Life cycle assessment of biomass based ethylene production in Sweden - is gasification or fermentation the environmentally preferable route?

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Abstract

Purpose To reduce its environmental impact, the chemical industry is investigating the biomass based production of chemicals such as ethylene, including fermentation and gasification conversion processes. However, a comprehensive study that compares the environmental impact of these biomass routes is missing. This study assesses and compares a wood gasification with a wood fermentation route to ethylene in Sweden, as well as, compares it with the commercialized sugarcane and fossil oil alternatives.

Method The study followed the methodology of life cycle assessment. A cradle-to-gate perspective for the production of 50 000 tonne ethylene /year was applied and the following impact categories were investigated: global warming (GWP), acidification (ACP), photochemical ozone creation (POCP), and eutrophication (EP).

Results and discussion Biomass acquisition including transport to the gasification plant were the major cause of the gasification route's GWP and POCP, suggesting improvements with regard to fuel source and machine efficiency. NO_x emissions from the gasification process had the main share on the ACP and EP.

The comparison of the gasification with a wood and a sugarcane fermentation route showed a lower impact for the gasification route. Among others things, this is caused by high emissions from transport and cultivation for the sugarcane route, and high emissions from enzyme and ethanol production for the wood fermentation route.

The results were less distinct for a comparison of the gasification with a fossil based route. Fossil based ethylene production was found to be preferable for the ACP and the EP, but less preferable for the GWP and POCP. However, it needs to be considered that the fossil route has been optimized for decades, and is still ahead of the gasification and other biomass routes.

Conclusions The study shows that a gasification based production of ethylene could outperform a fermentation based one; however further investigations are recommended, given the state of development of the investigated biomass routes. Moreover, based on the limited availability of biomass, further investigation into economical and ecological restrictions are of importance.

Keywords Fermentation • Gasification • LCA • Methanol • Sweden • Wood based ethylene

1 Introduction

In an effort to reduce its dependency on fossil resources and its release of fossil based greenhouse gas (GHG) emissions, such as CO_2, the energy and fuel industry has considerably increased its production of biomass based energy and fuels in recent years. For example, global bioethanol production increased from 24.7 million tonnes in 2005 to 69.7 million tonnes in 2011 (Naumann 2011), and biodiesel production grew from 3.4 million tonnes to 18.1 million tonnes (Naumann 2011) in the same period.

However, while the use of biomass as an energy source seems ubiquitous and has been part of the historical record for millennia, there are also other industrial options for using biomass, such as the production of chemicals and materials. In fact, the chemical industry has become aware of this potential, and the production capacities of biochemicals and biomaterials have been steadily increasing during recent years. For example, the production capacity of biodegradable bioplastics such as polylactic acid (PLA) and starch blends increased from 226 000 tonnes in 2009 to 486 000 tonnes in 2011 (european Bioplastics accessed August 22, 2013). In the same period the capacity of non-biodegradable bioplastics increased almost 30 times from 23 000 tonnes to 675 000 tonnes (european Bioplastics accessed August 22, 2013), with a considerable share of this capacity devoted to ethylene based plastics.

Considering the production of this biomass-based ethylene, it seems that biochemical (fermentation) conversion is currently the dominating process, since all biomass-based polyethylene (PE), is produced via ethylene from ethanol of fermented sugarcane (Braskem accessed September 11, 2011). However, a biochemical conversion route is not the only technology alternative to produce biomass based ethylene. There is also the option of using a thermochemical (gasification) route. The latter is of interest due to a higher robustness and its ability to handle a wider range of feedstocks (Foust et al. 2009). In addition, the potential environmental impact of a thermochemical route might be comparable or even lower than that of the fermentation route. For example, Mu et al. (2010) found that depending on how the co-products of the gasification process are handled, gasification could outperform fermentation for the production of ethanol from various feedstocks. Also Bright and Strømman (2009) present results that show gasification to be a better alternative from an environmental perspective. Moreover, Foust et al. (2009) reported that the emission profile for the gasification and fermentation process is similar, with the gasification process releasing slightly more CO_2. Collectively, these results suggest that a thermochemical route is a potential option to a fermentation route. In fact, ethylene production via gasification is already industrially investigated (Total accessed March 5, 2013), although with the focus on gasification of coal.

Sweden is conducting considerable research and development regarding biomass gasification and fermentation, though these efforts currently focus on the production of energy and

fuels. For instance, Sweden has a demonstration plant for the production of fuel ethanol via fermentation of wood (SEKAB accessed March 5, 2013), and for the production of biogas via gasification of wood (Business Region Göteborg accessed September 9, 2014) In addition, there are also plans to build an industrial scale wood gasification plant for the production of fuel methanol (VärmlandsMetanol AB accessed March 5, 2013). Eventually, these efforts could also lead to the production of biomass based chemicals such as ethylene, especially since Sweden's petrochemical cluster is mainly operating on this substance. In particular, when considering Sweden's vast forestry industry, a wood based production of ethylene could be a potential option to lower the dependence on fossil feedstocks and associated release of fossil GHG emissions.

Using the research and demonstration projects mentioned as an indicator there is the potential that gasification and/or fermentation could be used to produce ethylene from wood in Sweden in the near future. However, a comprehensive study that compares the two emerging routes and their environmental impact in this context is currently missing. Therefore, in this study we assess the environmental impact of ethylene production via wood gasification at an industrially relevant scale, including an investigation on how the choice of different woody feedstocks influences its environmental impact. This is especially relevant, since a whole spectrum of woody biomass, ranging from forest residues to pulp wood, could be used as feedstock.

In the second part of the study, we then compare the results of the gasification route with those from a previously assessed Swedish wood fermentation route (adapted from Liptow et al. (2013) – see Electronic Supplementary Material) with regard to their relative environmental preferability. Moreover, in order to investigate how an emerging wood gasification route would compare to the already industrialized alternatives, we compare the results of the gasification route with a sugarcane fermentation route and a route based on fossil oil (adapted from Liptow and Tillman (2012) – see Electronic Supplementary Material).

2 Wood gasification route to ethylene

2.1 Technical background

Fig. 1 shows the life cycle flowchart of the gasification route to ethylene also including the gasification and the methanol-to-olefin (MTO) process. The technical background description is structured accordingly.

2.1.1 Gasification process including methanol synthesis

In general, gasification processes can be divided into entrained flow, plasma, fixed bed, and fluidized bed processes (E4Tech accessed September 9, 2014). The latter is of special rele-

vance for Sweden, as the majority of its gasification plants (currently operating and planned) are operated on fluidized bed processes (Kolmorgen accessed September 11, 2014; Iskov and Bjarne Rasmussen 2013; Gunnarsson accessed September 11, 2014). Furthermore, the syngas produced from a gasification process, can be converted into a broad range of products, including e.g. ethanol and methanol. With this respect, Sweden is particularly interested in the production of methanol. In fact, it will have the first commercial scale methanol gasification plant globally (Ridjan et al. 2013).

With the above described process pathways in mind we sought for a technology and related data that would best represent what we judge to be a likely gasification process for Swedish conditions. With the Isaksson et al. (2012) study we found such a process, since:

They (Isaksson et al. 2012) investigate a fluidized bed process for the production of methanol, which is in the center of Swedish interests. Moreover, their process is operated in a standalone gasification plant, which allows for an assessment without disguising results behind process integration with other plants. Finally, the methanol yield for the process (0.51 MW methanol/MW feedstock) is within the range, found in current literature. For example, Tock et al. (2010) state a yield of 0.57 MW methanol/MW feedstock for their indirectly heated fluidized bed based process. A similar yield (0.55 MW methanol/MW feedstock) is also presented by Andersson et al. (2014), who investigate an oxygen blown entrained flow process. Moreover, Phillips et al. (2011) present 0.50 MW methanol/MW feedstock for an indirectly heated circulating fluidized bed based process.

Isaksson et al. (2012) process can be summarized as follows:

The gasification process begins with the pretreatment of the biomass feedstock. This includes chipping the biomass (if needed) and drying it to 15 % moisture content (see Fig. 2). Subsequently, the chipped and dried biomass is fed into the gasifier where it is converted to gas. Isaksson et al. (2012) propose an oxygen- and steam- blown circulating fluidized bed gasifier operated at a pressure of 25 bar and a temperature of 850°C. Oxygen instead of air is used as oxidizing medium, since it does not dilute the product gas with nitrogen. The latter would hinder the downstream conversion to methanol.

