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Decision Support for the Planning of Production Systems for Renewable Resources

Habilitationsschrift

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Abstract

For the substitution of fossil fuels with renewables, the use of biomass in production processes is often considered ambivalent regarding economic viability and other sustainability criteria. To address the sustainability and efficiency concerns associated with biomass conversion, concepts for multi-input and multi-output biorefineries have been discussed and tested. However, lacking economic viability, none have been realized on an industrial scale until today. Instead, biogas plants, mostly used for combined heat and power generation, have become the most prevalent biomass conversion process in Germany. Incentivized by feed-in tariffs and other subsidies, almost 10,000 biogas plants operate in Germany in 2019. These and other biomass-fueled plants can produce power flexibly, but at higher cost than most other renewable and fossil power plants.

In order to make sound decisions for production systems for renewable resources, comprehensive decision support is needed. The choices of capacity, configuration and location are among the major challenges for the planning of such production systems. This habilitation elaborates decision support by considering relevant strategic and operational aspects of production systems for renewable resources. The covered strategic aspects concentrate on the interdependent choices of plant capacity, configuration and location, which are addressed with nonlinear programming and geographic information systems. For plants for the conversion of biomass, large plant capacities lead to both economies of scale and rising specific transportation cost, which plays a major role for their economic viability. The operational aspect of scheduling flexible and programmable power generation and consumption is investigated as well because of its rising importance due to the increasing share of intermittent power generation from photovoltaic cells and wind turbines. Optimization models, application programming interfaces and available data sources are combined to offer the aspired decision support.

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List of Abbreviations

API	Application Programming Interface
ArcGIS	*commercial GIS software*
BAGV	Battery Automated Guided Vehicle
BARON	*commercial nonlinear optimization solver*
BC	British Columbia
BtL	Biomass-to-Liquid
C_4, C_5, C_6	hydrocarbons with 4,5 and 6 carbon atoms
CFE	Cassava Fuel Ethanol
CHP	Combined Heat and Power
CLC	Corine Land Cover
CONOPT	*commercial nonlinear optimization solver*
DME	Dimethyl-Ether
DR	Demand Response
DSI	Demand-Side Integration
DSM	Demand-Side Management
EA	Evolutionary Algorithm
EEG	(German) renewable energy law
EEX	European Energy Exchange
EPEX	European Power Exchange
ES	Evolutionary Strategy
FO	Flexibility Option
FLh	Full load hours
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System (*commercial optimization editor)*
GIS	Geographic Information System
GHG	Greenhouse Gas
GME	Gestore dei Mercati Energetici
IEA	International Energy Agency
IRR	Internal Rate of Return
KNITRO	*commercial nonlinear optimization solver*
$(k)Wh_{el}$/ $(k)Wh_{th}$	(kilo) Watt hour of electrical/ thermal energy
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
MILP	Mixed-Integer Linear Programming
MINOS	*commercial nonlinear optimization solver*
NLP	Nonlinear Programming
NO_X	Nitrous Oxides
NPV	Net Present Value
OSBL	Outside Battery Limits
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
PV	photovoltaic
ROI	Return On Investment
ODT	Oven Dry Tonnes
SMART	Simple Multi-Attribute Rating Technique
SNG	Synthetic Natural Gas
SNOPT	*commercial nonlinear optimization solver*
SOC	State-Of-Charge
SQP	Sequential Quadratic Programming
UC(P)	Unit Commitment (Problem)
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant

1 Introduction

Since the industrial revolution, the production of energy fuels and chemicals has been based on fossil resources, such as coal, oil and natural gas. As the available quantities of these fossil resources are finite, and their combustion causes significant CO_2 emissions, their continued use is commonly considered unsustainable. The increasing relevance of sustainability, highlighted by the ongoing public discussions regarding climate change and the efficient use of resources, is therefore a major challenge for the design of production systems in businesses that have hitherto relied on fossil resources (Geldermann et al., 2016a).

Sustainable decisions in a business context require a long-term goal orientation, the consideration of multiple perspectives, and therefore criteria, and theoretically sound decision support (Souren et al., 2016). Developing more sustainable production systems is especially challenging, as production systems using renewable resources differ significantly from those based on fossil resources both for energy and materials production. Two commonly cited challenges in this context are the intermittent power generation from wind turbines and photovoltaic (PV) cells on the one hand (Zweifel et al., 2018), and the more challenging production of energy fuels and chemicals from biomass instead of coal, oil or natural gas on the other (Gold and Seuring, 2011; Caputo at al., 2004).

Production systems can be characterized by their input, throughput and output. Feasible inputs must be procured and combined in a production process, thus becoming throughput, to ultimately be converted into the desired output (Gutenberg, 1976). These three stages represent the basic components of a production enterprise, namely procurement, production and distribution (Kellner et al., 2018). While all these components have already been the subject of extensive research in the context of many industries and fields of application, the continuous development and increasing importance of renewable energy and resources requires novel, problem-specific approaches.

1.1 Motivation

The challenges of intermittent renewable power production and biomass procurement play a connected role in the transition towards a more sustainable power supply, as biomass-based power plants, such as combined heat and power (CHP) and biogas plants, can produce power flexibly, potentially alleviating the intermittent production of wind turbines and PV cells to some extent. However, the production cost of a kilowatt hour (kWh_{el}) e.g. from biogas is higher than for most other renewables and fossil power plants at comparable full load hours (FLh), as shown in Figure 1 (Kost and Schlegl, 2018).

