Options for demand side management in biofuel production: A systematic review

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Summary
To minimize the emissions from the production of biofuels, one aim is to reduce or completely replace the amount of fossil fuels used for internal process energy. A conceivable solution is the use of volatile renewable energy sources such as solar and wind. The fluctuation of these energy sources in their production inevitably leads to a transformation to flexible power consumption, commonly referred to as demand side management (DSM). In current research, a wide range of processes has 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 is to create an overview of which processes in biofuel production can be considered for DSM use.

KEYWORDS
biorefineries, energy storage, energy transition, load shedding, load shifting, system flexibility, thermal energy storage

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 a carbon source for transportation fuels and the chemical industry has to be replaced by alternatives such as biomass or increased re-use of materials. Therefore,
numerous technologies are being developed to convert biomass in industrial biorefineries into biofuels and bio-based products.\textsuperscript{1} Since the availability of biomass is a major concern for the transition of the chemical industry to a bio-economy, the biomass itself should be converted with very high efficiency. The utilization of parts of the raw material as an 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.\textsuperscript{2} The flexible adjustment of a system’s power demand to follow the current power generation is commonly referred to as demand side management (DSM).\textsuperscript{7}

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 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. Section 3 proceeds with a list of existing literature that reviews a sum of different DSM processes, therefore categorized as other reviews of DSM options. Section 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 and,
3. quantify the relative amount of load or temperature variation each process step under consideration can provide.

Section 5 compares the main results of the review, summarizing the three previously named findings for each process area. Section 6 closes with a conclusion of the review and presents perspectives for future research.

2 | STRUCTURE AND TERMS OF THE REVIEW

2.1 | Considered biorefineries

For this review paper, process steps are investigated, that are most commonly operated and established in biofuel production for biodiesel,\textsuperscript{4} bioethanol,\textsuperscript{3} and biomethane.\textsuperscript{6} 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 (see Figure 1). 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 and auxiliaries (here, the production of hydrogen). The most common processes in the process chain of biofuel production are depicted in Figure 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 4.

2.2 | Terms in DSM research

Demand side management, 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 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.\textsuperscript{10,11}

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\textsuperscript{12,14} or even more precisely socio-economic or ecologic potential.\textsuperscript{10,15} While many contributions reviewed in this contribution, present different depths 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. 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., Klobasa, and Theurich. 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 4 is summarized in a graphic (Figures 4-7) that shows the given ranges of maximum and minimum operating points as the main parameters to represent the relative theoretical DSM potential and set limits to the operating window. The operating window will be described 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. If the deviation from the optimal operating point was described in temperature in Kelvin or power consumption in Watt, the load spectra were converted into percentages. These percentage terms represent the $\Delta T$ or $\Delta P$ of the temperature and power increase or reduction in relation to the optimum operating point at 100%, according to the following equations:

$$FOP_{\min/\max} = \frac{T_{\min/\max}}{T_{opt}} \quad \text{or} \quad P_{\min/\max} = \frac{P_{\min/\max}}{P_{opt}}$$

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

The FOL found for each process will be graphically depicted in Section 4. Figure 2 shows an example of the graphical demonstrations of the FOL used in this contribution.

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...
| Source                        | Region                        | Household devices | Commerce and services | Aluminium | Chlorine and other chemicals | Steel and other metals | Pulp, Paper and Wood processing | Cement | Glass and ceramics | Engine and machine construction | Sewage treatment | Air separation | Others |
|------------------------------|-------------------------------|-------------------|-----------------------|-----------|-------------------------------|------------------------|-------------------------------|--------|-------------------|---------------------------------|----------------|----------------|--------|
| Christoffersen et al. 2005   | Denmark                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Studer 2006/2007[21]         | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| McKane et al. 2008[22]       | California USA                |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Dena 2010[23]                | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Paulus and Borggreffe 2009[24] | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Wang et al. 2010[25]         | China                         |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Worrell et al. 2010[26]      | USA                           |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Paulus and Borggreffe 2011[27] | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Golonaker and Room 2010[28]  | Europe, Germany, USA          |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Apel 2012[29]                | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Ates et al. 2012[30]         | Turkey                        |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Sivell et al. 2012[31]       | Finland                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Gils et al. 2013[32]         | Europe, Northern Africa       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Klobasa et al. 2007/2013[33] | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Merkert et al. 2015[34]      | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Langrock 2015[35]            | Sweden                        |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Paramonova et al. 2015[36]   | Sweden                        |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Shureh et al. 2016[37]       | –                             |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Steurer 2017[38]             | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Arnold and Janßen 2018[39]   | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Ausfelder et al. 2018[40]    | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Baumgart 2018[41]            | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Ludwig 2018[42]              | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Söder et al. 2018[43]        | Northern Europe               |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Kilicete et al. 2019[44]     | USA                           |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Lawrence et al. 2019[45]     | Sweden                        |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Shafe-kluh et al. 2019[46]   | –                             |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Talei et al. 2020[47]        | Canada                        |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Nebel et al. 2020[48]        | Germany                       |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Hasan et al. 2022[49]        | Bangladesh                    |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
| Golmohamadi et al. 2022[50]  | –                             |                   |                       |           |                               |                        |                               |        |                   |                                 |                |                |        |
these articles generally includes the calculation of the theoretical DSM potential for a certain region by investigating technical barriers to implementing DSM in certain industrial processes. Table 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 identifies processes that can be operated flexibly and finds 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 4.

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. Since then, the range of investigated DSM-suited processes has expanded considerably.

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

The contribution by Merkert et al., provides an overview of methods to determine the DSM potential of industrial processes in the steel, paper, and cement industry, followed by a series of real industrial case studies in Germany. Prior examined the load profiles of electrical consumers in Germany, differentiating between summer and winter as well as working days and weekends. Sadler 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. 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 German Energy Agency (Ger. Deutsche Energie-Agentur - DENA) in 2010 expanding Stadler’s perspective to aluminum, steel, paper, cement, and chlorine processing.

Further study on the determination of the DSM potential of above mentioned industry processes was conducted by Gobmaier and Roon and Paulus and Borggrefe. Another DSM study was carried out in 2012 by Apel et al., including 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 contributes to the identification of analytical uncertainties and systematic delimitation of DSM-relevant applications. The development of the future theoretical DSM potential up to the year 2050 was estimated by Ladwig 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 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., 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., 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., described various technologies for energy storage and DSM according to their potential applications in the context of Germany’s transition toward a more sustainable energy system. While the article was written from a German perspective, the authors hope it will be of general interest to anyone working in the areas of energy systems or energy. Looking beyond Germany, Gils demonstrated 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., in which they compare DSM potentials and how they were estimated in seven northern European countries in order to compare general challenges and results. Christoffersen et al., investigated 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., and Lawrence et al., demonstrate advantages that DSM systems in the heavy industry can supply with a regional focus on Sweden. According to their calculations especially the pulp and paper industry shows great potential for the implementation of DSM strategies. Sivill et al., 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 incen-
tives, barriers in organizational matters as well as information and politics.

