REPORT f3 2013:23

A FUTURE BIOREFINERY FOR THE PRODUCTION OF PROPIONIC ACID, ETHANOL, BIOGAS, HEAT AND POWER – A SWEDISH CASE STUDY

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contributes to the development of sustainable fossil free fuels for transportation. The centre is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see www.f3centre.se). The report is also based on ongoing research projects financed by the Swedish Energy Agency, which we hereby acknowledge.

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SUMMARY

The overall aim of this f3-project is to assess whether energy integration of bio-based industries will contribute to improved greenhouse gas (GHG) performance, compared to biorefineries between which there is no integration or exchange of energy. Comparisons will also be made against production systems based on fossil feedstock. The biorefinery concept studied here is seen as an industrial symbiosis between one biorefinery in which straw-based ethanol, biogas, heat and power are produced and one biorefinery in which bio-based propionic acid is produced from glycerol and potato juice. The study has a Swedish perspective and the biorefinery is assumed to be located in Kristianstad in the southern parts of Sweden, due to the access to raw materials in the region.

This report also discusses and describes methodological challenges and potential solutions of how to adapt the LCA methodology to handle the specific preconditions regarding integrated biorefinery systems. In this study three different functional units (FU) are used; 1 kg of propionic acid (PRA) at factory gate, 1 kg anhydrous ethanol at factory gate and total production of PRA and ethanol in one integrated biorefinery system in one year.

A conclusion from this report is that process integration can lead to significant reductions of emissions. This is true even if results expressed per unit of a particular product within the system show an increase in emissions compared to a fossil reference product.

When the results are expressed per yearly production and include the two main products ethanol and propionic acid together, the integrated biorefinery system shows the best GHG performance. The GHG emissions will then be reduced by approximately 25%, compared with stand-alone biorefinery production, and 45% compared with integrated fossil-based biorefinery systems. The GHG performance will be further improved if the fossil natural gas assumed to be used in the biorefineries today, is replaced by biomass energy.

The different results depending on the functional unit (FU) selected show the importance of addressing this aspect in life cycle assessments of complex and integrated biorefinery systems producing several high-value products.

SAMMANFATTNING

I detta f3 projekt har vi undersökt miljöaspekterna av integration mellan bioraffinaderier i vilka propionsyra och etanol produceras i så kallad industriell symbios. Studien baseras på livscykelanalys (LCA) men har begränsats till att enbart inkludera utsläpp av växthusgaser. Studien är gjord utifrån ett svenskt perspektiv och baserat på råvarutillgång har Kristianstad i norra Skåne valts som en möjlig plats att bygga ett framtida bioraffinaderi liknande det som beskrivs i denna rapport.

I projektet behandlades även effekterna av olika metodmässiga val inom LCA vilket också beskrivs i denna rapport. I studien användes olika funktionella enheter (FE), 1 ton propionsyra respektive 1 ton etanol samt hela det integrerade bioraffinaderiets sammanlagda produktion under ett år. Förnybar propionsyra orsakade större utsläpp av växthusgaser än fossilbaserad propionsyra men etanolens miljöprestanda var signifikant bättre än bensin som den jämfördes med. Dessa resultat baseras på individuella FE, uttryckta per ton produkt. Att integrera produktionsanläggningarna i en industriell symbios medförde att de totala utsläppen för produktionen minskade vilket är positivt ur ett större samhällsperspektiv. Detta resultat baserades på en bredare FE, uttryckt per integrerat bioraffinaderi per år. En övergripande slutsats är därför att livscykelanalyser av integrerade bioraffinaderier kräver att systemgränserna expanderas i tillräcklig grad, vilket reflekteras i den funktionella enheten, så att den sammanlagda miljönyttan med industriell symbios till fullo beaktas.

CONTENTS

INTRODUCTION

The commercial interest in the development of resource efficient biorefinery systems producing multiple, high-value products, is increasing today. One reason for this is the increase in incentives for producing energy carriers and chemicals with low carbon footprint and good environmental performance. Examples of incentives are taxation of fossil fuels, the implementation of standardization systems regarding sustainability criteria for biobased fuels and chemicals, and consumers enhanced willingness to choose environmental adapted fuels and products (Höglund et al, 2013; Scarlant and Dallemand, 2011). Another reason is the enlarged competition of biomass feedstock for different purposes and between different industry sectors, leading to higher feedstock costs (see e.g. Swedish Energy Agency, 2012). To maintain profitability, biomass-based production plants and companies need to constantly improve their processes and products, e.g. by producing additional high-value products. Thus, biomass feedstock, which fulfills critical sustainability criteria, is a limited resource, which increasingly needs to be utilized in the most resource efficient way, such as in optimized biorefinery systems and plants.

Many of the biorefinery systems and plants previously described and studied are often limited to only the production of biofuels and energy carriers from a homogenous raw material, even though the concept of biorefinery can comprise even more than this. In previous studies the biorefinery concept has also often been assessed separately, but integration of plants in large industrial symbiosis systems has been given less attention even though some examples exist, see e.g. Martin and Eklund (2011), Sokka et al. 2010), Röyne et al. (2013) and Mirabella et al. (2013).

