2013 IREP Symposium-Bulk Power System Dynamics and Control -IX (IREP), August 25-30, 2013, Rethymnon, Greece

A Framework for and Assessment of Demand Response and Energy Storage in Power Systems

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Abstract—**The shift in the electricity industry from regulated monopolies to competitive markets as well as the wide-spread introduction of fluctuating renewable energy sources bring new challenges to power systems. Some of these challenges can be mitigated by using demand response (DR) and energy storage to provide power system services. The aim of this paper is to provide a unified framework that allows us to assess different types of DR and energy storage resources and determine which resources are best suited to which services.**
We focus on four resources: batteries, plug-in electric vehicles, commercial buildings, and thermostatically controlled loads. We define generic power system services in order to assess the resources. The contribution of the paper is threefold: (i) the development of a framework for assessing DR and energy storage resources; (ii) a detailed analysis of the four resources in terms of ability for providing power system services, and (iii) a comparison of the resources, including an example case for Switzerland.
We find that the ability of resources to provide power system services varies largely and also depends on the implementation scenario. Generally, there is large potential to use DR and energy storage for providing power system services, but there are also challenges to be addressed, for example, adequate compensation, privacy, guaranteeing costumer service, etc.
Keywords: **Demand response; energy storage; renewable energy integration; demand side management.**

I. Introduction

I.A. Background and Motivation

Electric power systems face many new challenges resulting from liberalization and the wide-spread introduction of fluctuating renewable energy resources. Traditionally, power systems were operated by vertically integrated utilities run as regulated monopolies. Electricity markets were introduced to improve economic efficiency and, subsequently, reduce customer rates. However, in these markets only the supply-side actively participates and the demand-side is largely inelastic, in part because loads generally have no financial incentive to modify their consumption. This may lead to problems such as high wholesale energy prices and generator market power [1]. Fluctuating renewables such as wind and solar affect both normal power system operation and the system's *operational security* [2], i.e., its ability to withstand sudden disturbances. For example, since fluctuating renewables are hard to predict, they may increase supply-demand mismatch, which increases the need for *ancillary services* (AS) that ensure power system *reliability* [3], [4]. Additionally, large-scale wind and solar installations may increase the frequency of contingencies [5], [6]. On the distribution level, uncoordinated operation of photovoltaics (PV) can cause voltage problems and reverse load flows [7], [8].

Demand Response (DR) and *Energy Storage* can mitigate some of these issues by increasing demand elasticity and hence improving energy market efficiency and/or power system reliability. In [9] DR is defined as "all intentional modifications to consumption patterns of electricity of end-use customers that are intended to alter the timing, level of instantaneous demand, or the total electricity consumption." In DR programs, electric loads make changes in response to time-varying electricity prices or in exchange for incentive payments from an aggregator, utility, or system operator. Similarly, energy storage resources, such as batteries, flywheels, etc., can improve market efficiency and system reliability by participating in energy markets or providing ancillary services. DR and energy storage have a number of advantages over other resources used for energy balancing and ancillary services including relatively fast response times and high ramp rates as well as some ability to address local problems. However, in contrast to conventional generators, DR and energy storage are generally small and distributed. Additionally, DR and energy storage have energy constraints, which have to be managed to ensure that loads can provide their primary service and storage units do not become full/empty when needed.

A key question is which types of resources are suited best to which service applications. Existing research on DR and energy storage tends to focus on a particular resource and how best to operate it for a particular task. Our contribution in this paper is to develop a unified framework and to asses four types of resources: *batteries*, *plug-in electric vehicles*, *commercial buildings*, and *thermostatically controlled loads*. We define nine *resource characteristics* to classify these resources. Furthermore, for each resource we introduce different implementation *scenarios*, which are meaningful to distinguish between, because they allow for different service applications. We also define *generic power system services*, which allow us to compare the resources in a structured way. How well a particular service can be provided by a particular resource scenario is rated by */* in tables, where the first star represents

978-1-4799-0199-9/13/ $31.00

a technical rating and the second star an economical rating. Both ratings have the following scale:

++	Very good	+	Good
0	Possible/ but not clearly advantageous	-	Not possible .

We base our analysis on the results of a number of research projects, many of which were conducted within our research group. Our framework is not only useful for comparing resources but also for long-term power system planning. If an extension in the portfolio of services is sought in some country, then the question arises which is the best combination of resources to provide these services in terms of quality, cost, user-acceptance, etc. Given data for a specific country, our framework provides a way of determining which investments would best enable service provision by DR and energy storage. We demonstrate this with an example case for Switzerland.

In Sections II and III, we introduce the resource characteristics and define the generic benchmark services that are used throughout this paper, respectively. Sections IV-VII analyze the four resources. For each resource, we describe the state of the art, characterize the resource, introduce the scenarios, and describe how well grid services can be provided within each scenario. Each section contains tables describing the resource characteristics as well as a rating of its potential for providing grid services. In Section VIII, the four resources are compared and discussed and an example case is presented. The paper concludes with Section IX.

II. Resource Characteristics

A resource's characteristics determine how well it is suited for a particular service. Here we define nine characteristics; the first six describe physical properties, while the last three characteristics are scenario-dependent.

(1) *Physical characteristics*:

Power capacity: The power capacity [kW] is the maximum amount of power that can be extracted (in the case of storage) or modified (in the case of loads). This is comparable to a generator's power capacity.

Energy capacity: The energy capacity [kWh] is the maximum amount of energy that can be stored (in the case of storage) or shifted (in the case of loads).

Ramp rate: The ramp rate [kW/min] is the maximum rate at which a device can move from one power level to the next. Conventional generators have relatively slow ramp rates of about 1-5% of total power capacity per minute. DR and energy storage resources are typically much faster.

Location: The location determines how the response affects the network. For some resources, the location can be chosen (e.g., batteries), but for many resources, it cannot be chosen (e.g., loads).

Response granularity: For some systems, it might only be possible to actuate the systems in discrete steps. For example, some compressors for heating/cooling are only able to operate at 100% or 0%. When these resources are used for DR, this leads to discrete changes in power consumption.

Response frequency: Some resources cannot be used arbitrarily often, e.g., some compressors have lockouts, meaning that after they have been switched on or off they can not be switched again for some time.

(2) *Scenario-dependent characteristics*:

Control/ communication: There are a variety of possible DR and energy storage control options including local control in response to frequency or voltage measurements, local control in response to price signals, control by an aggregator, and direct participation in electricity markets. Within each section, we also present variants of these options. Important considerations are 1) whether the communication system is uni-directional or bi-directional, 2) how often measurements can be taken, 3) how reliable the communication links must be, and 4) the installation cost.

Response time: The response time [s] is the duration from the time when a change in power is requested from the resource until the change takes place. Depending on the service, different response times are necessary.

Implementation requirements/ costs: For the sake of simplicity, we restrict ourselves to the additional installations that are necessary to provide the service in the described way (e.g., additional sensor placement).

III. Generic Power System Services

Electricity markets have evolved differently around the world. Additionally, the set of services procured by system operators differ around the world [10], [11]. In this paper, we do not adopt specific definitions but instead define a set of generic services that represent the spectrum of those commonly seen. We distinguish services on the basis of:

- *Grid level*: System level versus distribution level.
- *Timescale*: Frequency at which signals are sent and also the duration over which the signal can be expected to be zero-mean. Note that current services are not generally guaranteed to be zero-mean over specific timescales; however, here we assume that future services will have these guarantees so that energy-constrained resources can determine which power capacities they are able to offer without risking running into their energy constraints. This is also further discussed in Section VIII.
- *Accuracy level*: Precision in terms of both signal tracking and reliability of response. For example, ancillary services often require very high accuracy, and high penalties may have to be paid in case of failure to provide the service. In contrast, market-based services do not

usually require high accuracy. For example, a resource responding to dynamic prices or providing *balance group* (BG)[1] optimization does not need to follow the signal precisely; it simply pays more for energy in case of signal deviations.

(1) *System level ancillary services*:

Very fast services are consistent with the time-scale of primary frequency control or "droop" control. We assume signals are practically instantaneous and zero-mean over 5 minutes.

Fast services are consistent with the time-scale of secondary frequency control or automatic generation control (also known as load frequency control). We assume signals come every 1-10 seconds and are zero-mean over 15 minutes.

Medium-speed services are consistent with the time-scale of a range of different services including tertiary frequency control, spinning/non-spinning reserve, and load following. Here, we assume signals come every 1-10 minutes (e.g., in load following) or they come intermittently when faster timescale services need relief (e.g., in tertiary control) or the system experiences a contingency (e.g., spinning/non-spinning reserve). We assume that the signal is zero-mean over one hour (though currently these sorts of services are not usually zero-mean).

(2) *Market-based services*:

Medium-speed services are consistent with the time-scale of 5-minute energy market participation and BG optimization. Here we assume resources change their operating point every 5 - 10 minutes and signals are zero-mean over one hour.

Slow services are consistent with the time-scale of hourly energy market participation. Here we assume resources change their operating point every hour and signals are zero-mean over six hours.

Note that market participation does not necessarily provide a "service" to the system in the same way that ancillary service participation does. However, shifting energy consumption in response to market signals or in order to better follow contracted schedules both benefits the system and the individual resource or aggregator by minimizing its energy costs. Therefore, we consider market participation a "service" in this paper.

(3) *Distribution level services*:

Distribution grid support: Here we distinguish between **fast** services such as voltage support and **slow** services such as peak shedding for upgrade deferral.

Single customer support: This is consistent with end-user applications such as uninterruptible power supplies (UPS) or increase of PV self-consumption to minimize energy costs. We distinguish between **fast** services (UPS) and **slow** services (PV support).

[1]BGs are virtual aggregations of generators and loads used to support operational security; their primary task is to comply to the generation or demand schedule that has been reported to the Transmission System Operator day-ahead.

IV. Batteries

IV.A. Motivation and State of the Art

In contrast to DR where resources have functions outside of power system service provision, the sole usage of batteries is to store and provide electricity.

Due to a battery's fast reaction time and high ramp rate, there is a rising interest in the research community to use batteries for fast frequency control applications. Furthermore, the increasing demand for lithium-ion batteries for mobile electronic devices and electric vehicles had lead to more research and investment in the field. This is expected to bring down the cost of batteries in the long term. The power and energy capacity of a battery (and therefore its energy/power ratio) are independent design parameters, which allow us to customize battery capacities for specific applications. Finally, batteries can be placed at specific locations to ease congestion in the distribution grid. In order to recover high investment costs, research is focusing on providing different applications with the same battery, i.e. *multitasking* [12], [13].

