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Obstacles to demand response: Why industrial companies do not adapt their power consumption to volatile power generation

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ABSTRACT

Various flexibility options in power systems, such as storage, grid expansion, and demand flexibility, gain increasing importance to balance the intermittent power supply of renewables. On the demand side, especially the industrial sector represents promising potential for Demand Response, i.e., the alignment of its power demand with the current power supply of renewables. However, there exist various obstacles that currently prevent companies from investing in new or (fully) exploiting existing flexibility potentials. In this paper, we investigate how economic, regulatory, technological, organizational, behavioral, informational, and competence obstacles pose barriers for companies to adjust their power consumption flexibly. For this purpose, we combine both a structured literature analysis and a case study. For the case study, we conduct 16 interviews with energy experts from companies from different industries. Our findings reveal that due to technical risk of disrupting the production process, lacking revenues, and too low cost savings, companies do not flexibilize their power consumption. Moreover, in particular, contradictory legislative incentives and missing IT standardization and interoperability represent key obstacles. Therefore, our results constitute a basis for targeted policy making in order to foster the exploitation of (existing) flexibility potential of industrial companies on the demand side.

1. Introduction

In the course of the energy transition, the share of variable power from wind turbines and photovoltaic plants is continuously increasing in many countries (Hansen et al., 2019). With the associated growing generation intermittency, the power system faces the challenge of maintaining the necessary balance between power supply and demand. Hence, there is a need for additional flexibility, which refers to measures that adapt power generation and consumption (Lund et al., 2015). In the past, primarily the supply side, i. e., conventional power plants, provided the necessary flexibility. With the expansion of Renewable Energy Sources (RES), however, conventional power plants are pushed out of the market due to the merit order effect (Sensfuβ et al., 2008). In addition, RES are only able to offer limited flexibility as it is only possible to lower their feed-in. As a result, flexibility on the supply side is decreasing (Ding et al., 2018; Papaefthymiou et al., 2018). Papaefthymiou et al. (2018) describe this development as the "flexibility gap".

Literature indicates that there are mainly four flexibility options to address the flexibility gap: (New) flexibility on the supply side, flexibility through storage, flexibility in form of an expansion of the power grid, and flexibility on the demand side (Gils, 2016; Lund et al., 2015; Müller and Möst, 2018). Initial expenses for investing in energy storages are still high (Brouwer et al., 2016) and new transmission lines face long construction time with delays and public resistance (Perras, 2015). Therefore, flexibility on the demand side represents a promising solution to close the flexibility gap and is generally considered as a competitive flexibility option with comparatively low marginal costs (Gils, 2016).

The demand side typically includes the industrial, residential, commercial and public services, transport, agriculture/forestry, and fishing sector. Thereof, the industrial sector accounts for the largest share of power consumption (world average 40%) (International Energy Agency,

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2020). Given its high share, the industrial sector may exhibit great flexibility potentials (Sauer et al., 2019; International Energy Agency, 2020). Generally, there are fewer but more power intensive consumers in the industrial sector compared to the other sectors. The exploitation of (industrial) demand flexibility promises advantages for both, the power system's balance and for the flexibility supplier. Therefore, demand flexibility of the industrial sector may significantly contribute to closing the arising flexibility gap.

Despite significant potentials of demand flexibility for industrial flexibility suppliers and increasing possibilities to monetize Demand Response (DR) in recent years (Paterakis et al., 2017), many power-intensive companies still refrain from supplying flexibility (Unterberger et al., 2018). Only few existing publications explicitly examine obstacles to the implementation of demand flexibility in the industrial sector. Grein and Pehnt (2011) present some obstacles for DR in the specific case of refrigerating warehouses. Alcázar-Ortega et al. (2012) conduct a similar analysis specifically for the meat industry, whereas Zhang and Grossmann (2016b) take the perspective of a manufacturing company. Conducting a more holistic survey in 2013, Olsthoorn et al. (2015) identified and weighted obstacles for companies in Southern Germany. The authors distinguish their identified obstacles according to Cagno et al. (2013) into technological, information, regulatory, economic, behavioral, organizational, and competence obstacles. Their results indicate that disruption of operations, impact on product quality, and uncertainty about cost savings are the most relevant barriers (Olsthoorn et al., 2015). Also Alcázar-Ortega et al. (2015) identify obstacles of demand flexibility from an industrial consumer perspective but focus mostly on market and regulatory issues. Even though the work of Olsthoorn et al. (2015) and Alcázar-Ortega et al. (2015) provide a profound basis for this research area by identifying potential obstacles, both papers do not examine the obstacles in depth and answer the question why, e.g., certain regulations are obstacles for companies in establishing flexibility measures. In particular, it is necessary to understand why and how certain obstacles to demand flexibility affect the decision-making of companies with regard to demand flexibility. Being able to derive corresponding corrective policy measures, it is essential to understand the causes and interrelations of the respective obstacles to successfully remove obstacles in practice. Hence, in this paper, we address the following research question:

How are economic, regulatory, technological, organizational, behavioral, informational, and competence obstacles preventing companies in the industrial sector from (fully) exploiting existing or investing in new flexibility potential?

To answer this research question, in the first step, we accomplished a structured literature analysis on potential obstacles to the use of existing and investment in new industrial demand flexibility. In the second step, we conducted an interview case study with energy experts from German companies in the industrial sector. The result of this two-step approach is a detailed overview – based on the categorization of Cagno et al. (2013) – of obstacles and underlying causes in terms of demand flexibility from the viewpoint of companies in the industrial sector. This allows us to investigate whether the developments in the power system since the survey of Olsthoorn et al. (2015) in 2013 and Alcázar-Ortega et al. (2015) in 2015 have led to a reduction in or elimination of the obstacles for demand flexibility identified by the latter. Thereby, we can close a research gap by providing detailed insights into how the obstacles affect companies in exploiting their flexibility potential. Based on the identified obstacles and underlying factors, we finally derive policy recommendations for enhancing the current legal framework with respect to industrial demand flexibility. Therefore, the paper constitutes a basis for public decision-makers to reduce obstacles to the exploitation of and investment in industrial demand flexibility.

The paper is organized as follows. In Section 2, we describe the relevant concepts of Demand-Side Management (DSM) and DR as well as how companies can realize demand flexibility, following Section 3, where we present our research method. On this basis, in Section 4, we derive our main findings, i.e., obstacles in an economic, regulatory, technological, organizational, behavioral, informational, and competences context resulting from both the literature review and the multiple case study. Finally, in Section 5, we discuss our results while, in Section 6, we derive policy implications, conclude, and describe limitations of our paper.

2. Theoretical background

Based on existing literature, this section aims to clarify the terminology of DSM and DR as well as to describe general possibilities for companies to provide demand flexibility. Existing work often divides DSM into different categories, dimensions, and elucidate characteristics (Palensky and Dietrich, 2011; Feuerriegel and Neumann, 2014; Dudley and Piette, 2008). Palensky and Dietrich (2011) categorize DSM into five different types depending on their time interval and their impact on business processes. Within this categorization, DR generally comprises the short-term change of power consumption patterns (Palensky and Dietrich, 2011; Feuerriegel and Neumann, 2014). Since we focus on short-term flexibility in this paper, in the following, we refer to DR when we consider flexibility on the demand side.

Companies can generally provide three different kinds of short-term flexible loads when they implement DR measures: The first option is temporal load shifting that encompasses the interruption or postponement of a power-consuming process in order to reduce peak loads (Palensky and Dietrich, 2011; Fridgen et al., 2016; Feuerriegel and Neumann, 2014). Second, companies have the possibility to adjust power consumption by not undertaking previously planned activities. This is referred to as load shedding (Fridgen et al., 2017; Feuerriegel and Neumann, 2014). Third, a change between different energy carriers like power and gas creates further flexible loads (Haupt et al., 2020; Palensky and Dietrich, 2011).

By exploiting these short-term flexible loads, industrial companies have different possibilities to reduce power costs or generate profit. Generally, short-term power markets (Biegel et al., 2014; Clò et al., 2015) exhibit increased volatilities in power prices due to a growing share of RES (Nicolosi and Fürsch, 2009; Rintamäki et al., 2017). In addition to marketing flexibility on power markets, ancillary service markets allow companies to receive payments for providing flexibility to grid operators (Biegel et al., 2014). Companies can also use flexibility to reduce their power peak, i.e., the maximum power consumption during a specific time period, to lower grid-fee payments which primarily depend on the peak load. Another way to use flexibility relates to own power generation capacities that increase a company's independence from external (and uncertain) power prices.

3. Research method

In the following two sections, we describe our qualitative-empirical research approach in more detail. In order to provide a comprehensive overview of the existing obstacles, we first collect and analyze obstacles to the implementation of DR from literature. Here, we rely on the classification of the obstacles of Cagno et al. (2013) and Olsthoorn et al. (2015). Second, we describe the compilation of our multiple case study using 16 interviews with experts from German companies (Yin, 2017). This two-step approach allows us to identify (i) which obstacles appear both in the literature and in the case study and which obstacles are yet neglected (ii) by literature or (iii) by our interview partners. The multiple case study further enhances our knowledge on how these obstacles affect companies.

3.1. Literature review

Following the well-established approach for literature review by

Table 1
Databases and journals for the systematic literature search.

Databases	Journals
IEEEXplore	Energy Policy
Science Direct	Renewable & Sustainable
EBSCO Academic Search	Energy Reviews

Table 2
Search strings for the systematic literature search.

	Search Strings	
Demand-Side Management		Obstacle Barrier
Demand Response	*in all combinations*	Challenge Review
Demand-Side Integration	*with*	Evaluation Problem
Load Management		Experience

Webster and Watson (2002), we collected relevant literature by scanning the most common databases and specific journals – for which we found most articles in the previous database search – in the field of energy research. Table 1 lists the databases and journals we used.

To obtain a suitable selection of relevant literature, we combined similar terms of "Demand Response" with those for "Obstacle" into search strings (cf. Table 2).

After using the search strings (cf. Table 2) in the selected databases (cf. Table 1), we narrow the resulting literature down by analyzing the titles and, afterwards, the abstracts. Then, we thoroughly scan all volumes and issues (without applying search strings) of the two journals Energy Policy and Renewable & Sustainable Energy Reviews for which we have the most results in the search of the selected databases.

In each step, we apply specific exclusion and inclusion criteria (cf. Table 3). The selection process results in a final list of 137 publications that address obstacles to DR implementation.

We extend the selected literature by a backward (publications that are cited by the final 137 publications) and forward (more recent publications that cite the final 137 publications' list) literature search obtaining 15 further relevant publications. Fig. 1 illustrates the number of results per database as well as the results after applying the inclusion and exclusion criteria to title and abstract. In Fig. 1, the listed sources are in line with the order of the applied search strings. We exclude publications that we have already found in a previous database, i.e., duplicates, after scanning the resulting titles.

Out of the total 152 relevant papers, we find obstacles for industrial DR implementation in 83 papers. We remove the remaining 69 papers as they, e.g., examine pricing methods which did not follow directly from the abstracts of the respective papers. In order to structure the individual obstacles identified in the relevant publications, we follow the concept-centric organization of results as proposed by Webster and Watson (2002). Hence, for each article, we analyze which groups of obstacles were identified in the respective article. When grouping the obstacles into concepts, we use the seven categories of obstacles as presented by Cagno et al. (2013) and Olsthoorn et al. (2015).

3.2. Multiple case study

In the following, we illustrate the methodology for conducting the interviews and deriving the corresponding multiple case study according to Yin (2017). Our primary method for data collection are qualitative interviews. Interviews are a well-established method for qualitative research like case studies (Myers and Newman, 2007; Schultze and Avital, 2011). As the integration of multiple data sources is recommended to triangulate the results (Creswell and Poth, 2016), we incorporate different information sources (e.g., interviews and field observations, internal presentations and documents, publicly available media information). The information sources stem mostly from the publicly funded project "SynErgie": The German publicly funded project *Synchronized and Energy-Adaptive Production Technology for the Flexible Adjustment of Manufacturing Processes to a Volatile Energy Supply* (SynErgie) has been running since 2016 (Sauer et al., 2019). The project's goal is to improve the usage of companies' flexibility potential in Germany. Following purposive sampling method (Bhattacherjee, 2012), we define criteria for interview partner selection (e.g., actual involvement in energy management) and conduct 16 interviews with experts in energy management in person or via video calls. Note that the interviews stem from 14 different companies, as the interview partners of the Cases 11, 14, and 15 represent the same company. Due to the different areas of expertise, every interview represents one case. Table 4 gives an overview of the companies and interview partners of our multiple case study. The description of the interviewed partners (cf. Table 4) highlights that our interview partners come from both different industries and areas of competence. The order of interviewed partners in the table corresponds to the sequence in which we conduct the interviews. Each interview lasts from 45 to 90 min. We audio-recorded and transcribed each interview.

