The Green Biorefinery Concept: Optimal plant locations and sizes for Austria

Das Konzept der Grünen Bioraffinerie: Optimale Standorte und Anlagengrößen für Österreich

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Summary

The green biorefinery concept aims at utilizing grass silage to produce organic acids (i.e. amino acids and lactic acid), biomaterials, and bioenergy and preserving grassland areas in Austria. We have developed a mixed integer programming model that integrates spatially explicit data on biomass supply and heat demand as well as economic data on biorefinery plants. The model maximizes the profits of green biorefineries subject to regional resource endowments by selecting the optimal plant locations and sizes for Austria. Model results reveal that about 20 to 40 biorefineries can be established to optimally utilize the available biomass potential. The mean plant sizes range from 20,000 to 40,000 t of dry matter grass silage per year. The profitability is mainly determined by the variable production costs and amino acid prices.
Keywords: green biorefinery, mixed integer programming, spatial modelling

Zusammenfassung

Das Technologiekonzept der Grünen Bioraffinerie zielt auf die effiziente Nutzung von Grassilage zur Produktion von Amino- und Milchsäuren, Faserprodukten, Strom und Wärme, ab. Damit soll ein Beitrag zur nachhaltigen Nutzung und Erhaltung von Grünlandflächen in Österreich geleistet werden. In diesem Artikel präsentieren wir ein ganzzahlig lineares Programmierungsmodell, welches räumlich explizite Daten zum Biomasseangebot und zur Wärmenachfrage mit

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ökonomischen Daten zu grünen Bioraffinerien kombiniert. Das Modell maximiert die Profite aller Bioraffinerien in Abhängigkeit der regionalen Ressourcenausstattung, indem es die optimalen Anlagenstandorte und –größen wählt. Die Ergebnisse zeigen, dass 20 bis 40 Grüne Bioraffinerien mit Anlagenkapazitäten zwischen 20.000 bis 40.000 t Trockenmasse Grassilage pro Jahr möglich sind, wenn das errechnete Biomassepotential optimal genutzt wird. Die Wirtschaftlichkeit von Grünen Bioraffinerien wird maßgeblich von den variablen Betriebskosten und den erzielbaren Preisen für Aminosäuren beeinflusst.
Schlagworte: Grüne Bioraffinerie, ganzzahlig lineare Programmierung, räumliche Modellierung

1. Introduction

The fossil based economy will be transformed to a low-carbon bio-based economy in the coming decades due to concerns about climate change and energy security. Biomass will be essential for the production of chemicals, materials, and fuels. However, the contribution of biomass to a sustainable mix of these products is controversially discussed among experts and policy makers. Especially the effects of biofuels on world food prices have attracted much attention in the public discussion. Industries depending on biomass feedstock such as the pulp and paper industries have raised concerns about policies that promote bioenergy and claim that priority should be given to biomaterials (AUSTROPAPIER, 2011).
The efficient use of biomass feedstocks is a main principle of the biorefinery concept, which aims at efficiently converting biomass into a wide range of marketable products including food and feed, chemicals, materials, biofuels, electricity and heat (DE JONG ET AL., 2010). The vast diversity of biomass feedstocks and bio-based products requires a wide range of different approaches and processing technologies. In literature four major biorefinery concepts are described: the lignocellulosic feedstock biorefinery, the whole crop biorefinery, the green biorefinery and the two platforms biorefinery.
One of the biorefinery concepts promoted in Austria is the green biorefinery, because surplus grassland areas are expected to increase in the near future due to structural changes in agriculture (BMVIT, 2009).

It focuses on the use of grass silage for the production of amino acids, lactic acid, electricity and heat. Positive side-effects of grassland management are the preservation of typical cultural landscape and biodiversity. Currently, research focuses on improving the biorefinery processes as recovery rates and product yields are essential to guarantee the viability of the green biorefinery concept (MANDL et al., 2011). However, the whole biorefinery supply chain has to be considered when assessing the competitiveness of biorefineries. Therefore, this article aims at finding the most competitive locations and sizes of green biorefineries considering the whole supply chain in Austria.

2. Data and methods

A spatially explicit, mixed integer programming model has been developed to select optimal plant locations and sizes for green biorefineries in Austria. The model reveals the trade-off between economies of scale of plant sizes and the diseconomies of scale of biomass transport. The major limitations of larger biorefineries are the limited availability of biomass close to the plant, high transportation costs, and limited regional heat demand. It is therefore essential to integrate data on the location of biomass supply and heat demand data to determine the optimal size and locations of biorefineries. As the green biorefinery concept is relatively new and no commercial plants are in operation yet, data for the investment and operation costs of facilities is still uncertain. To deal with these uncertainties a Monte Carlo Simulation is performed to assess the effect of model parameter uncertainty on model results.