McKane et al.,22 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.,26 search for cost saving opportunities in the US American iron and steel industry by implementing energy price based efficiency measures based on case studies of real-world applications worldwide. Kiliccote et al.,43 identify attributes and quantify hourly availability of DSM resources in the commercial, industrial and residential sectors in the USA, focusing on the cement industry in the industrial sector. Talaei et al.,45 investigate GHG emission mitigation potential that results from DSM integration in the Canadian iron and steel industry.

Wang et al.,25 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.,30 categorized the steel, paper, cement, and ceramics industry as suitable for DSM practices and highlighted bottlenecks of these heavy industries with help of questionnaires and an analytical framework. Hasan et al.,47 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.,37 Shafie-khah et al.,45 and Golomhamadi48 do not consider special geographical regions but review other articles concerning DSM implementation strategies. Shoreh et al. summarize the main barriers that hinder the widespread utilization of DSM programs in household applications, aluminum 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 Golomhamadi again reviews DSM potentials in heavy industries like cement, aluminum, 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.

## 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. For each investigated and summarized process, a focus is put on technical restrictions limiting its flexibility. 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. 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 3.

### 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. 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 3 also consider the pulp and paper industry and cement handling in their research. The maximum FOL which was identified in named studies is summarized in Figure 4.
4.1.1 | Grinding

Due to its energy intensity, essential DSM potentials lie in the mechanical process (sawmills, grinders, refiners) for pulp production. Figure 4 shows the possibility of operating wood grinders between 0% and 100% of their peak load.\(^{55,56}\) Paulus and Borggrefe,\(^{27}\) Steuer,\(^{30}\) Gils,\(^{32}\) and Klobasa\(^{17}\) also indicated the possibility of a complete shutdown, but see the FOP\(_{\text{max}}\) at around 80%, which results in a FOL of 80% in their calculation. Helin et al.,\(^{55}\) Pulkkinen and Ritala,\(^{57}\) and Paulus and Borggrefe\(^{27}\) extended the research on DSM potentials in the paper industry by estimating the economic potential. Helin et al.\(^{55}\) focused only on the costs of short-term DSM in the 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 behavior of 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\(^{57}\) 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 a FOL of 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,\(^{27}\) 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\(_{\text{max}}\) is equivalent to the average load of refiners which is 250 MW and the FOP\(_{\text{min}}\) was defined by the average unutilized capacity of 62 MW. This results in a FOL of 125%. The pulp storage volume at the investigated paper mills was large enough to store material for 1.5 h at maximum capacity.

4.1.2 | Crushing

A unit operation concerning comminution is the crushing of material. Figure 4 depicts that many authors considered switching off crushers completely, some others stated that the load of crushers can be varied and running the crushers in partial load is the DSM function in consideration. In addition to the articles identifying the theoretical and technical DSM potential, Merkert et al.,\(^{34}\) Mitra et al.,\(^{58}\) Zhang et al.,\(^{59}\) Numbi et al.,\(^{60,61}\) and Vujanic et al.\(^{56}\) considered DSM optimization strategies for continuous energy-intensive processes such as crushers, with focus on maximizing the economic DSM potential.

Merkert et al.\(^{34}\) and Mitra et al.\(^{58}\) investigated a scenario where large crushers are connected in parallel with a material storage tank installed. The crushers provide a 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 al., 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 a FOL of 40% to 100% partial load variation, while the second one is an optimal switching on and off control leading to a FOL of 0% to 100%. It was demonstrated that an optimal switching controller has a greater potential to achieve a high reduction of both energy consumption and the 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. and for the day ahead by Zhang et al. 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 an inflexible downstream kiln were 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.

4.2 | Conversion processes

In biomass conversion, flexibility has already been studied by Trommler et al., Peters et al., Thrän, and Dotzauer et al., 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. Moreover, there are approaches to achieving a flexible biogas production through feed management and variably producing electricity with a controllable combined heat and power unit. In general, however, the current state of research neglects the aspect of flexible power consumption of biofuel production plants, whereas this would result in a more sustainable biofuel production.

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. Examples of catalysed reactions often found in DSM literature and biofuel production are fixed-bed methanation reactions and FT reactions. 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 have been analysed in this regard. In Figure 5 the FOL of these conversion steps considered in literature are compared.
4.2.1 | Anaerobic digestion

Solutions to enhance the flexibility of biogas plants through material storage were presented by Hahn et al.,\(^70\) and Bensmann.\(^71\) Biogas storage at the site of the plant represents the current state of practical implementation of demand-oriented biogas supply, for example, for flexible power generation.\(^72\) 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 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°C to 43°C) and (thermophilic: 43°C to 55°C).\(^73\),\(^74\) Studies were conducted by Obaya et al.,\(^75\) Chae et al.,\(^76\) Ahn and Foster,\(^77\) Lau and Fang,\(^78\) and El-Mashad et al.,\(^79\) on temperature fluctuations in thermophilic fermenter conditions as well as on mesophilic fermenter conditions by Chae et al.,\(^76\) and Ahn and Foster.\(^77\) Good process stability was demonstrated for fluctuations within these temperature limits.

In a study by Gao et al.,\(^80\) 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.,\(^76\) in the anaerobic digestion of pig manure. The mesophilic digester temperature varied between 25°C, 30°C, and 35°C. The methane content increased slightly with higher digestion temperatures. Temperature shocks of 35°C to 30°C and of 30°C to 32°C led to a reduction in the biogas production rate but recovered to the value of the control reactor within 40 h. Additionally, no permanent damage to the digestion rate was observed once it was set back to the starting temperature.

In a study by Luo,\(^81\) 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 was 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°C to 43°C) or thermophilic (43°C to 55°C) 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 stabilized again after a few days without leaving any long-term damage within the microbial community.

4.2.2 | Methanation

The flexibility of power-to-gas (PtG) processes, is currently being investigated to adapt to fluctuating input quantities from volatile renewable power supply. The dynamic operation of methanation reactors is favored to limit upstream storage capacities. The contributions by Theurich et al.\(^18\),\(^82\) 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 CO₂ methanation. They demonstrate, on the one hand, that this type of reactor 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.,\(^83\) and Herrmann et al.,\(^84\) with the help of dynamic simulation models. Simulation scenarios with load increases in varying degrees (between 25% and 100%) showed that the reactor temperature increased if the load increases.\(^83\) 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°C and 600°C. Herrmann et al.,\(^84\) 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 behavior. The flexibility limits of the modeling were based on the patent specification of Hitachi Zosen Inova EtoGas GmbH,\(^85\) according to which the space velocity in the first reactor stage lies in a range from 2000 to 8000 h⁻¹.
Kreitz et al., coupled a simple model of an alkaline water electrolyser with a detailed one dimensional heterogeneous model of a catalysed microstructured methanation reactor and improved temperature control was demonstrated. Higher operating temperatures could be applied without exceeding the critical catalyst temperature. The electrolytically produced H₂ was directly adapted to an exemplary wind power profile. The reactor was operated within a FOL of 21 to 182%. The simulation of the methanation reactor showed that the modulation of the H₂ 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 CO₂ methanation in a range from 170°C to 230°C and 200°C to 500°C. 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 H₂ dropout to return to the initial activity.

