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The flexibility deployment of the service sector - A demand response modelling approach coupled with evidence from a market research survey

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ABSTRACT

The flexible use of energy is seen as a key option to facilitate the integration of volatile renewable energy sources (RES) into the electricity sector. In this study, we focus on flexibility in the service sector, in terms of flexible technologies, experiences and willingness to participate in demand response (DR) actions. We analyse the technically possible future deployment of flexibility, the practically possible deployment of flexibility and also take the reduction of RES surplus electricity into account. Our results are based on survey data from over 1.500 service sector companies (offices, trade, hospitality) and modelling results with a time resolved DR model (eLOAD). The data show that service sector companies have few experiences in DR so far, which is among others caused by the unfavourable regulatory conditions to participate in flexibility markets. The currently most common forms of DR are load shedding and flexible tariffs and optimized purchase of electricity. Participation in DR varies between subsectors and company sizes, but on average all subsectors are interested in extending (automated) DR measures in the future. Our projections result in a possible technical deployment of flexible electricity of 7.74 TWh of which about 510 GWh can be used to reduce renewable surplus electricity (in case of a 50% RES share). In case of a 80% RES share, this can reach 1.63 TWh. Integrating the willingness of companies to participate in DR, the practical possible deployment results in 131 GWh reduction of renewable surplus electricity. This can be interpreted as a first-mover potential for DR. Future increased need for flexible demand could raise the profit for the companies and their willingness in participating in DR. Further analyses on most promising target groups of companies would help to tap the potentials and to create market offers as well as policies to incentivise participation.

1. Introduction

Over the course of the energy transition, the increase in volatile renewable energy sources (RES) will result in new challenges for the energy system. Flexible demand is seen as one way to mitigate these challenges and to ensure the security of supply, for example, by reducing peak loads and therefore potentially avoiding otherwise necessary network expansions, and by integrating electricity from renewable energy sources (RES). At present in Germany, mainly industrial enterprises participate in flexibility markets and their high loads compensate the fluctuations in supply [1]. Future developments will raise the value of flexible demand and may involve less energy-intensive sectors as well (such as services and households). Regarding the service sector, the loads available at each business site are smaller, but are more widespread regionally and energy consumption does not affect their core business activities. Their loads usually can be shifted immediately, but only over short periods. These characteristics might make the service sector's flexibility potential especially interesting for load balancing on a regional distribution grid level. Therefore, it seems worth taking a critical look at the potentials and options for smaller consumers to take part in flexibility markets, particularly since many studies already assume a deployment of these flexibility potentials [e.g. 2, 3, 4].

Measures to change electricity usage patterns on the demand side are referred to as demand response measures (DR, e.g. Ref. [5]). They aim to improve the utilization of variable renewable energy sources and support system stability. Furthermore, because they reduce the need for conventional power plants for load compensation and the need for additional electricity infrastructure, electricity prices can be lowered.

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Different definitions of DR potential need to be distinguished [6,7]. The *theoretical potential* can be seen as the upper limit of potential, e.g. summing up the loads or the consumption of all appliances that can be used for DR purposes. The *technical potential* also considers technical constraints, such as temperature-dependent availability, e.g. in the case of air conditioning (AC) or heat pumps. The *economic potential* takes economic viability into account, assuming that measures are only taken if they are profitable. Profitability depends on economic parameters such as energy prices, and financial parameters such as discount rates. The *practical potential* depends on perceived barriers and organisational restrictions, which influence the decision to take DR action. Both the economic and the practical potential may be influenced by policy settings that could increase the uptake of DR options.

The described potentials refer to different levels of demand flexibility on the consumer side (here: service sector companies). This flexibility is only needed for certain timeslots (e.g. to smooth the residual load) and thus cannot always actually be deployed. Hence, besides the potential, another important parameter is the actually *deployed flexibility*. This is the share of the potential flexibility, which is actually deployed, depending on the need for flexibility due to the availability of energy compared to demand at different points of time, i.e. it represents the amount of flexible electricity that is available and actually needed. It is therefore significantly lower than the technically available flexibility, since the need for flexibility on a national scale is often limited to hours with high PV production in summer or night hours with high wind production in winter. Not all the flexible technologies are available during these hours: for instance, air-conditioning is not usually available in winter. If the need for flexibility is reflected in electricity prices, the deployed flexibility is related to the economic potential, but differs in terms of price levels, additional efforts, investment costs and profitability calculations.

Previous studies have already estimated the DR potential for the service sector [2–4]. Depending on the database, method and projected year, the calculated theoretical, technical and economic potentials vary between 5 and 10 TWh/a flexible energy for the service sector in Germany.

The economic potential, in particular, also depends on the financial compensation for providing flexibility and low payments hinder the willingness to participate in DR. In Germany, different options exist to market demand-side flexibility. They derive from the need for reliable supplements on the supply side, and they integrate flexible options of electricity consumption, e.g. for balancing and frequency reserves. Flexible loads can be traded on the balancing or spot market. Additionally, loads can be used for congestion management under the Ordinance on Interruptible Load Agreements (Abschaltbare Lasten Verordnung, AbLaV) [8]. Other forms of demand-side management include time-variable tariffs, where electricity prices vary over time depending on the availability of electricity.

On Germany's balancing market and under the Ordinance on Interruptible Load Agreements, flexible loads need to prequalify to fulfil minimum standards. The regulatory environment to participate in DR is less favourable than in other countries [9]: Bid sizes and reaction times vary between 1 and 5 MW and from seconds to 15 min, respectively. To open the market to more customers, bid sizes and bidding cycles have recently been adapted [9]. In the latest revisions, pooling of loads is also permitted, e.g. by third party actors like aggregators, as is the participation of medium voltage grids thus facilitating participation for smaller customers and smaller loads. A standardized process (aggregator model) for contracting and financial compensation between the parties is currently in the works and has been thoroughly discussed by the German regulatory agency Bundesnetzagentur [10] and other relevant stakeholders.

Predominantly large, energy-intensive enterprises or third party players participate in the above mentioned markets. This year, about 60 providers prequalified; most of the participating enterprises were from the industrial sector or energy providers [11]. The service sector has not participated so far [1]. Before the revision of the AbLaV in 2016, it was only accessible for larger loads, which systematically excluded companies from the service sector. Indeed, only thirteen enterprises at the most participated under the previous ordinance [12].

In general, demand-side flexibility in the service sector is much less common than in industrial sectors. One reason is that most consumer loads do not fulfil the prequalification standards (e.g. minimum bids, guaranteed availability of loads, required technology and other technical/organisational issues, cp [13]). The energy consumption of the available flexible appliances in the service sector is usually smaller than the appliances typically used in industrial companies. Pooling might become a feasible option in the service sector, especially once standards are established for the aggregation. However, the possible rewards are relatively small compared to the effort needed to participate in the market. More common demand-side options for flexible loads are minimizing peak loads or atypical grid loads which result in lower grid fees for the customer. In Germany, consumers with special types of grid use can profit from lower grid fees (StromNEV§19, sec. 1 and 2) if either their consumption exceeds 10 GWh within 7000 utilization hours (intensive use) or their peak consumption lies outside defined high-load periods of the network operator (atypical grid use). In some cases, these advantages counteract participating in other flexibility options, because load reductions or peaks due to balancing might result in losing the (higher) privileges under the StromNEV.

