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The potential and usefulness of demand response to provide electricity system services

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HIGHLIGHTS

- We assess the usefulness of DR in a German renewables-only (future) power system.
- Shifting potential is constrained by consumer acceptance and process reconnection.
- We show that DR is useful as spinning & primary reserves and to dampen gradients.
- It is unsuited for secondary/tertiary reserve or covering long low sun/wind periods.
- Conclusion: DR has large potential for short-term shifts but not for longer shifts.

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ABSTRACT

The expansion of fluctuating renewable electricity sources creates new challenges for grid operators. One often suggested solution is demand-side response (DR): the adaptation of electricity consumption to generation. Here, we investigate what role DR could play to support system stability through fully remote-controlled (by the grid operator) shifts of individual processes in households and in the commercial and industrial sectors, testing the case of a high-renewables future in Germany. The grid operator is constrained by consumer acceptance of service interruptions, both in size and shift duration, and by technical boundaries. We find that DR has a large potential and is suited for short-term services such as spinning reserve or primary control and for damping residual load gradients. However, its potential is low for longer-term services like secondary/tertiary control or for satisfying residual load during low sun/wind times in a high-renewables future. We find that the potential for DR is not limited by the magnitude of shiftable capacity but by the maximum shift duration and the patterns of switching between positive and negative power demand, which makes DR useful for fast and short-term services but less useful for longer shifts.

1. Introduction

In order to honor the commitments of the Paris Agreement, the power systems around the world must become completely carbon-free by mid-century [1]. This means that the power systems across Europe and the world will need to vastly increase the share of renewables, including to full reliance on renewable sources [2]. In some regions, this transition is already happening today: for example, one third of the German power consumption was renewable in 2015, and more than ¾ of this came from fluctuating sources; by 2050, at least 80% of the German electricity shall be renewable, and almost all of this will be fluctuating [3,4].

In renewables-based power systems, grid operators will have two new and very different problems to solve. First, there will be more rapid supply gradients from renewable generators rapidly going on- or offline depending on the local weather [5]. Managing the ramping problem requires fast, but not necessarily long-lasting, reserve capacities. Second, there may be long periods, up to several consecutive weeks, of combined low wind and solar power generation, requiring additional power that must not respond quickly but must operate for an extended period of time. Options to address these problems include grid expansion [6–10], a low load-factor reserve as last-resort backup [11], or developing and deploying electricity storage [12–14]. All these options increase system cost [11,15,16], so that alternative solutions that minimize the need for supply-side balancing options could be economically attractive.

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Around the world, a much-discussed strategy is to increase the responsiveness of consumption, by allowing or forcing consumers to adapt their demand to the currently available supply via demand-side response (DR) schemes [17–19]. Already today, some industries participate in balancing markets with load shedding as positive capacity [20]. Households and the commercial sector are rarely included in balancing markets beyond the pilot project scale, but many expect a large DR potential in these sectors [20–22]. For example, the European Commission has mandated a roll-out of Smart Meters to at least 80% of European consumers by 2020, enabling their demand to be integrated into the balancing market [23]. The Commission especially envisions DR to play a large role as secondary and tertiary reserves [24–27]. Similar goals exist in other countries too: in our test case, Germany, the aim is to install 1.5 million Smart Meters, covering all customers consuming more than 6000 kW h/year [28,29].

Nevertheless, it is not clear which system services DR can best supply, especially not in fully renewable power system futures, in which most generation is fluctuating wind and solar PV power and the availability of dispatchable generation is limited, meaning that the demand peak when disconnected capacity is reconnected becomes more problematic than it is in today's fossil fuel-based systems. For such renewables-based systems, novel strategies to handle reconnection are needed, and we suggest one such strategy here (see Section 3.2). Further, the social acceptance of DR in households and the commercial sector may limit the potential for DR. In this article, we answer the research question *how large is the potential of DR to satisfy the different types of system services, and on which time-scales can DR do this most effectively?* By doing this, we add to the existing predominantly technical and techno-economic literature the impacts of social constraints on DR – meaning that disconnection rates are limited and processes must be reconnected after some time, which may cause further system instability if reconnections are not carefully planned and managed – and explicitly compare the usefulness of DR for different time-scales, from seconds to weeks, for a fully renewable power system in Germany.