Table 3
Inclusion and exclusion criteria for the systematic literature search.

Inclusion Criteria	Exclusion Criteria
- The paper focuses on identifying obstacles or negative experiences with DSM, DR or Demand-Side Integration (DSI).	- The paper does not address the research question of this paper in any manner.
- The paper has energy sector and grid balance related topics as its subject (e.g., DSM, DR, DSI).	- The paper does not have topics of the energy sector (i.e., other fields of study like medical science, biochemistry, or tourism) as its subject.
- The paper focuses on general DSM/DSI measures or on specific DR measures.	- The paper only focuses on energy efficiency as part of possible DSM measures.
- The paper focuses on general measures or on specific industrial measures.	- The paper only focuses on residential measures.
- The paper focuses on the general grid balance and encompasses several sources of energy.	- The paper focuses only on measures in reference to a single source of energy (e.g., wind power).
- The paper is recently published (dating at most back to the year 2000).	- The paper is published before the year 2000.

Table 4
Overview of the multiple case study.

Case	Business Domain	Employees worldwide	Interview partner(s)
1	Paper industry	>10,000	Manager energy procurement; Manager core process
2	Processing industry	>10,000	Manager process development
3	High-tech industry	>10,000	Energy manager
4	Food industry	>10,000	Project engineer
5	Automotive industry	>10,000	Energy commissioner
6	High-tech industry	>1000	Technical energy manager
7	Automotive industry	>10,000	Energy commissioner
8	Aluminum industry	>1000	Head of energy management; Energy product manager
9	Software engineering	ca. 600	Head of BU Energy
10	Chemical industry	>50,000	Energy manager
11	Energy Consulting	ca. 200	Consultant BU Energy & Mobility
12	Food industry	>5000	Head of energy management; Energy management expert
13	Chemical industry	>10,000	Energy strategy & policy
14	Energy Consulting	ca. 200	Head of BU Energy & Mobility
15	Energy Consulting	ca. 200	Consultant in electrical planning
16	Processing/ Automotive industry	>50,000	Energy manager; Manager for "Industrie 4.0"

The transcripts serve as a basis for the corresponding multiple case study.

We use a semi-structured protocol intended to elicit stories from the various companies (Myers and Newman, 2007). First, the interviewer and interview partner introduce themselves. Second, to minimize social dissonance in the interview, the interviewer explains how each interview will be anonymized and secured. In line with Schramm (1971), we ask the interview partners about factors like internal structures and processes that influence the decision about the implementation of DR. We also query how well the implementation of current flexibility-related projects works and how information systems and the respective services influence the success of DR. For the semi-structured interviews, we prepare general questions in sub-categories. Depending on the interview partner, we adapt those questions to the expertise of the interview partner. During the interviews, we tailor the questions to shift the interviews' focus depending on the interview partner's knowledge and actual expertise (Myers and Newman, 2007).

Finally, we follow the recommendations of Miles et al. (2014) regarding the two-stage process of inductive and deductive coding of gathered information: All authors analyze the data and document their conclusions about relevant obstacles independently of each other. Subsequently, we discuss the individual interpretations. Afterwards, three authors individually categorized all identified obstacles to one of the seven obstacle categories according to the taxonomy of Cagno et al. (2013). Then, we directly assigned all identified obstacles with identical individual suggested categorization to the corresponding category. However, in cases of differing suggested categorization, the authors discussed these cases and came to an agreement on the most suitable category. Finally, during the subsequent paper process, all authors iteratively combined similar obstacles and we partly re-assigned the categorization. Note that an obstacle may have relations to other categories, although we assign each obstacle to one of the seven categories.

4. Findings

In the following, we combine obstacles to DR from our systematic literature search with those obtained from our multiple case study grouped by the seven categories proposed by Cagno et al. (2013) and Olsthoorn et al. (2015). Although we assign each obstacle to one of the seven categories, note that an obstacle may have relations to other categories. There are also obstacles that would fit into more than one category – however, we assign these obstacles to a corresponding category that fits best from our point of view. For each category, we describe the identified obstacles and list them in a table. Each table includes the corresponding obstacles together with the literature sources and/or cases from which the obstacle originates. All obstacles have an ID, where the first letter describes the obstacle's category and a digit depicts the obstacle's number. This allows us to use cross-references between obstacles to reveal relations between the categories.

4.1. Economic obstacles

This section deals with the economic obstacles which include internal factors such as costs for the provision of flexibility and external factors like characteristics of power markets. Table 5 contains all identified economic obstacles and summarizes the corresponding literature and case(s).

E1 – Share of overall power cost too small within total production costs: If the share of power costs is too small compared to the total production costs, companies mostly do not even consider to realize flexibility in production.

E2 – Greater economic appeal of alternative measures to optimize power costs: The reduction of power costs through DR may be small compared to alternative measures to optimize power demand and, therefore, reduce power costs. Hence, in our case study, companies often prefer to implement measures that directly lead to visible savings in power costs

Table 5
Economic obstacles.

ID	Obstacle	Literature	Case(s)
E1	Share of overall power cost too small within total production costs	Gitelman et al. (2013), Jang et al. (2015), Sharma et al. (2019), Vine et al. (2003), Wohlfarth et al. (2020a), Wohlfarth et al. (2020b)	5, 9
E2	Greater economic appeal of alternative measures to optimize power costs	–	2, 4, 5, 6, 7, 9, 10, 12
E3	Lack of revenues through DR	Albadi and El-Saadany (2008), Annala et al. (2018a), Borsche and Andersson (2014), Cruz et al. (2018), Good et al. (2017), Feuerriegel and Neumann (2016), Honkapuro et al. (2015), Jang et al. (2015), Katz (2014), Kreuder et al. (2013), Luthra et al. (2014), McKane et al. (2008), Mlecnik et al. (2020), Nguyen (2010), Pinson et al. (2014), Rollert (2018), Shoreh et al. (2016), Torriti et al. (2010), Verpoorten et al. (2016), Wohlfarth et al. (2020b)	1, 3, 4, 5, 6, 7, 8, 10, 12, 13, 14
E3.1	(Power) cost savings through DR are low	Albadi and El-Saadany (2008), Alcázar-Ortega et al. (2015), Borsche and Andersson (2014), Katz (2014), Kleingeld et al. (2012), Olsthoorn et al. (2015), Paterakis et al. (2017)	1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 13, 14
E3.2	Price-spreads on spot markets too small	Alcázar-Ortega et al. (2015), Annala et al. (2018b), Koliou et al. (2013), Pinson et al. (2014), Rautiainen et al. (2017), Verpoorten et al. (2016)	2, 3, 9, 13
E3.3	(Potentially) decreasing profitability in ancillary service markets	Goulden et al. (2018), Liu (2017), Nolan and O'Malley (2015), Paterakis et al. (2017), Rautiainen et al. (2017), Rollert (2018)	2, 6, 8, 9, 10
E4	Costly flexibility investments necessary	Albadi and El-Saadany (2008), Alcázar-Ortega et al. (2015), Bradley et al. (2013), Cappers et al. (2013), Cruz et al. (2018), Dong et al. (2016), Good et al. (2017), Kreuder et al. (2013), Macedo et al. (2013), Nguyen (2010), Olsthoorn et al. (2015), Rollert (2018), Shafie-khah et al. (2019), Shen et al. (2014), Vine et al. (2003)	1, 8, 10, 11
E4.1	High IT investments necessary	Aghaei and Alizadeh (2013), Álvarez et al. (2017), Annala et al. (2018a), Bradley et al. (2013), Cappers et al. (2013), Hansen et al. (2014), Katz (2014), Kreuder et al. (2013), MacDonald et al. (2012), Nguyen (2010), Paterakis et al. (2017), Shen et al. (2014), Vallés et al. (2016), Vine et al. (2003), Olsthoorn et al. (2015)	1, 6, 7, 14
E5	Lack of access to external and internal capital	Good et al. (2017), Olsthoorn et al. (2015), Vine et al. (2003)	–
E6	Additional operating costs due to DR measures	Aghaei and Alizadeh (2013), Alcázar-Ortega et al. (2012), Alcázar-Ortega et al. (2015), Bradley et al. (2013), Cruz et al. (2018), Greening (2010), Jang et al. (2015), Kreuder et al. (2013), MacDonald et al. (2012), Langbein (2009), Olsthoorn et al. (2015), Shafie-khah et al. (2019), Shoreh et al. (2016), Vine et al. (2003), Wohlfarth et al. (2020b)	3, 10, 11
E7	Cost savings too far in the future	Katz (2014), Luthra et al. (2014), Olsthoorn et al. (2015), Vine et al. (2003)	8, 16
E8	Potential risk on production target values	Albadi and El-Saadany (2008), Bradley et al. (2013), Shoreh et al. (2016), Olsthoorn et al. (2015), Paterakis et al. (2017)	3, 4, 5, 6, 7, 10, 12, 13, 14
E9	Necessary hedging against non-availability of contractually reserved load for DR	Cappers et al. (2013), Katz (2014), Verpoorten et al. (2016)	8

in contrast to measures that need high upfront investments in the corresponding infrastructure (cf. E4, E4.1). In particular, there exist many options for companies to reduce power costs, e.g., by means of efficiency measures (cf. R6, R6.1) or tax and charge savings (cf. R3 – R5). By increasing energy efficiency and reducing grid fees, companies may achieve higher savings than with time-variable power prices which companies can only use to a very limited extent (cf. E3.2). The savings from grid fee reduction and/or tax and charge optimization are visible in the power bill and they are definite, i.e., a company knows its grid fee cost structure. Hence, companies are able to calculate with these savings as the price spreads on spot markets (cf. E3.2) or the renumeration by ancillary services are uncertain (cf. E3.3).

E3 – Lack of revenues through DR: As the economic potential for DR measures is too low, companies mostly do not want to invest/deal with the issue of demand flexibility at all. Many interview partners describe the current expected revenues from DR and the lack of profitable DR business cases as the main reason for non-implementation.

E3.1 – (Power) cost savings through DR are low: With regard to profitability (cf. E3), in particular, the savings in power costs with DR measures are relatively low in comparison with the effort for implementing them (cf. E4, E4.1, E6).

E3.2 – Price-spread on spot markets too small: One opportunity to monetize flexibility (cf. E3) is via energy-only markets and the price spreads between different periods. Currently, the price spread on spot markets for power between different time periods are small. Therefore, for companies which (indirectly) purchase power on such markets, this results in low power cost savings through DR.

E3.3 – (Potentially) decreasing profitability in ancillary service markets: The development on the balance power markets further hinders the business case for DR (cf. E3). Companies, which already provide flexibility, notice that revenues for balancing power products, e.g., for manual Frequency Restoration Reserve, are decreasing in recent years. Hence, certain flexibility markets may be only profitable for a short time until they reach a certain liquidity. Also, companies perceive further revenue reductions in the ancillary service markets as a high risk, as they may not achieve the required profitability in order to make up for the investments to being able to participate in the market. Some of the interviewed companies listed this economic risk as a critical factor for deciding against the implementation of a DR project.

E4 – Costly flexibility investments necessary: To enable the provision of flexibility, companies must make certain investments. Companies invest, for example, in the modernization of production plants and processes, in additional production capacities, and the underlying production infrastructure. Companies estimate these initial investments to be in a double-digit million range which is relatively high in comparison to other possible energy-related measures like increasing energy efficiency (cf. E2). Moreover, in advance of the implementation of the actual DR project, companies already have to invest in a thorough analysis of a potential DR project and its preparation (cf. I10).

E4.1 – High IT investments necessary: As a part of such investments (cf. E4), companies often have to invest in an appropriate IT infrastructure to enable both an automated use of flexibility and communication with relevant stakeholders to market flexibility. Depending on the IT prerequisites, the upfront costs for the IT infrastructure, e.g., the development of IT interfaces, often make up the largest part of the investment.

