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Strategies for Demand Side Management in Biorefineries – Exploring New Frontiers in Enhancing Load Flexibility and Optimization

Doctoral thesis

Lilli Sophia Röder

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Strategies for Demand Side Management in Biorefineries
Exploring New Frontiers in Enhancing Load Flexibility and Optimization

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Kurzfassung

Die verstärkte Nutzung erneuerbarer Ressourcen für die Stromerzeugung und die Entwicklung von Bioraffinerien für die Herstellung von Kraftstoffen für Transport und Wärme spielen bei der Erfüllung globaler Nachhaltigkeitsziele eine zentrale Rolle. Eine Möglichkeit die Nachhaltigkeit von Bioraffinerien zu steigern, ist die vollständige Abdeckung ihres Strombedarfs durch erneuerbare Quellen. Die Nutzung erneuerbarer, volatiler Energien unterliegt jedoch einer unbeständigen Stromversorgung. Ein vielversprechender Weg zur Bewältigung dieser Herausforderung ist die Umsetzung von Strategien zur Nachfragesteuerung (Demand Side Management, DSM). Durch DSM wird der Stromverbrauch in Reaktion auf Stromverfügbarkeit gesteuert, anstatt die Stromerzeugung zu regeln. Die zentrale Fragestellung ist dabei, wie diese Flexibilität von einzelnen Prozessen oder ganzen Prozessketten in neuen Anwendungsbereichen identifiziert und gewinnbringend genutzt werden kann. Dies soll anhand bislang noch nicht hinsichtlich ihres DSM-Potenzials untersuchten Bioraffinerien beantwortet werden.

Vor diesem Hintergrund wurde eine systematische Literaturrecherche zu bereits untersuchten Prozessen im Bereich DSM und Flexibilität durchgeführt und die Ergebnisse auf ihre Übertragbarkeit auf Bioraffinerien überprüft. Insbesondere mechanische Vor- und Nachbehandlungsprozesse weisen sich als sehr vielversprechend für die Integration von DSM aus. Ein weiteres zentrales Ergebnis dieser systematischen Untersuchung war der Nachweis, dass es in den bisher wenig untersuchten Bereichen des DSM zahlreiche Prozesse mit großen flexiblen Arbeitsbereichen gibt.

Das kumulierte theoretische DSM-Potenzial der Biokraftstoffproduktion in Deutschland wurde analysiert, um zu prüfen, ob ein DSM Einsatz in Bioraffinerien einen signifikanten Beitrag leisten kann. Die Ergebnisse dieser Analyse zeigen zum einem auf, dass Bioraffinerien ein vergleichbares DSM-Potential zu den in der Literatur gefundenen Werte für die Branchen Aluminium, Zement und Papier hat. Des Weiteren konnten besonders in Biomethan- und Biodieselanlagen für DSM vielversprechende Prozessschritte aufgedeckt werden.

Darüber hinaus ist die wirtschaftliche Tragfähigkeit des DSM-Einsatzes für die Anlagenplanung und den Betrieb entscheidend. Zu diesem Zweck wurde ein Entscheidungsunterstützungstool zur Bewertung wirtschaftlicher Parameter der DSM-Einführung entwickelt. Das Tool unterstützt die Berechnung einen optimalen Überdimensionierungsfaktor, bei dem die Einsparungen durch die flexible Reaktion auf Strompreisschwankungen möglichst weit über den dadurch erhöhten Investitionskosten liegen.

Um die flexible Anpassungsfähigkeit von Prozessschritten zu beurteilen, wurden dynamische Simulationsstudien durchgeführt. Dafür wurde eine Prozesskette innerhalb einer Biomethananlage betrachtet. Die Kombination des Entscheidungsunterstützungssystem mit dynamischen Simulationsstudien hat zu zwei wesentlichen Erkenntnissen geführt. Zum einen können einzelne Prozessschritte, die bei individueller Betrachtung kein ökonomisches DSM-Potential aufweisen, bei Überdimensionierung die Dynamik der gesamten Prozesskette erhöhen und somit zu Kosteneinsparungen führen. Zum anderen werden durch Trägheiten im System geringere Kosteneinsparungen erreicht als ursprünglich bei statischer Betrachtung angenommen.

Summary

Increased utilization of renewable resources for electricity generation and development of biorefineries for production fuels for transport and heat play a central role in meeting global sustainability goals. Biorefineries themselves can further increase their sustainability by meeting their electricity needs entirely with renewable sources. However, increased utilization of renewable, volatile energies results in an intermittent electricity supply. A promising way to address this challenge is to implement demand side management (DSM) strategies. DSM adapts electricity consumption on the demand side in response to electricity availability, rather than managing electricity production. The central question is how flexibility can be identified and profitably utilized in new areas of application. This question is to be answered on the basis of the case study of a previously uninvestigated industrial sector, biorefineries.

Against this background, a systematic literature study was carried out on processes in the field of DSM and flexibility that had already been investigated and the results were checked for their transferability to biorefineries. Mechanical pre- and post-treatment processes in particular proved to be very promising for the integration of DSM. Another key result of this systematic investigation was the proof that there can be numerous processes with large flexible working areas in this for DSM previously little investigated areas.

In addition to flexibility, a high energy input is also important for the application of DSM. The cumulative theoretical DSM potential of biofuel production in Germany was analyzed to determine whether biorefineries can make a significant contribution in this regard. The results of the analysis show, on the one hand, that the DSM potential of biorefineries is slightly lower but comparable to the values found in the literature for the aluminum, cement and paper industries. Furthermore, particularly promising process steps for DSM were identified in biomethane and biodiesel plants.

The economic viability of DSM is crucial for every plant operator or during plant design. For this purpose, a decision support tool has been developed to evaluate the economic parameters of DSM implementation. The tool determines the optimal oversizing factor where the savings from the potential flexible response to electricity price fluctuations exceed the increased investment costs as much as possible.

To assess the flexible adaptability of process steps, a dynamic simulation was carried out. For this purpose, a process chain within a biomethane plant was considered. The decision support tool was extended to include the mathematical representation of the intermediate storage as part of an overall system and a scheduling optimization was carried out reacting to dynamic electricity prices. The combination of the decision support tool with dynamic simulation led to two insights. On the one hand, that intermediate steps, which show no economic DSM potential when oversized individually can enhance the dynamics of the entire process chain when flexibilized, and thus lead to cost savings. On the other hand, however, due to inertia in the system, lower cost savings are calculated than originally assumed when considered in steady-state.

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Nomenclature

Equation Symbols

a	maximum average electricity price	€ (kW h)$^{-1}$
AT	annual throughput	t a^{-1}
b	electricity price variation	€ (kW h)$^{-1}$h^{-1}
C	costs	€
EPC	electric power consumption	W
F	factor	–
FOL	flexible operating load range	%
I	investment	€
i	interest rate	%
j	actual process step under consideration	–
k	scheduling time slots throughout specified time period	–
L	level	m
$\dot{m}$	mass flow	t a^{-1}
n	total number of processes to be investigated	–
OpH	yearly operating hours	h a^{-1}
P	potential	€ a^{-1}
p	electricity price	€ (kW h)$^{-1}$
R	economies of scale factor	–
r	expense ratio	% a^{-1}
SEC	specific electricity consumption	kWh t^{-1}
SMD	specific raw material demand	t t^{-1}
t	varying time period	h
$TheoDP$	theoretical DSM potential	kW
V	volume	m^3
ϱ	density	kg m^{-3}
τ	fixed time period	h

Subscripts

app	application
av	average
buf	buffer tank
$buf(j)$	buffer tanks upsteam process step j, where j is a natural number and it ranges from 1 to n and n is the number of processes considered
$buf1, buf2$	buffer tanks upsteam process step 1 and 2

$capex$	capital expenditure
dec	decanter centrifuge
dep	depreciation
dyn	dynamic
$econ$	economic
$elec$	electirc
$ideal$	idealized
in	in flowing
k	scheduling time slots
max	maximum
min	minimum
$opex$	operational expenditure
oph	operating hours
os	oversizing
out	out flowing
P	process step
$P(j)$	process step j, where j is a natural number and it ranges from 1 to n and n is the number of processes considered
$P1, P2$	process step 1 and 2
pb	pay back
$real$	realistic
ref	reference
ro	reverse osmosis
sts	steady-state
$totex$	total expenditure
uf	ultrafiltration
$year$	of the considered year

Abbreviations

ACM	Aspen Custom Modeler
ASU	air separation unit
CHPP	combined heat and power plant
CNG	compressed natural gas
COD	chemical oxygen demand
DBFZ	Deutsches Biomasseforschungszentrum gemeinnützige GmbH
DDGS	dried distillers grains with solubles
DEC	decanter centrifuge
DENA	German energy agency *Ger.: Deutsche Energie Agentur*

DR	demand response
DSM	demand side management
EEG	Renewable Energy Sources Act *Ger.: Erneuerbare-Energien Gesetz*
FOL	flexible operating load range
FOP	flexible operating point
FT	Fischer-Tropsch
GD	guidance document
GHG	greenhouse gas
PCC	post-combustion CO_2 capture
PEM	protone exchange membrane
PtG	power-to-gas
RE	renewable energies
RO	reverse osmosis
SAnMBR	submerged anaerobic membrane bioreactor
UCO	used cooking oils
UF	ultrafiltration

Publications

This thesis is based on the research performed by the author during her time as a research associate at the working group of separation processes and process development of the Deutsche Biomasseforschungszentrum gemeinnützige GmbH and supervised by the Laboratory of Fluid Separations at Ruhr University Bochum between Mai 2020 and Mai2024.
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Chapter 1. Introduction

1.1 Background and motivation

The challenge of global warming and the global pursuit of sustainability goals have increased the urgency to find ways to reduce greenhouse gas emissions. The expanded utilization of renewable resources for electric power production and the development of biorefineries play a central role in this regard. Renewable electricity, especially from sources such as wind and solar energy, is fluctuating because it depends on natural, weather-dependent factors that are not constant. The magnitude of these fluctuations can be significant and can lead to electricity production that does not always match the required demand.

Biorefineries convert biomass into valuable products such as biofuels and chemicals, which helps to reduce the dependence on fossil resources. Although biorefineries are already considered sustainable through the use of biomass as a feedstock, they can further increase their sustainability by meeting their electricity needs entirely with renewable energy and reducing their CO_2 emissions throughout the supply chain. Renewable electricity would then play a key role in biorefineries as electricity needs would be met, while at the same time avoiding fossil fuels or internal fuel recirculation and improving their carbon footprint.

However, the increased utilization of renewable, fluctuating energies leads to a volatile electricity supply. One promising way to deal with this challenge is to implement demand side management (DSM) strategies. DSM strategies aim to control and adjust electricity consumption on the demand side instead of optimizing electricity generation. The underlying principle involves consumers adaptability — whether households, companies, or industrial plants — of their electricity consumption to supply.

DSM means that consumers can, for example, increase their electricity consumption when an abundance of renewable electricity is available or reduce it when supply is scarce. Thus, DSM defines the flexible operation of a plant or process in response to fluctuating electricity availability. These fluctuations directly influence the price of electricity, which is low when there is an oversupply of renewable electricity and low electricity demand and *vice versa*. Thus, implementing DSM can mean increasing electricity consumption when electricity costs are low and reducing electricity consumption when electricity costs rise.

The feasibility of DSM critically depends on the necessity of electricity with a significant share in final electricity demand and the flexibility of operational options [1]. Consequently, previous studies have predominantly concentrated on processes with substantial electricity demand [2–8]. In the short term, prioritizing processes that fulfil these criteria appears promising. However, a long-term perspective requires the inclusion of other major electricity consumers to address the challenges associated with the expansion of renewable electricity sources. The investigation of new industries for DSM is thus becoming increasingly vital in response to the growing imperative for sustainable energy practices [9]. Biorefineries emerge as a compelling area of research, offering the potential to facilitate innovative integration of renewable energies into the

production of green fuels and chemicals. In these sectors, the awareness of sustainability and a reduction of greenhouse gas (GHG) emissions along the entire value chain is especially well developed.
Furthermore, the future efficient and sensible use of these green fuels requires a strategic approach to waste as little of the fuel produced as possible for the internal electricity requirements of the biorefineries [10]. With this in mind, finding ways to integrate other renewable energies effectively into biorefineries is interesting and essential. Here, the recovery of internal heat or, where appropriate, the electrification of heat-intensive processes is crucial, with electricity being sourced from renewable energies such as solar and wind. This is done by replacing heat-driven processes with technologies that use renewable electricity. Heat pumps, for example, can be used to valorize low-temperature waste heat efficiently with the help of electricity. Electric heating systems powered by renewable electricity can be used instead of oil or gas burners. Distillation columns require large amounts of heat traditionally provided by burning fossil fuels. Membrane processes powered by electricity can be an energy-efficient alternative. These electricity-driven processes can be powered directly by renewable electricity and are, therefore, more climate-friendly than processes that use fossil-fueled heat. Renewable electricity production is already significantly more mature than renewable heat or fuels, which are also needed more urgently in other sectors such as shipping and aviation.
By integrating DSM in biorefineries and thus adapting to fluctuating electricity production, biorefineries can use a higher share of renewable electricity, reduce their electricity costs and greenhouse gas emissions, and relieve stress on the electricity grid [10]. This integration, therefore, represents a promising opportunity to enhance the economic viability of green fuels and products while promoting sustainable practices.

1.2 Structure and approach

The presented thesis investigates biorefinery processes' flexibility to identify their optimal use in DSM programs. Biorefineries, which are complex systems with numerous individual processes, offer a fertile ground for establishing a new industry ready for DSM. Therefore, the key research question to be answered, is if and how new applications for DSM can be identified.
Before delving into this new field of research to evaluate processes for DSM, it is thus essential to examine the existing state of research to determine whether DSM is feasible in this context. For this purpose, Chapter 2 presents a systematic literature review of processes in biorefineries that have already been investigated for DSM or flexibilization. This review serves to document the current state of the art while identifying processes that are particularly flexible and identifying areas within biofuel production that have insufficiently or not at all been explored. This analysis makes it furthermore possible to exclude processes that have already been extensively investigated from further investigation and analysis in this research project.
Chapter 2 is dedicated to a detailed examination of the current literature on DSM opportunities in biorefineries and addresses the following research questions:

1. How can the relative amount of load or temperature variation, that each process step under consideration can provide, be quantified?

2. Which process steps in biofuel production are flexible in terms of their mode of operation?
3. What technical constraints limit the flexibility of these process steps?

Another step in identifying new applications for DSM is to pinpoint an industrial sector with significant electricity consumption - an integral leverage point. It is crucial to analyze the sector's likelihood for market growth potential and its impact in terms of sustainability. Moreover, the economic viability of change in process design or operation is crucial for any operator or plant designer. Therefore, it is necessary to consider the extent to which DSM integration is economically viable now or in the foreseeable future.

Having identified processes that exhibit flexibility, the next step for DSM research is therefore to quantify the integral lever of application in this area to validate its relevance and potential. Examples of industries where this has already been investigated include aluminum, cement, or paper [3, 8, 11–15]. These industries, alongside electrolytic processes [16–18], are significant in DSM research due to their high specific electricity requirements, flexibility, and large production capacities.

The theoretical DSM potential of the biorefinery case study is analyzed in Chapter 3. Germany is chosen as an exemplary region, as it is one of the largest producers of biomethane [19], which are significant in DSM research due to their high specific electricity requirements, flexibility, and large production capacities. The methodology to analyze the theoretical DSM potential involves a systematic approach starting with the identification of relevant mass flows and specific electricity consumption of the flexible processes [8, 15]. The integration of the flexibility potential analyzed in Chapter 2 enables the identification of the theoretical DSM potential of the inspected processes. By aggregating the theoretical DSM potentials of these processes, the overall potential for the biofuel production sector in Germany can be determined. As several industrial sectors in Germany have already been investigated concerning DSM, this cumulative value can be compared with these sectors to estimate the integral leverage. Processes with the highest theoretical DSM potential can be identified within biofuel production in Germany, revealing areas of particular interest for further DSM research.

The main results of Chapter 3 include the extrapolation of the theoretical DSM potential in biofuel production. Reference concepts were developed for the main biofuel production chains investigated, and processes with high electricity demand and the possibility of flexible operation were identified. The most important questions for this DSM calculation in biofuel production are:

1. What is the total energy and biomass demand for the types of biorefineries in scope?
2. What are the main process steps and their cumulative energy demands?
3. What is the resulting theoretical DSM potential for the individual process steps?
4. How does biofuel production's cumulative theoretical DSM potential compare to other sectors?

If the integral leverage proves considerable, the next question is: What are the actual measurable benefits for plant operators that can be considered during plant design?

The DSM roadmap of the German Energy Agency (DENA) [20], Leinauer *et al.* [21], and Lashmar *et al.* [22] see the main challenges in the provision of information and data to improve companies' knowledge of DSM markets. These studies show a need for flexibility but that the implementation is still complex and bound to risks. In an attempt to address these challenges, indices and methods have been presented in the literature to assess large and micro processes for their DSM and flexibility potential [23–27].

However, the literature still lacks an indicator to quickly understand the economic suitability of a process for DSM application - a decision support tool for plant design that is valid for continuously operated processes and easily applicable without complex simulations and optimization studies. The question of why DSM measures have not yet been implemented widely is of crucial importance. For plant operators, the focus is primarily on financial profitability. However, there is frequently insufficient information for plant operators to make an informed decision on the economic viability of DSM measures. Chapter 4 thus promotes an understanding of the economic suitability of a process for DSM implementation during plant design.

To tackle this issue, a decision support tool is developed to address the question regarding DSM's economic feasibility. Even with limited optimization or modelling expertise, the tool helps estimate whether the respective processes are conducive to DSM implementation. Specifically, the focus is on continuously operated processes that would necessitate oversizing to guarantee uninterrupted production, should they be identified as attractive for DSM utilization.

As a case study, the tool is applied to a biomethane biorefinery because of processes that are identified as flexible in Chapter 2 and a high theoretical DSM potential calculated in Chapter 3. The theoretical analysis illustrates how the tool works and identifies processes within the system that have high and low economic DSM potential. At the same time, the case study under consideration enables the investigation of the tool's benefits and limitations.

The main objective of Chapter 4 is to develop a decision support tool that helps evaluate and rank unit steps in terms of their economic potential for DSM implementation. The most important questions to be answered in Chapter 4 are:

1. Which process steps within a specific biofuel production plant are economically suitable for the implementation of DSM?
2. How can these economic effects be calculated as quickly and easily as possible?
3. What are the most critical factors influencing the feasibility and profitability of oversizing processes for DSM implementation?

The current flexibility in biorefineries is thus examined in the first chapters. In addition to capturing the existing potential, expanding the current flexibilities is crucial. As aptly recognized by Hochhaus and Bruns *et al.* [28], the flexibilization of downstream processes can create additional flexibility in an otherwise rigid system. Within the previously investigated biomethane biorefinery, a process cascade is therefore examined in more detail to analyze whether the flexible operation of up- and downstream processes can enhance flexibility and DSM profitability of the overall system. A dynamic simulation of the process chain is beneficial in enabling a realistic analysis, especially for the transient behavior of the individual process steps.

The tool, as presented in Chapter 4, is limited to the analysis of individual processes and a very theoretical perspective, allowing further scope for development to better integrate a practical perspective. The process step within the process cascade, which have already been examined individually using the decision support tool in Chapter 4, are to be considered in Chapter 5 as part of an overall system. For this purpose, the decision support tool is extended to mathematically represent the buffer tanks in between flexible process steps as an integral part of the overall system. The entire process chain can be optimized by extending and implementing the tool in an optimization software. The flexibility of the up- and downstream processes is also considered, allowing new flexibility optimization possibilities to be uncovered. Furthermore, the dependence of part-load or ramping of processes on the separation efficiency is represented time-dependently in a dynamic simulation. The transient behavior of the process steps and resulting effects on the DSM potential are thus dynamically considered.

The main objective of Chapter 5 is to extend and use the previously developed decision support tool in a dynamic simulation study while looking in depth at relevant processes. It presents an economic evaluation of DSM interaction in a digestate treatment cascade through a steady-state and dynamic simulation and postulates that by considering interactions between processes, the design capacity of the storage could be reduced. This could help identify and quantify DSM applications' benefits on a plant scale rather than a process step scale. The possibilities and limitations of the steady-state and dynamic optimization strategies were evaluated. The main research questions to be answered are:

1. What is the impact of considering shared buffer storage tanks in a process cascade on a plant's overall economic DSM potential?
2. What influence does transient behavior have on the economic DSM potential of processes?
3. How valid are the results of the steady-state evaluation of the decision support tool described in the previous chapter?

Finally, Chapter 6 summarizes the results of this thesis and gives an outlook on future research questions.

Chapter 2. Flexibility Option in Biofuel Production[1]

In current research, a wide range of processes have been identified to be suitable for DSM application. Although biorefineries have not yet been tested for DSM application, it is noteworthy that many of the DSM suitable processes are employed in biofuel plants. Thus, this contribution offers a comprehensive overview of DSM options drawn from literature with a special focus on process steps, which have been analysed for operational and capacity flexibility and which are found in or are transferable to biorefinery systems. By identifying process steps in biofuel production that can be operated flexibly, this extensive literature study helps to find technical restrictions limiting the overall process flexibility. The scope of this contribution to create an overview of which processes in biofuel production can be considered for DSM use.

2.1 Introduction

Strategies like the European Green Deal aim to transfer our economy into an energy and resource efficient system, with zero net-emissions of greenhouse gases (GHG), but still allowing economic growth. The use of crude oil as carbon source for transportation fuels and the chemical industry has to be replaced by alternatives such as biomass or an increased re-use of materials. Therefore, numerous technologies are being developed to convert biomass in industrial biorefineries into biofuels and bio-based products [29]. Since the availability of biomass is a major concern for the transition of the chemical industry to a bioeconomy, the biomass itself should be converted with a very high efficiency. The utilization of parts of the raw material as energy carrier for process energy requirements should thus be minimized and the integration of volatile renewable energy (RE) is to be considered. Taking the fluctuation in availability of solar and wind power into account, operational adaptations of biorefineries would need to be studied in order to be able to react flexibly to those energy volatilities. This can lead to synergies between the requirements for future electricity grid operation and cost-efficient utilization of renewable electricity for process energy [20]. The flexible adjustment of a system's power demand to follow the current power generation is commonly referred to as demand side management (DSM) [30]. Research on DSM shows a continuously growing number of studies on the investigation of various processes in a non-biofuel related context, which are being examined in terms of their flexibility and applicability for DSM and their energetic potential in this regard. The share of biorefinery research is likewise becoming increasingly important in the literature concerning sustainable science technology. Studies on biorefineries are often accompanied by the development of most efficient energy balances and minimizing GHG emissions. The common ground of both research areas is their aim to save energy costs. Against this background, the main objective of this review is to analyse and discuss DSM options found in literature. A special focus is laid on processes or process steps, which have been analysed for operational and capacity

[1] Substantial parts of this chapter are published in Röder, L. S.; Gröngröft, A.; Grünewald, M.; Riese, J. (2022): Options for demand side management in biofuel production. A systematic review. *International Journal of Energy Research* .DOI: 10.1002/er.8353.

flexibility and which are found in or are transferable to biofuel production systems. For this objective this systematic review will first explain the structure and terms used in this contribution that are relevant for the comprehensibility of the review in Section 2.2. Section 2.3 proceeds with a list of existing literature that review a sum of different DSM processes, therefore categorised as other reviews of DSM options. Section 2.4 presents the resulting review of articles found on DSM options in biofuel production, highlighting relevant research articles that have investigated flexibilization, scheduling or demand adaptation. This section will:

1. identify process steps in biofuel production that can be operated flexibly,
2. find technical restrictions limiting the flexibility of these process steps,
3. and quantify the relative amount of load or temperature variation each process step under consideration can provide.

Section 2.5 compare the main results of the review, summarizing the three previously named findings for each process area. Section 2.6 closes with a conclusion of the review and presents perspectives for future research.

2.2 Structure and terms of the review

2.2.1 Considered biorefineries

For this review paper process steps are investigated, that are most commonly operated and established in biofuel production for biodiesel [31], bioethanol [32] and biomethane [33]. The structure of a biorefinery is divided into process areas, each of which combines different tasks in the biofuel production chain. In total, a broad spectrum of technologies and processes is required in biofuel production [34–36]. These processes were categorized in this review article into groups for: pre-treatment of raw material, conversion of biomass to a dedicated product, refinement of the main product, auxiliaries (here, the production of hydrogen). The most common processes in the process chain of biofuel production are depicted in Figure 2.1. The three biorefinery types require multiple refinement steps, to meet the specifications for the biofuel and further by-products. The process steps shaded in grey have been found in DSM literature and will thus be discussed in Section 2.4.

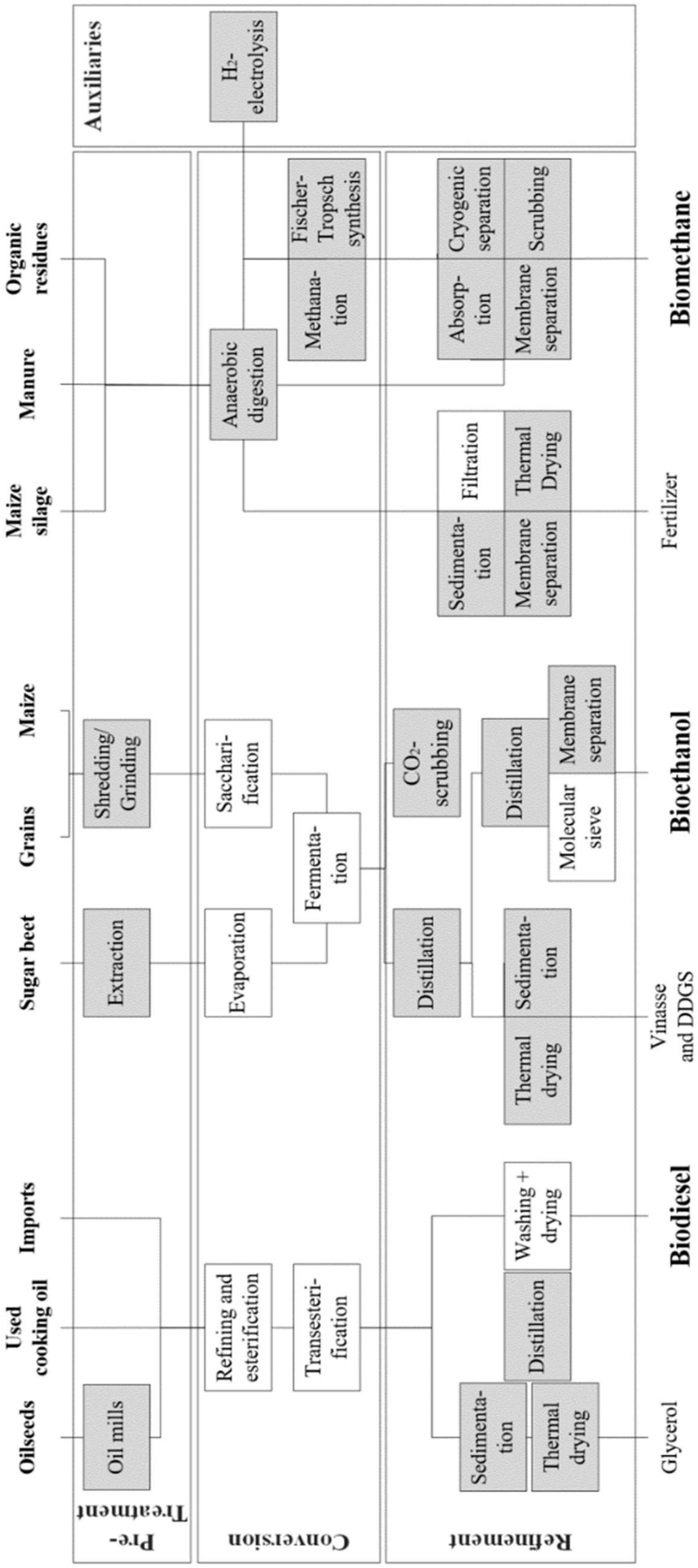

Figure 2.1: Typical structure with associated process steps of biodiesel, bioethanol, and biomethane plants. [34–36]

2.2.2 Terms in DSM research

DSM, direct demand response (DR), load management and demand-side integration are often used synonymously. Literature classifies DSM into two different areas: energy efficiency, which involves reducing the demand for the provision of a service or product. Demand-side response or DR, which involves fluctuations in electricity demand as a response to changing electricity prices or incentives. Direct DR describes DSM, where the production plant is operated and scheduled according to the electricity availability. Indirect DR refers to the effects direct DR has on downstream processes. [1, 37]

An important parameter to quantify the effect of DSM options is the DSM potential. The definition of DSM potential is very broad. In literature, a basic distinction is made between theoretical, technical, and economic potential [38–40] or even more precisely into socio-economic or ecologic potential [8, 37, 41]. While many contributions reviewed in this contribution, present different depth in detail to their DSM potential calculations, a special focus is laid on the theoretical DSM potential considered in each of the articles. More precisely, the operating window which is limited by the parameters under which equipment can function flexibly safe and efficient. In order to be able to meet the requirements of flexible power consumption and storage, system components must be capable of handling different and fluctuating load cases. Achieving this is possible if a process can handle one of the following DSM functions: Load shifting, load shedding or storing as described by Zeilinger *et al.* [42], Klobasa [14], Theurich [43]. The limits of this operational flexibility lead to the delimitation of the DSM operating window.

To give an overview and summary of the studies investigated for this review, each process area in Section 2.4 is summarized in Figure 2.7, that shows the given range of maximum and minimum operating point as the main parameters to represent the relative theoretical DSM potential and set limits to the operating window. The operating window will be describes by two different scenarios in this contribution. The flexible operating load range (FOL) in which a process can be operated without compromising the product quality or quantity. The availability of a shiftable or shedable load is indicated as a percentage relative to the specific nominal power demand and describes the FOL. Figure 2.2 shows an example of the graphical demonstrations of the FOL used in this contribution.

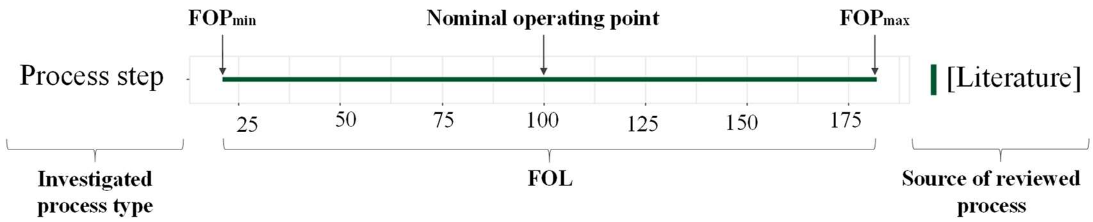

Figure 2.2: Example of graphical demonstration of flexible operating load as found in literature.

If the deviation from the optimal operating point was described in temperature in Kelvin or power consumption in Watt, the load spectra was converted into percentages. These percentage terms represent the ΔT or ΔP of the temperature and power increase or reduction in relation to the optimum operating point at 100%, according to the following equations:

$$FOP_{min/max} = \frac{T_{min/max}}{T_{opt}} \quad (2\text{-}1) \qquad FOP_{min/max} = \frac{P_{min/max}}{P_{opt}} \quad (2\text{-}2)$$

$FOP_{min/max}$: lowest and highest operating point [%]
$T_{min/max/opt}$: lowest and highest tolerated or optimal operating temperature [K]
$P_{min/max/opt}$: lowest and highest tolerated or optimal operating power consumption [W]

The FOL found for each process will be graphically depicted in Section 4.

2.3 Literature review on DSM potential studies

Numerous reviews on DSM as well as studies that consider a wide range of different processes for their investigations, have previously been conducted. The goal of these articles generally includes the calculation of the theoretical DSM potential for a certain region by investigating technical barriers in implementing DSM in certain industrial processes. Table 2.1 shows an overview of processes considered by different authors concerning the calculation of DSM potentials. Similar to this contribution, each of the studies on DSM potentials identify processes that can be operated flexibly, find technical, economic or social barriers limiting the flexibility of these process steps. Finally the relative amount of load or temperature variation each process step under consideration can provide and the theoretical DSM potential is calculated. The operating ranges identified for the individual process steps are described in Section 2.4.

Table 2.1: Processes considered in DSM studies.

Source	Region	Household devices	Commerce and services	Aluminium	Chlorine and other	Steel and other metals	Pulp, Paper and Wood	Cement	Glass and ceramics	Engine and machine	Sewage treatment	Air separation	Others
Christoffersen *et al.* 2005 [44]	Denmark		x			x	x	x		x			x
Stadler 2006/2007 [45, 46]	Germany	x											x
McKane *et al.* 2008 [2]	California USA	x	x	x		x	x	x	x		x		x
Dena 2010 [3]	Germany	x	x	x	x	x	x	x					

Source	Region	Household devices	Commerce and services	Aluminium	Chlorine and other	Steel and other metals	Pulp, Paper and Wood	Cement	Glass and ceramics	Engine and machine	Sewage treatment	Air separation	Others
Paulus and Borggrefe 2009 [4]	Germany	x		x	x	x	x	x					
Wang *et al.* 2010 [47]	China	x	x			x							
Worrell *et al.* 2010 [48]	USA					x							
Paulus and Borggrefe 2011 [13]	Germany			x	x	x	x	x					
Gobmaier and Roon 2010 [5]	Europe, Germany, USA		x		x	x	x		x	x			
Apel 2012 [12]	Germany	x	x	x	x	x	x	x			x		
Ates *et al.* 2012 [49]	Turkey					x	x	x	x				x
Sivill *et al.* 2012 [50]	Finland					x	x						x
Gils *et al.* 2013 [51]	Europe, Northern Africa		x	x	x	x	x	x				x	x
Klobasa *et al.* 2007/2013 [6, 14]	Germany	x	x	x	x	x	x	x					
Merkert *et al.* 2015 [52]	Germany					x	x	x					
Langrock 2015 [53]													
Paramonova *et al.* 2015 [54]	Sweden					x	x						x
Shoreh *et al.* 2016 [55]	-	x		x	x			x					x
Steurer 2017 [56]	Germany	x	x	x	x	x	x	x	x			x	x
Arnold and Janßen 2018 [37]	Germany	x		x	x	x	x	x					
Ausfelder *et al.* 2018 [7]	Germany		x		x	x	x		x	x			
Baumgart 2018 [57]	Germany	x	x	x	x	x	x	x	x			x	x
Ladwig 2018 [8]	Germany	x	x	x	x	x	x	x					
Söder *et al.* 2018 [58]	Northern Europe	x	x				x						x
Kiliccote *et al.* 2019 [59]	USA	x	x					x					x
Lawrence *et al.* 2019 [60]	Sweden							x	x				x
Shafie-khah *et al.* 2019 [61]	-	x	x	x		x	x	x					x
Talaei *et al.* 2020 [62]	Canada					x							
Nebel *et al.* 2020 [41]	Germany	x		x	x								
Hasan *et al.* 2021 [63]	Bangladesh					x	x	x		x			x
Golmohamadi *et al.* 2022 [64]	-	x	x	x	x	x	x	x	x	x			x

Concepts for including the demand side in energy planning have been researched with increasing intensity since the 1980s, when the term itself was first coined and defined by Gellings and Chamberlin [65]. Since then, the range of investigated DSM-suitable processes has expanded considerably.

As Germany is one of the largest energy and electricity consumers per capita [66, 67], but also holds a high share of electricity from RE sources in gross electricity consumption [68], it is a country that has often been investigated for DSM potentials in literature.

The contribution by Merkert *et al.* [52] provides an overview of methods to determine the DSM potential of industrial processes in steel, paper and cement industry, followed by series of real industrial case studies in Germany. Prior [69] examined the load profiles of electrical consumers in Germany, differentiating between summer and winter as well as working days and weekends. Sadler [45] used these load profiles in his investigations with the aim of assessing the extent of the theoretical DSM potential on the consumer side in order to create the basis for the integration of large amounts of RE. Stadler built his investigation on both modelling of thermal storage devices and laboratory tests [46]. Based on Stadler's model, the technical and economic DSM potential of individual household applications and cross-sectional technologies in Germany was investigated by the Germen Energy Agency (Ger. deutsche Energie-Agentur - DENA) in 2010 [3] expanding Stadler's perspective to aluminium, steel, paper, cement, and chlorine processing. Further literature on the determination of the DSM potential of above mentioned industry processes were conducted by Gobmaier and Roon [5] and Paulus and Borggrefe [13]. Another DSM study was carried out 2012 by Apel *et al.* [12], including an extensive research and evaluation of existing work concerning DSM investigations. The content of the examined articles is generally limited to the determination of the maximum potential for shifting loads from the household, commercial, and industrial sectors, assuming the availability of technical solutions. The work of Steurer [56] contributes to the identification of analytical uncertainties and to the systematic delimitation of DSM-relevant application. The development of the future theoretical DSM potential up to the year 2050 was estimated by Ladwig 2018 [8] so as to assess the role of DSM even with a high share of RE. The future development of DSM potential in the industrial sector depends primarily on improvements in the efficiency of technologies as well as the economic situation.

The aim of the work by Baumgart [57] was to show that DSM potentials can represent alternatives to other flexibility options such as flexible electricity generation from a technical point of view and to what extent they can be economically superior to them. The findings by Arnold *et al.* [37] described that in order to decrease or increase production, depending on RE availability and grid stability, plants and processes may no longer operate at their optimum levels. The analysis by Nebel *et al.* [41] underlines the growing importance of DSM in an energy system based on rising shares of RE integration, and shows that DSM flexibilities are suitable for raising the overall ecological potential.

Ausfelder *et al.* [7] described various technologies for energy storage and DSM for their potential applications in the context of Germany's transition towards a more sustainable energy system. While the article was written from a German perspective, the authors hope it will be of general interest for anyone working in the areas of energy systems or energy. Looking beyond Germany, Gils [51, 70] presented the procedure and results of an assessment of the theoretical DSM potentials in Europe and North Africa.

A further review on the demand side flexibility potential in Europe was carried out by Söder *et al.* [58] in which they compare DMS potentials and how they were estimated in seven northern European countries in order to compare general challenges and results. Christoffersen *et al.* [44] investigate the incentives to implement DSM systems in Danish manufacturing companies, stating that policy instruments can and must be used if major improvements in energy efficiency through energy management are the goal. Paramonova *et al.* [54] and Lawrence *et al.* [60] demonstrate advantages that DSM systems in heavy industry can supply with a regional focus on Sweden. In Sweden especially the pulp and paper industry factors greatly in the DSM potential calculations. Sivill *et al.* [50] identified challenges in the implementation of DSM in the steel and paper industry section of Finland. Drivers for DSM implementation were often found in economic incentives, barriers in organization matters as well as information and politics.

McKane *et al.* [2] search for barriers in automated DSM in California USA by identifying the greatest potential for DSM in sawmills and wood preservation, food manufacturing and waste water and sewage treatment. Worrell *et al.* [48] search for cost saving opportunities in the US American iron and steel industry through implementing energy price based efficiency measures based on case studies of real-world applications world wired. Kiliccote *et al.* [59] identify attributes and quantify hourly availability of DSM resources in the commercial, industrial and residential sectors in the USA, focussing on the cement industry in the industrial sector. Talaei *et al.* [45] investigates GHG emission mitigation potential that result from DSM integration in the Canadian iron and steel industry.

Wang *et al.* [47] study DSM strategies in different provinces of China, by identifying industrial consumers in Beijing, steel plants in Jiangsu as well as residential participants in Guangdong. Ates *et al.* categorized the steel, paper, cement and ceramics industry as suitable for DSM practices and highlight bottlenecks of these heavy industries with help of questionnaires and an analytical framework. Hasan *et al.* [63] state that DSM practices are especially important in developing countries. Barriers and drivers are identified for energy intensive industries like cement, paper, and waste water treatment in Bangladesh.

Shoreh *et al.* [55], Shafie-khah *et al.* [61], and Golmohamadi [64] do not consider special geographical regions but review other articles concerning DSM implementation strategies. Shoreh *et al.* summarize the main berried that hinder the widespread utilization of DSM programs in household applications, aluminium and chemical production and the cement industry. Shafie-khah *et al.* categorize business models of commercial and industrial DSM to analyse the impact of energy management strategies. The very recent review of Golomahamadi again reviews DSM potentials in heavy industries like cement, aluminium and oil refining plant. He surveys software tools and solution methodologies identifying peak shaving, valley filling and load shedding effects on the reduction in energy cost consumption.

All these studies have in common that they include the calculation of the theoretical DSM potential of many different processes in a certain area of consideration ranging from FOP_{min} 0%

to almost FOP_{max} 175%. They examine the operating range of the named processes or process steps and additionally consider the contribution that storage technologies (thermal, electrical, material, etc.) can provide to exploit or expand the DSM potential in certain industry sectors. In order to be able to investigate the DSM potential of a further industry sector that has not yet been investigated in these studies, the biofuel production industry, the following section will give an overview of processes found in biofuel production, which can be used for DSM purposes.

2.4 Literature review on DSM options in biofuel production plants

This section discusses processes, which have been analysed for operational and capacity flexibility and which are found in or are transferable to biofuel production systems. Thereby process steps in biofuel production are identified that can be operated flexibly. According to the main process groups, this review paper will be categorized into subsections. The number of articles found for each section and process step is summarized in Figure 2.3.

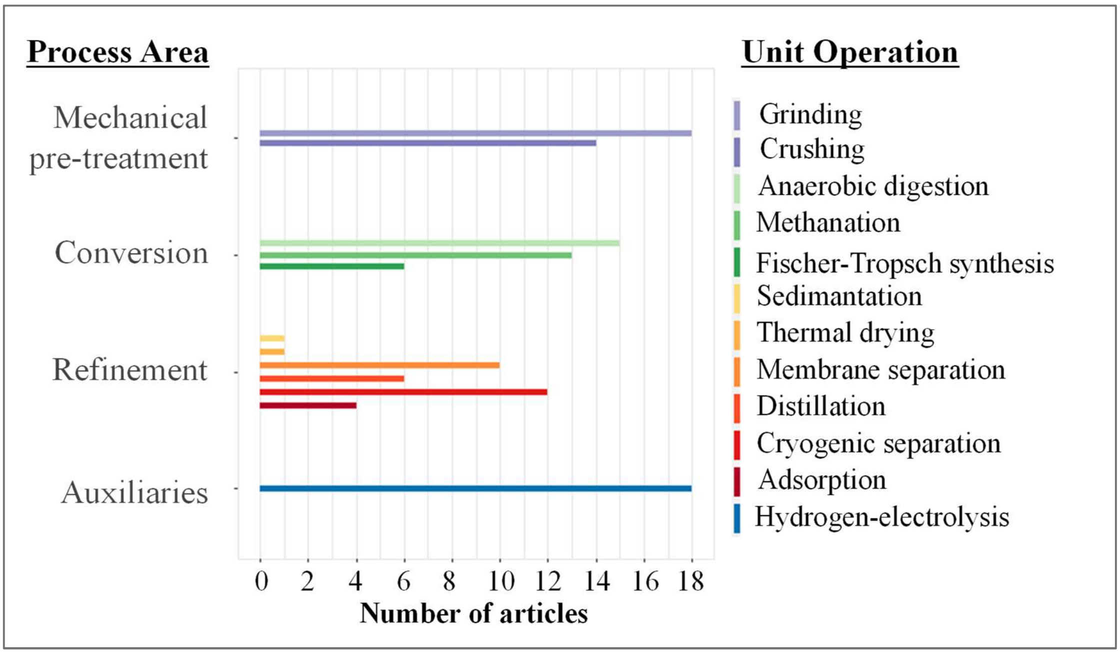

Figure 2.3: Number of articles found per unit operation categorizes in biorefinery sections.

