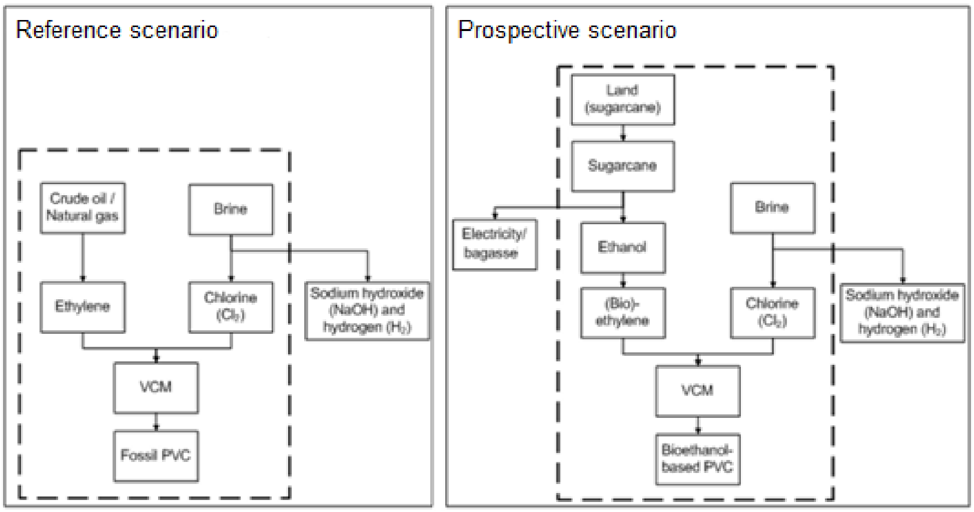

Figure 1: Simplified flowchart of fossil-based PVC (left) and bioethanol-based PVC (right), expressing the system boundaries of the foreground system for the main raw materials with the dotted lines

feedstock is sugarcane, from which the juice is fermented into (hydrous) ethanol, which is converted into ethylene through dehydration. We considered that 62% of sugarcane was being harvested through burning techniques (this percentage will gradually decrease in the future, for Brazil).

2.1.2. *Functional unit*

The functional unit chosen for this case study was 1000 kg of PVC resin. This functional unit was used for all five Prosuite endpoints.

2.1.3. *System boundaries (spatial/temporal scope, flowcharts)*

This case study referred to a cradle-to-gate analysis of PVC. Both reference and prospective scenarios were considered to be produced in Brazil, with data mainly based on the year 2010. The system boundaries can be visualized in Figure 1. More details about the life cycle inventory (LCI) of the two scenarios can be seen on Alvarenga et al. (2013).

2.2. Case specific methodology

2.2.1. *Impact on human health*

Impacts on human health were evaluated in two perspectives:

- Environmental perspective, for which we used the Recipe Endpoint methodology version 1.07 (Goedkoop et al. 2010) based on the LCI. According to the recommendations of Pawelzik et al. (2013), in cradle-to-gate LCA studies of biobased products, the carbon capture and biogenic carbon emissions should be considered. Therefore, we adjusted the Recipe methodology for the category 'climate change' affecting the endpoint category human health, to include the capture and emissions of biogenic CO_2.
- Occupational perspective, for which we used the EXIOPOL Input-Output model, based on economic assessment at different sectors (agriculture, mining, manufacturing, electricity, construction, trade, transport, finance, and services). The health effects included are lung cancer, leukaemia, chronic obstructive pulmonary disease, asthma, noise induced hearing loss, low back pain, and fatal/non-fatal injuries. Matrix calculations allow estimating the total occupational health effect for each economic sector and the total contribution of all sectors to an occupational health effect. It also allows finding the total contribution to occupational health of a technology

Both are expressed in Disability Adjusted Life Years (DALY). The assessment was made at product level.

2.2.2. *Impact on natural environment*

The impact on the natural environment was calculated according to the ReCiPe methodology (Goedkoop et al. 2010) based on the LCI. According to the recommendations of Pawelzik et al. (2013), in cradle-to-gate LCA studies of biobased products, the carbon capture and biogenic carbon emissions should be considered. Therefore, we adjusted the Recipe methodology for the category 'climate change' affecting the endpoint category natural environment, to include the capture and emissions of biogenic CO_2. The assessment was made at product level.

2.2.3. *Impact on exhaustible resources*

The impact on exhaustible resources was calculated according to the ReCiPe methodology (Goedkoop et al. 2010), based on the LCI. The assessment was made at product level.

2.2.4. *Impact on prosperity*

We elaborated an estimation of life cycle costing for the reference and the prospective technologies. Then we used that analysis as input to the EXIOPOL Input-Output model, as explained in the reports of WP2. The assessment was made at economy-wide level.

2.2.5. *Impact on social well-being*

The method for the social well-being assessment is provided in the reports of WP4. The assessment was made at product and economy-wide levels.

2.2.6. *Integration*

The integration of the five endpoint impact categories was performed according to the reports of WP5.

2.3. Results and discussion

2.3.1. *Impact on human health*

Impacts on human health were evaluated at the environmental perspective and at the occupational perspective. The results can be seen in Table 1 and Figure 2.

Table 1. Results of the impact on human health of the reference and prospective scenarios (unit is in DALY)

Endpoint impact category	Reference	Prospective	Relative difference
Human health (environmental)	2.43E-03	3.09E-03	27%
Human health (occupational)	7.72E-05	1.15E-04	49%
Human health (total)	2.51E-03	3.21E-03	28%

The results on the impacts on ´human health (occupational)´ are relatively similar to the impacts on ´human health (environmental)´, i.e., prospective scenario cause more impacts than reference technology. It is not straightforward to track-down the reasons for the former, but most probably they are due to different characterization factors between agricultural (at prospective technology) and the chemical industry (at reference technology) sectors. Regarding the impacts on human health (environmental), the prospective technology had higher results mostly due to emissions at the sugarcane cultivation stage (affecting mainly particulate matter formation and photochemical oxidant formation), even though it had better results in the climate change category.

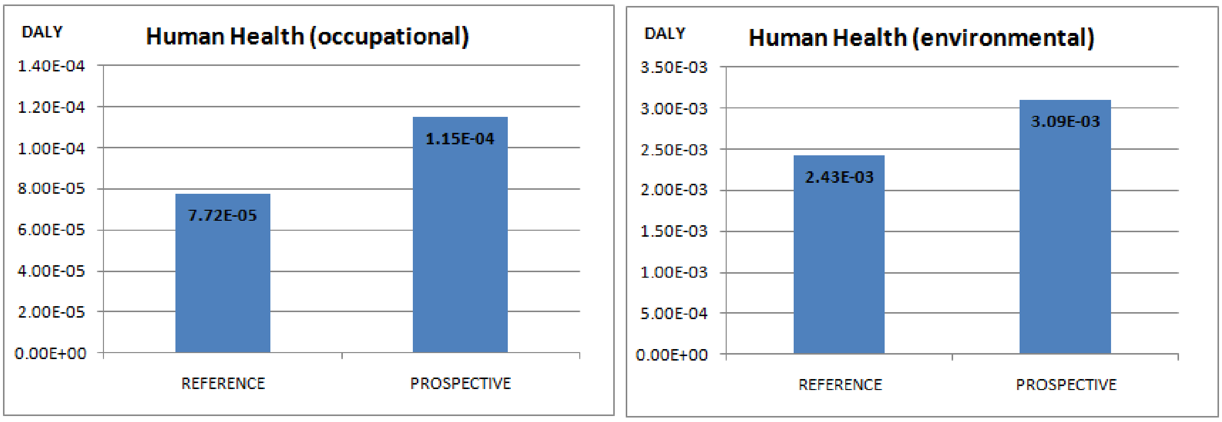

Figure 2: Results of the impact on human health at the occupational perspective (left) and the environmental perspective (right) of the reference and prospective technologies

2.3.2. *Impact on natural environment*

The results of the impact on natural environment can be seen in Table 2 and Figure 3. The unit of this category is species.year.

Table 2. Results of the impact on natural environment of the reference and prospective scenarios (unit is in species.yr)

Endpoint impact category	Reference	Prospective	Relative difference
Natural environment	1.27E-05	1.39E-06	-89%

A high difference can be seen between the prospective and the reference technologies, regarding impacts on natural environment. The prospective technology has the potential to reduce 89% of the impact on the reference technology. The main reasons for that is the high contribution to mitigate climate change in the prospective technology (due to the biogenic carbon storage in the bioethanol-based PVC), which is able to compensate the higher impacts on land use, eutrophication, and ecotoxicity (among other categories), based on the Recipe methodology.

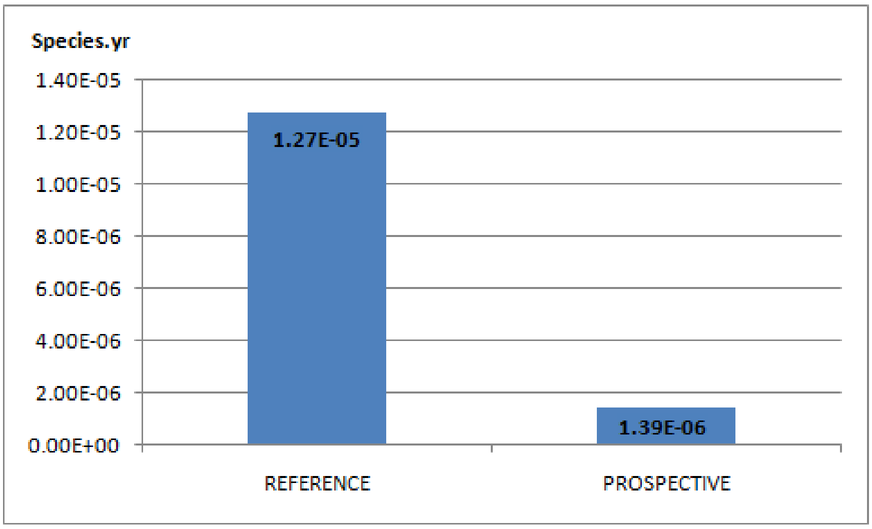

Figure 3: Results of the impact on natural environment of the reference and prospective technologies

It is important to give a "red-flag" in this endpoint category: In this environmental assessment we did not consider possible indirect land use change (iLUC) impacts due to expansion of sugarcane production for the prospective technology. This was not done due to lack of consensus on how to deal with iLUC in LCA. If these impacts are considered, the environmental impacts on natural environment of the prospective technology can increase.

2.3.3. Impact on exhaustible resources

The results of the impact on exhaustible resources can be seen in Table 3 and Figure 4. The unit in this category is in Dollars (US$).

Table 3. Results of the impact on exhaustible resources of the reference and prospective scenarios (unit is in U.S. Dollars)

Endpoint impact category	Reference	Prospective	Relative difference
Exhaustible resources	1.60E+02	5.02E+01	-69%

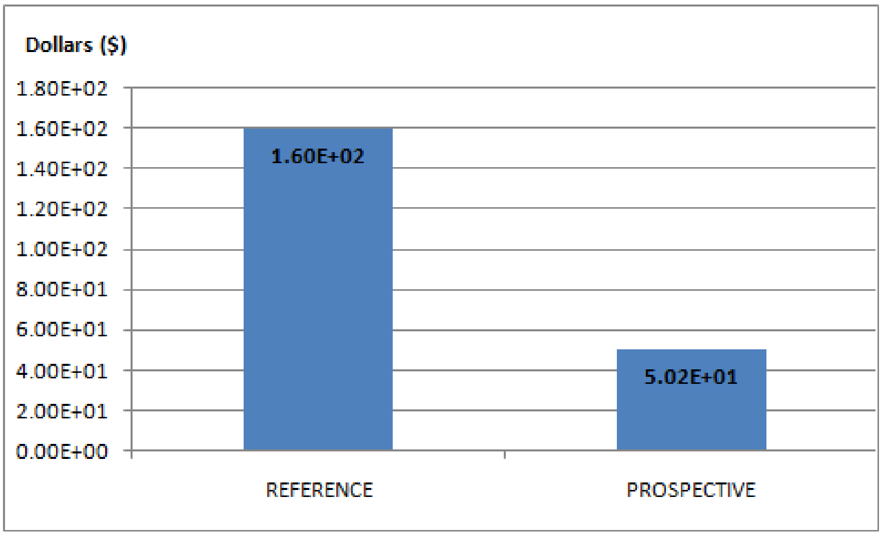

Figure 4: Results of the impact on exhaustible resources of the reference and prospective technologies

The reference technology has higher impacts on exhaustible resources mainly due to the feedstock of ethylene. While in the reference technology the feedstock is fossil, i.e. exhaustible, in the prospective technology the feedstock is biomass (sugarcane). As it can be seen in Table 3, the prospective technology can reduce 69% of the impacts on exhaustible resources from the reference technology.

2.3.4. Impact on prosperity

Impacts on prosperity were evaluated according to the methodology proposed in WP2. The results can be seen in Table 4. Currently the production cost of the prospective technology is higher than the reference technology, mainly due to different prices of fossil ethylene and ethanol (for biobased ethylene). Since the prospective and reference technology are produced within the same industry, it is considered that the differences in costs are not transferred to the final consumer, i.e., to their final prices. On top of that, it is considered (in this case study) that the prices/costs of fossil and biobased ethylene will be approximately the same in the near future, mainly due to the expected rise in the crude oil price. This is the main reason why the results in the 'total costs' indicator is the same for the prospective and reference technologies.

As a result, the final endpoint indicator (global GDP), presented the same results for the prospective and the reference technology, showing that there are no extra impacts (positive or negative) on prosperity due to the introduction of the prospective technology. It is important to mention anyway that the impacts on prosperity (as the global GDP) have different direction of preference than the environmental indicators, i.e., the highest the value the best is the option.