2.1 Regional biomass supply and feedstock costs

One of the main arguments for promoting the green biorefinery concept in Austria is to provide an alternative utilization path for meadows. Therefore, grass silage is considered as only biomass source. The site-specific forage yields are simulated with the biophysical process model EPIC (WILLIAMS, 1995) for the meadow areas in Austria, using data on weather, soil, topography, and different land management practices. Results refer to regional biomass production potentials within a grid of 1 km^2 size. The biomass supply is aggregated to 254 supply regions of 20 km² in order to increase the performance of the MIP model. EPIC yields a total annual biomass supply of 8.84 Mt (million tonnes) dm (dry matter) on about 795,000 ha of meadows. The amount of green biomass available for the utilization in green biorefineries is estimated to be as high as 0.5 to 1.0 Mt dm per year (KROMUS et al., 2004).

2.2 Potential biorefinery sites

The pre-selection of an appropriate number of potential biorefinery sites is necessary to balance model solution time with the feasibility of solutions. Potential locations for the biorefineries are assumed to be at the centres of the 20 km² grid cells. These 254 sites are reduced to 100 potential biorefinery sites by selecting those cells where biomass supply is above 10,000 t dm and where demand is greater than 4,000 MWh of heat during the summer season.

2.3 Transportation costs

Transportation costs represent an important limiting factor for large scale biorefineries. We have used the public available road network data for Austria (OPENSTREETMAP, 2011) to calculate the transportation costs. The actual road network distances are included by calculating a distance matrix from all biomass supply regions to all potential biorefinery sites using the ArcGis Network Analyst. The transportation costs per tonne fresh matter depending on the transport distance are calculated based on DÖRING et al. (2010). Costs for digestate transportation are included based on data of AMON et al. (2008).

2.4 Capital Costs

Capital costs also determine the optimal plant size of green biorefineries. So far, green biorefineries have been realized only on pilot or demonstration scale. Therefore, data for green biorefineries at industrial scale are not available yet. The investment costs used in the model are based on estimations and first results of the pilot plant in Utzenaich (MANDL et al., 2011). Economies of scale for larger biorefineries are calculated by using the following scaling function:

$$\left(\frac{cost_{base\_capacity}}{cost_{new\_capacity}}\right) = \left(\frac{base\_capacity}{new\_capacity}\right)^{scaling\_factor}$$

Typical values for scaling factors range from 0.63 for grain and cellulosic ethanol plants up to 0.80 for power plants (JACK, 2009) – a larger scaling factor implies less economies of scale. In our analysis, we have used a scaling factor of 0.77 because large scale biogas plants, which are necessary to process the press cake produced in green biorefineries, exhibit little economies of scale.

2.5 Heat Demand

Waste streams of the green biorefinery are utilized together with the press cake in a biogas plant. The generated surplus heat is assumed to be fed into local district heating networks. However, heat losses and heat transportation costs increase significantly with distance. Thus, spatial explicit heat data from SCHMIDT et al. (2010) is used to consider its effect on optimal biorefinery locations and sizes. The data provides the heat demand in MWh for summer and winter periods at 1 km^2 resolution.

2.6 Biorefinery supply chain optimization model

The biorefinery model is formulated as mixed integer programming (MIP) model. The decision whether to build a biorefinery at a certain location is included as binary variable in our model. Other decisions variables are the size of each biorefinery and the amount of biomass transported from each biomass supply region to the different biorefinery sites. The model maximizes the total biorefinery supply chain profits subject to the regional resource endowments.

The optimal biorefinery locations and sizes are chosen among 100 preselected locations and 10 possible sizes. Biorefinery revenues are determined by achievable product yields and commodity prices such as amino acids, lactic acid, electricity and heat. We consider the costs of feedstock procurement, transportation from supply regions to biorefineries, capital costs for the biorefineries and variable operation costs for converting grass silage into various products. The following constraints are implemented in the model:

- biomass transport from the supply points is limited by their maximum biomass potential,
- biorefinery production is limited by biomass supply and biorefinery capacity,
- only one size of biorefinery can be established at each site, and
- heat revenues are limited by surplus heat and regional heat demand.

2.7 Sensitivity Analysis

The green biorefinery concept is relatively new and no green biorefineries are operating on industrial scale in Austria so far. Thus, the values of many input parameters such as capital and operation costs or product prices are uncertain. This requires a robust method to assess the key uncertainties in designing optimal supply chains. SATELLI (s.a.) recommended Monte Carlo Simulation of input parameters as proper method to carry out global sensitivity analysis for nonlinear programming models. We carried out a Monte Carlo Simulation with 500 runs to identify the impact of single model parameters variations on mean biorefinery profits and capacities. The analysis includes all relevant model parameters such as product prices, product yields, feedstock costs, transportation costs, capital costs, variable costs and the regional heat demand. The lower and upper bounds for the parameter variations are set to 75% and 125% of the initial parameter value. The results of the Monte Carlo Simulation are used to build a regression model by regressing input parameters on output variables. From the regression model, elasticities are estimated which show how much a change in an input parameter affects the output.