As far as the authors are aware of, integration of batteries in power grids (at both transmission and distribution levels) is still rare, except in Japan where grid codes and tariff structures provide an incentive to use large-scale batteries to reduce wind farm output fluctuations [14]. Most of the other applications are specific to remote locations that are either not connected to the main grid, or depend on a sole generator or line. A few pilot projects were launched over the last years [15], but were primarily pursued to gain technical and feasibility knowledge.

IV.B. Characterization of Resource and Scenario Definition

Different battery technologies are available, see e.g. [16], [17]. A key factor when determining whether or not to install a battery is the operating costs. The operating costs (consisting of degradation costs and costs due to losses) are very high for two reasons: First, the degradation costs (per kWh cycled), which depend on the investment costs and the operative lifetime, are very high. Second, the round-trip efficiency is only about 80%, which contributes to significant costs due to energy losses. How to adequately attribute the investment costs to the operating costs is generally a hard problem, since the battery degradation is influenced by a number of complex, non-linear phenomena depending on the state of charge, charge/discharge rate, and temperature [18], [19].

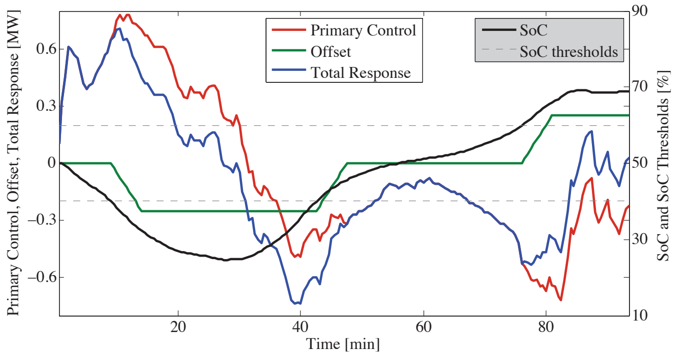


Fig. 1: From [20]: Illustration of the offset principle, which could enable batteries to participate in today's fast frequency control markets.

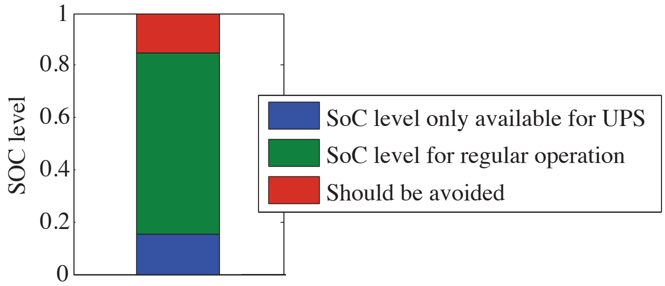


Fig. 2: SOC level available for different application types.

From a service perspective, the main point of distinction is the purpose and hence location of a battery. Three scenarios are distinguished in the following:

(a) Large Battery (LABA)
(b) Distributed-DSO (DDSO)
(c) Distributed-customer (DCUS)

(a) Large Battery (LABA): Large batteries in the range of several MW can provide system level services. System level ancillary services can be provided anywhere in the grid assuming it is robust enough.

(b) Distributed-DSO (DDSO): Batteries are sized and placed according to specific distribution grid needs. The main goal is to help DSOs operate the grid by postponing or eliminating the need for upgrade of grid components (transformers, lines, cables). Such batteries would be installed at 16kV or 400V levels, and their power rating could be anything in the range from a few tens of kW to one MW, depending on the size of the grid components to be supported. These batteries could also be used for system level services through aggregation.

(c) Distributed-customer (DCUS): End-users purchase and operate batteries located in/next to their own buildings in order to reduce their demand charge (peak shaving), to have uninterruptible power supply (UPS), to avoid PV curtailment, or to increase PV self-consumption [21]. The placement is therefore not necessarily optimal from a distribution grid perspective, as only the interests of individual customers are considered. The customers could either be households, in this case a typical size of 10kW could be assumed; or commercial/ industrial customers, in this case the batteries could be considerably larger. Here as well, batteries can provide system level applications through aggregation. They could also provide distribution grid applications, but one should be aware that most of the end-use customer-focused services are in effect the same as DSO-focused services, e.g., customer peak shaving is the equivalent of upgrade deferral on the DSO side.

In contrast to DR resources, we assume here that reliability does not change with level of aggregation: Thousands small batteries have the same potential for system-level application as a single large battery of equivalent energy and power capacities. However, large batteries can be expected to be less expensive than aggregations of many small batteries of equivalent size, e.g., because less communication infrastructure is necessary. Tables I and II describe the characteristics of batteries which are also detailed in the following.

- *Power capacity*: Design parameter.
- *Energy capacity*: Design parameter.
- *Ramp rate*: 0 to full power in a few electrical cycles.
- *Location*: When the focus is on distributed grid support, the location can be determined freely (a priori). It is also possible to use an aggregation of batteries to provide applications to the whole grid.
- *Response granularity*: Continuous.
- *Response frequency*: Unlimited.
- *Response time*: Instantaneous.
- *Control/ communication*: For providing system level services a bi-directional communication link is needed to optimally coordinate and control the batteries. The DCUS scenario in particular could use existing IP-based communication infrastructure.
- *Implementation cost*: High cost is the main limitation for battery deployment. Although the costs are expected to decrease, they will probably remain quite high for the foreseeable future. [22] estimates the cost per installed kWh to be around 460€ in 2015 and 300€ in 2020.

IV.C. Possible Service Applications for the Electricity Grid

Table III gives an overview of possible power system services provided by batteries.

System level ancillary services

Very fast service and fast service. Their fast reaction time and high ramp rate make batteries a possible candidate for these services, although they are still too expensive today. Since current primary and secondary frequency control signals are not guaranteed to be zero-mean within a short time-frame,

TABLE I: Physical characteristics of batteries.

Property	Description
Power capacity [kW]	Design parameter
Energy capacity [kWh]	Design parameter
Ramp rate [kW/min]	0 to full power in a few electrical cycles
Location	Design parameter
Response granularity	Continuous
Response frequency	Arbitrary

TABLE II: Scenario-dependent characteristics of batteries.

Property	Large battery (LABA)	Distributed DSO (DDSO)	Distributed customer (DCUS)
Response time	Instantaneous		
Control/communication	Bidirectional communication link		
Implementation cost	Battery and communication infrastructure		
Power capacity [kW]	$\geq$ 1MW	10 kW - 1 MW	10 kW - 200 kW
Location	Arbitrary	Grid bottlenecks	Individual buildings

TABLE III: Technical and economical rating of power system services provided by batteries.

System level ancillary services		Large battery (LABA)	Distributed DSO (DDSO)	Distributed customer (DCUS)
Very fast		++/0	++/0	++/0
Fast		++/0	+/0	+/0
Medium-speed		0/0	0/0	0/0
Market-based services		**Large battery (LABA)**	**Distributed DSO (DDSO)**	**Distributed customer (DCUS)**
Medium-speed		-/-	0/0	0/0
Slow		-/-	0/0	0/0
Distribution level services		**Large battery (LABA)**	**Distributed DSO (DDSO)**	**Distributed customer (DCUS)**
Distribution grid support	Fast	0/0	++/0	+/0
	Slow	0/0	++/0	+/0
Single customer support	Fast	-/-	-/-	++/+
	Slow	-/-	-/-	++/+

different methods have been proposed to allow batteries with a rather small energy/power ratio to participate in fast frequency control markets [23], [24], [20]. In these works, it is assumed that batteries are allowed to offset their frequency control response to only respond to fast and zero-mean deviations, while slower and non zero-mean components would be passed on to slower units, as shown in Fig. 1. This principle aims to maintain the SoC within an acceptable range. The modification is done by adding a time-dependent offset (green) to the requested response (red) to form the battery's response (blue). The offset would then be canceled out by slower power plants. These plants could be activated through either a slower time-scale frequency control mechanism, intra-day market, or bilateral contracts with the batteries. Since the energy capacity of batteries is more expensive than their power capacity and since frequency control is remunerated based on power capacity, the smaller the energy/power ratio, the more attractive this application becomes for batteries. [20] shows that the rules for the offset mechanism play a key role for profitability.

Medium-speed service. This needs a higher energy/power ratio, which makes batteries too expensive for this service.

Market-based services

Slow service and medium-speed service. Due to the high cost of cycled kWh, it currently makes little sense to install batteries for the purpose of trading in markets.

Distribution level services

Distribution grid support. DSOs can use batteries to provide support to the distribution grid when it becomes overloaded. Advantages of using batteries for this service compared to DR are that the DSOs can determine their specific location, batteries are very reliable, and they are easy to control. Because of their high cost per cycled kWh, batteries are more suitable for services that are rarely called but have a high return per cycled kWh than for more frequent services with a low return per cycled kWh. An example of upgrade deferral with batteries can be found in [15]. A 1.2 MW battery is used there to support a 20 MVA distribution transformer. The peak load on the transformer happens during the hottest days of the year, approximately from 2 to 6 pm. This leaves the battery available for other applications at relatively well defined periods.

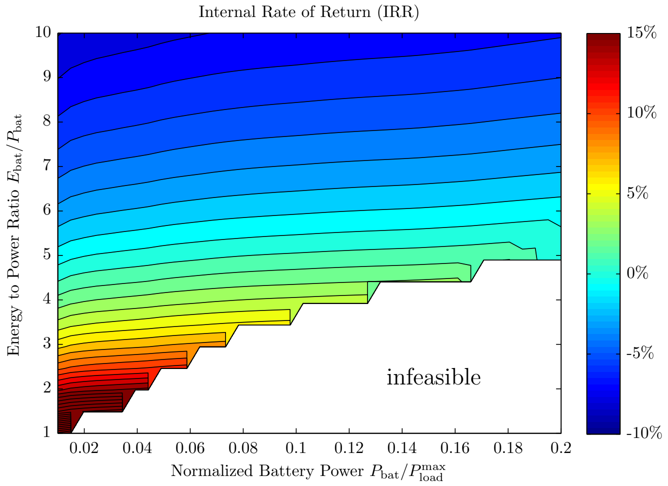


Fig. 3: Internal Rate of Return (IRR) of a MPC controlled peakshave application as a function of the energy to power ratio E/P and the battery power P_{bat} normalized to the maximum load of a standard industrial load profile with a battery calendar lifetime of 15 years, total number of 3000 cycles, investment cost 330€ /kWh.

Single customer support. UPS is already now frequently provided by batteries. In a multitasking approach, a battery could provide UPS at the same time as other services, as long as enough energy is available to always provide UPS. This could be ensured by reserving the lowest SoC level to UPS as shown in Fig. 2. Operating a battery in this low SoC level leads to higher degradation costs and can only be justified for an application with high revenue per cycled kWh, such as UPS. Peak shaving is also a promising application. As a slow service, power factor correction can also be provided from the battery inverter. When customers are facing a limitation on PV export due to line or network constraints, a battery can be used to store PV electricity rather than curtailing it, if the degradation cost is lower than the regular electricity tariff. Finally, if the trends in battery prices and PV feed-in tariffs continue, arbitrage with the PV feed-in tariff could become a successful application, as customers would use the battery to store excess PV electricity at low feed-in tariffs.