After the gasification, the resulting product gas, which consists mainly of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), water (H_2O), CO_2, tars, and some other hydrocarbon compounds, is cleaned and conditioned. The procedure starts by cracking the tars and other hydrocarbons into carbon monoxide and hydrogen. Following this, particles and other impurities are removed by passing the gas through a cyclone, a bag filter, and finally a wet scrubber. The cleaned gas is then reformed in an oxygen-blown autothermal reformer (ATR), in order to convert the methane and other hydrocarbons still present in the gas into carbon monoxide and hydrogen. This is followed by the water-gas-shift reaction, during which the

hydrogen to carbon monoxide ratio is adjusted to fit the downstream synthesis to methanol. The conditioned and cleaned gas is then converted to methanol using a Cu/Zn/Al catalyst at a pressure of 90 bar and a temperature of 240°C. The formed methanol is purified in flashes and separation columns. The reaction also delivers some gaseous by-product, which is burned to fuel the process.

2.1.2 MTO process

The next step on the route to ethylene is the conversion of methanol to olefins in a process called methanol-to-olefins (MTO). Though the MTO process is already commercialized (e.g. China has five plants operating an MTO process (METHANEX accessed September 14, 2013) industrial process data are not available yet and the below process description is based on literature (Joosten 1998), also see Fig. 3.

The MTO process is a catalytic dehydration of methanol at a pressure ranging from 1 to 3 bars and a temperature ranging from 350°C to 500°C. The dehydration delivers a mixture of ethylene, propylene and some C4 compounds (which are not further specified by Joosten (1998) but could include butene and alike). The ratio between products depends on the catalyst used and to a minor extent on the temperature applied. Typical ethylene to propylene ratio ranges from 1.2 to 1.5 (Joosten 1998), although for his particular process Joosten (1998) states a ratio of 1t ethylene to 1.11t propylene. In addition, the process also delivers some by-products such as methane and ethane, which are used to cover parts of the process' energy demand.

2.2 Scope

The assessment of the gasification route to ethylene included all life cycle steps from biomass acquisition, to biomass gasification and conversion to methanol and finally the production of ethylene (cradle-to gate approach, see Fig. 1). An exception was made for the impact assessment on global warming. It included the end-of-life (final oxidation), since the greenhouse gas emissions of this phase affect the relative difference between the fossil and the biomass routes.

The study followed the ISO standard for LCA (2006) and applied an attributional LCA perspective, in that average data were used for electricity supply, and allocation through economic partitioning, was used for multi-output processes, following Tillman (2000). The same approach was applied in the LCA studies of the other routes used for comparison. Furthermore, a reference group of relevant stakeholders followed and reviewed the assessment.

Scenario assessed:

The following section describes the scenario used to assess the gasification route. It is intended to represent a potentially feasible situation in five to ten years in Sweden, without any claim to be predictive.

During the construction of the scenario, scale and location of the production proved to be crucial issues. On the one hand, for ethylene production to be industrially relevant, it must be produced in quantities sufficient for industrial scale applications. Moreover, logistics issues need to be considered, such as whether to produce the ethylene at the location of use or elsewhere. On the other hand, there is a limit to the scale at which biomass may be collected to one location, due to both transport cost and to area requirements for storage and handling. In addition, there is a limit to how fast biomass grows and how many competing uses for wood, such as timber, pulp and paper, and fuels, can be covered at the same time. These issues were considered during the construction of the assessed scenario.

Regarding the location and scale of the ethylene production and hence the MTO process, the following assumptions were made. The MTO plant was assumed to have a production capacity of 50 000t ethylene/yr, since in an earlier study this was found to be a minimum capacity for industrial applications (see Liptow et al. (2013) for more detail). Moreover, it was assumed that the MTO plant is located in Stenungsund (Sweden), since this is the only petrochemical cluster in the country where ethylene is used. In addition, this location does not only have relevant competence at hand, but also allows for process integration with other processes (not investigated in this study).

The possible location and size of the gasification and methanol plant turned out to be less straightforward. Current plans for building a gasification plant including methanol synthesis in Sweden are based on a plant feedstock capacity of approximately 200 000 tonnes dry matter/year (t DM/yr) (estimate based on data published by VärmlandsMetanol AB (accessed February 14, 2013)(accessed February 14, 2013)). However, gasification plants approximately five times this size (approximately$1x10^6$ t DM /yr) are considered technically feasible in literature, in the time frame considered in this study (Isaksson et al. 2012; Holmgren et al. 2012). Therefore, a gasification plant of such size was assumed for this assessment according to the following reasons:

(1) A gasification plant of this size would fully cover the methanol demand of the MTO unit,

(2) The cost (construction, labor, maintenance) for one big instead of several smaller plants can be expected to be lower in comparison (personal communication with Glenn A. Taylor, former Manager at B.F. Goodrich, Brecksville, Ohio/USA, September 2014), and

(3) $1x10^6$ t DM /yr is a volume that can be handled using current infrastructures with respect to inbound logistics, since similar volumes are currently handled by large Kraft pulp mills in Sweden.

In summary, the scenario was scaled as follows:

One million tonnes DM feedstock per year is assumed to be converted to 413 000 t methanol/yr, which in turn is converted to around 161 000 t olefins/yr, of which 65 000 t is ethylene (Joosten 1998).

However, communications with industrial stakeholders revealed that the handling of such large quantities of biomass in the chemical cluster in Stenungsund would likely be hindered by spatial restrictions. For this reason, the gasification plant was assumed to be located in conjunction with a close-by pulp mill in Väröbacka, 100 km south of Stenungsund. This would also allow for the use of already existing infrastructure as well as potential process integration with the pulp mill (not investigated here).

Currently planned gasification plants in Sweden are, to a large extend, intended to be supplied with tree tops and branches also known as GROT (Swedish acronym for GRenar Och Toppar) (E-On Sverige AB; Nyström; Gobigas and Göteborg Energi accessed September 3, 2014). The latter is now mainly used for energy purposes (Energimyndigheten accessed August 14, 2014), with approximately one third of the total GROT potential currently being taken out of Swedish forests. However, despite the option to increase the outtake of GROT significantly, it seems this potential is to a large extent already intended to be used for energy purposes (Energimyndigheten; Skogsindustrierna accessed August 14, 2014). Especially for new uses, such as the production of chemicals, this is important to consider, since it might imply that they cannot be supplied on GROT only. Moreover, it also urges to investigate into other potential feedstock options (e.g. energy wood, sawmill chips and pulp wood) for these uses. However, though competition for these feedstock options might exist as well, it is beyond this study's scope to try to predict its development. Instead, we developed two feedstock scenarios that are intended to be potential future states of extreme nature. In more detail, the scenarios were constructed as follows:

Scenario (1) - GROT only

In scenario (1) the gasification plant is fed only with the wood fraction advocated to be used in current plans for gasification plants in Sweden, i.e. GROT (Gobigas and Göteborg Energi ; Nyström ; E-On Sverige AB accessed September 3, 2013). Further, in the scenario all GROT in a geographical area large enough to feed the gasification plant is used for this purpose (under consideration of ecological and economic restrictions). This implies that the production of ethylene economically outcompetes all other GROT uses.

Scenario (2) - Feedstock mix

In scenario (2) the production of ethylene is based on a mixture of less valuable wood fractions. It is assumed the complete volume of these fractions; in a geographical area large enough to feed the gasification plant are used for this purpose. Phrased differently, the gasification plant economically outcompetes all alternative uses of these biomass fractions in its vicinity with one exception. This is the fraction used for timber production, which is assumed to be too valuable for gasification. The result is a feedstock mix consisting of pulp and energy wood (low quality round wood), sawmill chips and GROT (the quantities of the different fractions were based on availabilities in the South of Sweden (Götaland) - see Table 1 in the Electronic Supplementary Material).

Data sources:
Current Swedish data were used for all forestry activities and for the production of sawmill chips, assuming no significant changes in the next 5 - 10 years. For the gasification process and all subsequent processes up to the ethylene production, literature data based on process simulations and technology reports were used due to the absence of industrial scale data. Moreover, data for current average Swedish electricity production as reported by Börjesson et al. (2010) was used in the study. It was assumed that these data can be used for the time frame assessed in this study based on projections of the IEA (International Energy Agency) (2011).

Functional Unit:
The functional unit is 50 000t ethylene at the gate of the ethylene production plant.