Fischer and Freund, as well as Iglesias Gonzalez and Staub, expected variable load operation limits of 50% to 100% of the maximum load of catalysed reactors, constrained by hot spot temperatures. Fischer and Freund considered critical reactor dynamics during the reactor design which were integrated into an underlying optimization problem. The approach was modelled based on steady state experimental data using the methanation of CO₂. Iglesias Gonzalez and Schaub investigated the hydrogenation of CO₂ 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. highlights recent developments, challenges, and future directions for catalysts under dynamic reaction conditions.

### 4.2.3 Fischer-Tropsch synthesis

A process concept using RE from fluctuating wind power and CO₂ to produce liquid hydrocarbons is Fischer-Tropsch (FT) synthesis. The economic performance of the process was evaluated by König et al. A buffer cavern acts as a bridge between the strongly dynamic electrolysis unit and the continuous chemical FT synthesis. H₂ is stored if surplus power is available and used when the H₂ 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 CO₂ according to König et al. A FOPₘᵢₙ of 70% is recommended for liquid hydrocarbon processes based on RE.

Pfeifer et al. considered a PtG plant where electrolytically produced H₂ is stored in a tank and fed together with CO₂ in a required stoichiometry ratio to the FT stage. By applying RE data, a minimum H₂ storage time of 1.3 h was calculated to operate the FT plant, 365 days per year without intermediate shutdown with the capability to accept a FOPₘᵢₙ of 17% and a FOPₘₘₐₓ of 190%.

According to Loewert and Pfeifer, the efficiency of the FT synthesis can be optimized by 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 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., it was proven that highly load flexible operation in micro-structured FT reactors in combination with a dynamic H₂ electrolyser with multi-parameter changes in the 1-min regime is feasible and fully controllable.

Iglesias Gonzalez et al., pursued a similar approach to Theurich et al., for the CO₂-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 behavior 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 FOPₘᵢₙ 50% and FOPₘₘₐₓ 100%.

### 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. Flexibilities in the purification of bio-based products have been investigated for sedimentation, thermal drying, membrane separation, distillation, cryogenic separation, and absorption processes. A comprehensive review of flexibility.
options in liquid-liquid extraction was conducted by Polyakov a et al. The possible FOL of investigated process steps that are found in biofuel production and can be operated flexibly are summarized in Figure 6.

4.3.1 | 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. 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.

4.3.2 | Thermal drying

The article by Harper et al. details the development of a decision support system for DSM programs in industrial drying. Air drying, heat pump drying, and airless drying were investigated 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 drying system is considered to be switched off completely in Harper's study, the convective air dryer runs at a FOPmin 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 programs.

4.3.3 | Membrane separation

Studies by Käufler et al., Bognar et al., Loutatidou et al., Ghobeity and Mitsos, Williams et al., Jiang et al., Prathapaneni and Detroja, and Pohl et al. have shown that implementing a DSM in reverse osmosis (RO) desalination plants is technologically feasible. 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. modeled the system behavior 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 to variable pressure, possible pressure alterations were set from 7.0 bar to 12.5 bar.

Prathapaneni and Detroja 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., 107 Ghobeity and Mitsos, as well as Williams et al., 105,106 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 FOPmax 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 by 20% and 22% lead to a maximum cost saving potential of 7%.

Simulations of Bognar et al. 103 allow a RO desalination plant to operate variably consuming load between 37 and 108 MW. As the nominal load lies at 67.7 MW the FOL results in 55% to 169%. Bognar et al. summarized that desalination as a 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., 102 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 a 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., 104 The desalination plant was modelled as a variable flow RO plant in which pressures and flows were varied within a FOL of around 55% to a maximum of 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 the RO plant by 50% is the most attractive option.

4.3.4 | Distillation

For the integration of distillation processes in DSM programs, Hoffmann et al., 110 propose an advanced modeling 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, and operational and design parameters. In further work, Hoffmann et al., 111 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 FOPmin of 30%. Beyond this point, first stages start to run dry and a further decrease in the load is not possible.

Measures to enhance the flexibility and reduce start-up times of tray distillation columns were described by Riese 2016. 112 Those measures aim at developing new apparatus designs 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. are aiming at an internal structuring of the column to enhance capacity flexibility 113 and reduce start-up times. 114 The internal segmentation of the column enables the independent operation of singular segments and, due to the proposed column design, 115 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%.

4.3.5 | Cryogenic separation

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

Studies focusing on the air compressors in ASU have been conducted by Teichgraeber et al., 116 Karwan and Klebis, 117 and Kopanos et al., 118 Teichgraeber et al. considered a two-compressor system with a FOL between 35% and 100%. Ramping rates reported in literature vary, but
The authors aim at developing a control 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 the storage of previously produced product. During shutdown mode, 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.,\textsuperscript{124} who also investigated a simple ASU scheme with an integrated storage and power network, originally presented by Johannsson.\textsuperscript{125} Interesting here is the objective to adapt the operation of the ASU toward minimizing GHG emissions rather than operating costs by utilizing time-resolved information on the composition of the power mix.

### 4.3.6 Absorption

Herrmann et al.,\textsuperscript{84} 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$_{\text{min}}$ was determined by de-wetting of the packing and the FOP$_{\text{max}}$ by flooding of the column. Both phenomena lead to a significant decrease in separation efficiency during operation. This process analysis leads 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.,\textsuperscript{126} 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.,\textsuperscript{127} 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 CO₂ compression subsequent to the capturing. Three control strategies were developed: constant CO₂ capture rate by manipulating the lean solvent flow, constant total solvent flow in absorber and desorber and maintaining constant CO₂ 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 CO₂ 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 CO₂ capture rate than manipulating reboiler temperature. The other strategies investigated might be useful for the start-up or shutdown of the process.

Zaman and Lee analised the possibility to enhance the flexibility of and switching off a CO₂ capture plant employing 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 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.

