Economic and environmental analysis of an emerging biorefinery concept as a guide for early technology development

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ABSTRACT

This paper presents a biorefinery concept based on emerging conversion processes by which forestry residues and micro-algae are converted into an array of bulk and specialty chemicals. Due to the early development status of the individual processes and conversion routes investigated for the concept, not only is there a lack of fundamental process data, but even the spectrum of products to be obtained from the bioconversion processes is currently unknown. This paper elaborates on the opportunities and challenges associated with linking technology development to systems analysis for a process at a very early development stage, with examples from the biorefinery project described above. Examples of key assumptions for the system studied will be presented. Furthermore, a reasonable size for the plant will be proposed and the feasibility of the biorefinery will be evaluated based on general mass balances and techno-economic estimations for the system and a discussion about environmental impacts.

KEYWORDS

Biorefinery, Lignocellulosic, Systems analysis

INTRODUCTION

Integrated biorefineries based on lignocellulosic biomass conversion provide an opportunity for efficient co-production of bio-based fuels, chemicals and materials. For this type of multi-product biorefinery there is an essential need for Process Systems Engineering (PSE) to understand how process design and operating parameters affect the biorefinery's energy, environmental and economic performance. Systematic process synthesis and modelling efforts enable the application of knowledge generated during lab-scale technology development for assessment of the expected performance of the overall biorefinery plant at an industrial scale. Furthermore, process integration, techno-economic analysis, and environmental analysis (e.g. LCA) are important tools for defining the optimal product and process configurations and design and operating parameters of the multi-product biorefinery system, and for identifying bottlenecks and critical parameters in the process that need to be further researched in lab-scale experiments to improve the process performance.

The need for systematic methodologies for design and analysis of biorefineries has been pointed out in several papers, which also highlight a number of challenges and a significant need for further research in this area. Since new biorefineries must compete with existing fossil-based production routes, optimized production is crucial. According to Kokossis and Yang [1], biorefinery design and analysis will therefore require systematic use of more advanced systems engineering tools. The role of PSE tools has also been discussed by Jiménez-González and Woodley [2], who conclude that PSE has a vital role to play in the development of bioprocesses. However, the requirement for further development of PSE tools is also recognized, as well as the need for an increasing dialogue amongst different disciplines. As an example in line with the latter statement, Jacquemin et al. [3] discuss the potential for better integration between PSE tools and LCA methodology. Alvarado-Morales et al. [4] outline a methodology based on a collection of modelling and simulation tools for evaluation of a bioethanol production process. Other modelling frameworks have also been proposed and applied specifically to the bioethanol production process, for example, by Furlan et al. [5]. Although these methodologies are essentially generic, the studied bioethanol case has the advantage of having extensive data readily available. Alvarado-Morales et al. [4] conclude that data availability will be a major challenge for the use of simulation tools in biorefinery applications. For example, more than 50% of the chemicals in their studied biorefinery systems were not found in the simulator database. Dimian [6] also underlines that the simulation of biotechnological processes with existing all-purpose software tools is not straightforward. Despite this, and a number of other challenges mentioned, process modelling and simulation is considered to be useful for biorefinery applications, for example, for flowsheeting and economic analysis.

This paper will elaborate on the opportunities and challenges associated with linking technology development to systems analysis for a process in a very early development stage, with examples from a specific biorefinery project. Examples of key process configuration decisions (e.g. the pretreatment) and methodological assumptions (e.g. the system boundaries) will be presented and a set of important variables to be optimized will be identified. A reasonable size for the plant will be proposed and general mass balances and techno-economic estimations for the system will be derived, and environmental improvement potential (focusing on climate change) discussed.

STUDIED SYSTEM

This paper presents a future biorefinery concept based on emerging conversion processes by which forest residues and micro-algae are converted into an array of bulk and specialty chemicals (Figure 1). The main products of the biorefinery will be adipic acid, produced by microbial conversion of carbohydrates and aromatic chemicals, produced by bioconversion of lignin. The potential of microalgae as a source of added value chemicals will also be assessed.

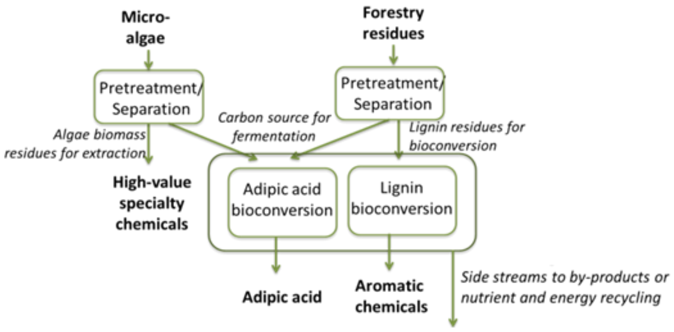

Figure 1. Biorefinery concept for production of adipic acid, aromatic chemicals and specialty chemicals from microalgae and forest residues.