Variable electricity tariffs are characterized by prices that vary depending on time, load, consumption or load management issues [14]. The most common variable tariffs are time-of-use (TOU), critical peak pricing (CPP) and real-time pricing (RTP) that differ in the timespan of scheduling. In Germany, the EnWG (Energiewirtschaftsgesetz - German Energy Industry Act) obliges energy providers to offer variable tariffs. Currently, however, most energy providers use the simplest form of TOU tariffs with two price periods, e.g. day and night rates. Often these tariffs are combined with specific technologies like night storage heating. A few suppliers or aggregators already offer a kind of RTP tariff, where electricity prices vary depending on exchange prices [15]. With the growing significance of renewable energies, the number of offers might increase.

Given the current developments in the energy transition and the energy system, the conditions for trading flexible energies will change. Recent revisions of the participation requirements for the balancing markets and the development of the aggregator model indicate the increasing importance of flexible loads and participating parties. To tap into a larger share of the potentials offered in the service sector, the economic incentives must be improved, because participating in the market under current conditions is either impossible or economically unattractive for less energy-intensive companies.

The aim of this study is to assess the technical and practical flexibility deployment in order to estimate the possible contribution of the service sector to flexible demand options. The technical flexibility potential considers the total technically available flexible load of the service sector. The practical flexibility deployment refers to the share of companies willing to conduct DR. The technical and practical flexibility deployment differs from the technical and practical potential in that the former refers to the actually deployed flexible energy according to the actual need for flexibility. In contrast, the technical or practical potential describes the available flexible energy whether it is needed or not. We also estimate the economic benefit of the deployed flexibility on the basis of a real-time price. In the case of a real-time price, no prequalification standards need to be considered to evaluate the potentials unlike for the balancing market, for example.

We (i) examine the current state of DR actions and starting points in the service sector in Germany in a market research survey. The results include the assessed willingness of the service sector to participate in DR and an estimation of the accessible consumption provided by the flexible appliances in this sector. Using the insights gained, we (ii) calculate the technically and practically deployable share of flexible energy of the service sector using the time-resolved eLOAD[1] model [16], which optimizes the national DR deployment based on the least-cost scheduling of flexible loads. We conclude (iii) with an estimation of the economic benefits and an outlook to future changes in energy demand considering flexible appliances in the service sector.

2. Methods and data

2.1. Market research survey

To evaluate the current state of flexible loads and the deployment of demand-side management in the service sector, a market research study was initiated within "EnSYS-FlexA" and "AVerS", two projects funded by the German Federal Ministry for Economic Affairs and Energy. The focus lies on estimating flexibility potentials while considering certain preconditions as well as restrictions and acceptance issues influencing the potential to use flexible loads for DR.

To focus on the most relevant subsectors of the service sector, we conducted a preceding deeper analysis of the subsectors' shares in electricity consumption and the availability of flexible cross-cutting technologies (cp [17]). Cross-cutting technologies refer to technologies that are used across the whole service sector such as ventilation/air conditioning (V&AC), refrigeration/freezing (RF), heat pumps (HP), (electric) hot water heaters (HW) and night storage heaters (NSH). The results of this analysis indicated that offices, trade and hotels/restaurants are the most relevant subsectors: Together they account for 70.5 TWh/a (i.e. more than 50% of the service sector's total electricity consumption and about 14% of Germany's total electricity consumption) with large shares of consumption in flexible cross-cutting technologies. The quantitative data we used as input for our approach are derived from a survey of our three selected subsectors. The data were collected between May and July 2017 with the help of a market research institute. The data were obtained using CATI (computer assisted telephone interviews) with the person in charge of energy issues at each company. The survey contained items on the measures taken regarding DR, plans to implement DR measures and general preparedness for automated DR options as well as facilitating conditions like BMS (building management system) or energy management systems. Our final sample contains 1584 complete datasets and is structured as Table 1 shows:

Large enterprises: more than 50 employees; medium enterprises: 10–49 employees; small enterprises: less than 10 employees.

In order to assess a sufficiently high and comparable number of enterprises within every category of size and subsector, the distribution of enterprises is not representative regarding these characteristics. Thus, we weighted our results regarding sectors and categories of sizes according to the distribution in Germany given by the Federal Statistical Office [18] to obtain results in line with the representative population.

The survey also contained questions about the availability and dimensions of flexible appliances. On this basis, we calculated the energy consumption of flexible appliances for the surveyed subsectors (for details, see Ref. [19]). This consumption data is the basis for calculating the deployed flexibility using eLOAD.

Table 1
Sample structure of the quantitative survey (derived from Wohlfarth et al. [19]).

Sectors	Number of enterprises	Company size	Number of enterprises
Offices	675	**Small**	456
Retail/trade	553	**Medium**	691
Hotel, lodging, restaurants	356	**Large**	437
Total	1584		

Assessing the willingness of companies to participate in DR aims at analysing the practical potential, i.e. the share that will realistically contribute to the total deployed flexibility. In contrast to technical potential estimations, unwilling companies are not counted because their technical potential cannot be used. The willing share symbolizes "first-movers", who are relatively easy to persuade and whose potentials are more easily accessible. On the other hand, although there is no guarantee that unwilling companies will ever participate, the willing ones can act as role models that may influence hesitant companies and make them more willing to participate.

2.2. The eLOAD model

We calculate the deployment of flexibility using eLOAD – a model that optimizes the scheduling of flexible loads to consume electricity in hours with low retail prices, therefore generating savings in electricity procurement through arbitrage. The eLOAD (energy LOad curve ADjustment) model [16] uses the share of flexible loads in the service sector and their total electricity consumption as input to calculate the optimal deployment of flexibility.

eLOAD addresses the active adjustment of the load curve through DR. In this study, we use eLOAD to determine the least-cost scheduling of flexible loads on the demand-side depending on an hourly pricing signal (real-time price). The hourly pricing signal is an exogenous model parameter and in our study, it is calculated based on the residual load[2] taken from Ref. [24], and adjusted after the deployment of each cohort of flexible loads. Since the pricing signal correlates with the residual load, the least-cost scheduling of the flexible load also simulates the potential contribution of demand-side technologies to residual load smoothing and RES integration.

Residual load smoothing enables the efficient operation of existing electricity generation assets and grid infrastructure as well as reducing the need for investment in new capacities [20]. As mentioned above, a major input to the eLOAD are the hourly generation profiles of renewable energy sources. Most of the renewable energy sources are characterized by volatile supply. In 2017, Germany already reached a RES share of 36% in gross electricity consumption [21]. The target share of renewable energies in gross electricity consumption in 2030 is 50% as stated in the German government's "Energiekonzept" [22]. The coalition agreement of 2018 intends to increase this target to 65% [23]. When modelling our results, we assumed a share of about 50% of renewable energy sources in the power mix. We also analysed an additional scenario with an 80% share of renewable energies for sensitivity purposes.

The specific shares assumed for renewable energies in net electricity generation are: 15% PV (47.2 TWh), 41% onshore wind (112.0 TWh), 25% offshore wind (69.1 TWh) and 17% others (e.g. biomass) (45.1 TWh). The total final electricity demand in Germany is 520 TWh in this scenario. Time resolved renewable electricity production and production profiles are taken from the base scenario of the long-term scenarios of the German Ministry for Economic Affairs and Energy ([24], p.223, Table 60). We refer to this scenario as the 50% RES-scenario.

The optimal load schedule for processes that are particularly suited to DR is calculated with eLOAD based on the electricity consumption pattern (i.e. the load profile[3]) of the respective process, as well as techno-economic parameters and restrictions (e.g. capacity, storage or organisational constraints). A mixed-integer optimisation is carried out

[1] www.forecast-model.eu.