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 H₂ and O₂ as hydrogen may be needed in biofuel production. Figure 7 compares FOL found in literature on H₂ electrolysis. The flexibility options for this methanation step in PtG plants are reviewed in Section 4.2. The possibility to use H₂ storage in order to be able to flexibilize the energy demand of downstream unit operations was investigated by König et al. and Pfeiffer et al.

4.4.1 Hydrogen electrolysis

A review by Carmo et al. comprehensively highlights and reviews proton exchange membrane (PEM) systems for H₂ electrolysis. The challenges related to electro-catalysts, solid electrolytes, 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% FOPmin of alkaline electrolysis, PEM electrolysis can be run at 0%–10% FOPmin, enabling a much greater FOL. The IRENA hydrogen report provides an in-depth perspective on the nexus between H₂ and RE, on H₂ supply economics in light of the rapidly falling cost of RE and the role of H₂ in the energy transition, as well as on existing challenges that have hampered H₂ development to date.

A review of the role of energy storage with a special focus on long term storage was conducted by Blanco and Faaij 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. 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 extent through grid-connected demo projects. The scope of hydrogen-to-X pathways has also progressed over the years, especially to integrate industrial applications.

Investigating DSM application for the PEM electrolyzers, Herrmann et al. observed the system response to

![Figure 7 Flexible operating load range of hydrogen electrolysis as found in literature](image-url)
dynamic power input. Higher \( \mathrm{H}_2 \) production at higher than nominal capacity can lead to the increased degradation of electrodes. For flexibility purposes, a \( \text{FOP}_{\text{max}} \) 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.\(^{133}\) 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, results in significant deviations of the operating conditions.

Simulation models of an electrical power system developed by Kaiee et al.\(^{134}\) include steam turbine generation units, electrolyzers, conventional loads, and wind farms.\(^{135}\) As many as 24 electrolyzers with a nominal load of 2 MW each are considered, with a \( \text{FOP}_{\text{min}} \) of the electrolyzers 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 electrolyzers can provide useful frequency support to the power grid.

The economic analysis of Mukherjee et al.\(^{136}\) 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.\(^{137}\) 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 electrolyzers and thus allowing a FOL between 15% and 150%, can provide considerable benefits to ease renewable intermittency, while also supporting the deployment of \( \mathrm{H}_2 \) vehicles to help decarbonize the transportation sector.

Hosseini and Wahid\(^{138}\) perform thermodynamic analyses of the concentrated photovoltaic and electrolysis systems for solar \( \mathrm{H}_2 \) production. Alkaline water electrolysis was distinguished as the most promising electrolysis process for efficient and the near-term large-scale solar \( \mathrm{H}_2 \) 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 aluminum or chlorine by Gerés et al.\(^{139}\) Kiaee et al.\(^{140}\) Wang et al.\(^{141}\) Otashu et al.\(^{142}\) Simkoff and Baldea,\(^{142}\) and Brée et al.\(^{143}\) (see also Table 1 in Section 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.\(^{17}\) These studies on flexibilization in electrolytic processes follow the same control and optimization principles as \( \mathrm{H}_2 \) electrolysis, yet are not processes found in biorefineries.

### 5 | COMPARISON OF RESULTS ON DSM OPTIONS IN BIOFUEL PRODUCTION PLANTS

In this section, the processes named in Section 4 will be compared and the results are 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 from 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 8 graphically summarizes in a box plot diagram the distribution of the FOL per unit operation discussed in this review. The purpose 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.

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 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 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, the 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\(_{\text{min}}\) and FOP\(_{\text{max}}\) occur 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 a 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 H₂ 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 8). This is partly because the studies investigated have different approaches to 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 FT synthesis, flexible operation aims at reacting to fluctuating H₂ 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 processes, 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\textsubscript{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 to a variable pressure limit the FOP\textsubscript{min}. Other studies however consider switching off the RO plant completely resulting in the lower whisker of the boxplot diagram (Figure 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\textsubscript{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\textsubscript{min} has been analysed around at 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 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 H₂ electrolysis, this process is very promising for DSM applications and is already applied

![Image](https://example.com/figure8.png)
today. Lower flexibility restrictions depend on the type of electrolysis used. The FOP\textsubscript{min} is limited by the concentration of H\textsubscript{2} in oxygen at the anode side. The FOP\textsubscript{max} is limited to 150\%, as at higher than nominal operation the degradation of the electrode rises.

In summary, it could be demonstrated that many processes in biofuel production have a large FOL, making it seemingly relevant for DSM integration. From this review, it becomes clear, that especially mechanical processes and electrolysis offer a great flexibility potential 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.

6 | CONCLUSION AND PERSPECTIVES

A systematic review of options for DSM in biofuel production was presented in this contribution. Overall it 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.\textsuperscript{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\textsuperscript{1,144,145}, their impact on energy consumption and the flexibilization of it should be studied for future DSM applications. More production will lead to 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.

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REFERENCES

1. Ambaye TG, Vaccari M, Bonilla-Petriciolet A, Prasad S, van Hullebusch ED, Rtimi S. Emerging technologies for biofuel production: a critical review on recent progress, challenges and perspectives. J Environ Manage. 2021;290(1):112627. doi: 10.1016/j.jenvman.2021.112627

2. DENA, Roadmap Demand Side Management: Industrielles Lastmanagement für ein zukunftsfähiges Energiesystem. Berlin: Deutsche Energie-Agentur GmbH (dena), 2016. Accessed October 14, 2019. https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9146_Studie_Roadmap_Demand_Side_Management.pdf

3. Kakran S, Chanana S. Smart operations of smart grids integrated with distributed generation: A review. Renew Sustain Energy Rev. 2018;81(2):524-535. doi:10.1016/j.rser.2017.07.045
4. Garg A, Chauhan BVS, Vedantam A, Jain S, Bharti S. Potential and challenges of using biodiesel in a compression ignition engine. In: Agarwal, AK, Valera, H. (eds), Potential and challenges of low carbon fuels for sustainable transport. Energy, Environment, and Sustainability. Singapore: Springer. 2021. doi:10.1007/978-981-16-8414-2_9

5. Naumann K., Oehmichen K, Zeymer M, Meisel K, Anfahrt I, Trainer P., Monitoring Biokraftstoffsektor (4. Auflage). Available https://www.dbfz.de/pressemediathek/publikationsreihen-des-dbfz/dbfz-reports/dbfz-report-nr-11

6. Moioli E, Schildhauer T. Negative CO2 emissions from flexible biofuel synthesis: concepts, potentials, technologies. Renew Sustain Energy Rev. 2022;158:112120. doi:10.1016/j.rser.2022.112120

7. Majer S. Eds., Technical principles and methodology for calculating GHG balances of biodiesel, 1st edn. Leipzig: DBFZ, 2016. http://www.dbfz.de/fileadmin/user_upload/Referenzen/Broschueren/Handreichung_Biomethane_english.pdf