Impacts assessed:
In the study, the following potential environmental impacts were assessed:
- Global warming (GWP)
- Acidification (ACP)
- Eutrophication (EP)
- Photochemical ozone creation (POCP)

Biogenic CO_2 emissions are not included in the assessment of global warming potential. Instead, we have chosen to present and discuss these emissions at the inventory level and to present them together with the inventory for fossil CO_2 emissions, based on the following reasons:

(1) The inventory of biogenic CO_2 is relevant for biomass based chemicals, because every carbon atom that does not end up in the product is an inefficiency. Therefore, a biogenic CO_2 inventory is an important source for guiding optimization of industrial processes that are based on biomass feedstocks. Moreover, comparing inventories for biogenic and fossil CO_2 release can provide an additional guidance to prioritize which areas in a process require the most immediate attention.
(2) Though several methods (e. g. (Cherubini et al. 2011; Pingoud et al. 2012)) for the impact assessment of biogenic CO_2 have been developed in recent years, they are still subject to intensive and critical methodological debate. For this reason, an application at this point seemed moot. However, impact assessment may be applied to our results at a later stage when the methodology has become more robust.
(3) Comparing different routes with regard to their biogenic CO_2 inventory can function as an additional guidance for the selection between routes, since lower emissions are an indication for higher efficiency.

Impact on biodiversity and water availability:
The impact on biodiversity and water availability due to the production of biomass based ethylene was outside the scope of this study, although we recognize the importance of these impacts.

2.3 Inventory

Data sources and assumptions for all processes from wood acquisition to ethylene production are given in this section. The full inventory tables are presented as Electronic Supplementary Material in Table 1 to Table 5. The Supplementary Material also contains the data for the wood and sugarcane fermentation route, as well as the data for the fossil route (Table 6 to Table 8).

Feedstock acquisition

GROT

For the acquisition of the GROT data from Lindholm et al. (2010) was used, as given in Table 2 in the Electronic Supplementary Material. Specifically, the data set for chipped residues coming from the South of Sweden was used, which includes all processes from forwarding (transport of the wood from the forest to the roadside) to chipping. The chipped wood is then transported to the gasification plant (see 'Transport activities' section for more detail).

Pulp wood and low quality round wood

The same data were used for the acquisition of pulp wood and low quality round wood, since both wood qualities can be assumed to undergo the same forestry operations.

Data on primary energy use valid for South Sweden (SW2) from González-García et al. (2009) (Table 2, Electronic Supplementary Material) were combined with emission data from Lindholm et al. (2010). For this purpose, all fuels reported by González-García et al. (2009) were assumed to be diesel and all machines were treated like forest machines. Furthermore, the data by González-García et al. (2009) include transport of workers for the different forestry operations, which could not be distinguished. For this reason, worker's transport is included, though it may be assumed that this transport is of minor importance.

Sawmill chips

For sawmill chips production Swedish data as reported in Liptow et al. (2013) were used. The data includes all forestry steps (seedling production, site preparation, regeneration, cleaning and logging operations and delivery of the timber to the mills) as well as the production of the sawmill chips.

Transport activities

GROT transport to the gasification plant

A comparison between the feedstock need of the gasification plant and the GROT available in Götaland revealed that approximately 60 % of the available quantity would be needed to feed the plant. This would lead to transport activities covering a large part of the Götaland region, including transport distances up to 200km (see below for more detail on this distance). For comparison, the Värmlandsmethanol plant, which is five times smaller, is intending to source GROT from within a 150 km radius (Nyström accessed September 3, 2014).Transport activities were estimated as follows:

Firstly, it was assumed that the GROT is evenly distributed over the area of Götaland excluding the islands Gotland and Öland. After that, the area of Götaland was divided into a raster of hexagons (see Fig. 7 in the Electronic Supplementary Material). Each hexagon has a radius of 50km each. With the help of this raster it was then estimated that the transport distance for the GROT spans from 50km for the hexagons closest to the gasification plant, up to 200km for the ones furthest away (it was assumed that all transport starts in the middle of the respective hexagon). The related emissions were based on data from NTM (Network for Transport and Environment)(accessed on April 13, 2013), which are presented in Table 5

(Electronic Supplementary Material). In addition, Table 5 also includes the emission data for energy and fuel production.

Transport of mixed wood sources to gasification plant

In order to assess the transport in the mix scenario the following procedure was used, together with emission data from NTM (accessed on April 13, 2013).

In a first step, the quantities of the different wood fractions (see Section 2) were estimated within a 50km radius around the gasification plant, implying transport over this distance. This was done following the above described hexagon procedure, in combination with data for the availabilities of the different wood fractions. Only for the sawmill chips this procedure was not applied, since one of the two sawmills within this radius is located next to the assumed gasification plant, and the other is approximately 40 km away.

In a second step, the radius was then extended to 100 km (implying 100km transport), since the sum of all fractions in the first 50 km were insufficient to cover the gasification plant's feedstock demand. Again, the hexagon procedure was used in order to estimate the quantities of the different wood fractions within this extension. Subsequently, the derived quantities were added to the estimates from the first step. The addition started with the pulp wood, which was identified as the fraction of biggest quantity. This was followed by adding the quantity for the second biggest fraction, which was GROT. Together with the quantities from the first step, this was found to be sufficient to cover the feedstock demand of the gasification plant. As a result the remaining fractions and their respective quantities were not considered.

Methanol transport to the MTO plant

The transport of methanol to the MTO plant was assumed to be 100km and was assessed using data from NTM (accessed April 13, 2013) (accessed on April 13, 2013).

Gasification including synthesis to methanol

The model of the gasification process, including methanol synthesis, was based on an environmental study by Foust et al. (2009), and a technology study by Isaksson et al. (2012). The latter (Isaksson et al. 2012) provided data with regard to feedstock input, energy consumption, and product output, while the study by Foust et al. (2009) was used to estimate on-site NO_x emissions of the gasification process (see Table 3 in the Electronic Supplementary Material). Though Foust et al. (2009) assess the production of ethanol from poplar via an indirect gasification process; their data were used due to the absence of emission data for oxy-

gen blown gasification of softwood and subsequent methanol synthesis. These data were verified with a study by Pa et al. (2011), who found emissions to be in a comparable range.
In addition, Foust et al. (2009) also present data for SO_2 emissions. However, since SO_2 release is influenced by the sulfur content of the biomass, SO_2 emissions were not taken into account. Instead, it was assumed that the sulfur content of the woody biomass is negligible, following Pa et al. (2011). Moreover, sulfur removal measures taken on-site might decrease potential SO_2 emissions even further.
Apart from on-site emissions, the gasification process also causes off-site emissions due to consumption of catalysts and electricity. The impact from electricity consumption was modeled using data from Börjesson et al. (2010), whereas the production of catalyst was disregarded, since based on data from Mu et al. (2010) their impact was negligible in comparison to the other life cycle steps.
Finally, since the gasification process provides some excess heat in addition to methanol, the environmental burden of the process was partitioned between these two outputs based on prices (Table 3, Electronic Supplementary Material).

Methanol-to-Olefin (MTO) process

For the MTO process, electricity and external fuel consumption data according to Joosten (1998) were used in conjunction with electricity data from Börjesson et al. (2010) (see Table 5, Electronic Supplementary Material) and data from PE International (accessed August 5, 2011) and CPM database (accessed July 12, 2012) for external fuel. The latter was assumed to be natural gas. Moreover, for the combustion of the process' gaseous by-products emission data for natural gas were applied, under the simplification that all by-products could be approximated with methane. The amounts of by-products were based on data by Joosten (1998) and are presented in Table 4 in the Electronic Supplementary Material.
As the name of the process indicates, the MTO process does not only deliver ethylene but also other olefins such as a propylene and C4 compounds. For this reason, the environmental burden of the process was partitioned between those products based on revenue, assuming that future price developments will lead to similar revenue ratios, see Table 4 (Electronic Supplementary Material) for more detail.

3 Results and discussion

The Results and Discussion section starts with the assessment of the gasification route, followed by its comparison with the wood and sugarcane fermentation route, as well as, with the fossil oil based alternative.