For each investigated and summarized process a focus is put on technical restrictions limiting the flexibility of it. The limits of these restrictions in the operational flexibility of a system quantify the relative amount of load or temperature variation, the DSM potential, each process step under consideration can provide.

2.4.1 Mechanical pre-treatment

Articles that consider load shifting potential are often connected with the possibility of fast start-up and shut-down of a process. The maximum FOL which was identified in named studies is summarized in Figure 2.4.

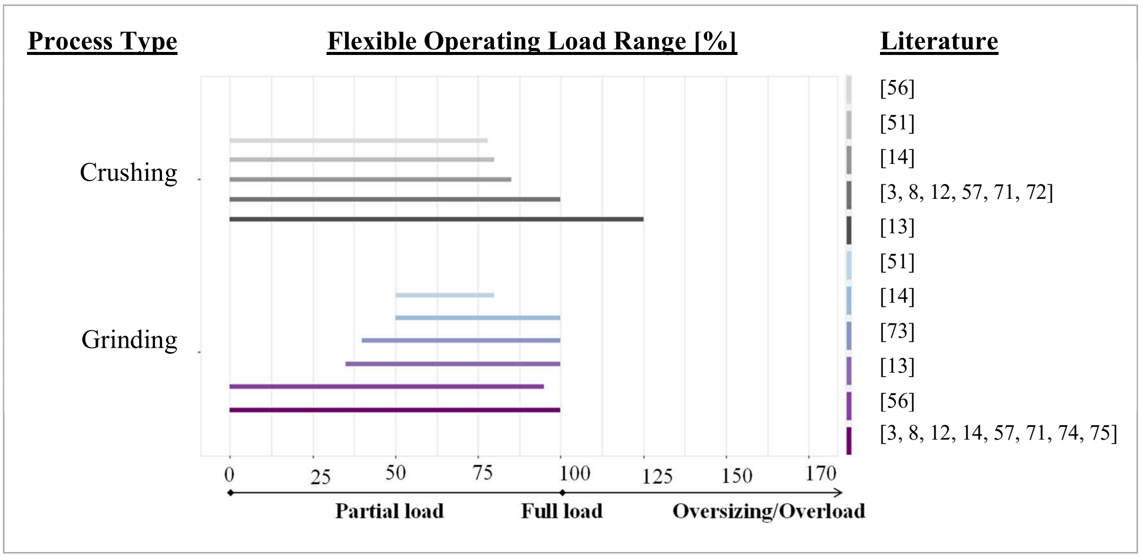

Figure 2.4: Flexible operating load range of mechanical pre-treatment processes as found in literature.

Unit operations that are often mentioned for this and can also be found in biofuel production plants in a transferable sense are grinding steps in pulp and paper and crushers in the cement industry. Some of the studies mentioned in Section 2.4 also consider the pulp and paper industry and cement handling in their research.

Grinding

Due to its energy intensity, essential DSM potentials lie in the mechanical process (sawmills, grinders, refiners) for pulp production. Overall it was seen that the possibility of operating wood grinders between 0 and 100% of their peak load [3, 6, 8, 12, 52, 57, 71, 76]. Steurer, Gils and Klobasa also indicated the possibility of a complete shutdown, but see the FOP_{max} at around 80%, which results in a FOL 80% in their calculation [13, 14, 51, 56]. Helin *et al.* [71], Pulkkinen and Ritala [72] and Paulus and Borggrefe [13] extended the research on DSM potentials in the paper industry by estimating the economic potential.

Helin *et al.* [71] focused only on the costs of short-term DSM in paper industry, indicating higher variable costs. While other works estimated DSM potential from a technical or theoretical point of view, Helin *et al.* stated that DSM capacities are only used if the industry considers them profitable, and therefore the socio-technical potential was estimated. The annual balancing energy potential of the case study was evaluated by simulating the behaviour on the Finnish balancing energy market in 2014. The investigation reveals that the refiners can be operated between 0 and 100% and the parallel operation of three refiners offers a high flexibility potential. Pulkkinen and Ritala [72] present methods to manage operational decision making tasks under uncertainty by the scheduling of thermo-mechanical pulp production with uncertainty in production cost and demand. They stated that to maintain quality requirements only a full production can be referred to as either “on” or “off” resulting in an FOL 100%. The electricity price was estimated as a daily average of the Nordic markets. In the optimized plant schedule, costs were minimized by shutting down refiners at high electricity prices.

According to Paulus and Borggrefe [13] significant load shifting potential in the paper industry exist, due to the possibility to store the pulp. This potential can be used either on the spot market or through the positive and negative tertiary reserve markets. The FOP_{max} is equivalent to the average load of refiners which is 250 MW and the FOP_{min} was defined by the average unutilized capacity of 62 MW. This results in an FOL 125%. The pulp storage volume at the investigated paper mills was large enough to store material 1.5 h at maximum capacity.

Crushing

A unit operation concerning comminution is the crushing of material. While many authors considered switching off crushers completely [3, 6, 8, 12, 57, 74–76] some others stated that the load of crushers can be varied and running the crushers in partial load is the DSM function in consideration [13, 14, 51, 56, 73]. In addition to the articles identifying the theoretical an technical DSM potential, Merkert *et al.* [52], Mitra *et al.* [74], Numbi *et al.* [73, 77], Vujanic *et al.* [76] and Zhang *et al.* [75] considered DSM optimisation strategies for continuous energy-intensive processes such as crushers, with focus on maximizing the economic DSM potential.

Merkert *et al.* [52] and Mitra *et al.* [74] investigated a scenario where large crushers are connected in parallel with a material storage tank installed. The crushers provide an FOL of 100% with parallel graduations. Merkert *et al.* presented several options on how enterprise-wide optimization can help to integrate DSM options. Mitra *et al.* used the exemplary scenario to present a model for the optimal operational production planning for continuous power-intensive processes that participate in DSM programs reacting to price signals.

Through the simulation results of Numbi et a. [73], two optimal control techniques were developed for the energy management of a jaw crushing station under both physical and operating constraints. The first technique was referred to as a variable load in an FOL of 40 to 100% partial load variation, while the second one is an optimal switching on and off control leading to an FOL of 0 to 100%. It was demonstrated that an optimal switching controller has a greater potential to achieve high reduction of both energy consumption and cost of an exemplary crushing process.

The high economic DSM potential of cement crushers was proven by investigating how to optimally decide its regulation contributions within a few minutes by Vujanic *et al.* [76] and for the day ahead by Zhang *et al.* [78] by switching off individual crushers in a cement plant. In the case presented by Vujanic *et al.*, there are two crushing machines whose separate scheduling for one week is investigated without considering downstream processes. In the case study by Zhang *et al.* a cement plant with four crushing machines and the inflexible downstream kiln was considered. Zhang *et al.* assumed that a large intermediate material storage facility and an electricity storage system are also installed to mitigate fluctuations in the electricity grid and ensure a high degree of load flexibility. The closeness to reality presented by Zhang *et al.* helps plant operators to understand better, how much profit can be earned from DSM participation, encouraging industrial loads to actively contribute to power system operation.

2.4.2 Conversion processes

In biomass conversion, flexibility has already been studied by Trommler *et al.* [79], Peters *et al.* [80], Thrän [81] and Dotzauer *et al.* [82] from another perspective. Their studies focus on biogas plants as controllable, regenerative power generators in order to balance frequency fluctuations within the power grid. In this context, the named authors investigate the spatial and temporal shift of biogas production steps. Additionally, the possibility of intermediate storage of biogas, its conversion into biomethane and its feed into the natural gas grid are considered [81]. Moreover, there are approaches to achieve a flexible biogas production through feed management and to variably produce electricity with a controllable combined heat and power unit [80]. In general however, the current state of research neglects the aspect of a flexible power consumption of biofuel production plants, whereas this would result in a more sustainable biofuel production. In Figure 2.5 the FOL of these conversion steps considered in literature are compared.

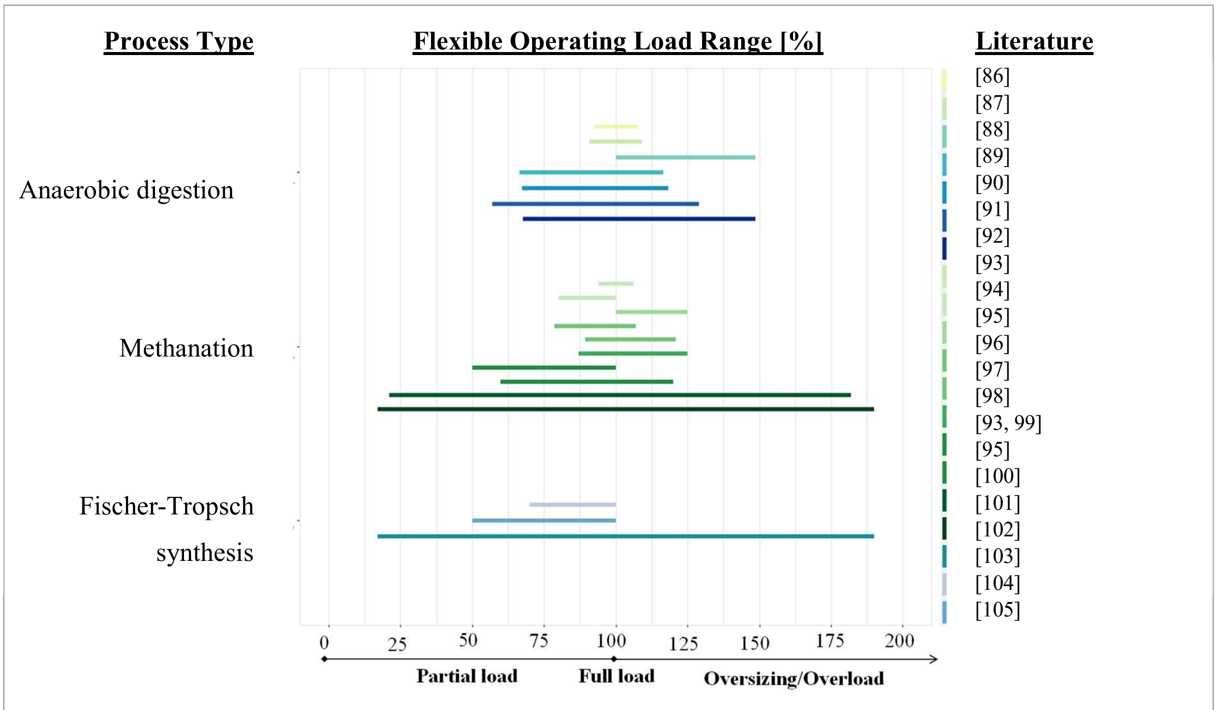

Figure 2.5: Flexible operating load range of conversion processes as found in literature.

Since conversion is usually associated with an optimum or maximum temperature, the difficulty is to control the process so that this FOL is not exceeded or undercut. Nevertheless, it has been proven in past literature, that a certain fluctuation in temperature and load is permissible. Bruns *et al.* give an overview of catalysed reactions under conditions of capacity flexibility [83]. Examples of catalysed reactions often found in DSM literature and biofuel production are fixed-bed methanation reactions and FT reactions [84, 85]. In methanation or FT synthesis, load flexibilization necessities often result from upstream dynamically operated processes, which leads to fluctuating input flows. Temperature is another factor that has been investigated for flexible control in conversion techniques. Especially anaerobic digestion but also methanation has been analysed in this regard.

Anaerobic digestion

Solutions to enhance flexibility of biogas plants through material storage were presented by Hahn *et al.* [106] and Bensmann [107]. Biogas storage at the site of the plant, represents the current state of practical implementation of demand-oriented biogas supply, e.g. for flexible power generation [108]. Hahn *et al.* investigated the possibilities and potentials of flexibilizing biogas plants through an adapted control of gas production in biogas plants concept on a small-scale. A decisive advantage of the proposed technology is the possibility to interrupt the biogas production for several days and to restart it within a few hours.

The flexibility aspect of temperature variation in the fermentation step that can play a role in flexible biogas production could also be considered as flexibilization of the energy demand leading to the definition of the FOL. Reactor processes are considered stable in the respective FOL (mesophilic: 37 ºC to 43 ºC) and (thermophilic: 43 ºC to 55 ºC) [86, 109]. Studies were conducted on temperature fluctuations in thermophilic fermenter conditions [86, 87, 89–91, 110] as well as on mesophilic fermenter conditions [86, 89, 91]. Good process stability was demonstrated for fluctuations within these temperature limits.

In a study by Gao *et al.* [88], the effects of thermal fluctuations on the performance of the microbial community structure in mesophilic anaerobic digestion were investigated for over one year. The results showed that the system was very resistant to temperature fluctuations in terms of chemical oxygen demand (COD) removal. The residual COD in the treated digestate was slightly higher at 55 °C than at 37 °C and 45 °C. The biogas production rate and biogas composition stayed almost constant with changing temperatures.

The effects of fermenter temperatures, temperature shocks and feed rates on biogas yield and methane content were evaluated by Chae *et al.* [89] in the anaerobic digestion of pig manure. The mesophilic digester temperatures were varied between 25, 30 and 35 °C. The methane content increased slightly with higher digestion temperatures. Temperature shocks of 35 to 30 °C and of 30 to 32 °C led to a reduction in the biogas production rate, but recovered to the value of the control reactor within 40 hours. Additionally, no permanent damage to the digestion rate was observed once it was set back to the starting temperature.

In a study by Luo [92], three identical continuously stirred reactors were regulated at a mesophilic temperature condition of 37 °C. Within the analysis, the temperatures in the reactors were changed to 25 °C, 45 °C and 55 °C. The results showed that however big the temperature disturbances, the same amount of methane production at a stable state were found in all three reactors. However, after the biogas reactors were returned to the original temperature conditions, new stationary microbial community populations were detected in all biogas reactors after a maximum of 10 days.

In general, it can be argued that fluctuations exceeding the mesophilic (37 ºC to 43 ºC) or thermophilic (43 ºC to 55 ºC) FOL lead to increased acid concentration and reduced biogas rate. However, depending on the duration and magnitude of the temperature change, with adapted feeding after reaching the original operating temperature, the process could be stabilised again after a few days without leaving any long-term damage within the microbial community.

Methanation

The flexibility of PtG processes, is currently being investigated to adapt to fluctuating input quantities from volatile renewable power supply. The dynamic operation of methanation reactors is favoured to limit upstream storage capacities. The contributions by Theurich *et al.* [43, 96] investigated the dynamic operation of a fixed-bed reactor at flow rate ramps with a variation of the ramp time and the influence of product recycling rate in CO_2 methanation. They demonstrate, on the one hand, that this type of reactors enhances the FOL and, on the other hand, that the system's response to varying feeds is attenuated by the recycling loop, thus reducing the system's sensitivity to changes and more tolerant to flexibilization.
The operational flexibility of fixed-bed methanation was investigated by Rönsch *et al.* [95] and Herrmann *et al.* [98] with help of dynamic simulation models. Simulation scenarios with load increases of varying degrees (25 and 100%) showed that the reactor temperature increased if the load increases [95]. In order to prevent deactivation of the catalyst by exceeding the permissible operating temperature, the operating range of conventional methanation nickel catalysts is stated to be in the limits between 300 and 600 °C. Herrmann *et al.* [98] provide a model-based analysis for the individual technologies electrolysis, absorption and catalysed fixed-bed methanation. The aspect of load variation in a catalysed reactor, was examined by enlarging the feed flow and observation of the product gas composition with simultaneous monitoring of the process behaviour. The flexibility limits of the modelling were based on the patent specification of Hitachi Zosen Inova Etogas GmbH [111], according to which the space velocity in the first reactor stage lies in a range from 2000 h^{-1} to 8000 h^{-1}.
Kreitz *et al.* [100] coupled a simple model of an alkaline water electrolyzer with a detailed one dimensional heterogeneous model of a catalyzed micro-structured methanation reactor and improved temperature control was demonstrated [112]. Higher operating temperatures could be applied without exceeding the critical catalyst temperature. The electrolytically produced H_2 was directly adapted to an exemplary wind power profile. The reactor was operated within an FOL of 21 to 182%. The simulation of the methanation reactor showed that the modulation of the H_2 inlet signal leads to vigorous variations in methane concentration and hot spot temperatures. The PtG plant must consequently be adapted either by a more robust methanation reactor or by adding a purification stage to follow the load profile of wind energy production very closely.
Tauer *et al.* and Mutz *et al.* also examined temperature variation in catalytic fixed-bed reactors for CO_2 methanation in a range from 170 °C - 230 °C [97] and 200 °C - 500 °C [94]. Temperature profiles were measured and the effect of a changing volumetric flow was studied. The experimental data found optimal reaction conditions with high methane yield under fluctuating temperature profiles. In the methanation step however, a lower catalytic performance was observed due to residuals of partly oxidized Ni, indicating that an efficient reactivation step is necessary after a H_2 dropout to return to the initial activity.

Fischer and Freund [93] as well as Iglesias Gonzalez and Staub [99] expected variable load operation limits of 50 to 100% of the maximum load of catalysed reactors, constrained by hot spot temperatures. Fischer and Freund presented consider critical reactor dynamics during the reactor design and that were integrated into an underlying optimization problem. The approach was modelled based on steady state experimental data using the methanation of CO_2. Iglesias Gonzalez and Schaub [99] investigate the hydrogenation of CO_2 over iron catalysts to short-chain hydrocarbons. A specific reactor design for flexible operation with gas recycling is a consequence of the constraints resulting from product partial pressures and reaction temperature. The comprehensive work by Kalz *et al.* [113] highlights recent developments, challenges, and future directions for catalysts under dynamic reaction conditions.

Fischer-Tropsch synthesis

A process concept using RE from fluctuating wind power and CO_2 to produce liquid hydrocarbons is Fischer-Tropsch (FT) synthesis. The economic performance of the process was evaluated by König *et al.* [103]. A buffer cavern acts as a bridge between the strongly dynamic electrolysis unit and the continuous chemical FT synthesis. H_2 is stored if surplus power is available and used when the H_2 demand exceeds its generation. The liquid product is also stored in tanks. Reducing the costs for electrolyser systems and electricity through DSM are the key factors for creating a profitable production scenario of liquid hydrocarbons from RE and CO_2 according to König *et al.*. A FOP_{min} of 70% is recommended for liquid hydrocarbon processes based on RE.

Pfeifer *et al.* [101] considered a PtG plant where electrolytically produced H_2 is stored in a tank and fed together with CO_2 in a required stoichiometry ratio to the FT stage. By applying RE data, a minimum H_2 storage time of 1.3 hr was calculated to operate the FT plant, 365 days per year without intermediate shutdown with the capability to accept a FOP_{min} of 17% and a FOP_{max} of 190%.

According to Loewert and Pfeifer [102] the efficiency of the FT synthesis can be optimized exploiting the benefits of micro-structured packed-bed reactors. The benefits arise not only from high conversion and productivity, but also from its capability to overcome the natural fluctuation of RE. Loewert and Pfeifer [102] highlighted and evaluated a system for fluctuating feed gas and temperature in a pilot scale FT synthesis. In a subsequent work by Loewert *et al.* [114] it was proven that highly load flexible operation in micro-structured FT reactors in combination with a dynamic H_2 electrolysis with multi-parameter changes in the one-minute regime is feasible and fully controllable.

Iglesias Gonzalez *et al.* [104] pursued a similar approach to Theurich *et al.* [96] for the CO_2-based flexibilities in the production of FT fuels. To increase flexibility, the recycling rate of the reaction products was used as a degree of freedom for reaction control. They concluded that a crucial point of this configuration might be the behaviour of upstream separation units under variable load conditions. The aim was to keep conversion almost constant and minimize the fluctuations in the recycle ratio between full and part load operation, by modifying reactor temperature. The reactor operated dynamically between FOP_{min} 50% and FOP_{max} 100%.

2.4.3 Refining processes

In biomethane and bioethanol production fermentation solid residues must be separated or dewatered. In industrial use sedimentation, thermal drying and filtration have proven successful for this purpose [85, 115]. Flexibilities in the purification of bio-based products have been investigated for sedimentation, thermal drying, membrane separation, distillation, cryogenic separation, and absorption processes. The possible FOL of investigated process steps that are found in biofuel production and can be operated flexibly are summarized in Figure 2.6.

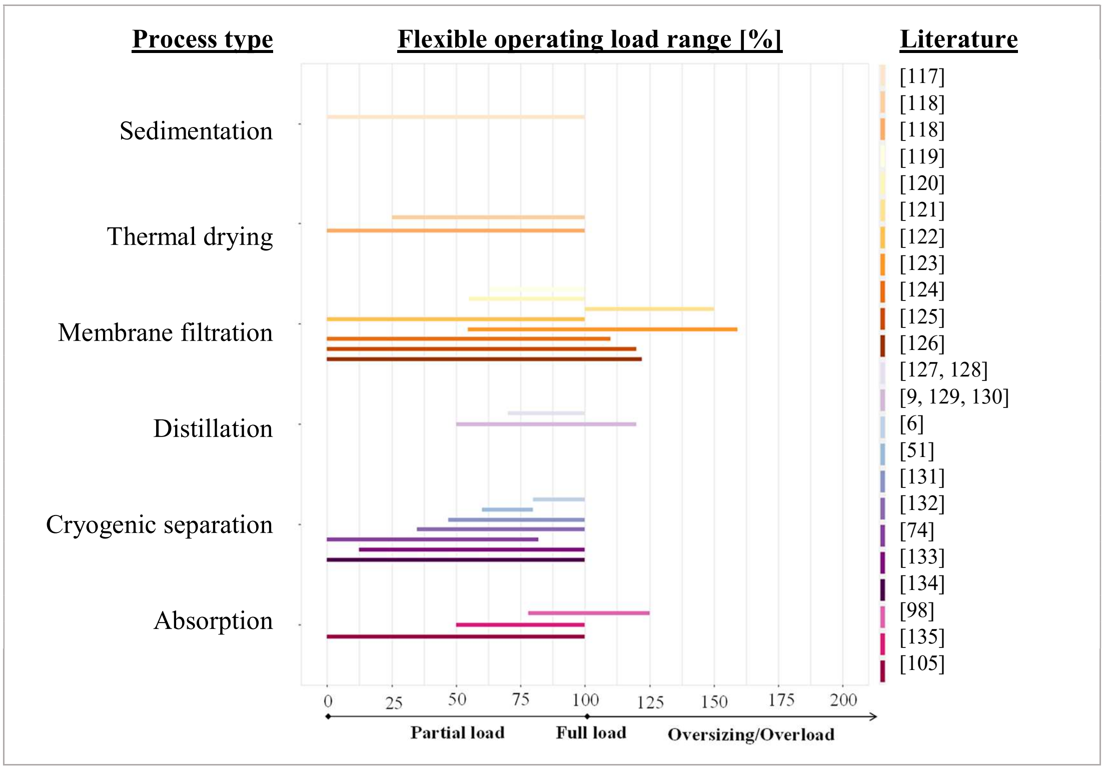

Figure 2.6: Flexible operating load range of solid, liquid, and gas refinement as found in literature.

A comprehensive review on flexibility options in liquid-liquid extraction was conducted by Polyakova *et al.* [116].

Sedimentation

In the FlexChemistry research project, flexibility options in the infrastructure operation of a medium-sized German chemical park were identified, evaluated by simulation and implemented in an operational environment by Zipperling *et al.* [117]. Two centrifuges with a shiftable load of approx. 50 kW each were identified in the sludge drying process, whereby the shifted sludge drying processes must be compensated for at another time. This requires storage capacities and an oversizing of the centrifuges. Conversely, when the centrifuges are switched off as planned, up to 100 kW of load can be compensated for as so-called negative flexibility.

Thermal drying

The article by Harper *et al.* [118] details the development of a decision support system for DSM programs in industrial drying. Air drying, heat pump drying, and airless drying was performed using a range of temperatures from 30 °C to 90 °C, 30 °C to 70 °C, and 120 °C to 150 °C respectively. Relative humidity control varied from 0 to 40%. While the airless dying system is considered to be switched off completely in Harper's study, the convective air dryer runs at a FOP_{min} of 25% of the nominal load. According to Harper *et al.*, the nature of drying technology presents opportunities for targeting energy inefficient processes and for proposing solutions through DSM programmes.

Membrane separation

Studies have shown that implementing a DSM in reverse osmosis (RO) desalination plants is technologically feasible [119–126]. Implementing a DSM in desalination plants is promising, because produced water can be stored easier and less expensive than electricity. On this background, Pohl *et al.* [119] modelled the system behaviour of a simple RO plant under varying process parameters such as feed pressure, recovery or feed flow. It is clearly displayed that a broad load range can be obtained with variable feed pressure. The results show that under volatile power supply a membrane system should be operated with constant permeate recovery. The applied pressure has a higher impact on energy consumption than the feed flow. Since to that point it was not yet clearly investigated which negative effects are related with a variable pressure, possible pressure alterations were minimized to 7.0 bar to 12.5 bar.

Prathapaneni and Detroja [122] consider a RO desalination plant that is segregated as units and each unit can be operated independently as required. A direct DSM is incorporated into the sizing process to determine the optimal flexible operation of the desalination plant. With the proposed method, the system lifetime costs can be reduced by a maximum of 5.69% in a FOL of 100%.

In the work by Jiang *et al.* [124], Ghobeity and Mitsos as well as Williams *et al.* [125, 126] an optimization designed to reduce the operational cost of a seawater RO system was studied. In all studies switching off the system is considered. To enhance operational flexibility and economic potential a storage tank was considered by Jiang *et al.* as the buffer between freshwater production and sale. A FOP_{max} of 110% of the nominal operating point is considered. Compared with the conventional operation more than 26% of the cost savings can potentially be achieved by the proposed method. Approaches by Ghobeity and Mitsos and Williams *et al.* of oversizing the desalination plant 20% and 22% lead to a maximum cost saving potential of 7%.

Simulations of Bognar *et al.* [123] allow a RO desalination plant to operate variably consuming load between 37 MW and 108 MW. As the nominal load lies by 67.7 MW the operating rang results in 55 to 169%. Bognar *et al.* summarized that the desalination as deferrable load in a micro grid requires less additional fossil energy. The technical and economical DSM potential were also analysed for wind powered seawater desalination with RO by Käufler *et al.* [121]. Käufler *et al.* emphasize its capability and potential to be implemented in medium and large-scale plants. The authors state that oversizing the desalination plant is a feasible option tolerating an FOL of 100 to 150%.

A techno-economic analysis of producing desalinated water for strategic water storage by utilizing wind power was investigated by Loutatidou *et al.* [120]. The desalination plant was modelled as a variable flow RO plant in which pressures and flows were varied within an FOL of around 55% to maximal 150% to match the available hourly RE production. Its water production rate was variable avoiding the need for ineffective power storage. Loutatidou *et al.* conclude that from a technical point of view, oversizing of the RO plant by 50% is the most attractive option.

Distillation

For the integration of distillation processes in DSM programs, Hoffmann *et al.* [127] propose an advanced modelling approach based on a reformulation of the well-known modelling equations for distillation processes to enable a description of appearing and disappearing phases at different column states. Phenomena regarded are weeping and entrainment of liquid, limitations regarding mass transfer efficiencies as well as downcomer dynamics. Despite high specific energy consumption, Hoffman *et al.* demonstrate that DSM application is limited in distillation columns due to complex interactions of hydrodynamics, operational and design parameters. In a further work, Hoffmann *et al.* [128] investigate a process coupled with the dynamic operation of a chlorine alkali electrolysis. Here, DR scenarios are investigated for an integrated vinyl chloride monomer production plant which also consists of a flexibly operated distillation column for ethylene dichloride purification. Results, verified by real plant data, show that proper operation of the column is possible for a reduction of gas loads from the FOP_{min} of 30%. Beyond this point, first stages start to run dry and a further decrease of load is not possible.

Measures to enhance the flexibility and reduce start-up times of tray distillation columns were described by Riese 2016 [9]. Those measures aim at the development of new apparatus design to overcome hydrodynamic limitations. To reduce the start-up times buffer tanks to store intermediates from the column are installed along the height of the column. This measure curtails the start-up period by 25%. This reduction in start-up time is comparable with optimized start-up procedures for conventional columns. Nevertheless, the installation of buffer tanks can help to reduce the loss of valuable material. Further measures described by Riese *et al.* aiming at an internal structuring of the column to enhance capacity flexibility [129] and reduce start-up times [136]. The internal segmentation of the column enables the independent operation of singular segments and, due to the proposed column design [130], a start-up of adjacent segments by pre-defined concentration and temperature profiles. This design approach leads to an increase in FOL from 50% to 120% and a reduction of start-up time of > 90%.

Cryogenic separation

As research on air separation unit (ASU) flexibilization is very broad, this contribution focuses on selected research work which highlight technical measures to enhance flexibility or to improve performance with respect to. However, a reduction of operation costs by adapting operation to volatile electricity prizes is the main motivation and highly interconnected with the determination of optimal trajectories for flexible operation. Thus, a strict division and classification of research work is not always possible.

Studies focusing on the air compressors in ASU have been conducted by Teichgraeber *et al.* [132], Karwan an Klebis [137] and Kopanos *et al.* [138]. Teichgraeber *et al.* consideres a two-compressor system with an FOL between 35% to 100%. Ramping rates reported in literature vary, but representative values are 2% load increase and decrease per minute for conventional systems, with up to 8% per minute measured in small plants [132]. Teichgraeber *et al.* stated that the ASU ramp rate can be shut on and off completely, within the one-hour discretization steps used in this work. Karwan *et al.* [137] represent ASU activities in three configurations: entire shut down, compressor and related equipment are in use, and compressor and liquefier are active. Karwan *et al.* [137] found that market response to real time pricing is preferred to purchasing electricity under time of use in those situations where there is a great deal of flexibility, i.e. lightly loaded plants and or short ramp-up times. Kopanos *et al.* [138] address simultaneously optimising the compressor maintenance and operation tasks for air separation. In their study minimum operating times and investments for compressors were ignored. The emphasis has been on the modelling of the pipeline network rather than on the compressor operation.

Zhang *et al.* [131] adapted the operation of an ASU to the availability of RE within an FOL of 47% to 100%. Additionally, the ASU was coupled with a cryogenic energy storage system that is suitable for either oxygen or nitrogen to offer additional operational possibilities. Cost savings are possible using an electricity storage system. For an overall efficiency of 80%, a cost reduction of 12.1% and 22.6% per week for a plant utilization of 60% and 40% respectively, were achieved. Cost savings increase with increasing efficiency of the storage system but decreasing utilization. However, additional investments for the energy storage systems were not examined and may change the perspective. While Zhang *et al.* solved the problem from a systems perspective, Caspari *et al.* [139] looked at the process controller necessary to adopt the operation of ASUs to varying electricity prices. Therefore, the authors solved a so-called economic non-linear model predictive control problem. The aim here was to use the control layer for DSM directly instead of an additional scheduling layer for the overall process.

In another study on the DSM of ASUs, Caspari *et al.* [133] investigated different operating modes incorporating a further liquefaction cycle and corresponding storage tanks for liquid nitrogen and oxygen. The aim of this process configuration is to enable as much DSM potential as possible by implementing moderate process configurations. Therefore, the authors first perform a steady-state design optimization [133] and a subsequent study on optimal operation again using the economic non-linear model predictive control approach [140]. Results show, that a variation of power from 3.5 to 28 MW is possible resulting in a large overall operating window with respect to the electricity and a reduction of operating costs of 14% for a time horizon of two weeks.

Ierapetritou *et al.* [134] also investigated an operation strategy with three different modes. During regular operation, 20% of the total power demand is required for the compression of air, whereas 80% is required for the liquefier. In the assisted operation mode, the liquefier is shut down and liquid needed for refrigeration is taken from storage of previously produced product. During

shutdown mode the all parts of the plant are shut down. An optimization framework is developed that incorporates all three operation modes and adapts operation to power price variability.
A different approach was pursued by Kelley *et al.* [141] who also investigate a simple ASU scheme with an integrated storage and power network, originally presented by Johannson [142]. Interesting here is the objective to adapt the operation of the ASU towards minimizing GHG emissions rather than operating costs by utilizing time-resolved information on the composition of the power mix.

Absorption

Herrmann *et al.* [98] investigated the integration of a CO_2 capture process in a PtG framework, using biogas as a carbon source. The authors performed a case study regarding the flexibility of the PtG process chain, considering a proton exchange membrane (PEM) electrolysis plant, a CO_2 capture process based on absorption with monoethanolamine and a two-stage methanation. As packed columns were considered, the FOP_{min} was determined by de-wetting of the packing and the FOP_{max} by flooding of the column. Both phenomena lead to a significant decrease in separation efficiency during operation. Process analysis lead to a FOL of the absorption-desorption cycle of 78-125% around the nominal operating point ensuring sufficient CO_2 capture rate and biogas with a quality that meets gas grid requirements.
Luu *et al.* [143] present a comprehensive study on the controllability of the amine-based post-combustion CO_2 capture (PCC) process. The authors proposed three different control schemes and test them against fluctuations in flue gas flows and CO_2 content in flue gases. Control variables are the CO_2 capture rate, energy performance of the process and reboiler temperature. The latter is restricted by energy demand for solvent regeneration on the lower limit and solvent degradation at the upper limit. Degrees of freedom to adapt to fluctuations are lean solvent flow rate and reboiler duty. Results show, that the chosen model predictive control strategy is most efficient and able to prevent constraints to be violated. The authors take changes in flue gas flow rate and CO_2 content in the flue gas of ±12% into account.
The PCC process is also investigated by Mechleri *et al.* [135]. The authors aim at developing a control strategy for the PCC process for a FOL of the upstream power plant of 50-100% around the nominal load in an integrated flowsheet of the overall process, including the power plant and the CO_2 compression subsequent of the capturing. Three control strategies were developed: constant CO_2 capture rate by manipulating the lean solvent flow, constant total solvent flow in absorber and desorber and maintaining constant CO_2 capture rate by manipulating the heat duty of the desorber supplied by the power plant, and a combination of both, switching between both aforementioned strategies. The authors explicitly state challenges for a flexible operation of separation columns as already discussed in the scope of continuous distillation. Results show that critical parameters such as CO_2 capture can be maintained even if the operation of the power plant is significantly fluctuating. Manipulating the lean solvent flow rate seems more promising to control the CO_2 capture rate than manipulating reboiler temperature. The other strategies investigated might be useful for start-up or shutdown of the process.

Zaman and Lee [105] analysed the possibility to enhance flexibility of and switching off a CO_2 capture plant by means of integrated material storage or capture level reduction and a combination of both. The authors study the effect of different storage capacities and electricity cost profiles that motivate flexible operation. Results show, that OPEX savings compared to steady-state operation are highest for the combination of storage and capture level reduction. Maximum cost savings of 11.08% were reached over the fixed-point operation, respectively. Taking CAPEX into account, savings become smaller for the storage strategy and for the combination of storage and capture level reduction. This is comprehensible as large storage facilities need to be installed for the investigated 303 MW power plant.

2.4.4 Provision of auxiliary materials and reactants

In this subsection focus is laid on articles that consider the possibility of using fluctuating RE supply in order to split water into H_2 and O_2 as hydrogen may be needed in biofuel production. Figure 2.7 compares FOL found in literature for H_2-Electrolysis.

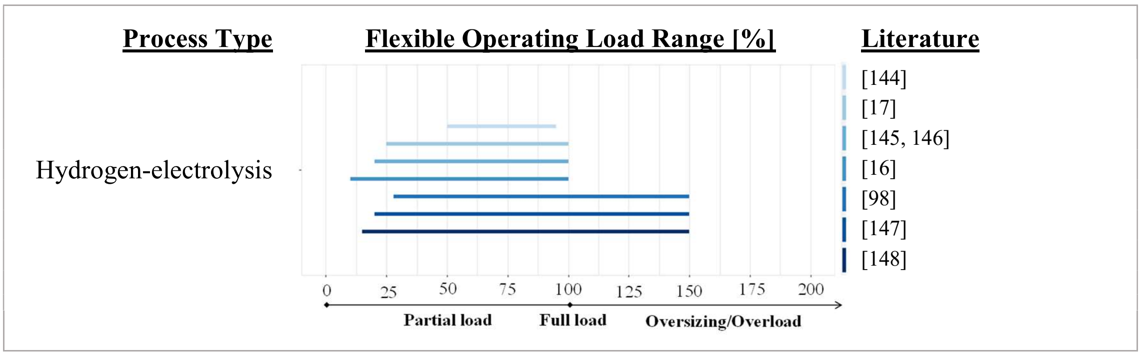

Figure 2.7: Flexible operating load range of hydrogen electrolysis as found in literature.

The flexibility options for this methanation step in PtG plants are reviewed in Section 2.4.2. The possibility to use H_2 storage in order to be able to flexibilize the energy demand of downstream unit operations was investigated by König *et al.* and Pfeifer at al. [101, 103].

Hydrogen electrolysis

A review by Carmo *et al.* [16] comprehensively highlights and reviews proton exchange membrane (PEM) systems for H_2 electrolysis. The challenges related to electro catalysts, solid electrolyte, current collectors, separator plates and modelling efforts are addressed. In regards to the flexibility of the process, it is stated that in comparison to the 30 to 40% FOP_{min} of alkaline electrolysis, PEM electrolysis can be run at 0-10% FOP_{min}, enabling a much greater FOL. The IRENA hydrogen report provides an in-depth perspective on the nexus between H_2 and RE, on H_2 supply economics in light of the rapidly falling cost of RE and the role of H_2 in the energy transition, as well as on existing challenges that have hampered H_2 development to date [149].
A review of the role of energy storage with a special focus on and long term storage was conducted by Blanco and Faaij [150] of more than 60 studies (plus more than 65 studies on PtG) on power and energy models based on simulation and optimization. It was found that the

combination of sectors and diverting the electricity to another sector can play a large role in reducing the storage size. A further review of 192 Power-to-X demo projects in 32 countries is presented by Chehade *et al.* [151]. Results demonstrate that the characteristics of the demo projects have developed significantly over the years: electrolysis capacity increased for both PEM and alkaline systems. The potential for DSM operation is being investigated to a growing extend through grid-connected demo projects. The extend of hydrogen-to-X pathways has also progressed over the years, especially to integrate industrial applications.

Investigating DSM application for the PEM electrolysers, Herrmann *et al.* [98] observed the system response to a dynamic power input. Higher H_2 production at higher than nominal capacity can lead to the increased degradation of electrodes. For flexibility purposes, an FOP_{max} of 125 % was chosen. A possible temporary overload of 150 % is said to be possible but this requires sufficient sizing of the peripheral equipment and cooling.

The implementation of a DSM in a polymer electrolyte membrane (PEM) has been studied by Eichman *et al.* [17]. Using a 40 kW alkaline and PEM electrolyser, they showed that a PEM electrolyser takes 0.2 s to complete 99.1% of a 25% ramp-down from its operating level. For a 75% ramp-down, the PEM electrolyser completes 96.7% of the required ramp-down in 0.2 s. However, the injection of the intermediate in the downstream process, if not temporally buffered, this results in significant deviations of the operating conditions.

Simulation models of an electrical power system developed by Kiaee *et al.* include steam turbine generation units [146], electrolysers, conventional loads, and wind farms [145]. As many as 24 electrolysers with a nominal load of 2 MW each are considered, with a FOP_{min} of the electrolysers of 20%. Electrolysers capable of a reasonable fast DR are already available on the market today. Kaiee *et al.* were the first to demonstrate, based on these dynamic characteristics, that electrolysers can provide useful frequency support to the power grid.

The economic analysis of Mukherjee *et al.* [144] of a flexibilized PtG plant illustrates the economic potential of providing emissions reductions and ancillary services. The study considers an electrolyser operating in a FOL between 50% and 95%. To further quantify this potential, Wang *et al.* [148] project the hourly system-wide balancing challenges in California up to 2025 as more RE are deployed and electricity demand continues to grow. The results show that oversizing electrolysers and thus allowing an FOL between 15% and 150%, can provide considerable benefits to ease renewable intermittency, while also supporting the deployment of H_2 vehicles to help decarbonize the transportation sector.

Hosseini and Wahid [147] perform thermodynamic analyses of the concentrated photovoltaic and electrolysis systems for solar H_2 production. Alkaline water electrolysis was distinguished as the most promising electrolysis process for efficient and the near-term large-scale solar H_2 production process. Hosseini and Wahid find that alkaline water electrolysis can be operated at 20% to 150% of the nominal load capacity.

Other electrolytic processes that have often been considered for DSM implementation are the obtaining of high-purity aluminium or chlorine [146, 152–156] (see also Table 2.1 in Section 2.3). Aluminium and chlor-alkali electrolysis play a major role in DSM research, due to their high production rate and specific energy consumption. The production of copper and zinc through electrolysis was briefly addressed by Klobasa [14]. These studies on flexibilization in electrolytic processes follow the same control and optimisation principles as H_2 electrolysis, yet are not processes found in biorefineries.

2.5 Comparison of results on DSM options in biofuel production plants

In this section, the processes named in Section 2.4 will be compared and the results summarized. For each of the four predefined process areas – mechanical pre-treatment, conversion, refining and provision of auxiliary materials and reactants – multiple process steps have been identified as flexibly operable. Technical restrictions limiting the flexibility of these process steps can be derived of this review for each of these process steps. Finally the relative amount of operating load or temperature variation each process step under consideration can provide was analysed from the respective papers studied. Figure 2.8 graphically summarizes in a box plot diagram the distribution of the FOL per unit operation discussed in this review. The urpose of this figure is to compare the FOL of the processes reviewed in this article. This allows processes with comparatively high FOL to be identified.

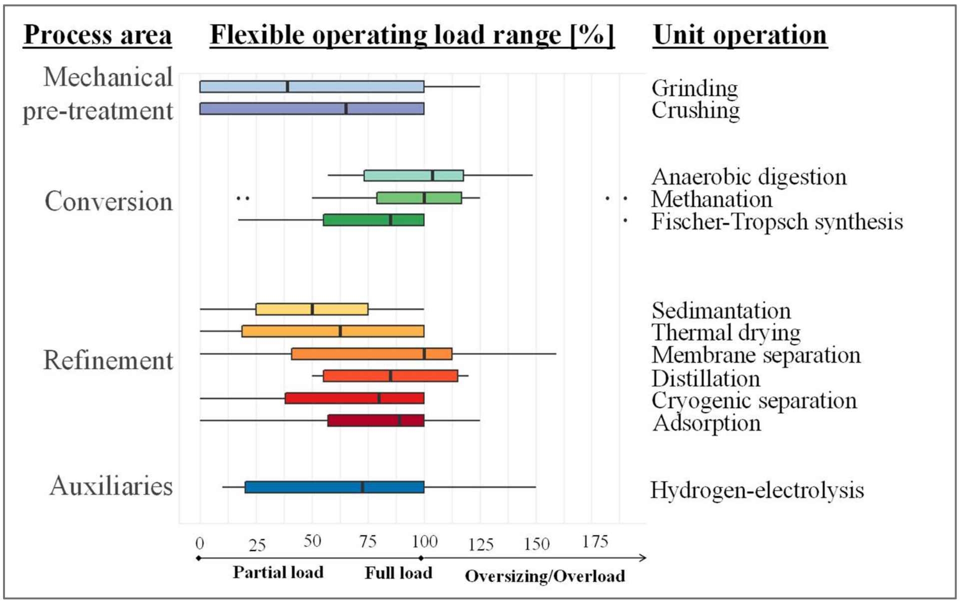

Figure 2.8: Distribution of the operating load range per unit operation found in this review.