[2] The residual load equals the system load minus the generation of fluctuating renewable energies.

[3] For details regarding the generation of process-specific load profiles and there application in the eLOAD model, see Ref. [16].

to determine the least-cost scheduling of the load under the assumed price signals. The objective is formally described as

$$Min \sum_{i=h_{min}}^{h_{max}} \sum_{j=i+ct+h_{max}-1}^{i-ct+h_{max}+1} \left\{ ls_{ij} \cdot \left[p_j \cdot (1+|j-i| \cdot cif_{ls}) - p_i \right] \right\}$$

where $i \neq j$ are counting variable and $i, j \in [h_{min}; h_{max}]$ i.e. $i, j \in [0, oi - 1]$. With the shifted load ls, the optimisation interval $[h_{min}; h_{max}]$ with the optimisation interval length *oi,* the cycle time *ct*, the consumption increase factor *cif,* the hourly electricity price *p* [16].

As a result, the model delivers a quantitative assessment of deployed load shifting, providing detailed information about the seasonal, weekly and hourly load shifting availability of the individual appliances. It generates a smoothed residual load curve that can be used in an electricity market model to quantify the impacts of DR on the electricity system.

eLOAD is an established model that has frequently been used in German and European studies for policy makers and industrial customers [25]. For this study, the methodology to represent the share of flexible technologies in the model was complemented by the consumers' willingness to provide flexibility for the energy system; this reflects the practical potential. Using empirically assessed data on electricity consumption and adding the aspect of willingness derived from the survey data is a methodological improvement compared to the former approach. We also estimate the deployed flexibility of the service sector: The technically deployed flexibility assumes all companies participate in DR with their flexible appliances. We refer to the practically deployed flexibility (or first-mover flexibility) if only willing companies participate.

2.3. Assessing the flexibility potential of the service sector

The total consumption of all the flexible appliances together can be regarded as the theoretical potential provided by service sector companies. The actually deployed flexibility is smaller, because the total theoretical potential can neither be used technically nor is it always required when available. The actual deployment involves the load profiles or the need for flexible electricity to smooth the load profiles and assumptions regarding technical restrictions on using the flexible appliances for DR. In order to calculate the actual flexibility deployment, we include this consumption data (theoretical potential) in the eLOAD model.

In the following sections, we compare the deployed flexibility if 100% of the service sector's flexible consumption is available (technical deployment) vs. if only willing companies participate in DR (practical deployment).

Thus, we distinguish the following concepts:

- *Consumption of flexible appliances:* The electricity consumption related to flexible technologies, i.e. V&AC, RF, HP, HW and NSH. This can be seen as a theoretical potential and is the basis for modelling the technically and practically deployed flexibility.
- *Technical flexibility deployment:* This is the electricity consumption of flexible technologies of the service sector deployed to smooth the residual load. Compared to the consumption of flexible appliances, appliance-specific parameters for load shifting (e.g. maximum duration of load shift and availability of appliances depending on time and season) are taken into account as well as the need for flexibility depending on the residual load. It is assumed that 100% of the companies of our selected subsectors of the service sector participate in DR.
- *Practical flexibility deployment:* This uses the same determinants as the technical flexibility potential but additionally takes into account the willingness of companies to participate in DR (as determined from the survey), i.e. not 100% of the sector's companies participate in DR. Only the willing companies contribute to the total flexibility deployment.
- *Reduction of RES surplus[4] electricity:* We use this exemplary concept to show that more flexibility is not necessarily better in every case: The generation of renewable electricity varies during the year and depending on weather conditions, so renewable surplus electricity and the availability of flexible technical appliances do not always match in time and amount. Therefore, the RES surplus that can be reduced using flexible appliances is only a share of the total technical flexibility deployment.

3. Results

3.1. Flexible shares and willingness to provide flexibility - results of the market research survey

3.1.1. Current state and future options of demand response in the service sector

Based on our weighted survey data, we calculated the shares of enterprises in Germany in our selected subsectors that already conduct DR (temporal adjustments in electricity consumption, including time shifting or load shedding) and those who are generally willing to do so (Table 2). Our definition of DR willingness is described below.

The share of companies who already conduct DR differs regarding size and subsector. The highest shares are enterprises trading and dealing with food (food retail and restaurants). The size of enterprises also plays a role, with large enterprises (more than 50 employees) conducting DR significantly more often than small ones. However, the service sector features the largest share of enterprises with fewer than 10 employees, so they should not be left out of our calculations.

Only a small share (3.5%) of the total sample already conducts DR. Different DR options were possible as were multiple options: Most of the enterprises already conducting DR do load shedding (about 57%, lowering the peak load). Time-variable tariffs, optimized purchase of electricity (e.g. at the power exchange) and bilateral agreements (i.e. individual contract, e.g. concerning power cut-offs) are also common with between 20 and 30% of enterprises. Time-variable tariffs are stated more often in offices; optimized purchase is more common in the trade sector than in the other sectors, while bilateral agreements were rarely mentioned in the trade sector.

To learn more about the potentials for DR in the service sector, we also asked if the participants of the survey could imagine implementing DR in their company, i.e. automatically or externally controlled reactions to price signals. The answers were given on a 5-point Likert-scale between "definitely not" (1) and "definitely yes" (5). Those companies that stated they would at least agree to participate (rating 3 to 5) or those that already conduct DR (i.e. optimized energy purchasing, time-variable tariffs, load shedding, participation in balancing markets, or agreements on load cut-offs) were counted as "willing to conduct DR". According to their answers, the willing share in the selected subsectors of the service sector is 16.5%; again, the shares vary between the subsectors.

3.1.2. Flexible electricity consumption in the service sector

Besides the willingness to use it, the specific DR potential depends especially on the availability of flexible appliances and their electricity consumption.

Table 3 shows the yearly consumption of flexible appliances in the service sector. The numbers for V&AC and Refrigeration are taken from Wohlfarth et al. [19]; the numbers for hot water, HP and NSH are derived from Schlomann et al. [26] (water), Kleeberger et al. [27] and

[4] RES surplus: when the residual load reaches negative values it can be taken as an indicator that (locally) the renewable electricity production exceeds the electricity consumption.

Table 2
Current and future DR in the service sector (% refer to the share of companies).

Sectors	Share of enterprises conducting DR	DR willingness[a]	Company Size	Share of enterprises conducting DR	DR willingness
Offices	1.6%	12.8%	**Small**	3.1%	13.7%
Retail/trade	4.2%	17.3%	**Medium**	6.3%	19.4%
Hotel, lodging, Restaurants	10.7%	31.8%	**Large**	14.6%	29.2%
Total	3.5%	16.5%	**Total**	3.5%	16.5%

[a] DR willingness includes the companies already conducting some kind of DR and those stating they can well imagine conducting automatically or externally controlled DR.

Table 3
Consumption of flexible appliances in the three selected subsectors of the service sector in 2017 in GWh/a (derived from Ref. [19]).

Electricity consumption in GWh/a		Offices	Trade	H&R	Total
V&AC	Ventilation	650	1195	429	2273
	AC	1552	3704	304	5560
Refrigeration and freezing (RF)	Fridges	53	1252	1768	3073
	Freezer	11	581	934	1527
	Cooling room	18	2863	849	3730
	Freezing room	9	608	324	942
Hot water (HW)	Electric water heating	900	700	1300	2900
	Sum	3193	10904	5907	20004
HP	Heat pumps				298
NSH	Night storage heating				1785
	Total				**22087**

H&R: Hotels, lodging & Restaurants, Trade: Wholesale & Retail trade.