3. Results and Discussion

3.1 Profitability of green biorefineries

The model results demonstrate that green biorefineries are an economic viable option for the utilization of green biomass. Except some outliers, the mean profits vary between 115 and 125 € / t dm biomass for the different biorefinery locations. The most important cost element for green biorefineries are the variable operating costs, which contain costs for feedstock fractioning, downstream processes and biogas production (figure 1).

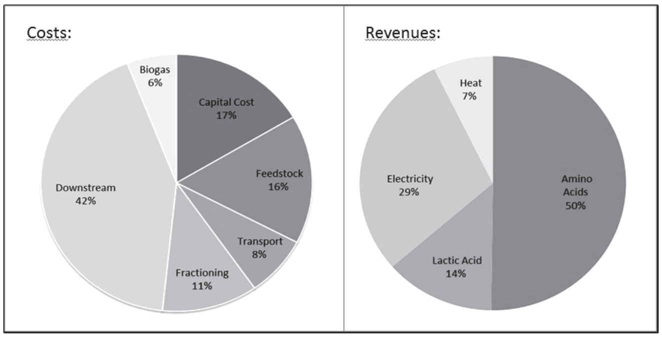

Figure 1: Structure of costs and revenues on average of 500 simulation runs

Downstream costs account for 42% of the total production costs. They include all costs for the separation of the silage press juice into marketable amino- and lactic acid products. On the revenue side amino acids is the key product, accounting for half of the total revenues.

3.2 Optimal locations and sizes

The assessment of favourable biorefinery locations is based on Monte Carlo Simulation results. The number of times a location is chosen in the optimization model is used as indicator for the economic sensitivity of specific locations to changing parameter values (figure 2).

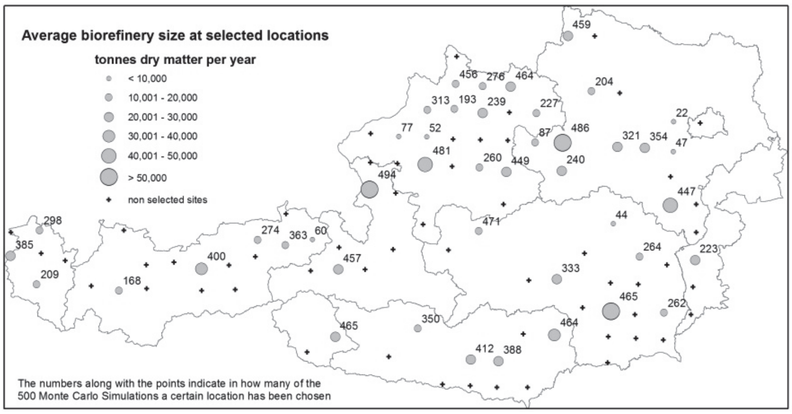

Figure 2: Selected biorefinery locations and their average capacity

The size of the points indicates the annual biorefinery capacity and the numbers indicate the number of simulations results that included a certain location.The Monte Carlo Simulation results reveal that 20 to 40 biorefineries with annual capacities from 20,000 to 40,000 t dm would optimally utilize the biomass potential of about 880,000 t dm grass silage. Biorefineries with annual capacities of more than 40,000 t dm are only feasible in regions which have a high biomass density as well as significant heat demand. Mean feedstock transportation distances range from 10 to 40 km depending on the regional biomass supply and the realized plant size.

3.3 Sensitivity Analysis

The results confirm that the profitability of green biorefineries is mainly determined by the prices for amino acids and the variable downstream costs. The optimal capacity of biorefineries is driven by the trade-offs between transportation and capital costs. Ranges of elasticities have been computed for the parameters, which have significant influence on the biorefinery capacity (figure 4). According to these results, a one percentage increase in capital costs is associated with the same increase in the optimal biorefinery capacity. Varying transportation costs result in slightly lower changes.