In this report, biorefineries without energy integration between them are called stand-alone plants even though they in many aspects are integrated biorefineries by themselves. In a case-study, we study a hypothetical integrated biorefinery system, using biochemical processes, from an environmental point-of-view. The outputs from the biorefinery system are liquid and gaseous biofuels, platform chemicals, and additional energy carriers. The inputs consist of food industry waste, by-products from biofuel production, and crop residues from the surrounding agriculture. No primary biomass feedstock is utilized which thereby minimize the risk of increased competition of arable land and potential indirect land use changes.

Development of biorefineries comes with several technical challenges but also the environmental evaluation of biorefinery concepts is challenging. Traditional life cycle assessment (LCA) is primarily designed for conventional production systems and not for complex, integrated production systems including multiple feedstock inputs and multiple product outputs. Therefore, there is still need for discussion of some basic methodological choices in LCA of biorefineries. In a recent report by Ahlgren et al. (2013), some methodological key issues when performing an LCA of a biorefinery system was identified and discussed. Some of these issues are summarized below.

First of all, biorefineries produce several high-value outputs rather than one main product and co-products. This means that the **choice of functional unit** is very important. The functional unit is the basis of all calculations in an LCA and the unit on which the environmental impact is expressed. For bioenergy products, it could be 1 MJ or kWh, while for bio-materials it could be 1 kg active ingredient of a specific biochemical product. For a biorefinery producing several functions, choice of functional unit is less obvious. It could even be the case that additional functional units are needed for the same study.

Furthermore, the environmental impact somehow has to be divided over the high-value products. This can be done either by **allocation or by systems expansion** (e.g. Finnveden et al., 2009). Allocation means dividing the impact based on physical or economic properties of the products. Systems expansion means that the study is expanded to include the effects the products will have on other production systems. As Cherubini et al. (2011b) point out, this choice is critical for the outcome. However, if there are many output products, as in a biorefinery system, system expansion requires many assumptions and much data collection, which is a time-consuming task. The many assumptions can also increase the uncertainty of the results. In some cases, economic allocation is preferred.

Other very important issues are the **system boundaries**, whether to use average or marginal **input data**, and the **time perspective** used.

Further, the LCA-methodology connected specifically to biomass use has gone through much development, but still faces some issues. For example, during recent years there has been intensive debate on how to include **land use changes** in the LCA-calculations (Sanchez et al., 2012). Another issue currently being discussed is how to treat the timing of sequestration and emission of **biogenic carbon**. For biorefinery systems this applies both for the raw material, e.g. the carbon in living biomass and soil, and for the products, e.g. production of bioplastics that will not be combusted for a number of years.

It is outside the scope of this project to explore all these issues, however we do include different functional units in the results, and we return to the methodological issues in the discussion.

1.1 AIM AND OBJECTIVES

The overall aim is to assess whether energy integration of bio-based industries will contribute to improved greenhouse gas (GHG) performance, compared to biorefineries between which there is no integration or exchange of energy. Comparisons are also made against production systems based on fossil feedstock.

A second aim of this report is to discuss and describe methodological challenges and potential solutions of how to adapt the LCA methodology to handle the specific preconditions regarding integrated biorefinery systems.

This report is intended to be useful for LCA practitioners since it provides an example of a new and a more complex system and which methodological issues that could be encountered. It can also be useful in strategical discussions among potential investors regarding further development of biorefineries into more integrated concepts.

METHODS AND ASSUMPTIONS

1.2 SYSTEM DESCRIPTION

The biorefinery concept studied here is seen as an industrial symbiosis between one biorefinery in which straw-based ethanol, biogas, heat and power are produced and one biorefinery in which bio-based propionic acid is produced from glycerol and potato juice. Glycerol is a by-product generated in an existing biodiesel plant (producing rape methyl ester, RME), whereas the potato juice is a waste product in an existing plant producing starch from potato. The two biorefineries that are part of the industrial symbiosis have been described in previous studies; the production of propionic acid from glycerol has been studied by, among others, Ekman and Börjesson (2011), Dishisha et al. (2012) and Tufvesson et al. (2013). Production of second generation ethanol from agricultural residues has been widely studied by numerous researchers but the particular production system in this study refers to the ones described by Ekman et al. (2013), Börjesson et al. (2013). The stand-alone and integrated biorefinery systems are shown in Figures 1-3.