8. Meisel K. Eds., Technical principles and methodology for calculating GHG balances of bioethanol: guidance document. Leipzig: DBFZ; 2016 Version 1.0. https://www.dbfz.de/fileadmin/user_upload/Referenzen/Broschueren/Handreichung_Bioethanol_english.pdf

9. Oehmichen K., Naumann K, Postel J, et al., Eds., Technical principles and methodology for calculating GHG balances of biomethane, 1st edn. Leipzig: DBFZ, 2015. https://www.dbfz.de/fileadmin/user_upload/Referenzen/broschueren/Handreichung_Biomethan.pdf

10. Arnold K., Janßen T., Demand side management in industry: necessary for a sustainable energy system or a backward step in terms of improving efficiency? Wuppertal: Wuppertal Institut für Klima. Umwelt, Energie; 2018. https://nbn-resolving.org/urn:nbn:de:bsz:wup4-opus-69405

11. Bruns B, Di Pretoro A, Grünewald M, Riese J. Flexibility analysis for demand-side management in large-scale chemical processes: an ethylene oxide production case study. Chem Eng Sci. 2021;243(1):116779. doi:10.1016/j.ces.2021.116779

12. Mercure J-F, Salas P. An assessment of global energy resource economic potentials. Energy. 2012;46(1):322-336. doi:10.1016/j.energy.2012.08.018

13. Kaltenschmitt M, Streicher W, Wiese A. Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte: mit 83 Tabel len. Berlin: Springer; 2006. doi:10.1007/3-540-28205-X

14. Ströbele W, Pfaffengerber W, Heuterkes M. Energiewirtschaft: einführung in theorie und politik. 2nd ed. München: Oldenbourg; 2010. doi:10.1524/9783486716740

15. Nebel A, Krüger C, Janßen T, Saurat M, Kiefer S, Arnold K. Comparison of the effects of industrial demand side management and other flexibilities on the performance of the energy system. Energies. 2020;13(17):4448. doi:10.3390/ener13174448

16. Zeilinger FX, Einfelt A. Simulation der Auswirkung von Demand Side Management auf die Leistungsaufnahme von Haushalten, 2011. Accessed 2015. https://www.researchgate.net/publication/265894165_Simulation_der_Auswirkung_von_Demand_Side_Management_auf_die_Leistungsaufnahme_von_Haushalten

17. Klobasa M. Dynamische Simulation eines Lastmanagements und Integration von Windenergie in ein Elektrizitätsnetz auf Landesebene unter regelungstechnischen und Kostengeskichtspunkten. Düren: Dissertation; 2007.

18. Theurich S. Unsteady-state operation of a fixed-bed recycle reactor for the methanation of carbon dioxide. 1st ed. Düren: Dissertation; 2019.

19. Christoffersen LB, Larsen A, Togbye M. Empirical analysis of energy management in Danish industry. J Clean Prod. 2006;14(5):516-526. doi:10.1016/j.jclepro.2005.03.017

20. Stadler I. Demand response: Nichtelektrische Speicher für Elektrizitätsversorgungssysteme mit hohem Anteil erneuerbarer Energien. Zugl: Kassel, Univ., Habil., 2006. Berlin: dissertation.de. 2006. http://digbib.ubka.uni-karlsruhe.de/volltexte/digital/2/869.pdf

21. Stadler I. Power grid balancing of energy systems with high renewable energy penetration by demand response. Utilit Policy. 2007;16(2):90-98. doi:10.1016/j.jjepol.2007.11.006

22. McKane AT. Opportunities, Barriers and Actions for Industrial Demand Response in California. 2008. doi: 10.2172/945364

23. DENA, dena-Netzstudie II: Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015–2020 mit Ausblick 2025.Berlin: Deutsche Energie-Agentur GmbH (dena), 2010. Accessed October 21 2019. https://www.dena.de/fileadmin/user_upload/Download/Dokumente/Studien___Umfragen/Endbericht_dena-Netzstudie_II.PDF

24. Paulus D-W-I, Borggrefe F. Economic potential of demand side management in an industrialized country—the case of Germany. 2009. https://www.researchgate.net/publication/229015036_Economic_potential_of_demand_side_management_in_an_industrialized_country-the_case_of_Germany

25. Wang J, Boyd CN, Hu Z, Tan Z. Demand response in China. Energy. 2010;35(4):1592-1597. doi:10.1016/j.energy.2009.06.020

26. Worrell E, Blinde P, Neelis M, Blomen E, Masanet E. Energy efficiency improvement and cost saving opportunities for the U.S. Iron and steel industry. LBNL-Report. https://wwwosti.gov/servlets/purl/1026806https://wwwosti.gov/servlets/purl/1026806

27. Paulus M, Borggrefe F. The potential of demand-side management in energy-intensive industries for electricity markets in Germany. Appl Energy. 2011;88(2):432-441. doi:10.1016/j.apenergy.2010.03.017

28. Gobmaier T., von Roon S. Demand response in der industriestatistik. Zugl: Kassel, Univ., Habil., 2006. Berlin: dissertation.de. 2006. http://digbib.ubka.uni-karlsruhe.de/volltexte/digital/2/869.pdf

29. Apel R, VDE-Studie: Demand Side Integration: Lastverschiebungspotenziale in Deutschland: Studie der EnergieTechnischen Gesellschaft im VDE: Gesamttext. Frankfurt am Main: ETG VDE, 2012. https://www.ved.de/etg/publikationen/studien/etg-vde-studie-lastverschiebungspotenziale

30. Ates SA, Durakbasa NM. Evaluation of corporate energy management practices of energy intensive industries in Turkey. Energy. 2012;45(1):81-91. doi:10.1016/j.energy.2012.03.032

31. Sivill L, Manninen J, Hippinen I, Ahtila P. Success factors of energy management in energy-intensive industries: development priority of energy performance measurement. Int J Energy Res. 2013;37(8):936-951. doi:10.1002/er.2898

32. Gils HC. Assessment of the theoretical demand response potential in Europe. Energy. 2014;67:1-18. doi:10.1016/j.energy.2014.02.019

33. Klobasa M, Angerer G, Lüllmann A, Schleich J, Buber T. Agora Energiewende- Lastmanagement als Beitrag zur Deck-
ung des Spitzenlastbedarfs in Süddeutschland: Endbericht einer Studie von Frauenhofer ISI und der Forschungsgeellschaft für Energiewirtschaft. 2013. Accessed October 21, 2019. https://www.agora-energiewende.de/fileadmin2/Projekte/2012/Lastmanagement-als-Beitrag-zur-Versorgungssicherheit/Agora_Studie_Lastmanagement_Sueddeutschland_Endbericht_web.pdf