Table 4. Results of the impact on prosperity of the reference and prospective scenarios

Midpoint category	Reference	Prospective	Relative difference	Absolute difference	Δ per FU (prospective to reference)	Δ per $ (prospective to reference)
Production Volume (Monetary)	9.94E+02	9.94E+02				
Production Volume - functional units	1.00E+00	1.00E+00				
Total Price (€ per FU)	9.94E+02	9.94E+02	0%	-8.19E-04		-1.00E+00
Direct Capital Requirements (€ per FU)	1.12E+02	1.06E+02	-6%	-6.41E+00		-1.13E-01
Direct Compensation of Employees (€ per FU)	1.72E+01	1.70E+01	-1%	-1.54E-01		-1.73E-02
Total Compensation of Employees (€ per FU)	4.35E+02	4.84E+02	11%	4.96E+01		-4.37E-01
Import Dependency - FU - %	1.15E-01	1.13E-01	-2%	-2.02E-03		-1.34E-04
Fincancial Risk - FU Capital Cost/Total Cost	1.13E-01	1.06E-01	-6%	-6.45E-03		-1.71E-04
Total Compensation of Employees - Economy Wide	5.51E+13	5.51E+13	0%	4.96E+01	4.96E+01	
Total Capital Compensation - Economy Wide	1.72E+13	1.72E+13	0%	1.13E+01	1.13E+01	
Import Dependency - Economy Wide - €	1.60E+12	1.60E+12	0%	-2.66E+01	-2.66E+01	
BW linkages - Economy Wide	3.30E+00	2.94E+00	-11%	-3.61E-01		
FW linkages - Economy Wide	2.97E+00	2.97E+00	0%	-2.29E-10		
Structural index - Economy Wide	4.68E+02	4.68E+02	0%	1.87E-10		
Capital Productivity - €/€	6.74E+00	6.74E+00	0%	-4.03E-12		
Labour Productivity - €/€	2.10E+00	2.10E+00	0%	-1.76E-12		
Labour Productivity - €/hours	1.54E+07	1.54E+07	0%	-1.00E-05		
Resource Productivity	7.97E+05	7.97E+05	0%	-7.37E-06		
Novelty						
Domestic GDP - Economy Wide - €	2.14E+13	2.14E+13	0%	-3.09E+01	-3.09E+01	
Global GDP - Economy Wide - €	1.16E+14	1.16E+14	0%	-7.05E+00	-7.05E+00	

2.3.5. *Impact on social well-being*

Impacts on social well-being were analyzed through six quantitative indicators (knowledge-intensive jobs, total employment, global income inequalities, regional income inequalities, child labour, and forced labour), and five qualitative indicators (change in risk perception, possibility of misuse, trust in risk information, stakeholder involvement, long-term control functions).

The results of the five qualitative indicators were done through interpretation of the social aspects on the case study. However, we did not follow the procedure at the section "dealing with expert elicitation" from the report of WP4, which requires this step to be done through different experts in the area. This was not done due to lack of time, since the final report from WP4 was delivered only two weeks before the deadline for the case studies. Therefore we performed the qualitative assessment ourselves.

Since the final use of the product in the reference and the prospective technology is the same, for the indicators 'change in risk perception', 'possibility of misuse', 'trust in risk information', and 'long-term control function' we interpreted that these indicators do not indicate any reasons of concern between the reference and prospective technologies (for our case study). Even though there are some differences on stakeholder involvement between the fossil ethylene industry (reference technology) and the sugarcane-ethanol industry (prospective technology), we think that there are no reasons for concern in the indicator 'stakeholder involvement' as well.

We made a simplified uncertainty analysis in the qualitative indicators, as suggested in the report of WP4. For all indicators the final value was 3.75, which means a high uncertainty. This was mainly due to high uncertainties on Reliability and Temporal correlation.

The six quantitative indicators were generated from Exiopol, and are presented in Table 5.

Table 5. Results of the impact on social well-being of the reference and prospective scenarios

Endpoint impact category	Reference	Prospective	Relative difference
Knowledge-intensive jobs (hours/FU)	4.05E+00	3.92E+00	-3.17%
Total employment (hours/FU)	2.19E+01	2.73E+01	24.56%
Regional income inequalities (GDP difference between OECD and non-OECD countries)	-8.52E+02	-8.34+02	-1.99%
Global income inequality (GINI) (*economy wide*)	6.54E-01	6.54E-01	0.00%
Child Labour (hours/FU)	4.47E-01	6.77E-01	51.53%
Forced Labour (hours/FU)	3.31E-02	4.65E-02	40.52%

We used a five point Linkert scale to interpret these results, as suggested in the reports from WP4 (Figure 5). Through that we can evaluate that the prospective technology has a large increase in total employment (positive impact), but also a large increase in child labour and forced labour (negative impacts). The other indicators had negligible increase/decrease.

Knowldegde-intensive jobs

	Data analysis	
	2. A large increase in high-skilled work	More than 10% increase
	1. Moderate increase in high-skilled work	5% to 10% increase
X	0. A negligible increase or decrease in high-skilled work	-5% to 5% increase or decrease
	-1. Moderate decrease in high-skilled work	-5% to -10% decrease
	-2. A large decrease in high-skilled work	More than -10% decrease

Total employment

	Data analysis	
X	2. A large increase in total employment	More than 10% increase
	1. Moderate increase in total employment	5% to 10% increase
	0. A negligible increase or decrease in total employment	-5% to 5% increase or decrease
	-1. Moderate decrease in total employment	-5% to -10% decrease
	-2. A large decrease in total employment	More than -10% decrease

Regional income inequalities

	Data analysis	
	2. A large decrease in global income inequalities	More than 10% decrease
	1. Moderate decrease in global income inequalities	5% to 10% decrease
X	0. A negligible increase or decrease in global income inequalities	-5% to 5% increase or decrease
	-1. Moderate increase in global income inequalities	-5% to -10% increase
	-2. A large increase in global income inequalities	More than -10% increase

Global income inequalities

	Data analysis	
	2. A large decrease in global income inequalities	More than 10% decrease
	1. Moderate decrease in regional income inequalities	5% to 10% decrease
X	0. A negligible increase or decrease in regional income ine	-5% to 5% increase or decrease
	-1. Moderate increase in regional income inequalities	-5% to -10% increase
	-2. A large increase in regional income inequalities	More than -10% increase

Child labour

	Data analysis	
	2. A large decrease in child labour	More than 10% decrease
	1. Moderate decrease in child labour	5% to 10% decrease
	0. A negligible increase or decrease in child labour	-5% to 5% increase or decrease
	-1. Moderate increase in child labour	-5% to -10% increase
X	-2. A large increase in child labour	More than -10% increase

Forced labour

	Data analysis	
	2. A large decrease in forced labour	More than 10% decrease
	1. Moderate decrease in forced labour	5% to 10% decrease
	0. A negligible increase or decrease in forced labour	-5% to 5% increase or decrease
	-1. Moderate increase in forced labour	-5% to -10% increase
X	-2. A large increase in forced labour	More than -10% increase

Figure 5: Five point Linkert scale of six social midpoint indicators

According to the reports from WP4, only the six quantitative indicators should be grouped to be further used in the (overall) sustainability assessment, as the endpoint social well-being indicator. The results of this aggregation into a single score can be seen in Table 6. The normalization and weighting factors used are based on reports from WP4. The results can also be analyzed in an economy-wide perspective, and these results are presented in Table 7.

Table 6. Normalized values for the social indicators, based on the Exiopol model

Impact category	Values		Normalization factor	Normalized values	
	Reference	Prospective		Reference	Prospective
Knowledge-intensive jobs (hours/FU)*	4.05E+00	3.92E+00	1.95E+02	-2.08E-02	-2.01E-02
Total employment (hours/FU)*	2.19E+01	2.73E+01	8.98E+02	-2.44E-02	-3.04E-02
Regional income inequalities (GDP difference between OECD and non-OECD countries)	-8.52E+02	-8.35E+02	-2.19E+03	3.89E-01	3.81E-01
Global income inequality (GINI)**	-	-	-	-	-
Child Labour (hours/FU)	4.47E-01	6.77E-01	1.96E+01	2.28E-02	3.45E-02
Forced Labour (hours/FU)	3.31E-02	4.65E-02	2.22E+00	1.49E-02	2.10E-02
Social well-being (aggregated endpoint indicator)				6.35E-02	6.43E-02

* We multiplied the categories ‘knowledge-intensive jobs’ and ‘total employment’ by -1 because they represent another direction of preference than the other indicators.
** The GINI indicator is available only when making an economy-wide assessment (at Table 7)

With the aggregated social well-being endpoint indicator, the reference technology has better results (6.35E-02) than the perspective technology (6.43E-02), mainly due to higher child and forced labour and lower knowledge-intensive jobs for the latter, as illustrated in Figure 5 (lower values represent lower impacts).
The data obtained is sector-based, i.e., the quantitative social indicators are obtained through the sector they belong. That is probably the reason why the reference technology appeared to be a better option than the prospective technology for the knowledge-intensive jobs, child labour and forced labour (Table 5), while the prospective technology appeared to be a better option for total employment (Table 5). In other words, the agricultural sector requires more jobs (but less skilled) and is more susceptible to problems of child and forced labour. However, this can be analyzed as a limitation of this approach, since as technology advances in the

agricultural sector (which is required for the prospective technology from this case study), problems as child and forced labour and less skilled jobs should change in comparison to traditional agriculture.

Table 7. Normalized values for the social indicators, based on the Exiopol model, at an economy-wide perspective

Impact category	Values		Normalization factor	Normalized values	
	Reference	Prospective		Reference	Prospective
Knowledge-intensive jobs (hours/FU)*	7.53E+12	7.53E+12	8.98E+02	-8.39E+09	-8.39E+09
Total employment (hours/FU)*	1.63E+12	1.63E+12	1.95E+02	-8.39E+09	-8.39E+09
Regional income inequalities (GDP difference between OECD and non-OECD countries)	-1.42E+12	-1.42E+12	-2.19E+03	6.46E+08	6.46E+08
Global income inequality (GINI)	6.54E-01	6.54E-01	9.13E-11	7.16E+09	7.16E+09
Child Labour (hours/FU)	1.54E+11	1.54E+11	1.96E+01	7.84E+09	7.84E+09
Forced Labour (hours/FU)	1.95E+10	1.95E+10	2.22E+00	8.80E+09	8.80E+09
Social well-being (aggregated endpoint indicator)				1.28E+09	1.28E+09

* We multiplied the categories ‘knowledge-intensive jobs’ and ‘total employment’ by -1 because they represent another direction of preference than the other indicators.

When comparing the results of Table 6 (product-based perspective) and Table 7 (economy-wide perspective) we can see that the results changed, i.e., in an economy-wide perspective the results of the prospective technology are equal to the reference technology. This does not have to do solely with the inclusion of the GINI indicator in the economy-wide perspective, but it seems that when the latter perspective is used, the differences between the reference and the prospective technologies are negligible (as in the prosperity impact assessment, which is also economy-wide based). This is important to highlight the differences when making the assessment through changes at product level or at economy-wide level.

2.3.6. Integration

For the integration we used the results of Table 1, Table 2, Table 3, and Table 4, after dividing them with their normalization factors, and the results of Table 6 (which is already normalized in the last two columns). Regarding the normalization factors, we used data provided from WP3 for the Prosperity and Human health (occupational) impacts, and the normalization factors from Recipe methodology (Goedkoop et al. 2010), for Human health (environmental), Natural environment, and Exhaustible resources. For the three latter we chose not to use the normalization factors from WP3 to be consistent with the impact assessment method used, i.e., Recipe Endpoint (based on averaged hierarchist version for the World).

For the aggregation we used the proposition from WP5, i.e., showing the results in three levels: (1) At their endpoint values; (2) Making a weighted sum; and (3) Through Condorcet methodology.

* <u>At endpoint level</u>

The results at endpoint level for the five sustainability indicators can be seen in Table 8 and Figure 6.

Table 8. Normalized values at endpoint level, for the five sustainability indicators

Endpoint impact category	Reference Normalized value	Prospective Normalized value
Prosperity (*economy-wide*)	-1.25E+10	-1.25E+10
Social well-being	6.35E-02	6.43E-02
Human health	2.00E-01	2.59E-01
Natural environment	1.38E-02	1.52E-03
Exhaustible resources	6.53E-01	2.05E-01

It can be seen that the reference technology had better results for the Human health and social well-being endpoint categories. The prospective technology had better results for the natural environment and exhaustible resources. The category prosperity had a tie between the reference and prospective technologies. It is important to mention that, if the category social well-being would have been analyzed at economy-wide perspective (as prosperity), it would also be a tie.

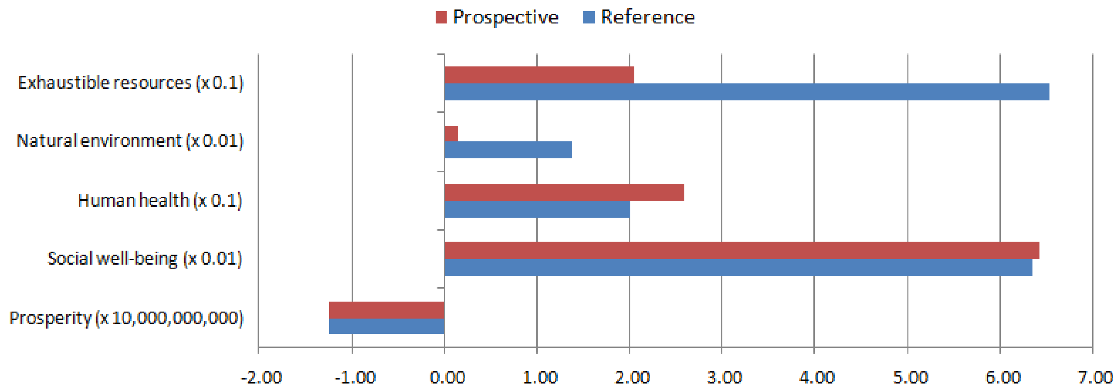

Figure 6: Normalized values at endpoint level for the five sustainability indicators

- Single score through weighted sum

The results as single score based on weighted sum can be seen in Table 9 and Figure 7. It is important to mention that with this method (weighted sum) the lowest (final) value represents the best option.