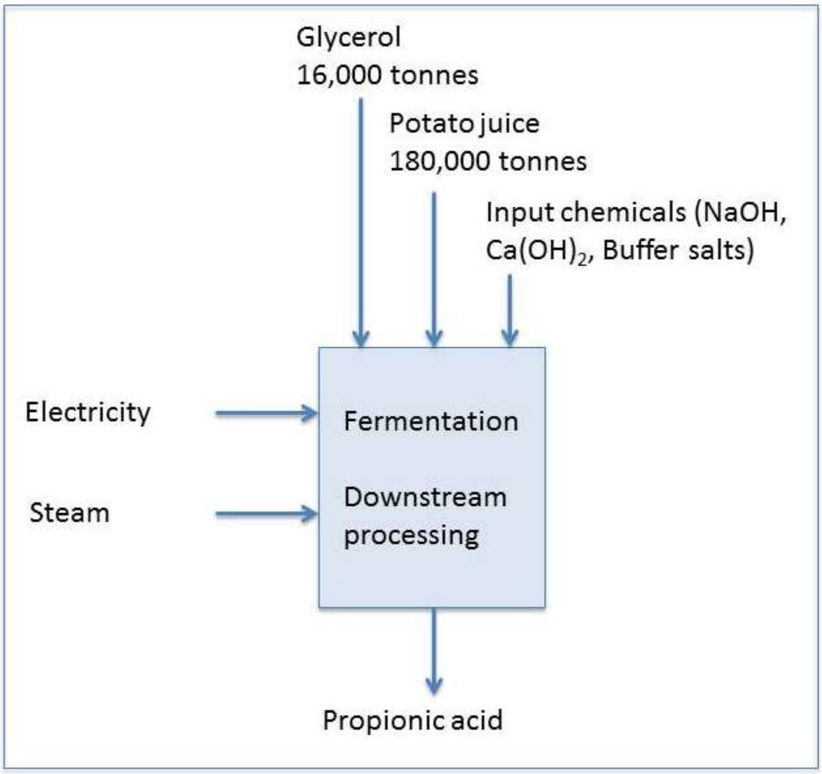

Figure 1. Stand-alone biorefinery for production of propionic acid from glycerol

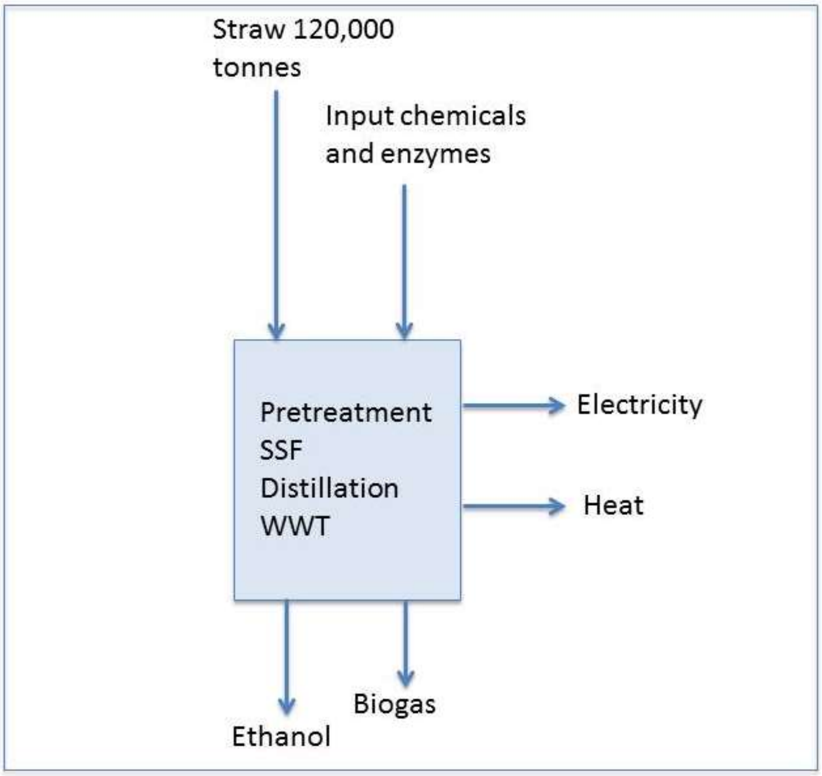

Figure 2. Stand-alone biorefinery for production of straw-based ethanol

In the ethanol plant, excess heat is produced that could be sold to, for example, a district heating system. However, the demand for district heat is both limited and seasonal. Improved energy efficiency in buildings as well as a warmer climate is estimated to reduce the demand for district heating in Sweden in the future. In addition to this, a large fraction of district heat sold in Sweden is generated from, for example, waste incineration or waste heat from other industries and should in those cases not be replaced. The PRA process on the other hand is highly dependent on energy production from external sources and can be used as a heat sink if integrated with the ethanol plant.