34. Merkert L, Harjunkoski I, Isaksson A, Säynevirta S, Saarela A, Sand G. Scheduling and energy – industrial challenges and opportunities. Comput Chem Eng. 2015;72:183-198. doi:10.1016/j.compchemeng.2014.05.024

35. Langrock T. Potentiale regelbarer Lasten in einem Energiesorgungssystem mit wachsendem Anteil Erneuerbarer Energien. Aachen: Büro für Energiewirtschaft, 2015. https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_19_2015_potentiale_regelbarer_lasten.pdf

36. Paramonova S, Thollander P, Ottosson M. Quantifying the extended energy efficiency gap-evidence from Swedish electricity-intensive industries. Renew Sustain Energy Rev. 2015;51(1):472-483. doi:10.1016/j.rser.2015.06.012

37. Shoreh MH, Siano P, Shafie-khah M, Loia V, Catalão JPS. A survey of industrial applications of demand response. Electr Pow Syst Res. 2016;141:31–49. doi:10.1016/j.epsr.2016.07.008

38. Steurer M. Analyse von Demand Side Integration im Hinblick auf eine effiziente und umweltfreundliche Energieversorgung. Dissertation Stuttgart. 2017.

39. Ausfelder F, Seitz A, von Roos S. Flexibilitätsoptionen in der Grundstoffindustrie: Methodik | Potenziale | Hemmnisse. DECHEMA-Chemie Ingenieur Technik. 2018. https://dechema.de/dechema_media/Bilder/Publikationen/Buch_FLEXIBILITAETSOPSIONEN-p-20003395.pdf

40. Baumgart B. Bereitstellung von nachfragegetriger Flexibilität bei vermehrter Einspeisung erneuerbarer Energien – Bedarf, Anreize und Potenziale. Dissertation. Duisburg, Essen: Universitätsbibliothek Duisburg-Essen; 2018.

41. Ladwig T. Demand Side Management in Deutschland zur Systemintegration erneuerbarer Energien. Dissertation. 5th ed. Dresden: Technische Universität; 2018.

42. Süder L, Lund PD, Koduvere H, et al. A review of demand side flexibility potential in northern Europe. Renew Sustain Energy Rev. 2018;91(99):654-664. doi:10.1016/j.rser.2018.03.104

43. Källcotte S, Olsen D, Sohn MD, Piette MA. Characterization of demand response in the commercial, industrial, and residential sectors in the United States. WIREs Energy En Wiley Interdisciplinary Rev Energy Env. 2019;5:288-304. doi:10.1002/wene.176

44. Lawrence A, Nehler T, Andersson E, Karlsson M, Thollander P. Drivers, barriers and success factors for energy management in the Swedish pulp and paper industry. J Clean Prod. 2019;223(2):67-82. doi:10.1016/j.jclepro.2019.03.143

45. Shafie-khah M, Siano P, Aghaei J, Masoum MAS, Li F, Catalao JPS. Comprehensive review of the recent advances in industrial and commercial DR. IEEE Trans Ind Inf. 2019;15(7):3757-3771. doi:10.1109/TII.2019.2909276

46. Talaei A, Ahiuzzaman M, Davis M, Gemechu E, Kumar A. Potential for energy efficiency improvement and greenhouse gas mitigation in Canada’s iron and steel industry. Energ Effic. 2020;13(6):1213-1243. doi:10.1007/s12053-020-09878-0

47. Hasan ASMM, Tuhan RA, Ullah M, Sakib TH, Thollander P, Trianni A. A comprehensive investigation of energy management practices within energy intensive industries in Bangladesh. Energy. 2021;232(9):120932. doi:10.1016/j.energy.2021.120932

48. Golmohamadi H. Demand-side management in industrial sector: a review of heavy industries. Renew Sustain Energy Rev. 2022;156(2):111963. doi:10.1016/j.rser.2021.111963

49. Gellings CW, Chamberlin JH. Demand-Side Management: Concepts and Methods. Lilburn, GA: Fairmont Press; 1987. https://wwwosti.gov/biblio/5275778

50. Statista. Electricity consumption worldwide in 2019. https://www.statista.com/statistics/267081/electricity-consumption-in-selected-countries-worldwide/

51. Statista. Primary energy consumption worldwide in 2020, by country. https://www.statista.com/statistics/263455/primary-energy-consumption-of-selected-countries/

52. Clean Energy Wire. Share of electricity from renewable sources in gross electricity consumption in European countries in 2019. https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts

53. Prior D Nachbildung der Energiebedarfsstruktur der privaten Haushalte: Werkzeug zur Bewertung von Energieeinsparmaßnahmen: VDI, 1997. https://www.econbiz.de/Record/nachbildung-der-energiebedarfsstruktur-der-privaten-haushalte-werkzeug-zur-bewertung-von-energieeinsparma%C3%9Fnahmen-prior-10000979642

54. Gils HC. Abschätzung des möglichen Lastmanagementeinsatzes in Europa,” 8. Internationale Energiewirtschaftstagung an der TU Wien, IEWT 2013; 2013. https://elib. ZfI.com/83717/1/Gils_Lastmanagementpotenziale_IEWT2013.pdf

55. Helin K, Käkki Anssi B, Zakeri RL, Syri S. Economic Potential for industrial demand side management in pulp and paper industry. Appl Energy. 2017;141:1681-1694. doi:10.1016/j. energy.2017.11.075

56. Vujanic R, Mariethoz S, Goulart P, Morari M. Robust integer optimization and scheduling problems for large electricity consumers. doi:10.1109/acc.2012.6314921

57. Pulkkinen P, Ritala R. TMP production scheduling under uncertainty: methodology and case studies. Chem Eng Proc Proc Intensif. 2008;47(9-10):1492-1503. doi:10.1016/j.cep.2007.06.017

58. Mitra S, Grossmann IE, Pinto JM, Arora N. Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes. Comput Chem Eng. 2012;38:171-184. doi:10.1016/j.compchemeng.2011.09.019

59. Zhang X, Hug G, Kolter JZ, Harjunkoski I. Demand response of ancillary service from industrial loads coordinated with energy storage. IEEE Trans Power Syst. 2018;33(1):951-961. doi:10.1109/TPWRS.2017.2704524

60. Numbi BP, Zhang J, Xia X. Optimal energy management for a jaw crushing process in deep mines. Energy. 2014;68:337-348. doi:10.1016/j.energy.2014.02.100

61. Numbi BP, Xia X. Optimal energy control of a crushing process based on vertical shaft impactor. Appl Energy. 2016;162:1653-1661. doi:10.1016/j.apenergy.2014.12.017