IV.D. Challenges and Open Questions

The main challenge for integration of batteries in the power grid is their costs. Since the operative lifetime (in cycles) is limited, the cost per kWh cycled is quite high. Depending on the assumptions and the type of load/generation profile (which influences degradation), the operative cost range is around 0.10-0.50€ per kWh cycled. In a first approximation, the energy capacity cost (number and size of cells) is proportional to the energy capacity [kWh] and the power cost is a function of inverter and converter size [kW]. Fig. 3 shows that when the battery is remunerated based on the power it delivers, the energy/power ratio is critical for profitability. In this example, the system is profitable for energy/power ratio smaller than 3. Degradation shortens the battery lifetime and significantly affects the economic viability of a service application. Since there is a non-linear relation between operating management and degradation, the total amount of energy to be delivered during the battery's lifetime is dependent on each individual control action. This complicates investment decisions, because they usually rely on utilization costs derived from integral terms such as calendar lifetime or the total number of cycles at a defined end of life capacity. Even though battery manufacturers provide such data for certain standard operating conditions, the calculation of the return on investment based on these quantities leads to uncertain results, because the actual operating regime can be very different than the one assumed by the manufacturer. Thus battery operation should take into account degradation-dependent utilization costs and use smart charging algorithms for battery lifetime maximization. Instead of using inaccurate heuristic rules to minimize degradation, this task can be delegated to a Model Predictive Control (MPC) framework. However, this requires a quantitative model of the degradation process [25].

V. Plug-in electric vehicles

V.A. Motivation and state of the art

The previous section dealt with stationary batteries. In this section, the focus is on batteries embedded in *plug-in electric vehicles* (PEVs). We use the term PEV to denote both plug-in hybrid electric vehicles and all-electric vehicles. Since the main purpose of these batteries is to provide mobility services, DR schemes are limited by the constraints imposed by the PEV end-use and are therefore affected by human behavior. Moreover, this resource is only available when a PEV is parked and plugged in and the parking locations typically change throughout the day.

Although PEVs are not a new phenomenon, none of the previous PEV hype has met expectations. Recently, there has been a renewed interest in PEVs, with many of the major car manufacturers releasing and/or announcing new PEV models. Currently the market share of PEVs is still low (e.g., 3.4% in the USA in 2012 [26]).

In many cases, vehicles are only used intermittently. Moreover, many trips are short and therefore do not utilize the full battery range [27]. For this reason, it is often possible to shift charging load in time without impacting end-use. Furthermore, an additional degree of flexibility could be gained with *Vehicle to Grid* (V2G) [28], whereby vehicles would discharge the energy stored in their batteries back to the grid. However, this type of PEV battery use comes at the price of additional battery degradation and only pays off in some cases. The V2G functionality, although not a technical challenge, is typically not yet available in PEVs. Although vehicles are parked most of the time and are therefore potentially available, they can only participate in DR if charging infrastructure is present at

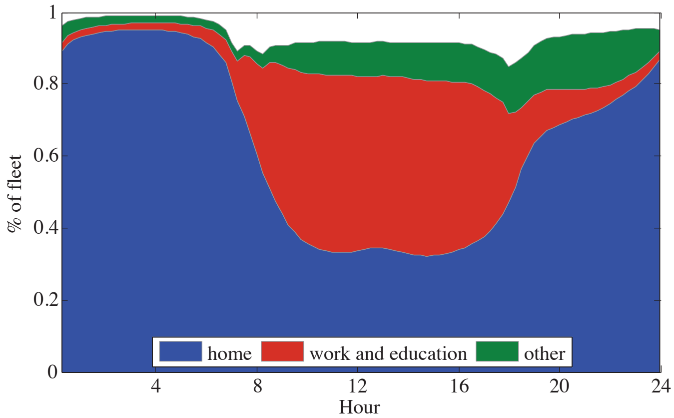


Fig. 4: Percentage of the fleet parked on a typical workday, by activity type. The date stems from a Swiss-wide transport simulation [44].

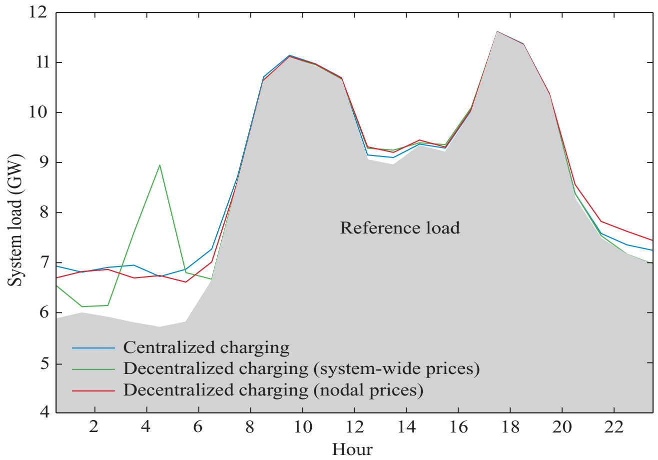


Fig. 5: From: [42]. Load profiles resulting from different smart-charging schemes.

their parking location. The widespread availability of charging infrastructure is therefore crucial, since it increases charging flexibility and resource availability.

Part of the research on the integration of PEVs into power systems deals with the impact of PEVs on grids and utilities [29]–[31], usually identifying the need for charging management or “smart charging” strategies. Simple schemes such as time-of-use (TOU) tariffs could be sufficient at low penetrations, but more complex charging schemes, either centralized [32], [33] or decentralized [34], [35] are probably required at later stages [36]–[39]. Another area of research concerns the use of PEVs to support the system, e.g., providing regulation power or contributing to the integration of renewable energy sources [28], [40], [41]. A literature review on smart-charging and ancillary service provision with PEVs can be found in [42].

Since PEVs are small, distributed resources, we usually assume the existence of an aggregator, which is in charge of managing the provision of services or coordinating smart charging. The aggregator serves as an interface between PEVs and other entities, such as the Transmission and Distribution System Operators, energy providers, electricity markets, etc. A literature survey on the economic and technical management of this agent can be found in [43].

V.B. Characterization of Resource and Scenario Definition

The main factors affecting the ability of PEVs to provide grid services are the existence of a communication channel and the control approach used. We define the following scenarios:

(a) Local measurements (LOME)
(b) Price incentives (PRIN)
(c) Control signal broadcast (CSIB)
(d) Advanced communication (ADCO)

(a) Local measurements (LOME): No communication channel with the vehicle, however, local frequency and/or voltage measurements can be performed by the PEV. These measurements could be used for droop control [45], [46].

(b) Price incentives (PRIN): PEVs respond to price signals and adjust charging in order to minimize their individual costs [36], [38], [47]. The prices could be fixed for a longer period of time, day-ahead or updated frequently (e.g., 5 minute market).

(c) Control signal broadcast (CSIB): Control signals are broadcasted to vehicles with short delays and their response can be measured. It is also possible to retrieve information from PEVs, such as their SoC or energy requirements; however only on a longer time-scale [48].

(d) Advanced communication (ADCO): It is possible to receive/send information from/to PEVs with very short delays. Different strategies such as direct control by an aggregator [36] or a bidding system are possible in this case [49], [50].

Table IV describes the characteristics of PEVs as a demand side resource, which are detailed in the following.

- *Power capacity*: The power capacity of an individual vehicle can be either limited by its own power electronics or by the capacity of the charging infrastructure it is connected to, but usually the latter is the limiting factor [40]. Here, we assume the power of the charging infrastructure to be in the range of 2-20 kW. Very fast charging stations have higher power ratings; however, these are typically only used when charging is urgent and hence there is no demand flexibility.
- *Energy capacity*: To determine the available energy capacity, we consider an aggregation of PEVs. The available capacity of a single vehicle at any given time is highly uncertain, since it depends on the driving patterns of the

user, which could be quite volatile. However, when aggregating a large number of vehicles the total potential available capacity, which varies throughout the day (e.g., it will typically be much higher at night), has a substantially lower variance [51]. Fig. 4 shows the percentage of the fleet parked on a typical workday, sorted by activity type. This data stems from a Swiss-wide transport simulation [44]. The figure illustrates the fact that the availability of resources is both time- and location-dependent. Based on the transport simulation, the average connection time in Switzerland ranges from 63% if vehicles can only charge at home to 85% if vehicles also can charge at work and educational institutions. To derive the energy capacity of the resource, the vehicle availability factors can be multiplied with battery capacities. Battery capacities of cars sold in the market today range from 12 kWh (e.g., Scion iQ EV) to 85 kWh (e.g., Tesla Model S). Typical values are in the range 15-25 kWh (e.g., Chevrolet Volt with 16 kWh, Nissan Leaf with 24 kWh). In the future, if per kWh prices of batteries decrease and their energy density increases, batteries could be larger. Finally, of the total connected PEV capacity, based on the traffic patterns from [44] and given the end-user constraints, we find that approximately 70% could be considered shiftable.

- *Ramp rate*: 0 to full power in a few electrical cycles.
- *Location*: Vehicles are connected to the low voltage distribution grid. Their main differences as compared to other loads is that they are mobile, i.e., they can connect to different locations in the system.
- *Response granularity*: Battery power output and input can be modulated continuously. Both the schemes with local measurements and with advanced communication can make use of this property. The granularity of the response with price or control signal broadcasts is given by the accuracy that the control can provide. With price signals even a small change in prices could trigger a large response. Moreover, this response may be hard to predict. With a control signal broadcast these problems are partially mitigated, but there is some uncertainty in the response.
- *Response frequency*: Arbitrary.
- *Response time*: Instantaneous.
- *Control/ communication*: The different assumptions on communication were detailed in the scenario definition.
- *Implementation costs*: For the local measurements scenario, there are additional costs at the individual vehicle level. In the rest of scenarios the costs are associated with the necessary communication infrastructure (increasing with more advanced communication), and local controllers at the PEVs, as well as the costs associated with the existence of an aggregator entity.

It is possible to combine the local measurement scenario with any of the remaining scenarios, i.e., they are not mutually exclusive: The communication based scheme could be used to determine the main set-point and local control could provide droop control. They are separated here for the sake of clarity.