E5 – Lack of access to external and internal capital: Companies often lack the necessary access to capital (depending on the degree of investment) to realize the described investments (cf. E4, E4.1). In particular, for small and medium-sized companies the necessary investments may be too high compared to their available (financial) capital.

E6 – Additional operating costs due to DR measures: Providing flexibility and performing the needed activities for these measures may increase the operational costs for companies. Exemplary operational costs are maintenance costs, information and transaction costs, costs regarding the handling of additional complexity, and costs associated with the integration of DR processes in existing systems of a company (cf. T4 – T4.1, T5, T6). Furthermore, DR measures may lead to higher expenditures on personnel. Even if companies involve external service providers to contribute expertise in providing flexibility (cf. O7), companies still need personnel to manage the service provider.

E7 – Cost savings too far in the future: A DR project is often only profitable in the long term. Hence, the payback period is often relatively long.

E8 – Potential risk on production target values: When providing flexibility, companies often fear the non-achievement of self-set production targets agreed upon with partners, such as delivery obligations for customers. DR measures include interrupting the currently operating process which may result in potential supply shortages and lost business opportunities. Companies usually have priorities regarding delivery and supply commitments which DR measures must not affect. As conflicts may arise between the provision of flexibility and process requirements, companies often have to prioritize the pre-scheduled production plan over altering the power demand to provide DR.

E9 – Necessary hedging against non-availability of contractually reserved load for DR: When reserving loads for a potential flexibility supply, the company as contractually committed DR provider has to deal with the risk of being called to provide flexibility when the company may actually not be able to provide this reserved flexibility. In this case, the company must hedge itself against the risk of violating DR contracts with some sort of (expensive) financial instrument.

4.2. Regulatory obstacles

Table 6 illustrates the regulatory obstacles we identified in literature and the case study. As our case study focuses on German companies most of the listed regulatory obstacles are based on German or respective European legislation.

R1 – Complex regulatory framework: In our cases, companies struggle to maintain an overview of numerous regulations in energy legislation which leads to a high complexity as well as a lack of transparency. Likewise, laws interrelate with each other which makes it difficult for companies to grasp the whole area of energy legislation. In our cases, several companies stated that the knowledge to conclude contracts and legal frameworks is currently not available.

R2 – Restrictive regulatory framework: The legislative definition of, e.g., ancillary services, is quite restrictive. Hence, the regulatory framework may limit the participation of certain flexibilities in ancillary services and may, therefore, limit the existing technical potential for DR.

R2.1 – Lack of access to time-variable electricity prices: We observed that it is difficult for companies to access time-variable electricity prices, e.g., by directly participating at energy-only markets. For trading energy products at energy-only markets like the EPEX Spot, companies usually need a broker for market access. However, even if companies can access time-variable electricity prices, the corresponding price spreads may be too small (cf. E3.2).

R2.2 – High costs and effort for prequalification: Companies must successfully perform a thorough prequalification for the participation in ancillary services, i.e., they must prove that they meet the corresponding requirements. This prequalification process is very costly and complex.

R2.3 – Flexibility product design: Product characteristics on the day-ahead, intraday, or ancillary services markets such as high minimum bid size, the notification time, or the required (fast) response time may limit a potentially high technical potential for DR.

R3 – Contradictory legal incentive: Laws in the energy sector sometimes contradict each other. Obstacles R4 – R9 illustrate such contradictory legal incentives in Germany. Consequently, the prioritization between different legal incentives is not clear for companies.

R4 – Distortion of the market signal by levies: In recent years, the number of hours with negative electricity prices on the day-ahead market has increased considerably. Nevertheless, companies cannot fully benefit from them, especially when companies have their own electricity generation capacity such as gas-fired power plants. Due to

Table 6
Regulatory obstacles.

ID	Obstacle	Literature	Case(s)
R1	Complex regulatory framework	Alcázar-Ortega et al. (2015), Annala et al. (2018a), Olsthoorn et al. (2015), Warren (2014), Wierman et al. (2014)	5, 6, 7, 14
R2	Restrictive regulatory framework	Annala et al. (2018b), Cappers et al. (2012), Feuerriegel and Neumann (2016), Good et al. (2017), Khripko et al. (2017), MacDonald et al. (2012), Olsthoorn et al. (2015), Paterakis et al. (2017), Rollert (2018), Shen et al. (2014)	–
R2.1	Lack of access to time-variable electricity prices	Alcázar-Ortega et al. (2015), Annala et al. (2018a), Lund et al. (2015), Paterakis et al. (2017), Rollert (2018), Wierman et al. (2014), Wohlfarth et al. (2020b)	6, 7, 8
R2.2	High costs and effort for prequalification	Kreuder et al. (2013), Paterakis et al. (2017), van Dievel et al. (2014), Wohlfarth et al. (2020a)	2, 4
R2.3	Flexibility product design	Alcázar-Ortega et al. (2015), Annala et al. (2018b), Bichler et al. (2022), Cappers et al. (2012), Clausen et al. (2014),Cruz et al. (2018), Eid et al. (2016), Good et al. (2017), Greening (2010), Grünewald and Torriti (2013), Hirst (2001), Katz (2014), Koliou et al. (2013), Liu (2017), Ma et al. (2013), MacDonald et al. (2012), Nolan and O'Malley (2015), Paterakis et al. (2017), Rollert (2018), Shoreh et al. (2016), Valdes et al. (2019), Verpoorten et al. (2016), Wohlfarth et al. (2020b)	2, 4, 7, 12, 14
R3	Contradictory legal incentive	–	8, 11, 13, 14
R4	Distortion of the market signal by levies or fixed prices	Eid et al. (2016), Good et al. (2017), Katz (2014), Kim and Shcherbakova (2011), Koliou et al. (2013), Paterakis et al. (2017), Richstein and Hosseinioun (2020), Shen et al. (2014), Valdes et al. (2019), Vallés et al. (2016), van Dievel et al. (2014), Vine et al. (2003), Walawalkar et al. (2010)	3, 4, 5, 12
R5	Conflicts with grid fee regulations	Richstein and Hosseinioun (2020), Wohlfarth et al. (2020a)	1, 2, 4, 5, 6, 8, 12, 13, 14, 15, 16
R6	Prioritization of energy efficiency measures	Shen et al. (2014), Torriti et al. (2010)	3, 4, 5, 6, 7, 9, 15, 16
R6.1	Conflicts with energy efficiency	Borsche and Andersson (2014), Wohlfarth et al. (2020b), Wohlfarth et al. (2020a)	1, 2, 4, 7, 8, 9, 11, 12, 13, 14, 16
R7	Penalties for not providing reserved flexibility	Cappers et al. (2012), Eid et al. (2016), Hirst (2001), Katz (2014), Li et al. (2012), Liu (2017), Verpoorten et al. (2016)	–
R8	DR not covered by legal framework for privacy and data security issues	Annala et al. (2018a), Paterakis et al. (2017), van Dievel et al. (2014)	–
R9	Lack of harmonization in the regulatory framework	Annala et al. (2018a), Luthra et al. (2014), Ma et al. (2013), Verpoorten et al. (2016)	–
R10	Globally heterogeneous legislation	Paterakis et al. (2017), Shafie-khah et al. (2019), Shoreh et al. (2016), van Dievel et al. (2014), Verpoorten et al. (2016)	2, 6, 16
R11	Lack of sufficient financial public funding	Hu et al. (2015), Kim and Shcherbakova (2011), Liu (2017), van Dievel et al. (2014)	4, 5, 8, 13, 14

levies and other charges, companies do often not receive a clear, but rather a "distorted" signal from the energy market. These charges are static and therefore do not correctly reflect the situation in the grid, i.e., the current share of intermittent RES. This obstacle is particularly evident in the case of negative prices considering the possibility of self-generation.

R5 – Conflicts with grid fee *regulations:* As already mentioned, a reduction of the grid fees is very attractive to companies. In particular, the German legislation for the calculation of grid fees contains an exemption for energy-intensive companies. In this regard, the so-called full load hours are relevant, which are equal to the purchased power divided by the peak load. If the full load hours exceed 7000 h and the purchased power 10 GWh, the company is entitled to receive individual and lower grid fees that lead to relevant savings for energy-intensive companies. Therefore, many companies of our interview partners use peak load management to reach this threshold level. Notwithstanding the fact that peak load management is one kind of demand flexibility, participating in any (other) DR program could increase the peak load and, therefore, endanger reaching the legal threshold for individual grid fees. Against this background, the remaining degrees of freedom for DR decrease considerably.

R6 – Prioritization of energy efficiency measures: Companies often focus on increasing energy efficiency motivated by both economic and ecological reasons (cf. E2). Most of the interviewed partners stated that their company is certified according to the ISO 50001 for systematic energy management which entails a certain reduction of levies (i.e., the EEG levy).

R6.1 – Conflicts with energy efficiency: Even if companies want to implement DR measures in addition to energy efficiency measures, there is often a conflict between DR and energy efficiency. This conflict typically results from the fact that the implementation of a DR measure may result in a deviation from the optimal operating point – with respect to energy efficiency. Hence, a DR measure could also have a negative impact on efficiency objectives. As the ISO 50001 requires a continuous reduction of power consumption, some companies fear the loss of certification if they participate in DR programs.

R7 – Penalties for not providing reserved flexibility: When reserving loads at balancing markets, these flexible loads need to be available to the corresponding extent if they are called upon. If a company is not able to provide the reserved flexibility problems, it has to pay financial penalties which represent an economic risk (cf. E9).

R8 – DR not covered by legal framework for privacy and data security issues: Within the DR legislation, there is often a lack of specific rules in the context of privacy and data security of DR. In particular, this concerns data from metering infrastructure and data management responsibilities with regard to new intermediaries like aggregators.

R9 – Lack of harmonization in the regulatory framework: DR programs and products represent fairly new elements of the energy market. Regulators might not consider all interactions with other energy laws when adopting new energy laws. Therefore, the legislator has not yet completely harmonized new areas of legislation, e.g., for balancing markets, with the existing legislation of the energy sector.

R10 – Globally heterogeneous legislation: The legislation on DR differs between countries, which especially poses an obstacle for globally operating companies. Even though there exists an EU Directive addressing DR, countries can adjust the implementation of this directive on the national level. As a result, European markets lack homogeneous DR products leading to a different treatment of flexible loads in European countries which requires additional knowledge and resources in companies.

R11 – Lack of sufficient financial public funding*:* Companies in our cases also depict insufficient public funding to promote the implementation of DR. Public funding may foster the profitability and certainty of long-term DR projects.

4.3. Technological obstacles

Table 7 summarizes all identified technological obstacles.

T1 – Technical risk of disruption of production process: Providing flexibility often goes along with interrupting the production process or with not continuing it as originally planned to adapt the power consumption. Process operators expect malfunctions (e.g., due to newly developed technologies), which may lead to a violation of the daily operational production constraints and a loss of troubleshooting ability. Some interview partners referred to the production as something like "crown jewel(s)" which a company does typically not want to touch and affect by flexibilization at all. Hence, the interview partners consider an intervention in the main production process to be too risky.

T2 – Technically infeasible to reduce peak load: We observed in our cases that, to some extent, companies' processes are technically infeasible to flexibly adjust their electricity demand. First, many of the companies in our case study lack over-capacities to shift their production to other periods. When a production process runs 24/7 at full capacity, companies struggle to find an alternative time slot to shift loads to. Second, when adapting a production process (cf. T1), it is often (technically) not possible to flexibly operate production processes since the companies objectives include, among others, to optimize the production processes towards an efficient and constant operation point (cf. R6, R6.1). Additionally, production processes can be too "sluggish" to respond within the required reaction times for ancillary services. Moreover, some processes exhibit interdependencies with other (subsequent) processes or dependencies on external factors that make it difficult to isolate or shift/shed such processes separately.

T3 – Risk of lower product quality: When companies provide flexibility by, for instance, varying the power consumption and duration of a production process, there is a risk of lower product quality, e.g., in the process for the liquefaction of gases like for air separation.

T4 – High requirements of IT: Providing flexibility usually goes along with high IT requirements (e.g., speed, accuracy, and automation), both externally and internally. In particular, DR for ancillary services has high external requirements, e.g., the corresponding control units for the flexible loads. The corresponding IT system further needs to comprise a concept for possible errors in the production which typically entails great effort for the company.