Fig.4 shows the results for the GROT and mixed wood gasification scenario to ethylene.
As can be seen, there is no considerable difference between the two feedstock scenarios for all investigated impacts, apart from the GWP. The later is slightly higher for the GROT scenario, mainly due to its higher need for transport. Moreover, the processes dominating the investigated impacts are the same between the two scenarios, though different impacts are dominated by different activities.
In general, the following processes are of importance for the different impacts: (1) the gasification process including synthesis to methanol for the ACP and the EP, (2) the biomass acquisition for the GWP, and (3) the ethylene production (MTO process) and biomass transport for the GWP and the POCP. Especially for the GROT scenario, transport turns out to be key, since sourcing from a considerable part of the Götaland area would be needed. Furthermore, comminution (chipping of the material at the road side using diesel as fuel for the equipment) and forwarding (transport of GROT out of forest and to the roadside) during GROT acquisition are considerably affecting the scenario's GWP. The activities during biomass acquisition are also of importance for the mix scenario. However, here the logging operations (thinning, final felling and extraction) related to the pulp wood fraction are of significance, due to the fraction's high share on the feedstock mix.
As regards the role of the ethylene production (MTO process) for the GWP and POCP, this is mainly caused by the process' energy demand and the related emissions. Particularly, the CO_2 emissions from burning external fossil fuels and the CH_4 emissions from the combustion of external, as well as, internal fuels, contribute to the process' impact.
Internal emissions are also of relevance for the gasification process. However, in this case, it is the NO_x emissions leaving with the process' flue gas, which cause its significant share on the ACP and EP.
With the above key contributors in mind, the following paragraphs discuss potential process developments and other factors that could influence our findings.
One potential development of relevance for the mix scenario, is the use of hybrid machines (machines that both harvest and forward) for the logging of energy and pulp wood. In fact, such machines could reduce the energy consumption of logging by up to 50 % (González-García et al. 2009), which would notably decrease the GWP for the mix scenario and the impact of the biomass acquisition.
Another development of interest for the biomass acquisition is the application of semi-automatic harvesting systems. They could cut logging fuel consumption by up to 20 % (Lindholm 2010), leading to a decrease for the mix scenario's GWP. Further decreases can also be achieved by using cleaner fuels; however, the investigation of such developments is outside this study's scope.

Although the ethylene production (MTO process) was identified as a key contributor, an estimate about potential developments or process variations is challenging due to the lack of data. However, increased yield and reduces fuel consumption would improve the environmental performance of the process.

The scenarios assessed in this study include one big gasification plant for the production of methanol, which leads to considerable transport for the biomass. Potentially, several smaller plants could reduce this transport and its impact. However, before drawing final conclusions, the advantages and disadvantages of different scales of gasification plants need to be further investigated, including the consideration of ecological and economical effects.

Fluiduzed bed gasification seem to be the type of process most investigated in Sweden (see Section 2), though there are other process options as well. One such option is a pressurized entrained flow biomass gasification process (PEBG), as e.g. investigated by Andersson et al. (2014). In comparison to the assessed gasification process, the PEBG process has a slightly higher methanol yield, produces some excess heat (0.16 MW_{heat} /MW input) and consumes considerably more electricity (0.12 MW_{el}/MW input, in comparison to the here assessed 0.009 MW_{el} /MW input). Hence, also with a PEBG process, the gasification would still be an environmental key contributor. Although, the ACP and EP, which are the impacts most influenced by the gasification process, would decrease by approximately 20 %. This is due to the process' higher methanol yield and the production of excess heat. Both factors lower the methanol's share on the environmental burden of the biomass acquisition and the gasification process. Moreover, they buffer the increased emissions caused by the process' higher electricity consumption.

The results also show that there is clear need for reduced NO_x releases from the gasification process. This would be of special relevance for the ACP and EP and further investigations are recommended.

Though this study assesses an industrial scale production, Sweden's total ethylene production capacity is approximately 12 times bigger (Borealis AG accessed October 22, 2013) and cannot be covered by GROT only, even when excluding other uses. In fact, to cover the total Swedish ethylene production would take approximately $8.8*10^6$ t DM. In comparison, the GROT potential is around 4.9×10^6 t DM (Skogsstyrelsen 2008), including GROT from thinning and from regeneration felling. Therefore, investigations into other feedstock options are highly recommended, considering that Sweden's chemical cluster aims for a complete biomass based production by 2030 (Josefsson accessed September 22, 2014).

Fig. 5 shows the alternative routes to ethylene, for a comparison with the gasification results. The figure includes the results for the following four routes:

(1) gasification route for GROT, (2) fermentation of wood followed by dehydration of ethanol to ethylene in Sweden, (3) fermentation of sugarcane in Brazil followed by the production of ethylene in Sweden, and (4) a conventional route from fossil oil via naphtha cracking in Sweden.

As can be seen in Fig. 5, the wood fermentation and gasification route could be said to be in a comparable range for the EP. However, for all other investigated impacts (GWP, ACP and POCP), the fermentation route has a clearly higher potential impact. This is mainly caused by the high emissions from enzyme (biological catalyst) production, the NO_x and SO_2 emissions released during ethanol production (fermentation and upgrading) and the ethylene emissions from the ethylene production. In comparison, for the gasification route the production of catalyst was found to be of negligible impact. Moreover, concerning the release of ethylene emissions, the data used for the inventory of the ethylene production did not provide any estimates on such emissions. Therefore, the impact investigated here might be underestimated and further research is recommended.

In summary, the comparison between the wood fermentation and gasification route favors gasification. This was also found in an earlier study by Bright and Strømman (2009), who compare the production of wood ethanol in Norway via fermentation and gasification. However considering that both routes are still on an emerging status, future assessments that follow their development are of importance. In addition to the potential impacts of the wood fermentation route, Fig. 5 also shows the impacts of a sugarcane route. As can be seen, the sugarcane route is less preferable for all investigated impacts. This is predominantly caused by GHG emissions released during the cultivation phase, SO_2 and NO_x emissions from long distance transport and ethylene emissions from ethylene production. Especially the impact from cultivation and transport is worth noticing, since this shows that both activities could become of increased significance in case of imported feedstocks and feedstocks with cultivation needs differing from Swedish wood.

Finally, as a point of reference, Fig. 5 also includes the potential impacts for a fossil oil route. The comparison with the gasification route shows varying results, with the fossil alternative having a considerably higher GWP and POCP. The latter is mainly caused by emissions from the long-distance oil transport. In addition, the estimated emissions for the gasification route might be incomplete, particularly with regard to ethylene emissions from the MTO-process. Moreover, the higher GWP found for the fossil ethylene, is caused by the release of fossil CO_2 during the different production steps, and from the potential oxidation of the product made from the ethylene.

With regard to ACP and EP, the gasification route has a higher potential impact mainly due its considerable NO_x release during the gasification. However, it needs to be kept in mind,

that the fossil route has been optimized over decades including measures such as NO_x removal, which in the future might also be expected for the gasification route. Future improvements are a general point to consider for all biomass based routes presented in this study. For this reason, we would like to stress, that our assessment is only one snapshot in time and future assessments might reveal fewer or smaller differences among the biomass routes.

Biogenic CO_2

As has been stated in the Goal and Scope definition, we also present inventory results for biogenic CO_2 in order to support further development. These results are shown in Fig. 6, together with inventory results for fossil CO_2. For the biogenic CO_2 it should be noted, that the figure only presents emissions and not uptake by plants. This is due to the current methodological uncertainties related to the assessment of this process within LCA.

Fig. 6 is divided into two parts, with the upper part (6a) showing the results for the gasification scenarios and the lower part (6b) showing the results for the alternative routes. As can be seen (6a), there is no considerable difference in inventories for the two gasification scenarios. Moreover, for both scenarios the amount of biogenic CO_2 exceeds the fossil amount, with the gasification process including methanol synthesis having a considerable share on this. Therefore further optimization in order to reduce biogenic CO_2 and to use the biomass as efficiently as possible is recommended. This is especially true for biomass based by-products, such as GROT, which are of limited availability.

The comparison of the gasification inventory with the inventories of the other biomass routes (see Fig. 6b) shows a comparable amount of biogenic CO_2 for the wood fermentation route. Similar results were also found by Foust et al. (2009), who show that the conversion of wood to ethanol via fermentation and gasification leads to a similar CO_2 emission profile for both processes. Although, Foust et al. (2009) do not account for biogenic and fossil CO_2 emissions separately, it can be deduced that all on-site CO_2 emissions are biogenic, since in their study both processes are energy self-sufficient.

Furthermore, the inventory of the sugarcane route shows a significantly bigger amount of biogenic CO_2 when compared to the gasification. This is mainly due to CO_2 emissions from pre-harvest burning and from bagasse combustion during ethanol production. However, legislative measures to phase out pre-harvest burning until 2031 (Galli 2011) and further optimization of the ethanol mills (Macedo et al. 2008) can be expected to noticeably decrease biogenic CO_2 emissions from the sugarcane route.