Table 9. Normalized values at endpoint level, for the five sustainability indicators, and the generation of a single score result through weighting sum

Endpoint impact category	Reference Normalized value	Prospective Normalized value	Weighting factor (based on WP5)	Reference Final value (after normalization and weighting)	Prospective Final value (after normalization and weighting)
Prosperity (*economy wide*)	-1.25E+10	-1.25E+10	0.10	-1.25E+09	-1.25E+09
Social well-being	6.35E-02	6.43E-02	0.25	1.59E-02	1.61E-02
Human health	2.00E-01	2.59E-01	0.30	6.01E-02	7.78E-02
Natural environment	1.38E-02	1.52E-03	0.25	3.46E-03	3.80E-04
Exhaustible resources	6.53E-01	2.05E-01	0.10	6.53E-02	2.05E-02
Single score				-1.25E+09	-1.25E+09

Through this aggregation technique the prosperity impacts showed a very high contribution in the final single score result, since it could only be assessed at an economy-wide perspective. Because the impacts on prosperity were similar in the reference and prospective technologies, the final results were very close (1.25E+09). However, if we analyze in more detail, we can see that the prospective technology has a small advantage over the reference technology (Figure 7 and Table 9), in the order of the 11^{th} decimal place. This is mainly due to lower impacts on exhaustible resources and natural environment from the prospective technology, which were able to compensate its higher impact on human health and social well-being (as previously mentioned).

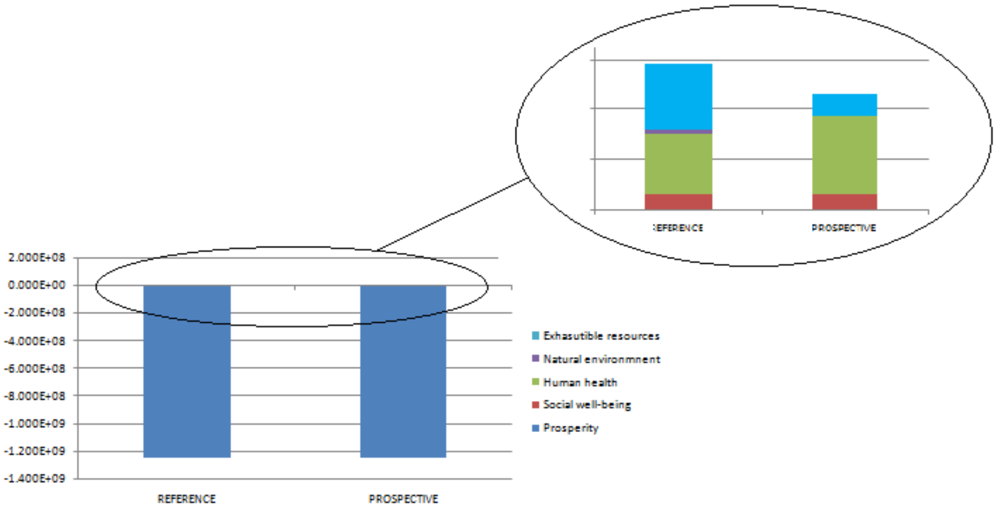

Figure 7: Single score results for the reference and prospective technologies through weighting sum, with a closer overview on the differences between them for four impact categories

As it can be seen, the single score through weighting sum was highly influenced by the results of the prosperity. This is because we aggregated results on economy-wide perspective (from the latter) with product-based perspective (other categories). Therefore, we recommend using weighting sum only when performing the impact assessment with the same perspective (i.e. economy-wide or product-based) for all impact categories.

Another approach could be to represent solely the differences between prospective and reference technologies, through the weighting sum. In this way, the different approach used in the Prosperity assessment (done at an economy-wide level) would not influence the final results. The results can be vizualized in Table 10 and Figure 8, where a negative value means a positive impact with the introduction of the prospective technology, and a positive value means the opposite.

Table 10. Single score through weighting sum by analyzing solely the differences between prospective and reference technologies

Endpoint impact category	Reference Normalized value	Prospective Normalized value	Absolute difference (prospective - reference)	Weighting factor (based on WP5)	Final value of the differences (after normalization and weighting)
Prosperity	-1.25E+10	-1.25E+10	0.00E+00	0.10	0.00E+00
Social well-being	6.35E-02	6.43E-02	7.85E-04	0.25	1.96E-04
Human health	2.00E-01	2.59E-01	5.90E-02	0.30	1.77E-02
Natural environment	1.38E-02	1.52E-03	-1.23E-02	0.25	-3.08E-03
Exhaustible resources	6.53E-01	2.05E-01	-4.48E-01	0.10	-4.48E-02
Single score					**-3.00E-02**

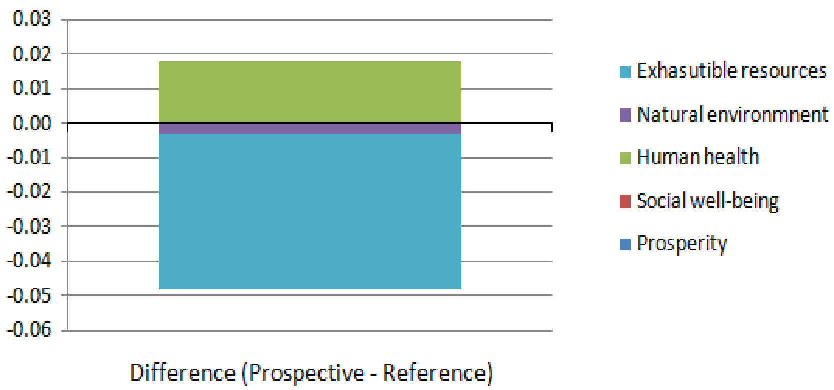

Figure 8: Single score results for the reference and prospective technologies through Condorcet

In this way it is easier to visualize that the prospective technology has better results for the final weighted score (-3.00E+-02). The improvements on natural environment and exhaustible resources outweighed the worse results on human health and social well-being. By analyzing solely the difference between the prospective and reference technologies through the weighting sum seemed to produce consistent results independently if the assessment was done at product-based or economy-wide perspectives.

- <u>Single score through Condorcet methodology</u>

The results as single score based on the Condorcet methodology can be seen Table 11 and Figure 9. It is important to mention that through this technique, the highest value is the best option (the opposite of the weighted sum).

Table 11. Normalized values at endpoint level, for the five sustainability indicators, and the generation of a single score result through Condorcet (1 = best option; 0 = worst option)

Endpoint impact category	Reference	Prospective	Reference	Prospective	Weighting factor (based on WP5)	Reference	Prospective
Prosperity	-1.25E+10	-1.25E+10	1	1	0.10	0.10	0.10
Social well-being	6.35E-02	6.43E-02	1	0	0.25	0.25	0
Human health	2.00E-01	2.59E-01	1	0	0.30	0.30	0
Natural environmnent	1.38E-02	1.52E-03	0	1	0.25	0	0.25
Exasutible resources	6.53E-01	2.05E-01	0	1	0.10	0	0.10
TOTAL						0.65	0.45

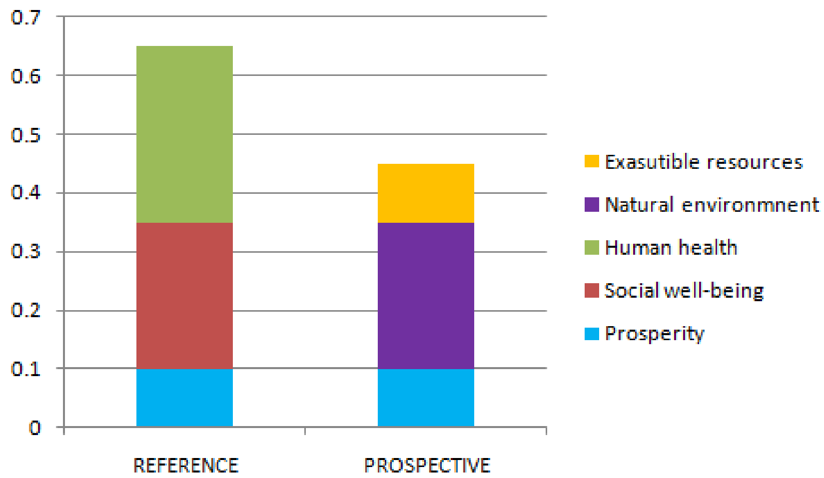

Figure 9: Single score results for the reference and prospective technologies through Condorcet

For the Condorcet aggregation approach the reference technology was the best option. This is because through this approach the degree at which one option is better than the other is not taken into account, as in the weighted sum. Thus, because the reference technology was a better option for human health and social well-being, with weighting factors of 0.30 and 0.25 (and the prosperity was a tie), that was the best option in an overall single score result. As it can be seen, through the Condorcet methodology the final results were not mainly influenced by the Prosperity impacts, and the differences between the two technologies was clearer. Therefore, it is important to mention that an advantage of the Condorcet over the weighting sum is that it does not matter if the assessments of the different endpoint categories were done in different perspectives (product-based or economy-wide), since the final score is obtained by comparisons at each endpoint category at a time.

2.4. Conclusions

After analyzing the five endpoint indicators we can see that the prospective technology had better results in two of them (natural environment and exhaustible resources) and the reference technology had better results in other two (social well-being and human health), while in the category prosperity there was a tie. With the integration methods proposed, the prospective technology can be considered as the best option for the weighting sum, but for the Condorcet the reference technology is the best option.

The proposed sustainability assessment methodology by the Prosuite project, with five endpoint indicators, appeared to be applicable in our case study. With that we could generate information regarding the three pillars of sustainability, in an integrated way.

However, these results should be analyzed with care, since this is a case study used to test the methodology proposed by the Prosuite project, and currently it has some issues that need to be highlighted:

- The environmental assessment had to be done through the Recipe methodology, since the characterization factors of WP3 were not yet available. In this sense, the results presented in this report may be different when using the characterization factors of WP3;
- Since we used the Recipe methodology for the environmental assessment, we also used their normalization factors (also because the normalization factors from Prosuite were not yet available), while for the other endpoint indicators we used normalization factors from Exiopol. In this sense, there might be some inconsistency in the integration section because we used normalization factors from different sources (Recipe and Exiopol);
- We chose to make the social well-being assessment at product-based perspective (i.e., not at economy-wide perspective). Therefore the GINI indicator was not included, but (at economy-wide) it presented the same values for the reference and prospective technologies;
- The assessment was hybrid, i.e., it was sector-based for prosperity, social well-being and human health (occupational), and process-based for exhaustible resources, natural environment, and human-health (environment). This allows some inconsistencies with the level of details for each endpoint category;
- The aggregation based on weighting sum was strongly influenced by prosperity due to the results being represented only at economy-wide perspective. Therefore it is important to highlight that the weighting sum should be done solely to the difference between two technologies, and not for their results separately (as it seems that prosperity impacts can be assessed only at economy-wide perspective);
- On top of that, we would like to make it clear that these results are rather to test the prosuite methodology. The results of this case study may be different from what is presented in this report after some issues are solved.

Moreover, it is important to mention that the application of this case study was not done through OpenLCA software, but through excel (for social, economic, occupational human health, and the integration) and Simapro (for the environmental assessment).

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3. Case study 3: Bio-based versus synthetic resins for paint

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3.1. Goal and scope of the case study

3.1.1. Scientific background and description of the case study

In this case study, an assessment is made of biobased and synthetic resins. Resins are used as binders in paints. Together with pigments, solvents and additives they form the paint. The study has been performed in cooperation with DSM resins (NL), who provided most of the data. DSM resins produces a wide range of resins that can be classified into acrylic resins, polyurethane resins and alkyd resins. Alkyd resins can be further subdivided into solvent-based alkyd resins as well as water-based alkyd emulsions.

Alkyds are products made from an alcohol and an acid or acid anhydride, hence the name alkyd, alcohol and anhydride. Alkyds consist of three major components; a polyhydric alcohol (also called poly-alcohol or polyol), an acid anhydride and a vegetable oil or fatty acid (Häussinger et al., 2007; Seidel, 2001). The most commonly used poly-alcohols are pentaerythritol and glycerol. Phthalic and maleic anhydride are the most commonly used acid anhydrides and soybean oil (and fatty acids) are used in the majority of the alkyds made, although numerous other natural oils can be used (Häussinger et al. 2007; Seidel, 2001). Alkyds as such are highly viscous products. A diluent or thinner is added to make the product easier to handle. In a solvent-based alkyd around 10% diluent is used and in a water based alkyd the alkyd is emulsified with water. The vegetable oil or fatty acid that is used makes them (partly) biobased products and as such they have been chosen within Prosuite as a biorefinery case study.

Acrylic resins are made out of acrylates or methacrylates. These acrylates and/or methacrylates are then polymerized to form an acrylate ester, which has the general formula C3H3O2R were R is an alkyl group. The structure is shown below;

CH2 = CH - (C = O) - OR

Methyl-, ethyl-, n-butyl- and ethylhexyl acrylate are the most commonly produced acrylates, whereas methyl and n-butyl methacrylate are the most important methacrylates produced (Häussinger et al., 2007)

Polyurethanes are actually a group of very diverse products, with different compositions and correspondingly different characteristics (Häussinger et al., 2007). They have in common though that they are all produced by a polyaddition process. The common principle behind this process is shown below;

R - N = C = O + H - O = R → R’ - NH - (C = O) - O – R’

This reaction is one between an isocyanate and an alcohol and is the most common one. The reaction can however also occur between an isocyanate and an amine or between isocyanate and an organic acid.