Wolf et al. [28] (heat pumps), and Klobasa [2] and Wolf et al. [28] (night storage).

Table 3 shows that especially air conditioning and cooling rooms have a high share in the total electricity consumption of the service sector companies, but they are not equally distributed over the different subsectors. Trade accounts for more than half of the total consumption of the analysed subsectors.

3.2. Technical and practical flexibility deployment - results of the eLOAD model

Table 4 lists the electricity consumption of the processes in the service sector that are considered for modelling flexibility deployment under the condition of increased renewable integration (section 2.2) and gives the options for load shifting: The scheduling of circulation pumps and V&AC is limited and can be shifted by 1 h maximum to ensure a constant provision of heat and fresh air and thus comfortable conditions. Additionally, we assume that AC is only used at high temperatures. Heat pumps, hot water and refrigeration processes are considered to be equipped with a physical storage, e.g. a hot water tank. Their load shifting potential is calculated endogenously in the eLOAD model, considering storage restrictions and the hourly storage discharge; for details, see Ref. [16].

When modelling the technical flexibility deployment, we use these shifting parameters and the specific consumption (Table 4 and section 3.1.2) of each flexible appliance, assuming that all appliances present in the companies are generally available for flexible use. The practically deployed flexibility involves only the share of companies that stated their willingness to participate in DR.

In the following, we analyse the described scenario with 100% availability of the flexible technologies (section 3.2.1) and compare it to the practical case including data from the survey on the willingness to participate in DR (section 3.2.2). The economics of the flexibility deployment are assessed in section 3.2.3 in the case that electricity price arbitrage (difference between peak and off-peak prices) is the source of economic benefit.

Table 4
Shifting parameters of flexible appliances.

Appliance		Electricity consumption GWh/a	Avg. hourly useable storage capacity in MWh[a]	Max. load shifting duration[b]
V&AC	Ventilation	2273	–	1 h
	AC	5560	–	1 h
Refrigeration and freezing (RF)	Fridges	3073	±945	1 h
	Freezers	1527	±480	1 h
	Cooling rooms	3730	±867	24 h
	Freezing rooms	942	±243	24 h
Hot water (HW)	Electric water heating	2900	±795	24 h
HP	Heat pumps	298	±231	24 h
NSH	Night storage heating	1785	±5660	24 h

V&AC: Ventilation & Air-conditioning, RF.: Refrigeration and freezing, HW: Hot water, HP: Heat pumps, NSH: Night Storage Heaters.

[a] Amount of shiftable load and frequency depend on the available storage capacity. The storage size is calculated endogenously in the model; for details, see Ref. [16].

[b] The maximum load shift duration is an exogenous model parameter. The load shifting duration of appliances without a storage is limited to 1 h to avoid loss of comfort. Appliances with a storage can shift their loads in an interval of 24 h, since electricity prices are currently available one day ahead in Germany.

3.2.1. Technical flexibility deployment - results of the 100% participation scenario

We first look at the average uncontrolled load profiles of the considered processes in the service sector (Fig. 1 upper graph, for details on the load profiles, see Ref. [29]). The consumption for heat provision is increases in winter and the heating profiles are characterized by more or less continuous electricity consumption over the course of the day, and a large share of consumption at night in the case of night storage heating (NSH). The consumption for ventilation and air-conditioning is higher in summer, which is due to the demand for air-conditioning that only occurs on hot days. The electricity consumption for ventilation and air-conditioning as well as for refrigeration already coincides quite well with the low residual load during summer midday hours (due to high shares of renewables in the scenario). In winter, the residual load has the lowest values in the early morning hours that feature no particularly high electricity consumption.

When considering DR (Fig. 1 bottom figure), the load is shifted primarily towards midday hours and early morning hours with a relatively low residual load in summer and winter (i.e. where renewables are abundant). In summer, the shift towards midday is more favourable, while early morning hours are preferred in winter. Overall, the largest flexibility can be provided by ventilation and air-conditioning processes, but, most of this can only be provided in summer. For both seasons, refrigeration and freezing processes show the highest available flexibility since the refrigeration chambers have a large internal storage.

Our analysis of flexible processes across the different subsectors

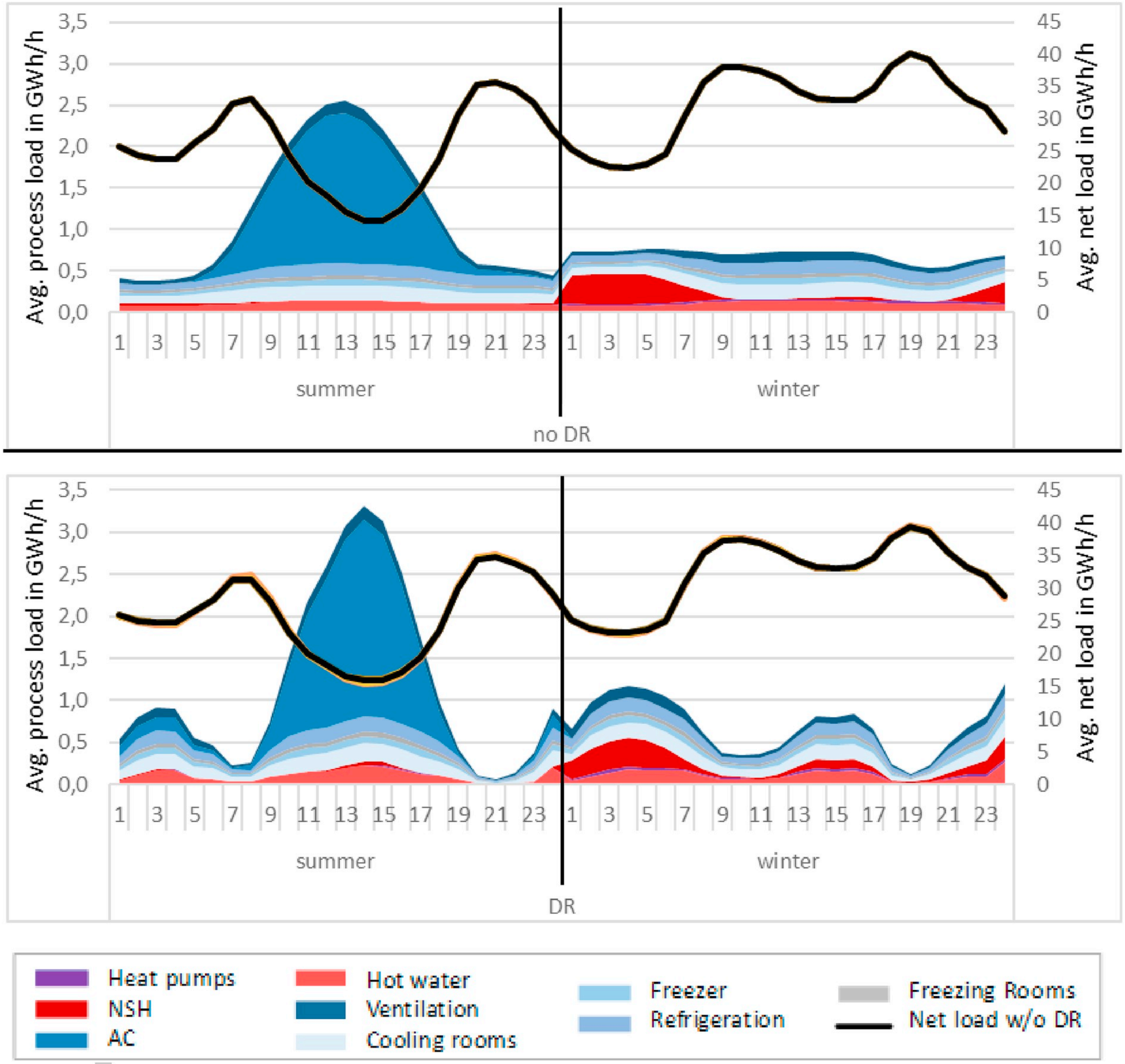

Fig. 1. Average process loads (area plot, left scale) and residual load (black line, right scale) in the 50%RES-scenario, uncontrolled (above) and with 100% participation of DR options (technical deployed flexibility) (below).