Even outside the power sector, processes using biomass inputs play an important role in the context of production systems for renewable resources. In the other energy sectors, i.e. the sectors for heat and transportation fuels, biomass is currently almost the only feasible alternative for the prevalent fossil fuels, at least until e-mobility reaches a relevant market share (Zweifel et al., 2018). This is also true for material uses of renewables, where biomass plays an important role both as an established raw material (e.g. construction timber) and as the potential basis to produce bio-chemicals. In the context of cascading use of renewables, biomass can be used in several industries before ultimately serving as an energy fuel (Geldermann et al., 2016b). Consequently, biomass is an important input for renewable energy and resources.

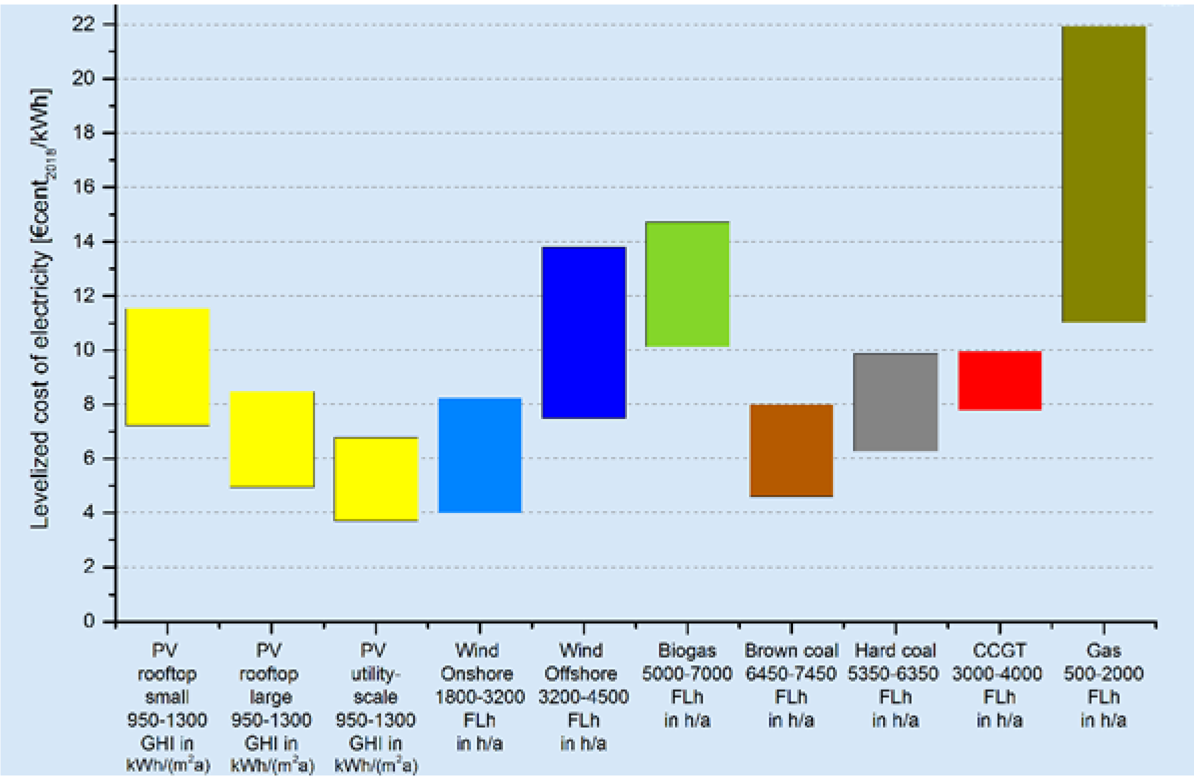

Figure 1: Levelized cost of electricity of renewable energy technologies and conventional power plants at locations in Germany in 2018 (Kost and Schlegl, 2018)

For decisions associated with the production of outputs from biomass, input and throughput decisions, which deal with the combination and conversion of inputs (Gutenberg, 1976; Dyckhoff and Spengler, 2010; Kellner et al., 2018), are particularly relevant. Biomass conversion plants are faced with specific constraints on the economically viable quantity of suitable input materials, as the low density of biomass strongly increases specific transportation costs if distances increase. The severity of this trade-off and the resulting optimal production plant capacity depend on the availability of input materials in the vicinity of a biomass conversion plant's location. This basic phenomenon is challenging for almost all plants processing biomass, including those for food production from agricultural products. For plants producing biofuels from crops or biogas from corn and animal wastes, it is especially important, as biomass inputs with very low energy densities must be dealt with (Caputo et al., 2004). For inputs such as residual wood or straw, which are frequently considered as inputs for a relatively sustainable supply of renewable resources and bioenergy, the trade-off between economies of scale and rising specific transportation cost is of central importance for the determination of plant capacities.

While biomass conversion plants are therefore particularly limited in input capacity, they potentially offer a large portfolio of renewable material products and energy fuels. The product portfolio of a biomass conversion plant depends on the employed combination of conversion processes, also referred to as the plant's configuration. Thus, as both the annually available quantity of biomass and the capacity of each individual conversion plant are limited, decisions concerning a plant's capacity, configuration and location need to be made to achieve a suitable combination of feasible input materials, conversion processes and products. While capacity, configuration and location decisions are strategic (Dyckhoff and Spengler, 2010; Kern, 1992), the operational level also need to be considered in the production management of renewable energy plants. If product prices change frequently, as in the power market, an optimized production scheduling is required. Proposing adequate quantitative decision support models for the planning and operation of production systems for renewable resources is the core objective of this habilitation.