Another observation, though not directly linked to the comparison of the routes, is the finding that all biomass alternatives have a significantly bigger inventory of biogenic CO_2 than of fos-

sil CO_2. This is partly due to the biogenic CO_2 that could potentially be released from the ethylene containing product. In addition, CO_2 emissions due to feedstock losses (process inefficiencies) are of biogenic origin.

4 Conclusions

The comparison of the gasification route with the wood fermentation and the already commercialized sugarcane route showed the preferability of the gasification route. However, for all three routes, and particularly for the biomass conversion part (fermentation and gasification), there is room for development that would be worth looking into, once data is available.

The comparison with the fossil alternative showed a higher impact for the fossil route with respect to global warming and photochemical ozone creation. However, for the latter, this finding is less certain due to data gaps. Regarding the other two investigated impacts, the gasification route was found to have a higher impact, in comparison, and further improvements such as NO_x removal in the gasification process are recommended. In addition, improvements would also be of relevance for the biomass acquisition and transportation phase of the gasification route.

The consideration of an industrial scale of production revealed the potential issue of limited biomass availability. Especially for the GROT, supplying industrial production could be a considerable challenge, both due to competing uses and due to the circumstance that for large industrial scale production GROT quantities are insufficient. Therefore, it is recommended to further investigate into a wider spectrum of biomass options, while considering ecological and economic restrictions.

The inventorying of biogenic CO_2 indicated the potential of such inventories for the identification of potential environmental key contributors and possible improvement opportunities. Moreover, though the methods for the assessment of biogenic CO_2 are still being debated, there is a need for data and inventories for biogenic CO_2, in order to apply assessment methods for biogenic CO_2, when these have reached a more robust state.

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Figure captions

Fig. 1 Life cycle of wood based ethylene produced via gasification; transport omitted in the figure for clarity reasons but included in the assessment

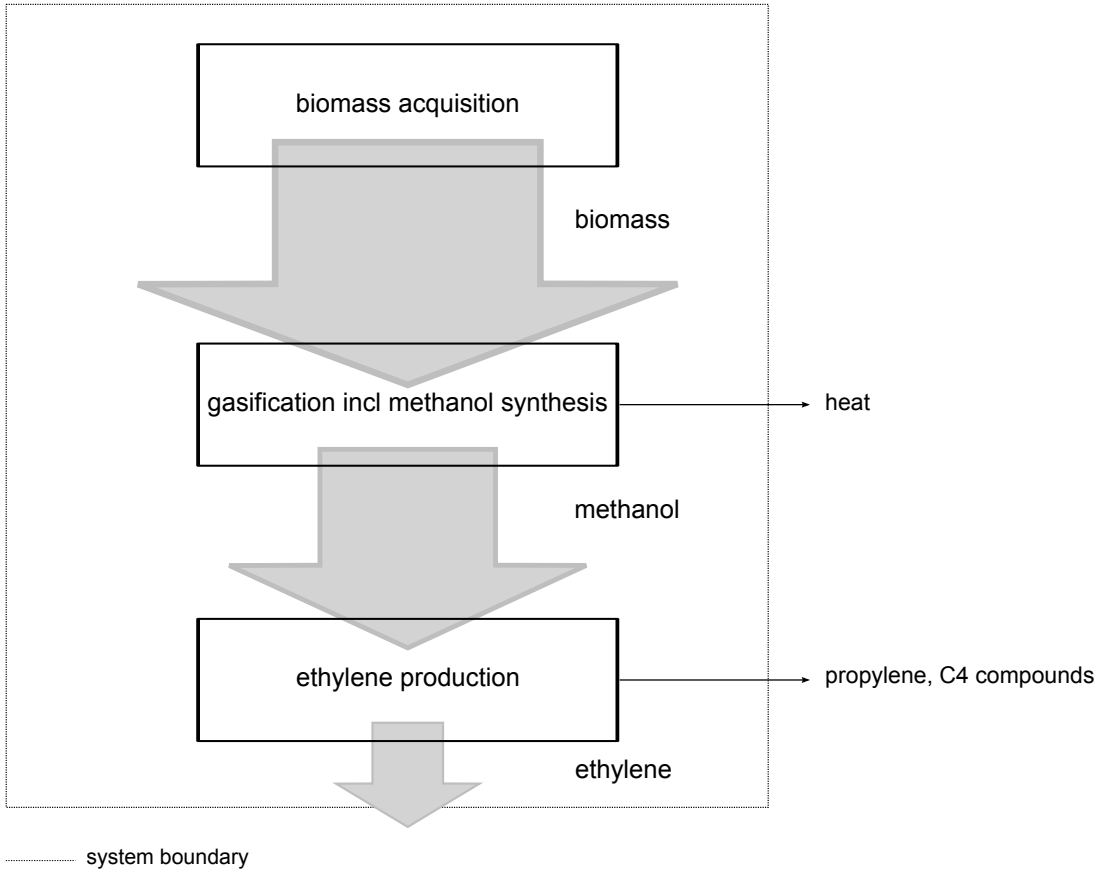
Fig. 2 Flowchart of the gasification process including methanol synthesis (adapted from Isaksson et al. 2012); ASU - air separation unit; ATR - autothermal reformer

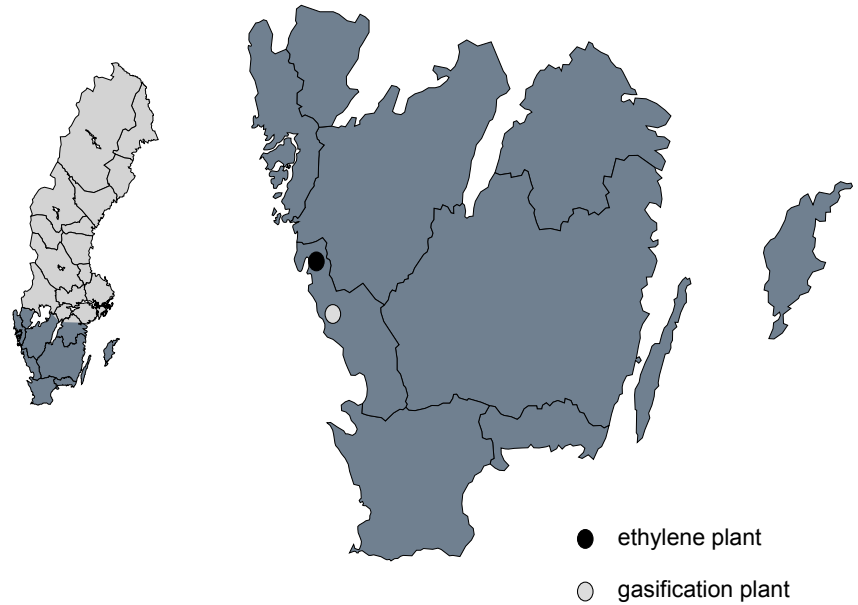
Fig. 3 Schematics of the MTO process

Fig. 4 Impact potentials for the production of ethylene from GROT and wood mix via gasification

Fig. 5 Impact potentials for wood fermentation, sugarcane fermentation and fossil oil based ethylene (note the GWP for the fossil oil route also contains potential CO2 emissions from the ethylene)

Fig. 6 (a) Biogenic and fossil CO2 inventory for the gasification scenarios, (b) biogenic and fossil CO2 inventory for the alternatives routes to ethylene