In the public debate, resins and paints are surrounded by controversies and misconceptions. For example, water-based paints are believed to be less harmful for human health, simply because they use water as a solvent. The influence of other substances in the paint is then neglected and only a full assessment of all stages in the life cycle can reveal what the real impact on humans and the environment is. Also, it does not go without saying that biobased resins have lower impacts on the environment, simply using biobased feedstocks. Some assessments of paints have been conducted in the past (e.g Oliveira and Song (2011) and Besamusca (2010)). These studies mainly concerned environmental aspects. Recently, the European coatings branche organisation CEPE has started a project for the life cycle inventory of raw materials for coatings that has resulted in a database with some 300 raw materials, representative for the entire coatings industry. A special tool has been developed to estimate the 'eco-footprint' of different types of paints (CEPE, 2013)

In this study, we will perform a full sustainability assessment of two novel alkyd resins and compare them with an older alkyd resin, with an acrylic dispersion and with a polyurethane dispersion. The methodology for the sustainability assessment has been developed in the European Prosuite project (Prosuite, 2009) and covers the environmental, economic and social domain, in industry often referred to as people (i.e. social), planet (i.e. environmental), profit (i.e. economy) or the 'triple-bottom-line' (Elkington, 1994). As set out in a paper by Blok et al. (2013), such a triple bottom line has some disadvantages mainly related to overlaps of midpoint indicators across the three domains. Therefore a five-pillar approach is proposed and as such applied in this sustainability assessment. It covers the following endpoints:

1. Impact on human health
2. Impact on natural environment
3. Impact on exhaustible resources
4. Impact on prosperity
5. Impact on social well-being

In this study, we will present results for each of these five endpoint categories and combine them into an overall sustainability assessment. The methodologies for the calculation of the economic endpoint is extensively described in Wood et al. (2012) and Ereev and Patel (2011). For the environmental assessment, both the Recipe methodology by Goedkoop et al. (2012) and Prosuite characterisation factors (Dong et al., 2013) have been used. The social assessment is based on the guidelines by Haaster et al. (2013).

We will now give a short overview of the functional unit of this study (1.1.2) followed by the system boundaries (1.1.3) and a case specific methodology (1.2). In Section 1.3 the results of each of the endpoints are outlined. Section 1.4 presents the conclusions.

3.1.2. Functional unit

For the impacts on human health, natural environment and exhaustible resources initially a functional unit approach is applied. In the final integration they are transformed in a technology wide scenario. The assumptions for a technology wide scenario are described in Section 1.2. The functional unit for this study is:

- Resin for covering an outdoor-area of 1 m^2 during 4 years.

Table 1 gives an overview of the different products that will be analyzed:

Product type	Product name	Supply form	Basis	Novel / conventional	Biobased /synthetic
Alkyd emulsion	Bio-new-1	57% in water	Water-based	Novel product	Partly biobased
Solvent-based alkyd	Bio-new-2	90% in aliphatic white spirit	Solvent-based	Novel product	Mainly biobased
Reference alkyd mixture	Bio-conv	85% in aliphatic white spirit	Solvent-based	Conventional product	Mainly biobased
Acrylic dispersion	Synth-1	47% in water	Water-based	Conventional product	Synthetic
Polyurethane dispersion	Synth-2	37% in water	Water-based	Conventional product	Synthetic

Table 1: Selection of products analyzed.

The amount of resin that is needed to fulfill the functional unit depends on the specific properties of the resin regarding solids content, coverage and durability. If the solid content is lower, more resin is required for similar coverage. And if the durability is lower, repaint is required after some years. The additional features that are needed to calculate the reference flows of the functional unit are listed in Table 2.

Product name	Fraction solids (wt%)	Coverage (g solids /m^2)	Durability (yrs)	Area of application	kg/functional unit
Bio-new-1	57	50	4	Outdoor, stairs and dormers	0.088
Bio-new-2	90	50	8	Outdoor, wood	0.028
Bio-conv	85	50	6	Out-/indoor, wood	0.039
Synth-1	47	50	4	Outdoor, stairs and dormers	0.106
Synth-2	37	50	4	Outdoor, stairs and dormers	0.135

Table 2: Specific properties of the various resins and resulting reference flows

3.1.3. System boundaries

The temporal scope is present technology but we have also included a scenario for 2030. The regional scope is Europe. The system boundaries are cradle-to-grave. Incineration is assumed in the waste stage.

An overview of the life cycle of biobased alkyds is shown in Figure 1 below. The production of paint is not included in this analysis. We focus on the resin only. This means that impact related to pigments, additional solvents and additives have not been taken into account nor has process energy to produce the paint. This could involve additional differences among the resins.

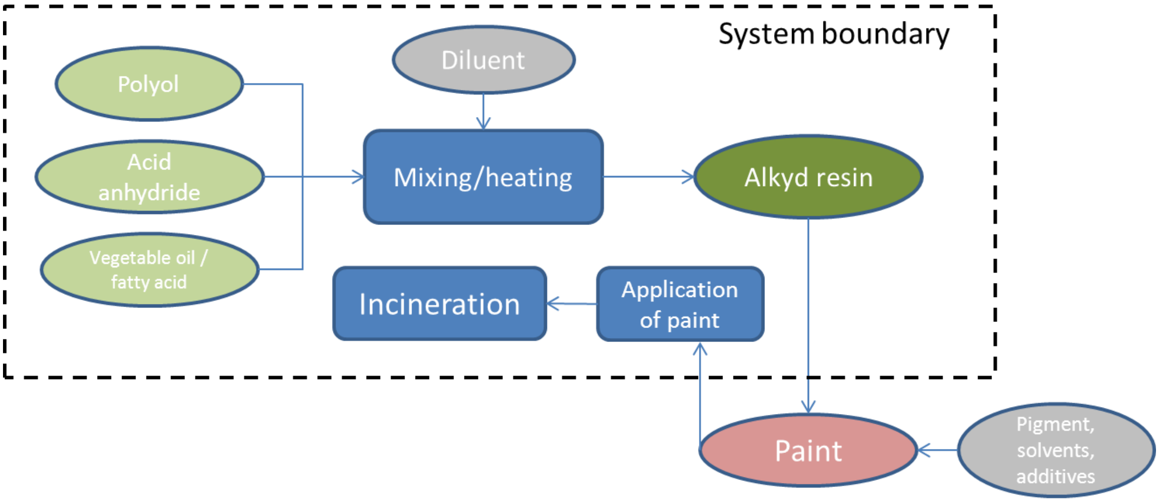

Figure 1: Flowchart of the life cycle of biobased alkyds.

3.2. Case specific methodology: estimating market shares

For the macroeconomic assessment, an estimate has to be made for future market volumes. The market volumes of the resins produced by DSM are based on data in Hofland (2012) and personal communication with the author (Hofland). Hofland (2012) provides market volumes for a variety of resins in the geographical region 'Europe, Middle East and Afrika (EEMA)'. Since we are interested in market volumes for Europe only the values have to be slightly corrected. An overview of the data and some correcting assumptions (i.e. share European market) is show in Table 3. Since it is very uncertain how the resins market will develop in the coming years, it is assumed that it will remain stable until 2030. Therefore the market volume in 2030 is assumed to be similar to the market volume in 2013 (personal communication with Ad Hofland).

Type of resin	Equivalent resin this study	Market volume EEMA 2013 (1000 tons solid)	Share European market (%)	Market price (€/ton solid)	Market volume EU 2013 and 2030 (1000 €)
High solids alkyd	Bio-new-2	100	70	2350	164500
SB alkyds	Bio-conv	105	70	4260	313110
Alkyd emulsions	Bio-new-1	100	70	8110	567700
PUD	Synth-2	125	95	4390	521312.5
Acr.disp / high end	Synth-1	140	90	3330	419580

Table 3: EU-market volumes DSM resins in 2013 and 2030.

SB: Solvent-based

PUD: Polyurethane dispersion

Acr. Disp: Acrylic dispersion

3.3. Results and discussion

3.3.1. Impact on human health

	Unit	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Env human Health	DALY	4.32E-07	2.33E-07	3.39E-07	6.68E-07	6.50E-07
Occ human health	DALY	7.62E-09	7.49E-09	6.76E-09	1.44E-08	2.95E-08
Consumer human health	DALY	1.37E-10	2.71E-10	4.59E-10	1.65E-10	2.11E-10

Table 4: Results for impact on human health

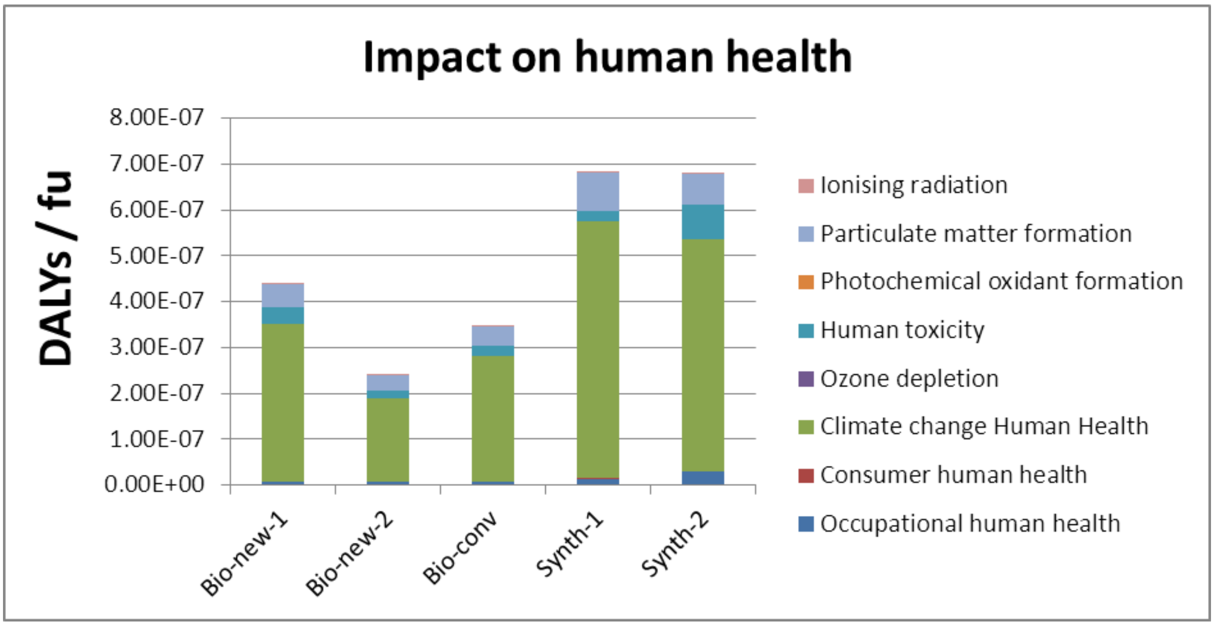

Figure 2: Results for impact on human health shown graphically

Table 4 and Figure 2 show the impacts on human health, taking into account both environmental human health, occupational human health and consumer human health. The results for this impact category show that both novel biobased alkyd resins (Bio-new-1 and Bio-new-2) have lower impacts compared to the synthetic resins (Synth-1 and Synth-2). Impacts are lowest for Bio-new-2 which are also lower compared to the reference alkyd mixture (Bio-conv). Impacts of Bio-new-2 are somewhat higher than Bio-conv. The figure also shows that impacts are dominated by impacts on environmental human health and impacts on occupational human health and consumer human health have a very minor contribution. Overall, impacts on human health are dominated by impacts on climate change. Figure 3 and 4 show the contribution of various subprocesses of Bio-new-1 and Bio-new-2 to climate change. It shows that the main contributor to climate change is the incineration of the waste after it has been disposed of. A similar pattern is also observed for the other resins.