In the pre-treatment of biomass, mechanical processes such as grinding, crushing, or milling are very suitable for DSM use. Provided that intermediate storage facilities are installed upstream and downstream, comminution processing equipment can be switched off quickly and easily and, depending on the unit, the equipment can also be operated in partial load modes. The technical restriction is the size of the storage which limits the time, for which the process can be switched off. As can be seen in Figure 2.8 that mechanical pre-treatment steps find their interquartile range of FOL at 100%.

In biotechnological conversion processes such as anaerobic digestion or ethanol fermentation, temperature is an essential factor for the efficiency of the reaction. The aspect that makes this section of biorefineries very interesting for the use of DSM is the tolerance towards a certain disturbance of temperature (-43% to +49%). Limitations in the FOP_{min} and FOP_{max} occour from increased acid concentration and reduced biogas rate. Investigations on ethanol fermentation demonstrate that although temperature variation is possible, the strong dependency of the conversion process on optimal temperature will usually lead to decrease in process efficiency when deviations occur.

In DSM literature on catalytic conversion processes, methanation and FT synthesis have been investigated for indirect DR, operating in accordance with the flexibly produced H_2 input stream. Limiting factors, resulting in a small FOL, are the high sensibility to hot spot temperature or catalyst deactivation. The FOL of the methanation step shows outliers in the box plot diagram (see Figure 2.8). This is partly because the studies investigated have different approaches on the definition of flexibility. On the other hand, some studies have specifically aimed at expanding the existing FOL. Suggested measures are aimed at enlarging the FOL by oversizing reactors in catalysed chemical conversion but also at minimizing the transition time between stationary operating points. In Fischer-Tropsch synthesis the aim of flexible operation is to react to fluctuating H_2 input streams and to keep conversion almost constant nevertheless. A rather small FOL of 50% was determined.

The simple possibility of intermediate storage in solid-liquid separation steps such as sedimentation or membrane separation as well as the possibility of switching the processes on and off makes DSM integration very promising in mechanical by-product treatment. In sedimentation intermediate storage size limits the time of DSM application. In thermal drying, the moisture content of the resulting product and thus the product quality is decisive for determining the FOP_{min}. The results of the gathered data on membrane separation in RO show that a membrane system should be operated with constant permeate recovery under fluctuating wind power. The applied pressure has the highest impact on energy consumption. In some studies the negative effects related with a variable pressure limit the FOP_{min}. Other studies however consider switching off the RO plant completely resulting in the lower whisker of the boxplot diagram (Figure 2.8). The limit in DSM application will then be determined by the size of intermediate storage tanks.

The analysis of various important apparatuses for liquid and gas purification shows that their FOL is limited under certain circumstances. Due to the free phase interfaces between gas and liquid, which are required for the mass and heat transfer between the phases, a complex situation arises regarding hydrodynamics within the apparatus. Results from investigations on flexibility in distillation columns, show that proper operation of the column is possible for a reduction of gas loads from the nominal operating point. However beyond this FOP_{min}, first stages start to run dry and a further decrease of load is not possible. In cryogenic separation, the opportunities but also constraints often arise from the flexible operating load management of the gas compressors. The FOP_{min} has been analysed around 35%. The deviations however arise from the different unit operations that are considered for DSM within the separation process. In some cases the

liquefiers, in other cases the compressors and sometimes a combination of the two are considered. In absorption separation, the lower limit for flexibility was defined by de-wetting of the packing and the upper limit by flooding of the column. Both phenomena lead to a significant decrease in separation efficiency during operation. The large deviations in the FOL box plot found on absorption processes (see Figure 2.8) result from investigations on enhancing flexibility in this process step, similar to studies on methanation flexibility.
Due to the fast possible response time and the relatively high FOL in hydrogen electrolysis, this process is a very promising for DSM applications and is already applied today. Lower flexibility restrictions depend on the type of electrolysis used. The FOP_{min} is limited by the concentration of H_2 in oxygen at the anode side. The FOP_{max} is limited to 150%, as at higher then nominal operation the degradation of the electrode rises.
In summary it could be demonstrates that many processes in biofuel production have a large FOL, making it seemingly relevant for DSM integration. From the review it becomes very clear, that especially mechanical processes and electrolysis offer great flexibility potentials in DSM application. High sensitivities in operational conditions of conversion and gas refining processes lead to high constraints in process flexibilization. However new design methods and modes of operation have been analysed respectively and show promising results in expanding existing FOL.

2.6 Conclusion and perspectives

A systematic review of options for demand side management in biofuel production was presented in this contribution. Overall is can be stated that indeed many process steps in biorefineries have been identified as flexibly operable. As numerous different technologies are found in the process chain of transforming biomass in industrial biorefineries into biofuels, technical restrictions can vary greatly from storage capacities, product quality or process deactivation. Each individual process step will therefore have to be considered individually in case of DSM application.
Especially in downstream mechanical separation, multiple processes have been investigated but little literature exists on the individual processes, while papers on electrolysis and mechanical pre-treatment abound. Completely missing process steps are found especially in the conversion of biomass to biofuel. Although many process steps have already been identified as flexible, there is still a lot of research potential open for investigation. In methanation and anaerobic digestion temperature variation boundaries have been identified. However, DSM measures are aiming at adapting the electricity demand at current available RE production. Therefore process heat would have to be generated by electrical energy in order to use these process steps for DSM. Currently, only very few, and especially small biofuel production plants generate process heat electrically [16, 18]. An interesting aspect in the implementation of a DSM in biofuel production could be to look into electrifying more thermal biofuel production steps. Low temperature processes such as anaerobic digestion in biomethane production could be especially relevant for this research since the relatively large FOL promises good DSM applicability.
Since the bio-based industries' market share is likely to increase [29, 157, 158], their impact on energy consumption and the flexibilization of it should be studied for future DSM applications.

More production will lead to a higher energy consumption and thus the impact of DSM integration will rise. As DSM programs aim at using energy at times of high RE penetration, the integration of biofuel production plants in a DSM program could contribute greatly to the extension of RE integration. Furthermore higher energy consumption at times of high RE share in the electricity grid would also make biofuel production even more sustainable. It is not possible to quantify from this systematic review how high the actual DSM potential of a process or a plant is. It is important to first understand how intensively the processes are used, what the specific electricity demand and, derived from this, how high the energy load of the respective processes is. The combination of the energy load and the FOL can then yield the theoretical DSM potential. In combination with the calculation of the energy demand of biofuel production, this paper lays the foundation for the intended subsequent investigation of the theoretical DSM potential of biofuel production.

Chapter 3. The Theoretical Demand Side Management Potential in Biofuel Production[2]

This chapter demostrates the results of a DSM study on the implementation of a DSM in biofuel biorefineries. By specifying reference concepts that could represent biofuel production plants, the specific mass and energy consumption for the individual process steps in these reference concepts was analyzed through literature study. The annual throughput and energy consumption of process steps in biofuel production 2019 could then be calculated, enabling the identification of the most energy-consuming process steps. Subsequently, possible flexible operating load ranges of the individual process steps in biofuel production were identified. These findings allowed an assessment of the potential for different process units of biorefinery systems concerning the quantitative adaptability of the electricity load – the theoretical DSM potential. An approximate theoretical DSM potential of 146 MW has been identified for biofuel production in Germany. This cumulated theoretical DSM potential in biofuel production was compared to other industrial processes, demonstrating the magnitude and importance that the implementation of a DSM in biofuel production can contribute.

3.1 Introduction

In order to achieve the energy and climate protection goals of the German government, a reduction of greenhouse gas (GHG) emissions in the transport sector is of great importance. To this end, various measures are being considered and evaluated within the framework of the Mobility and Fuels Strategy of the German Government [159]. Biofuels are currently proving to be an essential renewable alternative in the mobility sector and are expected to contribute significantly to sustainable mobility in the future [160]. One aim is to reduce or completely replace the amount of fossil fuels used for this internal process energy to minimize the emissions produced during the processing of the biofuel. Since the availability of biomass is a major concern for the transition of the chemical industry to a bioeconomy, the utilization of parts of the raw material as an energy-carrier for process energy requirements should however also be minimized. If the ecological balance of production is however also to be improved, a conceivable solution is the use of volatile renewable energy (RE) sources such as solar and wind for process energy provision. For RE integration in biofuel production, the fluctuation of these energy sources in their production would inevitably also require a transformation to flexible power consumption. The adjustment of a system's power demand to follow the current power generation and subsequently flexible production concepts is commonly referred to as demand side management (DSM).

[2] Substantial parts of this chapter are published in Röder, L. S.; Gröngröft, A.; Grünewald, M.; Riese, J. (2022): Assessing the demand side management potential in biofuel production; A theoretical study for biodiesel, bioethanol, and biomethane in Germany. *Biofuels Bioproduncts & Biorefining*. DOI: 10.1002/bbb.2452.

In the context of this paper, the question arises of how flexible the operation of continuously operated processes in biofuel production is. In order to clarify the integral impact of a DSM implementation in biofuel production, the theoretical DSM potential will be compared with theoretical DSM potentials that have already been calculated for other industries. Due to the high global production rates [32], the three different types of biofuels that are further investigated in this report are biodiesel, bioethanol, and biomethane.

Today, the European Union is by far the most important biodiesel producer in the world, with a share of almost 37% of global production, and leading production in Germany [161]. In bioethanol production, Europe ranks third after the USA and Brazil, with the highest production in Germany, France and Italy [161]. In biogas production, Germany is leading in production worldwide with close to 10.000 biogas plants. Biogas upgrading to biomethane and use as a biofuel are also high in Europe where approximately 2.2 million tonnes of crude oil equivalent of biomethane are produces which accounts for almost 63% of the total biomethane production worldwide [162, 163]. Germany is by far the largest market, and home to two-thirds of Europe's biogas plant capacity [19]. Given the high production volumes and the good data availability for biofuel production, Germany will be considered as a case study for the calculation of the theoretical DSM potential for biofuel production. The biofuel production quantities of the individual processes vary annually, as they depend strongly on the economic situation. For this reason, the production volume for 2019 was used, as the data for this year is relatively up-to-date and widely accessible.

The main results of this work are the extrapolation of the theoretical DSM potential in biofuel. For the main biofuel production chains investigated, reference concepts were developed and processes with high electricity demand and the possibility of flexible operation identified. The key results that can be derived thereof are:

1. the presentation of the total energy and biomass flows
2. the calculation of theoretical DSM potentials for process steps
3. the comparison of the cumulated theoretical DSM potential with other industries

of biofuel production in Germany for the year of 2019. By identifying processes with high DSM potential, this assessment lays the foundation for prioritizing plants for further DSM investigations.

The remainder of this contribution is structured as follows. This section introducing the necessity and interest of implementing a DSM in biofuel plants is followed by Section 3.2 explaining the methods of how to conduct the calculation of the DSM potential. Section 3.2 contains the identification of suitable biofuel reference plants and required parameters for the theoretical DSM potential calculation. The key results of this contribution are summarized in Section 3.3. Section 3.4 closes with a discussion on how the investigation of this DSM potential can help by expanding the currently available industrial DSM potential, and why in the near future this potential could grow significantly.

3.2 Methods and materials

This contribution aims at quantifying electricity consumption in biofuel production which can be postponed or interrupted for a certain period of time, making them accessible for DSM. Process steps that can temporarily change their load will therefore have to be identified. In order to make a selection, the following criteria that were defined by Ladwig [8] are used for this evaluation:

(A) The process has a comparatively high specific electricity consumption (SEC) or electric power consumption (EPC). Accordingly, a large potential can be exploited by controlling only a few processes.

(B) The process should have a flexible operating load range (FOL) and be able to be started up and shut down at short notice.

In many cases the temporal availability of DSM activation often referred to as application or switch-off time depends primarily on installed intermediate storage and potential oversizing of the processes. This investigation is beyond the scope of the paper and will not be explicitly analyzed. However minimum and maximum switch-off times have to be kept in mind when planning DSM implementation. The applied method for identifying the theoretical DSM potential is illustrated in Figure 3.1. Parameters identified through literature study are shown in shaded boxes. Parameters that were calculated using these literature values are shown in white boxes.

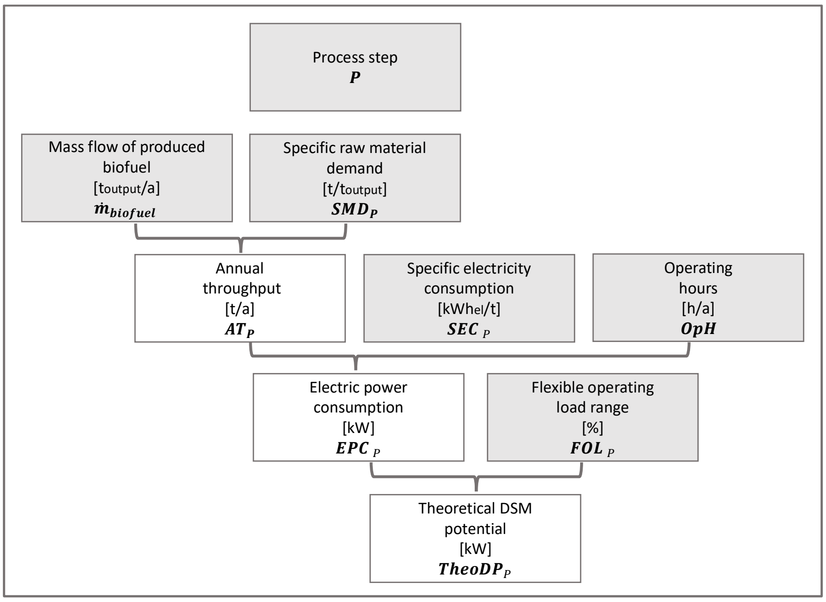

Figure 3.1: Method for calculating the theoretical DSM potential of process steps.

As a starting point for the investigations, a review of existing bioethanol, biodiesel, and biomethane plants in Germany was carried out. The focus of this contribution is placed on the most commonly used processes and input substrates for the respective biofuel production processes. In a second step for each of those reference concepts, a further literature study was carried out to identify the mass flow for each biofuel type $\dot{m}_{biofuel}$ as well as the specific raw material demands (SMD) that are necessary to produce the biofuels respectively. The annual throughput (AT) of the individual process steps P can then be calculated using the following formula:

$$AT_P = \dot{m}_{biofuel} * SMD_P \tag{3-1}$$

Thirdly, by multiplying the calculated AT with the SEC divided by the yearly operating hours (OpH) of the process (P), the hourly EPC can be determined.

$$EPC_P = AT_P * \frac{SEC_P}{OpH} \tag{3-2}$$

The SEC and OpH were also retrieved from literature. The calculation of the collective biofuel electricity consumption uses an average of the SEC and AT requirements found in literature. The amount of hourly electricity demand of the energy-intensive processes in biofuel production usually neither depends on the season or time of day nor the outside temperature. For this reason, the hourly electricity consumption can be assumed to be almost constant. Full load hours of 8000 hours are assumed for all biorefinery types based on the average annual utilization [34, 36, 85, 164, 165], resulting in a constant load profile over the year.

The next step consists in identifying process steps in biofuel production system with high SEC and EPC and thus fulfilling criteria (A). Furthermore the FOL, obtained from literature, will be identified in biorefinery process steps thus fulfilling criteria (B). Lastly, the $TheoDP$ of the biofuel production processes is determined in adaptation from Gils and Ladwig [8, 51] equally for all process steps by using the following equation:

$$TheoDP_P = EPC_P * FOL_P \tag{3-3}$$

Once the theoretical DSM potential for all processes p under consideration is calculated, the sum of all processes' $TheoDP_P$ represents the cumulated theoretical DSM potential for biofuel production.

$$TheoDP = \sum TheoDP_P \tag{3-4}$$

By comparing this cumulated value to other industry sectors which have been investigated for DSM potentials in the past, the impact of a DSM implementation in biofuel production can be demonstrated. In the following the materials for the reference concepts and literature sources for the above-mentioned parameters SMD, SEC, FOL will be summarized.

3.2.1 Reference concepts and specific raw material demand

Based on the available information on biofuel production found in the guidance documents on technical principles and methodology for calculating the GHG balance of biofuels [34–36], reference concepts were created for biodiesel, bioethanol, and biomethane production, in which comparable plants in terms of process technology are grouped together (cf. Figure 3.2). The quantities of main output material flow – biodiesel (3400 t), bioethanol (544 t), and biomethane (741 t) – produced 2019 have been identified by Majer *et al.* [36].

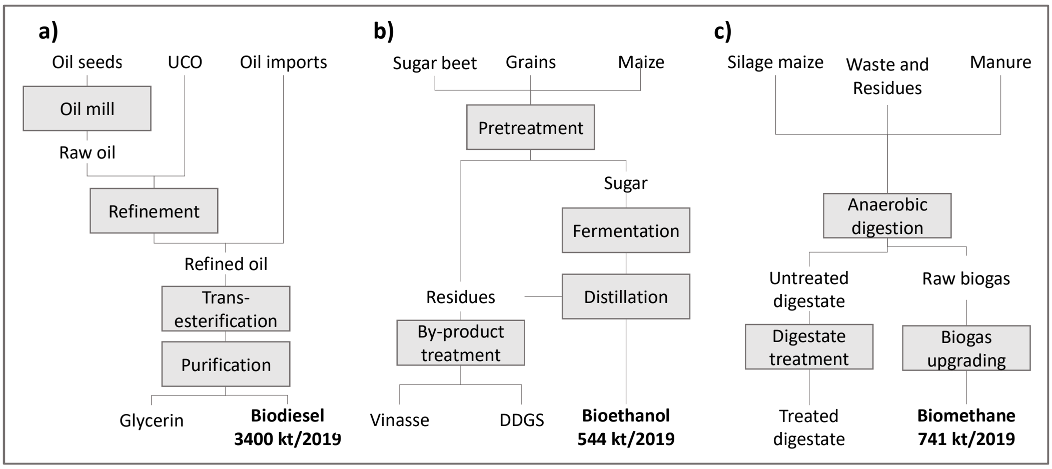

Figure 3.2: Reference concepts for biofuel production a) Biodiesel b) Bioethanol c) Biomethane.

Biodiesel is primarily produced from vegetable oils in Germany. The most important raw material for this is rapeseed oil with a share of 57% [166, p. 15]. Imported oils (soybean and palm oil) sum up to a share of 13% of which palm oil maintains a comparatively small share of 2%. In addition, other raw materials such as animal fats or used cooking oils (UCO) account for 30% of raw oils used for biodiesel [167].

In bioethanol production, a distinction is made between the utilization of starch- and sugar-containing crops. 2019 approximately 65% of bioethanol production in Germany was based on the fermentation of maize. Grains, being mainly wheat, barley, rye, and triticale accounted for 28% of the feedstock for bioethanol production. Both of which are considered starch containing crops. For the remaining 7%, sugar containing crops were used, i.e. sugar beet and sugar cane. [168]

Biomethane production consists of biomass fermentation, the separation of biomethane from the raw biogas, and the processing of the leftover digestate. As raw materials energy crops (58%), agricultural residues (28%), industrial organic waste (10%), and municipal waste (4%) are used as fermentation substrates. According to the European Biogas Association [163] the proportion of biogas upgrading processes in Germany in relation to biomethane production can be seen in Table 3.1.

Table 3.1: Proportion of biomethane upgrading processes used in Germany based on [8].

Upgrading type	Nr. of plants	Capacity [m³ /h]	Proportion used [%]
Chemical Scrubbing	73	43106	35
Water Scrubbing	60	32659	27
Pressure Swing Adsorption	44	22226	18
Absorption with Organic Solvent	21	16383	13
Membrane Filtration	20	8112	7

According to plant operator surveys only approximately one fourth of plant operators process the digestate [162]. Among the separation technologies, decanter centrifuges, screw presses, and belt filter presses are used most frequently. For the plant operators that did not provide any further information on their digestate treatments, it can be assumed that the digestate is applied directly as agricultural fertilizer without any further treatment steps.

The annual throughput and raw material input within the reference concepts of biofuel production are listed in Table 3.2.

Table 3.2: Mass requirements for process steps in biofuel production based on output material [34–36].

Biofuel type	**Raw material**	**Output material**	**Unit**	**Average SMD of raw material per tonne output material (based on average of)**	**Reference**
	Oilseed	Raw oil	t/t	2.415 (2.230 – 2.600)	[169–176]
	Raw oil	Refined oil	t/t	1.028 (1.010 – 1.045)	[36, 171, 177]
Biodiesel	Refined oil	Biodiesel	t/t	1.038 (0.995 – 1.080)	[36, 169, 171–173, 175, 177–181]
	Methanol	Biodiesel	t/t	0.150 (0.100 – 0.200)	
	Glycerin	Biodiesel	t/t	0.145 (0.090 – 0.200)	
Bioethanol	Starch containing crops	Bioethanol	t/t	3.076 (2.703 – 3.448)	[34, 182–188]
	Sugar containing crops	Bioethanol	t/t	15.556 (11.111 – 20.000)	
	Energy Crops	Biomethane	t/t	3.844 (3.294 – 4.393)	[35, 189–193]
	Manure	Biomethane	t/t	15.533 (11.391 – 19.675)	
Biomethane	Municipal and Industrial Waste	Biomethane	t/t	34.048 (2.510 – 65.585)	
	Biogas	Biomethane	t/t	1.818	[35]

3.2.2 Specific electricity consumption

DSM measures are aiming at adapting the electricity demand to current available RE production. Therefore, process heat would have to be generated by electrical energy in order to use these process steps for DSM. Currently, only very few, and especially small biofuel production plants generate process heat electrically [34]. For this reason, only the electric energy consumption will be considered for the calculation of the theoretical DSM potential in biofuel production. For the previously explained reference concepts, Table 3.3 lists the SEC with respective literature source.

Table 3.3: Specific electricity requirements for process steps in biofuel production based on output material.

Biofuel type	Process step	Output material	Unit	Average of SEC (based on average)	Reference
Biodiesel	Small milling plant	Raw oil	kWh/t	325	[169–176]
	Medium milling plant			178	
	Big milling plant			136	
	Refinement and Esterification	Refined oil	kWh/t	12 (6 – 36)	[36, 171, 177]
	Transesterification and Purification	Biodiesel	kWh/t	39 (17 – 61)	[36, 169, 171–173, 175, 177–181]
Bioethanol from starch containing crops	Grinding ad Scarification	Bioethanol	kWh/t	94 (84 – 104)	[34, 85, 183, 194, 195]
	Ethanol fermentation		kWh/t	67 (56 – 78)	
	Distillation		kWh/t	15	
	Centrifugation		kWh/t	25	
	DDGS preparation		kWh/t	111	
	Pumps and transport		kWh/t	120	

Bioethanol from sugar containing crops	Shredding	Bioethanol	kWh/t	46	[34, 85, 183, 194–199]
	Extraction		kWh/t	21	
	Ethanol fermentation		kWh/t	67 (56 – 78)	
	Distillation		kWh/t	15	
	Vinasse preparation		kWh/t	57	
	Pumps and transport		kWh/t	120	
Biomethane	Anaerobic digestion	Biomethane	kWh/t	664 (202 – 1126)*	*
	Membrane filtration		kWh/t	632 (584 – 679)	[35, 161, 162]
	Water scrubbing		kWh/t	512 (401 – 623)	
	Pressure swing adsorption		kWh/t	485 (451 – 518)	
	Absorption with Organic Solvent		kWh/t	638 (540 – 735)	
	Chemical scrubbing		kWh/t	228 (211 – 245)	
	Decanter centrifuge	Digestate	kWh/t	4 (3 – 5)	[200]
	Press screw separator		kWh/t	0.45 (0.4 – 0.5)	
	Filter belt press		kWh/t	1.75 (1.5 – 2)	
	Digestate stirring		kWh/t	1	[201]

*See calculation for fermentation in biomethane production Table 3.4 and Formula (1) and (2)

For biodiesel oil extraction is only considered for rapeseeds. For UCO and oil imports the energy consumption for pre-treatment is neglected and no SEC was analyzed. In the SEC for rapeseed milling, a differentiation is made between small, medium, and big plants at which the oil is extracted as was assessed by Bernesson [169].

In bioethanol production, the SEC were gathered from the guidance document of bioethanol [34]. However, as in the guidance document no precision is made on the energy consumption of individual process steps, but on the whole plant itself, the DBFZ-Report 22 [85] was analyzed for further subdivision of SEC in bioethanol production. In the calculation of the EPC the conversion and main-product treatment, the SEC is considered equally for the starch and sugar

production chains. In the pre-treatment and downstream processing of by-products however, a distinction is made between the two production chains.
For biomethane conversion, only wet fermentation is considered. Alternative but much less frequently used processes such as dry fermentation or direct biomass gasification are not included in the mass and electricity balance [35, 168]. In biomethane production, the bandwidth of SEC for the fermentation process is very extensive as found in the guidance document of biomethane [35]. The big difference in results from varying parameters for the external electric process energy, the methane and energy content of biogas[35], and the electric use efficiency of CHPP [202, p. 21]. Big ranges in external electric process energy and energy content of biogas results from the strong dependency of these values on the type of biomass that is used for biogas production.

Table 3.4: Input parameters for the calculation of specific process energies in biogas production.

Parameter	Symbol	Unit	Value used (based on average of)	Reference
Density of methane	$\rho_{methane}$	Nm³/kg	0.717	[35]
Methane content of raw biogas	$c_{methane}$	%	55	[35]
Electric process energy needed from produced electricity of CCHP	$w_{ex,\ el}$	%	9.2 (6.4 – 12.1)	[202, p. 21]
Energy content of biogas	Q_{Biogas}	kWh/m³	6.3 (5.0 – 7.5)	[203]
Electric use efficiency of CCHP	η_{el}	%	37 (25 – 49)	[204]

The SEC is calculated from the electricity produced by a CHPP because electricity consumption of a biogas plant is usually specified as a percentage of the electricity produced by the typically connected CHPP. However, since biomethane production plants are considered in this assessment, the CHPP efficiency is merely used to calculate the electrical energy demand inversely from the typical own electricity demand of biogas digesters. Electricity production by a CHPP is otherwise not considered in this assessment.

3.2.3 Flexible operating load range

Table 3.5 lists the FOL of the processes considered in this study, classified by biorefinery type and process area. In general for the identification of the FOL the most commonly stated value identified by Röder *et al.* [205] is used. An oversizing of processes will not be considered, since the investigation is based on biofuel production that already exists and will not be changed in size of functionality. Assumptions made for processes that have not yet been investigated for DSM purposes but have to similarities to other processes in operation, will be explained in the following.

Table 3.5: Considered process steps with associated flexible operating ranges [205, 206].

Biofuel type	Process step	Value used [%] (considering mode of all values in the range of)
Biodiesel	Oil mill small	100 (30 – 125)
	Oil mill medium	100 (30 – 125)
	Oil mill big	100 (30 – 125)
	Refining and esterification	50 *
	Transesterification and refinement thermal	0 *
	Transesterification and refinement electrical	100 *
Bioethanol	Milling and transport	100 (30 – 125)
	Extraction and drying	100 (30 – 125)
	Fermentation	100 *
	Distillation	70 (30 – 70)
	Decanting	100
	DDGS preparation	0 *
	Vinasse preparation	0 *
	Auxiliaries	0 *
Biomethane	Fermentation	100
	Membrane filtration	45 (37 – 122)
	Water scrubbing	50 (47 – 100)
	Pressure swing adsorption	0 *
	Absorption with organic solvent	50 (47 – 100)
	Amine scrubbing	50 (47 – 100)
	Decanter centrifuge	100
	Press screw separator	100 *
	Filter belt press	100 *
	Digestate stirring	100 *

*Assumption based on similarities to other process steps

Around 2% of biodiesel production results from “small” biofuel plants as defined by Prinz *et al.* and Majer *et al.* [36, 207] with a nominal production capacity of 30 kt/a (cf. Appendix Table 8.2). As stated by Oehmichen *et al.* [36] in “small” biodiesel production the consumption of electricity can be particularly high since the process heat is often generated electrically. The tolerance toward a certain amount of temperature disturbance of conversion processes [205] could directly be addressed by increasing or decreasing the electric heating in “small” biodiesel plants or switching the heating generation off completely for a short amount of time. This leads to a maximum FOL of 100% but only for 2% of biodiesel production. As the available data on the shares of EPC of transesterification, distillation, decanting, and auxiliaries is limited, an average FOL for the refining and esterification of biodiesel production is assumed to be 50%.
Since the agitation in ethanol fermentation is carried out in intervals, the maximum amount of electricity needed for each interval is considered shiftable, resulting in a FOL of 100% [206, 208]. The small amount of electricity needed for the DDGS pelleting and the lack of information on the flexibility potential of vinasse treatment leads to the assumption that the FOL equals 0%. In addition to large electricity consumers of bioethanol plants listed in Table 3.5, there are also many smaller electricity consumers at the production site which consume relevant amounts of electricity and are summarized as auxiliaries that will not be considered for DSM use.
For biogas upgrading two categories will be considered for DSM use: absorption processes, and membrane filtration. In the case of gas refinement this assessment will not consider a complete switch off of these continuously operated processes. The analysis of various important apparatuses for liquid and gas purification shows that their FOL is limited under certain circumstances and a complete switch off is often not advised [9, 205]. Since an oversizing of equipment is also not considered, high-pressure membrane filtration with a FOL of 45% have most commonly been identified in [205]. In absorption processes for CO_2 absorption three publications have been found concerning flexibilities of the process, stating possible FOL of 47%, 50% and 100% [98, 105, 135]. Since the three publications have each named one different FOL, the median FOL of 50% will be considered in this assessment. Due to lack of data on flexibilization of the pressure swing adsorption process, the FOL will be considered as 0%. In digestate processing of biomethane plants, mechanical separation processes such as decanter centrifuge, press screw separator, and filter belt press are processes that can be switched on and off easily, which is why it is assumed that the separation steps are 100% flexible. Like the fermentation stirrer, the stirred digestate tank is also considered to be 100% flexible.

3.3 Results

The results of this contribution show the calculation of the overall electricity consumption of process steps in biofuel production estimated for the total amount of biodiesel, bioethanol, and biomethane production in Germany. This leads to the identification of electricity-intensive process steps. Furthermore, the calculation of the theoretical DSM potential, which can be accessed within this electricity consumption, was identified and estimated. The identified processes will thus meet the criteria (A) and (B) described in Section 3.2.

3.3.1 Mass and energy consumption of biofuel production in Germany

The results of the calculated EPC and AT for biodiesel, bioethanol, and biomethane production in Germany are illustrated with e!Sankey® in Figure 3.3. Biomass flows are demonstrated in green, the electricity demand in grey.

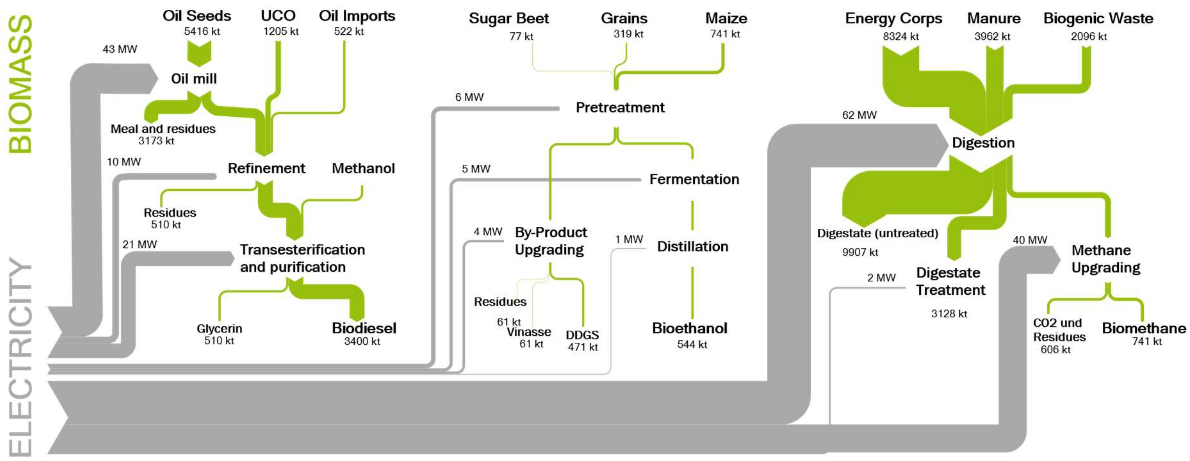

Figure 3.3: Material flows for biofuel production in Germany for a) Biodiesel, b) Bioethanol c) Biomethane.

In biodiesel production approximately 73.9 MW_{el} of electricity are consumed. Oil extraction is the largest consumer with 43.3 MW_{el} in terms of electricity. Refining the crude oil accounts for an electricity demand with 9.5 MW_{el}. With 21.1 MW_{el} electricity consumption esterification also has a minor impact on total electricity demand in relation to extraction. In small biodiesel plants, the consumption of electrical power is high in the transesterification and purification steps, as the process heat is often generated by electrical energy. Since "small" biodiesel production plants only make up approximately 2% of all biodiesel production [36, 207] (*c.f.* Appendix Table 8.2), this additional share of EPC does not have a major impact on the overall power consumption in conversion and purification for German biodiesel plants.

The production of bioethanol needs approximately 14.4 MW_{el} electricity in the production process. In terms of electricity consumption, the largest consumers are grinders and sugar extractors with 6.4 MW_{el}, the circulation of the fermentation broth with 4.5 MW_{el}, and the by-product treatment of DDGS and vinasse with 3.5 MW_{el}. Compared to biodiesel and bioethanol production this biofuel production chains makes up the smallest share of electricity consumption. In bioethanol production heat demand makes up the larger part of power consumption. DSM measures are aiming at adapting the electricity demand at current available RE production, which is why heat would have to be produced electrically to be able to be used for DSM purposes. Currently, only very few, and especially small biofuel production plants generate process heat electrically [16, 18] and thus make up a negligible share.

A total of 104.5 MW_{el} electrical power is consumed in the production of biomethane. The agitation of the fermenter tank accounts for the largest electricity demand with 62.2 MW_{el}. The fact that a large amount of biomass is needed in relation to the amount of biomethane produced leads to high electricity consumption, although the SEC is relatively low. The processing of the raw biogas into biomethane by CO_2-separation also consumes a non-negligible share. Especially the adsorption processes consume high amounts of 12.6 MW_{el} for water scrubbing, 7.4 MW_{el} for amine scrubbing, and 8.1 MW for pressure swing adsorption. Nevertheless, membrane filtration (7.8 MW_{el}) and absorption with organic solvents (3.9 MW_{el}) make up a considerable amount as well. In total, the methane processing consumes approximately 39.9 MW_{el} of electricity in biomethane plants in Germany.

The total electrical power consumption of biodiesel, bioethanol, and biomethane production chains sums up to a minimum of 137.8 MW_{el} and a maximum of 271.4 MW_{el} (cf. Appendix Table 8.1). Compared to the thermal energy consumption of 638.4 to 1365.5 MW_{th} (cf. Appendix Table 8.1) this seems so be a small amount. However, considering the fact that the costs per Megawatt hour of electricity exceed that of natural gas for heating by multitude [209], saving cost on electricity can still have the same effect as it would on thermal energy. As electricity price signals are already today highly fluctuating ad increasingly so in the near future, DSM strategies are therefore especially useful in electricity consumption.

3.3.2 Theoretical DSM potential of biofuel plants in Germany

This subsection discusses the results of the investigation to assess the theoretical DSM potentials of the individual biofuel production chains. The total amount of electrical power needed for the highest consumers, derived from the results of the previous subsection, in biofuel production is demonstrated in a bar graph diagram in Figure 3.4. For each biofuel type the electricity consumption is depicted alongside the theoretical DSM potential, comparing the total amount of electricity needed with the share of electricity consumption that is flexible. The deviations from the assumed average value are presented with confidence intervals which result from the bandwidths of required SMD (cf. Table 3.2) and the SEC in Section 3.2 (cf. Table 3.3). On the top of each bar, the distribution of the total and flexible electricity demand can be seen respectively, revealing processes with the greatest impact on the total theoretical DSM potential in the individual and total biofuel production chain.

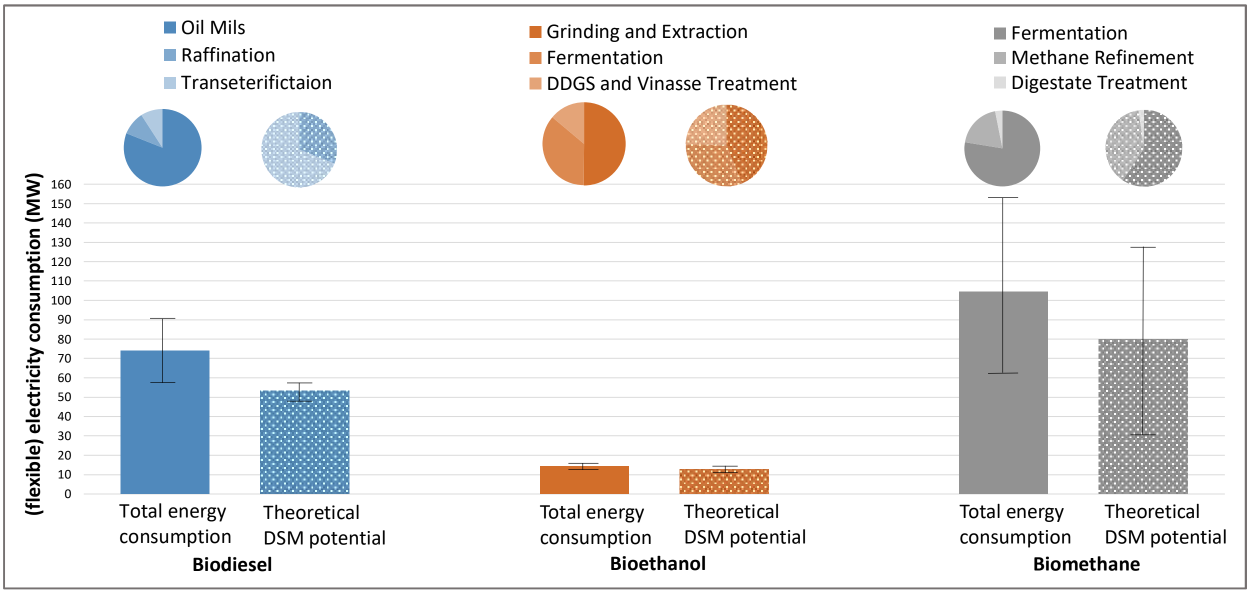

Figure 3.4: Total electricity consumption and theoretical DSM potential of Biodiesel, Bioethanol, andBiomethane in Germany for the year 2019.

A total DSM potential or 53.4 MW can be identified for biodiesel production. As depicted in Figure 3.4, the highest electricity consumers are the oil mils extracting vegetable oil from the oil seed. The 100% operating range leads to a high theoretical DSM potential of 43.3 MW. The FOL load range of 100% for the 2% of “small” biodiesel production accounts for 0.9 MW theoretical DSM potential in the refining process and 4.9 MW DSM potential in the transesterification. For the remaining 98% of biodiesel production, electricity consumption is still high (8.7 MW), resulting from multiple distillation and decanting steps. The operating load range of 50% for this section of biodiesel production leads to an average theoretical DSM potential of 4.3 MW in the refining process.

In total, the bioethanol production can provide an average theoretical DSM potential of 12.7 MW. As illustrated in Figure 3.4, the highest EPC is found in the comminution and extraction of sugar. Like the oil mills in biodiesel production, mechanical comminution steps are generally well suitable for DSM. By allowing this process step to shift its load flexibly by 100%, a theoretical DSM potential of 6.4 MW can be reached. The fermentation step in bioethanol production has a high EPC due to the agitation of the fermentation broth. Since agitation is carried out in intervals, the maximum amount of electricity needed for each interval is considered shiftable for a certain amount of time, resulting in an average DSM potential of 4.5 MW. In the downstream treatment of main and by-products of bioethanol, the highest FOL can be seen in the distillation of bioethanol and the decanting in DDGS preparation. As the distillation itself only consumes an average of 1.0 MW of electricity per year in bioethanol production in Germany, making use of the 70% FOL will result in a comparably small DSM potential, which is why only the by-product treatment in bioethanol production was considered for DSM use. Accessing the 100% FOL of the decanting in bioethanol production would lead to a DSM potential of 1.8 MW.

Biomethane production plants can provide a total theoretical DSM potential of 80.1 MW. The agitators in the fermenter make up for most of this flexible electricity consumption. Since the FOL has been identified to be as high as 100%, the theoretical DSM Potential in the fermentation step equals the total EPC of 62.2 MW. In the separation of the CO_2 from the biogas, the upgrading steps consume a high amount of electricity due to the high SEC. A theoretical DSM potential of 15.5 MW was identified. Most of the current existing biomethane and biogas production plants do not treat the remaining digestate after the fermentation process. Although the FOL is high, the total amount of theoretical DSM potential thus only sums up to 2.4 MW. The fact that a large amount of biomass is needed (14 382 kt) in relation to the amount of biomethane produced (741 kt) in 2019 leads to a high EPC. The deviation for the electricity consumption (46%) and thus also the theoretical DSM potential (57%) is very high for methane production in Germany for the year of 2019. This is due to the fact, that the ranges of mass requirements for 1 tonne of biomethane vary greatly depending on the input substrate used. The SEC also varies greatly with varying consistency and inertia of the biomass used. In future years, when waste products such as municipal waste and cow manure will be prominently used to produce biomethane, a generalization of substrate and electricity input requirements will become even more difficult.

This section demonstrated the magnitude of the theoretical DSM potentials of the individual biofuel production chains in Germany. Considering biofuel production capacities of the year 2019 (3952 t Biodiesel, 749 t bioethanol, and 743 t biomethane [32]) specifically biodiesel holds an average of theoretical DSM potential of 13.5 Watt, bioethanol of 16.9 Watt, and biomethane of 107.8 Watt per tonne of biofuel capacity. Though this study has used Germany as a regional case study, these approximate specific values can ease the transferability to other countries producing big amounts of biofuel. Brazil and the United States of America for example are big producers of bioethanol and biodiesel [161]. Biomethane, although mainly produced in Germany to this point, has become increasingly important in other countries such as Denmark, France, Italy and the Netherlands which have actively promoted biogas production.

3.3.3 Discussion of results and comparison with other DSM potentials

Section 3.3.1 shows the results of the mass and electricity balance, for each of the investigated biofuel types. The production steps with the largest EPC in biofuel production were identified. The theoretical DSM potential for the most electricity-intensive process steps was then calculated in Section 3.3.2. This subsection will summarize these results and set the relevance of integration of DSM in biofuel production into context by comparing them with the theoretical DSM potentials in other industry sectors.

In German biodiesel production, the highest electricity consumers are oil mils extracting vegetable oil from the oil seed. Oil mills are often decentralized and storage is provided. Due to the fact that they can be switched off and started up again quickly without causing significant production losses a high theoretical DSM potential was calculated. The high EPC and easy DSM accessibility make biodiesel plants especially interesting for DSM integration.

The production of bioethanol in Germany is not as high as the production of biodiesel and biomethane, thus the electricity consumption is neither. However, the easy accessibility of the individual DSM potential and the high specific bioethanol production per biofuel plant make it nevertheless interesting for DSM integration. This means that fewer plants have to be integrated into a DSM network in order to achieve the same amount of DSM potential that a significant higher number of biomethane plants would. This in turn results in less effort for the integration of regulation and control in relation to the amount of electricity consumed that can be flexibilized. Furthermore, one way to integrate more RE into the production of bioethanol would be to heat processes electrically. Heat demand is a significant aspect in the production of bioethanol. In some bioethanol plants, electrically driven, mechanical vapor recompression is already used instead of steam heating, e.g. in distillation, rectification, or evaporation of the stillage [34]. As a result, process steam can be reduced, but the EPC increases. The aspect that would make this section of biofuel production very interesting for the use of DSM is the tolerance towards a certain amount of temperature disturbance in these refinement steps [205]. This tolerance could directly be addressed by increasing or decreasing the electric heating generation in these electrically heated biofuel plants or switching the heating generation off completely for a short amount of time.