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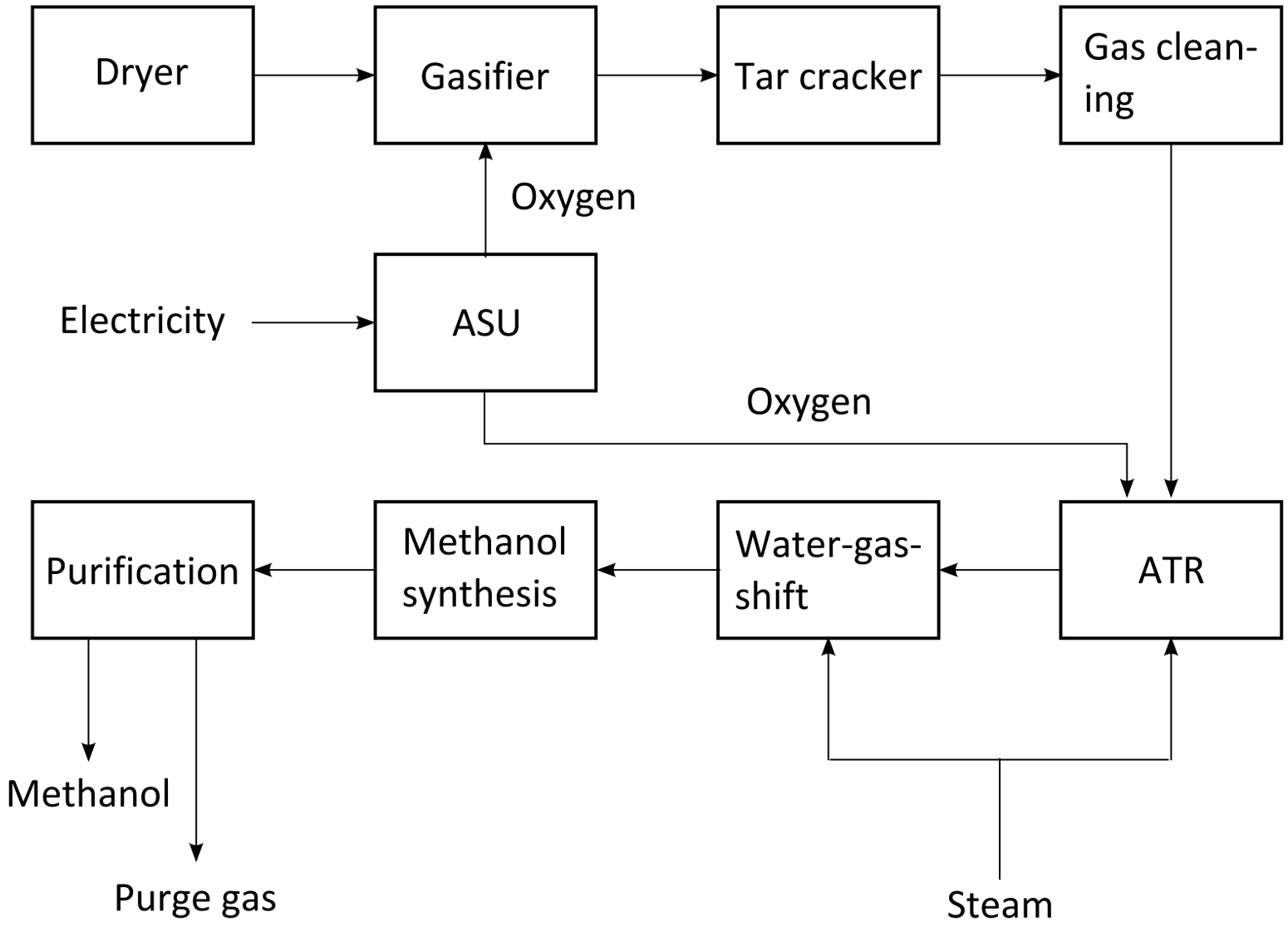

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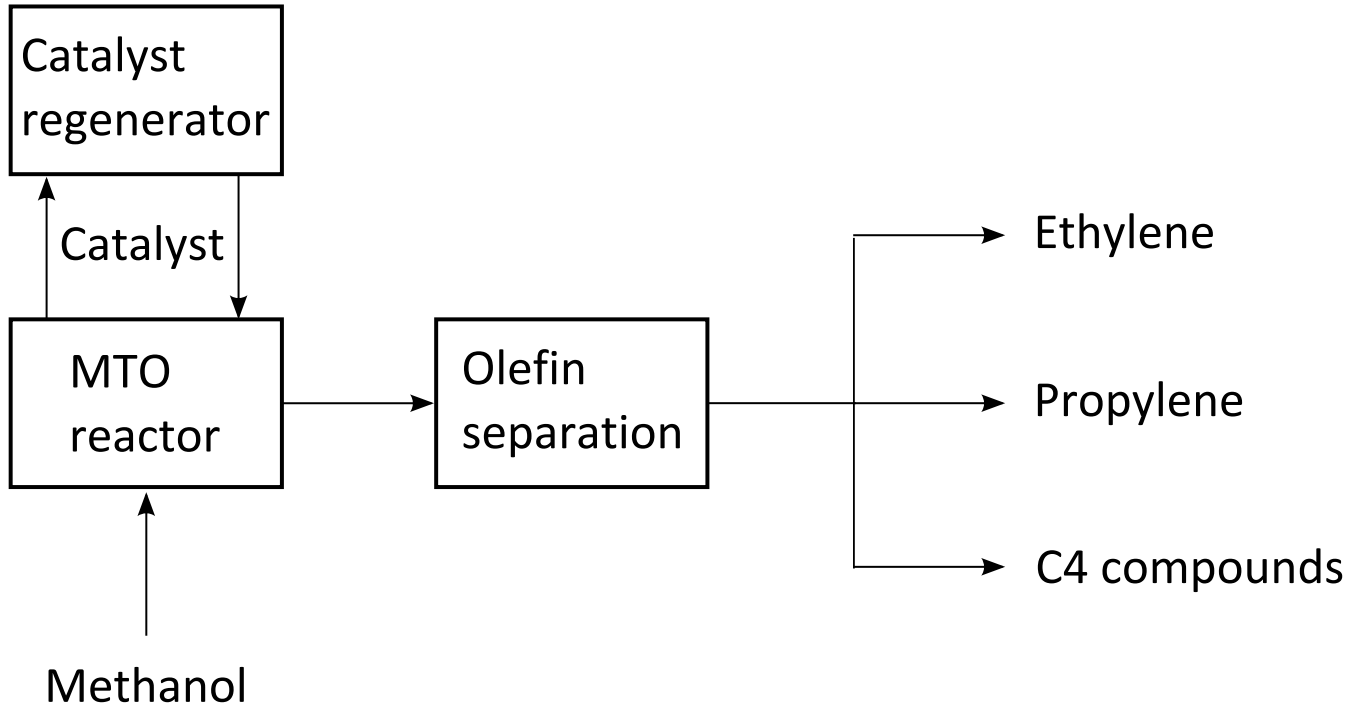

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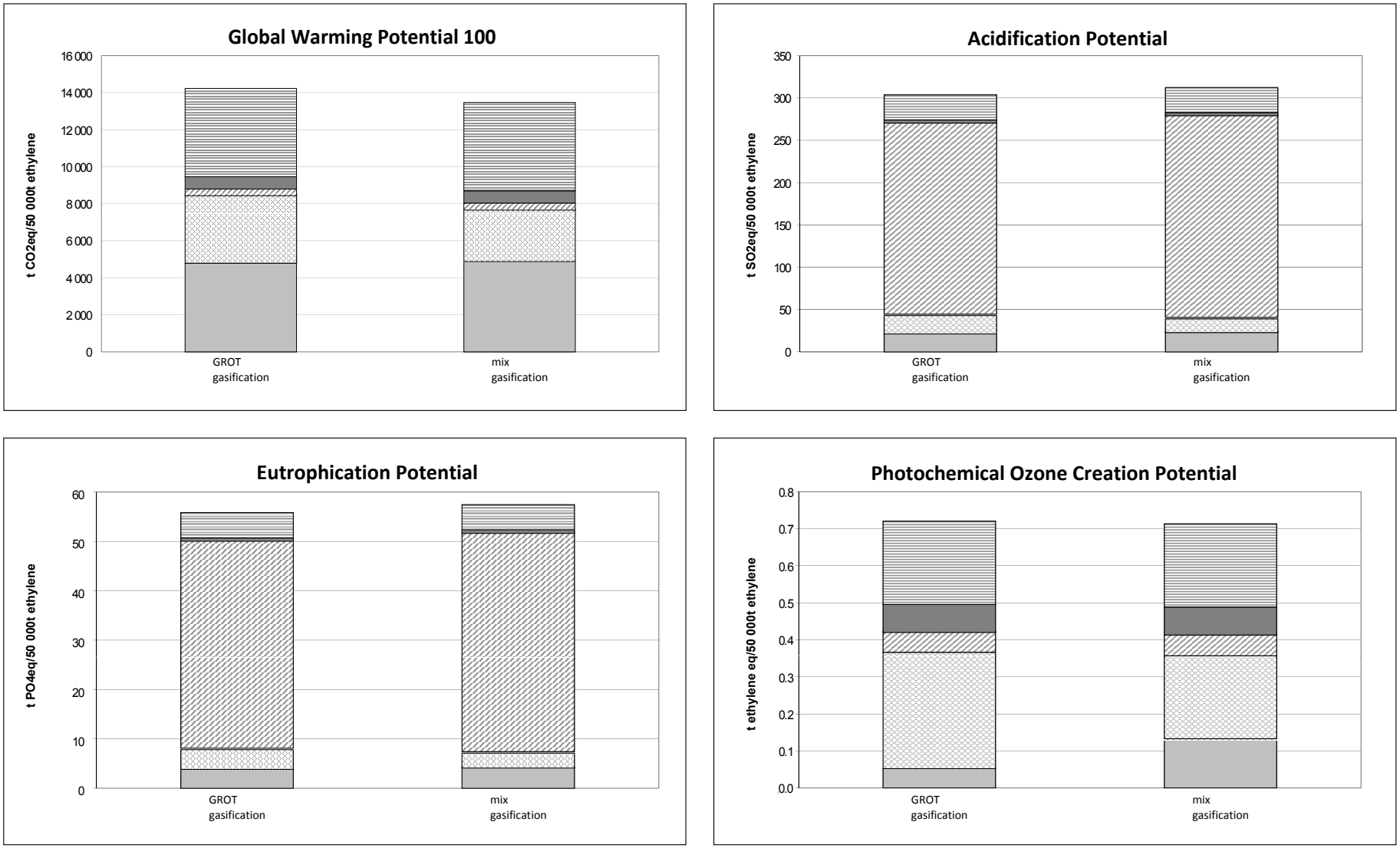