1.2 Overarching research questions and research objective

For production plants utilizing renewables, residuals from forestry and agriculture are preferred input materials, as there are only few competing uses for this kind of feedstock. In this context, efficient supply structures are especially important, as most kinds of residual biomass feature a low value per unit of volume, resulting in relatively high transportation cost. To support the design of such supply structures, one needs suitable models to determine optimal capacities, configurations and locations.

Optimization models have often been found to be appropriate methods to address the planning problems associated with biomass conversion plants and the associated supply networks. Such problems have been formulated as mixed integer linear programs (MILP) by Kim et al. (2011), maximizing profit by determining optimal capacities and locations. A different combination of problems, namely product portfolio and supply chain optimization for biorefineries, was addressed by Mansoornejad et al. (2010). MILP approaches were also employed by Walther et al. (2012) for location and technology selection from a set of ten potential locations and eight different conversion plant technologies and sizes. Instead of MILP formulations, Geraili et al. (2014) and Sharma et al. (2013) used a combination of the process engineering software Aspen Plus and MATLAB to optimize the net present value of a biorefinery by adapting its configuration and capacity. While Sharma et al. (2013) have identified biomass transport as a major bottleneck, they have not explicitly considered the spatial distribution of biomass.

This bottleneck was already analytically investigated by Overend in 1982, followed by the application of a nonlinear optimization approach by Jenkins (1997) to minimize the unit prices of a biomass conversion plant. Caputo et al. (2004), Cameron et al. (2007), as well as Wright and Brown (2007) assumed a circular, instead of rectangular, catchment area. Following this assumption, the specific transportation cost of the input biomass per ton of production capacity is proportional to the square root of the plant size (Kumar et al., 2003). When expressing the total transportation cost for input biomass as a function of plant size, an exponent of 1.5 can be derived (Wright and Brown, 2007; Lauven, 2014). Such functions make it possible to analyze interactions between different influencing factors, such as plant capacity and biomass transportation cost using nonlinear equations.

Ba et al. (2016) have compiled a comprehensive overview of methods of Operations Research that have been used for the performance evaluation of biomass supply chains. In order add to this body of knowledge, and to support sound investment decisions in the field of production systems for renewable resources, several research questions will be addressed in this habilitation:

- What is an optimal capacity to balance economies of scale and rising specific biomass transportation cost?
- What is the optimal configuration for a biomass conversion plant to produce valuable products without encountering prohibitive investment-related costs resulting from high investment in sophisticated upgrading and separation equipment?
- What is the best location to ensure feasible quantities of biomass inputs at economically viable cost?
- By how much can power revenues be increased by adapting an optimized scheduling?

While optimization models from Operations Research have successfully been applied to solve capacity, configuration and location problems in many industries, the problem is especially challenging for biomass conversion plants. This is because in the case of biomass conversion, these three aspects are intertwined: Depending on the location, the quantity of available inputs will differ, which leads to a different optimal capacity, which influences the optimal configuration. Therefore, decisions should not be made by consecutively considering these three aspects. Instead, feasible optimization techniques to adequately address each aspect must be identified and integrated into algorithms in order to consider all three aspects simultaneously or, at least, iteratively (Trippe et al., 2013).

Due to the challenge of ensuring viable biomass procurement costs, common plant capacities have been lower than for common fossil fuel-fired power plants. Consequently, the lower specific production costs and lower specific energy consumption that can usually be realized through economies of scale (Gutenberg, 1976; Geldermann, 2014), could only be realized to a limited extent. For exceptionally large capacities, the growth of biomass transportation cost even leads to diseconomies of scale, and thus limits feasible plant capacities (Ekşioğlu et al., 2015; Gold and Seuring, 2011; Maack et al., 2017).

Despite being limited in their effect, economies of scale nevertheless play an important role for the planning of biomass conversion plants. This is especially true for plants with multiple products, such as biorefineries. Biorefineries are plants that convert biomass into intermediates, energy fuels and chemicals, i.e. into a very similar set of products compared to crude oil refineries. As the conversion processes inside such a biorefinery are themselves subject to (process-specific) economies of scale, large biorefineries can sometimes produce outputs at competitive cost that would be too expensive when produced in a small biorefinery of the same configuration. At the same time, the production of valuable products plays a major role for the economic viability of biomass conversion plants.

The development of both economies of scale and specific transportation cost relative to biomass conversion plant capacity can be approximated with nonlinear optimization models. Due to the challenge of identifying the global optimum in nonlinear optimization problems, finding a suitable combination of modeling technique and nonlinear solver is critical to reliably solve such problems to optimality (Tawarmalani and Sahinidis, 2002).

Location planning has been a field of application for optimization modeling for more than 50 years, often attempting to determine the location of certain facilities, such as warehouses, within supply chain networks (Aikens, 1985; Melo et al., 2009). As biomass conversion plants can in principle be constructed in a large number of potential locations, a continuous solutions space (instead of a set of discrete locations) should be searched for the best location(s) (Günther and Tempelmeier, 2016). While choices between discrete locations are often modeled using mixed-integer linear programming (MILP), searching in a continuous solution space can be realized by applying heuristics if the duration to find optimal solutions becomes prohibitive due to the potentially large number of feasible locations.