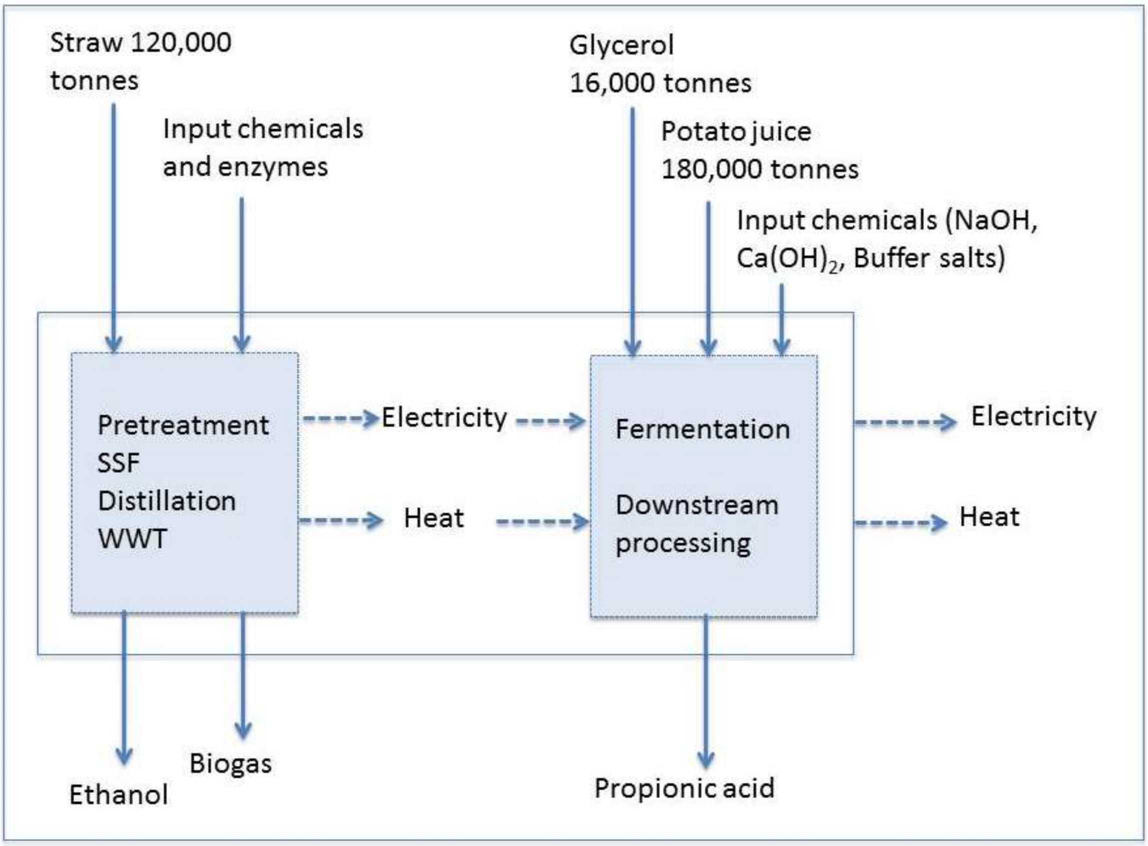

Figure 3. Integrated biorefinery system for production of propionic acid and ethanol

However, the heat that is produced in the ethanol plant is of lower quality than is required for the production of propionic acid. Based on Rosen (2013) it is assumed that the energy quality of steam is three times the energy quality of district heat and thus is only 1/3 of the energy embedded in the hot water from the ethanol production possible to utilize in the propionic acid plant. The remaining energy required must be provided by another energy source, here assumed to be natural gas, as it is in the stand-alone system. In the stand-alone system also electricity is assumed to be generated from natural gas as in Tufvesson et al. (2013).

As described previously, the raw material for the production of propionic acid is glycerol and potato juice. In Sweden biodiesel is mainly produced from rapeseed (RME) and the glycerol received in the existing process is of high purity and is thus suitable for use in further processes such as fermentation. However, a decrease in the production of glycerol is possible and the use of other substrates will also be possible for the production of propionic acid. A reason for the decreased availability of glycerol is the decreased production of biodiesel in Europe last years (European Biodiesel Board, http://www.ebb-eu.org/stats.php; http://blogs.nature.com/news/2013/09/european-parliament-votes-to-limit-crop-based-biofuels.html) The environmental and techno-economic effects of changing substrates were studied in a previous study by Tufvesson et al. (2013) and is not further included in this study.

Potato juice is a by-product from the production of potato starch. It is the liquid fraction that remains after starch, potato pulp and potato fibres have been extracted from the potato and it is rich in nutrient salts and proteins. An alternative application for the potato juice is as fertilizer but due to regulations this use has been restricted.

The ethanol plant produces ethanol, biogas, power and heat from straw as raw material. Also C5-sugars are fermented to ethanol even though that is not yet a mature technology but may be possible in a future system. A more detailed description of the ethanol production system is given by Ekman et al. (2013).

The biorefinery is assumed to be located in Kristianstad in the southern parts of Sweden. Based on previous studies (Ekman et al., 2013; Ekman and Börjesson, 2011) Kristianstad was identified as a promising location for a biorefinery due to the access to raw materials in the region, mainly straw and potato juice, as well as a district heating system of sufficient size to utilize some of the excess heat as base load. In Sweden RME is produced in Stenungsund on the west coast and not in the Kristianstad area but since this substrate is the one with the highest density, it can be transported to longest distance both from an environmental and economic perspective. Also in the city of Karlshamn not too far from Kristianstad glycerol is produced as a by-product from an industry that processes vegetable oil into both food and industrial products.