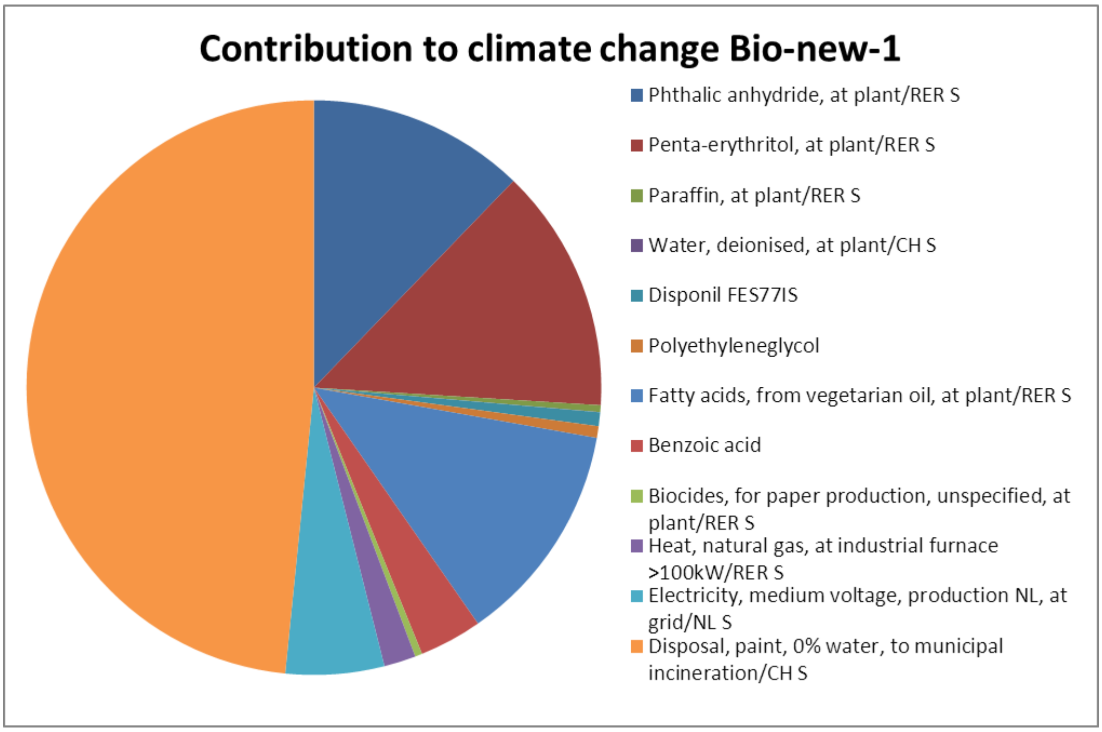

Figure 3: Contribution of various subprocesses of Bio-new-1 to climate change

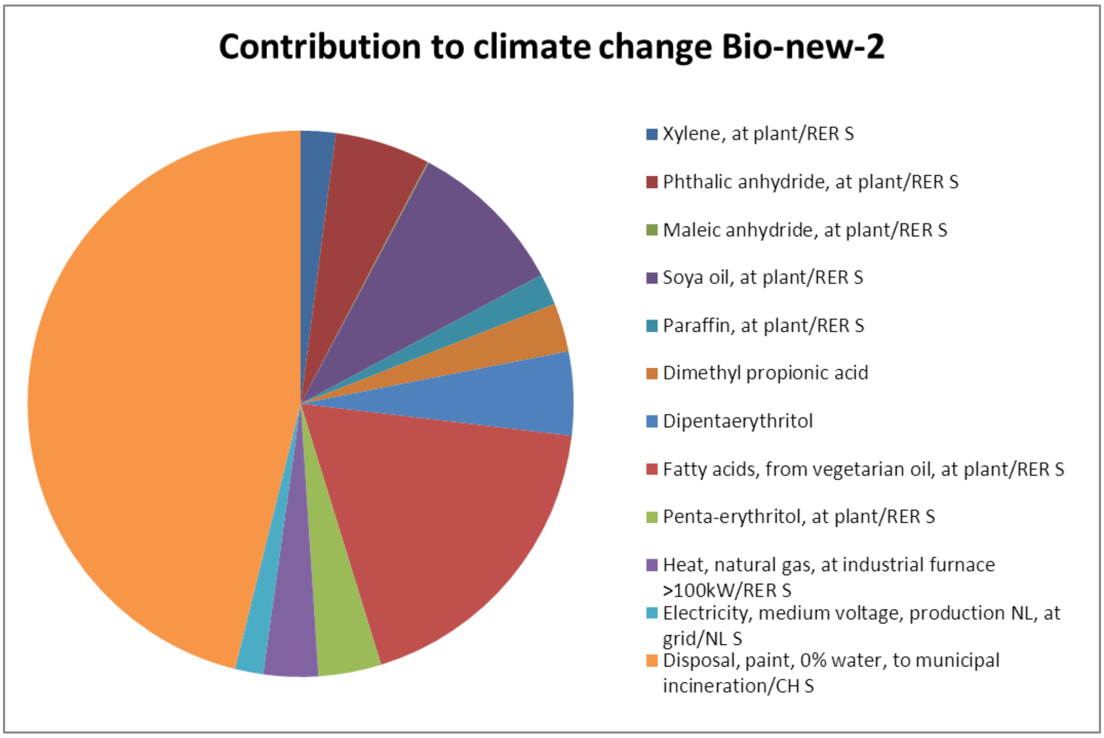

Figure 4: Contribution of various subprocesses of Bio-new-2 to climate change

3.3.2. Impact on occupation health

Figure 5 shows separately the impacts of the five resins on occupational human health. It shows that the novel biobased resins have lower impacts on occupational human health than the synthetic resins. However, compared to Bio-conv, impacts are slightly higher. The figure also shows that impacts are dominated by Injuries and Noise Induced Hearing Loss and to a lesser extent by Asthma.

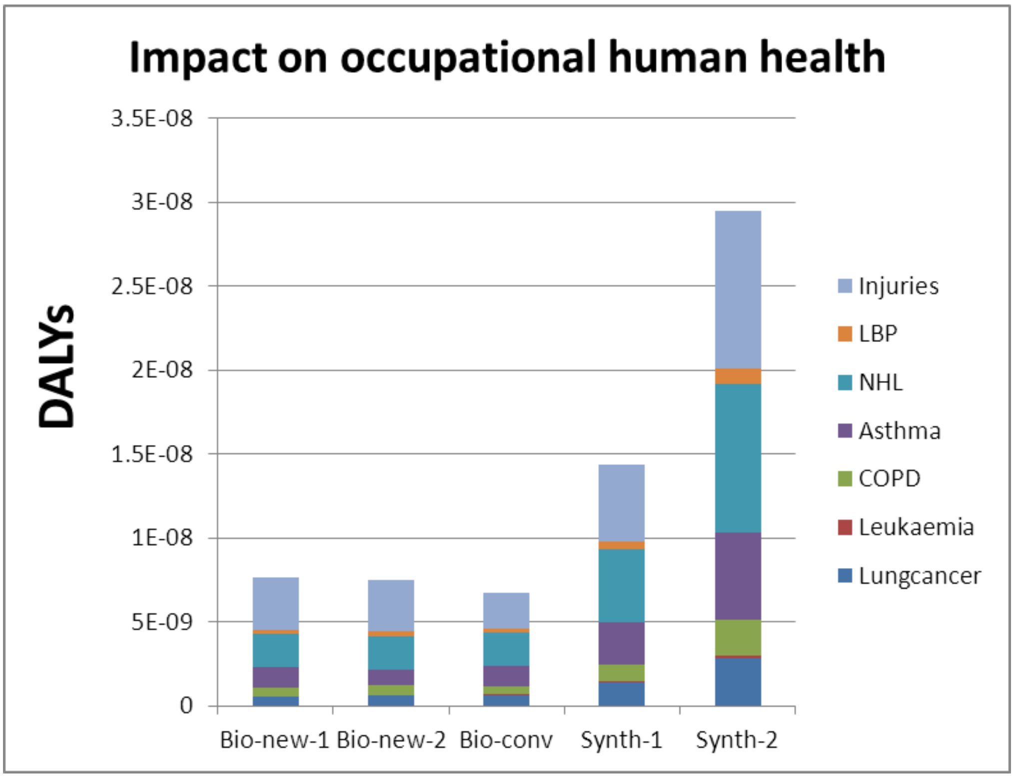

Figure 5: Impact on occupational human health of the five resins

LBP : Low Back Pain

NHL : Noise Induced Hearing Loss

COPD : Chronic Obstructive Pulmonary Disease

3.3.3. Impact on natural environment

The results for impact on natural environment are shown in Table 5 and Figure 6. It clearly shows that impacts of the biobased alkyd resins (both novel and conventional) are much higher than of the petrochemical resins. It furthermore shows that this is a result of the high impact on the midpoint category natural land transformation. This is due to the use of vegetable fatty acids in the biobased alkyd resins that are not used in the petrochemical resins. This is observed for Bio-new-2 and Bio-conv as well. The novel alkyd resins have higher impacts than the conventional alkyd resin (Bio-conv).

	Unit	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Impact on natural environment	species.yr	4.16E-08	3.20E-08	2.72E-08	3.23E-09	2.99E-09

Table 5: Results for impact on natural environment

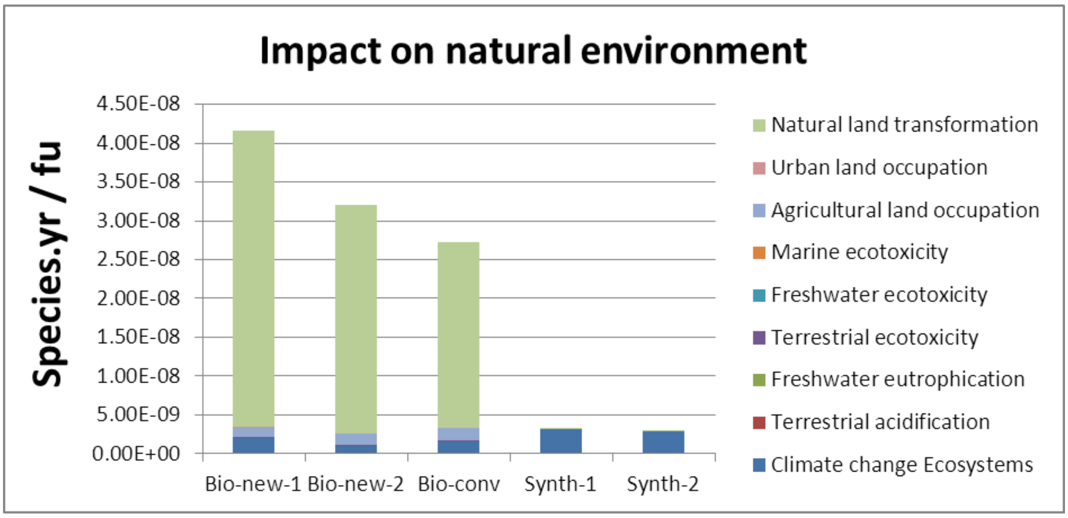

Figure 6: Results for impact on natural environment shown graphically

3.3.4. Impact on exhaustible resources

	Unit	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Impact on exhaustible resources	€	0.79	0.35	0.55	1.63	1.50

Table 6: Results for impact on exhaustible resources

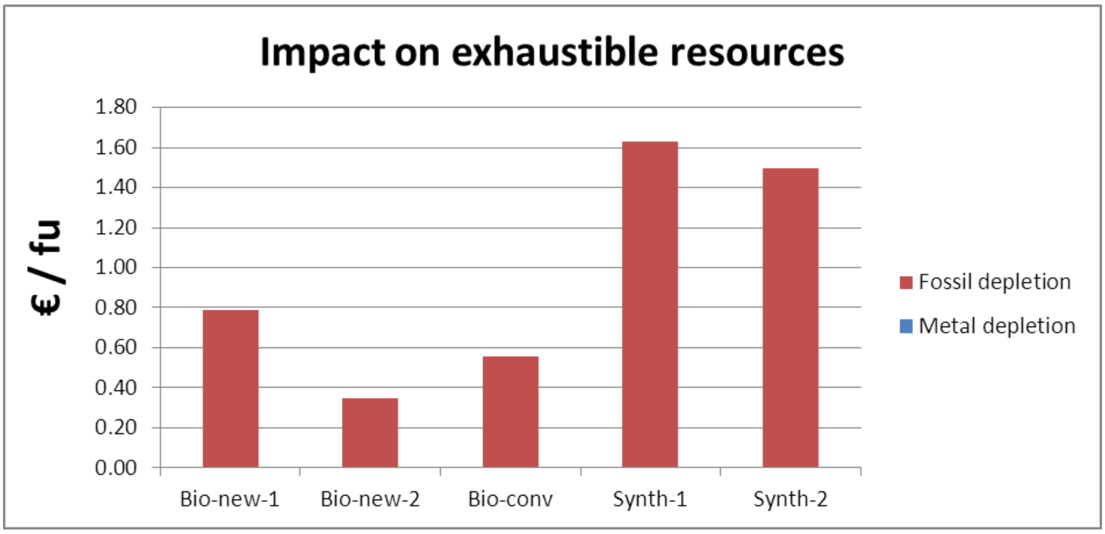

Figure 7: Results for impact on exhaustible resources

Table 6 and Figure 7 show the results for impact on exhaustible resources. It shows that all biobased alkyds have lower impacts than the petrochemical alkyds. However, Bio-new-1 has higher impacts than the conventional biobased alkyd mixture whereas Bio-new-2 has lower impacts. It also shows that the impacts on exhaustible resources are dominated by the contribution of Fossil depletion.

3.3.5. Impact on prosperity

In Table 7, detailed results are shown of the economic assessment, i.e. the impact on prosperity. Table 8 shows the impacts on GDP, both for EU and global. Tables 9a/b and 10a/b show the changes in GDP both for EU and Global. In Figure 8, the results are shown graphically for the costs per functional unit.