Once a biomass conversion plant has started its operation, scheduling decisions are another aspect to consider. For example, the revenues from the sale of its products can depend on changing market prices, which should be considered for scheduling decisions. In the context of power plants, scheduling decisions are usually modelled as unit commitment problems, which can be expressed as optimization problems. “Unit commitment” refers to a situation in which several alternative power plants (“units”) are available, and the operator of these plants needs to decide which of these are the most economic to satisfy power demand. Decisions in such unit commitment problems are usually made on an hourly or 15 minute-basis (Padhy 2004). The decisions on whether to operate a plant in each time frame are modelled as binary variables. Accordingly, unit commitment problems are therefore solved with binary or, more commonly, mixed-integer linear programming (MILP) models (Saravanan et al. 2013; Morales-España et al. 2015). The constraints in such unit commitment models represent operational considerations, such as ramp-up times, load constraints or storage limits (Valenzuela and Mazumdar 2001; Saravanan et al. 2013). Conversely, operators of electric loads such as battery charging stations can attempt to reduce their power purchasing costs by choosing times with low power prices for battery charging.

1.3 Methods

Modelling the nonlinear developments of both economies of scale and biomass transportation cost for different biomass conversion plant capacities (Wright and Brown, 2007) can result in the identification of local, instead of global, optima if the problem is neither convex nor concave (Rentizelas et al., 2009). When nonlinear problems comprise only few optimization variables, a piecewise linearization can be carried out (Geißler et al., 2012). However, some nonconvex nonlinear problems can be solved with available advanced nonlinear solver software instead of a piecewise linearization (Tawarmalani and Sahinidis, 2002). However, when the extent of the data in an optimization model becomes too great, or the nonlinear function is too “noisy” to employ exact nonlinear solvers, heuristics can be used to approximate good, but often not necessarily optimal, solutions (Rechenberg, 1994).

The quality of the decision support from optimization models depends on the extent and quality of the data that these models can process. As data becomes available from more and more different sources and applications, optimization models and applications can be combined, e.g. by using Application Programming Interfaces (APIs). APIs make it possible to develop an algorithm which can call upon optimization models or other kinds of software (Rauf et al. 2019). Even when no software other than optimization modeling editors and solvers are used, APIs can help to conduct advanced analyses over large datasets, e.g. by mimicking day-to-day planning with limited knowledge of the future. In terms of location planning, for example, the data stored in Geographic Information Systems (GIS) can be of value when geographic data is required for assessments such as transportation distances and realistic raw materials potentials (Maack et al., 2017).

The papers in this habilitation comprise several methodological developments. Combinations of exact optimization algorithms, heuristics and Geographic Information Systems are applied in the planning of production systems for renewable resources and in the operation of flexible power producers and consumers. As the economic viability is a major obstacle for the realization of such production systems, the presented optimization models and algorithms are primarily focused on economic criteria.

However, in addition to economic criteria, the increasing awareness and importance of sustainability means that ecological and social criteria should also be considered (Gold, 2011). Whenever sustainability is assessed and discussed, the weighting of the three dimensions economy, environment, and society as well as of the potentially numerous individual criteria needs to be agreed upon (Eigner-Thiel et al., 2013). While the importance, and consequently the weighting, of different criteria in a multi-criteria decision cannot be determined without consulting the actual decision maker(s), a specific visualization technique is developed to enhance transparency and thus aid in energy-related multi-criteria decision-making problems.

1.4 Areas of application

The developed methods are applied in three main fields of application. The first is the investment planning for biomass conversion plants, the second is sustainability assessments for bioenergy pathways and the third is the operation of flexibility options, including flexible power generation plants, storages and consumers. Figure 2 gives an overview of methods, areas of application and the research objective of this habilitation.

The economic viability of biomass conversion processes to produce biofuels, power and bio-chemicals has undergone several changes since the introduction of the German renewable energy law (EEG) in the year 2000. Often significantly influenced by tax exemptions, feed-in tariffs or other public subsidizing, biomass conversion processes have been considered an attractive investment in one year, only to lose this status when laws and regulations were altered. An example is the subsidy framework for biogas plants in the EEG of 2012, which was followed by a much more restrictive framework in the EEG of 2014. In addition to economic arguments, biofuels have been contested due to the “food versus fuel” debate and their life cycle emissions.