V.C. Possible Service Applications for the Electricity Grid

In the following, we comment on the different services that PEVs could offer. This is summarized in Table VI. In general, PEVs are more suited to services with low energy/power ratios, because of 1) the limited energy flexibility of the fleet and 2) increased battery degradation from additional battery cycling. Regarding the latter, it should be noted that some services can be offered without using the V2G mode, since, from a system perspective, a reduction in charging has the same effect as discharging. Using V2G for price arbitrage usually does not pay off [32], but can be attractive for services with a capacity payment on top of the energy payment, such as regulation or secondary frequency control [40].

System level ancillary services

Very fast service. Based on local frequency measures. In [45], PEVs in an islanded system with a large penetration of renewable energy sources participate in frequency control by changing their active power set-point according to a droop curve. An issue with this type of approach is that the aggregated controller gain changes over time as the number of connected vehicles changes. The additional costs of implementing such a scheme are probably low.

Fast service. Requires a fast and accurate response, which can be provided satisfactorily with a signal broadcast or with advanced communication. The main difference between the communication options is that better accuracy is possible with advanced communication since direct control is possible, as in [52]. [48] is an example of an indirect control approach. Here the aggregator broadcasts a signal and vehicles react only if they are capable of modifying their set-point accordingly without impacting end-use. To send the appropriate signal, the aggregator needs to estimate how many vehicles can provide up or down regulation. However, the aggregator only receives information from the vehicles every 5 minutes, while it broadcasts control signals to the vehicles every 10 s to respond to the TSO signal. Still, accurate responses can be achieved, as shown in [48]. However, the higher costs for an advanced communication infrastructure might not be justifiable.

Medium-speed service. Technically, it could be possible to offer this service with price incentives (low accuracy), control signal broadcasts (medium accuracy), or advanced communication (high accuracy). However, the energy/power ratio of medium services is typically high, which could be a major drawback due to increased battery degradation.

Market-based services

Slow service. Smart-charging usually refers to strategies to shape PEV load in a way that brings about one or several

TABLE IV: Physical characteristics of plug-in electric vehicles.

Property	Description
Power capacity [kW]	2-20 (per vehicle)
Energy capacity [kWh]	Per vehicle, average of aggregation: (availability [%])·(total energy capacity battery [kWh])·(shiftable part [%]) = (0.63 to 0.85) · (12 to 85) · 0.7
Ramp rate [kW/min]	0 to full power in a few electrical cycles
Location	Distribution grid, each vehicle is mobile
Response granularity	Continuous
Response frequency	Arbitrary

TABLE V: Scenario-dependent characteristics of plug-in electric vehicles.

Property	Local measurements (LOME)	Price incentives (PRIN)	Control signal broadcast (CSIB)	Advanced communication (ADCO)
Response time	Instantaneous			
Control/communication	Local measurements	Price signals	Fast broadcast, slow upstream	Fast bi-directional communication
Implementation cost	Upgrade for droop control	Communication infrastructure, local controllers, aggregator (Low)	(Medium)	(High)

TABLE VI: Technical and economical rating of power system services provided by plug-in electric vehicles.

System level ancillary services		Local measurements (LOME)	Price incentives (PRIN)	Control signal broadcast (CSIB)	Advanced communication (ADCO)
Very fast		+/+	-/-	-/-	-/-
Fast		-/-	0/0	+/+	++/0
Medium-speed		-/-	+/0	++/0	++/0
Market-based services		**Local measurements**	**Price incentives**	**Control signal broadcast**	**Advanced communication**
Medium-speed		-/-	+/+	++/+	++/0
Slow		-/-	+/+	++/+	++/0
Distribution level services		**Local measurements**	**Price incentives**	**Control signal broadcast**	**Advanced communication**
Distribution grid support	Fast	+/0	0/0	+/0	+/0
	Slow	-/-	+/+	++/+	++/0
Single customer support	Fast	+/0	0/0	+/0	+/0
	Slow	-/-	+/0	+/0	+/0

benefits, e.g., charging costs minimization or, from a system perspective, avoiding overloading assets. The general goal would be to shift the load to low-load or low-price hours. This could be achieved by setting the right price incentives or by controlling the vehicles indirectly with a signal broadcast or directly if fast bi-directional communication is possible. In the latter scenario, market-based control with individual bidding by PEVs is also possible. In [36], [37] a decentralized price-based control and a centralized, direct control approach are compared. In this paper, the goal of the aggregator is to minimize system generation costs while enforcing network constraints, as calculated with an Optimal Power Flow (OPF). Under the decentralized scheme, each vehicle minimizes its costs given the price profiles communicated by the aggregator day-ahead. These price profiles are themselves the results of an optimization performed by the aggregator. Under the centralized scheme the optimal aggregated charging profiles are directly calculated within the OPF, where PEV end-use constraints are modeled as constraints on a virtual battery aggregating individual vehicles. The load profiles for different charging strategies are depicted on Fig. 5. It can be seen that both the centralized and decentralized approach have a similar valley-filling type of structure as long as different price profiles are defined for different network nodes. If a single price profile is defined for the whole system, a strong charging simultaneity is induced at the time where the price reaches a minimum (referred to as synchronization and instability).

Medium-speed services. As in day-ahead markets, PEV charging can also be optimized on prices of markets that clear more frequently, such as 5-minute markets. A similar possible application would be BG optimization. In [53] a fleet of PEV is shown to be able to compensate the forecast errors of a wind power plant, when enough energy and power capacity are reserved based on a probabilistic wind forecast model.

Distribution grid services

Distribution grid support. Just as primary frequency control, voltage control (fast service) can be provided based on local measurements. The concept proposed in [46] considers a droop control for both frequency and voltage regulation. For this purpose, the PEV charging current is adjusted proportionally to frequency and voltage deviations outside a dead band. However, [46] assumes also that a central controller prioritizes either frequency or voltage response, so without communication the performance of this combined strategy would deteriorate. Since voltage control is provided locally, resource availability is a major issue because the availability of a PEV at a particular location is intermittent. Peak-shaving (slow service) in the context of PEV charging is usually understood as discharging energy from the batteries during peak times and charging during valley hours. This usually has a large negative impact on battery lifetime, unless there is only a short and sharp peak, and therefore a lower energy/power ratio. However, price differences between peak hours and low load hours typically would not suffice to cover the costs of battery degradation. On the other hand, network or supply infrastructure investments could be deferred. Therefore, an additional source of revenue for the vehicle could exist, making the service more attractive. If the goal of the service is to avoid increasing existing peaks (instead of reducing them) and to spread the load during the low-load period (valley-filling), this would be more attractive for PEVs since no discharging would be required. In this case, the analysis is very similar to that presented for smart-charging. If price signals are used, they would lead to a reduction in load diversity, since they incentivize vehicles to concentrate their charging on the same time period. At larger PEV penetrations, this effect could prove to be even more detrimental for transformer loading than leaving charging uncontrolled, as shown in [37].

Single customer support. In general, PEVs as a single entity are not reliable service providers, since they do not stay at the same location permanently. They can therefore be an additional help in providing some services when they are parked, especially at home during the night and at the workplace during the day, but they cannot by themselves have a large contribution. Examples could be voltage support with local measurements, especially if there is local generation, e.g., by photovoltaics. Another option is load smoothing, which requires local communications. For the moment, financial incentives to do this are very low or non-existing.

V.D. Conclusion

A challenge common to all the proposed schemes is the fact that profits need to be high enough for PEV owners to participate. Even if the aim of the services is to be non-disruptive, i.e., to respect the constraints given by the user, the degree of flexibility in the use of the vehicles is reduced. For example, if a driver decides to depart earlier than announced to the PEV aggregator, the battery might be not full enough for his purpose. It is hard to assess the value of the loss of this flexibility and therefore to identify which grid and market services can provide profits high enough to be attractive. Moreover, the different scenarios might need vehicle upgrades (e.g., local controllers). It is not clear if a vehicle manufacturer would have an incentive to incur these additional costs, since it is uncertain if the vehicle driver would really value this additional feature. Another challenge is the additional battery degradation if discharging is also considered [40]. Vehicle manufacturers might not want to cover this type of battery use under the battery guarantee. DR based on prices has two major drawbacks. First, exposing customers to price volatility is a controversial issue. Second, due to a loss of load diversity, synchronization and instability could be expected, especially at larger PEV penetrations. In the long term, more advanced control scenarios will be needed. There is a trade-off between the communication and computation requirements, and the speed, accuracy of the response as well as non-disruption of end-use. The type of scheme implemented will strongly depend on the characteristics of the smart metering infrastructure deployed. Finally, for some types of DR schemes, privacy might be an issue if PEVs participating need to communicate their preferences and status to an aggregator.

VI. Commercial buildings

VI.A. Motivation and state of the art

The main reason for using buildings for DR is their inherent thermal inertia, which allows us to shift in time the *Heating, Ventilation and Air Conditioning* (HVAC) load without compromising user comfort. Commercial buildings suitable for DR programs include office buildings, data centers, educational facilities, public administration premises, and refrigerated warehouses. Commercial buildings have advantages over residential buildings for participation in DR. First, a single commercial building may consume the same amount of power as hundreds of residential buildings and thus it has a higher potential to shed/shift power. Second, Building Automation Systems (BAS) are installed in many commercial buildings (one third of the buildings in the USA [54]) and they are usually integrated with the HVAC control systems. This is advantageous since a BAS can receive control signals from power system operators via internet.

Current DR programs generally use open-loop and heuristic DR controllers. For example, Fig. 6 shows load profiles from three days from two different commercial buildings that participated in a critical peak pricing program in California in 2008. Up to 12 times in the summer, DR events were called day-ahead; between 12 pm and 3 pm the electricity price was raised to three times the normal cost and between 3 pm and 6 pm it was raised to five times the normal cost, encouraging peak shedding and shifting. The blue curve shows the actual demand. The green line shows the prediction of the load without DR using the baseline method of [55], which is similar to those used by utilities. The DR strategies used were automated but open-loop. The plots show that DR via open-loop control can result in inconsistent event-to-event behavior

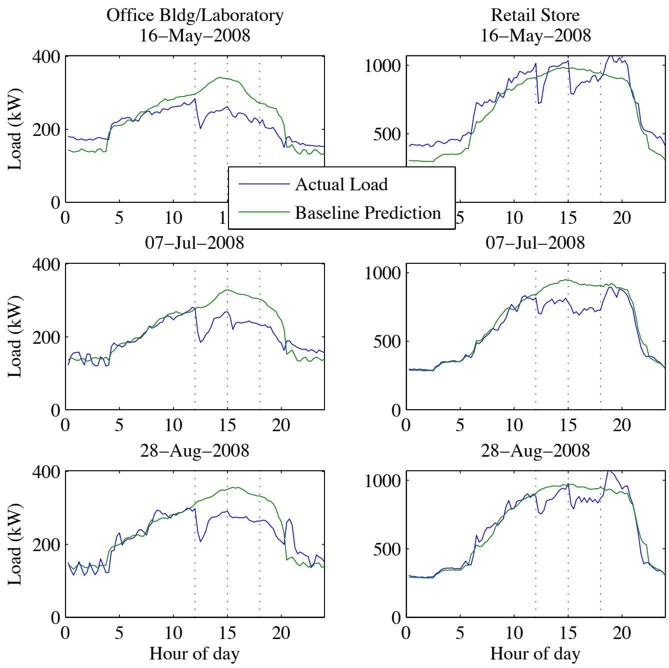


Fig. 6: Actual and baseline-predicted load of two California buildings on three days in 2008. Load data from Pacific Gas and Electric Company, California, USA. See [55] for more examples.

and responses that exhibit transients. This motivates the use of more advanced control strategies.