	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Production volume (€)	5.66E+08	1.64E+08	3.13E+08	4.18E+08	5.20E+08
Production volume (functional units)	2.59E+09	1.97E+09	3.99E+09	1.97E+09	1.29E+09
Total costs (€/fu)	0.219	0.083	0.078	0.212	0.404
Direct capital requirements (€/fu)	0.00062	0.0018	0.00240	0.00449	0.0092
Direct compensation of employees (€/fu)	0.003	0.015	0.020	0.006	0.053
Total compensation of employees (€/fu)	0.042	0.041	0.051	0.073	0.196
Import dependency–fu-%	14%	14%	14%	15%	17%
Financial risks – fu capital costs/total costs	0.28%	2.18%	3.08%	2.13%	2.29%
Total compensation of employees – full scale	5.507511 E+13	5.507497 E+13	5.507498 E+13	5.507522 E+13	5.507598 E+13
Total capital compensation – full scale	1.716884 E+13	1.716879 E+13	1.716879 E+13	1.716887 E+13	1.716902 E+13
Import dependency – full scale - €	1.596777 E+12	1.596700 E+12	1.596702 E+12	1.596810 E+12	1.597043 E+12
BW linkages – full scale	3.41	2.54	2.84	5.34	10.45
FW linkages – full scale	3.32	3.00	2.97	3.31	3.43
Structural index – full scale	467.8126	467.8129	467.8129	467.8124	467.8117
Capital productivity (€/€)	6.740250	6.740203	6.740202	6.740220	6.740234
Labour productivity (€/€)	2.10117191	2.10115688	2.10115601	2.10116171	2.10115559
Labour productivity	15,350,409	15,345,125	15,361,690	15,346,183	15,283,870

	Bio-new-1	**Bio-new-2**	**Bio-conv**	**Synth-1**	**Synth-2**
(€/hours)					
Resource productivity (€/€)	796674	796669	796669	796671	796671

Table 7: Results from the macroeconomic assessment

	European GDP – full scale - €	Global GDP – full scale - €
Bio-new-1	21415907857801	115719991805034
Bio-new-2	21416959405401	115721115883919
Bio-conv	21416979989599	115721133606265
Synth-1	21416272555827	115720325642221
Synth-2	21415233482270	115719069733210

Table 8: Results for impact on prosperity

Δ GDP (€) - EU	Bio-conv	Synth-1	Synth-2
Bio-new-1	-1072131798	-364698026	+ 674375531
Bio-new-2	-20584198.3	+ 686849574	+ 1725923131

Table 9a: Change in EU – GDP of prospective technologies compared to the reference technologies

Δ GDP (€) - EU	Bio-conv	Synth-1	Synth-2
Bio-new-1	-0.0050%	-0.0017%	+ 0.0031%
Bio-new-2	-0.0001%	+ 0.0032%	+ 0.0081%

Table 9b: Change in EU-GDP expressed as a percentage

Δ GDP (€) - Global	Bio-conv	Synth-1	Synth-2
Bio-new-1	-1141801231	-333837187	+ 922071824
Bio-new-2	-17722346	+ 790241698	+ 2046150709

Table 10a: Change in global GDP of prospective technologies compared to the reference technologies

Δ GDP (€) - Global	Bio-conv	Synth-1	Synth-2
Bio-new-1	-0.0010%	-0.0003%	0.0008%
Bio-new-2	-0.000015%	0.0007%	0.0018%

Table 10b: Change in Global-GDP expressed as a percentage

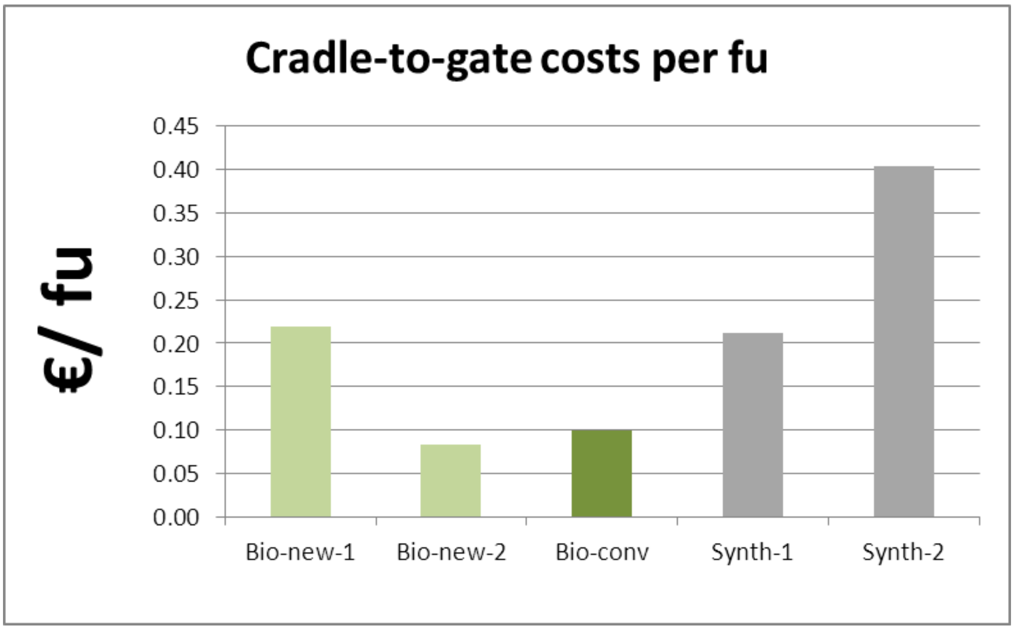

Figure 8: Cradle-to-gate costs of the resins expressed per functional unit.

Table 9a/b and 10a/b show that the novel biobased alkyds result in a decrease in GDP compared to Bio-conv (i.e. the conventional alkyd). Compared to Synth-2, however, there is an increase in GDP for both novel alkyds. Compared to Synth-1 Bio-new-1 results in a decrease in GDP, while Bio-new-2 results in an increase in GDP. Tables 9b and 10b show that the change is very minor, i.e. only a fraction of a percentage. These statements hold both for the results on European GDP as for Global GDP.

Figure 8 shows the cradle-to-gate total costs per functional unit (including profit). It clearly shows that Bio-new-2 has lower costs compared to all other resins on a functional unit base. The difference is largest compared to the petrochemical resins. Bio-new-1 has lower costs compared to Synth-2 but higher costs than Bio-conv and comparable costs as Synth-1. Table 7 shows some more detailed indicator results. It shows that for the indicator direct compensation of employees, costs are lowest for Bio-new-1. Bio-new-2 has lower costs than Bio-conv and Synth-2 but higher costs compared to the other resins. For total compensation of employees costs of all biobased resins are comparable but lower than the petrochemical resins. A similar pattern is observed for import dependency. Financial risks are comparable for all resins, with the exception of Bio-new-1 that has relatively low direct capital requirements.

Regarding backward linkages, especially the petrochemical resins show high values. This is explained by the fact that they have relatively high raw material and capital costs in comparison to the biobased resins and as such create relatively high upstream economy.

All other indicators show very comparable values and differences are observed only at the digit level.

Figures 9 to 13 show a cost breakdown of the cradle-to-gate costs of the five resins. It shows that raw material costs have a large share in the cradle-to-gate costs. Furthermore, profit has a large share, but considerably varies among the different resins. As it was confirmed by DSM, this explains to a large extent the viability of the resins. For example, Bio-conv actually has a loss (i.e. negative profit) and, hence, is gradually phased out.

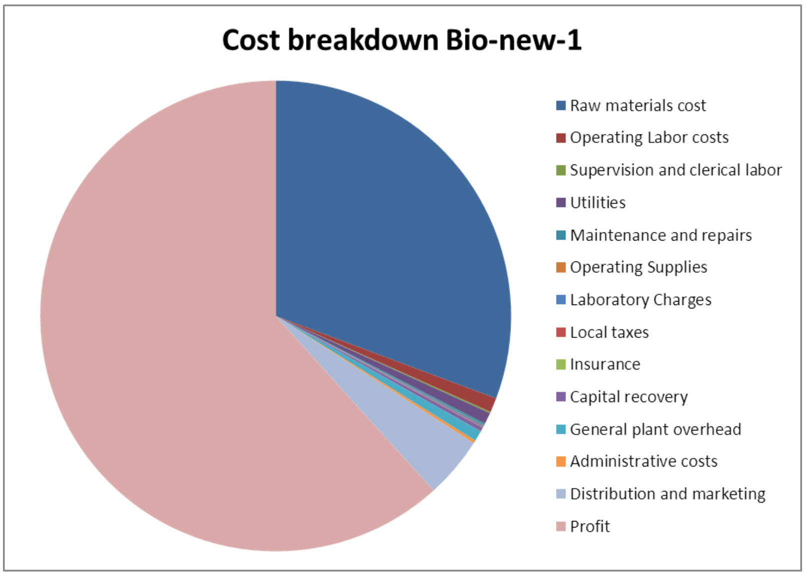

Figure 9: Cost breakdown Bio-new-1

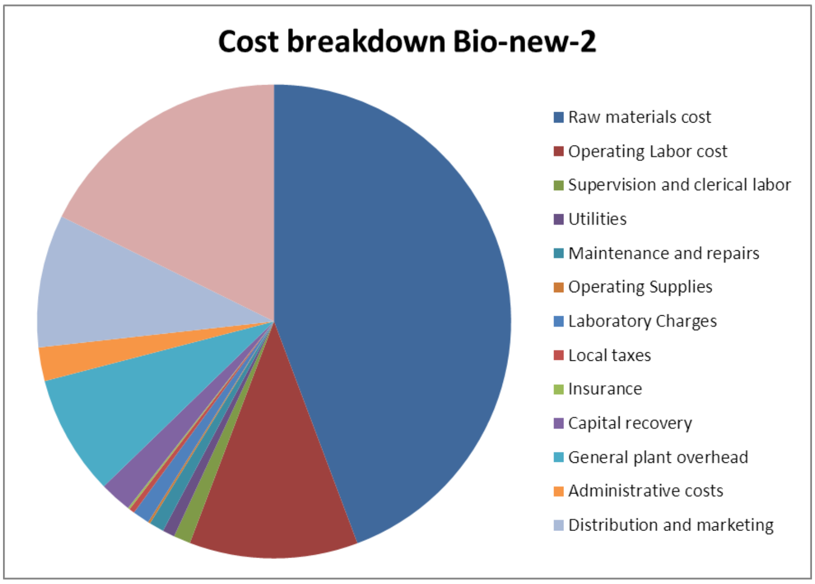

Figure 10: Cost breakdown Bio-new-2

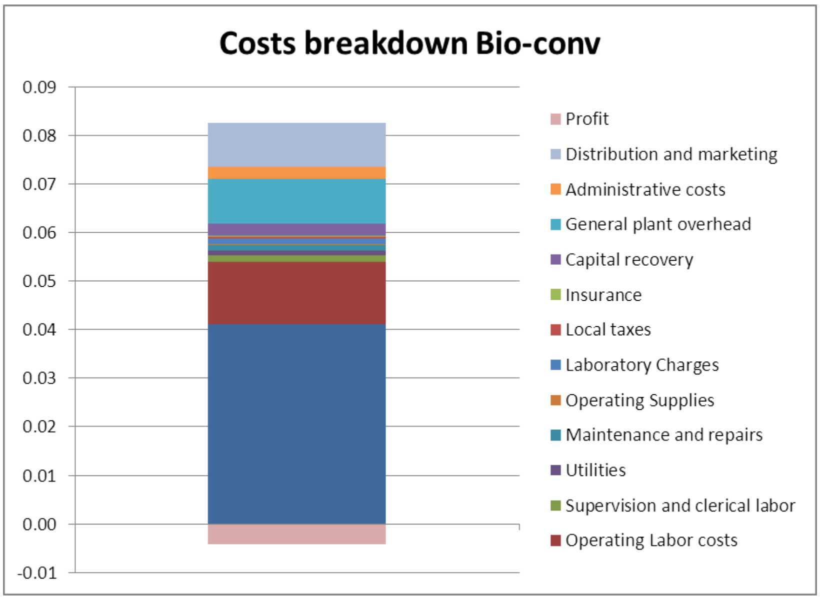

Figure 11: Cost breakdown Bio-conv

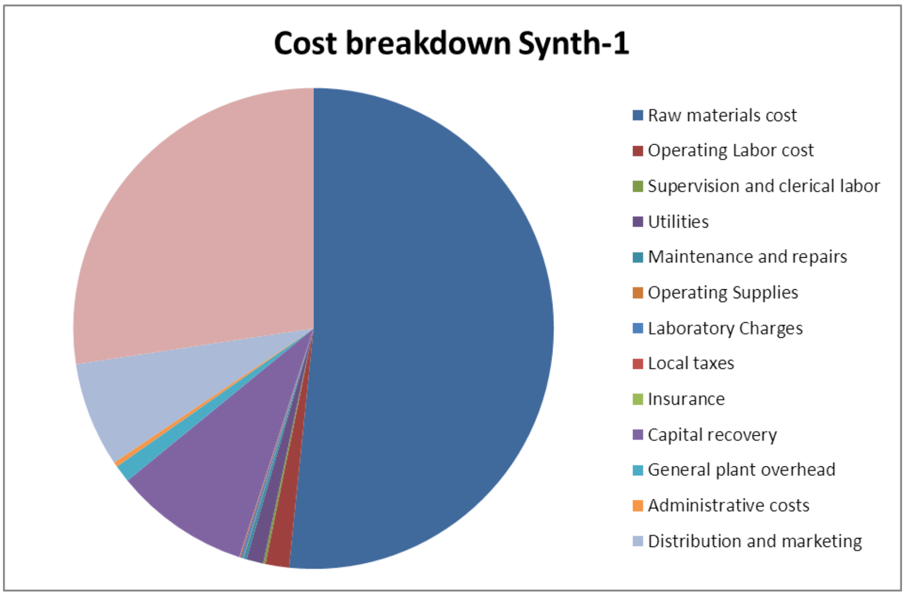

Figure 12: Cost breakdown Synth-1

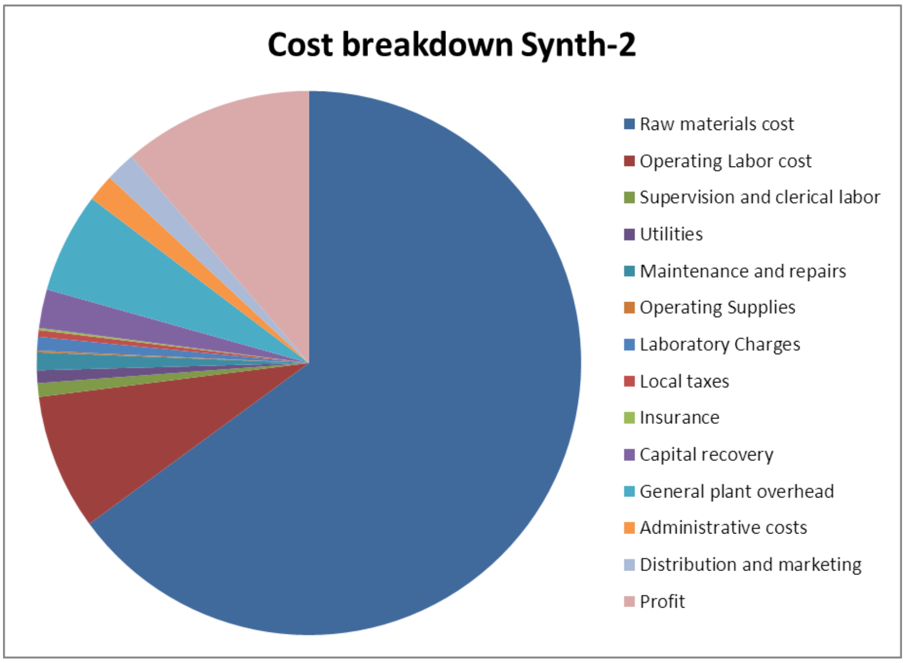

Figure 13: Cost breakdown Synth-2

3.3.6. Impact on social well being

For the determination of social impacts, partly data from the economic analysis are used. The economic indicators and the social indicators that are derived from them are shown in Table 11.