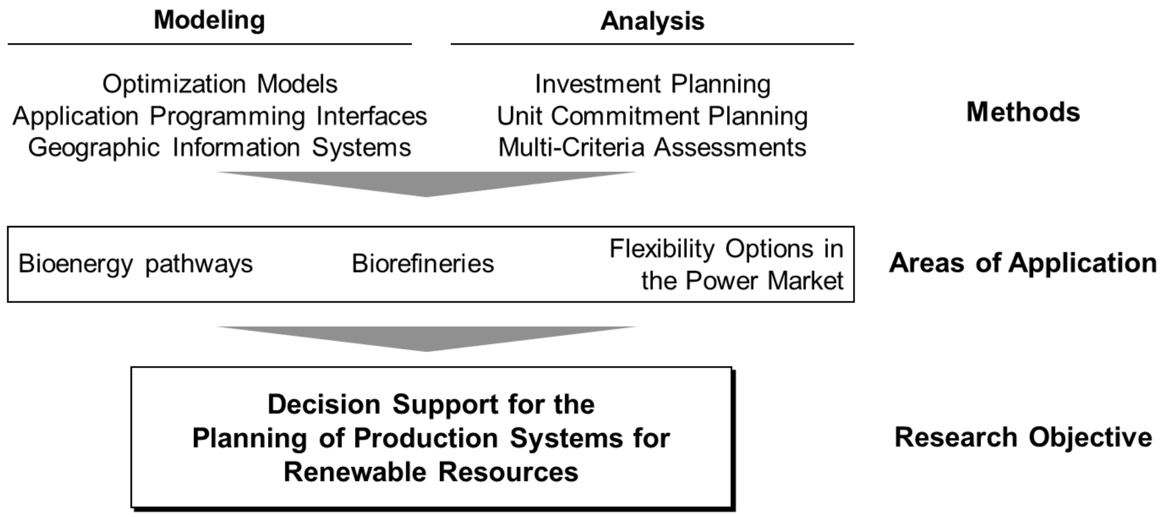

Figure 2: Research methods and objective

In order to deal with some of this criticism, *biorefinery* concepts have been developed: By using biomass as efficiently as possible to produce multiple products, biorefineries are considered a promising technology to replace fossil fuels in several fields of application in the future (Gold, 2011). Until biorefinery concepts can contribute to a more efficient use of the available biomass, the currently available combinations of input material, conversion technology and output, together labeled a “bioenergy pathway” (Sapkota et al., 2015), have to be judged by their sustainability performance to avoid some of the criticism that the use of biomass has met in the past.

Due to the rising share of intermittent renewable power sources, such as wind turbines and photovoltaic cells, flexibility of power generation and consumption becomes more important. As the German power market consists of both a day-ahead and an intraday market, two-stage approaches are employed to reflect this market structure (Huang 2017). Efficient use of the potential flexibility of flexible power generation and consumption is the third area of application that is investigated in this habilitation.

1.5 Habilitation overview

The remainder of this habilitation is organized as follows: The eight papers that this cumulative habilitation consists of are introduced (the full-texts are available through the links provided in the remainder of this sub-chapter) before conclusions are drawn in Chapter 2. An overview of the included papers, the journals in which they have been published, their publication status as well as an assessment of the extent to which the author of this habilitation contributed to a) the underlying idea, b) the execution of the conducted analysis and c) the writing and editing of the manuscript, can be found in Table 1.

Table 1: Contributions to the papers
from ■ (minor contribution) to ■■■■■ (entirely my contribution)

Paper 1: Determinants of economically optimal cassava-to-ethanol plant capacities with consideration of greenhouse gas emissions

Idea	■■■	Published (2014)	*Applied Thermal Engineering*			
Analysis	■■■■	Authors: L.-P. Lauven, B. Liu, J. Geldermann				
Manuscript	■■■	Impact Factor: 4,026	SJR: 1,769		VHB Jourqual 3:	**-**

Paper 2: Simultaneously optimizing the capacity and configuration of biorefineries

Idea	■■■■■	Published (2018)	*Computers and Industrial Engineering*			
Analysis	■■■■	Authors: L.-P. Lauven, I. Karschin, J. Geldermann				
Manuscript	■■■■	Impact Factor: 3,518	SJR: 1,334		VHB Jourqual 3:	**B**

Paper 3: Improving biorefinery planning: Integration of spatial data using exact optimization nested in an evolutionary strategy

Idea	■■	Published (2018)	*European Journal of Operational Research*			
Analysis	■■	Authors: T. Schröder, L.-P. Lauven, J. Geldermann				
Manuscript	■■	Impact Factor: 3,806	SJR: 2,205		VHB Jourqual 3:	**A**

Paper 4: Strategic Planning of a multi-product wood-biorefinery production system

Idea	■	Published (2019)	*Journal of Cleaner Production*			
Analysis	■	Authors: T. Schröder, L.-P. Lauven, T. Sowlati, J. Geldermann				
Manuscript	■■	Impact Factor: 6,395	SJR: 1,620		VHB Jourqual 3:	**B**

Paper 5: Using PROMETHEE to assess bioenergy pathways

Idea	■■	Published (2019)	*Central European Journal of Operations Research*			
Analysis	■■	Authors: T. Schröder, L.-P. Lauven, B. Beyer, N. Lerche, J. Geldermann				
Manuscript	■■	Impact Factor: 1,260	SJR: 0,51		VHB Jourqual 3:	**C**

Paper 6: Estimating the revenue potential of flexible biogas plants in the power sector

Idea	■■■■	Published (2019)	*Energy Policy*			
Analysis	■■■■	Authors: L.-P. Lauven, J. Geldermann, U. Desideri				
Manuscript	■■■■	Impact Factor: 4,880	SJR: 1,988		VHB Jourqual 3:	**B**

Paper 7: Two-stage unit commitment modeling for virtual power plants

Idea	■■■■■	Published (2019)	*Operations Research Proceedings 2018*			
Analysis	■■■■■	Author: L.-P. Lauven				
Manuscript	■■■■■	Impact Factor: -	SJR: -		VHB Jourqual 3:	**D**

Paper 8: Demand-side integration for electric transport vehicles

Idea	■	Published (2015)	*International Journal of Energy Sector Management*			
Analysis	■■	Authors: J. Schmidt, L.-P. Lauven, N. Ihle, L. Kolbe				
Manuscript	■■	Impact Factor: -	SJR: 0,33		VHB Jourqual 3:	**B**