VI.B. Characterization of Resource and Scenario Definition

Since a building's DR potential arises from its thermal inertia, the building type strongly affects its flexibility. Important parameters are the construction type and material (determining the thermal storage capacity), the window area fraction (determining the influence of solar radiation), the surface to volume ratio (determining heat transfer losses and ventilation needs), and the building standard with respect to energy efficiency and insulation quality. However, the parameters that influence building flexibility the most and determine the appropriate DR strategies are the HVAC type and the BAS. There are two families of HVAC systems: *Integrated Room Automation* systems (IRA), which are more common in Europe, and *Variable Air Volume* (VAV) systems, which are mainly used in the U.S. For BAS, we distinguish between *Complex BAS* and *Non-complex BAS*. Thus, the four considered scenarios are:

(a) IRA system with Complex BAS (IRAC)
(b) IRA system with Non-complex BAS (IRAN)
(c) VAV-system with Complex BAS (VAVC)
(d) VAV-system with Non-complex BAS (VAVN)

(a) IRA system with Complex BAS (IRAC): IRA systems are comprised of actuators for temperature and air quality control. In Europe, temperature control is mostly done with non-air-based systems (i.e., radiators, thermally activated buildings systems (TABS), floor heating, cooled ceiling). A ventilation system can assist the non-air-based systems in providing thermal comfort. However, the primary function of the ventilation system in Europe is air quality control. Hence, often the ventilation is fixed to a set point in order to guarantee a minimum air change rate. An overview of typical HVAC systems can be found in [56]. Modern commercial buildings with IRA systems commonly have complex BAS systems installed. These complex BAS systems enable communication via internet, but also lead to longer response times. The actuators for temperature control (heat pumps, water heaters, chillers) are connected to distribution systems, which have an inherent inertia. Therefore, changing the power consumption of these actuators does not have an immediate impact on thermal comfort. However, one needs to take into account technical limitations of the devices, e.g., limitations in switching frequencies for heat pumps for reasons of efficiency or wear [57]. In contrast, if the power consumption set point of the ventilation system is adjusted, the air quality changes within a couple of minutes.

(b) IRA system with Non-complex BAS (IRAN): These systems are potentially comprised of the same actuators as in (a), but they are controlled by a non-complex BAS. This case is commonly found in older commercial buildings in Europe, where usually only some of the aforementioned actuators are installed and ventilation is much less common.

(c) VAV systems with Complex BAS (VAVC): VAV systems are integrated ventilation and heating/cooling systems, which are comprised of air distribution systems with Air Handling Units (AHU), ducts and VAV boxes. In commercial buildings with VAV systems different DR strategies can be applied: uniform control of temperature set-points in building zones, control of the air distribution system (duct static pressure, fan speed or cooling valve position), or control of the central cooling/heating plant by modifying the chilled/hot water temperature [58]. In particular, the AHU fan speed can be instantaneously changed via the Variable Frequency Drive (VFD), i.e., a power electronic device, by varying the electric motor's input frequency and voltage. In VAV systems, it is important whether the electric power consumption of the chiller/heater that provides chilled/hot water to the AHU is independent of the fan power. If this decoupling exists, for instance in HVAC systems with water storage tanks, the building thermal dynamics are simpler and so is the respective control design problem [54]. On the other hand, HVAC systems without this decoupling can provide more flexibility to the grid at the cost of requiring a more complex control design.

(d) VAV systems with Non-complex BAS (VAVN): This is the same system as in (c) but with a non-complex BAS. This can be achieved by fixing the set points of some of the actuators and only controlling one of them, e.g., the fan speed. Such a configuration reduces the control complexity; however, it also leads to lower energy efficiency.

Tables VII and VIII summarize the physical and scenario-dependent characteristics of commercial buildings, respectively[2]. The characteristics are detailed in the following.

- *Power capacity*: In Europe, the average daily power consumption of a typical office building ranges from 130 kW to 380 kW [59]. From this about 10% [60] to 50% [61] can be expected to be shiftable. The other portion, for example lighting, cannot be shifted, only shed.
- *Energy capacity*: The energy capacity depends on the thermal storage capacity and the allowed comfort bandwidth. In [62] the flexibility of different buildings with IRA systems was assessed. Based on the results the energy capacity ranges from practically zero for passive buildings to approximately 4000 kWh for buildings with TABS. This means that in such buildings, part of the consumption can be shifted up to 10 hours without noticeable impacts on the occupants.
- *Ramp rate*: In [63], it was shown that large commercial buildings participating in load shedding may need 1.5-30 minutes to ramp from their pre-DR operating point to their DR operating point. This is in large part due to the design of BAS which includes cascading and interacting control loops, forced delays, and communication latencies [64]. However, with simple or properly designed BAS the ramp rate could be practically infinite.
- *Location*: Depending on their peak consumption, commercial buildings can be connected either to the medium or low voltage networks. If aggregations are formed to provide power system services, no constraints on geographical concentration of the buildings exist apart from any limitations introduced by the available communication network (and the grid).
- *Response granularity:* The granularity of building's response to DR signals depends on actuators' low level controllers. If only discrete control actions (e.g., on/off control or control in a few discrete power steps) are possible, this results in low granularity, unless several buildings are aggregated. This problem mainly appears in IRA buildings. On the other hand, VFDs of VAV systems can be controlled in a continuous manner resulting generally in a much higher response granularity.
- *Response frequency*: In commercial buildings, the response frequency to DR signals may be limited for two reasons. First, a building cannot respond to a DR signal unless its response to a previously received signal is finalized. Due to communication and control delays introduced by complex BAS this dead-time can be significant. Second, technical constraints of some actuators may prohibit prolonged control of its power consumption, e.g., a heat pump with compressor lockout requirements.
- *Response time:* Due to hierarchical control loops, complex BAS systems can lead to significantly long response times, whereas non-complex BAS systems offer much faster responses.
- *Control/ communication*: Because of their high power capacity, a few commercial buildings can already offer a significant amount of power system services. In particular, the bid size requirements of ancillary services markets may be fulfilled even with small building aggregations. Thus, direct load control schemes could be employed without excessive communication requirements due to the small size of the aggregation. In particular, since most BAS are already connected to the internet, IP-based communication protocols could be used for DR. Of course, price-based indirect control schemes are also applicable with commercial buildings.
- *Implementation cost*: In general, a controller that receives signals from the aggregator and reacts on them is needed at the building level, along with some sensors for information feedback. The integration of this controller into the BAS could be demanding for buildings with complex BAS. In some cases, a complete redesign of the BAS might be needed, which would drastically increase the implementation costs. At the aggregator level, a central controller is needed and its cost heavily depends on the sophistication level of the applied algorithms.

VI.C. Possible Service Applications for the Electricity Grid

Table IX gives an overview of possible service application provided by commercial buildings.

System level ancillary services

Very fast service. To achieve very fast response times, a complete change of BAS and building communication infrastructure would be necessary, which is not economically viable in the near term.

Fast service. Buildings with VAV systems can in principle offer fast services by exploiting the fast response of their VFD devices. In [54] it was shown that frequency regulation can be offered by a single building if the fan power is modified within a small range of 10% of its nominal power without noticeable impacts on indoor environment and without significant device wear. To the authors' knowledge, it is still an open question how well IRA systems can provide fast services. Probably, only IRA systems with non-complex BAS can respond fast enough for this service. In the U.S., utilities and ISOs are experimenting with provision of automatic generation control by commercial buildings. However, [65] found that there are significant barriers, e.g., slow energy management systems are not able to meet the service latency requirements. In Switzerland, a pilot project is currently investigating how refrigerated

[2]The values correspond to an average size office building with an area of 20000 m^2 and n is the number of buildings in the aggregation.

TABLE VII: Physical characteristics of commercial buildings.

Property	**Description**
Power capacity [kW]	$n \cdot \{13 - 190\}$
Energy capacity [kWh]	$n \cdot \{0 - 4000\}$
Ramp rate [kW/min]	0 to full power within 0-30 minutes
Location	Medium or low voltage network
Response granularity	Limited for actuators with on/off control, depends on the size of aggregation
Response frequency	Limited for heat pumps, depends on BAS complexity

TABLE VIII: Scenario-dependent characteristics of commercial buildings.

Property	**IRA, complex BAS (IRAC)**	**IRA, non-complex BAS (IRAN)**	**VAV, complex BAS (VAVC)**	**VAV, non-complex BAS (VAVN)**
Response time	Slower	Faster	Slower	Faster
Control/communication	Direct control, price control, IP-based communication is possible			
Implementation cost	BAS reprogramming (Higher)	Communication, control (Lower)	BAS reprogramming (Higher)	Communication, control (Lower)

TABLE IX: Technical and economical rating of power system services provided by commercial buildings.

System level ancillary services		**IRA, complex BAS (IRAC)**	**IRA, non-complex BAS (IRAN)**	**VAV, complex BAS (VAVC)**	**VAV, non-complex BAS (VAVN)**
Very fast		-/-	-/-	0/-	0/-
Fast		0/0	+/+	+/0	++/+
Medium-speed		++/0	++/+	+/0	+/+
Market-based services		**IRA, complex BAS**	**IRA, non-complex BAS**	**VAV, complex BAS**	**VAV, non-complex BAS**
Medium-speed		++/+	++/+	+/+	+/+
Slow		++/+	++/+	+/+	+/+
Distribution level services		**IRA, complex BAS**	**IRA, non-complex BAS**	**VAV, complex BAS**	**VAV, non-complex BAS**
Distribution grid support	Fast	+/0	+/+	++/0	++/+
	Slow	++/+	++/+	+/+	+/+
Single customer support	Fast	-/-	-/-	-/-	-/-
	Slow	++/+	++/+	+/+	+/+

warehouses can participate in the secondary frequency control market by controlling the temperature set points [66].