In the production of biomethane, the agitation of the fermenter tank accounts for the largest electricity demand, but the processing of the raw biogas into biomethane by CO_2 separation also consumes a non-negligible share. In total, the DSM potential in biomethane production was calculated to be as high as 80.1 MW, which is compared to 53.4 MW in biodiesel and 12.7 MW in bioethanol production the highest potential in biofuel production. However, the main DSM potential results from the agitation of almost 230 individual biomethane plants (cf. Appendix Table 8.3) [163]. Comparing that to the 47 oil mills [210] or 15 bioethanol plants (cf. Appendix Table 8.2), accessing the DSM potential in biomethane production would mean higher effort for the integration of regulation and control in relation to the amount of electricity consumption which is flexibilzed. However, with the renewal of the Renewable Energy Sources Act (Ger. Erneuerbare-Energien Gesetz - EEG) 2017, the operation of biogas plants with the purpose of electricity remuneration now provides only little financial incentive [16]. This is why the share of biogas plants currently operated in switching from electricity remuneration to methane production is likely to increase in the future. Thus, the DSM potential for methane production is likely to increase considerably.

Summing up all the individual theoretical DSM potentials for biofuel production in Germany results in an overall theoretical DSM potential for Germany of a minimum of 92.9 and a maximum of 199.1 MW in the year 2019. The accumulated results are shown in Figure 5 and are compared to other processes that were studied several times by different authors regarding their theoretical DSM potential.

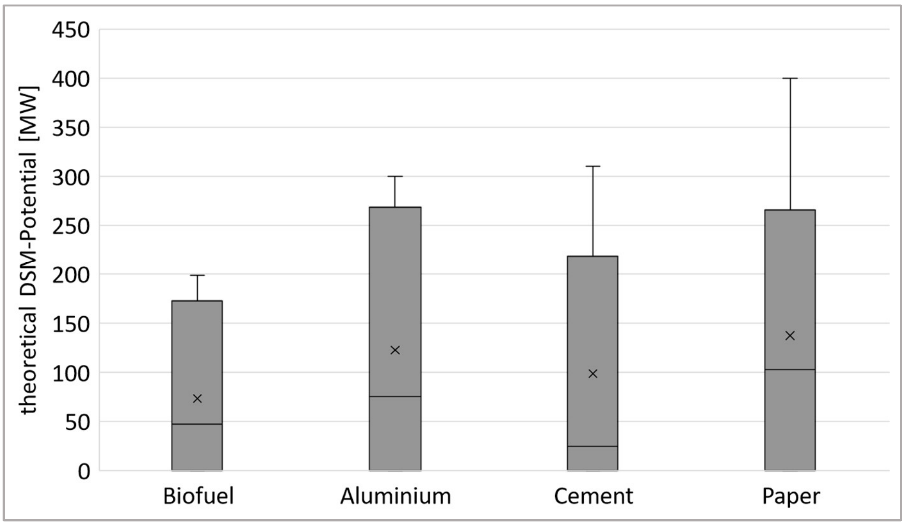

Figure 3.5: Theoretical DSM potential for biofuel compared to aluminium, cement and paper industry as found in literature [3, 8, 11–14, 211].

The large spread in the theoretical DSM potential of biofuel production results from the strongly fluctuating values for the electricity and biomass demand in biofuel production, which were shown in Table 3.2, Table 3.3 and Table 3.4. The average value however is in a comparable range to those found in the literature on aluminum, cement, or paper [3, 8, 11–15]. Differences in the literature studies result from the fact that in some cases different definitions for the theoretical DSM potential were considered and different base years and data were used.
The cumulated theoretical DSM potential in biofuel production shows that flexibilizing biofuel plants can provide a valuable extension of the existing theoretical DSM potential, as all processes in biofuel production investigated have a reasonable flexibility potential. They have a comparably high theoretical DSM potential to other industries, which have already been extensively investigated for DSM use and are even being applied in individual cases. The comparability with those processes for DSM application suggests that biofuel production could be a valuable contribution to DSM research and calls for further DSM investigation of this industry sector.

3.4 Conclusion

This contribution shows the results of a recent DSM study on the implementation of a DSM in biofuel production plants. The investigation of this paper concerns the theoretical amount of load that could be shed in biofuel production. This aims to investigate the integral leverage that the DSM implementation of a DSM in biofuel production could have, and thus to make the DSM potential comparable to other investigations on the theoretical DSM potential in MW. After identifying reference concepts that can represent biofuel production in Germany, the specific mass and electricity consumption for the individual process steps in these reference concepts was analyzed through a literature study. The annual throughput and electric power consumption of process steps in biofuel production could then be calculated, enabling the identification of the most electricity-consuming process steps. Subsequently, possible flexible operating load range of the individual process steps in biofuel production were identified. These findings allowed an assessment of the potential for different process units of biorefinery systems concerning the quantitative adaptability of the electricity load. An approximate theoretical DSM potential of 146 MW has been identified for biofuel production in Germany. This cumulated theoretical DSM potential in biofuel production was compared with other industrial processes, demonstrating the magnitude and importance that the implementation of a DSM in biofuel production can contribute. Specifically biodiesel holds a theoretical DSM potential of 13.5 Watt, bioethanol of 16.9 Watt, and biomethane of 107.8 Watt per tonne of biofuel production capacity. Though this study has used Germany as a regional case study, these approximate specific values can ease the transferability to other countries producing big amounts of biofuel. Moreover, variation in DSM potential resulting from technical development and improvements in processing efficiency such as electrification of thermal processes for increased renewable energy integration should be put to attention. Scenario analysis for important years in the future of climate change, such as 2030 or 2050, concerning DSM implementation in biofuel production would be an interesting field of research.

In summary, it can be stated that through accessible flexible operating window and material storage capacities biofuel plants could provide a substantial contribution to DSM research due to the high theoretically accessible DSM potential. Subsequent research with a focus on the flexible process steps identified in this contribution shall be conducted to determine whether the implementation of a DSM in biofuel production is feasible from an economic point of view. Since the theoretical DSM potential in biomethane production has been identified as the highest one in biofuel production, a case study will be conducted on a specific biomethane production site. The case study will determine optimal oversizing of process steps for maximum economic benefits through DSM implementation. The results will allow an assessment of the potential of different parts of the system regarding the temporal adaptability of the electricity load. In addition, it is important to examine whether the GHG balance of the entire plant improves without causing significant quality or output losses in production.

Chapter 4. The Economic Demand Side Management Potential in Biofuel Production [3]

DSM strategies are based on the flexibility to purchase electricity at times when prices are low, which can result in monetary benefits. One option to increase the flexibility of continuously operated processes is to oversize them. From an economic point of view, this leads to an increase in investment. DSM only serves an economic purpose if the monetary benefits exceed this increase in capital costs. The main goal of this contribution is to develop a decision support tool decision support tool to help evaluate unit operations regarding their feasibility for DSM implementation. In a case study, the decision support tool was applied to show its functionality on a biomethane production plant. The results show that with the help of the decision support tool, evaluating unit operations concerning their economic decision support tool potential is possible.

4.1 Introduction

Amidst the rapid expansion of renewable energy (RE) generation, the significance of power system flexibility has increased, necessitating its key role in facilitating the effective integration of RE into the power grid. Adapting power consumption to power generation — the so-called demand side management (DSM) — can enhance this flexibility. Various challenges involved in DSM integration currently make it difficult to integrate and market flexibility in the industry [212]. Sivill *et al.* [50] identified such challenges in the Finish industry, stating that today's data and indicators must allow for effective performance evaluation and decision support. Ming *et al.* [213] have found a need for specific economic incentive indices for power consumers under China's short- and long-term development goals. The DSM Roadmap of the German energy agency (Ger. Deutsche Energie Argentur — DENA) [212], Leinauer *et al.* [21], and Lashmar *et al.* [22] see the main challenges in information and data supply to improve the degree of companies' knowledge of DSM markets. These studies show a need for flexibility, but that implementation is still complex.
In an attempt to address these challenges, indices, and methodologies to evaluate large- and small-scale processes for DSM and flexibility potential have been presented in the literature. Dharme and Ghatol [23] developed a DSM quality and appreciation index. A flexibility index developed by Grossmann *et al.* [24] characterizes the maximum variance a system can sustain under steady-state conditions. Dimitriadis and Pistikopoulos [25] added dynamic factors to Grossmann's evaluation. Di Pretoro *et al.* [26] proposed a recent evolution of this approach, which present a switchability index that offers a quick decision support tool that allows for reasonable design decisions, considering the system's dynamics. A method to evaluate capacity

[3] Substantial parts of this chapter are published in Röder, L. S.; Etzold, H.; Gröngröft, A.; Grünewald, M.; Riese, J. (2023): Framework to evaluate the economic demand side management potential in continuous industrial processes - a biorefinery case study. *Biofuels Bioproduncts & Biorefining.* DOI: 10.1002/bbb.2558.

potentials in continuously operated chemical processes to detect the largest possible flexibility potential using this flexibility index has been investigated by Bruns *et al.* [27]. Merkert *et al.* [52] provide an overview of methods to determine the DSM potential of industrial processes. Evaluating DSM potentials Gils *et al.* [51], Klobasa *et al.* [6], Ladwig [8], Paulus and Borggrefe [13] have extended these methods to calculate the theoretical DSM potential of a specific region with a focus on differentiating seasonal influences, future perspectives or availability of technical solutions. However, these studies neglect a detailed calculation of the financial incentive.

Economic aspects of DSM implementation in research have been examined by Helin *et al.* [71], Pulkkinen and Ritala [72], Paulus and Borggrefe [13], Merkert *et al.* [52], Mitra *et al.* [74], Zhang *et al.* [131], Numbi *et al.* [73, 77], and Vujanic *et al.* [76], extended the research on DSM potentials by estimating the economic potential. It should be noted that in the literature, only a limited number of case studies can be found concerning the economic benefits of DSM. One reason for this is that the system under consideration needs specific characteristics that highlight the advantage of DSM optimization. Consequently, DSM impact studies are generally conducted based on a few well-established flexible processes. Optimal oversizing factors from an economic point of view have been investigated by Ghobeity and Mitsos [125], Williams *et al.* [126], Käufler *et al.* [121], Roh *et al.* [18], and Loutatidou *et al.* [120]. Schäfer *et al.* [214] extend the perspective on monetary aspects by investigating economically driven measures enhancing flexibility and their impact on reduced contributions to the residual load. These calculations include complex optimization strategies and dynamic simulations of well-known processes often investigated in DSM research, such as different types of electrolysis and desalination plants.

Literature still lacks an indicator to quickly understand the suitability of a process for DSM application — a decision support tool for plant design, valid for any given process and easy to apply, without any complex simulation and optimization studies. Therefore, this contribution aims to promote an understanding of the suitability of a process for DSM implementation during plant design. One of the goals of this decision support tool is to provide a tool to quickly and efficiently evaluate whether the analyzed system has the necessary economic characteristics that make a more in-depth study and DSM optimization helpful. The decision support tool was, therefore, applied to a case study that has, in that form, never been investigated in a DSM context — a biomethane biorefinery.

Applying a decision support tool for implementing DSM in a biorefinery case study is a compelling and justified approach. A systematic literature review was carried out by Röder *et al.* [205] prior to this publication, in which various processes from biofuel production were examined for their flexible operating load range. Through the literature review it could be concluded that mechanical pre-treatment of biomass is well-suited for DSM when intermediate storage facilities are in place, allowing for quick equipment shutdown and partial load operation. Biotechnological conversion processes like anaerobic digestion and ethanol fermentation tolerate temperature variations to a certain extent but may suffer from loss of efficiency when temperatures deviate from the optimum operating temperatures. Catalytic conversion processes, such as methanation and FT synthesis, can be flexible in response to varying H_2 input streams, but their flexibility is constrained by critical sensitivity to temperature and catalyst deactivation.

Intermediate storage and large flexible operating windows make DSM integration promising in mechanical by-product treatment, though storage size remains a limiting factor. However, mere knowledge of the flexibility possibilities of all these process areas does not allow any conclusions to be drawn about the leverage and economic viability of such DSM integration. It should nevertheless be noted, that the investigation of multiple process steps in biofuel production for DSM implementation is a compelling field of research.

Furthermore, the findings from the previous publication by Röder *et al.* [215], which highlight the high DSM potential in biorefineries, particularly in biomethane production, provide a solid basis for exploring DSM opportunities in this context. The European Biogas Association (EBA) plans 5,000 new biomethane production plants by 2030 and additionally wants to upgrade as many existing biogas plants as possible to biomethane production. Given this European biomethane expansion plan, the potential for DSM in biomethane will also increase significantly, making it even more important to optimize energy costs and resource use.

Lastly, the availability of comprehensible data from an earlier concept study by Etzold *et al.* [216] is a valuable advantage. This data can serve as a reliable basis for applying the decision support tool to the specific biorefinery concept under investigation. Furthermore, the biorefinery case study includes process steps that have not been thoroughly investigated for their DSM potential. This aspect represents an attractive opportunity for innovation and optimization, as unaddressed areas in the biorefinery process may offer significant energy cost saving opportunities.

The core unit of a biomethane biorefinery, the anaerobic digestion has previously been investigated by Röder *et al.* [206], demonstrating that there is a high potential for the economic use of the response to the fluctuations in the price of electricity in biogas production. In the following presentation of the decision support tool, the economic DSM possibilities of processes around the anaerobic digestion, are analyzed. Through that investigation the economic benefits of DSM implementation can be extended from the core unit of biomethane production to the entire plant. By applying the decision support tool to this new field, the study can uncover new insights and pioneer the application of DSM in previously unexplored areas.

Therefore, the main goal is to develop a decision support tool that helps evaluate and rank unit operations concerning their economic potential towards DSM implementation. The contributions of this paper are as follows:

1. The decision support tool is presented — an approach to determine which process steps are suitable for DSM implementation investigates the economic impact of the DSM on the process.
2. In an extensive case study, the production process of biomethane as a large-scale multi-step process is considered. For this example, all steps of the decision support tool are performed.
3. Individual process steps in an exemplary multi-stage process chain are thus selected for DSM implementation. Opportunities to enhance the profitability of a process plant through DSM are outlined.

4. The most important influencing factors for the feasibility and profitability of a DSM implementation are analyzed through sensitivity analysis.

The decision support tool consists of four main calculation steps which are each linked to a decision whether the next step is worth evaluation. The underlying methodology is presented in Section 2 of this contribution. Section 3 applies the decision support tool to the biorefinery concept to demonstrate its functionality. Section 4 presents the results of the case study, followed by Section 5, concluding the contribution and offering perspectives for further research.

4.2 Development of the decision support tool

In this section, we present the underlying methodology of the developed decision support tool, which aims to assist plant designers in deciding whether process steps or overall processes should be designed to implement DSM strategies. The idea of DSM is to use electricity more intensively at times of high RE production, hence when electricity prices are low. The advantages thus include saving energy costs and CO_2-emissions and, at the same time, aid grid operators in balancing intermittent generation from volatile RE energy. There are multiple ways to react to these electricity price signals, of which load shifting is the most common to achieve economic advantages without compromising product quantity. If a process is operated continuously, load shifting means that in times of high electricity spot prices, the process is switched off or operated in partial load. At times of low electricity spot prices, the process would have to produce enough product flow to compensate for the time the process was switched off. Adapting to these circumstances is possible by oversizing unit operations for individual process steps (F_{os}) and installing intermediate storage tanks.

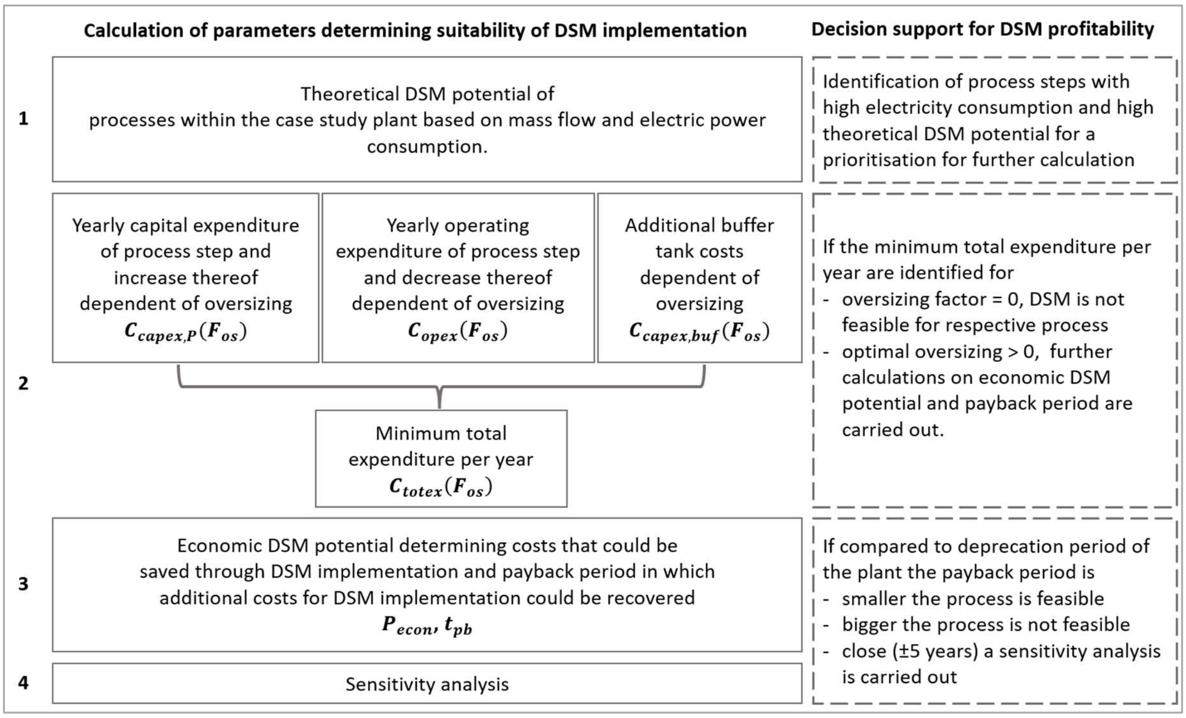

Figure 4.1: Decision support tool to evaluate essential economic parameters for the decision of a DSM implementation for continuously operated processes.

The newly developed decision support tool includes a multi-step framework to identify the cost savings potential by implementing DSM for continuously operated processes. All steps of the framework and corresponding decisions are graphically summarized in Figure 4.1.
The decision support tool consists of four main steps illustrated on the left-hand side of Figure 4.1. Based on the results of these four steps, decision support can be derived as illustrated on the right of Figure 4.1. Dashed lines outline the necessary decisions in each step. The decision values within the dashed line boxes are intended to serve as a suggestion, i.e., as a default value for a decision. They can be adapted according to the user's assessment but serve to facilitate an initial estimate if no specific values are available for the respective decision steps.
Symbols with respective units that are needed for the calculations of the decision support tool are listed in Table 4.1:

Table 4.1: Symbols with respective units needed for the calculations of the decision support tool.

Symbol	Unit	Explanation
$\boldsymbol{a_{year}}$	€/kWh	Maximum average electricity price of specific year
$\boldsymbol{b_{year}}$	€/(kW*h^2)	Electricity price variation of specific year
$\boldsymbol{C_{capex}}$	€/a	Capital expenditure per year
$\boldsymbol{C_{opex}}$	€/a	Operational expenditure per year
$\boldsymbol{C_{totex}}$	€/a	Total expenditure per year
$\boldsymbol{C_{totex,min}}$	€/a	Minimum total expenditure per year
$\boldsymbol{EPC_P}$	kW	Electric power consumption of process
$\boldsymbol{F_{os}}$	%	Oversizing factor
$\boldsymbol{I_P}$	€	Investment for process step at no oversizing
$\boldsymbol{I_{ref,P}}, \boldsymbol{I_{ref,buf}}$	€	Investment for reference process step, buffer tank
$\boldsymbol{i}$	%	Interest rate
$\boldsymbol{\dot{m}_{P,in}}\ \boldsymbol{\dot{m}_{P,out}},$	t/a	In- and out-flowing mass through process step
$\boldsymbol{\dot{m}_{ref}}, \boldsymbol{\dot{m}_{buf}}$	t/a	Mass flow through reference process, buffer tank
$\boldsymbol{P_{econ}}$	€/a	Economic DSM potential per year
$\boldsymbol{p_{elec}}$	€/kWh	Electricity price
$\boldsymbol{p_{elec,av,year}}$	€/kWh	Average yearly electricity price of specific year
$\boldsymbol{\varrho}$	kg/m³	Density of mass flowing through process
$\boldsymbol{R_P}, \boldsymbol{R_{buf}}$	-	Economies of scale of process step, buffer tank
$\boldsymbol{r_P}, \boldsymbol{r_{buf}}$	%/a	Expense ratio of process step, buffer tank (incl. depreciation, interest, maintenance, insurance, taxes, and wages)
$\boldsymbol{SEC_P}$	kWh/t	Specific electricity consumption
$\boldsymbol{\tau}$	h	Time period
$\boldsymbol{\tau_{oph}}$	h/a	Yearly operating hours
$\boldsymbol{t_{app}}$	h	DSM application time
$\boldsymbol{t_{dep}}$	a	Depreciation period

t_{pb}	a	Payback period
V_{ref}, V_{buf}	m³	Volume of refence, buffer tank

The decision support tool is applicable if the following is given:

- Electricity is bought at the spot market
- The unit operation considered is operated continuously (i.e., more than 7500 hours per year)
- The unit operation considered is flexible and can be switched off during operation or run in partial load
- Oversizing the individual process steps and installing intermediate material storage is possible

In the following, each step, corresponding evaluations, and decisions within the overall framework are presented and discussed in detail. A more thorough derivation of all the equations can be found in Appendix B.

4.2.1 Theoretical DSM potential

Evaluation

The first step of the decision tool consists in calculating the mass and energy balance of a continuously operated process under consideration. Each process step's electric power consumption (EPC) comprised of mass flow ($\dot{m}$) and specific electric power consumption (SEC) is determined. The theoretical DSM potentials of the considered processes are furthermore determined. The flexibility of a process is analyzed, and its technical applicability for DSM purposes is examined. This step can be adapted from, e.g., the assessment of Röder *et al.* [206]. A more detailed explanation of the approach to calculating the theoretical DSM potential of process steps in biofuel production can be found in that contribution. The analysis determines the theoretical DSM potential for processes in biofuel production for Germany on a country level. However, this approach can likewise be applied on a plant scale, as demonstrated in this study.

Decision

This step is necessary to identify processes with high power consumption and would thus have a high impact in flexibilizing its energy demand in a future system that relies on a flexible adaption to available electricity from RE. Processes with high flexibility, making them possible for DSM application, are distinguished. Since the following calculations are complex, and data inventory is not necessarily trivial, a preliminary prioritization can start after step 1. If more than ten process steps are still considered, the ten process steps making up 90% of the total theoretical DSM potential should be chosen.

4.2.2 Operational and capital costs dependent on the oversizing factor

Evaluation

DSM strategies are based on the flexibility to turn a process off and thus purchase electricity when prices are low, which can result in monetary benefits. One option to increase the flexibility of continuously operated processes is to oversize the process. From an economic point of view, this, however, leads to an increase in investment and, thus, capital costs. Implementing DSM only then serves an economic purpose if the monetary benefits exceed this increase in capital costs. The second step of the decision support tool follows a systematic economic assessment of the most promising unit operation identified in step 1 to identify an oversizing factor (F_{os}) at which a minimum total expenditure per year (C_{totex}) is reached. The F_{os}, at this point describes the best possible oversizing of the process step, causing minimum total running costs within the use of DSM. The applied method for identifying the respective parameters is illustrated in Figure 4.2 and Figure 4.4. Input parameters, determined, e.g., by literature review or process simulation, are shown in shaded boxes. Output parameters are shown in white boxes.

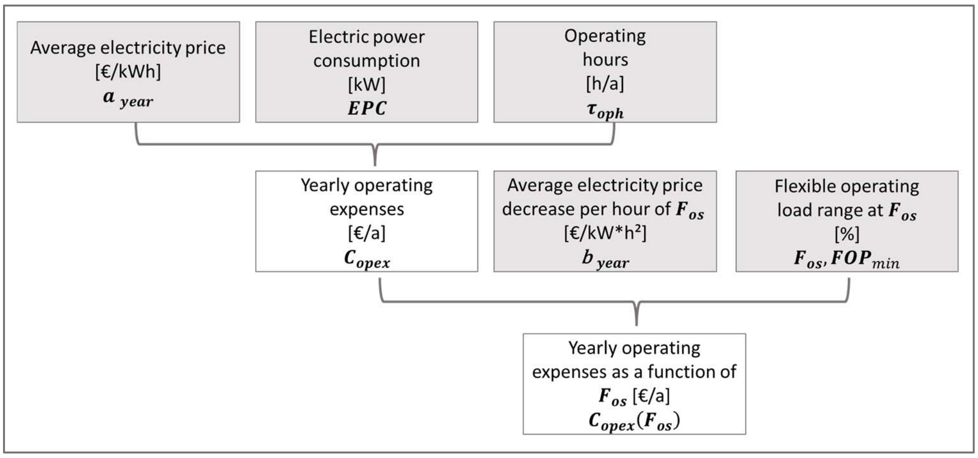

Figure 4.2: Method to calculate the most important parameters to determine operating expenditure as a function of oversizing.

As the idea of DSM based on load shedding is to shift electricity consumption to times of lower electricity prices (p_{elec}). To determine the benefits of oversizing a process in C_{opex}, it is therefore to gain preliminary information on a possible reduction of the average electricity prices $p_{elec,av}$ that this would cause.

To determine to what extent the p_{elec} drops for a specific year (b_{year}), depending on the time of DSM application (t_{app}), the approach is to create sorted p_{elec} for each day. This method can be observed in Figure 4.3 a) transitioning to Figure 4.3 b). Figure 4.3 a) depicts an exemplary year, showing exemplary p_{elec} subdivided into days. If the p_{elec} are sorted in descending order for each day, the resulting p_{elec} curve will exhibit the pattern depicted in Figure 4.3 b), with the highest price value occurring at hour zero and the lowest value at hour 23. A systematic analysis can be conducted to establish the mean p_{elec} for various time intervals, such as the hour with the highest cost, the hour with the second highest cost, and subsequent hours in descending order.

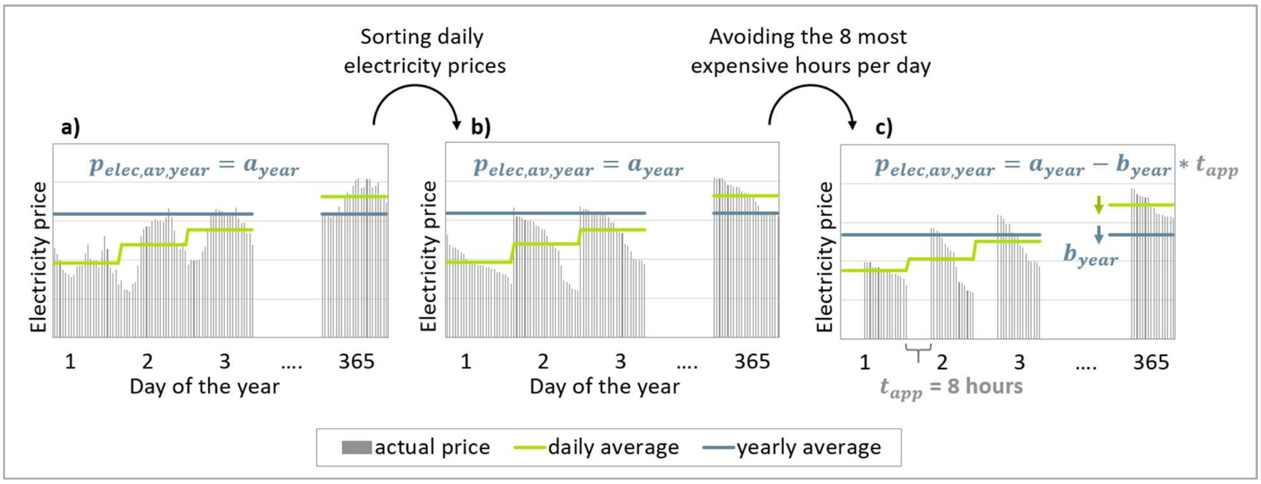

Figure 4.3: Method to determine electricity price drop dependent on demand side management application time.

The maximum average electricity price a_{year} is the average of all p_{elec} values for the considered year. If no p_{elec} peaks are avoided, then the average p_{elec} for the considered year ($p_{elec,av,year}$) equals a_{year}. For every hour which a unit operation can be switched off, the most expensive hour in terms of p_{elec} can be avoided each day for that year. By avoiding these expensive p_{elec} periods every day, the $p_{elec,av,year}$ thus drops. In Figure 4.3 c) this effect is demonstrated with the example of switching off a process every day during the 8 most expensive hour in terms of p_{elec}. The development of this decrease in the $p_{elec,av,year}$ is quasi-linear and can be described for a pre-defined period of time (τ), in this case, one day, by the following formula:

$$p_{elec,av,year} = a_{year} - b_{year} * t_{app} \tag{4-1}$$

In this investigation and case study, a time period of 24 hours is chosen. This same systematic analysis of the price drop in $p_{elec,av,year}$ can likewise be adapted for another τ.
The greater the oversizing factor F_{os} of a process step, the longer it can be switched off or run in partial load. Neglecting start-up and shut-down duration, the correlation between oversizing and DSM application time t_{app} in τ can be described as follows:

$$t_{app} = \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min}) \tag{4-2}$$

FOP_{min} describe the minimum load at which a process can be operated in. A previous study by Röder *et al.* [205] investigates the FOL of many different processes in biofuel production. This review can be consulted to define the FOP_{min} of investigated processes.

By multiplying the $p_{elec,av}$ Eq. (4-1) with the SEC_P, the annual mass flow $\dot{m}_P$, and operating hours τ_{oph}, the annual electric operating costs C_{opex} as a function of F_{os} are calculated by Eq. (4-3):

$$C_{opex}(F_{os}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} \quad (4\text{-}3)$$

This effect described in Eq. (4-3) assumes that the energy efficiency remain the same even through the process is operated flexibly. Applying Eq. (4-3) also assumes no product quality loss caused by the implementation of DSM. The reduction in C_{opex} corresponds to the benefit of oversizing a process step. A more thorough derivation of Equation (4-3) can be found in Appendix B.
To detect the disadvantages of oversizing a process, the degree to which investment costs and capital-linked payments C_{capex} rise due to oversizing must be determined (cf. Figure 4.4).

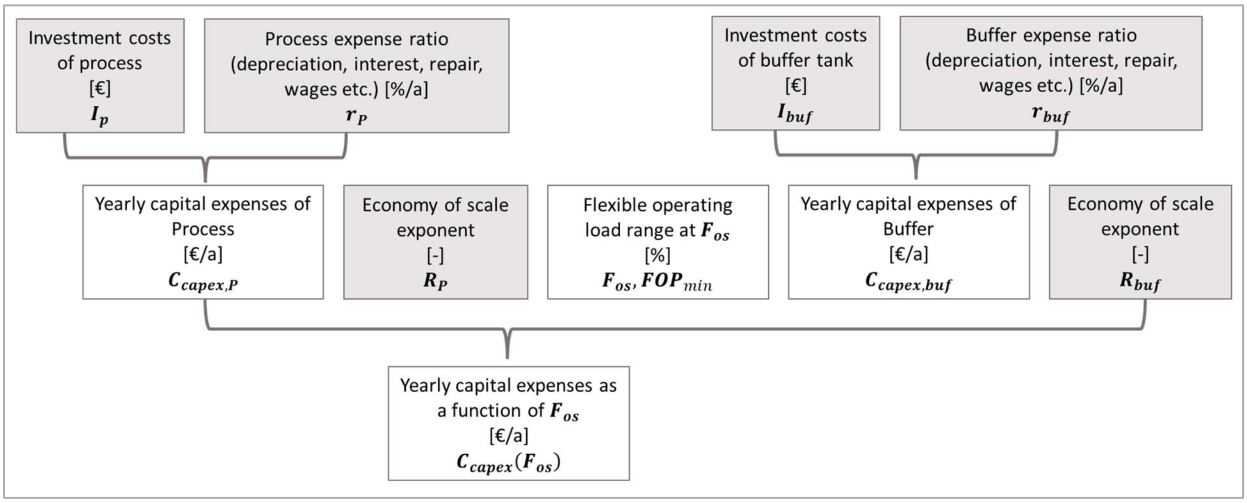

Figure 4.4: Method to calculate the most important parameters to determine the capital expenditure as a function of oversizing.

The investment costs increase if a process is expanded in size and capacity. In addition, there is a need for temporary material storage capacity to ensure that the flow of material to further downstream process steps is not interrupted during load shedding. The parameter to describe the capacity, thus, depends on the unit operation under consideration. Mass flow $\dot{m}_P$ or annual throughput is used to describe the capacity of continuously operated processes. The total volume of the buffer tank V_{buf} is calculated by adding the volumes of buffer tanks located up- and downstream of the process ($V_{buf,in} + V_{buf,out}$).

The in- and out-flowing mass flow $\dot{m}_{P,in}, \dot{m}_{P,out}$ of the considered process step are thus multiplied with t_{app} from Eq (4-2):

$$V_{buf,in} + V_{buf,out} = \frac{(\dot{m}_{P,in} + \dot{m}_{P,out})}{\varrho} * \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min}) \quad (4\text{-}4)$$

$$V_{buf} = \frac{(\dot{m}_{buf})}{\varrho} * \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min}) \quad (4\text{-}5)$$

If the investment I_{ref} and capacity $\dot{m}_{ref}$ or volume V_{ref} of a process step or buffer tank and the economies of scale exponent R_P, R_{buf} are known, the economies of scale approach to determine the investment I_P, I_{buf} for the given capacity is as follows [217]:

$$I_P = I_{ref,P} * \left(\frac{\dot{m}_P}{\dot{m}_{ref}}\right)^{R_P} \quad (4\text{-}6)$$

$$I_{buf} = I_{ref,buf} * \left(\frac{V_{buf}}{V_{ref}}\right)^{R_{buf}} \quad (4\text{-}7)$$

R_P and R_{buf} are the economy of scale exponents describing the change of specific investment costs with size. Expense ratios r_P and r_{buf} are the sum of depreciation, interest, maintenance, insurance, taxes, and wages estimated linearly depending on the investments or are taken from literature. Since not all expense rations change according to size, only interest i for the depreciation period t_{dep} and insurance is considered for r_P and r_{buf}.

The value for C_{capex} with additional storage investments I_{buf} as a function of the oversizing factor F_{os} can be calculated as follows:

$$C_{capex}(F_{os}) = I_P * r_P * (F_{os} + 1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{(\dot{m}_{buf}) * \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min})}{V_{ref}}\right)^{R_{buf}} \quad (4\text{-}8)$$

A more thorough derivation of Equation (4-8) can be found in Appendix B.
Buffer tanks hold up the incoming feed and store the out-flowing product. It is assumed that, at the very end of the process chain, buffer tanks are already employed to store the final product before it is retrieved or sold. Suppose the product is fed into a grid , e.g., methane into a gas grid or purified water into the water distribution system. This grid could then be considered a storage facility at the end of the process chain. If intermediate or upstream buffer tanks are already installed, this storage volume can be subtracted from the necessary storage volume V_{buf} needed to oversize the process step considered for DSM.

Finally, C_{totex} is the sum of C_{opex} and C_{capex} as a function of F_{os}. A more detailed version of (4-9) can be found in Appendix B .

$$C_{totex}(F_{os}) = C_{opex}(F_{os}) + C_{capex}(F_{os}) \tag{4-9}$$

By deriving the C_{totex} function, the slope of the total costs can be determined as a function of F_{os}. If all constants are known and inserted in the derived function, a minimum value $C_{totex}(F_{os,opt})$ dependent on F_{os} can be calculated, as depicted in a graphical demonstration in Figure 4.5. In the example, the optimal F_{os} would be around 100%, where $C_{totex}(F_{os})$ is at its minimum.

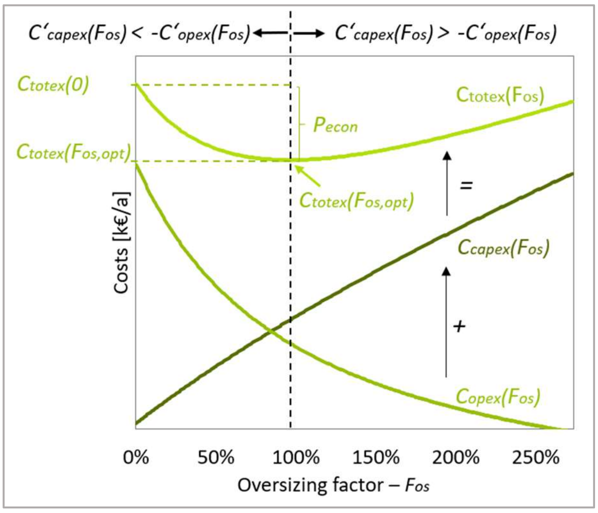

Figure 4.5: Graphical demonstration of parameters to determine the economic DSM potential.

Decision

If the slope of C_{capex} consistently exceeds that of C_{opex}, it is not profitable to oversize the process of consideration and consequently implement a DSM strategy. As a result, the use of DSM is only profitable if, within any range of F_{os}, the following condition is fulfilled (*c.f.* Figure 4.5):

$$C'_{capex}(F_{os}) < -C'_{opex}(F_{os}) \tag{4-10}$$

A more thorough derivation of Equation (4-10) can be found in Appendix B.

4.2.3 Calculation of the economic DSM potential and payback period

Evaluation

Once the operational and capital costs for oversizing and intermediate storage tanks are known, the feasibility of a DSM implementation can be considered. The additional cost of oversizing and the electricity cost savings per year determine the economic DSM potential P_{econ} the resulting payback period (t_{pb}) in step 3. If the profitability of DSM implementation is thus determined and $C_{totex,min}$ at a certain F_{os} is found, the difference between C_{totex} at no oversizing ($F_{os} = 0$) $C_{totex,0}$ and at $C_{totex,min}$ can be calculated. This value defines the P_{econ} of the process:

$$P_{econ} = C_{totex}(0) - C_{totex}(F_{os,opt}) \tag{4-11}$$

A detailed version of Equation (4-11) can be found in Appendix B .
The payback period t_{pb} of the DSM implementation is calculated by determining the additional initial investment caused by oversizing the process and installing additional buffer tanks during the whole t_{dep}, related to the associated benefit that the DSM entails. The economic advantages are the savings in C_{opex} due to oversizing F_{os}.

$$t_{pb} = \left(I_{ref,P} * r_P \left(1 - \left(F_{os,opt} + 1\right)^{R_P}\right) + I_{ref,buf} * r_{buf} * \left(\frac{\left(\dot{m}_{buf}\right) * \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \right) * \frac{t_{dep}}{EPC * \tau_{oph} * b_{year} * \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min})} \tag{4-12}$$

This equation assumes that the cost savings are the same for each year in the given time horizon. A more detailed description of the derivation of Equation (4-12) can be found in Appendix B .

Decision

It should be noted that t_{pb} must be shorter than t_{dep} of the process step for an economically feasible investment. If, in the process of calculating the P_{econ} of a process, many assumptions are made concerning implemented parameters, that the results might be linked to great uncertainties. If this is the case and t_{pb} is significantly shorter (5 years) than t_{dep} of the process step, it is defined that the overall process with the particular modifications (oversizing and buffer storage) can still be considered feasible for DSM purposes. If high uncertainties (e.g. greater than ± 10%) however are present or t_{pb} lies within 5 years to the t_{dep}, it is advised to carry out a sensitivity analysis to determine the probable outcome of the t_{pb} if changes are made in parameter implementation.

4.2.4 Sensitivity Analysis

A sensitivity analysis is recommended for informed decision-making if parameters are linked to assumptions and high uncertainties. Decision-makers can use the analysis to understand how sensitive the output is to certain changing input variables. Thus, it can help draw concrete conclusions and in making realistic decisions. Therefore, the last step of the decision support tool

for DSM implementation contains a sensitivity analysis. This is used to determine the influence of various parameters on the target value, in this case, the payback period t_{pb}.
After selecting relevant input parameters for the calculation, they are varied systematically. Starting from the base value used in the calculation, each parameter is decreased or increased step-wise. The course of the target value is considered. The greater the change in the target value when the parameter is varied, the more sensitive the parameter is to the calculation. As the sensitivity increases, the demand for the validity of the parameters increases since factors with a strong influence on the target value greatly influence the robustness of the overall results.

4.3 Application of the decision support tool to case study

This section describes the case study used to apply the decision support tool presented in this paper. The subsections list the parameters mentioned in Section 4.2 derived from the literature. Assumptions made for values not directly be found in the literature are explained.
The pilot plant investigated as part of the Pilot SBG project at the DBFZ was used as a case study [218]. The Pilot SBG project aims to convert hitherto unused biogenic residues, by-products, and waste as complementary raw material mixtures into biomethane as the main product. To this end, the DBFZ plans to construct an experimental-scale pilot plant at its site in Leipzig. The plant conceptualizes an anaerobic digestion with innovative up- and downstream processes to produce methane as a fuel. After sufficient experimental data generation and optimization at the pilot plant, the construction and planning of a commercial plant can be considered. For the economic evaluation of the DSM, the envisioned commercial plant was used as a case study for this contribution. Further information on the respective overall layout of the plant can be found in [216].

4.3.1 Parameters for the determination of the mass and energy balance

To determine the mass and energy balance, values previously described by Etzold *et al.* [216] were used for the case study investigation. In the contribution by Etzold *et al.* [216], an innovative concept and associated process steps are being considered, some of which are still very expensive due to the relatively low technology readiness level, an example being the hydrothermal pretreatment. Therefore, the biorefinery concept was adapted for the case study in this investigation to consider process steps and input substrates that are more commonly found in biomethane biorefineries. A simplified scheme of the biorefinery case study is depicted in Figure 4.6. The red numbers one to seven represent the position of potential buffer tanks that would have to be installed if the respective process step is oversized to achieve higher benefits from DSM implementation.
Wheat straw and cattle manure enter the biorefinery as raw material input in equal quantities. A straw cutter for straw chopping is considered for raw material preparation. Water is added to the anaerobic digestion process to reach a dry matter content in the fermenter of 8.9 wt.%. Instead of methanation synthesis for biogas upgrading, a more common CO_2-separation step, an amine scrubbing unit, is considered. The digestate produced during anaerobic digestion is separated in

a cascade of process steps, generating various by-products, such as solid and liquid fertilizers. The purified water is then recycled to the digestion step. The separation cascade comprises a screw press, decanter centrifuge, ultrafiltration, and reverse osmosis. More negligible electricity-consuming components, such as pumps and mixers at the production site, were not further considered for DSM use.