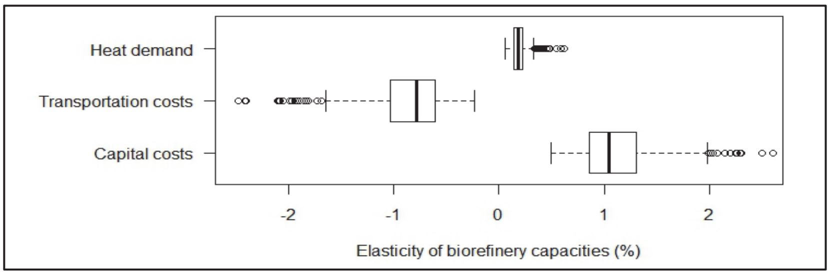

Figure 4: Elasticity between biorefinery capacities and model parameters (boxplots of distributions of parameters)

A third parameter showing significant influence is the regional heat demand. The optimal plant size increases with heat demand as more of the surplus heat can be utilized.

4. Conclusion

The technical feasibility of the green biorefinery concept has been demonstrated in previous studies (MANDL et al., 2011). This article focuses on the optimal design of a green biorefinery supply chain as well as on the identification of key determinants for the economic viability. The model results show that the profitability is largely dependent on the product prices and the variable downstream costs. However, learning effects for downstream technologies such as nanofiltration or electrodialysis could help lowering these costs in the near future. Furthermore, an optimal supply chain design is prerequisite for the economic viability of green biorefineries.

Future research should address the competition for grassland biomass between green biorefineries, biogas plants and feed production for dairy farms. Results of the Monte Carlo Simulation indicate that green biorefineries can compete with traditional grassland uses. Therefore, large scale biorefineries potentially result in higher regional prices for grass silage, particularly at favourable sites.

Moreover, the Monte Carlo Simulation results suggest that investments in green biorefineries can be risky due to the uncertainties of many parameters such as product prices or downstream costs. Therefore, risk management shall be a central component in the green biorefinery concept.

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References

AMON, T., HOPFNER-SIXT, K., AMON, B., BAUER, A., HANDLER, F., BLUMAUER, E., EDER, M., STÜRMER, B. and RITZMANN, A. (2008): Optimierung der Beschaffungs- und Distributionslogistik bei großen Biogasanlagen. Energiesysteme der Zukunft – Endbericht. Wien: BMVIT.

AUSTROPAPIER (Vereinigung der Österreichischen Papierindustrie) (2011): Papierindustrie zur Ökostrom-Novelle: Finanzierbarkeit und Effizienz müssen im Vordergrund stehen. URL: www.austropapier.at

BMVIT (Bundesministerium für Verkehr, Innovation und Technologie) (2009): Nutzung nachwachsender Rohstoffe Berichte aus Energie- und Umweltforschung. Fabrik der Zukunft – Hintergrundband -Teil 1, 2. Aufl. Wien.

DE JONG, E., LANGEVELD, H. and VAN REE, R. (2010): IEA Bioenergy Task 42 Biorefinery. URL: www.IEA-Bioenergy.Task42-Biorefineries.com

DÖRING, G., SCHILCHER, A., STROBL, M., SCHLEICHER, R., SEIDL, M. and MITTERLEITNER, J. (2010): Verfahren zum Transport von Biomasse-Nr. II–6/2010. Freising: Arbeitsgemeinschaft Landtechnik.

JACK, M. W. (2009): Scaling laws and technology development strategies for biorefineries and bioenergy plants. Bioresource Technology, Volume 100, 6324-6330.

KAMM, B., KAMM, M., GRUBER, P. R. and KROMUS, S. (2006): Biorefinery Systems – An Overview. In: Kamm, B., Gruber, P. R. and Kamm, M. (Eds.): Biorefineries – Industrial Processes and Products. Chichester: JohnWiley & Sons, Ltd.

KROMUS, S., WACHTER, B., KOSCHUH, W., MANDL, M., KROTSCHECK, C. and NARODOSLAWSKY, M. (2004): The Green Biorefinery Austria – Development of an Integrated System for Green Biomass Utilization. Chemical and biochemical engineering quarterly, 18, 1, 7-12.

MANDL, M., NOVALIN, S., REINHOFER, M., ASTLEITNER, D., VU, H. T., KROMUS, S., ZWICKMAIR, T., TAUBER, M., BÖCHZELT, H. and SCHNITZER H. (2011): Grüne Bioraffinerie Phase III - Entwicklung von Technologien zur Prozess-intensivierung hinsichtlich Gewinnung und Verwertung von Milchsäure, Aminosäuren und Fasern. Berichte aus Energie- und Umweltforschung. Wien: BMVIT.

OPENSSTREETMAP (2011): The Free Wiki World Map. URL: www.openstreetmap.org

SCHMIDT, J., LEDUC, S., DOTZAUER, E. and SCHMID, E. (2010): Potential of biomass fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. International Journal of Energy Research, vol. 34, 970-985.

SATELLI, A. (s.a.): Global sensitivity Analysis: An Introduction. Italy: European Research Centre of Ispra.

WILLIAMS, J. R. (1995): The Epic Model. In: Singh, V.P. (eds): Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colorado.

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