62. Zhang Q, Grossmann IE, Pinto JM. Optimal demand side management for cryogenic air separation plants. 2017, doi: 10.1007/978-3-319-42803-1_18
63. Trommler M. Flexibilisierung von Biogasanlagen in Deutschland: Ein Überblick zu technischen Ansätzen, rechtlichem Rahmen und Bedeutung für das Energiesystem. Hintergrundpapier. Leipzig: Deutsches Biomasseforschungszentrum DBFZ; 2016. https://edocs.tib.eu/files/o1fm17/884756831.pdf

64. Peters L, Uehlenuft F, Biernacki P, Steinigeweg S. Aktueller Stand der Flexibilisierungskonzepte von Biogasanlagen zur Abdeckung der Residuallast. Chemie Ingenieur Technik. 2018; 90(1–2):36-46. doi:10.1002/iict.201700101

65. Thrän D, Ed., Neue Wege zur Prozessoptimierung in Biogasanlagen: Abgeschlossene Vorhaben im BMU-Förderprogramm. Leipzig: DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH; 2014. https://www.researchgate.net/publication/338402835_Neue_Wege_zur_Prozessoptimierung_in_Biogasanlagen_abgeschlossene_Vorhaben_im_Förderprogramm_Teil_3

66. Dotzauer M, Kornatz P, Siegismund D. Bewertung von Flexibilisierungskonzepten für Bioenergienanlagen: Wirtschaftlichkeitsbetrachtungen für sieben Anlagenspiele. Deutsches Biomasseforschungszentrum gemeinnützige GmbH; 2018. https://www.unendlich-viel-energie.de/medialib/publikationen/bewertung-von-flexibilisierungskonzepten-fuer-bioenergienanlagen3

67. Bruns B, Herrmann F, Polyakova M, Grünewald M, Riese J. A systematic approach to define flexibility in chemical engineering. Int J Adv Manuf Process. 2020;73(4):74. doi:10.1002/amp2.10063

68. DENA. Power to X: Technologien. 2018. https://www.dena.de/fileadmin/dena/Dokumente/Pdf/607/9264_Power_to_X_Technologien.pdf

69. Braune M, Grasemann E, Gröninger A, Klemm M, Oehmichen K, Zech K, Eds., Die Biokraftstoffproduktion in Deutschland - Stand der Technik und Optimierungsansätze, 1st ed. Leipzig: Deutsches Biomasseforschungszentrum gemeinnützige GmbH; 2016. https://www.dbfz.de/pressemediathek/publikationsreihen-des-dbfz/dbfz-reports/dbfz-report-rr-22

70. Hahn H. Schlussbericht zum Verbundvorhaben: Regelung der Gasproduktion von Biogasanlagen (ReBi); Teilvorhaben 1: Verfahrenstechnische und energiewirtschaftliche Analyse und Bewertung. Kassel: Fraunhofer IWES; 2015. https://www.izes.de/sites/default/files/publikationen/20210131_BE20plus_Schlussbericht_31.01.2021_final.pdf

71. Bensmann AL. Modellbasierte Analysen zur Gestaltung und Betriebführung von Biogasanlagen. Dissertation München: Verlag Dr. Hut. 2016.

72. Häring G, Sonnleitner M, Wiedemann L, Zörner W, And Aschmann V. Technische Anforderungen an Biogasanlagen für die flexible Stromerzeugung. Biogas Forum Bayern, Nr. IV – 12/2013, 2013. https://www.biogas-forumbayern.de/publikationen/technische-anforderungen-an-biogasanlagen-fuer-die-flexible-stromerzeugung.pdf

73. Choorit W, Wisarnwan P. Effect of temperature on the anaerobic digestion of palm oil mill effluent. Electron J Biotechnol. 2007;10(3):376-385. doi:10.2225/vol10-iss3-fulltext-7

74. Bousková A, Dohnályos M, Schmidt JE, Angelidaki I. Strategies for changing temperature from mesophilic to thermophilic conditions in anaerobic CSTR reactors treating sewage sludge. Water Res. 2005;39(8):1481-1488. doi:10.1016/j.watres.2004.12.042

75. Obaya MC, Valdés E, Ramos J. Stability studies of thermophilic anaerobic sludges under suboptimal feeding conditions and temperatures. Acta Biotechnol. 1994;14(2):193-198. doi:10.1002/abio.370140213

76. Chae KJ, Jang AM, Yim SK, Kim IS. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. Biorsour Technol. 2008;99(1):1-6. doi:10.1016/j.biortech.2006.11.063

77. Ahn J-H, Forster CF. The effect of temperature variations on the performance of mesophilic and thermophilic anaerobic filters treating a simulated papermill wastewater. Process Biochem. 2002;37(6):589-594. doi:10.1016/S0032-9592(01)00245-X

78. Lau IWC, Fang HHP. Effect of temperature shock to thermophilic granules. Water Res. 1997;31(10):2626-2632. doi:10.1016/S0043-1354(97)00110-3

79. El-Mashad HM, Zeeman G, van Loon WKP, Bot GPA, Lettinga G. Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. Biorsour Technol. 2004;95(2):191-201. doi:10.1016/j.biortech.2003.07.013

80. Gao WJ, Leung KT, Qin WS, Liao BQ. Effects of temperature and temperature shock on the performance and microbial community structure of a submerged anaerobic membrane bioreactor. Biorsour Technol. 2011;102(19):8733-8740. doi:10.1016/j.biortech.2011.07.095

81. Luo G, de Francisci D, Kougias PG, Laura T, Zhu X, Angelidaki I. New steady-state microbial community compositions and process performances in biogas reactors induced by temperature disturbances. Biotechnol Biofuels. 2015;8:3. doi:10.1186/s13068-014-0182-y

82. Theurich S, Rönsch S, Güttel R. Transient flow rate ramps for Methanation of carbon dioxide in an adiabatic fixed-bed recycle reactor. Energy Technol. 2019;8(3):1901116. doi:10.1002/ente.201901116

83. Rönsch S, Matthischke S, Müller M, Eichler P. Dynamische Simulation von Reaktionen zur Festbettmethanisierung. Chemie Ingenieur Technik. 2014;86(8):1198-1204. doi:10.1002/cite.201300046

84. Herrmann F, Grünewald M, Riese J. Flexibility of power-to-gas plants: a case study. Chemie Ingenieur Technik. 2020; 92(12):1983-1991. doi:10.1002/cite.202000063

85. Hitachi Zosen Inova Etagas GmbH. Hocheffizientes Verfahren zur katalytischen Methanisierung von Kohlendioxid und Wasserstoff enthaltenden Gasgemischen. DE102009059310A.