The biorefinery is studied in an interdisciplinary collaboration project in which experimental research and systems analysis are combined for facilitating the sustainable production of several products in a highly integrated process concept.

CHALLENGES AND OPPORTUNITIES

Due to the early development status of the individual processes investigated within the project, not only is there a lack of fundamental process data, but even the spectrum of products is unknown at the current stage. Full reaction pathways for the potential products are generally not known. Furthermore, the pretreatment section is a key step, especially for the forest residues, but its optimum configuration depends on the products selected and their requirements on the bioconversion steps. Additional uncertainties are present for the raw materials, for example, regarding their composition and availability. For the micro-algae, the identification of promising species and the possibilities for cultivation and harvesting are other examples of issues that remain to be investigated.

Despite these difficulties, systems analyses provide important opportunities to guide the early-stage research activities. The evaluation of economic and environmental performance can be used to analyse how key process design and performance parameters influence the overall performance of the biorefineries studied, which can lead to a better understanding about how the individual process units should be designed in order to optimize the total system. Such knowledge will provide feedback to researchers engaged in development of specific unit conversion processes about which units are most important to study and under which operating conditions.

KEY PROCESS DESIGN PARAMETERS

A number of key decisions regarding the biorefinery still remain to be made, e.g:

- Systems related: e.g. scale (size of biorefinery) and time perspective
- Product related: e.g. lignin product and primary product from microalgae
- Process related: e.g. fractionation of forestry residues and recovery and purification of adipic acid

All of these are naturally interconnected. For example, the choice of fractionation method for the forestry residues will decide the form of the lignin for further bioconversion, and is therefore dependent on the desired lignin product.

FEASIBILITY EVALUATIONS

The starting point for the estimations has been to evaluate the feasibility of a biorefinery that produces the same amount of adipic acid as a typical fossil-based plant. At this point, several assumptions have been made that will later be subject to further analysis.

Size assumed for the biorefinery

The global production of adipic acid in 2012 was 2.3 million tons [7], divided over 23 worldwide production units [8]. Hence, the average production capacity of each unit is about 100 000 tons per year. This capacity has been assumed as a starting point for our biorefinery evaluation.

Estimation of raw material demand

Assuming that all of the carbohydrates needed for the bio-production of adipic acid will come from the forest residues, the amount of tops and branches required has been estimated. Further assumptions:

- Cellulose and hemicellulose content of tops and branches: 30%(w/w) and 31%(w/w) respectively
- Enzymatic hydrolysis yield (glucose): 75%(w/w)
- Amount of free C6 sugars after pretreatment and hydrolysis as mass percentage of incoming dry matter: 45%(w/w)
- Maximum theoretical yield from glucose to adipic acid via lysine: 41%(w/w) [9]
- Yield expressed as a percentage of the maximum theoretical adipic acid yield (assumed to be the same as for ethanol): 90%
- No losses assumed in the downstream processing

These assumptions lead to an estimated demand for tops and branches of 0.6 million dry tons/year. To assess the feasibility of using this amount of forestry residues, the value is compared to future potentials for outtake of forest residues in Sweden, which have been estimated to 28–31 TWh/year or approx. 5.5 million dry tons/year [10]. Hence, the forest residues needed for the adipic acid biorefinery would correspond to more than 10% of the future potential in Sweden. Such a large amount of biomass will lead to long transport distances and consequently to large transport costs for the raw material. It is also likely that the competition for this raw material will be strong, both from existing and future potential users, and the feasibility of this large plant can therefore be questioned. However, the capacity of 100 000 tons/year of adipic acid will be kept as a base case to evaluate the techno-economic potential. Nevertheless, this first estimation clearly indicates the importance of varying the capacity in further sensitivity analyses. The low energy density of biomass such as forest residues makes the contribution of feedstock transport cost to the total production cost more significant for a biorefinery than for a fossil-based plant. Therefore, the optimal size for a biorefinery could be very different from a fossil-based plant. One illustration of this is that typical sizes of pulp mills are less than one million dry tons/year while typical sizes of oil refineries are more than 15 million tons/year. However, as can be seen, the size chosen here is in the same size range as for typical pulp mills.