Medium-speed service. Experiences from pilot projects investigating integration of commercial buildings in non-spinning reserve markets have been published, as in [67]. In this approach, each building that participates in the program forecasts its hourly demand and load curtailment potential, which is then submitted to the ISO as available resource. The Open Automated Demand Response (OpenADR) communication protocol [68] is used to dispatch non-spinning ancillary services from buildings using price signals. In Italy, there exist load shedding programs for commercial buildings in emergency situations, which are divided into real time programs (without notice) and 15 min notice programs.

Market-based services

Medium-speed service. In [62], the authors developed a centralized algorithm based on MPC and a decentralized price-based algorithm to control an aggregation of office buildings

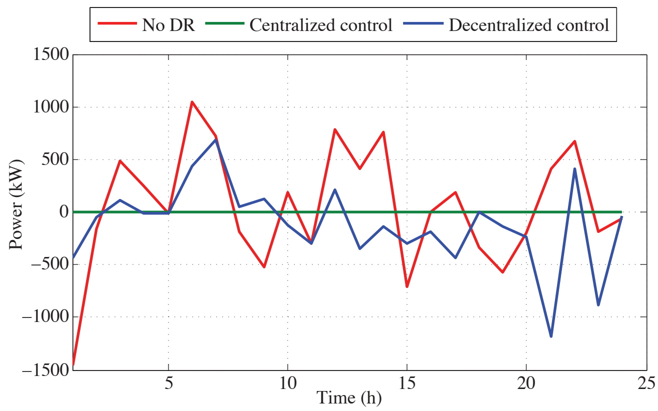


Fig. 7: From: [62]. BG schedule deviations without DR, with centralized control and with decentralized price-based control.

to minimize balancing energy costs. The simulation results of Fig. 7 show that deviations from the BG schedule can be reduced, which leads to a significant reduction in balancing energy costs (more than 50% in the investigated scenario).

Slow service. Several European countries have adopted Price Based Programs (PBP) as DR measures. An example is the Tempo tariff applied by the Electricité de France (EDF) to more than 100,000 small business customers and the Economy 7 TOU program for commercial customers in the UK [69].

In California large commercial buildings (greater than 200kW peak) are required to participate in dynamic pricing programs like critical peak pricing [70]. By raising electricity prices to many times the normal rate during peak hours, buildings are incentivized to shift, or even shed, consumption. In [60] detailed results of an OpenADR-based DR pilot program are presented. This is now a full-fledged program.

Distribution level services

Distribution grid support. Peak shedding has been shown effective in existing DR programs in California [55]. A faster service that can be provided by commercial buildings is voltage regulation to support RES integration. This is possible due to the high R/X ratios in distribution networks, which allows voltage regulation through active power control.

Single customer support. In individual commercial buildings, peak shedding and load shifting can be used to reduce electricity costs or maximize PV self-consumption. For peak reduction, different approaches have been proposed including simple rule-based control schemes as in [71] and more sophisticated optimization-based algorithms as in [72], [73]. For load shifting, the use of MPC was proposed in [74], [75], to incorporate information about future evolution of costs or production from renewables.

The effectiveness of load shifting with MPC has been shown on a typical office building in Basel, Switzerland equipped with TABS and ventilation [76]. On this building two experiments were carried out. A constant price signal was used from 18 November 2012 to 01 February 2013 and a time-varying price signal, which was repeated every day from 05 February 2013 to 14 February 2013. Comparing Figs. 8 and 9, a clear shifting of the heating power consumption of TABS to low-price hours can be observed. Part of the TABS and ventilation power between hours 13:00 and 20:00 cannot be shifted, because of end-user disruption.

VI.D. Summary and Open Questions

A few interesting observations can be made from Table IX. First, buildings with IRA systems are technically more suitable for medium-speed and slow services due to their slower thermal dynamics in comparison to buildings with VAV systems. On the other hand, buildings with VAV systems are technically more appropriate for fast services due to their fast controlled VFD devices. Third, from an economic point of view buildings with non-complex BAS are preferable for fast services since

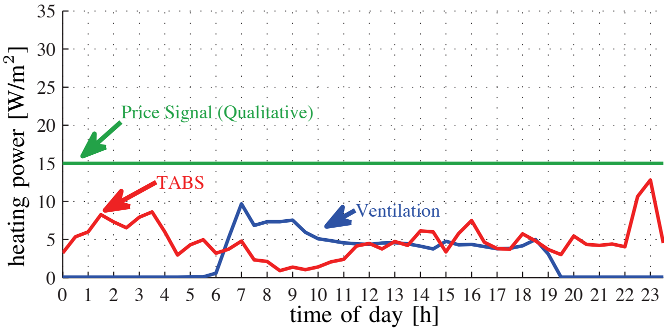


Fig. 8: From: [76]. Average heating power over 76 days in [W/m^2] of TABS and ventilation based on a constant price signal (shown qualitatively).

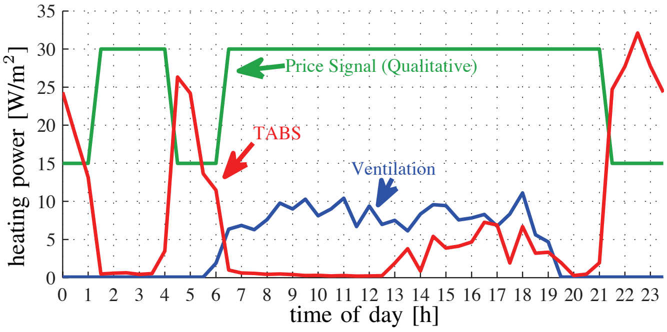


Fig. 9: From: [76]. Average heating power over 10 days in [W/m^2] of TABS and ventilation based on a time-varying price signal (shown qualitatively).

BAS reprogramming is less likely to be needed. In contrast, for medium speed services, the BAS complexity is less important.

A main challenge when using commercial buildings for DR is to work within the constraints of the existing BAS, which is usually not designed for DR applications, or to partially reprogram it in a cost-effective manner. Another challenge is determining the baseline, which is important to assess a building's performance in DR programs and design remuneration schemes [55]. Common DR baseline models are error prone [77], as can be seen in Fig. 6 since the prediction and actual load data deviate also during times without DR.

For office buildings it is also unclear who profits from participating in DR. The investment would probably be done by the owner of the building; however, the energy consumption and participation in power contracts usually concerns the tenant. If the building is used for DR, this might lead to non-energy-optimal behavior. In such cases, reimbursement mechanisms might be needed to achieve customer acceptance of DR schemes. Also, when a lot of measurements are taken and communicated, privacy concerns might be raised. In addition, the additional wear on HVAC systems must be quantified in terms of reduction in lifetime or repair costs.

VII. Thermostatically Controlled Loads

VII.A. Motivation and State of the Art

Similarly to a building envelope, Thermostatically Controlled Loads (TCLs) have thermal inertia, which can be used for DR. Small temperature deviations of TCLs do not impact the user comfort or service [78]. One way to control load aggregations to track power system signals is by changing the temperature set points of individual TCLs, e.g., [79]. Another way to control load aggregations is by on/off switching, e.g., [80], [81]. In this case, we can ensure that the control is *non-disruptive* [81]–[84] by switching TCLs only when they are operating within their hysteretic dead-band.

A large number of appliances must be aggregated to provide meaningful services to the power system. An advantage of using small loads for DR is that, in aggregate, continuous responses are possible. In [85] it is argued that aggregations of small resources may also be more reliable than single large resources. Also, TCLs have simpler dynamics than commercial building HVAC systems, and good control performance can be expected with simple controllers. Additionally, smaller loads are spatially distributed in distribution systems and may be able to address local problems. Finally, the total storage reservoir potentially available from these types of loads is vast [86]. However, coordinating the behavior of thousands of loads to achieve some desired objective while guaranteeing individual user needs is a challenging task, which requires the development of adequate load models and state estimation techniques. Additionally, the return per participant is low compared to other DR resources such as commercial buildings and electric vehicles.

VII.B. Characterization of Resource and Scenario Definition

We identified four scenarios to control large numbers of appliances. These scenarios differ in terms of control signal and whether the decision to control a specific appliance is taken locally or centrally.

(a) Control signal with centralized decision making (COCE)
(b) Control signal with decentralized decision making (CODE)
(c) Price signals to which the appliances react individually (PRDE)
(d) Distributed control, where local measurements lead to local decisions (DIDE)

Here, "control signal" refers to a signal which directly toggles the on/off state of a TCL; we do not consider temperature set point control in our examples, though in principle much of the same analysis would apply.

(a) Control signal, centralized decision making (COCE): An aggregator receives information from participating TCLs and sends on/off control signals. To reduce the required communication bandwidth, the on/off signals may be sent as a broadcast to all or a subset of the population. As on/off switching commands can override local controllers, local temperature constraint violations may occur. The aggregator might measure the state of some or every TCL (temperature, on/off state), or only aggregate power, e.g., at the substation. With current advanced metering infrastructure and with up to 600 customers connected to a low voltage transformer, it may take up to one hour to get readings from every meter [87], making it difficult to participate in fast DR. However, when measurements are rare, delayed, or completely unavailable the aggregator can employ models of the thermal dynamics of the loads along with state estimation techniques [81], [88].

(b) Control signal, local decision making (CODE): Similar to the previous architecture, we now assume that local decisions can be made. For example, we might broadcast control signals that direct loads to switch with a certain probability, possibly depending upon their current on/off state, temperature state, or state of charge. In this case, the local controllers can ensure that thermal constraints are kept. However, this means that the loads may not always react to the control signal in the desired way. Again, the effectiveness of the control is a function of the type, amount, frequency, and quality of information available from the loads to the aggregator, and models and state estimation are useful.

(c) Price signals (PRDE): In this case, price signals are communicated to the participants. The appliances then decide what kind of behavior is optimal for their own operation, e.g., delaying operation until the price is lower or planning a schedule for an air conditioner according to a day ahead price curve. Price control has some important advantages. Depending on the exact approach, the communication and control infrastructure can be kept very simple. Public acceptance may be more likely since control actions are not imposed on the loads – the consumers are free to decide whether it is beneficial to adjust their consumption or not. On the other hand, broadcasting a price signal to the whole population may result in poor control performance. It is hard to predict how the customers may react to prices, and certain price signals may lead to synchronization. When a feedback loop is introduced in the pricing scheme the system can become unstable, in particular for high shares of participants [78], [89].

(d) Distributed control (DIDE): It is also feasible to implement completely distributed control, where there is no central controller and frequency and/or voltage measurements are taken locally at the participating units.

Tables X and XI summarize the characteristics of TCLs which are detailed in the following.