1.3 ENVIRONMENTAL ASSESSMENT

The accounting method used is based on life cycle assessment (LCA), as described by the standards ISO 14040 and 14044 (ISO, 2006). The environmental impact is limited to emissions of greenhouse gases since this is the focus in recent policy and regulation of biofuels and bio-based products in e.g. EU (Directive 2009/28/EC and Directive 2009/30/EC). Further, this report aims to illustrate the impact on environmental performance by methodological choices such as choice of functional unit and system boundaries.

1.3.1 Functional unit

In this study three different functional units (FU) are used; 1 kg of propionic acid (PRA) at factory gate, 1 kg anhydrous ethanol at factory gate and total production of PRA and ethanol in one integrated biorefinery system in one year. The output-based FUs (1 kg propionic acid and ethanol respectively) are used to answer the questions of environmental impact of the particular products but the systems-based FU is used to answer questions about the total emissions from both systems and compared to a fossil-based reference system. By using the latter FU, the fact that PRA and ethanol are not produced in equal amounts is accounted for. The annual production of propionic acid is 10,000 tonnes and the annual production of ethanol is 35,000 tonnes.

1.3.2 Inventory

Details on the input data for the environmental assessment are given in Table 1. The propionic acid is compared to fossil-based propionic acid from Ekman and Börjesson (2011) and the ethanol is compared to petrol (Gode et al., 2011) at an energy basis. The biorefinery systems are in the base-case compared to fossil-based systems in which heat (Gode et al., 2011) and electricity (Lantz et al., 2009) are produced from natural gas. In the propionic acid plant, steam is produced from natural gas with an efficiency of fuel to steam of 76.9% according to Patel et al. (2006).

Table 1. Input data used in the calculations

Input	**Emissions**	**Reference**
Ethanol		
Straw	65 g CO_2-eq/kg DM	Börjesson et al., 2013
Enzyme	8 kg CO_2-eq/kg	Novozymes, 2012
Sulphur as SO2	0,84 kg CO_2-eq/kg	Ecoinvent, 2010
Ammonia (as N)	3,2 kg CO_2-eq/kg	Biograce, 2012
(NH4)2PO42- (as P)	3,7 kg CO_2-eq/kg	Ecoinvent, 2010
Molasses	0,1 kg CO_2-eq/kg	Flysjö et al., 2008
Propionic acid		
Glycerol	0,65 kg CO_2-eq/kg	Ekman and Börjesson, 2011
Potato juice	0,54 g CO_2-eq/kg	Ekman and Börjesson, 2011
NaOH	1,4 kg CO_2-eq/kg	Tufvesson et al., 2013
Ca(OH)2	0,012 kg CO_2-eq/kg	Ecoinvent, 2010
Energy		
Natural gas for steam production	69 g CO_2-eq/MJ	Gode et al., 2011
Natural gas-based electricity	460 g CO_2-eq/kWh	Lantz et al., 2009

Allocation based on economic factors is applied to account for by-products. The allocated loads are shown in Table 2.

Table 2: Allocated loads used in the analysis and the references on which the calculation of allocation factors are based.

Product	**Allocated load**	**Reference**
Inputs		
Glycerol	72 % / 3.5 %[1]	Tufvesson et al., 2013
Potato juice	0.4 %	Tufvesson et al., 2013
Straw	100 %	Börjesson et al., 2013
Outputs		
Propionic acid	100 %	Tufvesson et al., 2013
Ethanol	97.8 %[2] / 97.1 %[3]	Ekman et al., 2013
Biogas	1.7 %[2] / 1.7 %[3]	Ekman et al., 2013
Electricity	0,5 %[2] / 0.45 %[3]	Ekman et al., 2013
Heat	0 %[2] / 0,75 %[3]	Ekman et al., 2013

[1] Rapeseed oil from seeds/Glycerol from rapeseed oil
[2] Stand-alone biorefinery
[3] Integrated biorefinery system

When the environmental impact from the entire biorefinery systems is calculated, the changed composition of output must be accounted for since the entire amount of electricity produced is used in the propionic acid plant.

Table 3: Annual production of the products. In the stand-alone system heat is produced but since the demand for district heat cannot be guaranteed, the environmental load allocated to the district heat is Zero (see Table 2)

	Stand alone systems	**Integrated system**	
Propionic acid	10,000	10,000	tonnes/year
Ethanol	35,000	35,000	tonnes/year
Biogas	1,100	1,100	tonnes/year
Electricity	27,200	-	MWh/year
District heat	92,800	-	MWh/year

2 RESULTS

2.1 RESULTS

The GHG performance of the different production systems for propionic acid and ethanol is shown in Figure 4 and 5. The results show the performance for traditional fossil-based systems, the stand-alone biorefinery plants and the integrated biorefinery system co-producing propionic acid and ethanol. As can be seen in Figure 4, the production of ethanol from straw is, from a GHG perspective, favorable compared to petrol and the effect on the environmental performance caused by the integration is minor. The GHG emissions caused by the production of propionic acid are, on the other hand, worse than those caused by fossil-based propionic acid also when production takes place in an integrated system. This is due to the large demand for process energy, in particular electricity. Even after integration of the biorefinery systems natural gas is required to fulfill the energy consumed in propionic acid production. However, the environmental performance of bio-based propionic acid would be improved if the concentration of product in the fermentation broth is increased. That is however not included in this study but was assessed by Tufvesson et al. (2013) and Ekman and Börjesson (2011).