The trade-off between the two nonlinear items biomass transportation costs and economies of scale, and the resulting difficulties of determining an optimal plant capacity are challenges for the planning of biomass conversion plants. Paper 1, which was jointly initiated with Prof. Beibei Liu from Nanjing University during a research stay in Göttingen, addresses this issue for bioethanol plants based on cassava roots as input material. The optimization model is also used to investigate the trade-off between the return on investment and greenhouse gas emissions from transportation resulting from large plant capacities. The methodological approach of Paper 1 is to combine optimization models with results of Prof. Liu's life cycle assessments (LCA). As biomass yields (and environmental impacts) also depend on the use of fertilizer, an approximation of trade-offs between using (more) fertilizer for increased yields per hectare is conducted in scenarios. Paper 1 has been published in 2014 in Applied Thermal Engineering with the DOI http://dx.doi.org/10.1016/j.applthermaleng.2014.05.009.

A parallel Open Access Version is available on GRO.publications[1].

Paper 2 is the first of three papers dealing with multi-product biorefineries. It briefly introduces biorefineries as multi-input and multi-output biomass conversion plants. Determining optimal capacities becomes more complex once the above-mentioned nonlinear trade-off must be solved for several sub-plants, as this results in a multidimensional determination of optimal configurations, which results in a nonconvex objective function. To cope with this non-convexity, a suitable solver is selected. In contrast to the following two papers, Paper 2 is based in the assumption that biomass availability can be approximated by using an average value for a geographical area. Paper 2 has been published in 2018 in Computers and Industrial Engineering with the DOI https://doi.org/10.1016/j.cie.2018.07.014.

A parallel Open Access Version is available on GRO.publications[2].

As an investigation based on average values and without definite locations of biomass sources is very hypothetical, Paper 3 and Paper 4 employ a combination of exact nonlinear optimization, Evolutionary Strategy heuristics and Geographical Information Systems (GIS), implemented in Python script. This combination, which was conceptualized by Dr. Tim Schröder during his PhD activities that I co-supervized with Prof. Jutta Geldermann, is applied to the planning of two different biorefinery concepts in two real geographical settings, a synthesis gas biorefinery in Germany (Paper 3) and a lignocellulose biorefinery in Western Canada (Paper 4). Therefore, the capacity and configuration planning approach introduced in Paper 1 and Paper 2 is extended to include location planning as well. Paper 4 also introduces constraints to model limited sales volumes, as the markets for some of the discussed specialty chemicals are currently quite small. Paper 3 has been published in 2017 in the European Journal of Operational Research with the DOI http://dx.doi.org/10.1016/j.ejor.2017.01.016.

[1] https://publications.goettingen-research-online.de/handle/2/32319

[2] https://publications.goettingen-research-online.de/handle/2/71835

A parallel Open Access Version is available on GRO.publications[3].

Paper 4 has been published in 2019 in the Journal of Cleaner Production with the DOI https://doi.org/10.1016/j.jclepro.2018.12.004.

A parallel Open Access Version is available on GRO.publications[4].

Due to the importance of sustainability discourses in the European research project BIOTEAM, a multi-criteria visualization approach is presented in Paper 5. This approach was developed jointly with Dr. Tim Schörder, Beatriz Beyer and Dr. Nils Lerche to comprehensively visualize an assessment based on economic, environmental, and social criteria. If the substitution of fossil fuels by biomass is to be measured against these three dimensions of sustainability, and therefore the large number of criteria that each of the dimensions consists of, it becomes harder to comprehend the decision problem in its entirety. In order to compare several bioenergy pathways, i.e. combinations of inputs, conversion pathways and outputs, a comprehensive visualization for multi-criteria decision support is proposed to enhance transparency especially regarding the influence of different criteria weightings. Paper 5 has been published in 2019 in the Central European Journal of Operations Research with the DOI https://doi.org/10.1007/s10100-018-0590-3.

A parallel Open Access Version is available on GRO.publications[5].

Paper 6, initiated with Prof. Umberto Desideri during a research stay in Göttingen, deals with an operational planning problem for one of the most prevalent bioenergy pathways in Germany. Biogas plants, of which almost 10,000 were in operation in 2017 (Fachverband Biogas, 2018), can be outfitted with increased generator capacity to provide power flexibly instead of constantly. Flexible biogas plants are therefore so-called flexibility options (FO), which play an important role in energy systems with highly decentralized and intermittent power generation. As the supply and demand of power must always be balanced, the intermittent power supply from wind turbines and photovoltaic cells requires flexible power generation units and consumers, as well as storage units, to restore the balance. Paper 6 presents an analysis of unit commitment decisions for biogas plants in Germany and Italy over a time span of ten years to determine under which market environments sufficient additional revenue could have been earned to cover the investment-related cost of the investment in flexible power generation. Paper 6 has been published in 2019 in Energy Policy with the DOI https://doi.org/10.1016/j.enpol.2019.01.007.

A parallel Open Access Version is available on GRO.publications[6]

Biogas plants can be operated together with flexible consumers and storage units. As one way of monetizing flexibility in the power market is to participate in day-ahead and intraday trading

[3] https://publications.goettingen-research-online.de/handle/2/72009

[4] https://publications.goettingen-research-online.de/handle/2/72395

[5] https://publications.goettingen-research-online.de/handle/2/70989

[6] https://publications.goettingen-research-online.de/handle/2/114203.

in energy stock exchanges, Paper 7 proposes a two-stage algorithm for the aggregation of flexibility options with an intermittent photovoltaic plant in a virtual power plant (VPP). Paper 7 has been published in 2019 in the Operations Research Proceedings 2018 with the doi https://doi.org/10.1007/978-3-030-18500-8_22.