Table 5
Technical flexibility deployment in TWh/a (50%RES-scenario) in the selected subsectors.

	Unit	V&AC	RF	HW	HP	NSH	Total
Total	TWh	2.75	2.64	1.22	0.13	0.99	7.74
H&R	TWh	0.26	1.28	0.67	0.04	0.33	2.59
Offices	TWh	0.94	0.02	0.31	0.06	0.44	1.77
Trade	TWh	1.55	1.33	0.25	0.03	0.22	3.38

V&AC: Ventilation & Air-conditioning, RF.: Refrigeration and freezing, HW: Hot water, HP: Heat pumps, NSH: Night Storage Heaters.

reveals that V&AC has the highest electricity consumption and also results in the highest flexibility potential (Table 5). The same goes for the subsector trade that shows by far the highest electricity consumption in the considered processes (51% of the total subsector electricity demand) and thus the highest load shifting potential.

Table 6 lists the flexibility deployed to smooth the residual load and the contribution of each process to integrating RES electricity in the residual load in the case of the technical flexibility deployment (all companies participate in DR). In our calculations, V&AC processes already provide about 36% of the flexibility in the service sector, followed by refrigeration and freezing with about 34%. Regarding the contribution of the appliances to reduce surplus energy, the relations slightly differ: V&AC provide over 35%, followed by refrigeration and freezing with about 28%. Most of the RES surplus electricity occurs in

Table 6
Summary of flexibility deployment for different processes (50%RES-scenario) in the selected subsectors.

	Unit	V&AC	RF	HW	HP	NSH	Total
Electricity consumption of flexible technologies	TWh	7.83	9.27	2.90	0.30	1.79	22.09
Technical flexibility deployment	TWh	2.75	2.64	1.22	0.13	0.99	7.74
Reduction of RES surplus electricity	GWh	181	143	12.8	68.8	104.5	510

V&AC: Ventilation & Air-conditioning, Refr.: Refrigeration, HW: Hot water, HP: Heat pumps, NSH: Night Storage Heaters.

Table 7
Normalized shifted load for the different processes. The values are normalized to the month with the highest shifted load (eq. 100%) load in the 50% RES-scenario.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
AC	0%	0%	0%	2%	4%	46%	100%	42%	5%	0%	0%	0%
Cooling room	100%	86%	91%	84%	85%	83%	84%	88%	87%	93%	94%	95%
Freezer	100%	87%	91%	82%	86%	81%	83%	87%	88%	93%	94%	96%
Freezing room	100%	87%	92%	84%	86%	83%	85%	87%	88%	94%	94%	96%
Hot water	100%	90%	95%	85%	87%	89%	88%	88%	90%	94%	94%	94%
HP	84%	86%	100%	87%	59%	25%	8%	15%	49%	87%	84%	85%
NSH	74%	74%	100%	72%	49%	11%	0%	6%	37%	74%	72%	80%
Fridges	100%	87%	92%	85%	87%	83%	85%	88%	89%	93%	94%	97%
Ventilation	100%	87%	84%	75%	79%	65%	65%	70%	76%	82%	95%	98%

sunny summer midday hours when V&AC show particularly high availability.

Table 7 shows the deployment of flexible service sector technologies over the year. AC is only relevant in the summer and can therefore only be used then to make the electricity system more flexible. Conversely, heaters are hardly used in summer. Cooling appliances that are operated all year round can also be used in winter. In general, higher capacity utilization is achieved in winter.

Table 8 shows the contribution of the service sector to reducing surplus RES in GWh. The final line shows the RES surplus before DR (in yellow). The results show that, in sum, about 20% (510 GWh) of the total RES surplus (2.5 TWh) can be absorbed by the analysed service sector subsectors (offices, trade, hospitality). In specific months with low RES surplus, almost all the surplus electricity can be reduced with flexible appliances from these sectors.

The contribution of the service sector's flexible demand to the integration of RES is relatively small, as the flexibility options in the service sector can be deployed frequently (i.e. every day), but can only shift their loads for a few hours and in an interval of only one day. Therefore, if RES surplus occurs (almost) throughout the day, its reduction is hardly possible, because consumption cannot be shifted from hours without surplus to hours when RES surplus occurs. In this case, the flexibility options of the service sector only have a smoothing effect on the load. The difference between the reduction of RES surplus (510 GWh) and the technical flexibility deployment (7.74 TWh) implies that the service sector has the potential to contribute even more to reducing the RES surplus, but the availability of flexible loads does not match the surplus of renewable energies. In the 50% scenario, RES surplus is relatively concentrated in some periods, especially in autumn.

We therefore additionally analysed a scenario with a higher share of renewable energies, since we assume that this would increase the overlap of available flexible loads and RES surplus. The scenario with an 80% share of renewable energies (which is comparable to the target share of 2050) [22] shows that the reduction of RES surplus by the service sector would then be more than three times as high as in the 50% scenario (Table 9). Although the shifted load is the same as in the 50% scenario, the reduction of surplus RES is much higher in the 80% scenario, since situations with RES overproduction occur more frequently in the 80% scenario and the available flexibility in the service sector reduces negative residual load situations rather than merely smoothing the load curve.

3.2.2. *Practical flexibility deployment - results of the "realistic" participation scenario*

16.5% of service sector companies say they are willing to conduct automated DR measures in the future. It can be assumed that the share of willing companies will increase if the regulatory framework improves and there is incentivizing regulation. Especially the companies with high technical flexibility potentials (large companies and companies from the subsectors trade and restaurants) show significantly more interest in carrying out DR measures. This share can be seen as a first-mover potential. The above discussed technical flexibility deployment that assumes 100% participation of the regarded subsectors is reduced here, because only willing companies can be taken into account when estimating the practical potential. If only the willing share of companies contributes to the deployment of flexible energy, the practical flexibility deployment is reduced to 1.82 TWh (24% of the technically deployed flexibility).

This value is close to the weighted (i.e. representative) total sector willingness to deploy flexible technologies of 16.5% from the survey (see Table 10). The difference stems from the fact that the first MWh of flexibility is of the greatest value for the system. In cases where only a small amount of electricity needs to be shifted, it can be compensated with the practically deployed flexibility.