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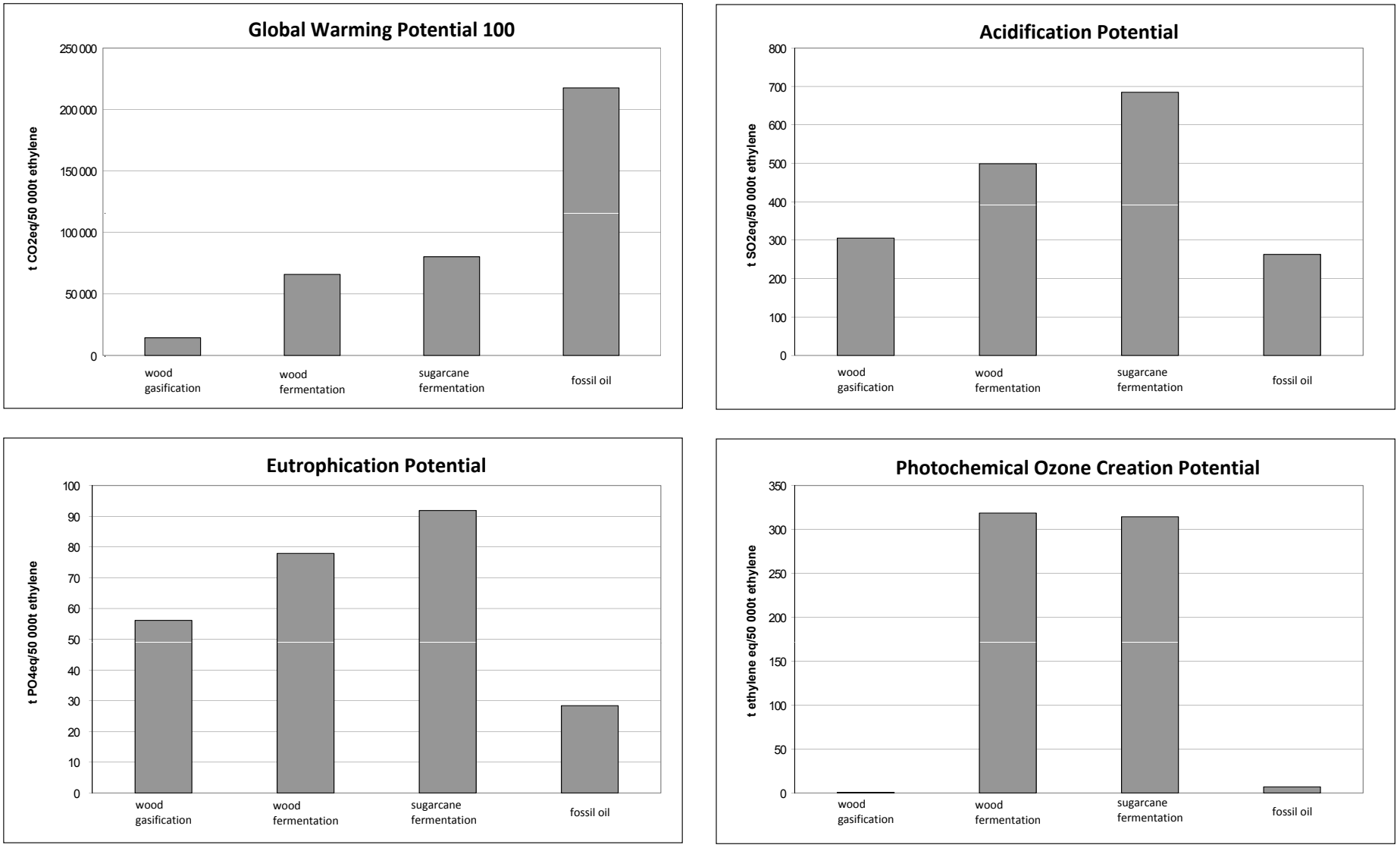
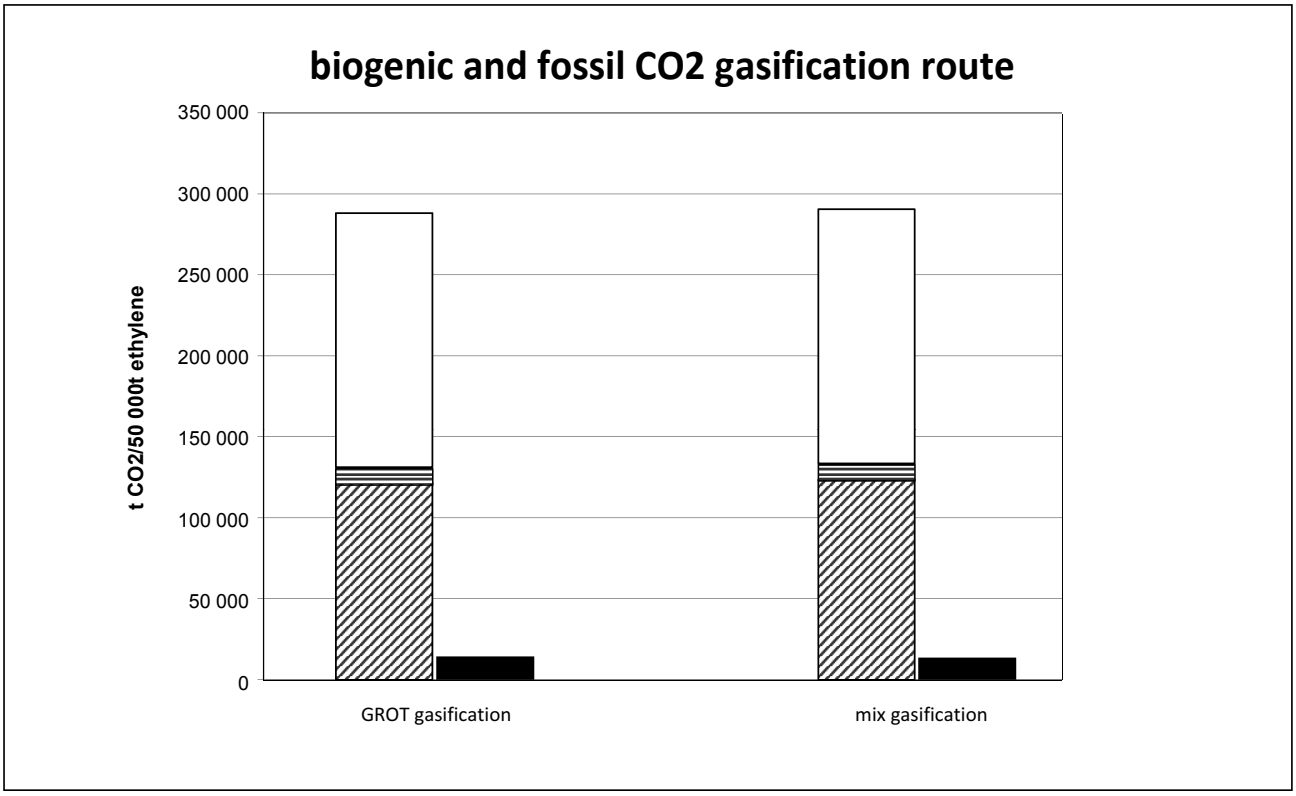
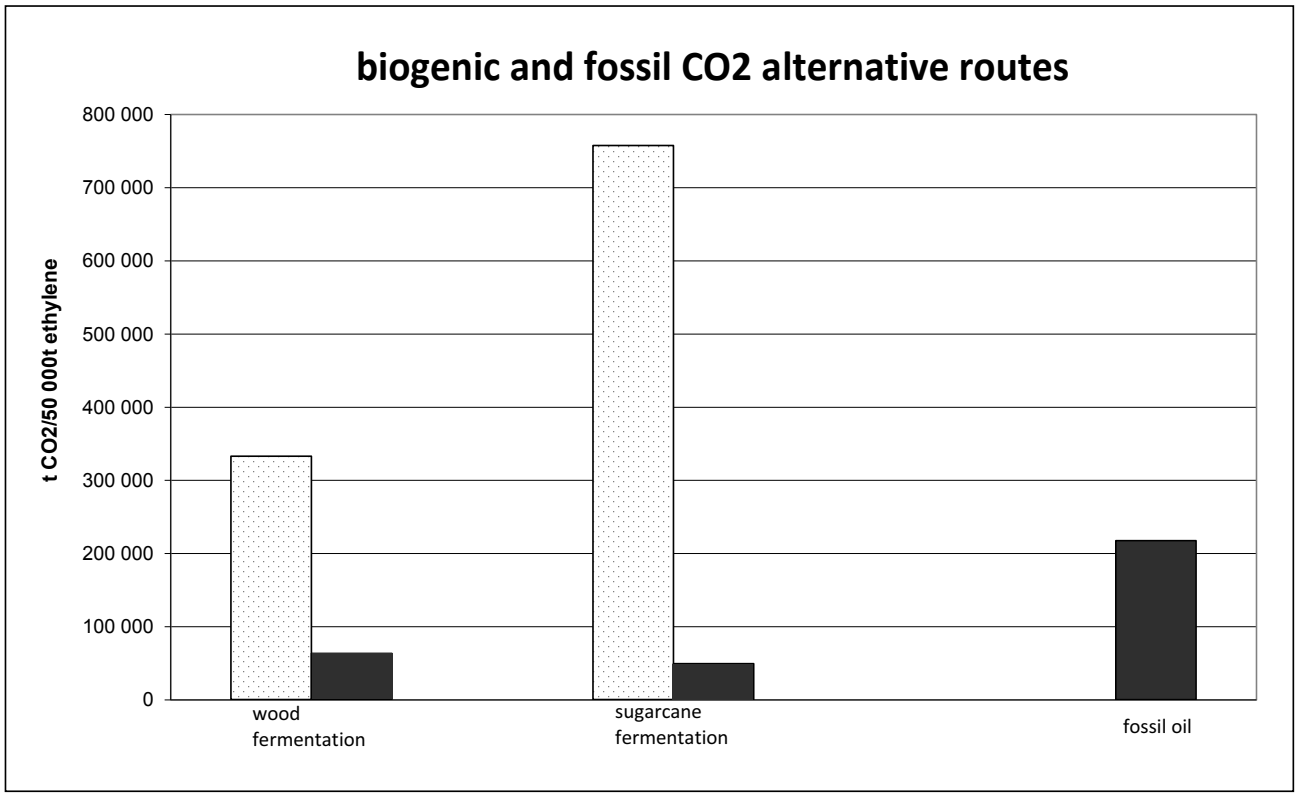