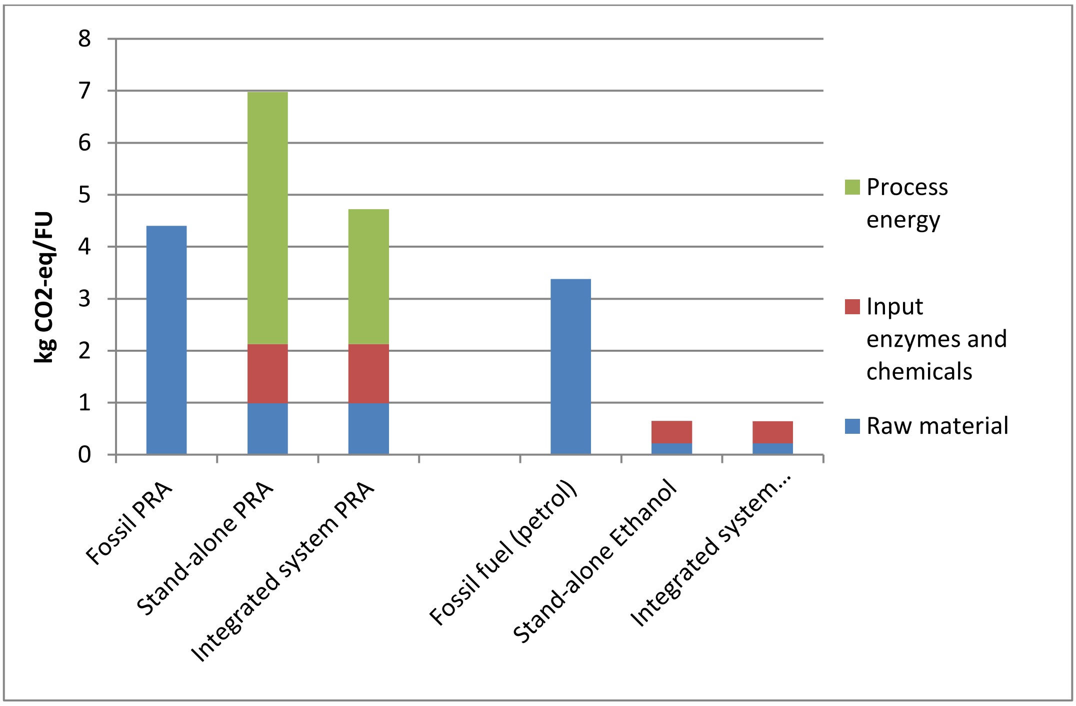

Figure 4: Emissions of GHGs per functional unit under different assumptions. For propionic acid the functional unit is 1 kg PRA at factory gate, for ethanol 1 kg of anhydrous ethanol at factory gate. For the reference product petrol, the FU is calculated on an energy basis to equal 1 kg of ethanol.

In order to assess the environmental impact from the entire systems as well as the impact of integration on a systems level, the functional unit *one integrated biorefinery in one year* was used. The results in that case are shown in Figure 5. The red color shows the part of total emissions that refer to the production of ethanol or the reference products and the blue color shows the same for PRA. The difference between the two reference systems is due to the fact that no electricity is sold outside the biorefinery as is shown in Table 3. The higher emissions caused by the reference system for separated systems are thus due to the additional production of electricity, here assumed to be produced from natural gas.

As was seen in Figure 5, the environmental performance is favorable for the integrated system even if the propionic acid on a per kg basis has a worse environmental performance than the fossil-based reference product, see Figure 4. The improved environmental performance for PRA is due to the replacement of fossil energy carriers in the production. However, also on a systems level it is the replacement of petrol with straw-based ethanol that is responsible for the major reductions of emissions. The raw material, glycerol, responds to 14% of the total environmental impact of propionic acid produced in a stand-alone plant and 21% of the environmental impact of propionic acid produced in the integrated system.