A parallel Open Access Version is available on GRO.publications[7].

Demand-side flexibility, which has not explicitly been included in Paper 6 and Paper 7, is the focus of Paper 8. Based on the BESIC research project and Dr. Johannes Schmidt's PhD research at the Chair of Information Management of Prof. Lutz Kolbe with a leading port operator in Germany, several use cases of applying flexible consumption in the context of battery automated guided vehicles (BAGV) are investigated together with Dr. Schmidt and Dr. Norman Ihle of the University of Oldenburg. In this field of application, constraints to optimize the loading of batteries depend on the operational flexibilities of the logistics processes. Paper 8 has been published in 2014 in Applied Thermal Engineering with the doi http://dx.doi.org/10.1108/IJESM-11-2014-0002.

A parallel Open Access Version is available on GRO.publications[8].

In the final Chapter, a conclusion is given to condense the results and insights of the previous chapters, including an outlook on related topics of interest that could be investigated in the future.

[7] https://publications.goettingen-research-online.de/handle/2/114204

[8] https://publications.goettingen-research-online.de/handle/2/15456

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2 Conclusion

The substitution of fossil resources with renewables leads to several challenges for the planning of production systems. Established planning approaches, which are based on the conditions of energy fuel extraction from mines or wells and continuous power output in power plants, must be adapted to be applicable for the planning of production systems for renewable resources.

Due to the wide distribution of potential biomass inputs, the planning of facility capacity, configuration and location is particularly important for production plants for the conversion of biomass into energy, fuels and materials. In the first four papers of this thesis, integrated algorithms for the planning of capacity, configuration and location have been introduced and applied on biofuel plants and biorefineries. The combination of geographic data in geographic information systems (GIS), Evolutionary Strategy heuristics and nonlinear solvers resulted in the development of a specific planning approach for such production plants.

As the number of potential alternative biomass conversion technologies is quite large, decisions to invest in biomass conversion plants require the consideration and comparison of many alternatives. Paper 5 has shown that an adequate visualization technique can improve decision support for problems with numerous criteria and several alternatives.

On the operational level, the increasing application of intermittent power sources results in the need to provide flexibility in the power market. Papers 6 through 8 deal with unit commitment decisions in the operation of flexibility options to show the potential role of bioenergy plants and other flexibility options in the power market.

In the following sub-chapters, the theoretical contributions are reviewed, before the limitations of the developed methods are discussed and implications for research and practice are outlined.

2.1 Theoretical contributions

An approach for the nonlinear optimization of capacity and configuration of biorefineries under simultaneous consideration of intermediate products, process-specific economies of scale and rising specific biomass transportation cost was implemented and presented in Chapter Paper 1. As the problem is nonconvex when optional sub-processes are considered, it can only be solved with suitable solvers, such as the BARON solver, if location planning is excluded, as explained in Paper 2. Once location planning is considered as well, the inclusion of biomass sources in the context of location planning with GIS leads to a noisy objective function. In conjunction with the large extent of geographic data that must be handled, solving such problems with exact optimization algorithms would not be feasible within a realistic time frame. Instead, the extended planning approach for capacity, configuration and location can be handled with the developed combination of exact nonlinear optimization and Evolutionary Strategy heuristics within a specifically developed Python-based metaheuristic, as demonstrated in Paper 3 and Paper 4.

While the Paper 1 through 4 focused on the strategic planning under economic considerations, the planning of biomass conversion plants can be aided by a multi-criteria assessment of criteria from all dimensions of sustainability. In order to handle numerous alternatives and criteria, the influence of weights in such a multi-criteria sustainability assessment of several alternatives can be facilitated by using an illustration as introduced in Paper 5.

In addition to the strategic planning of biomass conversion plants, operational issues have become more important in recent years, as renewable power plants are often operated flexibly, instead of constantly throughout the year. For a suitable optimization in the context of flexibility option aggregation, approachs including unit commitment optimization and a two-stage algorithm for the consideration of both day-ahead and intraday power prices has been presented Paper 6 through 7.

Papers 3, 4, 6 and 7 have also shown approaches to combine and adapt optimization models, application programming interfaces (APIs) and data sources to cope with increasingly challenging planning tasks. By using APIs, optimization models can be based on more potent (solver) software and more comprehensive data sources. Such combinations were implemented for the interdependent strategic planning of capacity, configuration and location and the operational unit commitment planning for renewable power generation. In the course of these implementations, several specific challenges were addressed.

2.2 Limitations

The presented planning approaches focus on the planning of the design and operation of production systems for renewable resources. Important issues that would require additional investigations would be, for example, consumers' attitudes and willingnesses to pay regarding renewable products, the roles of taxes and financing in the planning, realization and operation of production plants for renewable resources as well as the role of such plants in firms' corporate strategies and networks.