Fig. 5 Impact potentials for wood fermentation, sugarcane fermentation and fossil oil based ethylene (note the GWP for the fossil oil route also contains potential CO2 emissions from the ethylene)

6 (a)



6(b)



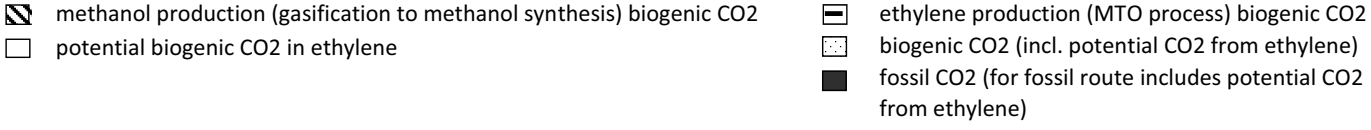


Fig. 6 (a) Biogenic and fossil CO2 inventory for the gasification scenarios, 6(b) biogenic and fossil CO2 inventory for the alternatives routes to ethylene; note the figure does not include carbon leaving with waste water streams, also note the difference in scale between figure 6(a) and 6(b)

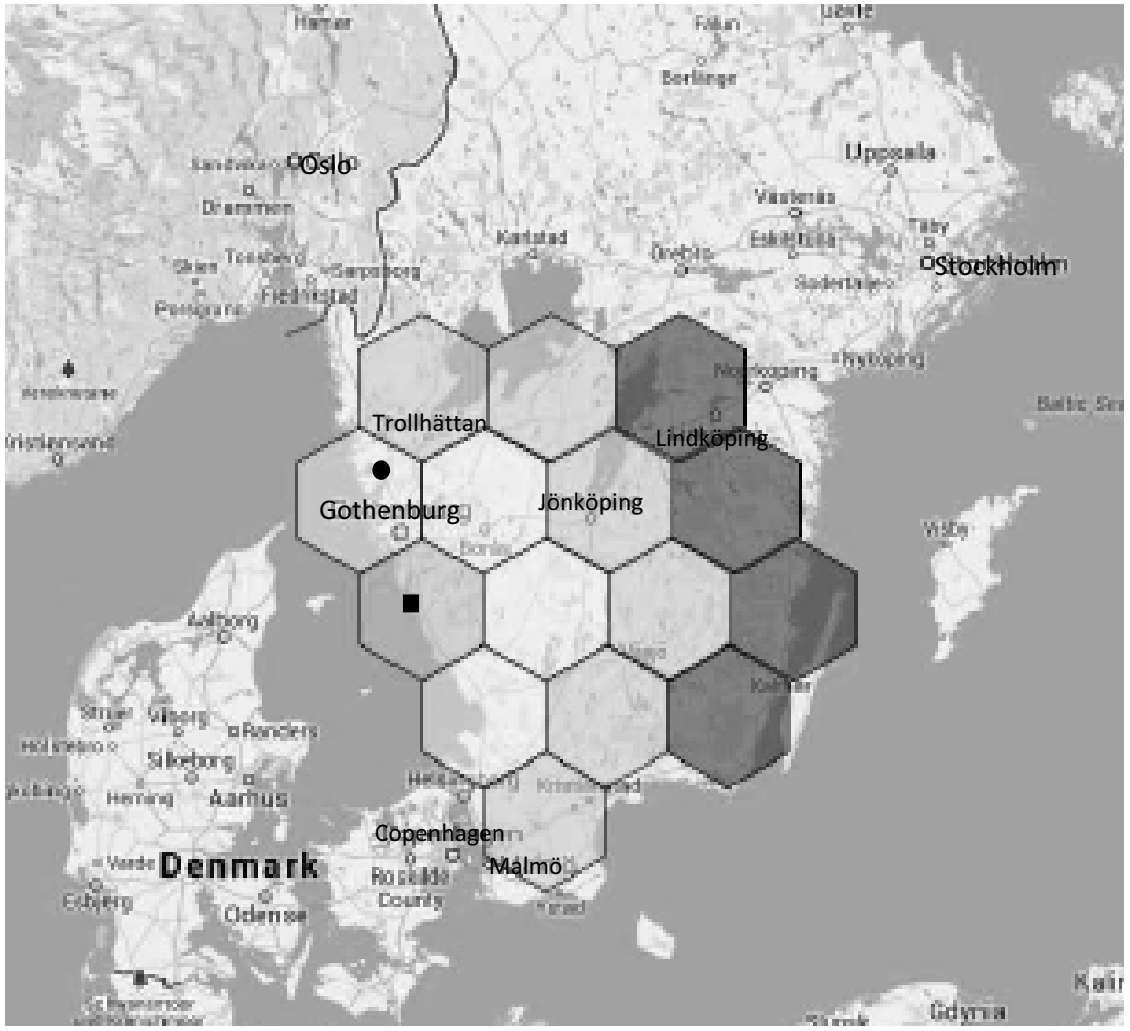


Fig. 7 Hexagon raster used to estimate the transport of biomass