Economic indicator	Social indicator
Labour	Total employment
Labour - high skilled	Knowledge intensive jobs
Child labour - hazardous	Child labour
Forced Labour	Forced labour
GINI	Income inequalities
Δ GDP OECD/Non OECD	Regional inequalities

Table 11: Social versus economic indicators

If a European perspective is assumed, economic results as shown in Table 12 and Table 13 are obtained. Note that these results concern the entire technology in Europe (both present and future; no changes are expected – see economic analysis) and it is, hence, not per functional unit. The consequences of European market penetration for the global economy is, however, accounted for by the input-output models that have calculated the results below.

	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Labour (hours)	7538709709838	7541231994538	7533174952727	7540763735448	7571590140591
Labour high skilled (hours)	1636587932580	1637671991702	1634215633113	1637468280577	1650686029888
Child labour – Hazardous	154005901672	154027292808	153958562689	154023427215	154286594590

(hours)					
Forced labour (hours)	19511111533	19512452049	19508134587	19512211424	19528740982
GINI - Global	0.653699849	0.653699806	0.65369967	0.65370022	0.653701013

Table 12: Input data for the social assessment of the resins

	GDP OECD	GDP non-OECD
Bio-new-1	57152941192269	58569306425391
Bio-new-2	57152914966165	58568230687666
Bio-conv	57152916264343	58568217377581
Synth-1	57152952845655	58568968025475
Synth-2	57153025649138	58570129984850

Table 13: GDP results of the resins for OECD and non-OECD countries

The novel technologies are compared to the conventional technologies by taking the difference between the indicator impact of the novel technology compared the impact of the conventional technology. As a next step, it is then expressed as a percentage to estimate the decrease/increase of the impact under concern.

The results of this assessment are shown in Tables 14a to 14b below. Tables 15a to 15b show the changes in percentages. Tables 16a to 16b show the changes in GDP for OECD and non-OECD countries. As can be seen from these tables, the changes are very minor for all social impacts considered. In other words, the differences between the results are very minor compared to the absolute values.

	Bio-conv	Synth-1	Synth-2
Bio-new-1	5610348074	-2054025610	-32880430753
Bio-new-2	8132632774	+468259090	-30358146053

Table 14a: Total employment

	Bio-conv	Synth-1	Synth-2
Bio-new-1	2405915766	-880347997	-14098097308
Bio-new-2	3489974888	+203711125	-13014038186

Table 14b: Knowledge intensive jobs

	Bio-conv	Synth-1	Synth-2
Bio-new-1	47946250	-17525543	-280692918
Bio-new-2	69337386	+3865593	-259301782

Table 14c: Child labour hazardous

	Bio-conv	Synth-1	Synth-2
Bio-new-1	3012895	-1099891	-17629450
Bio-new-2	4353411	+240625	-16288934

Table 14d: Forced labour

	Bio-conv	Synth-1	Synth-2
Bio-new-1	0.00000018	-0.00000037	-0.00000116
Bio-new-2	0.00000014	-0.00000041	-0.00000121

Table 14e: Income inequalities

	Bio-conv	Synth-1	Synth-2
Bio-new-1	+ 0.07%	- 0.03%	-0.43%
Bio-new-2	+ 0.11%	+ 0.01%	-0.40%

Table 15a: Total employment

	Bio-conv	Synth-1	Synth-2
Bio-new-1	+ 0.15%	- 0.05%	- 0.85%
Bio-new-2	+ 0.21%	+ 0.01%	-0.79%

Table 15b: Knowledge intensive jobs

	Bio-conv	Synth-1	Synth-2
Bio-new-1	+ 0.03%	-0.01%	- 0.18%
Bio-new-2	+ 0.05%	0%	-0.17%

Table 15c: Child labour hazardous

	Bio-conv	Synth-1	Synth-2
Bio-new-1	+ 0.02%	-0.01%	-0.09%
Bio-new-2	+ 0.02%	0%	-0.08%

Table 15d: Forced labour

	Bio-conv	Synth-1	Synth-2
Bio-new-1	+0.000028%	-0.000057%	-0.000178%
Bio-new-2	+0.000021%	-0.000063%	-0.000185%

Table 15e: Income inequalities

Δ non-OECD/OECD	**Bio-conv**	**Synth-1**	**Synth-2**
Bio-new-1	-1064119884	-350053302	739102590
Bio-new-2	-14608262	699458319	1788614212

Table 16c: Regional inequalities (absolute)

Δ non-OECD/OECD	**Bio-conv**	**Synth-1**	**Synth-2**
Bio-new-1	-0.0009196%	-0.0003025%	0.0006387%
Bio-new-2	-0.0000126%	0.0006044%	0.0015456%

Table 16d: Regional inequalities (relative)

3.3.7. Impact on social well-being

The overall score for the endpoint on social well-being is calculated based on the formula below:

$$S_{wb} = \frac{\sum_{i=1}^{6} W_{a,i} \times \left(\frac{I_i}{N_i}\right)}{6}$$

In which:

W_i = weighting factor for indicator i

I_i = the value of indicator i

N_i = the normalization factor for indicator i

It should be noted that some indicators should be minimized (i.e. a decrease is preferable) while others should be maximized (i.e. an increase is preferable). Since the indicators are represented by the delta (i.e. difference between new and old technology) deltas of indicators that should be maximized get a positive sign (they are added) while deltas of indicators that should be minimized get a negative sign (they are subtracted) Table 17 shows which indicators are added/subtracted. It also shows the normalization- and weighting factors that are used:

	Normalization factor	**Unit**	**Weighting factor**	**Added or subtracted**

Total employment	8.98E+02	Hours	1	Added
Knowledge-intensive jobs	1.95E+02	Hours	1	Added
Regional inequalities	-2.19E+03	€	1	Added
Income inequalities (GINI)	9.13E-11	N/A	1	Subtracted
Children in hazardous labour	1.96E+01	Hours	1	Subtracted
Forced labour	2.22E+00	Hours	1	Subtracted

Table 17: Normalization- and weighting factors for the social assessment

This results in the scores for social well-being shown in Table 18. A higher score is preferable. This means that both novel resins have relatively good results compared to Bio-conv. However, compared to Synth-2, results are less good and impacts on social well-being are better for this resin. Compared to Synth-1, Bio-new-2 shows better performance, whereas this is not the case for Bio-new-1, which shows a negative delta.

	Bio-conv	Synth-1	Synth-2
Bio-new-1	2386814	-929218	-14402851
Bio-new-2	3580356	264324	-13209309

Table 18: Impact on social well-being (relative)

In the final integration step at the end of the sustainability assessment the results should not be presented as differences (i.e. deltas) between the novel and the conventional technologies, but as absolute values. Therefore, the analysis is repeated below with absolute values. Note that if GDP of non-OECD countries is subtracted from GDP of OECD countries, the resulting difference is a negative value. Since the preferable situation is that GDP of non-OECD countries increases compared to GDP of OECD countries, the difference should be as high as possible and should decrease further below zero. Since the normalization factor for this impact category is negative (and hence, a preferable negative difference would become positive) this impact category is again added. The resulting scores are listed below in Table 19 and Figure 14. As can be seen all resins perform more or less similar and differences are very insignificant. It also shows that the contribution of regional inequalities is small in comparison to the contributions of the other impact categories.

	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Impact on social well-being	-6357470533	-6351267286	-6372756197	-6351717663	-6270875865

Table 19: Impact on social well-being (absolute)

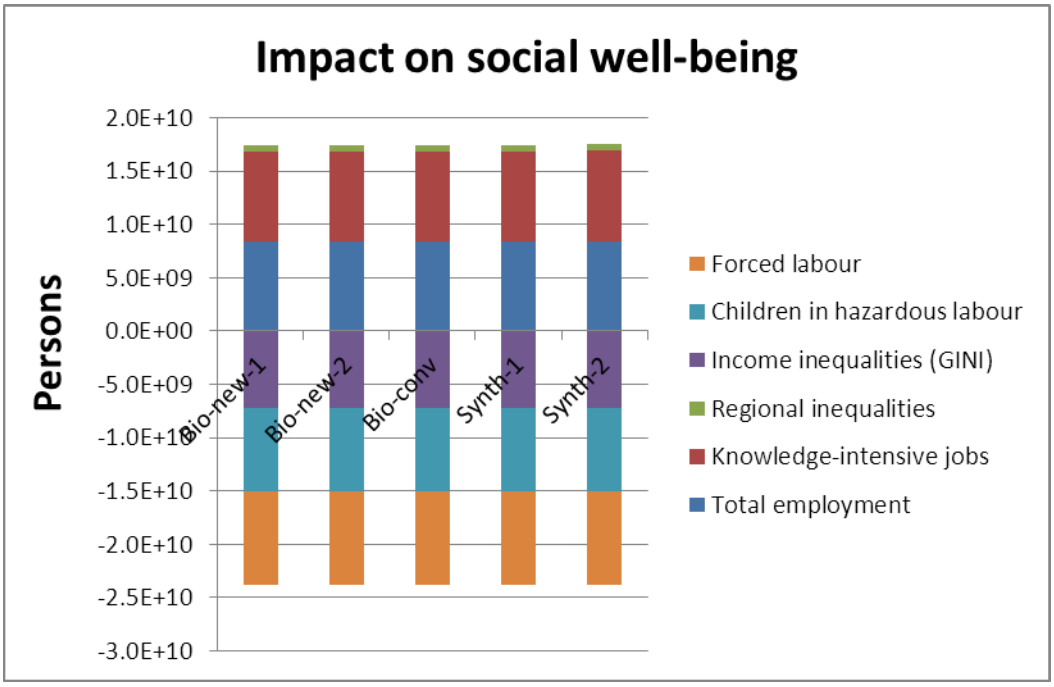

Figure 14: Impact on social well-being

3.3.8. Social indicators not related to the economic results

Some indicators are not determined based on the economic results. They are scored qualitatively using Likert scores. The Likert score is a score between -2 and +2, where -2 is least preferable and + 2 is most preferable. I case there is no difference between two alternatives, the score is 0.

Change in risk perception

The two petrochemical resins (Synth-1 and Synth-2) are both water-based. The novel alkyd emulsion (Bio-new-1) is also based on water. However the novel solvent-based alkyd (Bio-new-2), as the name indicates, is based on a solvent. Also the conventional alkyd is solvent-based. Since solvents have a risk of carcinogenity and other diseases for painters they are perceived at higher risks compared to water-based resins. This is, however, only a perception (!). The reality is that also water-based resins contain toxic components. Following the principles of the social guidance document, in which risks should be plotted to the degree they are perceived to cause high or low dread or to the degree risks are known or unknown, the results are as follows; The solvent based resins have risks that are perceived to have relatively low-dread: They concern only individuals and do not affect future generations. However, consequences can be fatal in case of cancer, but diseases occur possibly at higher age (after having worked with the paints for a considerable period). Solvent-based alkyds would be plotted somewhere half-way the dread Axis. The health effects are rather well-known based on experience from the past. This would mean that in the psychometric plot, the solvent based resins would be plotted somewhere between the lower-left and lower-right quadrant. However, compared to the water-based resins that are perceived to not have any health risks the risk perception would be significantly higher.

Possibility of misuse

The social guidance document provides a methodology for the assessment of this indicator that is based on the vulnerability of technologies to be used for misuse or terrorist attack. A set of indicators has to be scored based on expert judgement, i.e. 'accessibility', 'effort-protection design, sophistication of attack', degree of control over outcome' and 'security measures'. The novel resins are produced in a factory using a variety of material inputs. It is decided to focus on the production of resins in the factory only and not go in detail for the upstream life cycle of each of the material inputs. They are assumed to be produced in similar configurations (i.e. factories), which makes the scores for the resin factory representative for the entire life cycle. Furthermore, the novel and conventional resins are produced in the same factory, which makes the scores equal for the novel and reference technologies. Below a short support of each of the indicators and their scores is given.

Accessibility: The factories where the resins are produced are carefully secured. Entrance requires legitimation. Illegal access will only be possible by burgling which will be difficult given the security system. The score therefore is 2.

Effort-protection design, sophistication of attack: A secured and protected site is hardened to prevent damage. It requires extensive knowledge, skills and abilities to destroy, damage or steel the asset. The score is therefore 2.

Degree of control over outcome: In case the factory was attacked with, e.g. explosives or a bomb the target is almost directly harmed. In case of e.g. pyromania it is more difficult to directly harm the target. The score is estimated at 3.

Security measures: Factories are protected by security, but normally not by the army. A medium level of security is assumed. The score is 2.

Adding up these values leads to an overall score of 9. As a consequence, the likelihood of attack is 'moderately probable'. This holds both for the novel resins as for the conventional resins.