Even if the focus is on the design and operation of production systems, however, models like the ones presented in this habilitation are per definition simplifications of the modeled system and cannot cover all its aspects (Gutenschwager et al., 2017). The described optimization models and the resulting assessments of economic feasibility are designed for a preliminary assessment, which would have to be improved once more information becomes available in advanced planning stages. Consequently, there are several aspects that would deserve a more detailed investigation before an investment decision is made:

- The assumptions concerning the availability of biomass are an important limitation. While the developed planning tools can be adapted to account for changing availability (see Paper 3), the quantity of biomass that will be available is currently very uncertain, as well as future biomass prices for new conversion plants in the vicinity of existing biomass conversion pathways (Maack et al., 2017).
- Storage of biomass throughout the year, as well as challenges relating to specific times of biomass harvesting could lead to additional planning problems (Gold and Seuring, 2011; Malladi and Sowlati, 2018).

- In the modeling of the conversion processes, more detailed models could include material and energy losses, inhomogeneous or impure inputs (Sansaniwal et al., 2017), the production of undesired co-products and aspects like maintenance-related downtimes (Butemann and Schimmelpfeng, 2019).
- As the focus in the optimization models presented in Paper 1 through 4 is on input biomass procurement and transportation, distribution aspects have not been considered in detail. As the products of biomass conversion plants have higher energy and value densities, this should however not affect the usefulness of these papers' results significantly (Gold and Seuring, 2011).
- Ecological side-effects of indirect and direct land-use changes should be included into sustainability assessments of biomass conversion plants (Wolf et al., 2016)
- As biogas plants are usually CHP plants, modeling constraints regarding the provision of heat would also become necessary to realistically represent the degree of flexibility that these plants actually offer.
- Once good estimates of future price developments become available, methods like the real options approach, net present value or internal rate of return could be used instead of the return-on-investment calculations used for the economic considerations so far.

For assessments that include more than just economic criteria in the context of multi-criteria decision analysis, as discussed in Paper 5, it is difficult but important to obtain a meaningful weighting, as the relevant decision makers may not even be known, e.g. in policy decisions that need to be taken in several regions. Depending on the concrete problem, a criteria weighting that accurately represents the relevant decision makers' preferences should be aimed for.

While the unit commitment/ demand-side integration modeling in Papers 6 through 8 gives useful insights, it could gain more practical value if it included uncertain future prices more explicitly, e.g. by employing stochastic programming techniques (Schultz and Wollenberg, 2017). Also, depending on the flexibility options under investigation, more operational constraints (e.g. load distribution, ramp-up and maintenance times) should be included to more accurately approximate the real system behavior (Valenzuela and Mazumdar 2001; Saravanan et al. 2013).

2.3 Implications for future research and corporate practice

Several, simultaneous developments contribute to challenging decision-making in the planning and operation of production plants for renewable resources. Lacking economic competitiveness and the challenges of the food versus fuel and land-use change debates, as well as changing incentive schemes hamper the further construction of biomass conversion plants. In order to make informed decisions under these circumstances, it can be helpful to make use of available data in optimization models to enhance the representation of the real-world system. As APIs make it possible to combine optimization models and various kinds of data sources, they can be a major building block for such enhancements. As APIs can be used to include data or to allow for a repeated application of optimization models, implementing metaheuristics that coordinate the application of optimization models can improve the utility of optimization results, as several results in this thesis have shown. Inclusion of other data sources, as demonstrated for GIS in Paper 3 and Paper 4, leads to much more realistic results than e.g. the usage of average values in Paper 2.

If used to resemble daily planning of flexibility options, as in Paper 6 or Paper 7, API-enhanced optimization models can be used to assess the revenue potential of flexible power generators and consumers in the power market. The two-stage modeling of virtual power plants, as outlined in Paper 7, helps to model activities on both the day-ahead and on the intraday market. Such investigations are especially helpful since numerous use cases must be identified and compared, as Paper 8 shows. Use cases can be compared and judged depending on cost, market environment and achievable revenues or cost savings for individual flexibility options.

For the practical planning of biomass conversion plants with only one or two major products, such as biofuels or biogas plants, the analytical insights presented in Paper 2 could prove useful. Approximating an optimal capacity to maximize the return on investment by using formula (11) in Paper 2 could serve as a good starting point for capacity planning.

Concerning biorefineries, one of the central findings is the importance of a biorefinery's products' value. Biofuels and bioenergy are frequently discussed products, but the same quantity of biomass that would be required for them could also be used to produce bio-chemicals with much higher market value (Gold and Seuring, 2011). As bioenergy is currently not considered competitive in several energy markets, the production of products with a higher value could be a promising niche application, and therefore a more economically viable way of using scarce biomass (Zweifel et al., 2018). In addition, areas with large biomass availability, such as Canada or potentially Russia, appear more promising than locations in western Europe (as apparent e.g. in the comparison of Paper 3 and Paper 4).

For biogas plants and other flexibility options, it can be concluded that the added value of aggregation in VPPs should be quantified to develop corresponding business models. On the one hand, this means quantifying the value of internal load management within a Virtual Power Plant and determining the most efficient response to price signals, similar to the use cases described in Paper 8. On the other hand, aggregation can also introduce the possibility of direct marketing of intermittent renewables, such as PV plants, that could not trade in power markets independently, as such plants usually lack the required pre-qualification.

This habilitation has investigated planning problems that arise in the course of the substitution of fossil fuels by renewables. Several novel approaches have been presented to address the renewable-specific strategic and operational challenges of production plants for biomass conversion and flexible power generation. The presented approaches feature application programming interfaces for the combined application of optimization models with several kinds of data sources.

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