3.2.3. *Economic benefit of the flexibility deployment*

Financial profitability is an important incentive to participate in DR. We assume the electricity price depends on the residual load (see Section 2.2). To assess the economics of flexibility deployment, we therefore calculate the future electricity price using a polynomial function that connects the residual load of the eLOAD model in 2030 with the electricity price [30]. With this approach the model creates a real-time price for flexible demand. The price $C(t)$ in EUR/MWh with residual load $P(t)$ in GWh is calculated using the following equation:

$$C(t) = c_3 P(t)^3 + c_2 P(t)^2 + c_1 P(t) + c_0$$

with the hourly electricity price $C(t)$, the residual load $P(t)$, and the regression coefficients $c_3 = 0.0008$ $c_2 = -0.0922$, $c_1 = 5.0624$ and $c_0 = 27.415$. For a residual load equal to zero or negative, a linear correlation is used:

$$C(t) = P(t) + c_0$$

The described function was developed by Dallinger [30] based on experiences with the clearing results of an electricity market simulation model. The resulting hourly price time series shows an average price of $\overline{C} = 109$ EUR/MWh (considerably higher than the average in 2017:

Table 8
Contribution of the service sector to reducing the RES surplus in the 50% RES-scenario (GWh).

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
AC	0.0	0.0	0.0	0.0	0.0	4.2	65.6	42.6	1.7	0.0	0.0	0.0	**114**
Cooling room	1.2	2.1	8.6	0.4	2.8	0.3	4.1	6.7	6.4	7.3	6.5	6.1	**53**
Freezer	0.7	1.2	3.4	0.0	1.6	0.1	1.7	2.9	2.8	3.3	3.3	2.8	**24**
Freezing room	0.3	0.6	2.3	0.0	0.9	0.1	1.2	1.7	1.7	2.0	2.0	1.8	**15**
Hot water	1.5	2.3	10.3	0.3	5.1	1.2	6.7	8.8	8.3	10.8	7.1	6.3	**69**
HP	0.2	0.6	2.3	0.0	1.5	0.2	0.3	0.6	1.4	2.9	1.5	1.3	**13**
NSH	2.2	6.0	22.3	1.3	12.1	0.8	0.0	2.2	7.2	27.7	11.2	11.6	**105**
Refr.	1.2	2.3	8.2	0.3	3.4	0.3	4.3	6.2	5.4	6.7	6.9	7.2	**52**
Ventilation	1.7	2.5	10.3	0.0	3.8	0.1	6.2	7.9	7.4	10.2	8.8	8.3	**67**
Total	**9**	**18**	**68**	**2**	**31**	**7**	**90**	**80**	**42**	**71**	**47**	**45**	**510**
% RES surplus reduction	64%	62%	23%	100 %	20%	81%	40%	18%	14%	19%	25%	21%	20%
RES surplus	14	282	298	2	157	9	224	454	292	367	187	219	2505

Table 9
Shifted load and RES surplus reduction in the 80% RES-scenario.

	Unit	Technical
Flexibility deployment (shifted load)	*TWh*	7.75
Reduction of RES surplus electricity	*TWh*	1.63

Table 10
Summary of technical vs. practical flexibility deployment in the service sector.

	Unit	Technical	Practical	Ratio practical/ technical.
Consumption of flexible appliances	*TWh*	22.09	3.64	16.5%
Flexibility deployment (shifted load)	*TWh*	7.74	1.82	24%
Reduction of RES surplus electricity	*GWh*	510	131	26%

32.9 EUR/MWh[5]) and an average spread of $\Delta C = 6$ EUR/MWh between two consecutive hours. The price depends on the residual load and changes when the load curve changes.

Applying this price function, we find that 23 EUR/MWh per year can be achieved on average for each shifted MWh of electricity. The analysed sectors stand to gain around 178 million euros in revenue from the technical flexibility potential of 7.74 TWh.

3.2.4. *Future development of energy consumption*

We base our calculation of the consumption of flexible appliances on empirical data from 2017. It can be assumed that consumption might change in the future and thus also the available share of flexible demand. We therefore refer to data from Fraunhofer ISI [24] considering developments until 2030. Due to efficiency measures, the service sector sees decreasing electricity consumption between 2017 and 2030. The decrease is particularly due to improved energy efficiency and the phase-out of electric storage heating. Storage and direct electric heating are replaced with heat pumps by 2030. Table 11 shows the changes in consumption for each flexible technology.

The consumption of V&AC stays more or less the same. Although there will be gains in energy efficiency, the number of AC systems is expected to increase in the future. The number of NSH will decrease to the benefit of heat pumps, so the ratios change between the appliances contributing to the deployed flexibility. The overall consumption and the flexible potential will decrease, but incentives (affecting the willingness to participate, e.g. regulations and the increasing value of flexible demand) as well as improved technological standards facilitating the controllability of appliances will increase the realistic flexibility potential.

4. Summary and discussion

Our results show that only a small share of the considered subsectors from the service sector conduct DR so far (about 3.5%). The most common DR measures are load shedding, flexible tariffs and optimized purchase of electricity. One reason for the low share of companies from the service sector are the unfavourable regulatory conditions that impede participation (e.g. prequalification criteria, difficult market access/difficulties with load aggregation). In other countries with more favourable regulatory conditions, the participation in DR is higher [9, 31]. Due to the fact that service sector companies use fewer energy-intensive cross-cutting appliances and due to the large share of small companies in this sector, DR is also financially less attractive. Automatic or externally controlled DR measures are considered to tap the maximum potential. In our considered subsectors (trade, offices, hospitality), especially electrical cross-cutting appliances like VAC,

Table 11
Electricity consumption in 2030 of potentially flexible processes in the service sector and its development between 2017 and 2030.

	Unit	V&AC	RF	HW	HP	NSH	Total
2017	TWh	7.83	9.27	2.90	0.30	1.79	22.09
2030	TWh	7.83	7.69	1.33	0.35	0	18.20
2017 vs. 2030		0%	−17%	−54%	17%	−100%	−18%

Source: Fraunhofer ISI [24].

[5] Source: EPEX; taken from Fraunhofer ISE (https://www.energy-charts.de/price_avg_de.htm?year=all&price=nominal&period=annual).

refrigeration, heat pumps, electrical water heating and night storage heaters seem appropriate. The largest potentials can be ascribed to VAC and refrigeration processes.

We used the eLOAD model to calculate the deployment of flexible electricity that could be provided by flexible appliances in the service sector. The modelled deployment is market-based and supported by modelled price signals from a spot market. Other (mainly grid-based) incentive systems, and possible future incentives for flexible behaviour, such as variable grid tariffs, are neglected in this study, even though they could offer higher potential revenues. Since the service sector is not present on any of the potential flexibility markets, the analysed case in this study serves to provide insights into the available and usefully deployable amount of flexibility in this demand-side sector. We distinguished between technically and practically deployed flexibility. Technical deployment refers to the case where all flexible appliances participate in DR; practical deployment refers to the share of companies willing to provide their appliances for DR purposes (first-movers). The main results are summarized in Table 11. The *technical calculations* resulted in about 7.74 TWh of electricity shifted to smooth the residual load curve. The technical deployment of flexibility thus amounts to around 35% of the overall consumption of flexible appliances in the selected subsectors of the service sector (about 22 TWh), i.e. the theoretical potential in our scenario. This is due to the fact that not all the flexibility is necessary or available to smooth the residual load in every hour of the year. The same applies to the RES surplus reduction. Technically, renewable surplus electricity can be reduced by 510 GWh per year: Although there is a RES surplus of 2.5 TWh and a practical flexibility deployment of 7.74 TWh, it is not possible to reduce all the RES surplus. RES surplus often occurs with high peaks which cannot be absorbed by our selected sectors alone, or the duration of RES surplus is too long, so that a shift from hours without surplus to hours when surplus occurs is hardly possible. A higher share of RES could thus create more opportunities to integrate the flexibility potentials; our calculations for the 80% RES scenario result in 1.63 TWh.