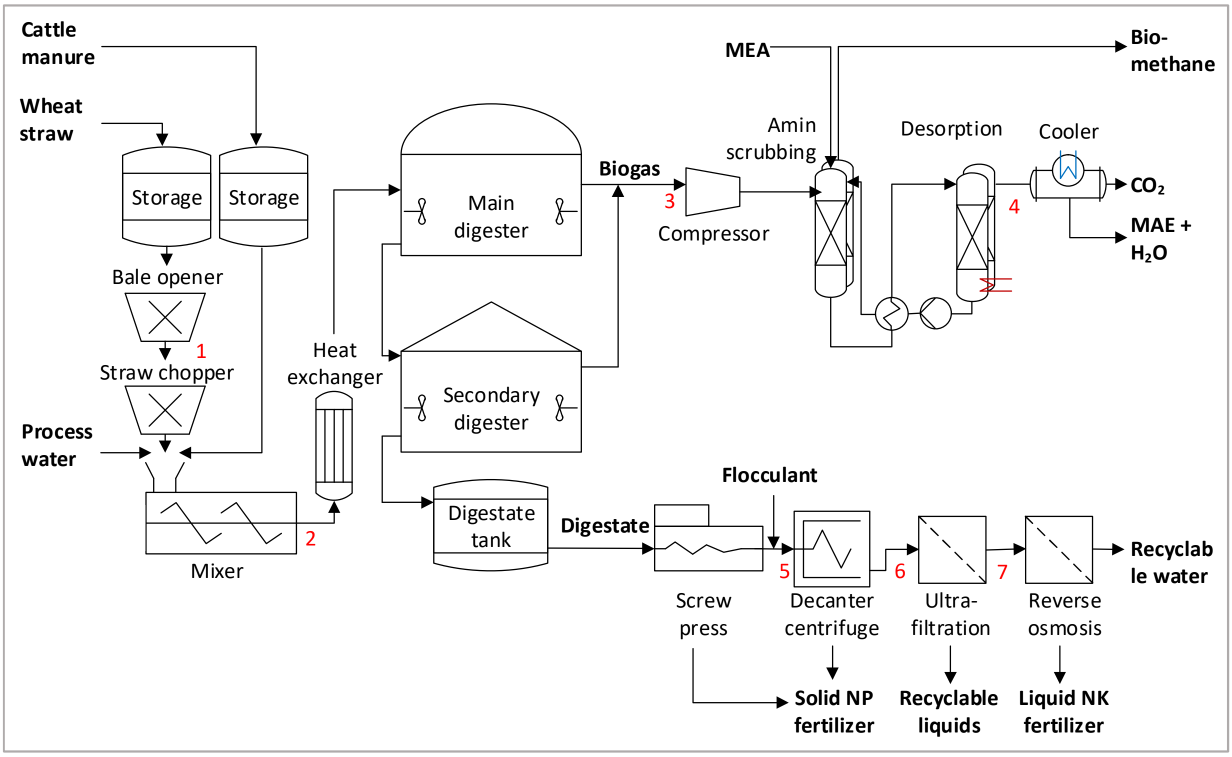

Figure 4.6: Simplified scheme of the biorefinery concept used as a case study, with necessary buffer tank locations indicated in red.

The commercial plant is scaled to produce $\dot{m}_{Product} = 700\ m^3/h$ of methane in the raw biogas, assuming a rural area with equal wheat straw and cattle manure availability. The overall operating hours (τ_{oph}) for the continuously operated processes are assumed to be 8000 h, as common in biogas plants [201].

Demand side management strives to flexibilizing electricity consumption. The decision support tool serves as an aid to decide whether flexibilizing a continuously operated unit operation serves an economic purpose. Thus, one of these limitations is that only unit operations that are operated continuously and consume electricity for more than 7500 hours per year can be investigated for the economic DSM potential with the presented tool. During anaerobic digestion the highest electricity consumption is caused by the agitation of the fermentation broth. Depending on the biogas plant, typical agitation intervals lie between 10 to 30 minutes per hour [189, 201, 219–221], resulting in 1300 to 4000 hours of agitator operation per year, making the tool not applicable to this unit operation.

Since the electricity consumption of the agitator in anaerobic digestion is very high and thus an important contributor to the operating costs (C_{opex}) of a biogas plant, there is a high DSM potential here. The approach, however, to flexibilization is different. Accessing the flexibility within the agitation of the fermenter in anaerobic digestion means shifting the necessary agitation time according to electricity prize profiles. Instead of oversizing the process, the DSM potential could thus be accessed by electricity price-adjusted agitation (EPAA). The principles of EPAA scheduling have been investigated for profitability by Röder *et al.* [206]. This is why the agitation of the fermentation broth will not be included in this case study to investigate possible DSM implementation.

4.3.2 Parameters for the determination of the theoretical DSM potential

The values needed to determine the theoretical DSM potential are the mass and energy balance results taken from the contribution of Etzold *et al.* [216] and the flexible operating load range FOP_{min}. A previous study by Röder *et al.* [205] catalogs the FOP_{min} of many different processes in biofuel production. This review is consulted to define the FOP_{min} of investigated processes. A further assessment by Röder *et al.* [215] applied these FOP_{min} for biofuel production plants and calculated average theoretical values. These values also apply to biomethane biorefinery. They were adopted in the same range for this case study.

4.3.3 Parameters for the determination of the economic DSM potential

In the following, all the relevant parameters needed for calculating the P_{econ}, as found in Figure 4.2 and Figure 4.4, are presented for this case study and, if necessary, put into further context.

Operational costs

Essential for determining the decrease of C_{opex} as a function of F_{os} is the determination of the drop of the average yearly p_{elec}, described by the parameter b_{year} (*c. f.* Figure 4.3). The value b_{year} depends on the duration for which a process can be switched off t_{app}. For $\tau = 24\ h$, the values for a_{year} and b_{year} can be found in the German power market database toolbox (GPM.db.tb). The GPM.db.tb is a data collection for power market data, primarily based on entsoE-raw data and several functions for creating analytical plots [222], from which Figure 4.7 was derived.

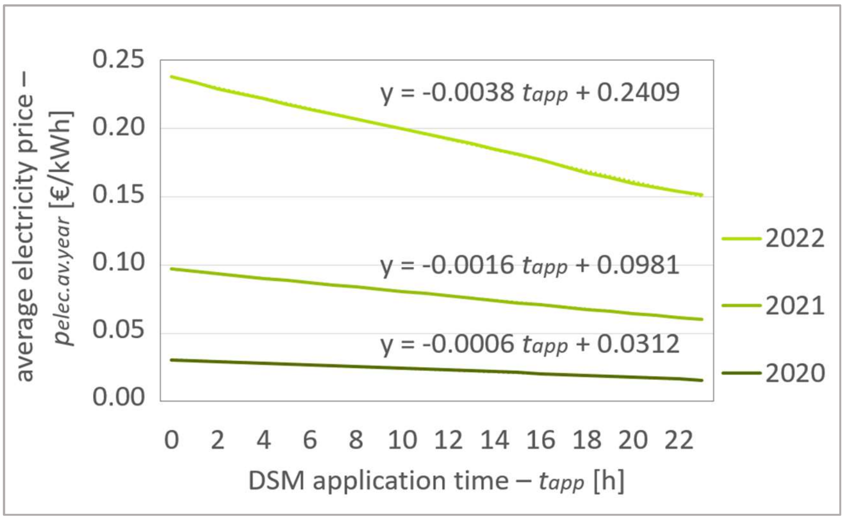

Figure 4.7: Decrease of average electricity price for 2020, 2021, and 2022.

In Figure 4.7 one can see, that for the year 2020 the a_{2020} was 0.0312 €/kWh. If every day that year, the most expensive hour is avoided of p_{elec}, this average electricity price drops by 0.0006 €/kWh. It can also be seen that a_{year} has been rising the last couple of years up to a value of 0.2409 €/kWh in 2022. However, b_{year}, which describes the electricity price variation for the respective year, has also been rising. That means that by avoiding the most expensive hours of p_{elec} in 2022 the $p_{elec,av,2022}$ drops by b_{2022} = 0.0038 €/(kW*h^2) per hour, the process is switched off daily.

Capital costs

The investment costs of all processes as well as r_P and r_{buf} are in accordance with the biorefinery concept investigated by Etzold *et al.* [216]. Insurance costs of 2% were assumed for all equipment and buffer tanks [201]. Interest rates i were calculated for all equipment with an average value of 4% [223]. Maintenance costs were considered to stay the same with oversizing of equipment which is why they do not influence the C_{capex} in this calculation. The total t_{dep} of the process steps and buffer tanks is 15 years [216]. The economies of scale factor for process steps R_P was considered 0.6 as a general rule of thumb assumption [224]. For buffer tanks, the economies of scale factor was assumed equal for all types of buffer tanks and set to be 1.
Deviating from the calculations in the contribution by Etzold *et al.* [216], instead of catalytic methanation downstream of the biogas production, investments for amine scrubbing for CO_2-separation processes were used ($\dot{m}_{ref}$ = 1 400 m³/h; I_{ref} = 3 075 k€ [201]). Catalytic methanation was not considered for the DSM calculation. Herein, literature is available that describes the DSM application under consideration of the flexibilization of electrolysis for dynamic H_2 production in methanation reactors [95, 98, 100, 144]. Buffer tanks were calculated, which are not initially planned for the reference plant and are only necessary due to the oversizing of the process steps for DSM use. Buffer tanks already present in the existing or planned plant were considered (cf. Figure 4.6). A distinction was made between buffer tanks that store gaseous

materials, dry solids (wheat straw), and fermentation digestate. Values found in the literature concerning investment costs of buffer tanks are listed in Table 4.2.

Table 4.2: Parameters from literature necessary for calculating buffer tank capital-linked expenses.

Stored material	V_{ref} [m³]	I_{ref} [k€]	Reference
Solids	134000	1460	[223]
Gas	1000	80	[225]
Digestate (liquid)	100	21.6	[226]

4.3.4 Sensitivity analysis

Since, in the considered case study, assumptions are linked to uncertainties in parameter estimation, a sensitivity analysis was carried out if t_{pb} results to be close to 15 years. b_{year}, EPC_P, I_P, R_P, I_{buf}, R_{buf}, and the interest rate i were chosen as sensitivity parameters. FOP_{min} should also be considered in the sensitivity analysis if applicable. t_{pb} is sensitive to all the listed parameters. The variations of the parameters were evaluated individually in each case and are listed in Table 4.3.

The variable b_{year}, which correlated with the extend of fluctuation in electricity prices, exhibits a 50% fluctuation range in upward and downward directions. Over the past few years, there has been a consistent upward trajectory, thus greater fluctuations, observed in the trend of this pricing factor. As political conditions are currently playing a major role, a substantial decline seems possible in the short term. In the long term, however, this parameter is expected to increase due to the expansion of RE.

Table 4.3: Sensitivity parameters with chosen values and expected uncertainties

Parameter	**Chosen value in the case study**	**Optimistic uncertainty**	**Pessimistic uncertainty**
$\boldsymbol{b_{year}}$	0.0038 €/(kW*h^2)	50%	-50%
$\boldsymbol{SEC_p}$	See Table 4.4	0%	-10%
$\boldsymbol{\dot{m}_p}$	See Table 4.4	10%	-10%
$\boldsymbol{I_P, I_{buf}}$	See Table 4.2 and Table 4.4	-30%	50%
$\boldsymbol{R_P}$	0.6	-20%	20%
$\boldsymbol{R_{buf}}$	1.0	-10%	0%
$\boldsymbol{i}$	11%	-10%	50%

The SEC_P of the plant is expected to remain constant. However, if changes occur in electricity consumption, a slight increase is expected initially, e.g., due to inefficiencies in the start-up of unit operations. For this reason, the parameter was adjusted upwards by 10%. Since anaerobic digestion is subject to large fluctuations and the properties of the biomass can also vary seasonally and annually, uncertainties of the mass flow of ± 10% should be considered as well. Investment costs are based on a cost estimate. According to the Association for the Advancement of Cost Engineering (AACE) cost estimation class 4, the results are subject to an uncertainty of -30% to +50%. The exponents representing the economies of scale were chosen differently for the process and the buffer tank. Both are varied by 40%, with the process varying between -20% and +20% and the buffer tank varying by -40%, depending on the baseline. The interest rates are varied between -10% and +50%, as interest rates are currently expected to rise rather than fall. The variations for FOP_{min}cannot be generalized as they are very dependent on the process step considered. Many processes can be switched off completely where FOP_{min} will not have an influence on t_{pb}. If the process, however, cannot be switched of but operated in partial load, then FOP_{min} is integrated in the sensitivity analysis.

4.4 Results

Following the proposed steps of the decision support tool, the parameters to calculate the mass and energy balance and the theoretical DSM potential were identified for all relevant process steps in the considered case study (cf. Section 4.3). Parameters found in the literature that lead to the determination of the overall theoretical DSM potential ($theoDP$) of the process steps are listed in Table 4.4. Table 4.4 shows the relevant type of buffer tank and the corresponding position, as indicated in Figure 4.6.

Table 4.4: Parameters needed for calculating the economic DSM potential based on [a] [216], [b] [205], [c]own calculations.

Unit operation	$\dot{m}$[a]	EPC_P[a]	FOP_{min}[b]	$theoDP$[c]	I_P[a]	**Buffer**	
	[kt/a]	[kW]	[%]	[kW]	[k€]	Type	Position
Bale opener	26	20	0	20	75	Solid	1
Straw cutter	26	48	0	48	98	Solid	1 + 2
Amine scrubbing	16	260	50	130	3182	Gas	-
Screw press	245	15	0	15	134	Liquid	5
Decanter centrifuge	279	174	0	174	197	Liquid	5 + 6
Ultrafiltration	232	142	0	142	1200	Liquid	6 + 7
Reverse osmosis	130	57	0	57	34	Liquid	7

The literature values for $\dot{m}, EPC, and\ theoDP$ indicate processes with high throughput, high electricity production, and a high theoretical DSM potential. The processes with an especially high $theoDP$ can then be further evaluated for the economic DSM potential. Determining the economic DSM potential, the optimal oversizing factor, the yearly surplus profit generated through DSM integration, and the resulting t_{pb} can also be calculated.

4.4.1 Theoretical demand side management potential

A large amount of water needed for anaerobic digestion also leads to large $\dot{m}$ in all digestate treatment steps. The resulting high substrate streams (*c. f.* Table 4.4) of 130 kt/a to 275 kt/a inevitably lead to high EPC of up to 174 kW. For the methane refinement step, thus the amine scrubbing, a small $\dot{m}$ can be seen. However, since the specific electric energy consumption originating from gas compression for amine scrubbing is high, the EPC for the amine scrubbing is comparable to or higher than those of the remaining process steps in the biomethane biorefinery.
After determining the mass flow and electric power consumption for each process step, the next step would consist in determining processes with high EPC and theoretical DSM potential in order to choose whether they are high enough for further consideration for the calculation of the P_{econ}.
A significantly high theoretical DSM potential could be detected in the CO_2-separation, the decanter centrifuge, and the ultrafiltration. Anaerobic digestion was not investigated further due to the fact that using the theoretical DSM potential does not result in oversizing the process. Since not more than ten process steps are considered at this point, all steps are included in the subsequent calculation of P_{econ}.

4.4.2 Economic demand side management potential

The optimal F_{os} and resulting P_{econ} of the individual process steps of the considered case study can were calculated according to the decision support tool and method explained in Section 4.2.3 (*c.f.* Figure 4.5). In Figure 4.8, two different examples of the calculation of the optimal F_{os} are depicted for a) the screw press separator and b) the bale opener. The C_{opex} and C_{capex} functions are shown, of which the sum equals the C_{totex} function.

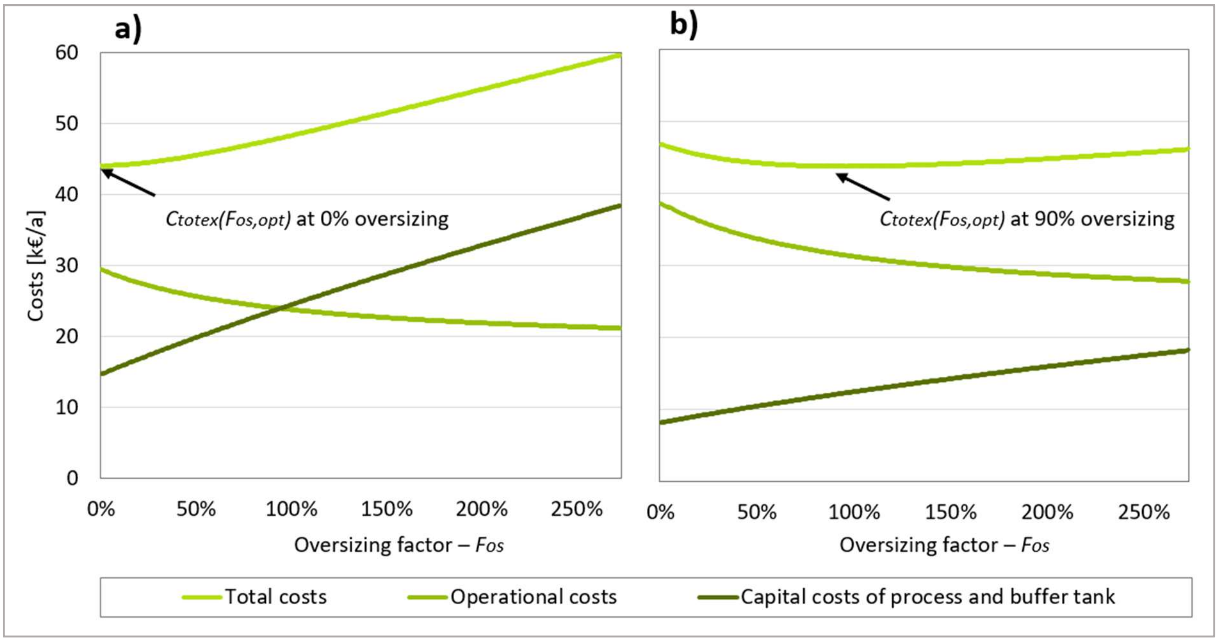

Figure 4.8: Exemplary demonstration of operational, capital, and total expenditure as a function of oversizing of a) screw press separator and b) bale opener.

On the left-hand side, Figure 4.8 a), C_{totex}, C_{opex}, and C_{capex} as a function of F_{os} are depicted for the screw press separator in the biorefinery case study. For this example, it is demonstrated that the C_{opex} function decreases with increasing F_{os}, while the C_{capex} function increases significantly. The C_{opex} function shows little dependency on F_{os} because the screw press separation has a relatively low EPC compared to investment costs. This leads to a steep increase of the C_{capex} function with increasing F_{os} and, thus, of the C_{totex} function. Since, in this example, for no value within the investigated range of F_{os} Equation (4-10) is true, the best F_{os} from an economic point of view is 0%; hence DSM implementation and thus oversizing this process is not profitable.

In Figure 4.8 b), C_{totex}, C_{opex}, and C_{capex} as a function of F_{os} are depicted for the bale opener in the biorefinery case study. For the bale opener close to an F_{os} of 0% the value of the negative slope of the C_{opex} function exceeds that of the C_{capex} function. This leads to a decrease of the C_{totex} function in small ranges of F_{os}, as Equation (4-10) is true. A minimum value of the C_{totex} function is reached at an F_{os} of 90%. This means that maximal monetary benefits of 2.7 k€ per year through DSM can be achieved with a bale opener that is 1.9 times larger than a continuously operated bale opener without flexibility possibilities for DSM implementations.

Table 4.5 lists the values for $C_{totex,0}(F_{os} = 0)$, $C_{totex,min}$, and the resulting P_{econ} and t_{pb} for all process steps considered, calculated according to the decision support tool presented in this contribution.

Table 4.5: Decision support tool results applied to a biorefinery case study.

Unit operation	$F_{os,opt}$ [%]	$C_{totex,0}$ [k€/a]	$C_{totex,min}$ [k€/a]	P_{econ} [k€/a]	P_{econ} [%]	t_{pb} [a]
Bale opener	90	47.0	44.3	2.7	5.7	8
Straw cutter	184	103.9	91.0	12.9	12.4	6
Amine scrubbing	0	600.5	600.5	0.0	0.0	-
Screw press	0	44.3	44.3	0.0	0.0	-
Decanter centrifuge	238	357.8	317.1	40.7	11.4	8
Ultrafiltration	0	405.7	405.7	0.0	0.0	-
Reverse osmosis	372	113.5	93.9	19.6	17.3	6

The results in Table 4.5 show that for three out of seven unit operations investigated, the optimal F_{os} is 0%. This means that due to high investment costs, benefits from oversizing the process do not exceed surplus expenditure spent on capital-linked costs. According to the decision support tool calculation, amine scrubbing, screw press separation, and ultrafiltration are, therefore, not suitable for DSM implementation with taken operational and investment parameters. The highest absolute P_{econ} was calculated for the decanter centrifuge. The highest relative P_{econ} seen as a percentage of the total costs was calculated for the reverse osmosis. Considering the payback period, the bale opener and straw cutter can also be considered very promising process steps for DSM implementation, although the P_{econ} is, in part, significantly lower.
However, it has to be noted that t_{pb} must be shorter than t_{dep} for an economically feasible investment. In the presented case study, the total t_{dep} of the process steps is 15 years. The payback periods of the digestate separation processes lie close to this t_{dep}. Though these values of 8 and 6 years are shorter than the considered t_{dep} of the process step. Uncertainties in the calculations could significantly affect the results of suitability for DSM implementation of this specific process.

4.4.3 Sensitivity analysis

In the calculations for the presented case study, parameter uncertainties greater than 10% are present. Thus, a sensitivity analysis should be carried out, even though t_{pb} does not lie within ±5 years of to the plant's t_{dep} = 15 years. The decanter centrifuge was chosen as an exemplary unit operation from this case study. Although the t_{pb} is comparably high, the cost savings through DSM implementation are calculated to be the highest. The sensitivity analysis helps determine which parameter uncertainties could affect the DSM implementation in such a way that it is in fact no longer feasible.
For a better interpretation, the cost structure of the previous calculation for the decanter centrifuge is shown in more detail in Figure 4.9. The savings or additional costs are shown as black columns. The C_{opex} savings clearly offset the additional C_{capex} costs. In addition, the

annual additional C_{capex} payments are low in relation to the original C_{opex} payments at 11%. Since the F_{os} for the decanter centrifuge is very high, a big buffer tank would have to be installed to make up for the times during which the decanter centrifuge is switched off. The C_{capex} for the buffer tank therefore have a comparable impact on the C_{totex} as the ones for the oversizing of the process itself.

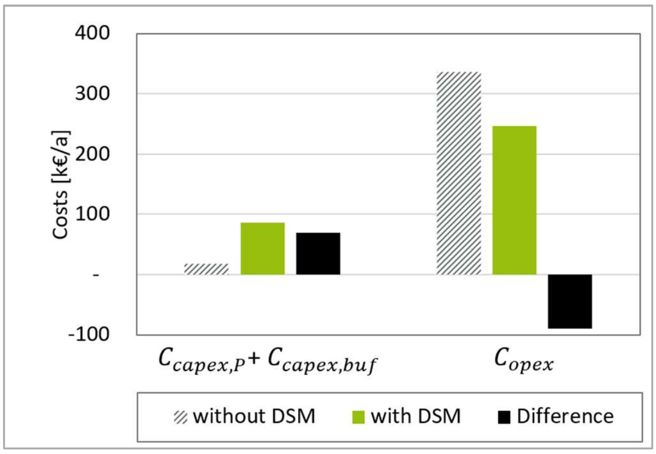

Figure 4.9: Cost structure of the demand side management impact for the decanter centrifuge.

Figure 4.10 shows the results of the sensitivity analysis. b_{year}, EPC_P, I_P, I_{buf}, R_{buf}, R_P, and the interest rate i were parameters implemented in the decision tool equations with high uncertainties. The variation of the parameters was evaluated individually in each case. The t_{dep} of the plant, which is 15 years is shown in a bold grey vertical line. t_{pb} must be shorter than t_{dep} for an economically feasible investment. If the grey cross-striped bar of a parameter which shows the sensitivity at pessimistic conditions, exceeds this line at 15 years, that means that in a pessimistic case of the respective sensitivity parameter, the DSM implementation would not be profitable.

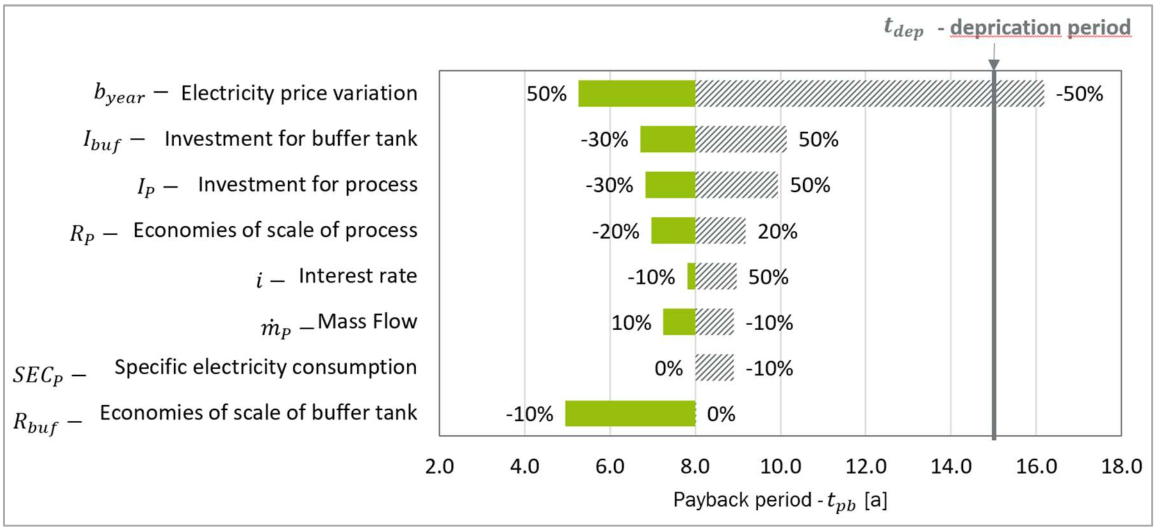

Figure 4.10: Tornado graph for the sensitivity analysis of all relevant factors affecting the payback period of DSM implementation.

Based on the selected parameter variation, the highest sensitivity results for b_{year}. This is due to its direct relationship with the potential revenue of DSM and the wide range of variation. The investments for the buffer tank and the process step have the second and third highest influence on t_{pb}, which is also due to high uncertainties, but still within a reasonable range. Since the highest possible value of 1 was used for R_{buf} in the case study, only a negative deviation is possible. The results in Figure 4.10 demonstrate that a small decrease in the economies of scale would shorten the payback period from more than 8 to almost 5 years. The respective rise in R_P, i, $\dot{m}_P$ and SEC_P increase the payback period in a less severe way. However, several parameters can vary simultaneously; thus t_{pb} may increase more significantly. Deviations in the parameters, which highly influence b_{year} and I_{buf} could each lead to an infeasibility of DSM implementation. On the other hand, with more optimistic values for b_{year}, I_{buf}, and R_P a much shorter payback may be achieved. Whereas again b_{year} has the strongest influence in this regard.

4.5 Summary

A comprehensive tool that evaluates the most important economic parameters for the decision support of a DSM implementation for continuously operated processes has been proposed. The decision support tool is based on a multi-step framework. Using this framework, single process steps within an industrial plant are investigated for mass flows, energy demands, theoretical DSM potentials, and several economic aspects of DSM implementation. The key aspect is determining the extent to which a process step should be oversized to maximize flexibility but not incur excessive additional costs.

In a case study, the decision support tool was applied to a biomethane biorefinery to show its functionality and applicability. The results of this study show that with the help of the presented decision support tool, the ranking of unit operations concerning their economic DSM potential is possible. This results in the possibility of evaluating the plant or individual process steps within a plant to determine whether DSM implementation is economically viable. The decision support tool helps to quickly understand the suitability of a process for DSM application based on comparatively small amounts of required information and complexity.

Overall is was shown that, although typically rigid and inflexible in operation, complex multi-stage processes can indeed have several intermediate process steps that can economically be used for flexible operation. However, dependent on the relation between specific investments and electricity consumption, the rise in investment costs might exceed the potential savings in electricity costs resulting from oversizing a process. It was thus demonstrated that not generally every process is feasible in DSM concepts, which is why a preliminary analysis with the decision support tool presented is recommended.

4.6 Discussion and perspectives

The most significant influencing factors for the feasibility of a demand side management implementation have been identified in the magnitude of the fluctuations in the price of electricity and specific investments for the oversizing and required buffer tanks. This is not surprising, as fluctuating electricity prices are a driving force for demand side management considerations. This large impact on the payback period is both an opportunity and a risk, as it is not easy to predict due to the complexity of the needed parameters. Therefore, the tool is especially suitable if electricity is bought at the spot market, and the investments for the process can be specific for continuous operation and oversized equipment.

When designing plants with oversizing, it is essential to acknowledge that processes cannot be precisely oversized according to predetermined values. In most cases, no equipment is available in the exact size recommended by the decision support tool. Hence, when opting for process oversizing, it is crucial to consider the limitations of available processes and buffer sizes.

Future work should also consider the dynamics of the processes or process steps suitable for demand side management. A detailed analysis of the processes identified as feasible for demand side management implementation will be conducted, taking shut-down and start-up duration into account. The modeled processes will react time-dependently to fluctuating electricity prices, analyzing the real-time economic effects and ecological advantages that the DSM implementation could entail. Furthermore, with the dynamic simulation environment, the investigation of interdependencies between process steps and limitations that could be caused by these interdependencies will be investigated. The possibility of flexibilizing a whole cascade of processes and thus saving buffer tank costs will be analyzed further.

Chapter 5. Optimization of design and operation of a digestate treatment cascade[4]

This chapter presents the results of the economic evaluation of integrating DSM into biofuel biorefineries through a dynamic simulation approach. A previously developed decision support tool for DSM implementation was extended to describe the size of intermediate buffer tanks as a function of oversizing up- and downstream processes. Design optimization of the process cascade determined the oversizing that allows the optimal balance of operational cost reduction through flexibility and capital cost increase through oversizing. Scheduling optimization validated the results of the steady-state optimization and show that, by considering interactions between processes, buffer tank capacity can be reduced, while increasing DSM potential.

5.1 Introduction

The expansion of renewable energy sources has led to fluctuations in electricity supply and, consequently, rising volatilities in electricity prices. Demand side management (DSM) has emerged as a solution to capitalize theses fluctuations, by adapting electricity consumption according to price profiles. DSM has numerous benefits, including reducing electricity costs, minimizing emissions, and relieving pressure on the electricity grid. However, DSM also demands a broad operational range and quick transitions between different operational states to achieve sufficient flexibility. This is particularly challenging for chemical processes, where the ability to ramp production capacities up or down at short notice is critical. Capacity flexibility is thus a key aspect of flexibility in DSM, as emphasized by Bruns *et al.* [83].

Although conventionally designed for fixed operational states with maximized product yield, large-scale industrial processes have an essential potential for DSM due to their energy-intensive nature [26]. Small changes in energy demand especially of processes that are electrically operated could have immense economic effects. Examples from large-scale industrial processes that illustrate the practical application of DSM are chlor-alkali electrolysis and cryogenic air separation plants, as illustrated e.g., by Roh *et al.* [18], Simkoff and Baldea [155], Caspari *et al.* [133] or Kelley *et al.* [141]. These electricity-intensive processes provide the inherent flexibility to adapt to production schedules, making them ideal for DSM integration. In addition to these and other well-established cases, various electricity and resource-intensive processes within the industrial sector have yet to be explored regarding their potential for systematic DSM implementation.

One of the DSM's current research objectives is to increase the flexible operating window of electricity-intensive processes [227]. Studies, such as research by Pohl *et al.* [119] and Loutatidou *et al.* [120] on reverse osmosis and Röder *et al.* [228] on biorefineries, investigated the idea of extending the operational flexibility through oversizing of process equipment. According to recent DSM research by Bruns *et al.* [1] and Hochhaus *et al.* [28], increasing the flexibility of downstream processes can widen the operational window of upstream processes.

[4] Substantial parts of this chapter are published in Röder, L. S.; Gröngröft, A.; Grünewald, M.; Riese, J. (2024): Optimization of design and operation of a digestate treatment cascade for demand side management implementation. *Computers and Chemical Engineering*. DOI: 10.1016/j.compchemeng.2024.108838.

This indirectly strengthens DSM, even in cases where direct response to electricity pricing is not the priority. The use of DSM in multi-process chains was explored for industrial processes such as pulp and paper production [60, 71], wastewater treatment [2, 12], and power-to-gas conversions [98, 150]. However, these studies mainly concentrate on individual unit operations and do not consider their process inherent interdependencies.

To evaluate the economic impact of flexibility enhancements, a decision support tool developed by Röder *et al.* allows for a preliminary assessment of the potential benefits [228]. A four-step framework underpins the decision support tool. Through proposed evaluations and decision-making, the framework first describes how to identify processes with high theoretical DSM potential. It then helps to determine the economic benefits and the additional financial costs of oversizing a process for DSM purposes. Based on this economic evaluation, the tool supports decision-making regarding the optimal degree of process oversizing, considering set equipment parameters and known fluctuating electricity prices, to achieve minimum total costs. Based on the consideration of results and the parameters used, the final step of the decision support tool is to determine the robustness of the results obtained from the economic evaluation and whether a sensitivity analysis is recommended.

The central idea behind the decision support tool is to determine the potential for oversizing a process step to maximise flexibility without incurring excessive capital costs. The advantages of the tool are that process engineers can quickly and easily determine in the design phase whether a process should be oversized for DSM integration or not, without the need for complex software or optimization calculations. The decision support tool however also reveals certain limits as will be explained in the following.

The study by Röder *et al.* [228] applied the decision support tool in a biorefinery case study and found that the digestate separation cascade within the biomethane biorefinery presents a high potential for DSM. However, only two out of four unit operations in the digestate separation cascade demonstrated monetary benefits through oversizing. The decision support tool does not consider the interaction between processes but examines each process individually. The synergy between oversizing to enhance flexibility and accommodating interdependencies is still an open topic in the field of DSM. This area of research is of particular interest, for example, in chemical and biofuel production, where several process steps could benefit from DSM integration and intermediate storage is a critical cost variable. In this context, making an entire process cascade more flexible could mean that intermediate storage can be avoided or minimized, reducing the cost of oversizing unit operations.

Moreover, the decision support tool is primarily intended for use as a theoretical aid and does not provide a highly accurate representation of the actual implementation of DSM. One example of idealization within the decision support tool is that it calculates precise values for process oversizing that may not be feasible in practice. Equipment of the exact size recommended by the decision support tool is, most likely, not available. Therefore, it is important to factor in the limitations of available processes and buffer sizes when deciding on process oversizing.

Lastly, the decision support tool disregards the transient behavior of the process steps. A detailed analysis of the processes identified as feasible for DSM implementation, taking ramp-down and start-up duration into account, is not considered. It would thus be necessary to model the process steps in a dynamic simulation approach to consider the time-dependent reaction to fluctuating electricity prices, analyzing the real-time economic effects and advantages that the DSM implementation could entail.

The dynamic simulation of industrial processes is crucial for operational flexibility and optimization. Despite the advanced technological development in this field, it is still a challenge to precisely model and simulate the dynamic start-up behavior of the newly introduced processes. In this context, it should be noted that previous studies and experiments on this topic are limited as industrial processes are still rarely operated flexibly and therefore there is a lack of comprehensive models and simulations that allow direct applicability to real plants. There are certainly publications in the literature that deal with the modeling and simulation of flexible processes. Some examples being a review of flexible operation of thermal power plants by Acagianos *et al.* [229], optimization studies of flexible operation in dynamic processes by Caspari *et al.* [230], Hochhaus *et al.* [28] or Hoffmann *et al.* [127] and a review of the modeling and implementation of flexible ramping products Wang *et al.* [231]. However the application is limited to specific plant configurations. Simulating the interaction of different plant components dynamically can be a complex task due to a large number of possible combinations. To better understand and simulate such dynamic processes, it might be necessary to perform specific experiments and collect data directly from the plant considered. This would help to develop more precise models and enable better prediction of start-up behavior.

The presented study thus seeks to investigate the possible economic benefits of DSM integration, using the previously developed decision support tool but expanding its possibilities. Specifically, this paper presents the results of a DSM study in a digestate separation cascade within a biomethane biorefinery that determined whether the integration of serial, flexible unit operations during plant design can reduce or eliminate the need for buffer tanks.

A method is proposed, in which, the decision support tool is extended and implemented in a optimization environment. A steady-state design optimization comprehensively evaluates whether the assessment of an entire process cascade can reveal additional saving opportunities. The results of this design optimization give a first estimation of the economic DSM advantages and set the foundation for the consideration of more realistic design parameters needed for the subsequent dynamic investigation. The dynamic simulation enables the consideration of the ramp-up and ramp-down phases of the unit operations. Process inertia and how it may affect the implementation of DSM can thus be investigated. The dynamic scheduling optimization then analyzes the unit operations' behaviour as they react to electricity prices from a more realistic perspective. Both optimization strategies aim to minimize the total expenditure of the process plant. The results of the steady-state design and the dynamic scheduling optimization are compared to one another to evaluate how significant the steady-state method of the decision support tool is. This highlights the possibilities and limitations of the steady-state and dynamic approach.

In conclusion, this paper aims to expand and employ our previously developed decision support tool in a simulation environment while delving deeper into relevant processes. It presents an economic evaluation of DSM interaction in a digestate treatment cascade through a dynamic simulation approach, and it hypothesizes that by considering interactions between processes, storage design capacity could be reduced. This could help to identify and quantify the benefits of

DSM applications on a process scale, rather than on a unit operation scale. It also evaluated the possibilities and limitations of the two optimization strategies.

5.2 Materials and method

The presented DSM study proposes a six-step method to investigate whether the integration of serial, flexible unit operations during plant design can reduce or eliminate the need for buffer tanks. The basis for the proposed method is the previously developed decision support tool [228] that allows for a preliminary assessment of the potential benefits of oversizing processes for DSM purposes. The initial decision support tool classifies processes in terms of their economic DSM potential and determines whether DSM implementation is economically profitable by integrating oversizing factors during the design phase. By strategically oversizing the process to accommodate occasional spikes in energy demand, the process operation can be adjusted in response to hourly changing electricity price variations, while maintaining constant production capacity. During periods of high electricity prices, the process can be selectively switched off or run in partial load, thus reducing operational costs. The potential increase in capital costs associated with oversizing the process is offset by the significant savings achieved during peak electricity price periods. This principle relies on the premise that the cost savings from avoiding high electricity prices outweigh the additional capital investment required for oversizing, resulting in overall cost efficiency and improved profitability. The decision support tool defines equations to calculate the monetary benefits in terms of yearly operational cost C_{opex} and capital cost C_{capex} as a function of the decision variable, the oversizing factor F_{os}, the sum of which equals the total costs C_{totex}. Table 5.1 lists all equation symbols used for calculations in the decision support tool and other relevant equations.

Table 5.1: Equation symbols needed for the calculation of decision support tool equations according to [228].

Symbol	Unit	Explanation	Type	
			Steady-state	Dynamic
$\boldsymbol{a_{year}}$	€/kWh	Maximum average electricity price of specified year	Parameter	-
$\boldsymbol{b_{year}}$	€/(kW*h^2)	Electricity price variation of specified year	Parameter	-
$\boldsymbol{C_{capex,P}}$	€/d	Capital expenditure of process per year	Result	Result
$\boldsymbol{C_{capex,buf}}$	€/d	Capital expenditure of buffer tank per year	Result	Result
$\boldsymbol{C_{opex}}$	€/d	Operational expenditure per year	Result	Result
$\boldsymbol{C_{totex}}$	€/d	Total expenditure per year	Objective function	Objective function

$\boldsymbol{F_{os}}$	%	Oversizing factor (decision variable)	Decision variable	Parameter
$\boldsymbol{I_P}$	€	Investment for process step at no oversizing	Parameter	Parameter
$\boldsymbol{I_{b,ref}}$	€	Investment for reference buffer tank	Parameter	Parameter
$\boldsymbol{\dot{m}_P}$	t/h	Mass flow through reference process step	Parameter	Decision variable
$\boldsymbol{\dot{m}_{buf}}$	t/h	Mass flow in buffer tank	Parameter	Decision variable
$\boldsymbol{p_{elec,av,year}}$	€/kWh	Average annual electricity price	Result	Result
$\boldsymbol{\varrho}$	t/m³	Density of mass flowing through process	Parameter	Parameter
$\boldsymbol{R_P}, \boldsymbol{R_{buf}}$	-	Economies of scale of process step, buffer tank	Parameter	Parameter
$\boldsymbol{r_P}, \boldsymbol{r_{buf}}$	%/a	Expense ratio of process step, buffer tank (including depreciation, interest, maintenance, insurance, taxes, and wages)	Parameter	Parameter
$\boldsymbol{SEC_P}$	kWh/t	Specific electricity consumption	Parameter	Parameter
$\boldsymbol{\tau}$	h	Considered time period for possible DSM application	Parameter	
$\boldsymbol{\tau_{oph}}$	h/a	Operating hours	Parameter	
$\boldsymbol{t_{app}}$	h	DSM application time	Result	Result
$\boldsymbol{t_{dep}}$	a	Deprecation period	Parameter	Parameter
$\boldsymbol{V_{buf,in}}$, $\boldsymbol{V_{buf,out}}$	m³	Buffer tanks located up- and down-stream of the process	Result	Parameter
$\boldsymbol{V_{ref}}$	m³	Volume of reference buffer tank	Parameter	Parameter

An essential part of the decision support tool is the electricity price dependent on the time that a process is switched off for, the DSM application time (t_{app}). This applies under specific conditions. First, it requires that electricity is purchased at spot market prices. Second, the unit operation in question must be operated continuously, meaning it runs for more than 7,500 hours per year. Additionally, the unit operation must be flexible, allowing it to be switched off during operation or run with a sufficient efficiency at partial load. Finally, it is essential that oversizing individual process steps and installing intermediate material storage are feasible. If these conditions are met, the fluctuating electricity price can be expressed as an annual average value that decreases in relation to the avoidance of electricity price peaks through strategic shutdowns. Though this seems to be a dynamic effect, there is a possibility to consider the decrease in electricity prices when a process is switched off in a steady-state manner, through the use of so-called cherry-picking values, as coined by Martin Dotzauer [232] and already adopted in our previous work [228]. As the name suggests, this means that only the best values, in our case the cheapest electricity prices, are (cherry-)picked. These values can be derived by calculating the average of all electricity prices over a given period, e.g. one year, followed by, for example, the average of the 23 lowest electricity prices per day, then the average of the 22 lowest electricity prices per day, and so forth. This method enables the determination of the average annual electricity price $p_{elec,av,year}$ contingent upon the avoidance of high-priced electricity periods over specific time intervals. The rate at which the average price decreases dependent on t_{app}, is described by b_{year} in the following equation:

$$p_{elec,av,year} = a_{year} - b_{year} * t_{app} \tag{5-1}$$

If a unit operation is operated continuously, thus $t_{app} = 0$, the average yearly electricity price equals a_{year}. The cherry-picking values can be obtained from the German power market database toolbox [232], from which b_{year} can then be calculated for a specific year. A more thorough description of this effect can be found in [228].