86. Kreitz B, Brauns J, Wehinger GD, Turek T. Modeling the dynamic power-to-gas process: coupling electrolysis with CO2 Methanation. Chemie Ingenieur Technik. 2020;92(12):1992-1997. doi:10.1002/cite.202000019

87. Kreitz B, Wehinger GD, Turek T. Dynamic simulation of the CO2 methanation in a micro-structured fixed-bed reactor. Chem Eng Sci. 2019;195:541-552. doi:10.1016/j.ces.2018.09.053

88. Tauer G, Kern C, Jess A. Transient effects during dynamic operation of a wall-cooled fixed-bed reactor for CO2 Methanation. Chem Eng Technol. 2019;42(11):2401-2409. doi:10.1002/ceat.201900367

89. Mutz B, Carvalho HWP, Mangold S, Kleist W, Grunwaldt J-D. Methanation of CO2: structural response of a Ni-based catalyst under fluctuating reaction conditions unravelled by
120. Caspari A. Economic nonlinear model predictive control of multi-product air Separation Processes. 2019. doi: 10.1016/j.jprocont.2019.10.008

121. Caspari A, Offermanns C, Schäfer P, Mhamdi A, Mitsos A. A flexible air separation process: 1. Design and steady-state optimizations. AIChE J. 2019;65(11):467. doi:10.1002/aic.16705

122. Caspari A, Offermanns C, Schäfer P, Mhamdi A, Mitsos A. A flexible air separation process: 2. Optimal operation using economic model predictive control. AIChE J. 2019;65(11):454393. doi:10.1002/aic.16721

123. Ierapetritou MG, Wu D, Vin J, Sweeney P, Chigirinskiy M. Cost minimization in an energy-intensive plant using mathematical programming approaches. Ind Eng Chem Res. 2002; 41(21):5262-5277. doi:10.1021/ie011012b

124. Kelley MT, Baldick R, Baldea M. Demand response operation of electricity-intensive chemical processes for reduced greenhouse gas emissions: application to an air separation unit. ACS Sustainable Chem. Eng. 2018;7(2):1909-1922. doi:10.1021/acssuschemeng.8b03927

125. Johansson T. Integrated scheduling and control of air separation unit subject to timevarying electricity price. Thesis. Stockholm. https://www.diva-portal.org/smash/get/diva2:855080/FULLTEXT01.pdf

126. Luu MT, Abdul Manaf N, Abbas A. Dynamic modelling and control strategies for flexible operation of amine-based post-combustion CO2 capture systems. Int J Greenhouse Gas Contr. 2015;39:377-389. doi:10.1016/j.ijggc.2015.05.007

127. Mechleri E, Lawal A, Ramos A, Davison J, Dowell NM. Process control strategies for flexible operation of post-combustion CO2 capture plants. Int J Greenhouse Gas Contr. 2017;57:14-25. doi:10.1016/j.ijggc.2016.12.017

128. Zaman M, Lee JH. Optimization of the various modes of flexible operation for post-combustion CO2 capture plant. Comput Chem Eng. 2015;75:14-27. doi:10.1016/j.compchemeng.2014.12.017

129. Carmo M, Fritz DL, Mergel J, Stolten D. A comprehensive review on PEM water electrolysis. Int J Hydrogen Energy. 2013;38(12):4901-4934. doi:10.1016/j.ijhydene.2013.01.151

130. IRENA. Hydrogen: A Renewable Energy Perspective. Abu Dhabi: International Renewable Energy Agency, 2019. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

131. Blanco H, Faaij A. A review at the role of storage in energy systems with a focus on power to gas and long-term storage. Renew Sustain Energy Rev. 2018;81:1049-1086. doi:10.1016/j.rser.2017.07.062

132. Chehade Z, Mansilla C, Lucchese P, Hilliard S, Proost J. Review and analysis of demonstration projects on power-to-X pathways in the world. Int J Hydrogen Energy. 2019;44(51): 27637-27655. doi:10.1016/j.ijhydene.2019.08.260

133. Eichman J, Harrison K, Peters M. Novel Electrolyzer Applications: Providing more than Just Hydrogen. 2014. https://www.enwg-veroeffentlichungen.de/aalen/Netze/Gasnetz/Netzan schluss-Biogas/technische-mindestanforderungseisung.pdf

134. Kiaee M, Cruden A, Infeld D, Chladek P. Improvement of power system frequency stability using alkaline electrolysis plants. Proc Instit Mech Eng Part A J Power Energy. 2013; 227(1):115-123. doi:10.1177/0957650912466642

135. Kiaee M, Cruden A, Infeld D, Chladek P. Utilisation of alkaline electrolysers to improve power system frequency stability with a high penetration of wind power. IET Renew Power Gener. 2014;8(5):529-536. doi:10.1049/iet-rpg.2012.0190

136. Mukherjee U, Walker S, Fowler M, Elkamel A. Power-to-gas in a demand-response market. Int J Environm Stud. 2016; 73(3):390-401. doi:10.1080/00207233.2016.1165479

137. Wang D, Muratori M, Eichman J, Wei M, Saxena S, Zhang C. Quantifying the flexibility of hydrogen production systems to support large-scale renewable energy integration. J Power Sources. 2018;399(5):383-391. doi:10.1016/j.jpowsour.2018.07.101

138. Hosseini SE, Wahid MA. Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy. Int J Energy Res. 2020;44(6):4110-4131. doi:10.1002/er.4930

139. Geres R, Kohn A, Lenz S, Ausfelder F, Bazzanella AM, Möller A. Roadmap Chemie 2050: Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland. 2019. Accessed October 22, 2019. https://dechema.de/dechema_media/Downloads/Positionspapiere/2019_Studie_Roadmap_Chemie_2050-p-2000590.PDF

140. Wang X, Teichgraeber H, Palazoglu A, El-Farra NH. An economic receding horizon optimization approach for energy management in the chlor-alkali process with hybrid renewable energy generation. J Process Contr. 2014;24(8):1318-1327. doi:10.1016/j.jprocont.2014.04.017

141. Otashu JI, Baldea M. Scheduling chemical processes for frequency regulation. Appl Energy. 2020;260:114125. doi: 10.1016/j.apenergy.2019.114125

142. Simkoff JM, Baldea M. Stochastic scheduling and control using data-driven nonlinear dynamic models: application to demand response operation of a Chlor-alkali plant. Ind. Eng. Chem. Res. 2020;59(21):10031-10042. doi: 10.1021/acs.ier.9b06866

143. Brée LC, Perrey K, Bulan A, Mitsos A. Demand side management and operational mode switching in chlorine production. AIChE J. 2018;65(7):e16352. doi:10.1002/aic.16352

144. Schröder J, Naumann K. Monitoring and analysing a hydrogen production system at the DBFZ, Leipzig. 2022. Biomasseforschungszentrum gemeinnützige GmbH; 2022.

145. Yadav KK, Krishnan S, Gupta N, et al. Review on evaluation of renewable bioenergy potential for sustainable development: bright future in energy practice in India. ACS Sustainable Chem. Eng. 2021;9(48):16007-16030. doi:10.1021/acs.suschemeng.1c03114

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