T4.1 – High effort and complexity within IT system: The development and installation of the IT system to control DR measures is typically associated with high costs for companies (cf. E4.1). First, companies need to initially adjust the production processes considerably, e.g., automate and interconnect. Next, companies have to set up software and communication protocols for the external interfaces with flexibility markets or respective aggregators. Moreover, the IT system has to process large, heterogeneous, and near-real-time data which is especially difficult when decisions are critically time-constrained.

T4.2 – Lack of computational capacity: During the execution of DR measures, companies have to process a large volume of data. Companies may lack the computational capacity for the optimization of DR measures and it can be a challenge to have the required computational capacity at an acceptable cost (cf. T4.1).

T4.3 – IT and data security: The appropriate handling of sensitive data is a critical factor in a DR information system. Many DR programs require interfaces to external partners (cf. T4 –T4.1). Therefore, these external interfaces and the IT system itself could be vulnerable to external manipulation or attacks. Depending on the company, data describing flexible loads is highly sensitive, as it may contain information on the amount of product orders of the company.

T5 – Lack of IT prerequisites in the company: Already existing IT systems and meters in the company rarely support the requirements for DR measures. For instance, machines at the company site hardly have any fully automated interfaces or interconnections to other systems. Also, existing monitoring and analysis systems do not collect the required data for DR measures.

T5.1 – Non-availability of appropriate technology to control the DR measures: The appropriate technology for a control and communication infrastructure for DR measures is partly not yet available. Current metering infrastructure may lack the signaling infrastructure and bandwidth capability needed to meet advanced DR requirements. Readily available equipment and communication packages are rarely

Table 7
Technological obstacles.

ID	Obstacle	Literature	Case(s)
T1	Technical risk of disruption of production process	Alcázar-Ortega et al. (2015), Annala et al. (2018b), Clausen et al. (2014), Grein and Pehnt (2011), Kreuder et al. (2013), Li et al. (2012), Lindberg et al. (2014), Lund (2007), McKane et al. (2008), Olsthoorn et al. (2015), Rautiainen et al. (2017), Rollert (2018), Shafie-khah et al. (2019), Shen et al. (2014), Shoreh et al. (2016), Vine et al. (2003), Wohlfarth et al. (2020b), Zhang and Grossmann (2016a)	3, 4, 5, 6, 7, 9, 11, 14, 16
T2	Technically infeasible to reduce peak load	Hu et al. (2015), Li et al. (2012), Lund et al. (2015), Olsthoorn et al. (2015), Richstein and Hosseinioun (2020), Shoreh et al. (2016), Valdes et al. (2019), Zhang and Grossmann (2016a)	1, 2, 3, 6, 7, 8, 9, 10, 13
T3	Risk of lower product quality	Alcázar-Ortega et al. (2012), Grein and Pehnt (2011), Heffron et al. (2020), Li et al. (2012), Olsthoorn et al. (2015), Shoreh et al. (2016), Zhang and Grossmann (2016a)	3, 6, 10, 16
T4	High requirements of IT	Cappers et al. (2012), Gelazanskas and Gamage (2014), Li et al. (2012), Ma et al. (2013), Shoreh et al. (2016)	1, 5, 7, 8, 9, 12, 13
T4.1	High effort and complexity within IT system	Borsche and Andersson (2014), Good et al. (2017), Langbein (2009), Li et al. (2012), Lindberg et al. (2014), Pelzer and Kleingeld (2011), Samad et al. (2016), Shen et al. (2014), Uddin et al. (2018)	4, 6, 7, 8, 10, 11, 14
T4.2	Lack of computational capacity	Good et al. (2017), Macedo et al. (2013), Shafie-khah et al. (2019)	–
T4.3	IT security and data security	Annala et al. (2018a), Cruz et al. (2018), Good et al. (2017), Hansen et al. (2014), Luthra et al. (2014), Macedo et al. (2013), Mlecnik et al. (2020), Olsthoorn et al. (2015), Olorunfemi and Nwulu (2018), Paterakis et al. (2017), Shafie-khah et al. (2019), Zhang and Grossmann (2016a)	4, 7, 8, 9, 16
T5	Lack of IT prerequisites in the company	Alcázar-Ortega et al. (2015), Baboli et al. (2011), Cappers et al. (2013), Cruz et al. (2018), Dong et al. (2016), Good et al. (2017), Katz (2014), Kleingeld et al. (2012), Fridgen et al. (2022), Kreuder et al. (2013), Macedo et al. (2013), Mlecnik et al. (2020), Sharma et al. (2019), Strbac (2008), Torriti et al. (2010), Uddin et al. (2018), Verpoorten et al. (2016)	4, 5
T5.1	Non-availability of appropriate technology to control the DR measures	Álvarez et al. (2017), Borsche and Andersson (2014), Greening (2010), Hirst (2001), Honkapuro et al. (2015), Luthra et al. (2014), Shen et al. (2014), Vine et al. (2003), Wohlfarth et al. (2020b)	–
T6	Lack of standardization of IT systems	Annala et al. (2018a), Dong et al. (2016), Good et al. (2017), Honkapuro et al. (2015), Hu et al. (2015), Luthra et al. (2014), Macedo et al. (2013), McKane et al. (2008), Pinson et al. (2014), Samad et al. (2016), Shen et al. (2014), Siano (2014), Vallés et al. (2016)	12, 16
T6.1	Lack of interoperability of IT systems	Good et al. (2017), Hirst (2001), Pelzer and Kleingeld (2011), Pinson et al. (2014), Shafie-khah et al. (2019), Shoreh et al. (2016), Siano (2014), Strbac (2008), van Dievel et al. (2014), Zhang and Grossmann (2016b)	–

available to companies.

T6 – Lack of standardization of IT systems: Currently, there is a lack of technical standardization. The latter applies to IT infrastructure in general, hardware and devices, software as well as data formatting, transfer, transformation, semantics (communication standards), and the communication with service providers. Without corresponding standards, the companies in our case study often have to develop their individual cost-intensive IT system and communication protocols with their partners, e.g., their aggregators. This not only increases the expense for implementation, but also leads to lock-in effects with respect to the individually implemented IT system.

T6.1 – Lack of interoperability of IT systems: The lack of standardization directly leads to a difficult interoperability of IT systems. The interoperability between the existing machinery, devices, and systems with various new types of technology and stakeholders is difficult to handle. This, for instance, hinders the communication with service providers and poses a challenge in the case a company wants to change its service partner, e.g., its aggregator.

4.4. Organizational obstacles

Table 8 collects all identified organizational obstacles.

O1 – Additional workload/General restrictions with respect to employees: The implementation of flexibility implies new workflows and potentially additional workload for employees in production and the energy department (cf. T1). The additional and altered workload must not exceed a certain level of complexity depending on the employees qualifications and fit with appropriate working models.

O2 – Internal guidelines regarding the duration of projects: For the implementation of DR projects, the companies in our case study often have ambitious targets with respect to profitability. Our interview partners emphasize their company's focus on short-to medium-term projects (approx. 3–5 years) that exhibit a certain Return on Investment (RoI). However, projects to optimize energy procurement, including the ones that make power demand more flexible, usually have a long-term horizon (approx. 10–12 years). Moreover, due to the uncertainty regarding future power price developments, it is difficult to reliably determine the RoI (cf. I2.1).

O3 – Lack of importance of sustainability: Some companies in our case study argue that even if profitability is small, they invest in DR due to its contribution to a sustainable energy system and to improve their image with regard to sustainability. However, the lack of profitability and direct economic benefits for companies often outweigh sustainability considerations.

O4 – Low priority of energy management and corresponding investments at top management: In some cases, the top management must decide on flexibility projects, as such projects involve risks in terms of technical feasibility and/or economic losses. However, the issue of DR is often not a priority for the top management which in turn is the reason why companies do not carry out DR projects at all or with a low budget/effort (cf. O2, O3).

O5 – Power procurement policy of company: Large companies often have a central energy management system, while individual company sites or subsidiaries do not have their own energy management or even their own energy budget. On the one hand, this can restrict the possibility of using flexibility, since communication must involve the central energy management system. On the other hand, it can lead to company sites obtaining a fixed electricity price, i.e., the electricity price is not variable over time, which implies that there is no incentive for flexibility in this respect (cf. R2.1). Furthermore, centralized power procurement could hamper possible initiatives by individual plants in monetization from DR projects.

O6 – Relevant decision makers do not have enough power within the organization: The relevant person for decisions regarding DR often does not have enough power within the company to successfully promote a DR project. This insufficient power of decision makers often stems from the prevailing structure of the company. This is, in particular, the case if the company does not regard energy concerns as part of its core business.

O7 – Multiple decision makers involved in decision process of projects: A DR project usually involves multiple decision makers, i.e., employees and decision makers from several departments like energy, production, and legal department. Accordingly, the decision making process is often long, complex, cost-intensive, and can prevent timely DR implementation.

O8 – Necessity/dependence on external service providers: Once the personnel resources or knowledge of a company are not sufficient to implement flexibility, external service providers become necessary (cf. T4 – T4.1). Complexity, in particular, legal as well as economic aspects, can further lead to the necessity of (additional) service providers (cf. E2, E3, R1). The lack of standardization, in particular, of IT measures (cf. T6), leads to the necessary development of individual (IT) solutions, which in turn can highly depend on the corresponding external service providers. Hence, cooperation with external partners can lead to lock-in effects.

4.5. Behavioral obstacles

Table 9 depicts all identified behavioral obstacles.

B1 – Lack of acceptance/skepticism among employees: There is often a lack of understanding why DR-related changes in the production occur. Therefore, employees may sometimes refuse to adapt new work processes if a company wants to establish these DR measures without motivating and informing employees about the reasons and motivations for these measures. If external experts implement the DR measures, the employees' reluctance towards new flexible processes may even increase due to a possibly skeptical view on external experts. Furthermore,

Table 8
Organizational obstacles.

ID	Obstacle	Literature	Case(s)
O1	Additional workload/general restrictions with respect to employees	Alcázar-Ortega et al. (2015), Jang et al. (2015), Kleingeld et al. (2012), Olsthoorn et al. (2015), Wohlfarth et al. (2020b)	7, 15
O2	Internal guidelines regarding the duration of projects	–	5, 7, 16
O3	Lack of importance of sustainability	Li et al. (2012), Nolan and O'Malley (2015)	1, 2, 3
O4	Low priority of energy management and corresponding investments at top management	Alcázar-Ortega et al. (2015), Annala et al. (2018b), Gitelman et al. (2013), Good et al. (2017) Greening (2010), Olsthoorn et al. (2015), Pelzer and Kleingeld (2011), Vine et al. (2003)	2, 4, 5, 9
O5	Power procurement policy of company	Lund et al. (2015)	4, 5, 7
O6	Relevant decision maker does not have enough power within the organization	Good et al. (2017), Grein and Pehnt (2011)	–
O7	Multiple decision makers involved in decision process of projects	Vine et al. (2003), Wohlfarth et al. (2020b)	–
O8	Necessity/dependence on external service providers	–	7, 8, 9, 10, 12

Table 9
Behavioral obstacles.

ID	Obstacle	Literature	Case(s)
B1	Lack of acceptance among employees	Bradley et al. (2013), Greening (2010), Verpoorten et al. (2016), Vine et al. (2003)	10, 11, 14, 15
B2	Skepticism towards fully automated interfaces	Annala et al. (2018a), Bradley et al. (2013), Cappers et al. (2012), Dyer et al. (2008), Good et al. (2017), Kleingeld et al. (2012), Luthra et al. (2014), Olorunfemi and Nwulu (2018), Vine et al. (2003), Wierman et al. (2014)	2, 4, 5, 6
B3	Perceived inconvenience of DR provision	Albadi and El-Saadany (2008), Alcázar-Ortega et al. (2015), Baboli et al. (2011), Bradley et al. (2013), Dyer et al. (2008), Good et al. (2017), Honkapuro et al. (2015), Kreuder et al. (2013), Nguyen (2010), Nolan and O'Malley (2015), Paterakis et al. (2017), Sharma et al. (2019), Uddin et al. (2018), Vine et al. (2003), Walawalkar et al. (2010)	–

flexibility measures pose new risks for employees as a malfunctioning implementation can cause damage to the machines and, thus, impair a trouble-free workflow.