The t_{app} not only influences the electricity price. The decision support tool is based on the premise that, at the end of a defined time period τ e.g. one day, the same cumulative product volume should be achieved with and without the implementation of a DSM strategy. Thus the longer t_{app} the more a process needs to be oversized. The oversizing factor F_{os} of a process step is dependent on t_{app}, according to the following equation:

$$F_{os} = \frac{t_{app}}{\tau - t_{app}} \tag{5-2}$$

Considering the drop of $p_{elec,av,year}$ (*c.f.* Eq. (5-1)) dependant on t_{app} or F_{os}, a bigger F_{os} then leads to lower electricity cost and thus lower C_{opex}. The C_{opex} of a specific process as a function of F_{os} can mathematically be described by the multiplication of the $p_{elec,av,year}$ with the specific electricity consumption SEC_P, the mass flow $\dot{m}_p$ through a process step and the operating hours τ_{oph} (e.g. 8000 h/a or 24 h/d) at no DSM implementation:

$$C_{opex} = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{F_{os}+1} \right) \right) * SEC_P * \dot{m}_p * \tau_{oph} \tag{5-3}$$

The F_{os} was determined on the premise that the daily cumulative product flow remains unchanged compared to continuous operation, even though the unit operation is turned off for t_{app}. A longer t_{app} and, thus, greater F_{os} also causes a rise in investment for process step I_p and buffer tank I_{buf} and thus influences the C_{capex} function. R_P and R_{buf} represent the economy of scale exponents that quantify the variation of specific investment costs relative to the size of the unit operation. The expense ratios r_P and r_{buf} encompass depreciation, interest, maintenance, insurance, taxes, and wages, estimated linearly based on the investment specifics or sourced from literature. Given that not all expense ratios exhibit size-dependent changes, only interest (i) over the depreciation period (t_{dep} = 20 a) and insurance are considered for r_P and r_{buf}. The calculation of C_{capex} as a function of the oversizing factor F_{os}, is outlined in Equation (5-4) and (5-5):

$$C_{capex,P} = I_P * r_P * (F_{os} + 1)^{R_P} \tag{5-4}$$

$$C_{capex,buf} = I_{buf} * r_{buf} * \left(\frac{V_{buf}}{V_{ref}}\right)^{R_{buf}} \tag{5-5}$$

The total volume of the buffer tank V_{buf} (*c.f.* Equations (5-5)) is calculated by adding the volumes of buffer tanks located up- and down-stream of the process ($V_{buf,in} + V_{buf,out}$). The in- and out-flowing mass flow $\dot{m}_{P,in}, \dot{m}_{P,out}$ of the considered process step are multiplied by t_{app} (*c.f.* Equation (5-2)) and divided by the mass flows density ϱ and are thus also dependent on F_{os}:

$$V_{buf} = V_{buf,in} + V_{buf,out} \tag{5-6}$$

$$V_{buf} = t_{app} * \frac{\dot{m}_{P,in} + \dot{m}_{P,out}}{\varrho} \tag{5-7}$$

The sum of C_{capex} and C_{opex} describes the total expenditure (C_{totex}) per year as described in Equation (5-8):

$$C_{totex} = C_{opex} + C_{capex,P} + C_{capex,buf} \tag{5-8}$$

The DSM implementation is economically beneficial if the decrease in C_{opex} exceeds the rise in C_{capex} with increasing F_{os}. If this function forms a minimum in a specific range of the F_{os}, then an optimal F_{os} factor can be found at which a unit operation will have the highest DSM benefit. By deriving the C_{totex} function, the slope of the total costs can be determined as a function of F_{os}. If all necessary parameters are known and inserted in the derived function, a minimum value for C_{totex} dependent on F_{os} can be calculated, as depicted in a graphical demonstration of the described dependencies in Figure 5.1. [228].

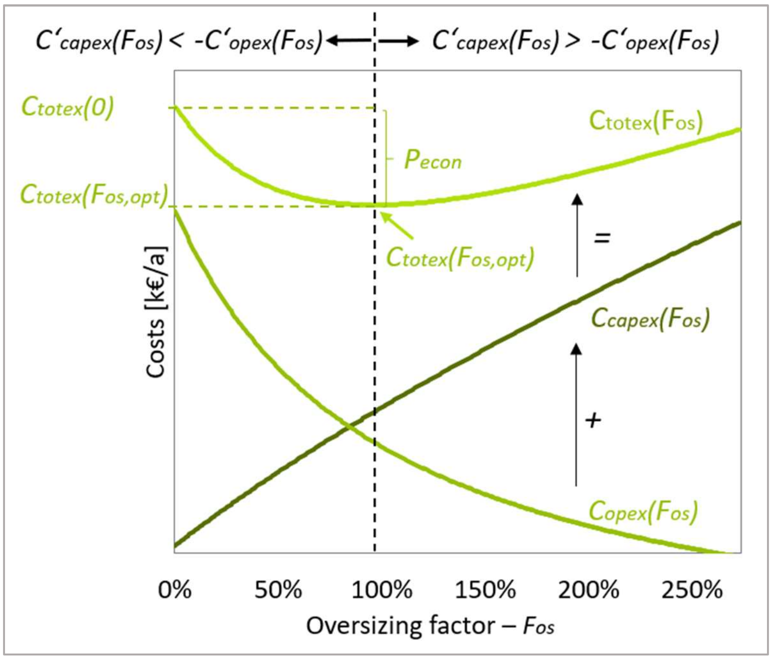

Figure 5.1: Graphical demonstration of parameters to determine the economic DSM potential. [228]

The decision support tool just described is the basis for the present research to answer the question of whether the integration of serial, flexible unit operations in the plant design can reduce or eliminate the need for buffer tanks. The methodology used to answer that question is divided into six steps as shown in Figure 5.2 that will be explained in the following subsections.

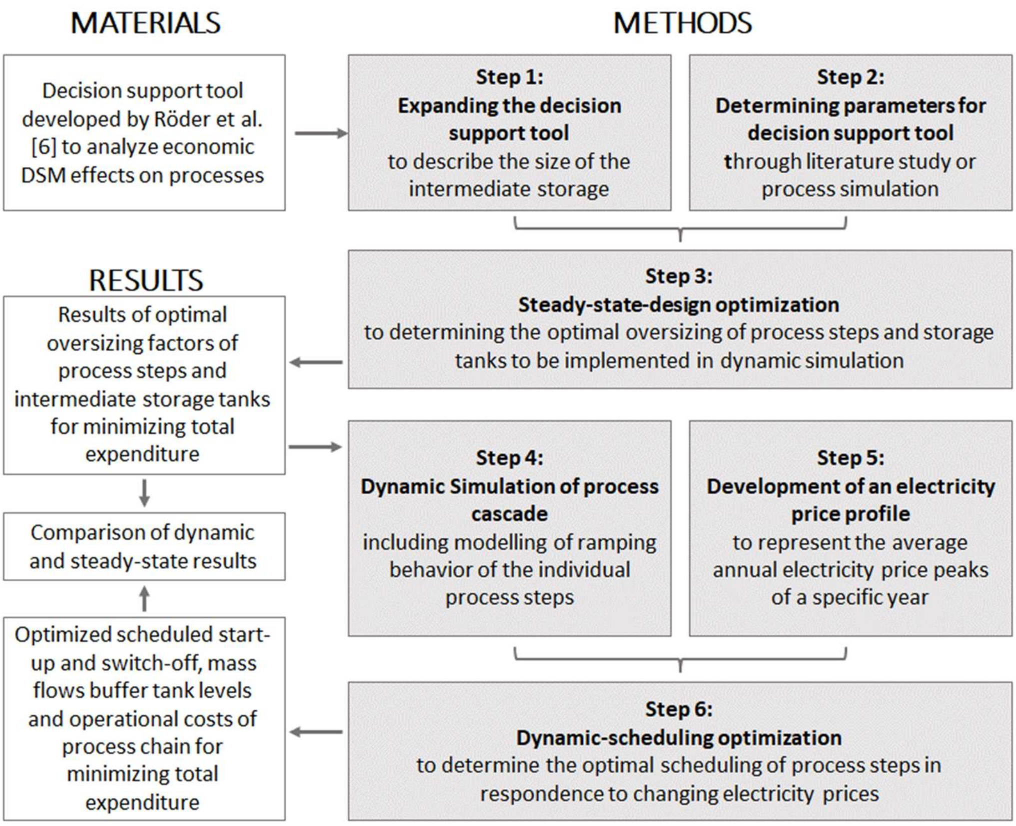

Figure 5.2: Graphical summary of methodology as applied in this study.

Step 1: Expanding the decision support tool

The first step of the proposed method entails developing additional equations that represent the size of the buffer tank as a function of the oversizing of the upstream and downstream processes. They are implemented to model the interactions between processes. In this way, the process steps can be represented in their interactions when oversizing and buffer tanks are in shared use. To determine the volume of shared buffer tanks, it is necessary to redefine the maximum mass flow going in and out of the buffer tanks as exemplarily depicted in Figure 5.3.

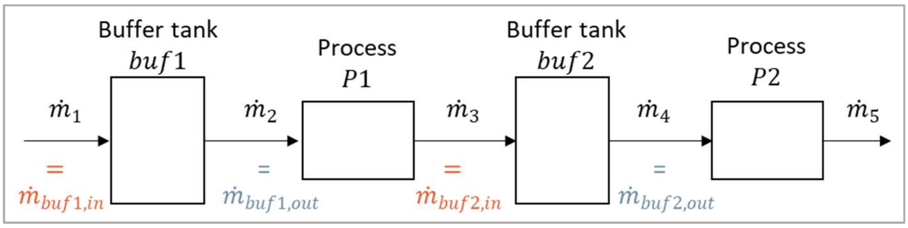

Figure 5.3: Exemplary block flow diagram of process cascade with intermediate buffer tanks.

In the presented method the in- and outflowing mass flows of the complete process cascade are considered to be constant. The associated buffer tank of a process is defined as always being situated upstream of the respective process considered for DSM purposes (*c.f.*Figure 5.3)..The maximum possible mass flow of $\dot{m}_{1,max}$ till $\dot{m}_{m,max}$ can be described dependent on directly surrounding process steps or buffer tanks by the following equations:

$$\dot{m}_{1,max} = \dot{m}_{buf1,in} = \dot{m}_{P,P1} \tag{5-9}$$

$$\dot{m}_{2,max} = \dot{m}_{buf1,out} = \dot{m}_{P,P1} * \left(1 + F_{os,P1}\right) \tag{5-10}$$

$$\dot{m}_{3,max} = \dot{m}_{buf2,in} = \dot{m}_{P,P2} * \left(1 + F_{os,P1}\right) \tag{5-11}$$

$$\dot{m}_{4,max} = \dot{m}_{buf2,out} = \dot{m}_{P,P2} * \left(1 + F_{os,P2}\right) \tag{5-12}$$

$$\dot{m}_{buf(j),in} = \dot{m}_{P,P(j)} * \left(1 + F_{os,P(j-1)}\right) \tag{5-13}$$

$$\dot{m}_{buf(j),out} = \dot{m}_{P,P(j)} * \left(1 + F_{os,P(j)}\right) \tag{5-14}$$

In the extended version of the decision support tool, multiple processes and intermediate storage units are considered rather than just a single process. New indices have been introduced: P_1 to P_n , to sequentially number the process units. The buffer tank upstream of each process unit is assigned the corresponding numbering. These indices apply to the inflowing mass flows in both the processes and buffer tanks, as well as to the corresponding oversizing factors $F_{os,P(j)}$, DSM application time $t_{app,P(j)}$, operational expenditure $C_{opex,P(j)}$, capital expenditure of the processes $C_{capex,P,P(j)}$, and the volumes of the associated buffer tanks $V_{buf(j)}$. j is a natural number and ranges from 1 to n, inclusively, and n describes the number of processes to be analyzed in a process cascade.

$$j \in \mathbb{N} \text{ and } 0 < j \leq n \tag{5-15}$$

The analysis period is defined as τ. The necessary volume of the intermediate buffer tanks equals the time the inflowing solid phase stream fills the buffer tank, subtracted by the time the following unit operation needs the process feed to flow into the process step. This effect is schematically demonstrated in Figure 5.4, using the buffer tank 2 ($buf2$) between process step 1 ($P1$) and process step 2 ($P2$) as an example, depicted in Figure 5.3.

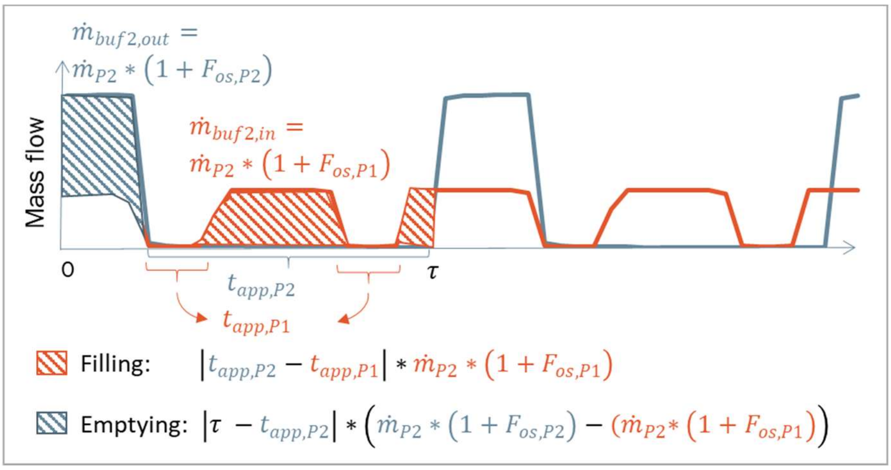

Figure 5.4: Graphical demonstration of the development of equations for buffer tank volumes dependent on the oversizing of up- and downstream processes.

The following equations describe the necessary volumes of the buffer tanks, and the interdependency between t_{app} and F_{os} being described in equation (5-2):

$$V_{buf1} = |t_{app,P1}| * \frac{\dot{m}_{P,P1}}{\varrho} \tag{5-16}$$

$$V_{buf2} = |t_{app,P2} - t_{app,P1}| * \frac{\dot{m}_{P,P2}}{\varrho} * (1 + F_{os,P1}) \tag{5-17}$$

$$V_{buf(j)} = |t_{app,P(j)} - t_{app,P(j-1)}| * \frac{\dot{m}_{P,P(i)}}{\varrho} * (1 + F_{os,P(j-1)}) \tag{5-18}$$

j is described in Eq. (5-15) and ϱ is the desity of the in- and outflowing mass stream. Implementing these equations (5-16) to (5-18) in equation (5-2) then leads to the following sum of the total costs of all process steps described in a single equation dependent on all relevant oversizing factors:

$$C_{totex} = \sum_{j=1}^{n} C_{opex,P(j)} + \sum_{j=1}^{n} C_{capex,P,P(j)} + C_{capex,buf} \tag{5-19}$$

With buffer tank costs being mathematically described as follows:

$$C_{capex,buf} = I_{buf} * r_{buf} * \sum_{j=1}^{n} \left(\frac{V_{buf}(j)}{V_{ref}}\right)^{R_{buf}} \tag{5-20}$$

With these adjustments, the size of the buffer tanks can now be calculated function of the oversizing of the upstream and downstream processes.

Step 2: Determining parameters for the decision support tool

The second step of the proposed method is to identify the parameters to be inserted into the equations of the decision support tool. If a plant and the associated investment costs and plant capacities as well as specific energy consumption are available, this is the best case as all parameters are known. If a plant already described in the literature is to be analyzed, these described values can be used. If no parameters are known and are also not available in the literature, it is necessary to conduct a techno-economic analysis of a plant before the analysis.
Furthermore, the equations and associated parameters of the decision support tool shall be implemented into the flowsheet environment of the Aspen Custom Modeller V10 (ACM) software. It is not strictly necessary to utilize ACM. It is possible to work with other software capable of steady-state optimization. However, for subsequent stages involving dynamic simulation, it is advantageous to use ACM. This simulation software can perform both the dynamic simulation of the process and the optimization functions simultaneously. When selecting suitable simulation or programming software, consideration should be given to its ability to perform these two tasks effectively.

Step 3: Steady-state design optimization

The third step consists of the steady-state design optimization of the process cascade and the determination of the required oversizing of the unit operations and intermediate buffer tanks. The goal is to find the optimal equipment sizing with the perfect compromise between significant operational cost savings and relatively minor capital cost increases through oversizing, where F_{os} can be any positive number:

$$F_{os,P(j)} \in \mathbb{R}^{+} \tag{5-21}$$

In extension to our previous study (*c.f.* [228]) on the optimal oversizing of process steps, Step 3 of the proposed method considers the interaction within a process cascade when connected processes are ramped up and down simultaneously, instead of focusing solely on individual processes.
The results of Step 3 steady-state design optimization do not yet provide information about the actual behaviour of the process cascade under fluctuating electricity prices. Instead, the average yearly electricity price $p_{elec,av,year}$ is used which decreases according to the cherry picking values described above and Eq. (5-1). This step aims to determine whether considering shared buffer tanks and, thus, interdependencies between the process steps leads to reduced capital expenses. The resulting design problem can be defined as follows:

$$\min_{F_{os,P(j)}} C_{totex,sts,ideal} \tag{5-22}$$

s.t. extended decision support tool model Eq. (5-19)
design constrains:
Eq. (5-21)

j is described in Eq. (5-15). The subscript $sts, ideal$ stands for the idealized optimization results of the steady-state optimization. These idealized design optimization results serve the purpose of setting an approach value for subsequently finding oversizing values that are closer to realistically purchasable sizes of processes. Thus, with these idealized results for $F_{os,P(j)}$ that result in $C_{totex,sts,ideal}$, the subsequent steady-state calculations are not performed with optimised F_{os}, but with more realistic values close to the optimised values. For this purpose, an increment of ΔF_{os}= 50% is defined as an assumption.

$$M_{os} = \{0; 0,5; 1; 1,5; 2; \dots\} \tag{5-23}$$

$$F_{os,P(j)} \in \left[F_{os,P(j),ideal} - 0,5; F_{os,P(j),ideal} + 0,5\right] \cap M_{os} \tag{5-24}$$

The resulting design problem can then be defined as follows:

$$\min_{F_{os,P(j)}} C_{totex,sts,real} \tag{5-25}$$

s.t. extended decision support tool model Eq. (5-19)
design constrains:
Eqs. (5-23) and (5-24)

j is described in Eq. (5-15). The subscript $sts, real$ denotes the more realistic optimization results of the steady-state optimization. The resulting minimum C_{totex} will then be found for F_{os} values in more realistic dimensions but close to the idealized ones.

Step 4: Dynamic modelling of process cascade

The fourth step of the proposed method is to dynamically simulate the investigated process cascade in ACM or to transfer an existing Aspen Plus V10 simulation to the ACM environment. By transferring the simulation, optimization calculations become possible through ACM's advanced functionalities. In addition, ACM allows for dynamic variations in the process, which is essential for DSM studies aimed at analysing hourly fluctuations in electricity prices.

This steps also involved the modelling of the ramp-up and ramp-down behaviour of the individual process steps and investigating the dependence of the flow rate on the process efficiency. The goal is to determine the time required for a unit operation to reach maximum efficiency after switching it on to consider this time delay in the dynamic optimization step. Depending on the investigated process maximum efficiency can be defined differently. Different efficiency criteria are decisive for different process categories: In mechanical shredding, a maximum reduction in particle size with low wear of the equipment is desirable, i.e. achieving a desired shredder speed. Separation processes should achieve a high purity of the separated components or the highest possible quantity of the desired separation product. Ideal efficiency in temperature increase processes is characterised by rapid and uniform heating to the desired temperature. Chemical conversion is about achieving high conversion rates of the starting materials into desired products with minimal unwanted by-products or waste. Electrolysis is about maximising the conversion of electrical energy into chemical products while minimising energy losses and electrode wear. These are just a few examples. In each category, the ideal efficiency varies depending on the process conditions, product specifications and environmental factors to be achieved. Therefore, in Step 4, the processes must be well understood and the ramp-up and ramp-down behaviour individually adapted or determined.

In the proposed method following variables are defined to describe the ramping behaviour of a process. Figure 5.5 illustrates these differences. One is the ramp-up shift and one is the ramp-up steepness. In the proposed method, the efficiency of a process is considered to be 0% when a unit operation is switched off. The ramp-up shift delineates the duration post-activation for the process to initiate operation and for the efficiency to surpass 0%. The ramp-up steepness characterizes the rate of increase in efficiency until the maximum achievable efficiency is reached. The sum of the ramp-up shift and the ramp-up steepness multiplied by the maximum efficiency then equals the ramp-up time.

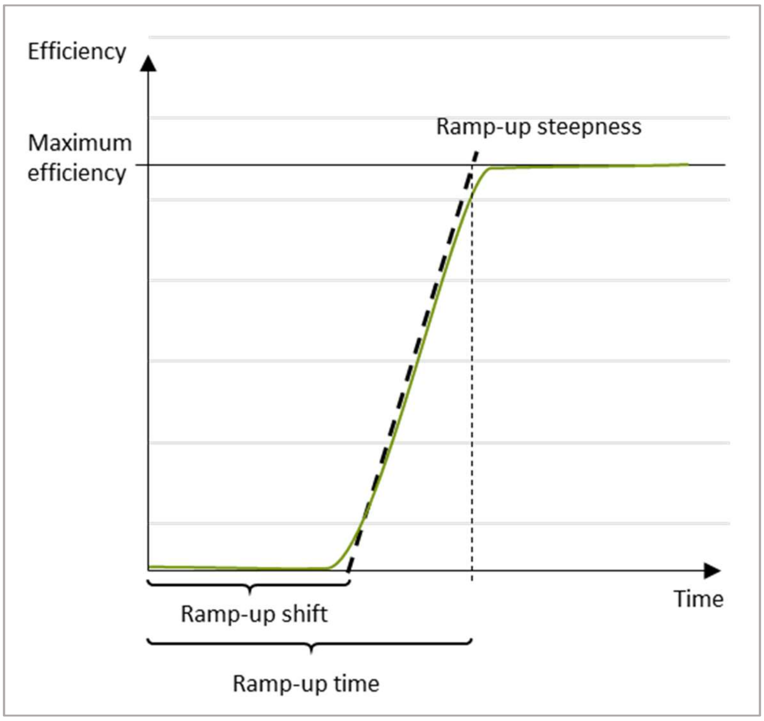

Figure 5.5:Exemplary graphical demonstration of ramping behavior of unit operation.

Due to lack of scientific data in this regard, we assumed that the quality of the final product would not decrease, but only the quantity. Therefore, when separation efficiency decreases due to the process ramping up or down, the process needs to be switched on longer than it would if no separation efficiency loss would occur. This ensures, that the same amount of product is produced by the end of the day. This ensures that despite the flexibility enhancement, the total product output remains constant.

Step 5: Development of a representative electricity price profile

Dynamic simulation allows the optimal scheduling of unit operations to be determined under more realistic conditions with fluctuating electricity prices, and the impact of ramp-down and ramp-up behaviour to be studied. To be able to react to electricity price fluctuations, it is necessary to integrate a dynamic electricity price profile into the dynamic simulation. One way to do this is to select sample days, as is commonly done in DSM research [27, 119]. An alternative approach is to use an average daily electricity price profile from a specific year. However, in this study, a new approach is proposed. Our study focuses on optimizing the operation under varying electricity prices, where the objective is to minimize costs by strategically managing when to avoid peak electricity prices. This dynamic approach is designed to mirror the effects achieved in steady-state optimization, where average electricity prices decrease proportionally with the avoidance of peak periods ("cherry-picking values").This is possible if the same electricity prices are used as a basis. In our preceding publication [228], the dependence of the electricity price decrease (b_{year}) on the switch-off time (also referred to as application time - t_{app}) of a unit operation is described. This dependency is also used for the steady-state optimization (Step 3). This developed profile is shown in Figure 5.6, where the daily average of electricity prices is also depicted for comparison.

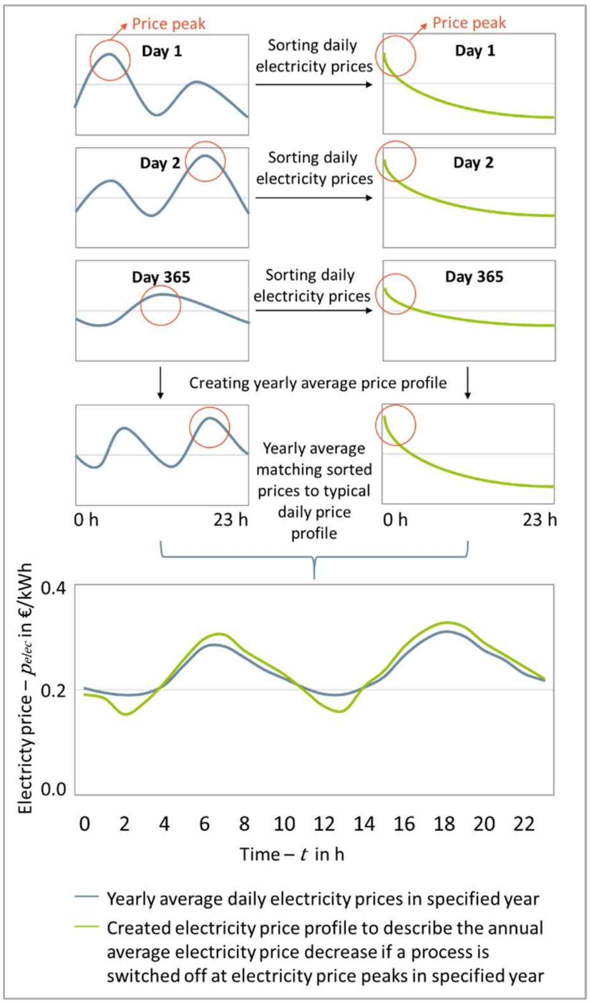

Figure 5.6: Daily average electricity price profile compared to the generated profile representing electricity price peaks.

This graphical representation demonstrates that the general course of the profiles is the same. However, because electricity price peaks do not always occur at the exactly same time over the course of a year, the actual hourly average electricity price profile is smoother than the developed profile. The developed profile supposes that the daily electricity price peaks always occur at the same time each day. As a result, price volatilities are more significant in the developed profile. In the methodology presented, it is supposed that the unit operations under consideration are always switched off at the daily electricity price peaks, regardless of when they occur each day. Therefore, it is more representative to react to this developed electricity price profile, in addition to the advantage of being able to compare the results of the steady-state and dynamic simulation. The resulting dynamic price profile with dynamic electricity prices can be found in the Appendix Table 8.6. For the dynamic simulation, an electricity price profile was thus developed that replicates the same effect as in steady-state optimization. For every hour that peak electricity prices are avoided, the electricity price decreases equivalently to what is observed in steady-state optimization scenarios. This dynamic representation allows for a direct comparison between scenarios.The newly developed electricity price profile however also represents the same effect and the course of the daily average of electricity prices in a specific year.

Step 6: Dynamic scheduling optimization of the process cascade, responding to changes in electricity prices

With the optimised design results of Step 3 and Eq. (5-25), the modelled ramping behaviour of Step 4, and the dynamic electricity price profile of Step 5, the dynamic optimization can now be calculated. The F_{os} for each process step $P(j)$ equal the results of Eq. (5-25) described as $F_{os,P(j),real}$. $j \in \mathbb{N}$ ranges from 1 to n and n describes the number of processes to be investigated for oversizing in a process cascade. The unit operation sizing is determined by setting the upper and lower limits of the mass flow in the dynamic initial values of the dynamic optimization, described as $\dot{m}_{P,P(j)} * (1 + F_{os,P(j)})$.

$$\dot{m}_{dyn,P(j)} \in [0; \dot{m}_{P,P(j)} * (1 + F_{os,P(j)})] \tag{5-26}$$

The buffer tank volumes are obtained from Eqs. (5-16) - (5-18) and are defined accordingly in the ACM simulation. The filling and emptying of the intermediate buffer tanks can then be represented in the ACM simulation using the tank levels. As dynamic constraints, the buffer tank levels are set to be the same at the end of the day as at the beginning of the time period τ.

$$L_{buf,P(j),k=0} = L_{buf,P(j),k=\tau} \tag{5-27}$$

where L is the tank level in meters and the subscript k here denotes the scheduling time slots throughout the specified time period k = 0, ..., τ. The time steps are piece-wise constant discretized in one-hour steps. The resulting scheduling problem can then be defined as follows:

$$\min_{\dot{m}_{dyn.P(j)}} \; C_{totex,dyn} \tag{5-28}$$

s.t. extended decision support tool model Eq. (5-19)
operational constraints:
Eq. (5-26), (5-27)
design constraints:
Eqs. (5-23), (5-24)

The subscript dyn here denotes the dynamic optimization result.

The dynamic electricity prices will be used to calculate the operational expenditure:

$$C_{opex} = \int_{o}^{\tau} p_{elec,dyn}(t) * SEC_{P(j)} * \dot{m}_{dyn.P(j)}(t) \tag{5-29}$$

After the dynamic scheduling optimization, the results from the steady-state and dynamic simulation were compared. This served two primary goals. First, to verify that the steady-state optimization provides realistic values. This is crucial to ensure that the steady-state assumption is appropriate for the process and that the results obtained from the decision support tool are relevant in practice. Furthermore, it was analyzed whether the steady-state optimization tends to provide optimistic or pessimistic estimates.

5.3 Case study

To demonstrate the functionality of the method, the proposed six-step procedure was applied to a case study. Etzold *et al.* [216] showed in the evaluation of a biomethane biorefinery that electricity is the parameter with the third highest influence on the total costs and has the highest influence on greenhouse gas emissions. These aspects also make it an interesting case study for DSM implementation. In our previous study (*c.f.* [228]) the decision support tool evaluated the profitability of oversizing process steps for DSM purposes for all the process steps of the biorefinery concept described by Etzold *et al.*, including the CO_2 separation, and the mechanical preparation. The anaerobic digestion process has a non-continuous electricity consumption pattern, which excludes it from the scope of the current tool's requirements. Nonetheless, an investigation into this was also conducted following a different method [206]. The results showed that especially in the downstream digestate treatment, high DSM potential can be seen for the oversizing of the decanter centrifuge (DEC) and reverse osmosis membrane filtration (RO), whereas no DSM oversizing potential was identified for the intermediate ultrafiltration (UF). A simplified block flow diagram of the biomethane biorefinery with a more detailed breakdown of the unit operations of the digestate separation cascade is depicted in Figure 5.7. This process cascade is an interesting aspect of the planned investigation – evaluating the extent to which a parallel flexibilization of process steps connected in series can cause further cost minimization through the use of DSM.

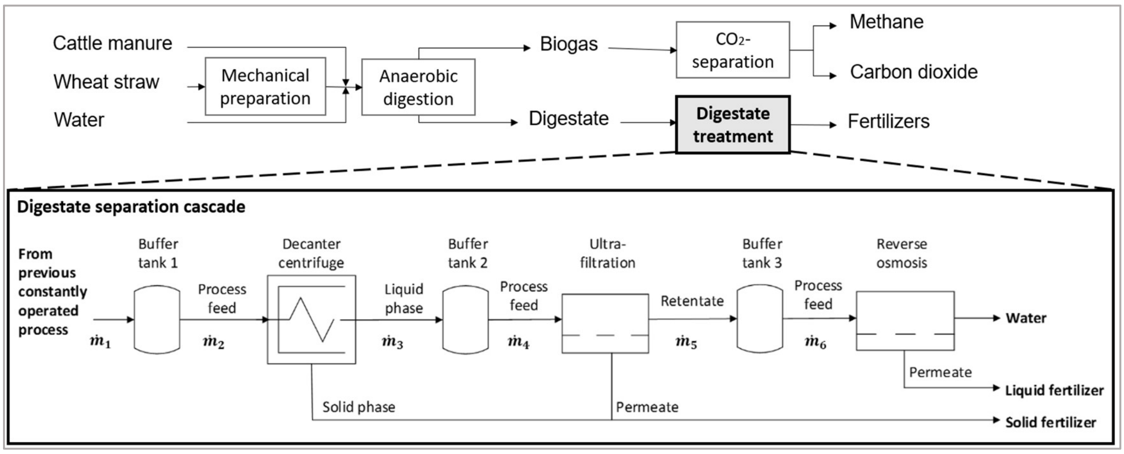

Figure 5.7: Digestate separation cascade of the biomethane biorefinery for which demand side management implementation was investigated (as described in [216]).

To apply the proposed method described in Section 5.2 the relevant unit operations have to be identified to fill the expanded equations (5-10) till (5-20). $P1$ is the decanter centrifuge (DEC), $P2$ is the ultrafiltration (UF) and $P3$ is the reverse osmosis (RO). The associated buffer tanks are situated upstream of the respective process steps, as depicted in Figure 5.7.
To determine the parameters for the equations of the extended decision support tool, values that were previously determined in the study by Etzold *et al.* [216] were used. The publication describes a process simulation with Aspen Plus that was used for the calculation of the mass and energy balances and the subsequent determination of investment and operational costs. These values for $\dot{m}_P$ of DEC, UF and RO and ϱ of the respective mass flows needed for equations (5-10) till (5-20) can be found in the Appendix B. The equations and associated parameters of the decision support tool were implemented into the flowsheet environment of the ACM V10 software.
For the steady-state optimization the total costs $C_{totex,sts,ideal}$ of the digestate separation cascade of $n = 3$, including DEC, UF and RO, will be minimized in Eq. (5-22), with the operational and capital expenses of process step Eqs. (5-3) - (5-4), the volumes of buffer tanks from Eqs. (5-16) - (5-18) and new equation for capital expenses of buffer tanks Eq. (5-20) and τ_{oph} = 24h . The idealized steady-state optimization finds values for $F_{os,dec,ideal}$; $F_{os,uf,ideal}$; $F_{os,ro,ideal}$ that minimize the objective function and are members of the set of positive real numbers.
With these optimization results, the subsequent steady-state calculations are performed with optimised F_{os}, but with more realistic values close to the optimised values, that are members of the set of M_{os} as described in Eqs. (5-23). The $C_{totex,sts,real}$ will be minimized in accordance with Eq. (5-25) with the constraints for $F_{os,dec}$; $F_{os,uf}$; $F_{os,ro}$ from Eq. (5-24).
For the dynamic simulation of the digestate separation cascade the Aspen Plus simulation described by Etzold *et al.* was transferred to the ACM environment as depicted in Figure 5.7. All separation steps were calculated with ACM separator blocs (SEP) with separation efficiencies according to [216] and Appendix C. To analyze the ramping behaviour of the three investigated process steps the newly introduced parameters – ramping-shift and ramping-steepness were determined for all three unit operations individually. Figure 5.8 illustrates these differences.
For the DEC, separation starts once the volume in the DEC is filled. This means that after the start of the overall process, there is a time delay before the DEC separation starts, termed ramp-up shift. The ramp-up time thus equals the ramp-up shift of the DEC. We undertook scientific validation of the proposed procedure, by engaging with subject matter experts relevant to the field of digestate separation, ensuring the reliability of the implemented approach.
A different ramp-up behaviour is assumed for the simulation of UF and RO. Here, separation occurs immediately at the start of the process, but the maximum separation efficiency is reached after a specific ramp-up time. This leads to a gradual increase of the separation efficiency, called ramp-up steepness (*c.f.* Figure 5.8). The ramp-up time of the UF and RO thus depends on this ramp-up steepness.

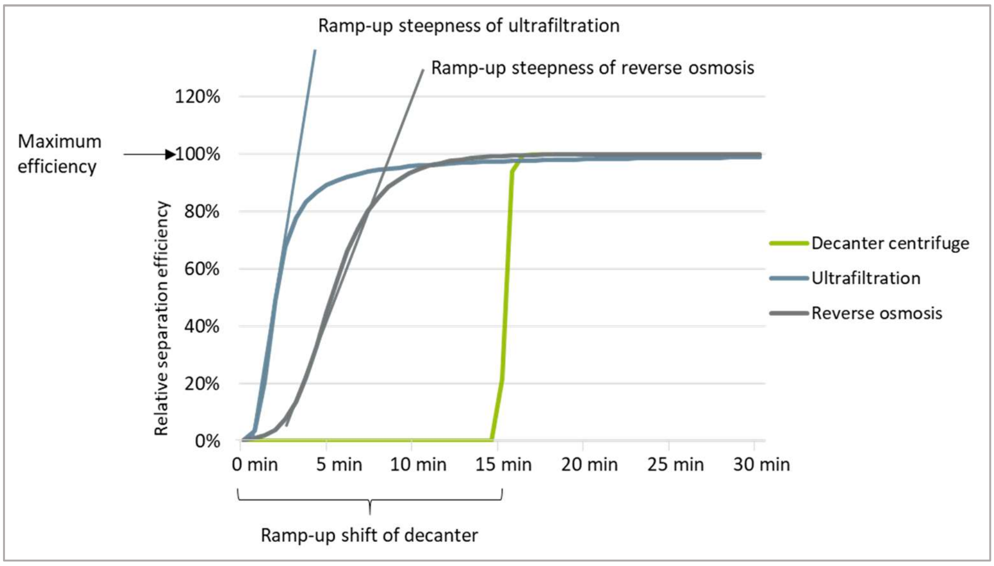

Figure 5.8: Ramp-up behaviour of digestate separation processes regarding their separation efficiencies as implemented in the dynamic simulation.

These effects are implemented in the simulation for the ramp-down of the three unit operations. It should be noted that only limited literature sources are available for such ramp-up behaviours of the relevant unit operations since most industry-scale processes are operated continuously. For this reason, assumptions were necessary, which were examined in detail in a subsequent sensitivity analysis concerning their effects on the results.

For the dynamic optimization a volatile price profile as proposed in Step 5 and listed in Appendix Table 8.6 for the year 2022 was implemented. According to this electricity price decrease function also described in [228], the average annual electricity price a_{year} in 2022 is 0.2409 €/kWh for the case that no unit operations within the process cascade were switched off. With a t_{app} of one (most expensive) hour per day, this average annual electricity price decreases by b_{2022}, thus by 0.0038 €/kWh. Implementing $t_{app} = 5$ hours results in an average electricity price of $p_{elec,av,2022} = -0.0038 * (5) + 0.2409 = 0.2219\ €/kWh$.

The F_{os} for DEC, UF, and RO equal the results of the steady-state optimization with more realistic oversizing factors described as $F_{os,dec}; F_{os,uf}; F_{os,ro}$ of Eq. (5-25). Parameters in the dynamic simulation that are influenced by the determined F_{os} are the processing capacity of the individual unit operations, or, in other words, the maximum mass flow entering the process, and the buffer tank sizes – $\dot{m}_{2,max}$, $\dot{m}_{4,max}$, and $\dot{m}_{6,max}$. The dynamic variable optimization parameters are $\dot{m}_{dyn,dec}$, $\dot{m}_{dyn,uf}$, and $\dot{m}_{dyn,ro}$ (*c.f.* Eq. (5-26)) which can vary between zero and the respective maximum mass flow. These maximum mass flows were calculated by implementing the process nominal mass flows at no oversizing (Table 8.7) and the optimised F_{os} resulting from the steady-state optimization (Step 3) in equations (5-10) - (5-14). The buffer tank volumes were determined by using equations (5-2) and (5-16) - (5-18) as shown in Table 5.2:

Table 5.2: Calculating maximum mass flow through process and buffer tank volumes as constraints for dynamic optimization.

Parameter	Unit	Equation	Eq. Nr.
$\dot{m}_{2,max}$	t/h	$\dot{m}_{P,dec} * \left(1 + F_{os,dec}\right)$	(5-30)
$\dot{m}_{4,max}$	t/h	$\dot{m}_{P,uf} * \left(1 + F_{os,uf}\right)$	(5-31)
$\dot{m}_{6,max}$	t/h	$\dot{m}_{P,ro} * \left(1 + F_{os,ro}\right)$	(5-32)
$V_{buf,1}$	m³	$\frac{\dot{m}_{P,dec}}{\varrho} * \left(1 - \frac{1}{F_{os.dec} + 1}\right) * \tau$	(5-33)
$V_{buf,2}$	m³	$\frac{\dot{m}_{P,uf}}{\varrho} * \left(1 - \frac{1 + F_{os,uf}}{1 + F_{os,dec}}\right) * \tau$	(5-34)
$V_{buf,3}$	m³	$\frac{\dot{m}_{P,ro}}{\varrho} * \left(1 - \frac{1 + F_{os,uf}}{1 + F_{os,ro}}\right) * \tau$	(5-35)

By implementing the V_{buf} in the dynamic ACM simulation environment and setting the $\dot{m}_{n,max}$ as maximum values for the control variables, it is possible to minimize C_{totex} for the entire cascade by dynamic optimization with $Tau = 24h$. Further dynamic constraints were the buffer tank level of the last process steps $L_{buf,dec}$, $L_{buf,uf}$, and $L_{buf,ro}$, which were to be equal at time $t = 0$ h and $t = 24$ h *c.f.* Eq. (5-27) with a tolerance of 0.1 tonnes. The optimization resulted in the mass flows entering the process steps being switched "on" and "off" dependent on electricity prices.

The optimization problem is implemented and solved in Aspen Custom Modeler V10 using a Direct Multi-Objective Successive Quadratic Programming Optimizer (DMO SQP) successive quadratic programming optimizer with a solver tolerance of $1*10^{-5}$. Our approach leverages well-informed initial values for oversizing, derived from previous work. Additionally, the given electricity price profile allows us to set initial values for fluctuating mass flows very close to their optimal values. Given these well-informed initial values, the local solutions obtained are expected to be close to the global optimum. The high-quality initial estimates significantly enhance the optimizer's ability to converge to optimal or near-optimal solutions. The DMO SQP was chosen due to its balance of computational efficiency and the high quality of local solutions it provides. While it does not guarantee a global optimum, the use of well-informed initial ensures that the solutions are practical, robust, and nearly optimal for the given problem context.

To ensure the validity of the results obtained from the DMO SQP optimization process, different initial starting points were chosen. Without such thorough validation, comparing local solutions across different cases might be significantly influenced by optimality gaps.

Furthermore, a sensitivity analysis was carried out to trial the newly introduced parameters from Step 4. The parameters of ramp-up steepness and ramp-up shift are addressed. If the data basis for the input parameters is poor and expert opinions and assumptions were relied on, the sensitivity analysis is considered a crucial step. This step is essential to verify whether the results

of the dynamic optimization are significant or whether it is necessary to perform a new simulation with more realistic ramp-up and ramp-down times, which must be determined through experiments. It is of particular importance to ensure that the modelling of the unit operation is realistic and provides accurate insights. Other sensitivities, such as investment costs, that do not have a dynamic factor have already been considered in the previous publication, which presents the decision support tool (*c.f.* [228]). They are thus not considered again.
For the sensitivity, the DEC ramp-up shift was investigated to result in ramp-up times of 5, 10, 15, and 20 minutes. For the ramp-up steepness, the original assumption was that the DEC starts immediately when the level set point is reached. Therefore, the sensitivity only considered a degrading steepness. Three sensitivities for the steepness were investigated by considering ramp-up times of up to 10 minutes until the DEC reaches maximum efficiency. The optimization results of these conditions are then compared to each other to investigate the dependence of the economic DSM potential on ramp-up behaviour.
Another sensitivity analysis was conducted for varying electricity prices. Following the previously mentioned publication on economic DSM potential, which examined the sensitivity of the payback period to ±50% more or less fluctuating electricity prices, this report also dynamically explores how more or less fluctuating electricity prices could impact the economic potential of DSM integration.
In the presented analysis, electricity price fluctuations were incrementally increased or decreased in 10% steps up to ±50%, and the impacts on the economic DSM potential were examined. The decanter centrifuge is again used as an example to demonstrate this sensitivity. This approach helps to understand how sensitive the economic potential of DSM integration is to changes in electricity prices.