Our results are thus first relevant for managing a German fully renewable future, as our data is based on the structure of the German electricity demand. However, the most important determinants of the usefulness of DR – in particular the maximum shift duration – is very likely to be similar in Germany as in other countries: Germans, just as Greeks, Japanese or Chileans, will all want their washing machine to finish reasonably on time, and not in several days' time; a disconnected copper smelter must be reconnected within a few hours, regardless of in which country it stands. Further, although the different sectors have different weight in different countries, all countries have households, industry and a commercial sector: hence, the potentials may vary across countries, but all factors we address here will be present in every country, and especially in industrialized countries. The fluctuations of renewables will also follow similar patterns in other countries, especially in other temperate countries. Hence, our conclusions will be of interest to policy-makers and electricity sector actors seeking ways for secure decarbonization of a fully renewable future power system, not only in Germany but in all industrialized countries.

2. Literature review

In the last decade, a large number of studies analyzing how DR can flatten peak load or act as operating reserve was published. The literature is rather heterogeneous in terms of methodology and geographic and sectoral focus, and many articles have assessed the potential for DR both for Germany and other geographic contexts, but none have included all factors – a comparison of the usefulness of DR across all timescales, inclusion of social acceptance constraints, and a way to make use of the reconnection peak in a high-renewables future – in the same paper. For the first time, we do that here.

We find three broad groups of DR studies: while the earliest studies assessed the capacities in principle available for load-shifting (first group), later studies used these potentials to provide system-specific services, either on long (second group) or short (third group) timescales.

Analyzing the ability of various processes to shift or shed loads, a first set of studies assessed the potential of DR as the technically shiftable power. These studies identify large potentials, often several gigawatts, concluding that high shares of secondary and tertiary ancillary services could be provided by DR, and that large capacities during peak demand can efficiently be shifted into off-peak times [21,22,24,30–32]. Klobasa [22] was among the first to develop a method for this (an approach that was further developed and used by others [31,32]), deducing a theoretical potential from the total power demand of a process and then multiplying this with a *load management factor,* which extracts the not shiftable electricity share and thus determines the technical load shift potential. While Klobasa distinguishes potentials by season and finds available load shifting power of 15 GW in summer and 28 GW in winter in Germany, Gils uses a similar method but distinguishes between positive and negative power and estimates 93 GW for load reduction (shifting/shedding) and 247 GW for load increase (advancing) for all of Europe [32]. In contrast, Stadler investigates the usefulness of DR for peak clipping and finds that peak demand in Germany can be completely shifted into off-peak times. He also indicates that supplying power during long low sun/wind periods in a high-renewables future, would only be possible with additional thermal electricity-consuming processes [21]. These studies thus show that the potential of DR is large, but without explicitly applying the potentials on scheduling tasks, time/day-dependency or social constraints of load shifts.

A second group of studies explicitly examines the usefulness of DR as non-spinning (secondary, tertiary and longer) reserve, to fulfill currently existing power market functions with respect to scheduling tasks and their regulatory boundaries. While most early studies in this group examined slow and longer-term operations (e.g. shifts from day to night), several more recent studies found significant advantages of using DR for shorter-term, fast application.

Among these studies are such investigating the usefulness of DR for load regulation purposes, finding that DR has economic and technical advantages compared to power plant reserves and short- to medium-term storage technologies. Importantly, this literature shows that DR can be used on sub-hourly timescales, allowing peak load management to improve the utilization of generators and avoid system balancing expenses in the short term [33–36]. For example, Gils [33], using a deterministic linear optimization program, and Behboodi et al. [36], using numerical methods, optimize dispatch and DR in high-renewables futures, concluding that DR is very useful for peak shaving, as it can be used to manage the load without mentionable impact on hourly average costs. In a very different approach, Xu et al. propose a hierarchical management system for scheduling residential DR that deals with distribution grid tasks coordinating two different timescales and operation levels of DR; they show that their scheduling method can reduce the operating costs while smoothing the tie-power fluctuations using DR responding to intra-hour incentives [27].

Other studies in this group assess the usefulness of DR for non-spinning ancillary services and show that DR can reduce the requests of expensive positive secondary and tertiary reserves from TSOs [20,37,38]. For example, Nistor et al. investigate the