B2 – Skepticism towards fully automated interfaces: Since the implementation of flexibility mostly implies an intervention in production (cf. T1, T3), most companies in our case study aim only for a semi-automatic operation and, hence, deem human control within the processes as necessary because they perceive the risk of a fully automatic control as too high. Moreover, negative experiences with some large IT projects possibly increases the risk aversion towards IT-related projects such as DR.

B3 – Perceived inconvenience of DR provision: Due to bounded rationality and habits, employees and management generally perceive the participation at DR programs as an inconvenience since it differs from the accustomed workflow (cf. O1). As DR programs require changes in operating procedures or may negatively interfere with primary objectives, e.g., faultless production, of the company and the employees, employees as well as management often relate DR measures to a loss of comfort.

4.6. Informational obstacles

Table 10 comprises all identified informational obstacles.

I1 – Lack of transparency and asymmetry of information: Due to the variety of possibilities to market demand flexibility for companies, there is a lack of overview regarding certain flexibility markets and products as well as how they can be contractually structured. For instance, some interviewed companies do not have sufficient information about the market and clearing mechanisms to design contracts for flexibility provision. Companies in our study stated that from a company's point of view asymmetric information, e.g., the bidding strategy of other market players in flexibility markets, represent a challenge. Overall, there is often a lack of transparency of the price formation in the context of the bidding competition with other market players, e.g., in ancillary services. However, information transparency is necessary to, on the one hand, send appropriate price signals with respect to the timely demand for DR. On the other hand, market and other related information are the basis for optimal bidding decisions and production planning. Information asymmetry at the expense of companies may also affect aggregators, e.g., in the case an aggregator does not have complete information on companies' preferences for load management and consumption.

I2 – Uncertainty regarding financial implications: Due to the uncertainty of electricity prices (cf. I2.1), the amount of network fees (cf. R5), electricity cost savings etc. through DR and the uncertain economic value of ancillary services in the future (cf. E3.3), companies have difficulties in long-term planning of a DR project (cf. I6). For instance, for ancillary services, companies do not know ex ante how often they need to activate their flexibility for which they receive remunerations.

I2.1 – Risks and uncertainties regarding price forecast: The price forecast for flexibility markets or rather the value of flexibility on different markets is difficult and very uncertain (cf. E3.3). Furthermore, it is unclear what potential impact the entry of new DR providers would have on the market price.

I3 – Uncertainty about future regulations and legislative developments: Generally, frequent changes in regulations lead to increased complexity and uncertainty with regard to the regulatory framework (cf. R1). This, in turn, leads to low transparency regarding how long a currently existing regulation will be in place. Consequently, next to just maintaining legal conformity, companies in our case study have difficulties anticipating changes from upcoming regulations. This results in a lack of planning security. However, as DR mostly bases on long-term projects (cf. O2), it requires a rather stable regulatory framework for certain amortization. Some companies in our case study have already made negative experiences during the implementation of energy projects where a change in regulation has led to a negative impact on the project results.

I3.1 – Unclear interpretation of legislation: The regulatory framework is to some extent unclear for the responsible company department and the associated employees, which can lead to different interpretations even by legal experts. Therefore, these companies, then, either do not deal with DR projects further or need external support.

I3.2 – Uncertainty regarding allocation, roles, and responsibilities: For certain roles and responsibilities, the companies of our interview partners lack a clear understanding who of the market participants should fulfill different roles, e.g., for the development of decentralized flexibility resources. This leads to an uncertain allocation of the roles and responsibilities between flexibility providers, utilities, and aggregators.

I4 – Lack of standardized baseline calculation for DR market: The company's baseline of power consumption is a calculated reference to determine the difference in load which results from a DR measure. This difference, then, serves as a basis to calculate the remuneration for the provided flexibility and to verify that a company has deviated in a certain amount from its baseline, i.e., the company executed the contracted DR measure. However, it is difficult to determine this baseline which often leads to imperfect, unreliable, and inaccurate results when calculating the remunerations based on the baseline reference.

I5 – Technological measures for implementing DR unknown: The technological tools for implementing DR measures are mostly unknown to the company (beforehand). Accordingly, the companies in our case study often do not know their (potential) technical tools and which of those would fit best for implementing DR measures within their production processes (cf. T5.1, T6). Hence, a company has either to rely on external knowledge to identify the appropriate technological tools (cf. O8) or extensively staff employees with DR and IT knowledge on a DR project.

I6 – Costly and uncertain DR project analysis: Referring to Obstacles I1 – I5, many elements, e.g., financial calculations, for a precise analysis of a DR project are very uncertain. Further planning uncertainty stems from the lack of instruments for project analysis and forecasting the amount of DR measures that the company will activate and monetize in a certain time period, among other things. Due to this uncertainty, companies typically struggle to set up concrete projects, although they have already first concepts for DR projects.

Table 10
Informational obstacles.

ID	Obstacle	Literature	Case(s)
I1	Lack of transparency and asymmetry of information	Cruz et al. (2018), Good et al. (2017), Katz (2014), Langbein (2009), Nolan and O'Malley (2015), Paterakis et al. (2017), Torriti et al. (2010), Vine et al. (2003), Wohlfarth et al. (2020b)	10, 16
I2	Uncertainty regarding financial implications	Annala et al. (2018b), Borsche and Andersson (2014), Cappers et al. (2013), Eissa (2011), Good et al. (2017), Grein and Pehnt (2011), Kim and Shcherbakova (2011), Liu (2017) Pinson et al. (2014), Olsthoorn et al. (2015), Vine et al. (2003), Wohlfarth et al. (2020b)	2, 4, 11, 16
I2.1	Risks and uncertainties regarding price forecast	Borsche and Andersson (2014), Cappers et al. (2013), Goulden et al. (2018), Grein and Pehnt (2011), Hu et al. (2015), Katz (2014), MacDonald et al. (2012), Shafie-khah et al. (2019), Zhang and Grossmann (2016a)	–
I3	Uncertainty about future regulations and legislative developments	Alcázar-Ortega et al. (2015), Good et al. (2017), Goulden et al. (2018), Greening (2010), Hirst (2001), Olsthoorn et al. (2015), Rautiainen et al. (2017), Vallés et al. (2016), Warren (2014), Wohlfarth et al. (2020b)	4, 5, 6, 7, 11, 12, 16
I3.1	Unclear interpretation of legislation	–	6
I3.2	Uncertainty regarding allocation, roles, and responsibilities	Annala et al. (2018a), Honkapuro et al. (2015), Katz (2014), Rollert (2018), Siano (2014), Valdes et al. (2019), Vallés et al. (2016)	–
I4	Lack of standardized baseline calculation for DR market	Alcázar-Ortega et al. (2015), Good et al. (2017), Grünewald and Torriti (2013), Hirst (2001), Liu (2017), Nolan and O'Malley (2015), Samad et al. (2016), Shoreh et al. (2016), Warren (2014)	–
I5	Technological measures for implementing DR unknown	Li et al. (2012), Olsthoorn et al. (2015), Rautiainen et al. (2017)	–
I6	Costly and uncertain DR project analysis	Alcázar-Ortega et al. (2015), Eissa (2011), Grein and Pehnt (2011), Hu et al. (2015), Katz (2014), Li et al. (2012), Nolan and O'Malley (2015), Paterakis et al. (2017), Shafie-khah et al. (2019), Shoreh et al. (2016), Strbac (2008), Vine et al. (2003), Wierman et al. (2014), Zhang and Grossmann (2016b)	1, 3, 10

4.7. Competence obstacles

Table 11 summarizes all identified competence obstacles.

C1 – Lack of (internal) resources: The companies in our case study often have no or too few internal resources to deal intensively with DR projects. Due to regular outsourcing of energy management projects as a result of internal capacity problems, these companies also lack experience of implementing projects independently from external resources and partners.

C2 – Employees lack needed skills: The employees often lack the appropriate knowledge to implement and operate DR measures.

C3 – Lack of knowledge about the production process and existing flexibility potential: In order to be able to implement flexibility measures, the company needs precise knowledge of the own production processes to actually use the corresponding flexibility potential. However, in some of our cases, there is a lack of knowledge about the own production processes, which prevents a company from determining its flexibility potential. Also, companies in our case study do not always collect energy data at all. Even in the case where they collect it, the companies often do not process or analyze them due to the lower priority compared to production data.

C4 – Lack of knowledge about energy markets and the potentials of DR: The flexibility domain is often perceived as being very specific and complex. Often, the necessary knowledge, especially about regulation, is missing in the companies of our interview partners (cf. I2 – I3.1).

5. Discussion

The interviews we conducted provide us with insights into obstacles that prevent companies from marketing their demand flexibility. In total, combining the results of the literature analysis and the case study, we identify 63 obstacles. Out of these 63 obstacles, we identified 16 obstacles exclusively from literature, 5 obstacles in the interviews conducted, and 42 obstacles stem from both existing literature and our interviews. With all 63 obstacles, we are able to address our research question by identifying how economic, regulatory, technological, organizational, behavioral, informational, and competence obstacles prevent companies in our cases in the industrial sector from (fully) exploiting existing or investing in new flexibility potential.

Even though, we conducted a relatively small number of interviews, i.e., we have 16 interview partners, we are positive to have identified the major part of obstacles for companies. Fig. 2 illustrates the number of new obstacles identified after each case. Note that the interview ID corresponds to the order in which we conducted them. Generally, the figure reveals that with each case we identified less new obstacles. Within the last five interviews, we could not identify a new obstacle, even though our case study represents companies from various business domains with different company sizes. However, the interview partners still gave new insights from their perspectives to already existing obstacles. Overall, this observation might be an indicator for a saturation of new findings with regard to new obstacles. In parallel, we confirm these obstacles with a comprehensive literature review. Hence, we consider the collected obstacles of the previous section as generalizable.

In fact, our results confirm and extend the findings of literature on

Table 11
Competence obstacles.

ID	Obstacle	Literature	Case(s)
C1	Lack of (internal) resources	Good et al. (2017), Grein and Pehnt (2011), Wohlfarth et al. (2020b)	5, 7, 13
C2	Employees lack needed skills	Dyer et al. (2008), Greening (2010), Good et al. (2017) Grein and Pehnt (2011), Kleingeld et al. (2012), Luthra et al. (2014), Mlecnik et al. (2020), Olsthoorn et al. (2015), Shafie-khah et al. (2019), Shoreh et al. (2016), Vine et al. (2003), Wohlfarth et al. (2020b)	–
C3	Lack of knowledge about the production process and existing flexibility potential	Alcázar-Ortega et al. (2015), Grein and Pehnt (2011), Kleingeld et al. (2012), Nolan and O'Malley (2015), Shoreh et al. (2016)	5, 9, 15, 16
C4	Lack of knowledge about energy markets and the potentials of DR	Alcázar-Ortega et al. (2015), Baboli et al. (2011), Dyer et al. (2008), Gitelman et al. (2013), Good et al. (2017), Hirst (2001), Kim and Shcherbakova (2011), Luthra et al. (2014), Nolan and O'Malley (2015), Pinson et al. (2014), Paterakis et al. (2017), Verpoorten et al. (2016), Vine et al. (2003), Warren (2014), McKane et al. (2008)	1, 4, 9, 12, 14

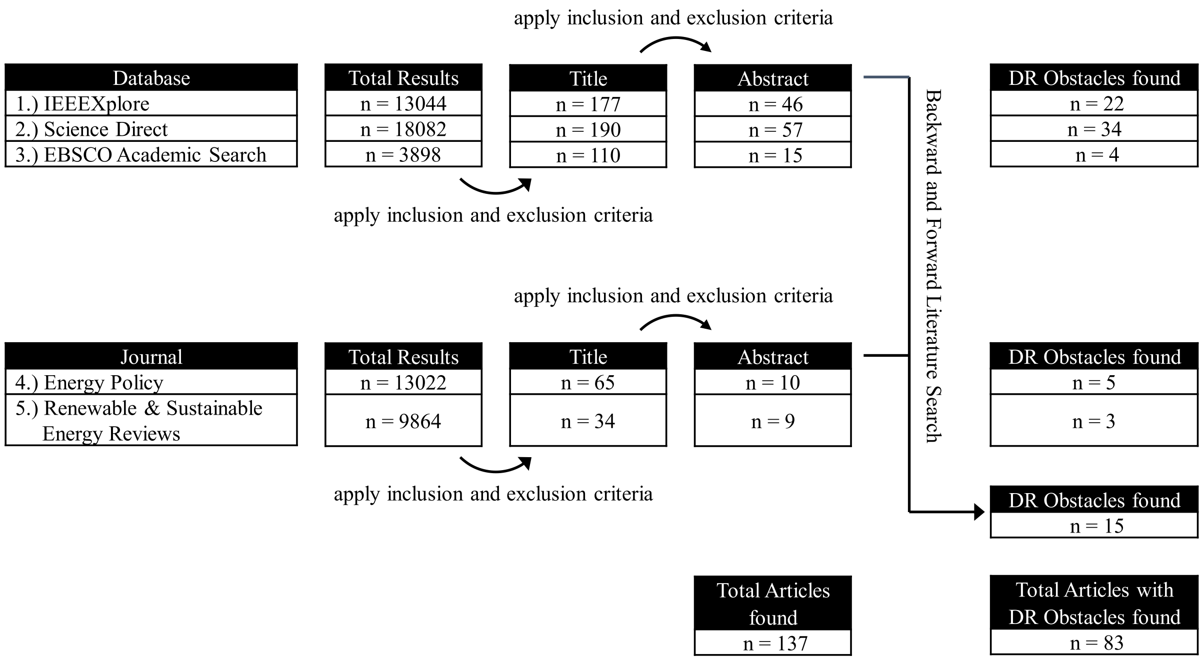

Fig. 1. Visualization of the literature search.