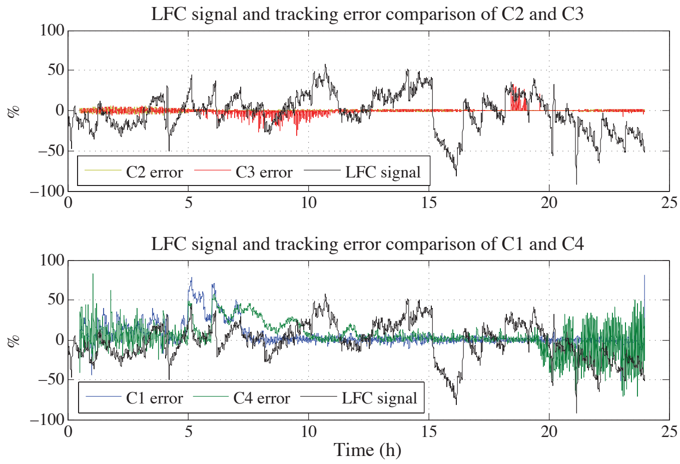


Fig. 10: From [90]: LFC signal and tracking error of strategies C1, C2, C3 and C4.

- *Power capacity*: The power capacity scales with the number of appliances taking part in a control scheme. While each appliance has a power rating in the range of some kW, the total power capacity can be substantial. For example, the Kanton of Zurich has around 100 000 Electric Water Heaters (EWHs) with a total power rating of more than 440 MW.
- *Energy capacity*: The energy capacity is determined by the thermostat limits limits and storage size of the appliance as well as by the use pattern. In [86] the energy capacity of air conditioners, EWHs, heat pumps, and refrigerators in California es estimated, and we based our numbers in the table on the numbers derived there.
- *Ramp rate*: On to off or vice versa in less than a second.
- *Location*: TCLs are spatially distributed. While most TCLs are in the residential sector, they can be found in the commercial and industrial sector as well. Appliances are generally connected to a low-voltage network.
- *Response Granularity*: Individual responses are on/off. As more TCLs are added to an aggregation, the response becomes more and more continuous.
- *Response frequency*: Increased switching is not desirable because it can degrade equipment. Some TCLs such as heat-pumps have compressors with lock-outs, meaning that after they have been switched they are unable to switch again for some time. This limits the response frequency of a single load; however, larger aggregations of loads can follow high frequency signals if the control scheme is designed to manage the lock-out constraints of individual TCLs by intelligently distributing the switching.
- *Response time*: Depends heavily on the control and communication scheme.
- *Control/ communication*: This is discussed in the scenario definitions.
- *Implementation cost*: Depends heavily on the control and communication scheme. Costs would result from uni- or bidirectional communication systems, local computation for local decision making, etc.

VII.C. Possible service applications for the electricity grids

Table XII gives an overview of possible service applications provided by TCLs.

System level ancillary services

Very fast service. Very fast services are possible through distributed control, as explored in [91]–[93].

Fast service. Fast services can be provided by TCLs via control signals and either centralized or decentralized decision making. For example, a direct load control algorithm to enable tracking of frequency regulation signals with aggregations of EWHs is presented in [94], which shows that a population of 33,000 EWHs can provide a 2 MW bi-directional regulation signal for 24 hours per day. Much of the recent research in this area has focused on developing aggregate system models suitable for control synthesis, e.g., [79], [81], [95]–[98], and state estimation [81]. State estimation aims to minimize communications and therefore costs.

In [90] LFC provision with aggregations of EWHs was investigated. Four control schemes were compared: two based on central decisions with full state (C2) or only switching state information available (C3), and two based on local decision making, aggregate power measurements and blocking of units (C1) or SOC broadcasting (C4). Strategies C2 and C3 result in 1.2 % and 8.7 % Mean Average Percentage Errors, respectively, while strategies C1 and C4 have intervals with very high tracking errors exceeding 50 %. This makes strategy C2 suitable for LFC, whereas C3 shows some potential. Strategies C1 and C4 might be of interest in applications with lower accuracy requirements, such as balancing group optimization or load shifting. Fig. 10 shows an extract of the LFC signal used in [90] and the resulting tracking errors of the four strategies during a day. The impact of strategies C2, C3 and C4 on customer comfort is minimal, whereas strategy C1 results in a considerable amount of temperature constraint violations. With the exception of strategy C1, all other strategies significantly increase the average number of switching actions per EWH.

There are also a number of pilot studies in this area. For example, the Swiss company Swisscom is using heat pumps for load frequency control. Users are not paid to participate, but the energy management system is paid for by Swisscom. Control signals are sent via the Swisscom-owned mobile data network [99]. The PJM interconnection is also investigating the potential of EWHs to follow automatic generation control signals [100]. Testing is also going on at the Electric Power Research Institute (EPRI) [101].

Medium-speed service. Ref. [81] shows how aggregations of air conditioners could be used to provide load following

TABLE X: Physical characteristics of TCLs.

Property	Description
Power capacity [kW]	$n \cdot \{0.5 - 10\}\,\mathrm{kW}$
Energy capacity [kWh]	$n \cdot \{0.01 - 5\}\,\mathrm{kW\,h}$ (depending on device energy usage)
Ramp rate [kW/min]	Almost infinite
Location	Distributed, low voltage network
Response granularity	Depends on the number of participating units
Response frequency	High; for small aggregations: compressor lock-out times relevant

TABLE XI: Scenario-dependent characteristics of TCLs.

Property	Control, central (COCE)	Control, decentral (CODE)	Price, decentral (PRDE)	Distributed, decentral (DIDE)
Response time	fast, only limited by communication system			~ 0
Control	Control signal central decision making	Control signal local decision making	Price signals local decision making	Local measurements
Communication	bi-directional (ideal)	uni-directional (possible)	uni-directional	local
Implementation cost	Communication infrastructure, local controllers, aggregator (High)	(Medium)	(Low)	Upgrade for droop control

TABLE XII: Technical and economical rating of power system services provided by TCLs.

System level ancillary services		Control, central (COCE)	Control, decentral (CODE)	Price, decentral (PRDE)	Distributed, decentral (DIDE)
Very fast		-/-	-/-	-/-	+/++
Fast		++/0	+/++	-/-	-/-
Medium-speed		+/0	+/+	+/++	-/-
Market-based services		**Control, central**	**Control, decentral**	**Price, decentral**	**Distributed, decentral**
Medium-speed		+/0	+/++	+/++	-/-
Slow		+/0	+/0	+/0	-/-
Distribution level services		**Control, central**	**Control, decentral**	**Price, decentral**	**Distributed, decentral**
Distribution grid support	Fast	+/+	+/+	-/-	+/0
	Slow	+/+	+/+	+/+	-/-
Single customer support	Fast	-/-	-/-	-/-	-/-
	Slow	-/-	-/-	+/+	+/0

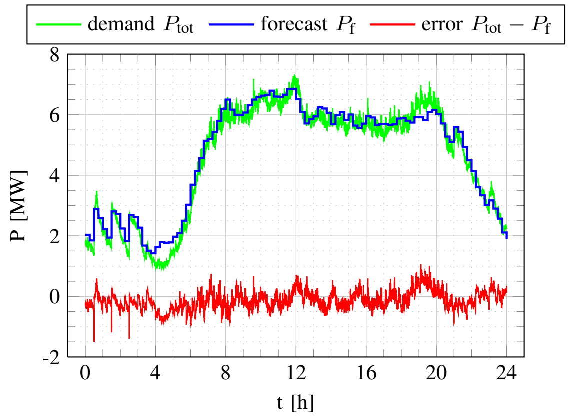
via control signals with decentralized decision making. The authors propose a Markov chain model of aggregate load dynamics and use state estimation techniques to minimize communication between the aggregator and the loads. The results show that, for some applications, only one-way communication may be needed, i.e., the loads may not need to provide any information to the central controller in real time.

Market-based services

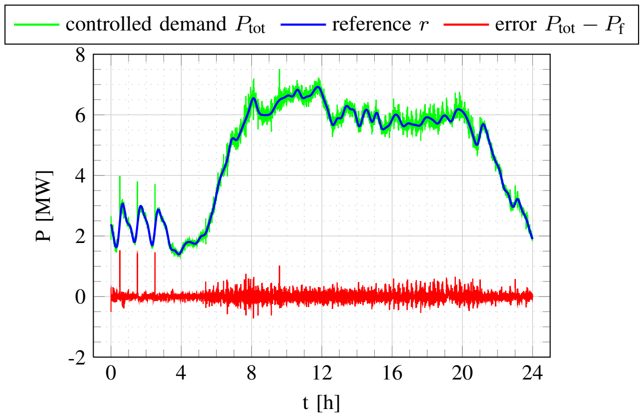
Medium-speed service. TCLs could provide a variety of medium-speed market based services. In [88], a control scheme based on state estimation and broadcast control (control signals, decentralized decision making) was used to achieve BG schedule compliance by controlling EWHs. A simplified model of the population taking into account only the switching state was used and only aggregated measurements at the substation were assumed. Estimation was performed by a particle filter. Even though these measurements are very noisy, accurate estimations of the number of switchable loads and thus a good tracking of the reference were achieved. Results are shown in Fig. 11. Fig. 11(a) shows the uncontrolled power consumption as measured at the substation. Deviations from the forecast are clearly visible, and the error is biased even over longer periods of time. With DR, longer forecast deviations are canceled out and the error is nearly zero-mean, as can be seen in Fig. 11(b).

In [102], a "time varying thermal battery model" was introduced to optimize TCL energy consumption against 5-minute energy market prices. The model keeps track of the energy state of the thermal battery as it evolves as a function of power draws below or above the baseline power consumption of the aggregation. In contrast to traditional batteries, the power and energy capacity of thermal batteries may vary as a function of time (e.g., for air conditioner aggregations the power and energy capacity varies with outdoor temperature). Since the model is coarse, it may not capture the underlying dynamics of the system and tracking can be poor. The many sources of uncertainty in this model are investigated in [103].

There have also been several pilot studies in this area. The Pacific Northwest National Laboratory conducted several pilot studies in 2006 to determine the potential for residential loads



(a) Load and load deviation without DR



(b) Load and load deviation with DR

Fig. 11: DR for Balance Group optimization. Direct control with local decision making and state estimation [88]

to participate in energy markets [104]. Residential customers preprogrammed their preferences for DR actions by their electric water and space heaters. Not only did the loads respond to dynamic electricity prices but they also contributed to price formation by bidding into a local marginal price market.

Slow service. TCLs with long thermal time constants such as EWHs can respond to electricity prices that vary on timescales of hours. In 2003, California conducted a pilot study to understand the response of residential customers to critical peak prices [105]. The study shows that residential customers can effectively participate in dynamic pricing programs, especially if they are equipped with programmable communicating thermostats and controls technology. In [106] three strategies based on timers and price sensitive thermostats are presented and the potential for reduction in consumer electricity costs by controlling EWHs to respond to dynamic electricity prices is assessed. In [75] appliances were used to optimize the consumption profile of a single household subject to dynamic tariffs. The “model city Mannheim”, part of the eEnergy projects in Germany, uses dynamic electricity tariffs to influence consumer behavior [107].