Another potential source of carbohydrates in the biorefinery is the microalgae. A microalgae species with carbohydrate content of 35% is assumed. There are species with higher carbohydrate contents, but since the microalgae in the biorefinery will not only be optimized for sugar production, but mainly for specialty chemicals, a value in the lower range has been chosen. The annual microalgae production is assumed to be 25 000 tons/year, corresponding to the size of a plant which would need all waste water available in the second largest city of Sweden for its nutrient supply [11]. Assuming further that there are no losses in fractionation and hydrolysis, about 9 000 tons of glucose can be produced each year from microalgae, corresponding to approximately 3% of the total glucose flow required. The assumptions regarding microalgae, and especially about the potential production, is highly uncertain. However, the above estimation indicates that the microalgae will not be able to contribute significantly to the adipic acid production in terms of sugar feedstock. However, other components of the algae can, for example, be important for nutrient supply to the yeast.

Techno-economic feasibility

Between 2005 and 2011, the price of adipic acid on the European market varied markedly, between 1 100 €/ton and 2 500 €/ton [12]. The variations can only partly be explained by variations in the price of the feedstock benzene. Instead, the market reacts strongly to closures of production capacity and inventory management by adipic acid consumers (nylon, polyurethanes, plasticizers, lubricant components and polyester polyols) – to supply and demand.

A new bio-based production plant for adipic acid would affect this balance of supply and demand, but the bio-based product can be expected to fill a niche market with a demand for renewable, environmentally friendly products. It is very difficult to estimate the potential added value of the product being green and it is likely to depend on the users of the adipic acid and their opportunities to profit from an increased value for the green component in their product.

The price of (fossil) adipic acid has been compared to the estimated price of the biomass raw material. The price of forest residues in Sweden today is about 17 €/MWh. This would correspond to about 560 €/ton adipic acid. Consequently, the raw material cost would be about 22–50% of the final product price. This can be compared to lignocellulosic ethanol for which feedstock costs are typically around 50–55% of total production costs [13]. On the other hand, the price of forest residues is likely to increase considerably in the future with rising costs related to CO_2 emissions from fossil fuels and support to renewable bio-products. The price for forest residues in 2030 in Sweden has been estimated at 32–43 €/MWh using a scenario tool for future energy market prices [14]. This would correspond to a raw material cost of 1 000–1 400 €/ton adipic acid, around the lower end of the market price range of adipic acid the last decade. This points to the importance of value-creation from the by-products of the bio-based adipic acid production. With upgrading of the lignin to valuable aromatic chemicals, with specialty chemicals production from microalgae and with recovery of energy or possibly other by-products from the hemicelluloses and unconverted sugars and lignin, the biorefinery would have an increased economic potential. Furthermore, the price of (green) adipic acid can naturally also be expected to increase in the future if the price of the oil-based feedstock increases. However, it is uncertain to what extent, due to the weak feedstock-product price correlation, uncertainty regarding future oil prices and whether renewable chemicals will be entitled to support in the same way as renewable energy products such as transport fuels often are.

Comparison of global warming potentials

Adipic acid has traditionally been produced via the oxidation of cyclohexanol and cyclohexanone with nitric acid. During this oxidation N_2O, a highly potent greenhouse gas (298 kg CO_{2eq}/kg N_2O), is formed with a theoretical emission factor of 300 kg N_2O/ton of adipic acid [15]. Even though the actual emissions can be substantially decreased using abatement technologies, the emission of N_2O remains a major concern regarding the global warming potential (GWP) of this traditional process and causes approx. 75% of its total GWP [16].

It is clear that moving towards a bio-based production of adipic acid leads to a large decrease in GWP because emissions of N_2O are eliminated in such a process. Furthermore, the fossil-based feedstock is replaced with forest residues, which will further reduce the GWP with approx. 10%. It should be noted that the use of enzymes in this bio-based process needs to be optimized in order to minimize GWP because enzyme production uses a significant amounts of fossil energy (see e.g. [17]).

CONCLUSIONS

This paper presents a first estimation of the techno-economic feasibility and environmental impacts of a biorefinery in which forestry residues and microalgae are converted into adipic acid and a range of other products. The analysis clearly points to key assumptions regarding systems, process, and product related decisions, which will influence the overall assessment of the biorefinery. It was also estimated that the raw material cost for adipic acid produced from forestry residues would correspond to approximately 22–50% of the final product price assuming today's price levels.

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