When considering the willingness to participate, our *practical calculations* resulted in 1.82 TWh flexibility deployment and 131 GWh reduction of renewable surplus electricity with the first-movers.

In another study [19], the same consumption data (theoretical potential) were used to estimate flexibility potentials that could be provided by the sector (irrespective whether or not they can be deployed at the point of time of availability). The technical potential, e.g. for VAC, resulted in 1/6 of the technical flexibility deployment (Table 12), assuming 1 h of load shifting on 30 days in summer, and in half of the technical flexibility deployment for refrigeration, assuming 2 h of load shifting each day of the year. Compared to these estimations, our results show an average of 6 h of daily load shifting for VAC (in sum on 30 days in summer) and 4 h of daily load shifting for refrigeration appliances to smooth the residual load. This indicates that the actual technical feasibility of flexibilisation (i.e. frequency and duration of loadshift parameters for appliances) needs further research, especially with respect to aspects of comfort.

In the conducted survey, we asked about the future potentials of DR. The participants were asked if they could imagine load management that automatically adjusts the consumption of their appliances assuming there were no additional costs for the control technologies. This question is naturally hypothetical and the answers are given based on current (e.g. technical and regulatory) experiences. If these circumstances and the incentives to participate improved in the future and such measures were better known, the willingness to provide flexible loads might be much higher. Regarding the willing share of companies, small companies with less than 10 employees dominate the results, because most companies in Germany fall under the category of small enterprises. Furthermore, the willingness to conduct DR is asymmetric: Compared to small companies, large companies are more willing, have higher energy consumption and are most likely our primary target group. The large enterprises in the service sector could function as role models for the subsequent broader rollout of DR. However, considering the willingness of possible participants in DR gives additional insights compared to exploring potentials based on only technical assumptions. Current research either does not consider the willingness of the service sector to provide flexibility or determines this based on simple assumptions.

Table 12
Overview of main results of the 50% (resp. 80%) RES scenario (TWh).

Consumption of flexible appliances	Technical flexibility deployment	Practical flexibility deployment	Technical reduction of RES surplus
22.09	7.74	1.82	0.51 1.63 (80% RES share)

Regarding the economic benefit of flexibility provision, our assumptions are comparable to the exploitation of spot market price spreads in a real-time price-based electricity tariff. The results related to a future higher share of RES depend heavily on the development of price spreads. We did not consider economic potentials in other flexibility markets like the balancing market, because they are mostly inaccessible or unattractive – especially to the small companies that make up a large part of the service sector. A further development of these markets, easier access and an extension of the aggregator model could help to tap flexibility potentials, raise acceptance and reduce the required organisational efforts.

The modelling of flexible loads could be extended to include other markets. In this case, the market could be chosen to match the load patterns and the availability of flexibility. So far, the decision to conduct a DR measure is modelled in eLOAD based on the spot market electricity price only. The model would need to be extended, e.g. by introducing commodity and capacity prices of the reserve markets.

Furthermore, incentive-based DR programmes also exist, such as direct load control or power cut-offs. In the eLOAD model, these programmes are only considered for industrial processes at the moment, such as primary aluminium production. Developing these options for smaller flexible loads would allow an even more holistic assessment of the potential benefits from DR and of the impact of additional DR programmes on process load adjustment and residual load smoothing.

Complementary to the energy quantities (MWh), the load peaks (MW) could be taken into account to evaluate a load-shifting potential. Their additional value comes from levelling and compensating peak loads, while our focus was on smoothing the residual load and integrating renewable energies.

Additionally, the calculation of DR with the eLOAD model is based on load profiles that reflect the consumption behaviour. However, these load profiles are of course based on statistical analysis and could change in the future. For further research, an analysis whether and to what extend the results change with different consumption behaviour would be an interesting research question.

5. Conclusions

Overall, we gained valuable insights into the current and future state of DR activities through a market research survey in the German service sector. These insights were used to improve the representation of the available flexible technologies in a DR model (eLOAD).

The main conclusions of our study are summarized as follows:

i. The share of companies conducting DR measures in the service sector is currently small (about 4%), but the share of companies willing to participate is more than four times as high as this (16.5%).
ii. The technical flexibility deployment for our selected subsectors is estimated at 7.74 TWh per year, which is around 35% of the theoretical DR potential (the consumption of flexible appliances)

because only a smaller share is technically available for flexible use and not always available when required.

iii. The modelling resulted in reducing the renewable surplus electricity per year by about 510 GWh with a 50% RES share and 1.63 TWh with an 80% RES share.

iv. The willingness to contribute to DR in the service sector needs to be considered. The share of willing companies can be seen as first-movers able to kick-start a trend to tap a large share of the technically available potential in the future.

Further research could include the modelling of other flexibility markets such as the balancing markets and additional DR measures. These options could increase the financial benefits of DR for companies. The effect of potential financial gains on the companies' willingness to participate in DR should also be analysed in detail.

Declaration of competing interest

None.

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References

[1] T. Weißbach, DSM – erfahrungen und Perspektiven aus Sicht eines Übertragungsnetzbetreibers (experiences and perspectives from the perspective of a transmission system operator), Transnet BW, Vortrag Im Rahmen Des Projekttreffens Demand Side Management in Baden Württemberg, Stuttgart 14 (2015) 12–2015.

[2] M. Klobasa, Dynamische Simulation eines Lastmanagements und Integration von Windenergie in ein Elektrizitätsnetz auf Landesebene unter regelungstechnischen und Kostengesichtspunkten (dynamic simulation of a load management and integration of wind energy into an electricity grid at the state level under control and cost aspects.). Doctoral thesis. ETH Zürich, Zürich. Nr. 17324, ., 2007. http://vg00.met.vgwort.de/na/16d43a23ed5f120d87067f41ebfbea?l=http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-686156.pdf.

[3] VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., Ein Notwendiger Baustein: Demand Side Integration, Lastverschiebungspotenziale in Deutschland (A Necessary Building Block: Demand Side Integration, Load Shifting Potential in Germany). ETG Task Force Demand Side Management. Juni 2012, Frankfurt a. M, 2012. Hrsg.

[4] Deutsche Energie-Agentur GmbH (dena), Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015 – 2020 mit Ausblick auf 2025 (integration of Renewable Energies into the German Power Supply in the Period 2015 - 2020 with Outlook for 2025), dena-Netzstudie II, Berlin, 2010.

[5] IEA – International Energy Agency, Roles and Potentials of Flexible Consumers and Prosumers. Demand Flexibility in Households and Buildings. IEA DSM Task 17, IEA DSM Enery Efficiency, 2016. Available: http://www.ieadsm.org/wp/files/IEA-DSM-Task-17-Subtask-10-role-and-potentials-2016-09-29.pdf.

[6] M. Rudolph, U. Wagner, Begriffe der Versorgungswirtschaft Teil D Energie Heft 1: Energiewirtschaftliche Grundbegriffe, (Terms used in the energy supply sector) VWEW Verlag, Frankfurt a. M, 1997.

[7] S. von Roon, T. Gobmaier, Demand Response in der Industrie. Status und Potenziale in Deutschland (demand response in the industry. Status and potential in Germany), München: Forschungsstelle für Energiewirtschaft e.V (2010).

[8] AbLaV, Verordnung über Vereinbarungen zu abschaltbaren Lasten (Verordnung zu abschaltbaren Lasten – AbLaV, Ordinance on Interruptible Load Agreements), BGBl. I S (2016) 1984.