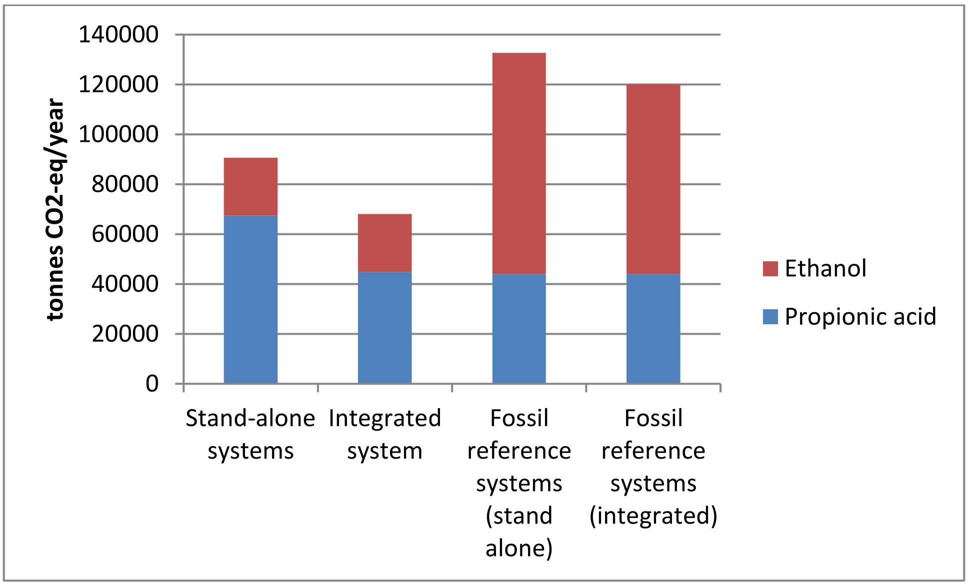

Figure 5: The emissions in one year caused by two stand-alone systems for production of propionic acid and ethanol respectively and a system in which the flows of heat and electricity are integrated between production units.

2.2 RESULTS FROM SENSITIVITY ANALYSIS

In this sensitivity analysis the effects of using by-products from the ethanol production with electricity as the factor on which optimization is based and wood chips as the additional energy input for steam production in the propionic acid plant. Electricity is chosen as the factor for optimization because that can be fully utilized in the production of propionic acid whereas an additional energy input is required to upgrade the hot water to steam regardless of amount. As is seen in Figure 6 the environmental performance of bio-based propionic acid in the integrated system is improved significantly compared to the fossil reference, when complete substitution with bio-based energy carriers is achieved.

However, an ethanol plant of this size would only be sufficient to supply an annual propionic acid production of 4300 tonnes. To produce the necessary quantities of electricity to supply an annual propionic acid production of 10,000 tonnes, the base case assumption in this report, approximately 276,000 tonnes of straw would be necessary. The theoretical straw supply in the Skåne region is 308,000 tonnes per year (Ekman et al., 2013). However, the uptake area would increase significantly and coupled to that also the transport distance which would have a high impact on the cost of straw. Theoretically a facility of this size could be built in Skåne but in any other Swedish region, import is necessary to cover the straw demand.

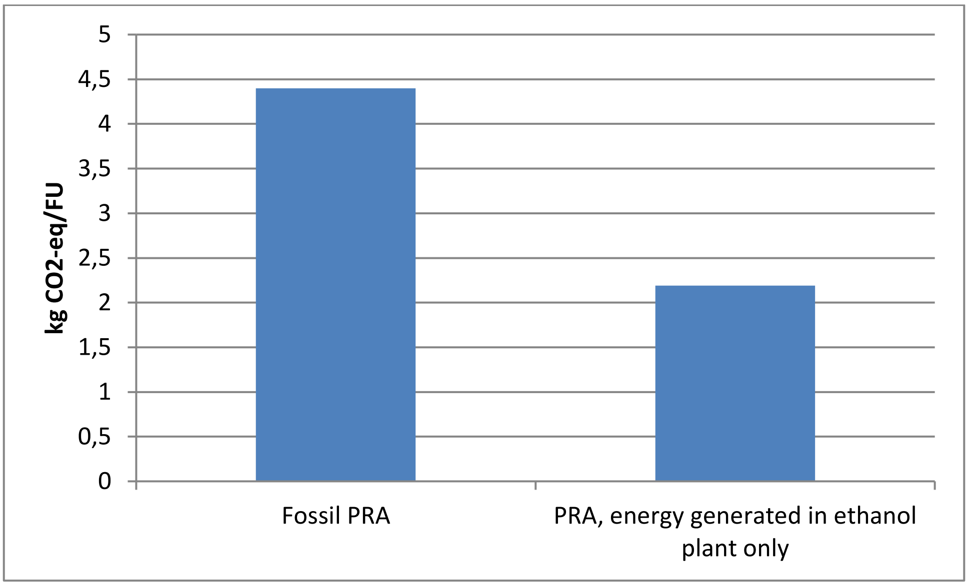

Figure 6: Emissions from propionic acid when complete substitution with bio-based energy carriers is achieved.

DISCUSSION AND CONCLUSIONS

A conclusion from this report is that process integration can lead to significant reductions of emissions. This is true even if results expressed per unit of a particular product within the system show an increase in emissions compared to a fossil reference product.

When the results are expressed per yearly production and include the two main products ethanol and propionic acid together, the integrated biorefinery system shows the best GHG performance. The GHG emissions will then be reduced by approximately 25%, compared with stand-alone biorefinery production, and 45% compared with integrated fossil-based biorefinery systems. The GHG performance will be further improved if the fossil natural gas assumed to be used in the biorefineries today, is replaced by biomass energy.

The different results depending on the functional unit (FU) selected show the importance of addressing this aspect in life cycle assessments of complex and integrated biorefinery systems producing several high-value products. Depending on the aim and purpose of the environmental assessment, different FU’s may be motivated to include, but a general recommendation is that the results should be presented using different and complementary FU’s to show the effects on the results (Ahlgren et al., 2013).