5.4 Results

This chapter presents the key findings and outcomes of the research, providing a comprehensive overview of the results that emerged from our steady-state and dynamic simulation analysis. Three steps of the six-step procedure described in the method section provide essential results for the subsequent step.
The steady-state optimization provided ideal, optimised values for the flexibility requirements (F_{os}) of the three process steps. Based on these ideal values, a more realistic F_{os} value could be determined for each process step, moving to an above and below lying 50% increment. The resulting value with the most significant cost savings compared to the $C_{totex,sts,ideal}$ without DSM was selected to set the design parameters in the dynamic simulation.
The dynamic optimization schedules ramping up and down of the three process steps, resulting in fluctuating mass flows, energy consumption, and buffer tank fillings. The optimised $C_{totex,dyn}$ were compared to $C_{totex,sts,ideal}$ of the steady-state simulation of all the individual process steps and the flexibilization of the whole digestate separation cascade.
Based on the results of this dynamic optimization, a sensitivity analysis was performed to check the sensitivity of the results to uncertainties in the ramp-up behaviour.

Steady-state optimization results of digestate separation cascade at ideal and realistic oversizing factors

The steady-state optimization of the digestate separation cascade, including the optimization of the intermediate buffer tank costs, did indeed yield deviations from the results obtained by individual consideration of process steps. The study by Röder *et al.* [228] showed that considerable cost savings of almost 182 € per day were achieved when the DEC was oversized by 238% and the RO by 372%. These values are shown in Figure 5.9 on the left. In ACM, a steady-state-optimised cost savings of just over 192 € per day was determined by considering shared intermediate buffer tank (see Figure 5.9 on the right) at optimised oversizing values of $F_{os,dec}$ = 228%, $F_{os,uf}$ = 25%, and $F_{os,ro}$ = 402%. This equates to additional savings of more than 10 € per day, or in total 3879 € per year. Considering shared buffer tank costs now also makes the oversizing of UF economically viable. This was not the case when the process steps were considered individually. It can thus be concluded that simultaneous flexibilization of the processes in a digestate separation cascade leads to an increased DSM potential.

Based on the optimised results with shared buffer tanks, eight further simulations were carried out to calculate the DSM potential of the digestate separation cascade under more realistic scenarios. For the more realistic scenarios, the simulation parameters were adjusted in 50% increments, both above and below the optimum, which are $F_{os,dec}$ = 200%/250%, $F_{os,uf}$ = 0%/50%, and $F_{os,ro}$ = 400%/450%.

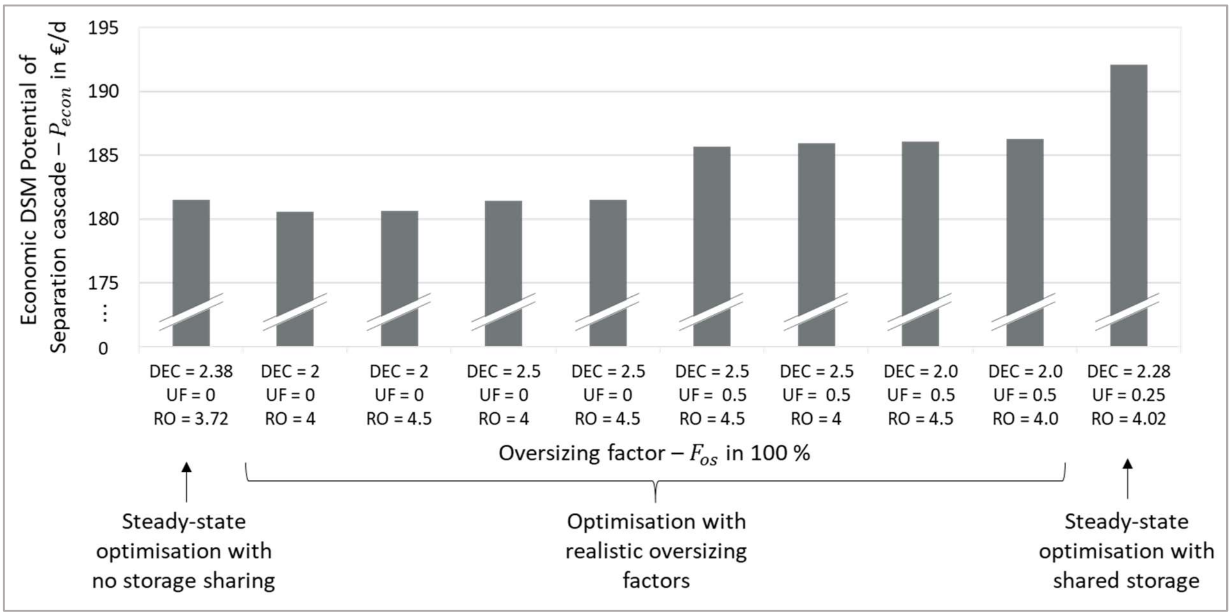

Figure 5.9: Steady-state optimization results of digestate separation cascade at ideal and realistic oversizing factors for decanter centrifuge (DEC), ultrafiltration (UF), and reverse osmosis (RO).

The resulting savings obtained from implementing DSM at these more realistic F_{os} are also shown in Figure 5.9. Employing more realistic values demonstrates that the economic DSM potential for the digestate separation cascade is at least 6 € per day less than the optimised outcome. At the same time, however, it can be seen that all scenarios with oversizing of the UF have a higher DSM potential. Thus, even when considering more realistic scenarios, it was found that oversizing the intermediate step adds value for DSM due to the shared buffer tank costs. The best results for P_{econ} were determined at $F_{os,dec}$ = 200%, $F_{os,uf}$ = 50% and $F_{os,ro}$ = 400%. Based on these design optimization results the necessary fixed parameters for the dynamic simulation and scheduling optimization were calculated.

Dynamic modelling and scheduling results of dynamic optimization

By implementing the optimised F_{os} valus for DEC, UF and RO, the design parameters – processing capacity of the individual unit operations and buffer tank volumes – were calculated according to Eq. (5-28) – (5-35) and are listed in Table 5.3.

Table 5.3: Results of calculated maximum mass flow through process and buffer tank volumes as constraints for dynamic optimization.

Parameter	Unit	Value
$\dot{m}_{2,max}$	t/h	105
$\dot{m}_{4,max}$	t/h	49
$\dot{m}_{6,max}$	t/h	84
V_{buf1}	m³	558
V_{buf2}	m³	336
V_{buf3}	m³	274

The resulting scheduling can be seen in Figure 5.10 a), where bars going up represent the process being switched on, and bars going down represent the process being switched off. Considering the ramp-up behavior described in Section 5.3 Step 4, the actual dynamic mass flows entering the processes $\dot{m}_{dyn,dec}, \dot{m}_{dyn,uf}, \dot{m}_{dyn,ro}$ can be seen with the specified time lag in Figure 5.10 b). Dependent on the separation efficiency of the respective process step, the liquid outlet leaves the process and is fed into the buffer tank, from which depending on the "on" and "off", it is then fed to the subsequent separation step. The resulting tank levels in relative values can be seen in Figure 5.10 c). As depicted, the buffer tank levels at 0 h and 24h are equal for all the respective buffer tanks – $L_{buf,dec,k=0} = L_{buf,dec,k=24}$. It can also be seen that the levels fluctuate between 20 and 80%; thus, critical levels are never exceeded. This is due to the fact that at typical dynamic electricity price profiles, two peaks are formed (*c.f.* Figure 5.6). The steady-state optimization problem described in this study considers a time interval of one day and idealizes a switch off at high electricity prices without considering the possibility of multiple numbers of switch offs and thus the possibility of a refilling a buffer tank throughout a day. The dimensions of the buffer tank are a result of this steady-state design optimization. The fluctuating buffer tank levels in Figure 5.10 c) are a result of the dynamic scheduling optimization, which does consider multiple electricity price peaks and hence multiple switch-offs.

In the lowest part of the graph, Figure 5.10 d), the values of the current electricity demand resulting from the mass flow being processed are shown. It is visible that the current demand follows the course of the electricity price in a mirror-inverted way. A high share of electricity is thus consumed at low-cost times and little electricity at high-cost times. This also has a corresponding effect on the C_{opex} of the entire plant, which is also shown in the diagram. Without DSM the C_{opex} costs would directly follow the electricity price profile. The difference in the cumulative C_{opex} is 1727 €/d with DSM compared to 2253 €/d without DSM. This results in a reduction of C_{opex} of 23% in total.

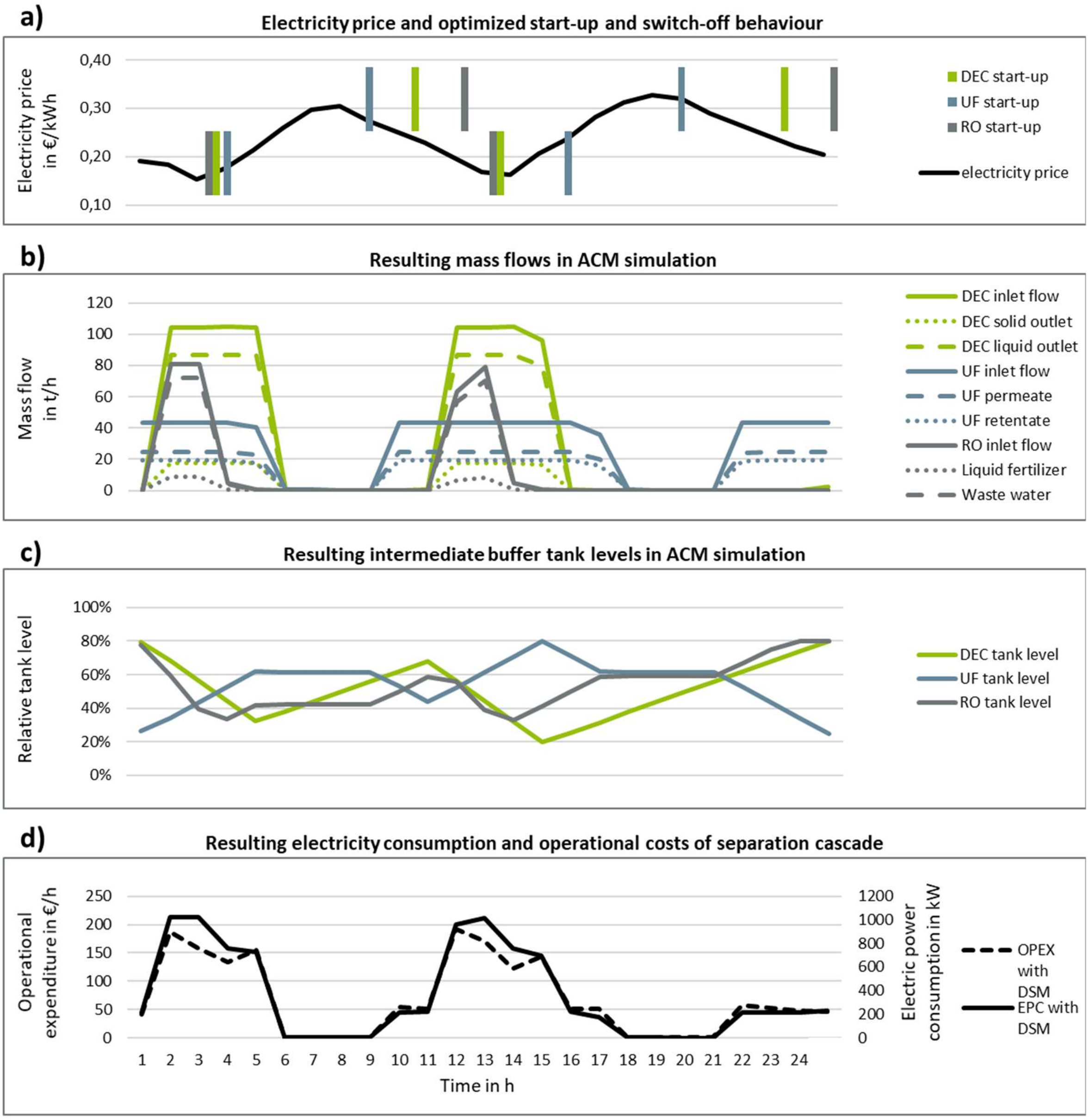

Figure 5.10: Scheduling results of dynamic optimization.

Comparison of dynamic optimization results with steady-state optimization results

The results of the dynamic scheduling in Figure 5.10 d) demonstrated the positive impact of DSM implementation on C_{opex}. However, oversizing process steps also leads to an increase in investment, which means that the savings on C_{totex} will not be as high as those shown for C_{opex}. Figure 5.11 shows the results of the savings thus the economic DSM potential P_{econ} for oversizing the process steps and responding to electricity prices. To be able to differentiate the effects of the individual unit operation oversizing, the dynamic optimization was performed for only RO oversized, only DEC oversized, RO and DEC oversized, and all three separation steps oversized. The reasonable previously estimated initial values lead to low computational effort. The computational time required to solve the scheduling problem based on the DMO SQP model, was for all runs approximately 150 seconds. The results were compared to those of the steady-state optimization to demonstrate whether similar results can be obtained with more realistic considerations.

As demonstrated in Figure 5.11, the same proportions in P_{econ} exist for the different process steps F_{os}. Oversizing and flexibilization of all three processes achieved the highest P_{econ}. Oversizing the DEC has the greatest influence: oversizing the decanter centrifuge by 200% results in a P_{econ} of 92 €/day in the dynamic optimization and 112 €/day in the steady-state optimization, oversizing the RO by 400% results in P_{econ} of 29 €/day in the dynamic optimization and 59 €/day in the steady-state optimization (*c.f.* left bars in Figure 5.11). However, the saving potential is also slightly lower in the more realistic dynamic analysis. The fact that the optimization responds at hourly intervals and the ramp-up behaviour of the unit operations leads to an inertia that does not always make it possible to respond to the electricity prices optimally. However, the basic conclusions remain the same. The oversizing of the process steps for DSM is profitable and considering the flexibilization of an intermediate process to save intermediate buffer tank costs can lead to even further savings, since the economic DSM potential P_{econ} is always above 0 €/day and highest for oversizing the UF by 50% (*c.f.* right bars in Figure 5.11).

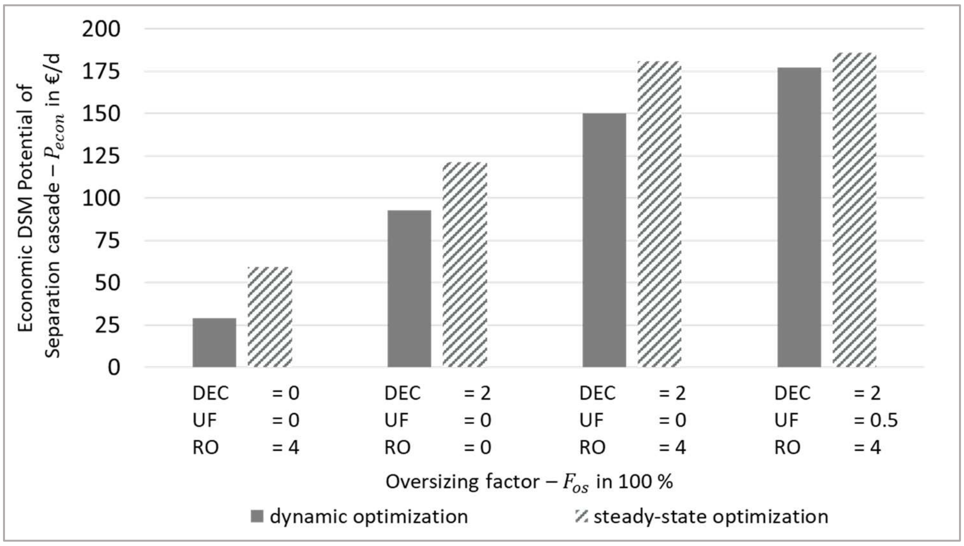

Figure 5.11: Comparison of dynamic optimization results with steady-state optimization results.

Results of the sensitivity analysis

To identify the effect of changes in the framework conditions and assumptions, sensitivity analysis was carried out for newly introduced input parameters, the separation efficiency dependent on the start-up behavior of the processes. The sensitivity analysis results show a tendency of increased economic DSM potential, P_{econ}, with faster ramping-up of a process to maximum efficiency after switch-on. The left side of the graph in Figure 5.12 depicts the steepness of the ramp-up behaviour. In the base case simulation, the DEC is defined to have an instant ramp-up, i.e. the light green curve in Figure 5.12 a) with a ramp-up in less than a minute and the resulting P_{econ} on the left-hand side of Figure 5.12 b). Therefore, only sensitivity in the pessimistic direction, i.e. slower ramp-up behaviour, was considered.

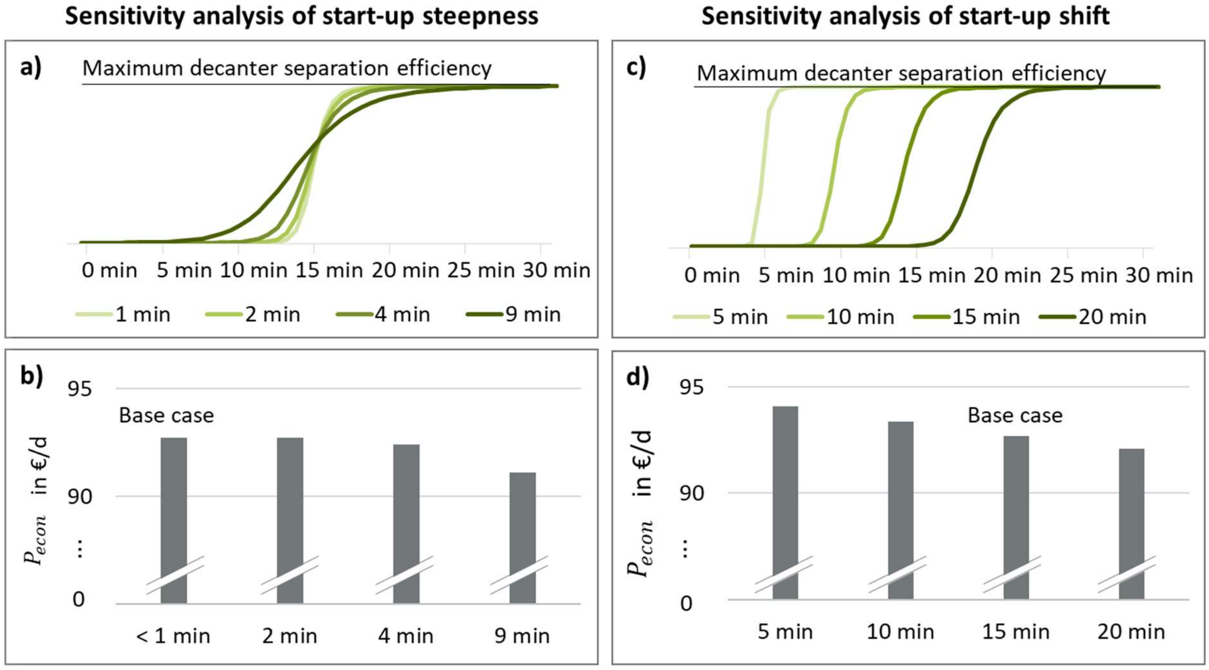

Figure 5.12: Results of sensitivity analysis of ramp-up behaviour of decanter centrifuge.

The P_{econ} of the DEC is about 93 €/d at the base case with immediate ramp-up after the start-up shift of 15 minutes. However, if the start-up time after the shift takes 2, 4, or even 9 minutes to get the system to maximum efficiency, this can lead to a reduction of the savings by a few euros. In Figure 5.12 c), the dependence of the start-up shift is depicted. Again, a fast-reacting system leads to potentially higher savings. The base case parameters in the simulation lead to a delayed start of the DEC by 15 min. As this is a very pessimistic value, two sensitivities were performed in a more optimistic direction and one by 5 min in a more pessimistic direction. The resulting economic potential in Figure 5.12 d) shows a linear decrease of the savings, which also continues at even more extreme values.

In summary, the influence of the time constants on the economic potential is very small. This is mainly because the scheduling discretization of the dynamic optimization is one hour. All start-up behaviour variations, however, move in a minute range. A more pessimistic approach is not realistic, even for very large inertial systems. It is much more likely that the dynamic of the system is much more agile than shown in these assumptions.

To ensure accuracy of the linear optimization approach, four starting points for the initial value sets for the dynamic process' throughput throughout one day were used. The approach involved approximating the optimum from different directions. In case A, it was assumed that the process was operating at maximum capacity continuously. Initial values were introduced for B based on the assumption that the process was operating at normal throughput without DSM, thus satisfying the tank level criterion. In case C, the initial values for the flow rate were set to zero, representing

the process being turned off. Furthermore, another initial loop was executed (D) where the process followed an inverse initial scheduling, positioning it furthest from the optimum.
To illustrate this approach, the example of the decanter centrifuge is presented. The initial optimization provided 4 preliminary set of values (*c.f.* Figure 5.13 – A, B, C, D). The optimized scheduled mass flow (green line in Figure 5.13) turnes out to be the same for all initial starting points.

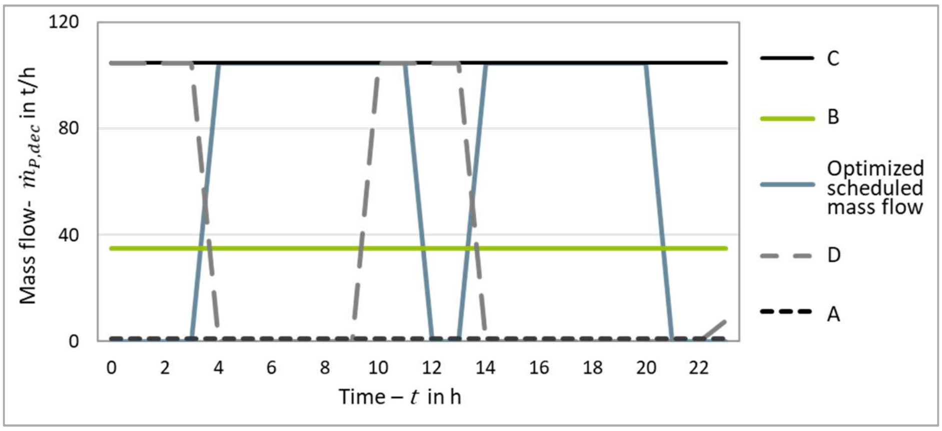

Figure 5.13. Results of optimization from different initial starting points.

The initialization to different starting points thus confirmed the optimal values proved effective in validating the optimization outcomes. It also ensured that the scheduling strategy was optimal across all stages of the process, offering a comprehensive solution for the entire process chain. The example of the decanter centrifuge clearly demonstrates how this approach can be applied to achieve reliable and optimal scheduling strategies. The results and optimization time for the optimization runs from the four different starting point can be found in Appendix Table 8.9.
One other uncertainty lies in the prediction of electricity prices. Over the past few years, there has been a consistent upward trajectory, resulting in greater fluctuations observed in the trend of this pricing factor. As political conditions currently play a major role, a substantial decline seems possible in the short term. However, in the long term, this parameter is expected to increase due to the expansion of renewable energy (RE). This is why electricity prices are subject to significant uncertainties in forecasting.
The results of the sensitivity analysis of the electricity price show a strong correlation between the fluctuations of the electricity price and the economic DSM potential as depicted in Figure 5.14. Considering a range from a worst-case (less fluctuations) to a best-case scenario (more fluctuations) of ±50%, in the worst case, this could lead to the economic DSM potential falling below zero. In such a scenario, the costs incurred from over-dimensioning the process could exceed the revenue generated from responding to fluctuating electricity prices.

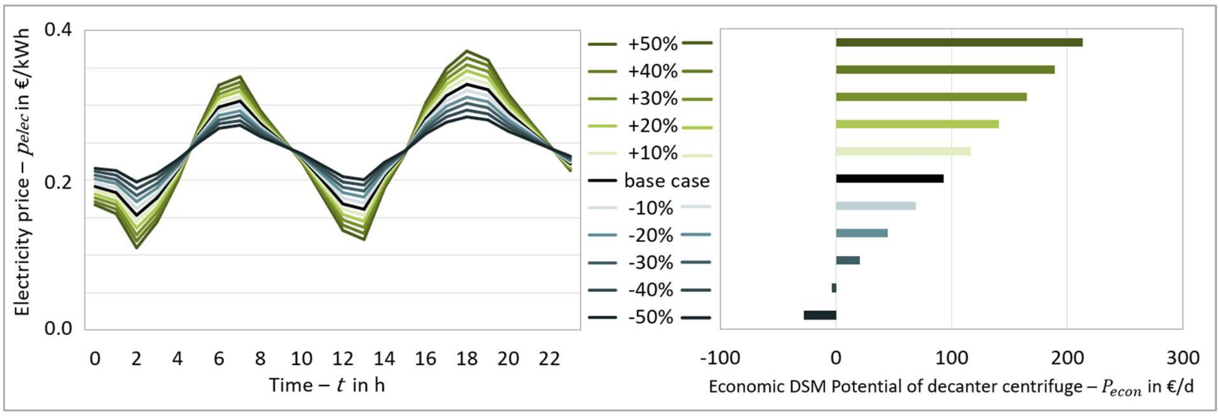

Figure 5.14: Sensitivity analysis of influence of intensity of electricity price fluctuations on economic DSM potential of decanter centrifuge.

5.5 Conclusion and perspectives

The presented study uses our previously developed decision support tool [228] in a dynamic simulation to evaluate the economic performance of demand-side management in a process cascade. The interaction of flexibilizing sequential process steps is investigated and how that could minimize the buffer tank capacity. Steady-state and dynamic optimizations were compared in a case study and sensitivity analyses are performed to gain insight into performance and adaptability of the proposed method.

In this work, we extended a decision support tool that evaluates the application of demand side management (DSM) within process chains. This tool enables not only the evaluation of individual processes but also the representation of interactions between processes. One significant advantage of this tool is its ability to quickly and easily assess the economic feasibility of processes for DSM applications. The extension introduced in this paper uncovers previously unidentified DSM potentials, providing plant designers with the opportunity to economically integrate additional processes into DSM, thereby achieving cost savings in overall annual expenditures. By incorporating the tool into a dynamic simulation and optimization environment, we can theoretically represent the dynamic effects on product quantity and quality changes. This advancement moves beyond the previously steady-state analysis, bringing it closer to a realistic dynamic representation of the implementation. The comparison between the steady-state and dynamic approaches reveals the benefits and drawbacks of the more complex dynamic methodology.

The results show that the flexibilization of intermediate steps to reduce the cost of buffer tanks offers significant economic benefits. The steady-state approach of our decision support tool was validated by comprehensive dynamic simulation and optimization, where only minor deviations were found, validating the functionality of the decision support tool. The results however also show that, through the consideration of more realistic oversizing factors and transient behaviour, the economic profitability of DSM integration is slightly lower than originally assumed through steady-state optimization with the decision support tool. Despite initial assumptions in the parameter selection, a sensitivity analysis was able to confirm the representativeness of the results.

The steady-state and dynamic approach both offer advantages and disadvantages when analyzing the profitability of oversizing processes for demand side management implementation. The advantages of the steady-state decision support tool include the speed and simplicity of the analysis, as no complicated software or optimization knowledge is required to quickly arrive at a rough result. In addition, the results are close to the more realistic dynamic view. By extending the decision support tool as presented in this paper, it is also possible to consider interactions between processes, which were also validated by the dynamic simulation and sensitivity analysis. The disadvantages include the lack of consideration of ramp-up and ramp-down behavior and the limitation in the synchronous flexibilization of several sequential processes. There is also no option to represent multiple start-up and ramp-down rhythms per day, although this can be extended. In general, the dynamic optimization provides more accurate and realistic results, which makes it easier to avoid wrong investment decisions.

An important consideration regarding the improvements of the steady-state calculations relates to neglecting the possibility of the filling and emptying of the buffer within a day. The calculation is based on a daily consideration, without the possibility that a process could be ramped up or down several times during the day, thus refilling the tanks between switch-off periods. This suggests that the savings could potentially be further increased if smaller time periods were considered. Given the typical daily pattern of electricity prices, it might be scientifically interesting to reduce the considered time period τ from 24 hours to 12 hours. It is, therefore, an area for future investigation that could reveal further optimization possibilities in terms of buffer tank sizing and economic efficiency.

One way to deepen and validate the results of the dynamic model would be to conduct experiments on the different unit operations – decanter centrifuge, ultrafiltration and reverse osmosis. This would be particularly useful regarding start-up and ramp-down behaviours, as well as for separation efficiency and product quality. In our study, we assumed that the quality of the final product remains unchanged despite variations in separation efficiency caused by the ramping up or down of processes. Investigating the actual impact of fluctuating separation efficiency on product quality and not only quantity could provide deeper insights and potentially improve the accuracy of the model. Real data from experimental studies could supplement the simplifications and assumptions made in the simulations. Experiments on the units would allow more precise insights into the actual performance of these units and ensure that the modelling and simulation adequately reflect reality. In addition, such experiments could help uncover potential challenges and opportunities for improvement in the practical operation of the process cascade and thus contribute to even more informed optimization.

The entire consideration assumes that electricity prices are known one day in advance with hourly resolution, as is common in DSM literature. This enables planning ahead of time and optimization of the process cascade to benefit from the most favourable electricity tariffs. An interesting extension of the presented multi-step framework would be to integrate price uncertainties in the optimization. This would consider the robustness and adaptability of the process cascade in real operating situations and help to develop possible operating strategies for energy management in dynamic environments. Eliminating such uncertainties could further improve the practicality and relevance of the results for actual industrial applications.

An additional factor influencing the achieved optimum results is the speed of process start-up. It can be surmised that the processes should be started faster, and thus may be necessary to consider a new design or improved dynamics to optimise this effect. The current hour-based scheduling discretization offers limited ability to represent these fast start-up processes accurately. Dynamic optimization based on shorter scheduling discretization time units could provide deeper insight into this behaviour and potentially help to improve process cascade performance further.

This paper focuses on the economic factors, as the scheduling optimization is intended to demonstrate cost reduction during plant operation. However, a valuable future research direction could be to investigate the potential ecological benefits. By consuming electricity at cost-effective prices, the tool often schedules consumption during periods when a significant amount of renewable energy is being supplied to the grid. A systemic greenhouse gas assessment, similar to the approach presented by Dotzauer *et al.* [233], could be applied to quantify these ecological benefits.

Chapter 6. Conclusions

The key research question of how new applications for DSM can be identified and analyzed was demonstrated using a biorefinery case study. The presented thesis investigates processes' flexibility to develop their optimal use in DSM programs. Biorefineries, as complex systems with many individual process steps, offer a broad field for the identification of a new industry for DSM application.

In a first step, areas in biorefineries that have already been investigated for flexibility or DSM application were identified in Chapter 2. A systematic literature review was conducted on processes already analyzed in the field of DSM and flexibility and transferred to processes found in biorefineries. The literature study provides an overview of the current state of the art. Highly flexible processes were identified, including hydrogen electrolysis, membrane separation, adsorption, and mechanical shredding. However, areas of biofuel production that have yet to be studied, such as sedimentation processes, were also determined.

To quantify the relative amount of load or temperature variation that each process step can provide, the potential flexibilities for all processes were obtained from studies and standardized to a common scale, referred to as the flexible operating window. This approach allows for consistent comparison of the range of variability each process step can accommodate, enabling the evaluation of their respective contributions to overall load or temperature flexibility. Thirty-one processes were examined and classified on the flexibility scale into four categories — mechanical pretreatment, conversion processes, refining, and auxiliary processes.

Of these four categories in particular, mechanical pretreatment processes show a high potential for flexibility. Provided that intermediate storage facilities are installed upstream and downstream, the comminution processing equipment can be switched off quickly and easily and often also be operated in partial load modes. The results of the literature study showed that mechanical pre-treatment steps find their flexible operating load range between 0 and 100%.

Conversion processes are more difficult to operate flexibly as they often involve maintaining high-temperature levels, sensitive microorganisms or catalysts, and phase transitions that preclude unstable process conditions. The aspect that makes this section of biorefineries interesting for the use of DSM is the tolerance in fermentation processes towards a certain disturbance of temperature (-43% to +49%).

In refining, solid-liquid separation processes (flexible operating load range from 0 to 150%) such as sedimentation or membrane separation, with easy, intermediate storage possibility and the ability to turn processes on and off, make DSM integration very promising. Data on membrane separation in reverse osmosis show that a membrane system can be operated flexibly with a constant permeate yield. Analysis of various liquid and gas refining processes shows that flexibility is often limited (flexible operating load range from 50 to 120%). The free phase boundaries between gas and liquid, which are necessary for mass and heat transfer, create a complex hydrodynamic situation.

Due to the fast reaction time and relatively high flexibility of H_2 electrolysis, this process is promising for DSM applications in auxiliary processes and is already in use today. The lower bounds of flexibility depend on the type of electrolysis used, with the minimum partial load being limited by the H_2 concentration on the anode side and the maximum overload limit being 150%, according to the literature, as electrode wear increases at higher than nominal power.

Overall, many, if not most, processes in biofuel production can be operated flexibly. Thus, a flexibility potential of these new industrial sector for DSM was detected. The next step in identifying new applications for DSM was to use the now-known flexible operating windows and combine those insights with significant electricity-consuming processes. In Chapter 3 the integral leverage point is determined and the theoretical DSM potential of biorefineries calculated.

The cumulative theoretical DSM potential of biofuel production in Germany was analyzed to examine whether biorefineries are competitive in this respect and can make a significant contribution. The total average electricity, heat and biomass demands for biofuel production in Germany in 2019 were determined: 205 MW_{el}, 1001 MW_{th} and approximately 23 million tons of biomass. Existing biorefineries in Germany, including their capacities and biomass inputs, were determined for this calculation. The specific energy requirements for all process steps were investigated for those already defined as flexible in Chapter 2. A cumulative electricity demand of 125 – 260 MW_{el} for the production of 3400 kt of biodiesel, 544 kt of bioethanol and 741 kt of biomethane was calculated. By multiplying the respective electricity demands according to the method of Gruber *et al.* [15], the theoretical DSM potential for all processes in Germany could be calculated. This multiplication resulted in a theoretical DSM potential of 57 – 91 MW_{el} for biodiesel, 12 – 15 MW_{el} for bioethanol and 56 – 153 MW_{el} for biomethane. Exceptionally high average potentials were identified for the processes of anaerobic digestion (62 MW_{el}) and methane refinement (15 MW_{el}) in biomethane production and oil mills (43 MW_{el}) in biodiesel production. For oil mils, this was due to the high specific electricity consumption. In contrast, the high production volume was the decisive factor for the high potential in biomethane plant processes.

Finally, the biofuel production's cumulative theoretical DSM potential was analyzed and compared to that of other industries. The cumulative theoretical DSM potential lies between 92 and 199 MW. Its average is slightly lower but overall in a similar range to those found in the literature for the aluminum (150 – 300 MW_{el} [12, 14]), cement (50 – 310 MW_{el} [3, 12]), and paper (205 – 400 MW_{el} [12, 14]) industries. This means that this sector offers comparable opportunities to control or flexibilize electricity consumption through DSM measures, as DSM integration would in industries that have already been investigated for DSM integration. A high theoretical DSM potential means a high integral lever of stabilizing and increasing the efficiency of the electricity grid through DSM measures, even if it is not the largest energy consumer itself. This opens up opportunities for grid control and sustainable use of energy sources. Although controlling many small plants or processes is more complex, it can also be advantageous for decentralized grid operators to manage them through DSM, as it allows for better integration and optimization of distributed energy resources.

Moreover, the economic viability of a process change is crucial for any operator or plant designer. In Chapter 4, the extent to which DSM integration is economically viable now or in the foreseeable future was investigated. For this purpose, a comprehensive tool was developed to assess the most critical economic parameters for decision support in the implementation of DSM for continuous processes. The tool is based on a multi-level framework. The key aspect is

determining the extent to which a process step should be oversized to achieve maximum flexibility without incurring excessive additional costs. An oversizing factor was defined that describes the best possible oversizing of the process step to achieve minimum operating costs when using DSM.
A case study demonstrates the tool's functionality in a biomethane biorefinery, indicating a high potential for flexibility and theoretical DSM in the previous chapters. This theoretical investigation shows how the tool works and identifies processes with high economic DSM potential within the investigated plant. No economic DSM potentials resulted for screw press and ultrafiltration, as well as CO_2 separation. Of the seven process steps studied, oversizing was advisable given the known parameters for four process steps: bale opener 90%, straw chopper 184%, decanter centrifuge 238%, and reverse osmosis 372%. The study showed that cost savings of almost 76 k€ per year or 4.6% and a payback period of 7.4 years can be achieved through oversizing for DSM purposes at the given parameters for one single, but representative process layout.
A sensitivity analysis of the implemented parameters was performed to analyze the robustness of the decision support tool. The economic factor of the payback period was chosen to determine at what point the payback period would rise to a value higher than the depreciation period (15 years), which would thus render oversizing for DSM purposes unprofitable. The highest sensitivity was found for fluctuations in electricity prices. This is due to its direct correlation with potential DSM revenues and the extensive variability (±50%) that could extend the payback period beyond the depreciation period. The investments for the buffer tank and the process step have the second and third highest impact due to high uncertainties (-30% to + 50%) but within a reasonable range of gaining a maximum of two years in the payback period, staying below the deprecation period. The sensitivity analysis showed that a slight (+10%) rise in economies of scale would reduce the payback period from over eight years to almost five years. The corresponding increases in process capacity and specific energy consumption have a minor impact on the payback period of under one year. However, the impact could be significantly greater since multiple parameters may change at the same time, compounding the increases in the payback period that each individual variation would cause.
Applying the tool to a case study also helped to analyze the advantages and limitations of the tool when considering individual processes within an overall plant. The tool helps evaluate and rank unit operations based on their economic potential for DSM implementation, allowing for a quick assessment of whether DSM is economically viable for specific processes. It identifies intermediate process steps in complex multi-stage processes that can be economically used for flexible operation, potentially leading to energy cost savings and reduced CO_2 and can uncover new insights and pioneer DSM applications in previously unexplored areas, offering opportunities for innovation and optimization. The tool, however, is limited to unit operations that are continuously operated and consume electricity for more than 7500 hours per year. The tool's effectiveness is influenced by the complexity of necessary parameters and the predictability of electricity price fluctuations, which can impact the payback period. When considering the actual oversizing of a process for DSM based on the tool's results, it is important to acknowledge that the tool generates highly precise and accurate values. In most cases, no equipment is

available in the exact size recommended by the decision support tool. Hence, when opting for process oversizing, it is crucial to consider the limitations of available processes and buffer sizes. Once a critical process for DSM has been determined, the next step is to simulate it to make this approach more accessible and to examine it in a more practical context. As for DSM integration, the aim is to assess how well a process can respond to dynamic electricity prices or signals, a dynamic simulation study of the process was conducted in Chapter 5. Processes within the separation cascade – decanter centrifuge, ultrafiltration, and reverse osmosis – which were analyzed individually in Chapter 4 using the decision support tool, were considered as part of an overall system in Chapter 5. For this purpose, the decision support tool was extended by mathematically representing the intermediate storage units as part of an overall system.

This extension and the implementation of the decision support tool in the Aspen Custom Modeler enabled the optimization of the whole separation cascade for digestate processing. The process chain was analyzed both in steady-state and dynamic operation mode in Chapter 5. The steady-state results showed that the economic DSM potential could be increased by considering the whole cascade compared to considering the processes individually. Chapter 4 showed that considerable cost savings in the separation cascade of almost 182 € per day were achieved when the DEC was oversized by 238% and the RO by 372%. In Chapter 5 the steady-state-optimized cost savings of just over 192 € per day were determined by considering shared intermediate buffer tanks at optimized oversizing values of 228% for the decanter, 25% for the intermediate process step – the ultrafiltration, and 402% for the reverse osmosis. This equates to additional savings of more than 10 € per day, or 3879 € per year.

Considering more realistic oversizing values of 250% for the decanter, 50% for the ultrafiltration, and 450% for the reverse osmosis resulted in cost savings of just over 186 € per day. This means that an additional 4 € per day could be saved by considering the whole process cascade compared to the consideration of individual process steps at optimized but maybe not realizable oversizing factors, or in total, 1460 € of additional cost savings per year. These realistic steady-state optimization oversizing factors – 250% for the decanter, 50% for the ultrafiltration, and 450% for the reverse osmosis – were implemented in a simulation environment for dynamic consideration with scheduling optimization.

For the dynamic optimization, varying electricity prices were considered depending on which oversized process steps were switched on and off. This led to savings in operation expenditure of 23% for the whole separation cascade. Considering the rise in capital expenditure for oversizing the process steps of the separation cascaded, the total economic DSM potential is 177 € per day, thus approximately 9 € per day less compared to the results of steady-state optimization at realistic oversizing factors. The fact that the optimization responds at hourly intervals and the ramp-up behavior of the unit operations leads to inertia, does not always make it possible to respond to the electricity prices optimally. However, the basic conclusions remain the same. The oversizing of the process steps for DSM is profitable, and considering the flexibilization of an intermediate process to save intermediate buffer tank costs can lead to even further savings since the economic DSM potential is always above 177 €/day and highest for oversizing the UF by 50%.

Furthermore, the possibilities and limitations of the two optimization strategies were evaluated. The steady-state and dynamic approaches both offer advantages and disadvantages when analyzing the profitability of oversizing processes for demand-side management implementation. The advantages of the steady-state decision support tool include the speed and simplicity of the analysis, as no complicated software or optimization knowledge is required to quickly arrive at a rough result. In addition, the results are close to the more realistic dynamic view. By extending the decision support tool presented in Chapter 4, it is possible to consider interactions between processes. The disadvantages include the need for more consideration of ramp-up and ramp-down behavior and the limitation in the synchronous flexibilization of several sequential processes.

In general, dynamic optimization provides more accurate and realistic results, which makes it easier to avoid wrong investment decisions. This comparative study helped to identify and quantify the benefits of DSM applications at the plant level rather than limiting them to the level of individual unit operations, showing that by considering interactions between processes, storage capacity could be reduced, flexibility expanded, and costs reduced.

In summary, the research findings presented in this thesis reveals the degree of flexibility already existing in biofuel processing and encourage the exploitation of this potential. The theoretical DSM potential was found to be comparable to already existing research areas in DSM literature. A tool has been developed to quickly and easily determine which processes are suitable for DSM from a technical and theoretical standpoint and a financial perspective. Using this tool, in combination with dynamic simulation and optimization, processes in a biomethane biorefinery were successfully identified and validated for a profitable DSM integration. The future need and motivation for actual implementation depend on the development of electricity price fluctuations, investment costs and political and regulatory developments.

Chapter 7. Outlook

The results presented in this thesis provide a comprehensive overview of the potential for flexibilization and corresponding challenges in biofuel processes. Processes that can already be operated flexibly or have been examined for DSM were identified, as well as those that have received little attention to date.

A central result of Chapter 2 is the identification of processes that are difficult to flexibilize due to their complex nature and the need for stable process conditions. These include, in particular, methanation reactors and distillation columns, which are strongly coupled to stable process conditions due to phase transitions which need new pathways in equipment design to increase their flexibility.

On the other hand, there are a number of processes that still need to be investigated for flexibility. These include the conversion processes in biodiesel and bioethanol production as well as individual treatment steps in various fuel production plants, such as biodiesel washing, the use of molecular sieves in bioethanol production and filter processes in the fermentation of residue treatment in waste streams. These processes thus offer potential for future research and the development of flexibilization strategies.

The electrification of many processes in biofuel production opens up new potential for the integration of DSM. Thermal processes, particularly those with a certain temperature tolerance, could become significant electricity storage systems through electrification. This possibility represents the advantage, that it not only contributes to the electricity grid's stability but also increases biofuel production's flexibility. Therefore, future research should focus on the detailed investigation and development of flexibilization strategies for processes that have received little attention to date. In addition, the integration of DSM into electrified thermal processes should be promoted to exploit the full potential of these technologies. Targeted development and optimization of these processes can significantly contribute to a sustainable energy supply and increase the electricity grid's resilience.