DR, in particular, the analysis of Olsthoorn et al. (2015). In terms of references per obstacle, i.e., how many interview partners addressed an obstacle, we find that some obstacles seem to be more crucial for the implementation of DR measures in companies than others. Table 12 summarizes the twelve obstacles with the highest number of references in our case study in decreasing order. Table 12 reveals that, in particular, specific economic, regulatory, and technological obstacles seem to prevent companies from exploiting DR. Obstacles of the categories organizational, behavioral, and competences are not part of the twelve obstacles with the highest number of references in our case study. From this observation, we deduce that these obstacles pose a subordinate role from the companies' point of view.

We also extend the existing body of knowledge by both describing how the obstacles prevent companies from realizing DR and by illustrating the interrelations between various obstacles. In particular, regulatory and economic obstacles as well as regulatory and technical obstacles exhibit interrelations that are still existent also eight years after the survey of Olsthoorn et al. (2015).

6. Conclusions and policy implications

The presented literature research and case study allows for a better understanding of how economic, regulatory, technological, organizational, behavioral, informational, and competence obstacles prevent companies in the industrial sector to flexibly adapt their power consumption. On this basis, we can derive several policy implications and draw our final conclusions.

In particular, Obstacles E2 – E3.3 illustrate that financial incentives are often insufficient for companies to invest in the implementation of DR. In order to promote DR, the responsible legislator could implement several measures. First, there is the possibility to expand current funding of public projects on industrial DR implementation. This could be particularly valuable to trigger flexibilization at companies where DR has not played a role so far due to low energy intensity (cf. E1). The prerequisite for this is that it should be also possible to trade smaller flexibility units on the markets (cf. R2.3). Second, the legislator could readjust taxes and levies for power purchases and, therefore, increase financial incentives for DR.

As Obstacle R4 illustrates, fixed taxes and levies on power prices distort the market signal and, thereby, reduce revenues from DR measures that base on the utilization of market price spreads. One way to increase the financial incentives via taxes and levies is to make these levies more "flexible", e.g., by coupling them to the respective market price.

Coming back to our case of Germany, for instance, the current design of grid fee regulation mostly hinders the provision of system-friendly DR measures. A company which needs to activate a contracted DR measure may reach a new individual peak load and, consequently, needs to pay higher grid fees (cf. R5). In order to create incentives for companies to become more flexible, new methods for calculating grid fees could eliminate such obstacles. Another current legislation that is in conflict with DR measures is the EEG levy, i.e., a levy for RES representing a conflict with energy efficiency (cf. R6,R6.1). Companies can reduce their EEG levy costs by proving increasing energy efficiency. However, if companies deliberately flexibilize their power demand, their efficiency may decrease. The legislator could resolve the trade-off between efficient and flexible power consumption by, for example, linking EEG levy reductions to the cumulative fulfillment of both requirements. Besides resolving the existing conflicts for DR in legislation, it is necessary to provide companies with a more long-term perspective (cf. I3 – I3.1). Ensuring that corresponding regulations are in place, at least as long as the implementation of DR projects takes (i.e., approx. 10–12 years), could give companies increased investment and planning security (cf. I2, I3,I6). Additionally, there is the need to better harmonize laws in the energy sector with laws from other sectors (cf. R9 – R10) on the one hand, and to align them with long-term policy goals on the other hand.

When it comes to the planning as well as the subsequent implementation of DR measures, companies often reach different technical limits (cf. T1,T2,T5,I5,C3). Missing standardized communication channels and programs as well as hardware, e.g., corresponding sensors, result in the difficulty of defining compatible interfaces between markets and the company system (cf. T6 – T6.1). To prevent companies from having to involve external providers and experiencing lock-in effects (cf. T6,T6.1,O7), appropriate market standards could be developed for this

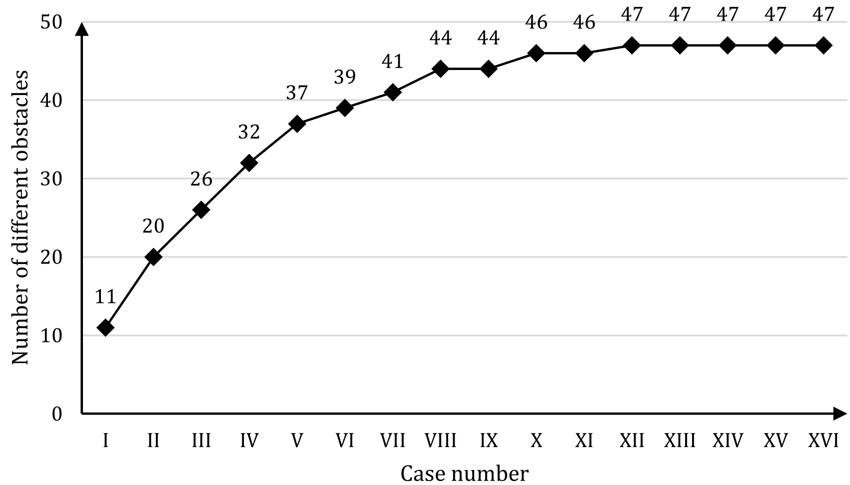

Fig. 2. Number of new obstacles after each interview.

Table 12
Number of references of obstacles in our case study.

# of references	Table	ID	Obstacle
12	Table 5	E3.1	(Power) cost savings through DR are low
11	Table 5	E3	Lack of revenues through DR
11	Table 6	R5	Conflicts with grid fee regulations
11	Table 6	R6.1	Conflicts with energy efficiency
9	Table 5	E8	Potential risk on production target values
9	Table 7	T1	Technical risk of disruption of production process
9	Table 7	T2	Technically infeasible to reduce peak load
8	Table 5	E2	Greater economic appeal of alternative measures to optimize power costs
8	Table 6	R6	Prioritization of energy efficiency measures
7	Table 7	T4	High requirements of IT
7	Table 7	T4.1	High effort and complexity within IT system
7	Table 10	I3	Uncertainty about future regulations and legislative developments

area also in order to reduce requirements and complexity of IT systems (cf. T4,T4.1).

In addition to developing standards, the legislator could also invest in research into flexible operation of production processes. Since companies often optimize their production processes for one certain efficient mode of operation, there is already a lack of technological prerequisites to operate DR (cf. T1,T2).

Concluding our research, flexibility within the power system increasingly represents an important option for a successful energy transition with a high share of intermittent RES. Whereas in the past mostly conventional power plants provided the required flexibility in power systems, flexibility on the demand side, especially in the form of DR, energy storage, and grid expansion will gain importance in the future. The industrial sector as a powerful lever can significantly contribute to flexibility in the power system, and, thus, support a further expansion of RES. Also, by aligning their production flexibly with fluctuating power prices, companies can reduce their power procurement costs and increase their competitiveness.

However, in order to implement DR measures, there is a need for appropriate conditions and incentives both within the company and the legislation. Our combined literature review and case study reveals that there are several obstacles that currently still prevent companies from flexibilizing their power consumption. Consequently, many companies have not yet or only partially tapped their potential for DR. Based on literature, e.g., Olsthoorn et al. (2015) and Alcázar-Ortega et al. (2015), that already have investigated the question which obstacles exist (for companies), we extend their research by detailed company insights and present in detail the backgrounds how these obstacles prevent companies from exploiting their (existing) flexibility potentials.

As we have illustrated, the identified obstacles from literature and our case study represent general obstacles for companies. However, note that some of the regulatory obstacles presented (cf. R2.2 – R6.1) relate to the European or, in particular, German legislation. As Obstacle R10 depicts, globally heterogeneous legislation may result in other or further obstacles which in turn can take on different forms for companies on their production sites.

Summarizing, our findings can form the basis for future research that could, in particular, develop detailed solutions to the existing obstacles faced by companies. In this respect, our previously listed policy implications may serve as a first research agenda for future work. With regard to our limitations, further research could examine these obstacles in an international context. Against the background of globally heterogeneous legislation, further research should analyze how specific regulatory obstacles in Germany, respectively Europe, also occur in other power systems and their corresponding legislative frameworks. Our derived recommendations for action from the identified obstacles illustrate that the trade-off between addressing various obstacles needs to be closely examined. In this context, special attention of future research could be paid to how market and regulatory rules should be balanced in order to provide companies with the best possible framework for providing DR, while also considering process efficiency. The cross-references and dependencies we identified between obstacles could form the basis for such an in-depth analysis on the framework conditions. At the intersection of economic and regulatory obstacles, future research could further analyze the effects of different taxation models on power prices and their functioning as a guiding signal for DR. Furthermore, when analyzing or conceptualizing a future energy market design, as well as their communication and digital interfaces, it is essential to take the technological status quo of the participants in the markets, e.g., participating companies, into account. For instance, future research could develop flexibility products with more degrees of freedom better considering the technical prerequisites, e.g., ramp rates, of potential market participants. By knowing the obstacles to demand flexibility, it is possible to implement targeted measures to resolve these obstacles. In this way, our work can contribute to creating appropriate conditions and incentives, both within the company and for external framework conditions, so that flexibility on the demand side can help shaping the way for a successful energy transition.

CRediT authorship contribution statement

Christina Leinauer: Conceptualization, Investigation, Writing – original draft, Visualization. **Paul Schott:** Conceptualization, Investigation, Writing – original draft, Visualization. **Gilbert Fridgen:** Conceptualization, Writing – Editing, Supervision. **Robert Keller:** Conceptualization, Writing – Editing, Supervision. **Philipp Ollig:** Conceptualization, Writing – Editing. **Martin Weibelzahl:** Conceptualization, Writing – Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Aghaei, J., Alizadeh, M.I., 2013. Demand response in smart electricity grids equipped with renewable energy sources: A review. Renew. Sustain. Energy Rev. 18, 64–72. https://doi.org/10.1016/j.rser.2012.09.019.

Albadi, M.H., El-Saadany, E.F., 2008. A summary of demand response in electricity markets. Elec. Power Syst. Res. 78, 1989–1996. https://doi.org/10.1016/j.epsr.2008.04.002.

Alcázar-Ortega, M., Álvarez-Bel, C., Escrivá-Escrivá, G., Domijan, A., 2012. Evaluation and assessment of demand response potential applied to the meat industry. Appl. Energy 92, 84–91. https://doi.org/10.1016/j.apenergy.2011.10.040.

Alcázar-Ortega, M., Calpe, C., Theisen, T., Carbonell-Carretero, J.F., 2015. Methodology for the identification, evaluation and prioritization of market handicaps which prevent the implementation of demand response: Application to european electricity markets. Energy Pol. 86, 529–543. https://doi.org/10.1016/j.enpol.2015.08.006.