[9] SEDC, Mapping Demand Response in Europe 2017. Mapping the Markets 2017, 2017. Available at: https://www.smarten.eu/2017/04/06/explicit-demand-response-in-europe-mapping-the-markets-2017/.

[10] BNetzA, Vorschlag aggregator-modell, Available at: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/VortraegeVeranstaltungen/Aggregator_Modell_606.pdf, 2016. Retrieved 03.03.2017.

[11] Regelleistungnet, List of Prequalified Providers of Operating Reserve. Status of 15.08.2018, 2018. Available at: https://www.regelleistung.net/ext/download/anbieterliste. Retrieved: 31.08.2018.

[12] Regelleistungnet, Sheddable loads – number of framework contracts, Available at: https://www.regelleistung.net/ext/static/abla, 2018. Retrieved: 31.08.2018.

[13] VDN – Verband der Netzbetreiber e.V. beim VDEW, TransmissionCode 2007. Netz- und Systemregeln der deutschen Übertragungsnetzbetreiber. Anhang D. Berlin, 2007. Available: https://www.regelleistung.net/ext/static/prequalification. retrieved 04.04.18.

[14] Christian Nabe, Catherina Beyer, Nils Brodersen, Harald Schäffler, Dietmar Adam, Christoph Heinemann, Tobias Tusch, Jost Eder, de Wyl, Christian, vom Wege, Jan-Hendrik, Simone Mühe, Einführung von lastvariablen und zeitvariablen Tarifen (introduction of load variable and time variable tariffs), Gutachten im Auftrag der Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen (2009) 2009.

[15] N.E.X.T. Kraftwerke, Variable Electricity Tariff "Best of 96", 2017. https://www.next-kraftwerke.de/virtuelles-kraftwerk/stromverbraucher/variabler-stromtarif. retrieved 22.09.2017.

[16] T. Boßmann, The contribution of electricity consumers to peak shaving and the integration of renewable energy sources by means of demand response, Dissertation, KIT, Karlsruhe, 2015. Fraunhofer Verlag, ISBN 978-3-8396-0919-4.

[17] K. Wohlfarth, M. Klobasa, A. Eßer, Setting course for demand response in the service sector, J. Energy Effic. Springer (2018), https://doi.org/10.1007/s12053-018-9728-3.

[18] Statistisches Bundesamt DeStatis, Statistisches Unternehmensregister. Unternehmen nach Wirtschaftsabschnitten und Größenklassen der sozialversicherungspflichtig Beschäftigten im Berichtsjahr 2013, Registerstand: 31.05.2015, 2015.

[19] K. Wohlfarth, M. Klobasa, R. Gutknecht, Demand response in the service sector – Theoretical, technical and practical potentials, Appl. Energy 258 (2020) 114089. https://doi.org/10.1016/j.apenergy.2019.114089.

[20] T. Boßmann, R. Elsland, A.-L. Klingler, G. Catenazzi, M. Jakob, Assessing the optimal use of electric heating systems for integrating renewable energy sources, Energy Procedia 83 (2015) 130–139, https://doi.org/10.1016/j.egypro.2015.12.203.

[21] A.G. Energiebilanzen, Auswertungstabellen zur Energiebilanz Deutschland (evaluation tables for the energy balance Germany), 1990 – 2017. Stand Juli 2018. Im Auftrag der Arbeitsgemeinschaft Energiebilanzen bearbeitet von: DIW Berlin und Energy Environment Forecast Analysis, 2018. Available: https://ag-energiebilanzen.de/index.php?article_id=29&fileName=ausw_30jul2018_ov.pdf. retrieved: 31.08.2018.

[22] Deutsche Bundesregierung, Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. 28. September 2010, 2010. http://www.bundesregierung.de/ContentArchiv/DE/Archiv17/_Anlagen/2012/02/energiekonzept-final.pdf?_blob=publicationFile&v=5. retrieved 05.09.2018.

[23] Bundesregierung, Ein neuer Aufbruch für Europa, Eine neue Dynamik für Deutschland, Ein neuer Zusammenhalt für unser Land, Koalitionsvertrag (coalition agreement) zwischen CDU, CSU und SPD. 19. Legislaturperiode, 2018. Available: https://www.bundesregierung.de/Content/DE/_Anlagen/2018/03/2018-03-14-koalitionsvertrag.pdf?_blob=publicationFile&v=6. retrieved 27.09.2018.

[24] Fraunhofer ISI, I.F.E.U. Consentec, W. TU, M-Five, TEP Energy, Langfristszenarien für die Transformation des Energiesystems in Deutschland. Modul 3: referenzszenario und Basisszenario (long-term scenarios for the transformation of the energy system in Germany. Module 3: reference scenario and baseline scenario), Studie Im Auftrag Des Bundesministeriums Für Wirtschaft Und Energie (2017). Online verfügbar unter, http://www.bmwi.de/Redaktion/DE/Downloads/B/berichtsmodul-3-referenzszenario-undbasisszenario.pdf?_blob=publicationFile&v=4.

[25] Fraunhofer ISI, IREES, TEP Energy, FORECAST/eLOAD Website, ., 2018. https://forecast-model.eu. (Accessed 29 June 2017).

[26] B. Schlomann, K. Wohlfarth, H. Kleeberger, L. Hardi, B. Geiger, A. Pich, E. Gruber, A. Gerspacher, E. Holländer, A. Roser, Energy Consumption of the Tertiary Sector (Trade, Commerce and Services) in Germany for the Years 2011 to 2013: Final Report to the Federal Ministry for Economic Affairs and Energy (BMWi). Karlsruhe, Munich, Nuremberg, February 2015, 2015, ISBN 978-3-8396-0691-9 available: http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-2855601.pdf.

[27] H. Kleeberger, L. Hardi, B. Geiger, Erstellen der Anwendungsbilanzen (energy balances) 2013 bis 2017 für den Sektor Gewerbe, Handel, Dienstleistungen (GHD), Im Auftrag der Arbeitsgemeinschaft Energiebilanzen e.V., Berlin, 2016. https://ag-energiebilanzen.de/index.php?article_id=29&fileName=tum_ageb_anwendungsbilanz_ghd_2016.pdf. retrieved 05.04.2018.

[28] S. Wolf, U. Fahl, M. Blesl, A. Voß, R. Jakobs, Analyse des Potenzials von Industriewärmepumpen in Deutschland (analysis of the potential of industrial heat pumps in Germany). Forschungsprojekt gefördert vom Bundesministerium für Wirtschaft und Energie (BMWi) und der Energie Baden-Württemberg AG (EnBW), Endbericht, Stuttgart, 2016.

[29] M. Jakob, S. Kallio, T. Boßmann, Generating electricity demand-side load profiles of the tertiary sector for selected European countries, in: 8th International Conference Improving Energy Efficiency in Commercial Buildings, IEECB'14, 2014.
[30] D. Dallinger, Plug-in electric vehicles integrating fluctuating renewable electricity LXIV, Kassel University Press, Kassel, 2013, 116 S.Zugl.: Kassel, Univ., Diss., 2012; Erneuerbare Energien Und Energieeffizienz, 20; ISBN: 978-3-86219-460-5.
[31] U. Reiter, M. Jakob, K. Wohlfarth, Policy Brief Demand Side Management – Empirical Data from the Services Sector. Policy Brief on the Findings of the REFLEX Project, 2018. Available: http://reflex-project.eu/public/paper-publications/. retrieved: 31.10.2018.