Trust in risk information

It is not expected that the introduction of biobased alkyds will change the extent to which reliable information is given in case of a hazard. Therefore, all scores are 0.

Stakeholder involvement

The novel resins are produced by the same company as the conventional resins (i.e. DSM). It is considered to be unlikely that policy on stakeholder involvement will change when shifting from one product to the other. Therefore, also for this indicator, all scores are 0.

Long-term control functions

Regarding the technologies as operated within the factory, it is expected that the novel biobased resins will be better controlled in the future compared to the conventional resins in the factories and on the market because control functions are currently improving. This was confirmed by an expert, i.e. Ad Hofland from DSM resins. However, the novel alkyd resins use third-world biobased feedstocks, i.e. fatty acids from vegetarian oil, which is produced from coconut oil, palm oil and palm kernel oil. When biobased crops are used for the production of chemical products, it means they are not available anymore as food for the local population. This would require reliable regulation to ensure that locals do not suffer lack of food or have to face increased food prices. Trust that people have in long-term control functions will therefore be higher for the conventional petrochemical resins than for the biobased resins. Table 20 shows the estimated Likert scores for the various comparisons.

	Bio-conv	**Synth-1**	**Synth-2**
Bio-new-1	+1	-1	-1
Bio-new-2	+1	-1	-1

Table 20: Long-term control functions

3.3.9. *Uncertainties*

Although a quantitative uncertainty assessment could not be made, some statements about the uncertainties is still possible. The input data for the environmental assessment (i.e. the process data that are used to calculate impact on human health, impact on the natural environment and impact on exhaustible resources) have been determined onsite at DSM. As such they can be considered rather reliable. An exception is the process energy, that had to be estimated from yearly energy statistics at DSM. Data are highly confidential, however, so it is not possible to show them in this report. The type of equipment that was used for calculating costs and macroeconomic impacts was an estimate and has not been determined on-site. However, it was checked with DSM and confirmed to be a reasonable estimate. Prices of the input materials, also needed for the microeconomic cost calculations, have been estimated by DSM, as well as future market volume predictions. Since the input data for the cost calculations are based on such estimates, the impacts that are related to the cost calculations (i.e. impact on prosperity and impact on social well-being) have highest uncertainty. However, since the differences between the five resins are so marginal, we expect the uncertainties not to influence the overall results of this sustainability assessment.

3.4. Conclusions

3.4.1. *Description of integration approaches*

In this study, the impacts on five endpoints related to sustainability have been calculated for the novel biobased alkyd resins compared to conventional resins. However, in order to ultimately judge the impact on sustainability of the various resins, the five endpoints have to be interpreted as a whole. In other words, they have to be integrated. For this purpose, two methodologies are proposed within Prosuite. The first is a compensatory approach, referred to as 'weighted sum'. The weighted sum approach aggregates the endpoint indicator values into a single indicator. The following equation is applied:

$$V_j = \sum_{i=1}^{n} v_{i,j} \times w_i$$

$$\sum_{i=1}^{n} w_i = 1$$

In which:

V_j = the aggregated score for alternative j

$V_{i,j}$ = the normalized score for endpoint indicator I for alternative technology j

w_i = the weight assigned to endpoint indicator i

n = the number of endpoint indictors (=5)

The second approach is 'outranking analysis' following the Condorcet rule. In this approach all alternatives are compared pairwise in a voting and the Condorcet winner is the candidate that beats all the others in a twosome confrontation. At the end, the amount of 'wins' are calculated for every alternative for each of the endpoints. The alternatives are then ranked accordingly. For a more comprehensive description we refer to Antunes et al. (2012).

For both approaches, we use the normalization and weighting factors listed in Table 21. For impact on social well-being, no normalization factor is available, for it has already been normalized internally. Further note that impacts on prosperity and impact on social well-being should be maximized while impacts on human health, impact on natural environment and impact on exhaustible resources should be minimized. This means that in the final integration impacts on human health, impact on natural environment and impact on exhaustible resources are subtracted, while impact on prosperity and impact on social well-being are added.

	Normalization factor	Unit	Weighting factor
Impact on human health	2.54E-02	DALY/person	0.3
Impact on natural environment	7.30E-05	Species.yr/person	0.25
Impact on exhaustible resources	7.90E+01	€/person	0.1
Impact on prosperity	9.24E+03	€/person	0.1
Impact on social well being	N/A		0.25

Table 21: Normalization and weighting factors used in the final integration

An overview of the endpoint results is listed in Table 21a and 21b. Table 21a shows the results per functional unit for the endpoint categories 'impact on human health', 'impact on natural environment' and 'impact on exhaustible resources'. The sustainability assessment, however, should be carried out technology wide. Therefore, these values are multiplied with the amount of functional units in a technology-wide scenario (see Table 7). This then results in the endpoint values from Table 21b.

	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2	Unit
Impact on human health	4.40E-07	2.41E-07	3.46E-07	6.83E-07	6.80E-07	DALY
Impact on natural environment	4.16E-08	3.20E-08	2.72E-08	3.22E-09	2.99E-09	Species.yr
Impact on exhaustible resources	0.79	0.35	0.55	1.63	1.50	€
Impact on prosperity	1.15720E+14	1.15721E+14	1.15721E+14	1.15720E+14	1.15719E+14	€
Impact on social well being	-6357470533	-6351267286	-6372756197	-6351717663	-6270875865	Persons

Table 21a: Overview endpoint results (expressed per functional unit)

	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2	Unit
Impact on human health	1.14E+03	4.74E+02	4.01E+00	1.34E+03	8.77E+02	DALY
Impact on natural environment	1.08E+02	6.30E+01	3.15E-01	6.35E+00	3.85E+00	Species.yr
Impact on exhaustible resources	2.04E+09	6.83E+08	6.43E+06	3.21E+09	1.93E+09	€
Impact on prosperity	1.1572E+14	1.15721E+14	1.15721E+14	1.1572E+14	1.15719E+14	€
Impact on social well being	-6357470533	-6351267286	-6372756197	-6351717663	-6270875865	Persons

Table 21b: Overview endpoint results (technology wide)

3.4.2. Final integration – weighted sum approach

The weighted sum approach results in the following singles score values (Table 22):

	Bio-new-1	Bio-new-2	Bio-conv	Synth-1	Synth-2
Impact on sustainability	-3.396E+08	-3.361E+08	-3.404E+08	-3.393E+08	-3.174E+08

Table 22: Weighted sum results for the five resins (unit: persons)

Figure 15 shows the contribution of the five endpoints to these results. It shows that the results are completely dominated by impact on prosperity and impact on social health, both being related to GDP. This immediately raises the question whether such weighted sum approach is suitable for the integration of the endpoints in this study. However, as such, this integration shows that the results are very similar for all alternatives and differences are insignificant.

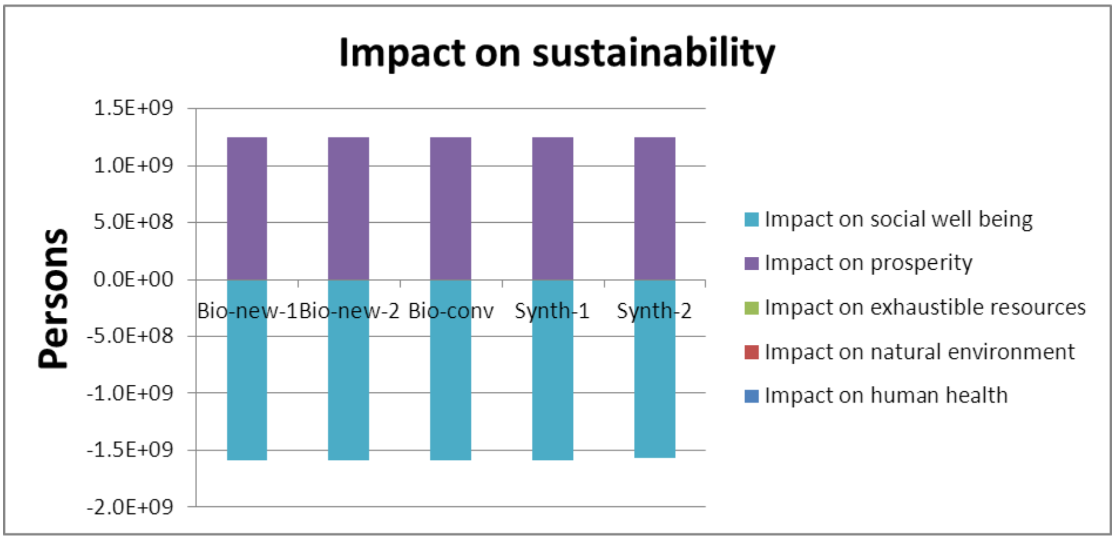

Figure 15: Impact on sustainability of the five resins following the weighted sum approach.

3.4.3. Final integration – Condorcet rule

The result of pairwise comparisons is shown in Table 23. It shows the amount of 'wins' for each of the resins and for each of the endpoints. Figure 16 shows the results graphically and also shows the contribution of the different endpoints to the final scores. The higher the score is, the better the performance on sustainability.

	Bio-new-1	**Bio-new-2**	**Bio-conv**	**Synth-1**	**Synth-2**
Impact on human health	1	3	4	0	2
Impact on natural environment	0	1	4	2	3
Impact on exhaustible resources	1	3	4	0	2
Impact on prosperity	1	3	4	2	0
Impact on social well being	1	3	0	2	4
Impact on sustainability	4	13	16	6	11

Table 23: Result of pairwise comparisons between the resins (Condorcet rule)

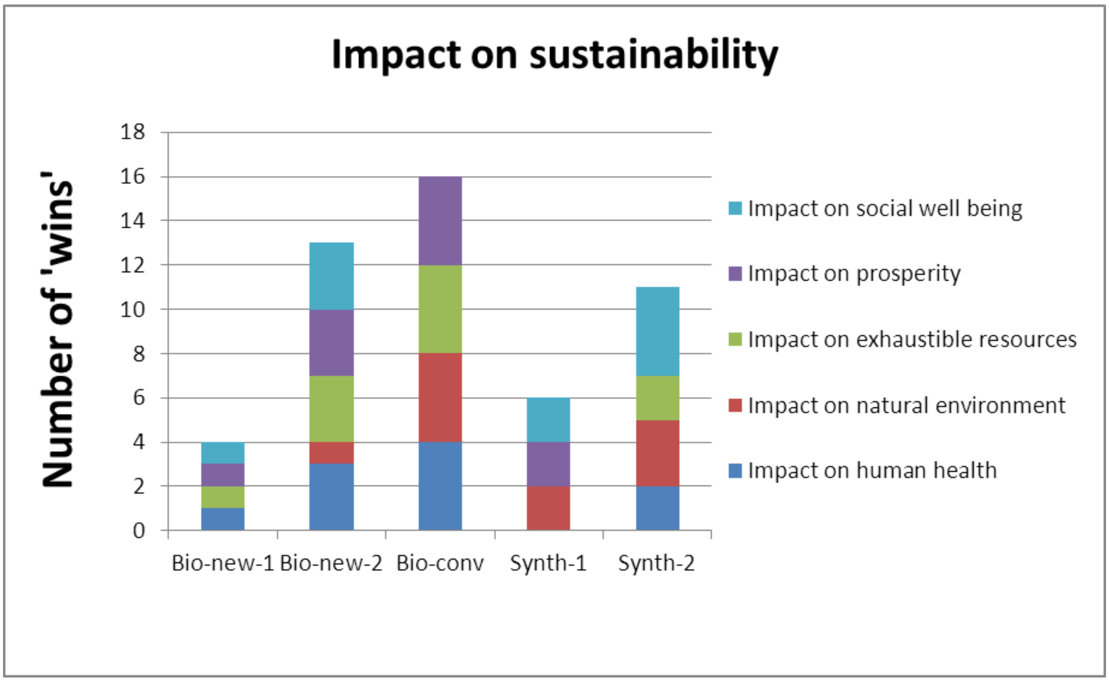

Figure 16: Results from the application of the Condorcet rule

Figure 16 shows that Bio-conv has the best performance on sustainability. Bio-new-1 has the worst performance, however, and hence is less preferable than the conventional resins. Bio-new-2 is more preferable than the synthetic resins but less preferable than the conventional alkyd resin (Bio-conv).

3.5. Overall conclusions

A sustainability assessment was conducted for five resins, produced by DSM. It concerned two novel biobased resins, one conventional biobased resin and two conventional synthetic resins. The assessment comprised impact on five endpoints, i.e. impact on human health, impact on natural environment, impact on natural resources, impact on prosperity and impact on social well-being. With respect to impact on human health, both biobased resins show better performance compared to the synthetic resins. However, Bio-new-1 has higher impacts than Bio-conv. The impacts on environmental human health dominate the impacts on human health and the contribution of occupational human health and consumer human health is negligible. With respect to impact on natural environment, all biobased resins score higher compared to the synthetic resins as a result of the high contribution of natural land transformation that is caused by the use of fatty acids. Impact on exhaustible resources is lower for the biobased resins compared to the synthetic resins. However, impacts of Bio-new-1 are higher than impacts of Bio-conv. Impact on prosperity is very similar for all resins due to the magnitude of the number. Differences are marginal. The same holds for impact on social well-being. These two endpoints dominate the sustainability assessment when a weighted sum approach is applied and as such, the result is very similar for all resins. However, if the Condorcet rule is applied, results are more different and it clearly shows that Bio-new-1 is less preferable from a sustainability point of view, whereas Bio-conv is most preferable. Bio-new-2 has better performance than the synthetic resins and Bio-new-1. However, it has worst performance than Bio-conv. Although there are considerable uncertainties, this study provides a first step towards a comprehensive sustainability assessment of resins produced with biorefineries.

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