Álvarez, C., Moreno, J.I., López, G., Gabaldón, A., Ruiz, M., Matanza, J., Guillamón, A., Valero-Verdú, S., López, M., 2017. Simplification and evaluation of demand response by the use of statistical aggregated models. CIRED-Open Access Proc. J. 2017 2901–2905.

Annala, S., Lukkarinen, J., Primmer, E., Honkapuro, S., Ollikka, K., Sunila, K., Ahonen, T., 2018a. Regulation as an enabler of demand response in electricity markets and power systems. J. Clean. Prod. 195, 1139–1148.

Annala, S., Mendes, G., Honkapuro, S., Matos, L., Klein, L.P., 2018b. Comparison of opportunities and challenges in demand response pilots in Finland and Portugal. In: 2018 15th International Conference on the European Energy Market (EEM). IEEE, pp. 1–5.

Baboli, P.T., Moghaddam, M.P., Eghbal, M., 2011. Present status and future trends in enabling demand response programs. In: 2011 IEEE Power and Energy Society General Meeting. IEEE, pp. 1–6.

Bhattacherjee, A., 2012. Social Science Research: Principles, Methods, and Practices. University of South Florida.

Bichler, M., Buhl, H.U., Knörr, J., Maldonado, F., Schott, P., Waldherr, S., Weibelzahl, M., 2022. Electricity markets in a time of change: A call to arms for business research. Schmalenbach J. Bus. Res. 1–26. https://doi.org/10.1007/s41471-021-00126-4.

Biegel, B., Hansen, L.H., Stoustrup, J., Andersen, P., Harbo, S., 2014. Value of flexible consumption in the electricity markets. Energy 66, 354–362. https://doi.org/10.1016/j.energy.2013.12.041.

Borsche, T., Andersson, G., 2014. A review of demand response business cases. In: IEEE PES Innovative Smart Grid Technologies. IEEE, Europe, pp. 1–6.

Bradley, P., Leach, M., Torriti, J., 2013. A review of the costs and benefits of demand response for electricity in the UK. Energy Pol. 52, 312–327. https://doi.org/10.1016/j.enpol.2012.09.039.

Brouwer, A.S., van den Broek, M., Zappa, W., Turkenburg, W.C., Faaij, A., 2016. Least-cost options for integrating intermittent renewables in low-carbon power systems. Appl. Energy 161, 48–74. https://doi.org/10.1016/j.apenergy.2015.09.090.

Cagno, E., Worrell, E., Trianni, A., Pugliese, G., 2013. A novel approach for barriers to industrial energy efficiency. Renew. Sustain. Energy Rev. 19, 290–308. https://doi.org/10.1016/j.rser.2012.11.007.

Cappers, P., Mills, A., Goldman, C., Wiser, R., Eto, J.H., 2012. An assessment of the role mass market demand response could play in contributing to the management of variable generation integration issues. Energy Pol. 48, 420–429. https://doi.org/10.1016/j.enpol.2012.05.040.

Cappers, P., MacDonald, J., Goldman, C., Ma, O., 2013. An assessment of market and policy barriers for demand response providing ancillary services in U.S. electricity markets. Energy Pol. 62, 1031–1039. https://doi.org/10.1016/j.enpol.2013.08.003.

Clausen, A., Ghatikar, G., Jørgensen, B.N., 2014. Load management of data centers as regulation capacity in Denmark. In: International Green Computing Conference. IEEE, pp. 1–10.

Clò, S., Cataldi, A., Zoppoli, P., 2015. The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. Energy Pol. 77, 79–88. https://doi.org/10.1016/j.enpol.2014.11.038.

Creswell, J.W., Poth, C.N., 2016. Qualitative Inquiry and Research Design: Choosing Among Five Approaches. Sage Publications.

Cruz, M.R., Fitiwi, D.Z., Santos, S.F., Catalão, J.P., 2018. A comprehensive survey of flexibility options for supporting the low-carbon energy future. Renew. Sustain. Energy Rev. 97, 338–353. https://doi.org/10.1016/j.rser.2018.08.028.

Ding, Y., Shao, C., Yan, J., Song, Y., Zhang, C., Guo, C., 2018. Economical flexibility options for integrating fluctuating wind energy in power systems: The case of China. Appl. Energy 228, 426–436. https://doi.org/10.1016/j.apenergy.2018.06.066.

Dong, J., Xue, G., Li, R., 2016. Demand response in China: Regulations, pilot projects and recommendations – A review. Renew. Sustain. Energy Rev. 59, 13–27. https://doi.org/10.1016/j.rser.2015.12.130.

Dudley, J.H., Piette, M.A., 2008. Solutions for summer electric power shortages: Demand response and its application in air conditioning and refrigerating systems. Refrig. Air Cond. Electr. Power Mach. 29, 1–4.

Dyer, C.H., Hammond, G.P., Jones, C.I., McKenna, R.C., 2008. Enabling technologies for industrial energy demand management. Energy Pol. 36, 4434–4443. https://doi.org/10.1016/j.enpol.2008.09.028.

Eid, C., Koliou, E., Valles, M., Reneses, J., Hakvoort, R., 2016. Time-based pricing and electricity demand response: Existing barriers and next steps. Util. Pol. 40, 15–25. https://doi.org/10.1016/j.jup.2016.04.001.

Eissa, M.M., 2011. Demand side management program evaluation based on industrial and commercial field data. Energy Pol. 39, 5961–5969. https://doi.org/10.1016/j.enpol.2011.06.057.

Feuerriegel, S., Neumann, D., 2014. Measuring the financial impact of demand response for electricity retailers. Energy Pol. 65, 359–368. https://doi.org/10.1016/j.enpol.2013.10.012.

Feuerriegel, S., Neumann, D., 2016. Integration scenarios of demand response into electricity markets: load shifting, financial savings and policy implications. Energy Pol. 96, 231–240. https://doi.org/10.1016/j.enpol.2016.05.050.

Fridgen, G., König, C., Häfner, L., Sachs, T., 2016. Providing utility to utilities: The value of information systems enabled flexibility in electricity consumption. J. Assoc. Inf. Syst. Online 17, 537. https://doi.org/10.17705/1jais.00434.

Fridgen, G., Halbrügge, S., Körner, M.-F., Michaelis, A., Weibelzahl, M., 2022. Artificial intelligence in energy demand response: A taxonomy of input data requirements. In: 2022 Proceedings of the 17th International Conference on Wirtschaftsinformatik. WI.

Fridgen, G., Keller, R., Thimmel, M., Wederhake, L., 2017. Shifting load through space – The economics of spatial demand side management using distributed data centers. Energy Pol. 109, 400–413. https://doi.org/10.1016/j.enpol.2017.07.018.

Gelazanskas, L., Gamage, K.A., 2014. Demand side management in smart grid: A review and proposals for future direction. Sustain. Cities Soc. 11, 22–30. https://doi.org/10.1016/j.scs.2013.11.001.

Gils, H.C., 2016. Economic potential for future demand response in Germany–modeling approach and case study. Appl. Energy 162, 401–415. https://doi.org/10.1016/j.apenergy.2015.10.083.

Gitelman, L., Ratnikov, B., Kozhevnikov, M., 2013. Demand-side Management for Energy in the Region. Institute of Economics, Ural Branch of the Russian Academy of Sciences.

Good, N., Ellis, K.A., Mancarella, P., 2017. Review and classification of barriers and enablers of demand response in the smart grid. Renew. Sustain. Energy Rev. 72, 57–72. https://doi.org/10.1016/j.rser.2017.01.043.

Goulden, M., Spence, A., Wardman, J., Leygue, C., 2018. Differentiating ‘the user’ in DSR: Developing demand side response in advanced economies. Energy Pol. 122, 176–185. https://doi.org/10.1016/j.enpol.2018.07.013.

Greening, L.A., 2010. Demand response resources: Who is responsible for implementation in a deregulated market? Energy 35, 1518–1525. https://doi.org/10.1016/j.energy.2009.12.013.

Grein, A., Pehnt, M., 2011. Load management for refrigeration systems: Potentials and barriers. Energy Pol. 39, 5598–5608. https://doi.org/10.1016/j.enpol.2011.04.040.

Grünewald, P., Torriti, J., 2013. Demand response from the non-domestic sector: Early UK experiences and future opportunities. Energy Pol. 61, 423–429. https://doi.org/10.1016/j.enpol.2013.06.051.

Hansen, J., Knudsen, J., Annaswamy, A.M., 2014. Demand response in smart grids: Participants, challenges, and a taxonomy. In: IEEE 53rd Annual Conference on Decision and Control (CDC), 2014. IEEE, Piscataway, NJ, pp. 4045–4052.

Hansen, K., Breyer, C., Lund, H., 2019. Status and perspectives on 100% renewable energy systems. Energy 175, 471–480. https://doi.org/10.1016/j.energy.2019.03.092.

Haupt, L., Körner, M.-F., Schöpf, M., Schott, P., Fridgen, G., 2020. Strukturierte Analyse von Nachfrageflexibilität im Stromsystem und Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen. Z. Energiewirtschaft 44, 141–160. https://doi.org/10.1007/s12398-020-00279-5.

Heffron, R., Körner, M.-F., Wagner, J., Weibelzahl, M., Fridgen, G., et al., 2020. Industrial demand-side flexibility: A key element of a just energy transition and industrial development. Appl. Energy 269. https://doi.org/10.1016/j.apenergy.2020.115026.

Hirst, E., 2001. Price-responsive demand in wholesale markets: Why is so little happening? Electr. J. 14, 25–37. https://doi.org/10.1016/S1040-6190(01)00194-4.