Here the results were presented for different functional units. The functional unit “per tonne produced product” will give information important for the producer of the investigated product. For example, the PRA producer can gain knowledge in the production of PRA in different ways, for fossil PRA, PRA from a stand-alone plant and PRA produced in an integrated system. The functional unit “one integrated biorefinery during one year” will on the other hand give information on the environmental performance connected to the whole plant, something that is more interesting from a societal perspective.

In this report, the environmental impact was quantified using economical allocation to handle by-products. A recognized problem with economical allocation is the sometimes large variations in prices of different products over time which directly affects the environmental performance. An alternative approach would be system expansion. However, system expansion requires availability of inventory data also for other products being replaced by the by-products produced in the biorefinery as well as for the raw material. In this case biogas, electricity and heat as well as either PRA or ethanol is produced replacing other products, and the products being replaced must also be well defined. A decision must be made weather average or marginal products are replaced, for example, biogas can replace both petrol and diesel as vehicle fuel, which can be seen as a substitution on the margin giving large environmental benefits, whereas the biogas can also be assumed to replace other biogas produced in an average biogas plant, which will only give minor effects on the environmental performance. The choice of method to handle by-products as well as whether to use average or marginal data relates to what type of LCA that is carried out (attributional LCA or consequential LCA) (Zamagni et al., 2012).

How to handle biogenic carbon and emissions caused by land-use changes are other issues of particular importance for the environmental performance of biorefinery system. The importance of including this and how they should be handled is decided on a case-to-case basis since it relates to the aim of the study. This report has a focus on the post-harvest effects of integration between industries and biogenic carbon and land-use changes were therefore not assessed here. However, the harvest of straw as energy feedstock may cause a reduction of the soil carbon content which will give a minor reduction in the overall GHG emissions (see e.g. Börjesson and Tufvesson, 2012).

Also the timing of emissions can be of importance, especially if perennial crops are used as feedstock and products that are not combusted directly are produced. An example is to use a tree that has grown for many years to produce fuel ethanol that is burnt straight away or if annual crops are used for production of plastic devices that are used for a number of years before they are either combusted or recycled (see e.g. Pawelzik et al. (2013)). In this example, however, the timing of emissions is a minor issue since the system utilizes residues that originate from annual agricultural crops and the produced products are assumed to be consumed directly.

Regarding the commercial implementation of integrated biorefinery system assessed in this case study several aspects need to be considered, besides its environmental performance. One such important issue is availability of raw material and energy. In Ekman et al. (2013) an inventory of straw resources in Sweden was performed. As expected, the largest resources were found in the southern parts of Sweden with the highest agricultural activities. The straw supply is not only dependent on the production of straw but also on competing application of the straw such as in animal husbandry. The energy sector in Sweden has not yet started to use straw on large scale but in Denmark straw is used in heat and power plants, sometimes co-fired with coal. In the biorefinery systems studied here, heat and power are produced as by-products and conventional heat and power plants can be replaced by biorefineries or complemented with these.

Another important issue for commercial implementation is location. As described previously in this report, the biorefinery is assumed to be located in southern Sweden close to the city of Kristianstad since this is a promising location for a biorefinery due to the access to raw materials in the region, mainly straw and potato juice, as well as a district heating system of sufficient size to utilize some of the excess heat as base load in the southern parts of Sweden based on previous studies (Ekman et al., 2013; Ekman and Börjesson, 2011). Kristianstad is also located in close vicinity to a harbor (in Åhus) in case there will be a deficit of raw materials in the region and supplies need to be purchased from elsewhere. Kristianstad is situated in a densely populated area that hosts one of the major universities in Sweden (Lund University) as well as a number of smaller universities (Kristianstad, BTH etc.) and competent staff can probably be easily recruited. These kind of additional prerequisites for a successful implementation need to be analyzed more in detail in future, multidisciplinary systems studies. However, several district heating systems in Sweden have made large investments to change to new biomass burners and the main fuel is forest-based fuels such as wood chips. Replacing this district heat with waste heat from a biorefinery would thus not necessarily contribute with as large reductions of emissions as if fossil fuels were replaced. However, this would decrease competition for raw materials that can replace fossil feedstock elsewhere. The effects of this have not been studied here but more research in this area is needed.

The idea of industrial symbiosis and the integration of different production processes also raises other, both technical and non-technical, barriers that need to be investigated. One obstacle to overcome is the security of supply, not only of raw materials but also the streams that are shared between the plants within the biorefinery system. For example, the PRA producer must be confident that excess energy from the ethanol production will be delivered over a long period of time. However, if electricity prices increase rapidly, the ethanol producer may want to optimize the production to get the highest output of electricity possible, limiting the excess energy for the PRA producer. Another obstacle is the ownership of the common "components" connecting the production facilities. Even if the integration is beneficial in a societal perspective, but only one of the producers benefits from it, the investment cost of the integration must be shared in an acceptable way between both the ethanol and PRA producers. Thus, for biorefinery systems like this to be developed, new business models need to be developed in parallel to the development of technology.

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