The theoretical DSM potential has so far been focused on Germany and the year 2019 in Chapter 3. It would be conceivable to extend this potential analysis to other countries, such as China or Brazil, where bio-based fuels are on the rise. This could reveal where the integration of DSM into biofuel production would have particularly great leverage on a global scale. Delving into future development scenarios could reveal potential challenges and opportunities, thus offering important recommendations regarding strategies for industry and policymakers to promote DSM.

DSM and its economic potential has been investigated for processes on a theoretical level in Chapter 4 and Chapter 5. The experimental investigation of the processes, identified in the dissertation as suitable for DSM, should be intensified. Experiments on the transient behavior of processes and unit operations suitable for DSM are needed in order to understand their dynamic efficiency adaption and reaction patterns. The integration of DSM into the research and development of new systems is essential as early as the development phase. This means that DSM applications should be included in designing new, flexible processes from the beginning. In this way, the advantages of DSM can be fully utilized and integrated into the development of innovative technologies.

Furthermore, in Chapter 4 and Chapter 5 the development, refinement and application of a decision support tool to assess the DSM potential from an economic point of view is addressed. The tool was applied in steady-state and dynamically in a simulation-optimization environment. Beyond the presented approach, there are a number of aspects that could be supplemented to the decision support tool or areas to which the tool could be applied. To this point, the tool has been applied to a process cascade in biomethane production - specifically to the processing of fermentation residue. Although the methane plant was selected specifically because of its high theoretical DSM potential, it would be useful to apply the tool to the other biofuel production processes in order to identify their economic DSM potential. Another investigable area includes extending bioenergetic to material use in the bioconversion sector, such as polymer production. The integration of new, complex chemical processes and all processes not previously investigated for DSM is also essential to exploit DSM's full potential.

From a methodological and technical point of view, extensions to the decision support tool are also possible, considering reaction to electricity prices in real-time and investigating the effects of time delays. A precise analysis of the reaction of processes to price changes is of central importance since price volatilities have not surprisingly been identified as the highest influencing factor for DSM profitability. The decision support tool contains assumptions and refers to the flexibility of electricity prices. Further assumptions could be eliminated, such as shortening the lifetime of a plant through flexibilization, by conducting experiments of real plants. Considering economic bonuses in the evaluation such as potential flexibility premiums, CO_2-tax or participation in flexible electricity markets would create further financial incentives for DSM integration that could become even more important in the future. The analysis of electricity price developments through multi-stochastic programming also provides deeper insight into the future development of DSM potential. Other flexibilities could also be added to the tool, such as the ability to react dynamically to electricity consumption and to, for example, biofuel prices or any other product wanted to be analyzed. Another investigation could entail flexible fuel production instead of flexible consumption, for example, when methane prices fluctuate, or a combination of the two.

A detailed analysis of DSM's impact on greenhouse gas emissions and the relief of the electricity grid is important to investigate the environmental aspects of DSM's application for processes. It is essential to consider the political and social relevance of these aspects to fully understand and exploit their potential economic opportunities, which can help stabilize the electricity grid.

In combination, the scientific and experimental development of a conversion process to intensify flexibilization, the theoretical identification of enhancing DSM potentials through electrification, and the validation of the presented results through practical application and experiments could help motivate plant operators to implement DSM. The results will help plant designers and operators make well founded strategic decisions with a high degree of practical applicability.

The theoretical identification of further potentials through electrification and future developments of global biorefinery capacities, the identification of greenhouse gas emission and grid stabilizing opportunities, and the analysis of social relevance could help policymakers make informed decisions on political incentives that should be implemented to promote DSM and make it an attractive solution for the industry.

Chapter 8. Appendix

Appendix A. Biofuel Production in Germany

This appendix lists all the values used for the calculation of the theoretical DSM in for biofuel Production in Germany. Those include the energy demand as well as specific material consumption and annual mass flow through considered processes. Furthermore the list of all biofuel, bioethanol and biomethane production sites to the date of consideration – 2019 – are listed.

Table 8.1: Energy demand for biofuel production in Germany.

		Specific material	**Annual mass flow[t/a]**	**Electricity demand min [MW_{el}]**	**Electricity demand max [MW_{el}]**	**heat demand min [MW_{th}]**	**heat demand max [MW_{th}]**	**Reference**
Biodiesel	Oil mill small	Raw oil	56	2.28	2.28	2.73	2.73	[166, 169, 234, 235]
	Oil mill medium	Raw oil	729	16.20	16.20	40.49	40.49	[166, 169, 234, 235]
	Oil mill big	Raw oil	1458	24.80	24.80	91.10	91.10	[166, 169, 234, 235]
	Oil refining	Refined oil	3332	2.31	15.04	26.61	40.49	[32, 36]
	Transesterification and purification	Biodiesel	68	0.59	1.13	0.54	0.83	[32]
	Total	**Biodiesel**	**3400**	**57**	**91**	**327**	**471**	
Bioethanol	Milling and Transport	Beet sugar	3332	6.94	25.45	161.97	289.24	[168]
	Extraction and Drying	Wheat sugar	68	3.45	6.42	3.31	5.90	[168]
	Fermentation	Raw alcohol	538.5	5.62	6.97	0.00	0.00	[168]
	Distillation	Bioethanol	5.5	0.05	0.05	1.36	1.36	[168]
	Decanting	Bioethanol from beet	544	3.78	5.30	64.76	64.76	[168]
	DDGS preparation	Bioethanol from beet	544	1.02	1.02	58.57	58.57	[168]
	Vinasse preparation	Bioethanol from wheet	539	1.68	1.68	41.08	41.08	[168]
	Total	**Bioethanol**	**544**	**24**	**27**	**261**	**261**	

Biomethane	Fermentation	Biomethane	741	3.81	3.81	94.24	94.24	[35, 163]
	Membrane filtration	Biomethane	99	8.16	8.16	0.00	0.00	[163]
	Water scrubbing	Biomethane	198	18.91	105.4	48.30	602.94	[163]
	Pressure swing adsorption	Biomethane	134	7.24	8.41	0.00	19.91	[163]
	Amine scrubbing	Biomethane	261	9.89	15.39	0.00	0.00	[163]
	Absorption with Organic Solvent	Biomethane	49	7.57	8.70	0.00	0.00	[163]
	Decanter centrifuge	Digestate	1043	6.89	7.98	0.00	0.00	[162]
	Press screw separator	Digestate	1043	3.31	4.50	0.00	8.53	[162]
	Filter belt press	Digestate	1043	0.39	0.65	0.00	0.00	[162]
	Digestate stirring	Digestate	9907	0.05	0.07	0.00	0.00	[162]
	Grid injection	Biomethane	719	0.20	0.26	0.00	0.00	[32, 163]
	Fuel compression	Biomethane	22	1.61	1.61	0.00	0.00	[32, 163]
	Total	**Biomethane**	**544**	**57**	**153**	**50**	**633**	

Table 8.2: List of biodiesel and bioethanol production sites in Germany.

Name of Production Plant	Product	Capacity [t/a]	Location	Source
SüBio GmbH	Biodiesel	2.000	Themar	[236]
BKK Biodiesel GmbH	Biodiesel	4.000	Rudolstadt	[236]
Delitzscher Rapsöl GmbH & Co. KG	Biodiesel	4.000	Wiedemar	[236]
LPV Landwirtschaftliche Produkt- Verarbeitungs GmbH	Biodiesel	4.000	Henningsleben	[236]
Osterländer Biodiesel GmbH & Co. KG	Biodiesel	4.000	Schmölln	[236]
Rapsol GmbH	Biodiesel	5.500	Lübz	[236, 237]
HHV Hallertauer Hopfenveredelungs-gesellschaft mbH	Biodiesel	6.000	Mainburg	[236]
ecodasa GmbH	Biodiesel	40.000	Burg	[236]
Biowerk Oberlausitz GmbH	Biodiesel	50.000	Oberlausitz	[236, 238]
Biowerk Sohland GmbH	Biodiesel	50.000	Sohland	[236, 238]

EAI Thüringer Methylesterwerke GmbH *	Biodiesel	50.000	Harth-Pöllnitz	[236]
KFS Biodiesel GmbH & Co. KG 1	Biodiesel	50.000	Cloppenburg	[236, 239]
KFS Biodiesel GmbH & Co. KG 3	Biodiesel	50.000	Kassel/Kaufungen	[239]
G.A.T.E. Global Atern. Energy GmbH/Gulf Biodiesel Halle GmbH	Biodiesel	55.000	Halle	[236, 237]
LubminOil*	Biodiesel	58.000	Lubmin	[236]
Tecosol GmbH Ochsenfurt*	Biodiesel	60.000	Ochsenfurt	[236, 237]
Glencore Magdeburg GmbH	Biodiesel	64.000	Magdeburg	[237]
Renewable Energy Group Europe (REG)	Biodiesel	72.000		[240]
Bioeton Kyritz GmbH*	Biodiesel	75.000	Kyritz	[236, 237]
Petrotec GmbH	Biodiesel	80.000	Südlohn	[236]
Emerald Biodiesel Ebeleben GmbH*	Biodiesel	85.000	Ebeleben	[236]
REG Germany AG	Biodiesel	85.000	Borken	[237]
DBE Biowerk GmbH*	Biodiesel	90.000	Tangermünde/Regensburg	[236]
REG Germany AG/Vital Fettrecycling GmbH - plant in Emden	Biodiesel	99.000	Emden	[236, 237]
ecoMotion GmbH	Biodiesel	100.000	Sternberg	[237]
KL Biodiesel GmbH & Co. KG*	Biodiesel	100.000	Lülsdorf	[236]
Südstärke GmbH	Biodiesel	100.000	Schrobenhausen	[236]
ADM Hamburg AG - plant in Leer	Biodiesel	120.000	Leer	[236]
BIO-Diesel Wittenberge GmbH	Biodiesel	120.000	Wittenberge	[236, 237]
Bunge Deutschland GmbH/ MBF Mannheim Biofuel GmbH	Biodiesel	120.000	Mannheim	[236, 241]
EOP Biodiesel AG*	Biodiesel	120.000	Falkenhagen	[236]
KFS Biodiesel GmbH & Co. KG 2	Biodiesel	120.000	Niederkassel-Lülsdorf	[242]
german biofuels GmbH	Biodiesel	130.000		[243]

Vesta Biofuels Brunsbüttel GmbH & Co. KG	Biodiesel	130.000	Brunsbüttel	[236]
BIOPETROL SCHWARZHEIDE GmbH *	Biodiesel	150.000	Schwarzheide	[236]
Rheinische Bioester GmbH	Biodiesel	150.000	Neuss	[236]
Verbio Diesel Bitterfeld GmbH & Co. KG (MUW)	Biodiesel	150.000	Greppin	[236, 237]
ecoMotion GmbH	Biodiesel	162.000	Lünen	[237]
Louis Dreyfus commodities Wittenberg GmbH	Biodiesel	190.000	Lutherstadt Wittenberg	[236, 237]
BIOPETROL ROSTOCK GmbH	Biodiesel	200.000	Rostock	[236, 237]
Verbio Diesel Schwedt GmbH & Co. KG (NUW)	Biodiesel	212.000	Schwedt	[236, 237]
Bio-Ölwerk Magdeburg GmbH	Biodiesel	250.000	Magdeburg	[236]
Mercuria Biofuels Brunsbüttel GmbH	Biodiesel	250.000	Brunsbüttel	[237]
NEW Natural Energie West GmbH	Biodiesel	255.000	Neuss	[236, 237]
ADM Mainz GmbH	Biodiesel	260.000	Mainz	[236]
Cargill GmbH	Biodiesel	275.000	Frankfurt/Main	[236, 237]
ADM Hamburg AG - plant in Hamburg	Biodiesel	300.000	Hamburg	
Vogtland Bio-Diesel GmbH	Biodiesel		Großfriesen	[236]
Süd-Chemie AG (Clariant)	Bioethanol	1000	Straubing	[244]
Barby (Cargill)	Bioethanol	39250		[245]
Suiker Unie GmbH	Bioethanol	55000	MeckPom - Anklam	[246]
Verbio Ethanol Zörbig GmbH & Co. KG	Bioethanol	98.625	Sachse Anhalt Zörbig	[245]
KWST GmbH	Bioethanol	31.560	Hannover	[236, 245]
Ful 21 Klein Wanzleben Refinery (Nordzucker)	Bioethanol	100000	Sachsen Anlaht Wanzleben	[236, 245]
Verbio Ethanol Schwedt GmbH & Co. KG	Bioethanol	181.470	Schwedt	[245]
Prokon	Bioethanol	94.680	Stade	[236]

CropEnergies Bioethanol GmbH (Südzucker)	Bioethanol	284.040	Zeiz	[236]
SASOL	Bioethanol	59.964	Herne	[236]
Danisco	Bioethanol	44.184	Anklam	[236]
Wabio	Bioethanol	9.468		[236]
Müllermilch	Bioethanol	7.890	Leppersdorf	[236]
Wabio Bioenergie (Bad Köstritz)	Bioethanol	6.627,6	Bad Köstritz	[236]
ESP Chemie GmbH	Bioethanol	7.890,0		[236]

*confirmed insolvencies in the biodiesel sector [236]

Table 8.3: List of biomethane production sites in germany [163].

GERMANY	Capacity [m³/h]	Substrate*	Upgrading type**	Start of Operation
Jameln	50	-	-	2006
Dümmer	630	-	-	2018
Zernin	700	-	CHS	2014
Parum-Parchim	600	-	CHS	2017
SachsendorfII	430	-	MEM	2012
Weitingen	5	-	MEM	2014
Koblenz	280	-	MEM	2018
Brunne	300	-	WAS	2011
ZörbigII	2500	AGR	CHS	2012
Karben	385	AGR	CHS	2012
Schwedt(Neuer-Hafen)	385	AGR	CHS	2014
Feldberg	385	AGR	MEM	2014
Vettin	770	AGR	PHS	2016
Blaufelden-Emmertsbühl	275	AGR	PSA	2010
Werlte	275	AGR	PSA	2007
Börger	500	AGR	PSA	2011
WerlteII	550	AGR	PSA	2013
Vahldorf/Jersleben	700	AGR	WAS	2019
Seelow	770	ENC	-	2011
Quesitz/Markransträdt	770	ENC	-	2012
Schöllnitz	770	ENC	-	2012
Stülpe	520	ENC	-	2014
Pirmasens	385	ENC	-	2016
Malchin	700	ENC	-	2018
Torgelow	700	ENC	-	2018
OebisfeldeII	770	ENC	-	2014
Könnern 2	1815	ENC	CHS	2009
Horn-Bad Meinberg	1100	ENC	CHS	2009
Lanken/Wotersen	410	ENC	CHS	2009

Tuningen	275	ENC	CHS	2009
Zeven	138	ENC	CHS	2009
Drögennindorf	385	ENC	CHS	2010
Grabsleben	385	ENC	CHS	2010
Unsleben	385	ENC	CHS	2010
Eggertshofen bei Fresing	275	ENC	CHS	2010
Dannenberg	220	ENC	CHS	2010
SchwedtII	770	ENC	CHS	2011
Barsikow	660	ENC	CHS	2011
Merzig	605	ENC	CHS	2011
Oberriexingen	523	ENC	CHS	2011
Jürgenshagen(bei Rostock)	385	ENC	CHS	2011
Malstedt	385	ENC	CHS	2011
Altenstadt/Hessen	770	ENC	CHS	2012
Haldensleben/Ohretal/Satuell	770	ENC	CHS	2012
Klein Wanzleben	770	ENC	CHS	2012
Pritzwalk-Neudorf(Wolfshagen)	770	ENC	CHS	2012
Eschbach/Breisgau(Heitersheim)	550	ENC	CHS	2012
Hahnennest	550	ENC	CHS	2012
Ebsdorfergrund	495	ENC	CHS	2012
Apensen/Grundoldendorf	385	ENC	CHS	2012
Rätzlingen	385	ENC	CHS	2012
Rosche	385	ENC	CHS	2012
Godenstedt	330	ENC	CHS	2012
Altenhof	770	ENC	CHS	2013
Rackwitz	770	ENC	CHS	2013
Arneburg	700	ENC	CHS	2013
Gardelegen	385	ENC	CHS	2013
Heidenau(Heidkoppel)	385	ENC	CHS	2013
Leizen	385	ENC	CHS	2013
Lüdershagen/Stralsund	385	ENC	CHS	2013
Marienthal	385	ENC	CHS	2013
Weißenborn-Lüderode	385	ENC	CHS	2013
Gellersen(Kirchgellersen)	358	ENC	CHS	2013
Groß	275	ENC	CHS	2013
Kroppenstedt	770	ENC	CHS	2014
Loop	450	ENC	CHS	2014
Kirchhain-Stausebach	385	ENC	CHS	2014
Lambsborn	385	ENC	CHS	2014
Staßfurt	770	ENC	CHS	2015
Barby	385	ENC	CHS	2015
Jabel/Waren	385	ENC	CHS	2015
Lenzen	770	ENC	CHS	2016
Thierbach	770	ENC	CHS	2016
Grabsleben	370	ENC	CHS	

Ronnenberg	358	ENC	CHS	2008
Einbeck	550	ENC	CHS	2009
Hardegsen	303	ENC	CHS	2009
Neuss-am-Niederrhein	165	ENC	CHS	2010
Altena	385	ENC	CHS	2011
Bruchhausen-Vilsen	385	ENC	CHS	2011
Hankensbüttel/Emmen	385	ENC	CHS	2011
Müden(Aller)	385	ENC	CHS	2011
Glentorf	385	ENC	CHS	2014
Zülpich	385	ENC	CHS	2014
ZevenII	138	ENC	MEM	2012
Köckte	358	ENC	MEM	2013
Sachsendorf	358	ENC	MEM	2013
Forst	770	ENC	MEM	2014
Schuby	350	ENC	MEM	2014
Dannheim/Arnstadt/Ilmenau	110	ENC	MEM	2014
Reimlingen	770	ENC	MEM	2015
Beetzendorf	385	ENC	MEM	2015
Wittenburg	385	ENC	MEM	2015
Penkun	770	ENC	MEM	2016
Neubrandenburg/Neuhardenberg	385	ENC	MEM	2016
Ilsede Solschen	700	ENC	MEM	2017
Könnern 1	358	ENC	PHS	2007
Maihingen	330	ENC	PHS	2008
Güstrow	5500	ENC	PHS	2009
Rathenow	550	ENC	PHS	2009
Lüchow	385	ENC	PHS	2009
Forchheim im Breisgau	550	ENC	PHS	2010
Schöpstal	770	ENC	PHS	2011
Lehma	605	ENC	PHS	2011
Lichtensee	825	ENC	PHS	2012
Zittau	275	ENC	PHS	2012
Wolfshagen	770	ENC	PHS	2014
Raitzen	660	ENC	PHS	2015
Gröbern	605	ENC	PHS	2015
Nordhausen(Bielen)	440	ENC	PHS	2015
Heygendorf	385	ENC	PHS	2015
Langenwetzendorf	750	ENC	PHS	2019
Bitterfeld-Wolfen	370	ENC	PHS	2019
Palmersheim-Euskirchen	385	ENC	PHS	2011
Pliening	275	ENC	PSA	2006
Straelen	275	ENC	PSA	2006
Mühlacker	550	ENC	PSA	2007
Schwaigern	1000	ENC	PSA	2008
Graben/Lechfeld	344	ENC	PSA	2008
Ettlingen	330	ENC	PSA	2008

LaupheimI	165	ENC	PSA	2008
Ketzin	110	ENC	PSA	2008
Aiterhofen/Niederbayern	1100	ENC	PSA	2009
Güterglück	660	ENC	PSA	2009
Eich in Karlmünz	385	ENC	PSA	2010
Schwandorf	1100	ENC	PSA	2011
Gollhofen-Ippesheim	770	ENC	PSA	2011
Oschatz(Leuben)	660	ENC	PSA	2011
Blankenhain	358	ENC	PSA	2011
Wriezen	358	ENC	PSA	2011
LaupheimII	330	ENC	PSA	2011
Leuben	770	ENC	PSA	2012
Sagard(Rügen)	715	ENC	PSA	2012
Aicha(Osterhofen)	660	ENC	PSA	2012
Riedlingen-Daugendorf	660	ENC	PSA	2012
Rhede	484	ENC	PSA	2012
Klein Schulzendorf/Trebbin	413	ENC	PSA	2012
Hohenhameln-Mehrum	358	ENC	PSA	2012
Brandis-Waldpolenz	770	ENC	PSA	2013
Kannawurf	770	ENC	PSA	2013
Lauterhofen	485	ENC	PSA	2013
Allendorf-Eder	193	ENC	PSA	2013
Mammendorf	380	ENC	PSA	2014
Menteroda	770	ENC	PSA	2015
Pessin	385	ENC	PSA	2015
Platten	770	ENC	PSA	2016
Wüsting/Hude	660	ENC	PSA	2009
Kerpen	550	ENC	PSA	2009
Eimbeckhausen	350	ENC	PSA	2011
Giesen	193	ENC	PSA	
Darmstadt-Wixhausen	165	ENC	WAS	2008
NiederndodelebenI	770	ENC	WAS	2009
Angermünde	358	ENC	WAS	2009
Dargun	1375	ENC	WAS	2010
Arnschwang	770	ENC	WAS	2010
Neukammer2(Nauen)	770	ENC	WAS	2010
Semd(Groß-Umstadt)	220	ENC	WAS	2010
Homberg/Efze	193	ENC	WAS	2010
Willingshausen/Ransbach	193	ENC	WAS	2010
Osterby	385	ENC	WAS	2011
Roßwein/Haßlau	385	ENC	WAS	2011
Holleben	358	ENC	WAS	2011
Stresow	358	ENC	WAS	2011
Darmstadt-Wixhausen II	330	ENC	WAS	2011
Wolnzach(Hallertau)	1210	ENC	WAS	2012

Fürth/Seckendorf	770	ENC	WAS	2012
Elsteraue	660	ENC	WAS	2012
Wölfersheim	660	ENC	WAS	2012
Barleben	413	ENC	WAS	2012
Ottersberg	358	ENC	WAS	2012
Röblingen-am-See/Stedten	358	ENC	WAS	2012
Achstetten	300	ENC	WAS	2012
Ramstein	38	ENC	WAS	2012
Brumby	770	ENC	WAS	2013
Hadmersleben	770	ENC	WAS	2013
Vehlefanz	770	ENC	WAS	2013
Eggolsheim(Kreis Forchheim)	385	ENC	WAS	2013
Biburg	350	ENC	WAS	2013
Marktongen	193	ENC	WAS	2013
Neuburg-Steinhausen	770	ENC	WAS	2014
NiederndodelebenII	770	ENC	WAS	2014
Nonnendorf	770	ENC	WAS	2014
Zerbst	770	ENC	WAS	2014
Fuhsetal	700	ENC	WAS	2014
Dessau-Roßlau	385	ENC	WAS	2014
Dorsten	385	ENC	WAS	2014
Halle/Westfalen	385	ENC	WAS	2014
Niederröblingen	385	ENC	WAS	2014
Haldensleben/Ohretal/Satuelle II	770	ENC	WAS	2015
Kodersdorf	770	ENC	WAS	2015
Weikersheim	385	ENC	WAS	2015
Beerfelde	770	ENC	WAS	2016
Bergheim/Paendorf	770	ENC	WAS	2016
Genthin	550	ENC	WAS	2016
Gommern	700	ENC	WAS	2017
Erdeborn	550	ENC	WAS	2017
Vahldorf	800	ENC	WAS	2019
Wetschen	688	ENC	WAS	2010
Uchte	770	ENC	WAS	2011
Schwarme	385	ENC	WAS	2011
Hellerwald/Boppard	770	ENC	WAS	2013
Oebisfelde-Weferlingen	770	ENC	WAS	2013
Hage	220	ENC	WAS	2013
Badeleben	220	ENC	WAS	2014
Vettweiß	303	ENC	WAS	2016
Zörbig	3025	FAB	CHS	2010
Schwedt	3025	FAB	CHS	2012
Kißlegg-Rahmhaus	275	FAB	MEM	2010
Anklam	770	FAB	PHS	2013
Geislingen	385	FAB	PSA	2014
Altenstadt Schongau	550	FAB	WAS	2009

Trebsen	550	FAB	WAS	2018
Badbergen	220	MSW	CHS	2005
Karft	550	MSW	CHS	2011
Rostock,-OT-Peez	193	MSW	CHS	2011
Tangstedt/Bützberg	385	MSW	CHS	2012
Berlin-Ruhleben	303	MSW	CHS	2013
Friesoythe(Heinfelde)	550	MSW	CHS	2015
Gröden Kelle/Malchow	358	MSW	MEM	2011
Augsburg	550	MSW	MEM	2013
Sinsheim	350	MSW	MEM	2017
Coesfeld/Höven	330	MSW	PHS	2013
Kleinlüder bei Fulda	550	MSW	PSA	2012
Kleinlüder bei Fulda II	310	MSW	PSA	2013
Pohlsche-Heide	275	MSW	PSA	2009
Alteno	413	MSW	WAS	2014
Frankfurt am Main	600	MSW		2018
Hamburg	275	SWW	CHS	2011
Industriepark Höchst	825	SWW	CHS	2011

*Main substrate use / feedstock type

AGR Agriculturaal Residues, Manure, Plant Residues
ENC Energy Crops
FAB Industrial Organic Waste from Food And Bewerage Industries
SWW Sewage Sludge and Waste
MSW Bio- and Municipal Waste
LAN Landfill

**Upgrading process (multiple methods can be used or combined)

CHS Chemical Scrubbing
CRY Cryogenic Separation
MEM Membrane Separation
PHS Physical Scrubbing
PSA Pressure Swing Adsorption
WAS Water Scrubbing

Equation derivations

Appendix B. Equation Derivation for DSM Decision Support Tool

This appendix provides a more detailed description of the equations presented in the decision support tool. For this purpose, all equations are presented again that are also available in the paper. Hence, there are some redundancies, which are, however necessary to improve the comprehensibility of the derivations.
Symbols with respective units that are needed for the calculations of the decision support tool are listed in Table 8.4.

Table 8.4: Symbols with respective units needed for the calculations of the decision support tool.

Symbol	Unit	Explanation
a_{year}	€/kWh	Maximum average electricity price of specific year
b_{year}	€/(kW*h^2)	Electricity price variation of specific year
C_{capex}	€/a	Capital expenditure per year
C_{opex}	€/a	Operational expenditure per year
C_{totex}	€/a	Total expenditure per year
$C_{totex,min}$	€/a	Minimum total expenditure per year
EPC_P	kW	Electric power consumption of process
F_{os}	%	Oversizing factor
I_P	€	Investment for process step at no oversizing
$I_{ref,P}, I_{ref,buf}$	€	Investment for reference process step, buffer tank
i	%	Interest rate
$\dot{m}_{P,in}$ $\dot{m}_{P,out,}$	t/a	In- and out-flowing mass through process step
$\dot{m}_{ref}$, $\dot{m}_{buf}$	t/a	Mass flow through reference process, buffer tank
P_{econ}	€/a	Economic DSM potential per year
p_{elec}	€/kWh	Electricity price
$p_{elec,av,year}$	€/kWh	Average yearly electricity price of specific year
ϱ	kg/m³	Density of mass flowing through process
R_P, R_{buf}	-	Economies of scale of process step, buffer tank
r_P, r_{buf}	%/a	Expense ratio of process step, buffer tank (including depreciation, interest, maintenance, insurance, taxes, and wages)
SEC_P	kWh/t	Specific electricity consumption
τ	h	Time period
τ_{oph}	h/a	Yearly operating hours
t_{app}	h	DSM application time
t_{dep}	a	Depreciation period
t_{pb}	a	Payback period
V_{ref}, V_{buf}	m³	Volume of refence, buffer tank

General equations

$$t_{app} = \left(\tau - \frac{\tau}{F_{os} + 1}\right) * (1 - FOP_{min}) \quad (8\text{-}1)$$

Calculation of the operational linked expenses as a function of F_{os}

$$p_{elec,av,year} = a_{year} - b_{year} * t_{app} \quad (8\text{-}2)$$

$$C_{opex}(F_{os}) = p_{elec,av,year} * SEC_P * \dot{m}_P * \tau_{oph} \quad (8\text{-}3)$$

Integrating (8-2) in (8-3):

$$C_{opex}(F_{os}) = \left(a_{year} - b_{year} * t_{app} * (1 - FOP_{min})\right) * SEC_P * \dot{m}_P * \tau_{oph} \quad (8\text{-}4)$$

Integrating (8-1) in (8-4):

$$C_{opex}(F_{os}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min})\right) * SEC_P * \dot{m}_P * \tau_{oph} \quad (8\text{-}5)$$

Calculation of the capital linked expenses as a function of F_{os}

$$V_{buf,in} + V_{buf,out} = \frac{(\dot{m}_{P,in} + \dot{m}_{P,out})}{\varrho} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min}) \quad (8\text{-}6)$$

$$V_{buf} = \frac{\dot{m}_{buf}}{\varrho} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min}) \quad (8\text{-}7)$$

$$I_P = I_{ref} * \left(\frac{\dot{m}_P}{\dot{m}_{ref}}\right)^{R_P} \quad (8\text{-}8)$$

$$I_{buf} = I_{ref} * \left(\frac{V_{buf}}{V_{ref}}\right)^{R_{buf}} \quad (8\text{-}9)$$

$$C_{capex}(F_{os}) = C_{capex,P}(F_{os}) + C_{capex,buff}(F_{os}) \quad (8\text{-}10)$$

Integrating (8-8) and (8-9) in (8-10):

$$C_{capex}(F_{os}) = I_{ref} * \left(\frac{\dot{m}_P}{\dot{m}_{ref}}\right)^{R_P} * r_P + I_{ref} * \left(\frac{V_{buf}}{V_{ref}}\right)^{R_{buf}} * r_{buf} \quad (8\text{-}11)$$

Integrating (8-6) in (8-11):

$$C_{capex}(F_{os}) = I_{ref,P} * r_P * (F_{os} + 1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min})}{V_{ref}}\right)^{R_{buf}} \quad (8\text{-}12)$$

Calculation of the total linked expenses as a function of F_{os}

$$C_{totex}(F_{os}) = C_{opex}(F_{os}) + C_{capex}(F_{os}) \quad (8\text{-}13)$$

Integrating (8-5) and (8-12) in (8-13):

$$C_{totex}(F_{os}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} + I_{ref,P} * r_P * (F_{os}+1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \quad (8\text{-}14)$$

Determination of the feasibility of DSM implementation

DSM economically beneficial if for any value of F_{os}, greater than 0, the following is true:

$$C'_{totex}(F_{os}) < 0 \quad (8\text{-}15)$$

Integrating (8-13) in (8-15):

$$C'_{capex}(F_{os}) + C'_{opex}(F_{os}) < 0 \quad (8\text{-}16)$$
$$C'_{capex}(F_{os}) < -C'_{opex}(F_{os}) \quad (8\text{-}17)$$

Derivative of (8-5) and (8-12) and integration in (8-17):

$$\frac{I_{ref,P} * R_P * r_P * F_{os} * (F_{os}+1)^{R_P} + I_{ref,buf} * R_{buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{F_{os}+1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}}}{(F_{os}+1) * F_{os}} < -\frac{\tau_{oph} * \tau * EPC_P * b_{year} * (1 - FOP_{min})}{(F_{os}+1)^2} \quad (8\text{-}18)$$

Calculation of the economic demand side management potential

$$P_{econ} = C_{totex}(0) - C_{totex}\left(F_{os,opt}\right) \quad (8\text{-}19)$$

$$C_{totex}(\mathbf{0}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{\mathbf{0}+1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} + I_{ref,P} * r_P * (\mathbf{0}+1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{\mathbf{0}+1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \quad (8\text{-}20)$$

$$C_{totex}(\boldsymbol{F_{os,opt}}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} + I_{ref,P} * r_P * (\boldsymbol{F_{os,opt}} + 1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \tag{8-21}$$

<u>Simplifying (8-20):</u>

$$C_{totex}(\mathbf{0}) = a_{year} * EPC_P * \tau_{oph} + I_{ref,P} * r_P \tag{8-22}$$

<u>Integrating (8-21) and (8-22) in (8-19):</u>

$$P_{econ} = a_{year} * EPC_P * \tau_{oph} - \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} + I_{ref,P} * r_P - I_{ref,P} * r_P * \left(\boldsymbol{F_{os,opt}} + 1\right)^{R_P} - I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \tag{8-23}$$

<u>Simplifying</u> (8-23):

$$P_{econ} = SEC_P * \dot{m}_P * \tau_{oph} * b_{year} * \left(\tau - \frac{\tau}{F_{os,opt}+1}\right) * (1 - FOP_{min}) + I_{ref,P} * r_P * \left(1 - \left(F_{os,opt} + 1\right)^{R_P}\right) + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{F_{os,opt}+1}\right) * (1 - FOP_{mi}\ )}{V_{ref}} \right)^{R_{buf}} \tag{8-24}$$

Calculation of payback period

$$t_{pb} = \frac{(C_{capex}(F_{os,opt}) - C_{capex}(0)) * t_{dep}}{C_{opex}(0) - C_{opex}(F_{os,opt})} \tag{8-25}$$

Inserting $F_{os,opt}$ and 0 in (8-12):

$$C_{capex}(\boldsymbol{F_{os,opt}}) = I_{ref,P} * r_P * (\boldsymbol{F_{os,opt}} + 1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \quad (8\text{-}26)$$

$$C_{capex}(\boldsymbol{0}) = I_{ref,P} * r_P * (\boldsymbol{0} + 1)^{R_P} + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{\boldsymbol{0}+1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \quad (8\text{-}27)$$

Simplifying (8-27):

$$C_{capex}(\boldsymbol{0}) = I_{ref,P} * r_P \quad (8\text{-}28)$$

Inserting $F_{os,opt}$ and 0 in (8-5):

$$C_{opex}(\boldsymbol{F_{os,opt}}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}}+1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} \quad (8\text{-}29)$$

$$C_{opex}(\boldsymbol{0}) = \left(a_{year} - b_{year} * \left(\tau - \frac{\tau}{\boldsymbol{0}+1}\right) * (1 - FOP_{min}) \right) * SEC_P * \dot{m}_P * \tau_{oph} \quad (8\text{-}30)$$

Simplifying (8-30):

$$C_{opex}(\boldsymbol{0}) = a_{year} * EPC_P * \tau_{oph} \quad (8\text{-}31)$$

Integrating (8-28) and (8-31) in (8-25): (8-32)

$$t_{pb} = \frac{\left(I_{ref,P} * r_P * \left(1 - \left(\boldsymbol{F_{os,opt}} + 1\right)^{R_P}\right) + I_{ref,buf} * r_{buf} * \left(\frac{\dot{m}_{buf} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min})}{V_{ref}} \right)^{R_{buf}} \right) * t_{dep}}{SEC_P * \dot{m}_P * \tau_{oph} * b_{year} * \left(\tau - \frac{\tau}{\boldsymbol{F_{os,opt}} + 1}\right) * (1 - FOP_{min})} \quad (8\text{-}33)$$

Appendix C. Parameters and results of Steady-State and Dynamic DSM Optimization

The following tables shows the utilised parameters for costs, mass flow, specific power consumption, and further relevant parameters for the calculation of the steady state optimization of Chapter 5 of the three separation steps concerned in the downstream digestate treatment and the dynamic electricity prices as implemented for dynamic optimization:

Table 8.5: Parameters for calculating the economic DSM potential of the three separation steps taken from [228].

Parameter	Unit	DEC	UF	RO
I_p	k€	197	1200	34
$\dot{m}_P$	kt/a	35	28	16
SEC_P	kWh/t	5	5	3.5
a_{year}	€/kWh		0.2409	
b_{year}	€/(kW*h^2)		0.0038	
$I_{b,ref}$	k€		21.6	
r_P	%/a		11	
r_{buf}	%/a		11	
R_P	-		0.6	
R_{buf}	-		1	
ϱ	t/m³		1	
τ_{oph}	h/a		8000	
τ	h		24	
t_{dep}	a		20	
V_{ref}	m³		100	

Table 8.6: List of dynamic electricity prices as implemented for dynamic optimization.

Time t h	Dynamic electricity price $p_{elec,dyn}$ €/kWh
0	0.1915
1	0.1839
2	0.1535
3	0.1763
4	0.2143
5	0.2599
6	0.2979
7	0.3055

8	0.2751
9	0.2523
10	0.2295
11	0.1991
12	0.1687
13	0.1611
14	0.2067
15	0.2371
16	0.2827
17	0.3131
18	0.3283
19	0.3207
20	0.2903
21	0.2675
22	0.2447
23	0.2219

The following tables shows the utilised parameters, variables and results of the steady-state and dynamic optimization as implemented in ACM of Chapter 5:

Table 8.7: Parameters, variables and results of steady-state optimization as implemented in ACM.

Parameters

	Value	Description	Units
a_year	0.2409	Maximum average price	€/kWh
b_year	0.0038	Electricity price decrease	€/(kW*h^2)
EPC_P_DEC	174.4	Elec. power consumption of proc	kW
EPC_P_RO	57.0	Elec. power consumption of proc	kW
EPC_P_UF	142.1	Elec. power consumption of proc	kW
I_P_DEC	196,645	Investment for reference process	€
I_P_RO	33,757	Investment for reference process	€
I_P_UF	1,200,420	Investment for reference process	€
Ibref	21,600	Investment for reference buffer tank	€
m_P_DEC	279,101	Mass flow through process	t/a
m_P_RO	130,242	Mass flow through process	t/a
m_P_UF	231,931	Mass flow through process	t/a
OpH	8,000	Yearly operating hours	h/a
R_P	0.6	Economies of scale of process	-
rBuf	0.11	Expense ratio of buffer tank	%/a
rP	0.11	Expense ratio of process	%/a
T	24	Time period	h
TimeScaler	3600	Seconds per model time unit	
Vbref	100	Volume of reference tank	m³

Resulting Decision Variables

	Value	Description	Units

OS_DEC	2.3	Oversizing factor	%
OS_RO	4.1	Oversizing factor	%
OS_UF	0.3	Oversizing factor	%

Resulting Intermediate Variables

	Value	Description	Units
t_app_DEC	16.67	DSM application time	h
t_app_RO	19.27	DSM application time	h
t_app_UF	4.95	DSM application time	h
p_elec_av_DEC	0.18	Average yearly electricity price of specific year	€/kWh
p_elec_av_RO	0.17	Average yearly electricity price of specific year	€/kWh
p_elec_av_UF	0.22	Average yearly electricity price of specific year	€/kWh
CAPEXBUF1	582	Capital expenditure per year for buffer tank	€/a
CAPEXBUF2	428	Capital expenditure per year for buffer tank	€/a
CAPEXBUF3	294	Capital expenditure per year for buffer tank	€/a
CAPEXBuf_DEC	1,065	Capital expenditure per year	€/a
CAPEXBuf_RO	314	Capital expenditure per year	€/a
CAPEXBuf_UF	224	Capital expenditure per year	€/a
CAPEXP_DEC	44,052	Capital expenditure per year	€/a
CAPEXP_RO	9,827	Capital expenditure per year	€/a
CAPEXP_UF	151,566	Capital expenditure per year	€/a
OPEX_DEC	247,763	Operational expenditure per year	€/a
OPEX_RO	76,441	Operational expenditure per year	€/a
OPEX_UF	252,409	Operational expenditure per year	€/a
TOTEX_DEC	292,825	Total expenditure per year	€/a
TOTEX_RO	86,562	Total expenditure per year	€/a
TOTEX_UF	403,975	Total expenditure per year	€/a

Resulting Objective Function

	Value	Description	Units
TOTEX_TOT	813009	Total expenditure per year	€/a

Table 8.8: Parameters, variables and results of dynamic optimization as implemented in ACM.

Parameters

Equation symbol	Value	Description	Unit
Gmax_DEC	0.831	Maximum separation efficiency	%
Gmax_RO	0.106	Maximum separation efficiency	%
Gmax_UF	0.562	Maximum separation efficiency	%
I_P_DEC	196,645	Investment for reference process	€
I_P_RO	33,757	Investment for reference process	€
I_P_UF	1,200,420	Investment for reference process	€
Ibref	21,600	Investment for reference buffer tank	€

OS_DEC	2	Oversizing factor	%
OS_RO	4	Oversizing factor	%
OS_UF	0.5	Oversizing factor	%
R_P	0.6	Economies of scale of process	-
rBuf	0.11	Expense ratio of buffer tank	%/a
rP	0.11	Expense ratio of process	%/a
SEC_P_DEC	5	Elec. power consumption of proc	kW
SEC_P_RO	3.5	specific Elec. power consumption of process	kW
SEC_P_UF	5	specific Elec. power consumption of proc	kW
StartupTime_DEC	12	Time to start up decanter	min
StartupTime_RO	0	Time to start up reverse osmosis	min
StartupTime_UF	0	Time to start up ultrafiltration	min
steepness_DEC	0	Steepness of jump (time to reach max. efficiency)	min
steepness_RO	5	Steepness of jump (time to reach max. efficiency)	min
steepness_UF	2	Steepness of jump (time to reach max. efficiency)	min
Vbref	100	Volume of reference tank	m^3
FlowMax_DEC	34.9	Mass flow at no oversizing	t/h
FlowMax_RO	16.3	Mass flow at no oversizing	t/h
FlowMax_UF	29.0	Mass flow at no oversizing	t/h

Results of involatile intermediate variables

Equation symbol	Value	Description	Unit
VCAPEXBUF1	558	Capital expenditure per day for buffer tank	€/day
VCAPEXBUF2	348	Capital expenditure per day for buffer tank	€/day
VCAPEXBUF3	274	Capital expenditure per day for buffer tank	€/day
CAPEXBuf_DEC	51	Capital expenditure per day	€/day
CAPEXBuf_RO	18	Capital expenditure per day	€/day
CAPEXBuf_UF	33	Capital expenditure per day	€/day
CAPEXP_DEC	115	Capital expenditure per day	€/day
CAPEXP_RO	27	Capital expenditure per day	€/day
CAPEXP_UF	461	Capital expenditure per day	€/day

Results of dynamic intermediate variables at t=0 h and t=24 h

Equation symbol	Value (t=0h)	Value opt. (t=24h)	Description	Unit
OPEX_DEC	0	762	Cumulative operational expenditure	€
OPEX_RO	0	217	Cumulative operational expenditure	€
OPEX_UF	0	744	Cumulative operational expenditure	€
TOTEX_DEC	165	928	Cumulative total expenditure	€

TOTEX_RO	45	262	Cumulative total expenditure	€
TOTEX_UF	494	1,241	Cumulative total expenditure	€

Dynamic constraint variable

Equation symbol	Value (t=0h)	Value opt. (t=24h)	Description	Unit
RET_UF	0,0	0,1	Current retentate tank level	t

Results of objective function

Equation symbol	Value (t=0h)	Value opt. (t=24h)	Description	Unit
TOTEX_TOT	679	2,406	Total expenditure per year	€

Table 8.9: Optimization results for optimization at different initial starting points.

Optimization identifyer	**Nr. of evalua-tions**	**Objective function result**	**Accuracy**	**Required functions**	**Gradient evalua-tions**	**Optimization Time**
A	8	947.3372	4.10E-09	16	17	2.68 sec
B	5	947.3372	5.49E-13	10	11	2.09 sec
C	52	947.3372	1.30E-13	96	101	17.46 sec
D	37	947.3372	7.41E-11	68	72	13.28 sec

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