Honkapuro, S., Valtonen, P., Tuunanen, J., Partanen, J., Järventausta, P., 2015. Demand side management in open electricity markets from retailer viewpoint. In: 2015 12th International Conference on the European Energy Market (EEM). IEEE, pp. 1–5.
Hu, Z., Kim, J.h., Wang, J., Byrne, J., 2015. Review of dynamic pricing programs in the US and Europe: Status quo and policy recommendations. Renew. Sustain. Energy Rev. 42, 743–751. https://doi.org/10.1016/j.rser.2014.10.078.
International Energy Agency, 2020. Electricity final consumption by sector. URL: https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20consumption&indicator=Electricity%20final%20consumption%20by%20sector.
Jang, D., Eom, J., Kim, M.G., Rho, J.J., 2015. Demand responses of Korean commercial and industrial businesses to critical peak pricing of electricity. J. Clean. Prod. 90, 275–290. https://doi.org/10.1016/j.jclepro.2014.11.052.
Katz, J., 2014. Linking meters and markets: Roles and incentives to support a flexible demand side. Util. Pol. 31, 74–84. https://doi.org/10.1016/j.jup.2014.08.003.
Khripko, D., Morioka, S.N., Evans, S., Hesselbach, J., de Carvalho, M.M., 2017. Demand side management within industry: A case study for sustainable business models. Procedia Manuf. 8, 270–277. https://doi.org/10.1016/j.promfg.2017.02.034.
Kim, J.H., Shcherbakova, A., 2011. Common failures of demand response. Energy 36, 873–880. https://doi.org/10.1016/j.energy.2010.12.027.
Kleingeld, M., Groenewald, H., Van Rensburg, J., 2012. Practical problems experienced with industrial DSM projects. In: 2012 Proceedings of the 9th Industrial and Commercial Use of Energy Conference. IEEE, pp. 1–6.
Koliou, E., Eid, C., Hakvoort, R., 2013. Development of demand side response in liberalized electricity markets: Policies for effective market design in europe. In: 2013 10th International Conference on the European Energy Market (EEM). IEEE, pp. 1–8.
Kreuder, L., Gruber, A., von Roon, S., 2013. Quantifying the costs of demand response for industrial businesses. In: IECON 2013-39th Annual Conference of the. IEEE Industrial Electronics Society, IEEE, pp. 8046–8051.
Langbein, P., 2009. Lessons learned from real-life implementation of demand response management. In: 2009 IEEE/PES Power Systems Conference and Exposition. IEEE, p. 1. –1.
Li, L., Sun, Z., Tang, Z., 2012. Real time electricity demand response for sustainable manufacturing systems: challenges and a case study. In: 2012 IEEE International Conference on Automation Science and Engineering (CASE). IEEE, pp. 353–357.
Lindberg, C.F., Zahedian, K., Solgi, M., Lindkvist, R., 2014. Potential and limitations for industrial demand side management. Energy Proc. 61, 415–418. https://doi.org/10.1016/j.egypro.2014.11.1138.
Liu, Y., 2017. Demand response and energy efficiency in the capacity resource procurement: Case studies of forward capacity markets in ISO New England, PJM and Great Britain. Energy Pol. 100, 271–282. https://doi.org/10.1016/j.enpol.2016.10.029.
Lund, H., 2007. Renewable energy strategies for sustainable development. Energy 32, 912–919.
Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. 45, 785–807. https://doi.org/10.1016/j.rser.2015.01.057.
Luthra, S., Kumar, S., Kharb, R., Ansari, M.F., Shimmi, S.L., 2014. Adoption of smart grid technologies: An analysis of interactions among barriers. Renew. Sustain. Energy Rev. 33, 554–565. https://doi.org/10.1016/j.rser.2014.02.030.
Ma, O., Alkadi, N., Cappers, P., Denholm, P., Dudley, J., Goli, S., Hummon, M., Kiliccote, S., MacDonald, J., Matson, N., et al., 2013. Demand response for ancillary services. IEEE Trans. Smart Grid 4, 1988–1995.
MacDonald, J., Cappers, P., Callaway, D., Kiliccote, S., 2012. Demand response providing ancillary services: A comparison of opportunities and challenges in US wholesale markets. In: Proceedings of Grid-Interop 2012. California Digital Library.
Macedo, M.N.Q., Galo, J.J.M., Almeida, L.A.L., Lima, A.C.C., 2013. Opportunities and challenges of dsm in smart grid environment. In: Fries, S., Dini, P. (Eds.), Proceedings of the Third International Conference on Smart Grids, Green Communications and IT Energy-Aware Technologies (ENERGY 2013). IARIA, Wilmington, DE, USA, pp. 156–160.
McKane, A.T., Piette, M.A., Faulkner, D., Ghatikar, G., Radspieler Jr., A., Adesola, B., Murtishaw, S., Kiliccote, S., 2008. Opportunities, Barriers and Actions for Industrial Demand Response in California. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States). Technical Report.
Miles, M.B., Huberman, A.M., Saldaña, J., 2014. Qualitative Data Analysis: A Methods Sourcebook, 3rd. SAGE Publications.
Mlecnik, E., Parker, J., Ma, Z., Corchero, C., Knotzer, A., Pernetti, R., 2020. Policy challenges for the development of energy flexibility services. Energy Pol. 137, 111147. https://doi.org/10.1016/j.enpol.2019.111147.
Müller, T., Möst, D., 2018. Demand response potential: Available when needed? Energy Pol. 115, 181–198. https://doi.org/10.1016/j.enpol.2017.12.025.
Myers, M.D., Newman, M., 2007. The qualitative interview in is research: Examining the craft. Inf. Organ. 17, 2–26. https://doi.org/10.1016/j.infoandorg.2006.11.001.
Nguyen, D.T., 2010. Demand response for domestic and small business consumers: A new challenge. In: IEEE PES Transmission and Distribution Conference and Exposition, 2010. IEEE, Piscataway, NJ, pp. 1–7.
Nicolosi, M., Fürsch, M., 2009. The impact of an increasing share of RES-E on the conventional power market—the example of Germany. Z. Energiewirtschaft 33, 246–254. https://doi.org/10.1007/s12398-009-0030-0.
Nolan, S., O'Malley, M., 2015. Challenges and barriers to demand response deployment and evaluation. Appl. Energy 152, 1–10. https://doi.org/10.1016/j.apenergy.2015.04.083.
Olorunfemi, T.R., Nwulu, N., 2018. A review of demand response techniques and operational limitations. In: 2018 International Conference on Computational Techniques, Electronics and Mechanical Systems (CTEMS). IEEE, pp. 442–445.
Olsthoorn, M., Schleich, J., Klobasa, M., 2015. Barriers to electricity load shift in companies: A survey-based exploration of the end-user perspective. Energy Pol. 76, 32–42. https://doi.org/10.1016/j.enpol.2014.11.015.
Palensky, P., Dietrich, D., 2011. Demand side management: Demand response, intelligent energy systems, and smart loads. IEEE Trans. Ind. Inf. 7, 381–388.
Papaefthymiou, G., Haesen, E., Sach, T., 2018. Power system flexibility tracker: Indicators to track flexibility progress towards high-RES systems. Renew. Energy 127, 1026–1035. https://doi.org/10.1016/j.renene.2018.04.094.
Paterakis, N.G., Erdinç, O., Catalão, J.P., 2017. An overview of demand response: Key-elements and international experience. Renew. Sustain. Energy Rev. 69, 871–891. https://doi.org/10.1016/j.rser.2016.11.167.
Pelzer, R., Kleingeld, M., 2011. Cost effect of non-performing DSM projects. In: 2011 Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy. IEEE, pp. 26–29.
Perras, S., 2015. Electricity Transmission Line Planning: Success Factors for Transmission System Operators to Reduce Public Opposition. Saechsische Landesbibliothek-Staats-und Universitaetsbibliothek Dresden.
Pinson, P., Madsen, H., et al., 2014. Benefits and challenges of electrical demand response: A critical review. Renew. Sustain. Energy Rev. 39, 686–699. https://doi.org/10.1016/j.rser.2014.07.098.
Rautiainen, A., Koskela, J., Vilppo, O., Supponen, A., Kojo, M., Toivanen, P., Rinne, E., Järventausta, P., 2017. Attractiveness of demand response in the nordic electricity market - Present state and future prospects. In: 2017 14th International Conference on the European Energy Market (EEM). IEEE, pp. 1–6.
Richstein, J.C., Hosseinioun, S.S., 2020. Industrial Demand Response: How Network Tariffs and Regulation Do (Not) Impact Flexibility Provision in Electricity Markets and Reserves. DIW Berlin Discussion Paper. Technical Report.
Rintamäki, T., Siddiqui, A.S., Salo, A., 2017. Does renewable energy generation decrease the volatility of electricity prices? An analysis of Denmark and Germany. Energy Econ. 62, 270–282. https://doi.org/10.1016/j.eneco.2016.12.019.
Rollert, K.E., 2018. The underlying factors in the uptake of electricity demand response: The case of Poland. Util. Pol. 54, 11–21. https://doi.org/10.1016/j.jup.2018.07.002.
Samad, T., Koch, E., Stluka, P., 2016. Automated demand response for smart buildings and microgrids: The state of the practice and research challenges. Proc. IEEE 104, 726–744.
Sauer, A., Abele, E., Buhl, H.U., 2019. Energieflexibilität in der deutschen Industrie: Ergebnisse aus dem Kopernikus-Projekt-Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung (SynErgie). Fraunhofer Verlag.
Schramm, W., 1971. Notes on Case Studies of Instructional Media Projects.
Schultze, U., Avital, M., 2011. Designing interviews to generate rich data for information systems research. Inf. Organ. 21, 1–16. https://doi.org/10.1016/j.infoandorg.2010.11.001.
Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Pol. 36, 3086–3094. https://doi.org/10.1016/j.enpol.2008.03.035.
Shafie-khah, M., Siano, P., Aghaei, J., Masoum, M.A., Li, F., Catalão, J.P., 2019. Comprehensive review of the recent advances in industrial and commercial DR. IEEE Trans. Ind. Inf. 15, 3757–3771.
Sharma, B., Gupta, N., Niazi, K., Swarnkar, A., Vashisth, S., 2019. Demand response in the global arena: Challenges and future trends. In: 2019 8th International Conference on Power Systems (ICPS). IEEE, pp. 1–5.
Shen, B., Ghatikar, G., Lei, Z., Li, J., Wikler, G., Martin, P., 2014. The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges. Appl. Energy 130, 814–823. https://doi.org/10.1016/j.apenergy.2013.12.069.
Shoreh, M.H., Siano, P., Shafie-khah, M., Loia, V., Catalão, J.P., 2016. A survey of industrial applications of demand response. Elec. Power Syst. Res. 141, 31–49. https://doi.org/10.1016/j.epsr.2016.07.008.
Siano, P., 2014. Demand response and smart grids - A survey. Renew. Sustain. Energy Rev. 30, 461–478. https://doi.org/10.1016/j.rser.2013.10.022.
Strbac, G., 2008. Demand side management: Benefits and challenges. Energy Pol. 36, 4419–4426. https://doi.org/10.1016/j.enpol.2008.09.030.
Torriti, J., Hassan, M.G., Leach, M., 2010. Demand response experience in Europe: policies, programmes and implementation. Energy 35, 1575–1583. https://doi.org/10.1016/j.energy.2009.05.021.
Uddin, M., Romlie, M.F., Abdullah, M.F., Abd Halim, S., Kwang, T.C., et al., 2018. A review on peak load shaving strategies. Renew. Sustain. Energy Rev. 82, 3323–3332. https://doi.org/10.1016/j.rser.2017.10.056.
Unterberger, E., Buhl, H.U., Häfner, L., Keller, F., Keller, R., Ober, S., Paulick-Thiel, C., Reinhart, G., Schöpf, M., Simon, P., 2018. The regional and social impact of energy flexible factories. Procedia Manuf. 21, 468–475. https://doi.org/10.1016/j.promfg.2018.02.146.
Valdes, J., Poque González, A.B., Ramirez Camargo, L., Valin Fenández, M., Masip Macia, Y., Dorner, W., 2019. Industry, flexibility, and demand response: Applying German energy transition lessons in Chile. Energy Res. Social Sci. 54, 12–25. https://doi.org/10.1016/j.erss.2019.03.003.
Vallés, M., Reneses, J., Cossent, R., Frías, P., 2016. Regulatory and market barriers to the realization of demand response in electricity distribution networks: A European perspective. Elec. Power Syst. Res. 140, 689–698. https://doi.org/10.1016/j.epsr.2016.04.026.
van Dievel, P., de Vos, K., Belmans, R., 2014. Demand response in electricity distribution grids: Regulatory framework and barriers. In: 2014 11th International Conference on the European Energy Market (EEM). IEEE, Piscataway, NJ, pp. 1–5.

Verpoorten, K., de Jonghe, C., Belmans, R., 2016. Market barriers for harmonised demand-response in balancing reserves: Cross-country comparison. In: 2016 13th International Conference on the European Energy Market (EEM). IEEE, Piscataway, NJ, pp. 1–5.

Vine, E., Hamrin, J., Eyre, N., Crossley, D., Maloney, M., Watt, G., 2003. Public policy analysis of energy efficiency and load management in changing electricity businesses. Energy Pol. 31, 405–430. https://doi.org/10.1016/S0301-4215(02)00071-X.

Walawalkar, R., Fernands, S., Thakur, N., Chevva, K.R., 2010. Evolution and current status of demand response (DR) in electricity markets: Insights from PJM and NYISO. Energy 35, 1553–1560. https://doi.org/10.1016/j.energy.2009.09.017.

Warren, P., 2014. A review of demand-side management policy in the UK. Renew. Sustain. Energy Rev. 29, 941–951. https://doi.org/10.1016/j.rser.2013.09.009.

Webster, J., Watson, R.T., 2002. Analyzing the Past to Prepare for the Future: Writing a Literature review. MIS Quarterly, pp. xiii–xxiii.

Wierman, A., Liu, Z., Liu, I., Mohsenian-Rad, H., 2014. Opportunities and challenges for data center demand response. In: 2014 International Green Computing Conference (IGCC). IEEE, Piscataway, NJ, pp. 1–10. https://doi.org/10.1109/IGCC.2014.7039172.

Wohlfarth, K., Klingler, A.L., Eichhammer, W., 2020a. The flexibility deployment of the service sector-a demand response modelling approach coupled with evidence from a market research survey. Energy Strat. Rev. 28, 100460.

Wohlfarth, K., Worrell, E., Eichhammer, W., 2020b. Energy efficiency and demand response–two sides of the same coin? Energy Pol. 137, 111070.

Yin, R.K., 2017. Case Study Research and Applications: Design and Methods. Sage publications.

Zhang, Q., Grossmann, I.E., 2016a. Enterprise-wide optimization for industrial demand side management: fundamentals, advances, and perspectives. Chem. Eng. Res. Des. 116, 114–131.

Zhang, Q., Grossmann, I.E., 2016b. Planning and scheduling for industrial demand side management: advances and challenges. In: Alternative Energy Sources and Technologies. Springer, pp. 383–414.