Distribution level services

Distribution grid support. In most of Europe, EWHs are currently only allowed to heat at night, being switched by utilities via ripple control. Heat pumps used for space heating commonly have contracts that allow blocking (i.e., forced to turn off) for a certain period of time, usually one hour. Several Californian utilities have programs to remotely switch off air conditioners when the grid is stressed. For example, Pacific Gas and Electric Company offers the SmartAC Program [108] in which control devices are installed in AC units and customers are compensated for participation. Jackson Energy Authority in Tennessee has started a pilot program to remotely switch water heaters during peak periods [109].

Single customer support. TCLs can be used to increase PV self-consumption by shifting the consumption in intervals with high PV production, as in [110].

VII.D. Challenges and Open Questions

There are several challenges which need to be addressed when implementing any of these advanced DR schemes. For example, in all schemes the return per participating unit is very low [86]. An economically viable Demand Response (DR) scheme should therefore try to minimize the cost of communication, measurement, and control infrastructure. This can be supported by using state estimation techniques [81], [88]. Additionally, collection of detailed data about electricity consumption and even appliance use patterns raises data privacy concerns. Schemes based on state estimation inherently protect the privacy of the end-customer. Another challenge is to fairly split the profits/risks between all involved parties including potentially thousands of loads and the aggregator. It may be hard to measure the effect of each load because that requires a baseline, an estimate of what would have happened if there was no DR. One way to avoid baselines for settlement is to use price signals; however, as mentioned, price signals can lead to stability problems [89]. Each scenario requires communication channels to be in place. Right now, there are many standards competing on all levels of communication complexity, making investment decisions hard. Due to the liberalization of the energy markets and introduction of the BG concept in Europe, there might be two or more BG with conflicting optimization targets in the same distribution grid. Also, it is hard to measure the demand of a specific BG in real-time, and even a posteriori accounting for the contribution of a BG when providing a specific service is not trivial. Last, it is important to ensure that the provision of system level frequency control does not create additional stresses at local distribution systems, such as voltage deviations or transformer/line overloading. In this direction, [111] proposed a hierarchical control algorithm to enable the combined provision of secondary frequency control and voltage regulation by TCLs, with the aim of maximizing RES integration.

Despite all the challenges, many different ways to implement a DR schemes with TCL are feasible. Generally, these loads can react rapidly and in aggregation have a substantial power rating. While some DR schemes are already in place, it can be expected that TCLs will play a much more important role in providing a fast and accurate source of flexibility in the future electricity grid.

VIII. Comparison and Case Study

VIII.A. Comparison

This section combines the analysis of the previous four sections, providing a comparison of the four resources in terms of their ability to provide power system services. Table XIII contains the same generic services as used before, but now provides ratings for each of the four resources. The rating for a particular service and resource is given by the best rating of the corresponding service and resource amongst all considered scenarios. Hence, it is a kind of summary of the previous tables, containing only the most promising options. As Table XIII shows, each of the services can be provided by at least one resource. However, how well a resource can provide a particular service, from both a technical and economical perspective, varies widely amongst resources.

System level ancillary services

For very fast services, batteries are well-suited because they are reliabe and fast and this service only requires a small energy/power ratio. The only drawback of batteries is their high investment cost. The batteries of electric vehicles are likewise reliable and fast. With a high penetration of PEVs service provision would also be economically viable, because only moderate additional investments are needed to enable local measurements. Commercial buildings cannot respond fast enough to provide this service or would require an immense additional investment to do so. TCLs can provide this service and this option is expected to be economically viable. Also for fast services, batteries and PEVs are well-suited. However, today it is more economically viable to use commercial buildings and TCLs for this service. For medium services, batteries are also technically feasible, but not a viable option for economic reasons. Here, PEVs, commercial buildings, or household appliances are better candidates.

Market-based services

For market-based services, reliability is less important. The reason for participating in markets is arbitrage. Arbitrage is the only return as there is no payment for providing power capacity as with most ancillary services. Also, for this service, typically a higher energy/power ratio is beneficial. Hence, batteries are most likely not an economically viable option. Rather, one would use the existing flexibility from other DR and energy storage options. For both medium and slow services, PEVs and commercial buildings are well suited. TCLs are also suited for medium services, whereas the provision of slow services is usually not economically viable.

Distribution level services

Batteries can reliably provide distribution grid support, both fast and slow, and have the advantage that their location can be chosen. PEVs, commercial buildings, and household appliances can provide this service as well. Commercial buildings are suited best here, because only a few entities can provide the required power and energy capacity at moderate costs. For single entity support, batteries and EVs can provide both fast and slow service. For batteries, this service is already economically viable and being used. Commercial buildings and household appliances can only provide slow services here.

VIII.B. Discussion

We have seen that the resources can potentially provide a range of services. Here we discuss the main challenges that need to be addressed in order to use the resources.

A major problem arises from the fact that currently the control signals for services are not guaranteed to be zero-mean over some time. For traditional generators, this is not a problem. DR and energy storage resources, on the other hand, have limited energy capacities. Batteries, for example, can be discharged to provide a service, but at some point also need to be recharged; the same holds for thermal storages. Therefore, if the service provision needs to be guaranteed (as for ancillary services) a time over which the signal is zero-mean must be fixed, in order to enable DR and energy storage resources to assess a priori whether they have enough energy capacity to guarantee the service provision. In the proposed generic service definitions, we assumed the control signals to be zero-mean over specific time intervals in order to assess the ability of the resources to provide specific services. In reality, these control signals are often not zero-mean. In this case, the service might be provided by a combination of DR and energy storage resources and traditional generators (see also the discussion of the offset principle in the battery section). In the U.S., several Independent System Operators (ISOs) are considering mechanisms to ensure that fast services are zero-mean [112]–[114].

Further challenges include the problem of privacy if measurements are taken and communicated; or, if prices are taken as incentives, synchronization effects and instabilities. Also, one should think about how to combine the different services, since there is an interdependence between the system and distribution level. Finally, when designing the control schemes, one should have in mind that the DR resources also have an

TABLE XIII: Technical and economical rating of power system services provided by different resources.

System level services		Batteries		Plug-in Electric Vehicles		Commercial Buildings		TCLs	
Very fast		++/0	(all)	+/+	(LOME)	0/-	(VAVC/VAVN)	+/++	(DIDE)
Fast		++/0	(LABA)	+/+, ++/0	(CSIB/ADCO)	++/+	(VAVN)	+/++	(CODE)
Medium		0/0	(all)	++/0	(CSIB/ADCO)	++/+	(IRAN)	+/++	(PRDE)
Market-based services		**Batteries**		**Plug-in Electric Vehicles**		**Commercial Buildings**		**TCLs**	
Medium		0/0	(DDSO)	++/+	(CSIB)	++/+	(IRAC/IRAN)	+/++	(CODE/PRDE)
Slow		0/0	(DDSO)	++/+	(CSIB)	++/+	(IRAC/IRAN)	+/0	(COCE/CODE/PRDE)
Distribution level services		**Batteries**		**Plug-in Electric Vehicles**		**Commercial Buildings**		**TCLs**	
Distribution grid support	Fast	++/0	(DDSO/DCUS)	+/0	(LOME/CSIB/ADCO)	++/+	(VAVN)	+/+	(COCE/CODE)
	Slow	++/0	(DDSO/DCUS)	++/+	(CSIB)	++/+	(IRAC/IRAN)	+/+	(COCE/CODE/PRDE)
Single customer support	Fast	++/+	(DCUS)	+/0	(LOME/CSIB/ADCO)	-/-	(all)	-/-	(all)
	Slow	++/+	(DCUS)	+/0	(PRIN/CSIB/ADCO)	++/+	(IRAC/IRAN)	+/+	(PRDE)

original purpose, which should not be disturbed too much. In some cases, advanced control strategies are necessary, to allow both, power service provision and end-user service.

Another big challenge comes from the fact that resources must be incentivized to provide services. This can either be done by applying time-varying electricity prices or by payments from an aggregator, utility, or system operator. If additional investments are necessary to provide services, then the expected economic return needs to pay back the investment at some point. There is uncertainty both for the economic return and the full deployment costs. A significant economic return can be difficult in some cases, e.g., when the service is provided by a very large number of entities as with TCLs, where the return has to be split among many participants. A further problem with the economic return is determining the baseline for the compensation, i.e., assessing how much a resource reacted for providing the particular service on top of the load consumed for other reasons.

All of the above-mentioned challenges and uncertainties make the investment decision a difficult one. Furthermore, uncertainty arises from the unknown price evolution of batteries as well as the unknown future penetration of electric vehicles. Giving estimations of the investment cost for the different resources is beyond the scope of this paper and a hard problem because it highly depends on many unknown parameters. Therefore, we tried in this paper is to name the additional technical installations that are necessary to use this resource for service provision. If an investment decision is to be made, one has to assess how much these additional installations cost given the current situation in a particular country.

VIII.C. Example case study: Switzerland

In this section, we present a small example case study for Switzerland. This is not meant to be conclusive, but rather meant to explain how Table XIII can be used for a specific case.

In order to understand what are the different services needed in Switzerland, we analyze the frequency spectrum of the generation in Switzerland using the method in [115]. The total generation of Switzerland is approximated as

$$P_{tot} = P_{load} - P_{prim,act} - P_{sec,act} - P_{tert,act} \ ,$$

where P_{load} denotes the measured load and $P_{prim,act}$, $P_{sec,act}$, and $P_{tert,act}$ the activated primary, secondary, and tertiary control reserves, respectively. Due to unavailability of data, in- and outflows from neighboring countries are neglected. The frequency spectrum of the total generation is calculated using the Fast Fourier Transform (FFT) and plotted in Figs. 12 and 13.

From the figures, we can see that the predominant frequencies correspond to days, 12 hours, and 1 hour, mainly as a result of market clearings. Cycling times of 15 minutes and less are visible. Shorter cycling times occur due to ramping as well as load and generation fluctuations. Further, we find that the amplitudes of the predominant frequencies decrease with higher frequencies meaning less storage is needed to provide short-term flexibility.

If DR and storage are to be used for a particular service, we propose to use the following procedure to assess investment decisions:

Procedure to assess investment decisions
(1) Determine which service is to be provided.
(2) Determine the necessary energy/power ratio of this service.
(3) Use Table XIII to choose options.
(4) Determine physical capacity of these options.
(5) Evaluate options economically.
(6) Give recommendations.

We now follow in the above-mentioned steps.

(1) Assume that we would like to increase the amount of DR and storage in the fast service level ancillary service. Hence, the signal comes every 1-10 seconds and is zero-mean over 15 minutes.

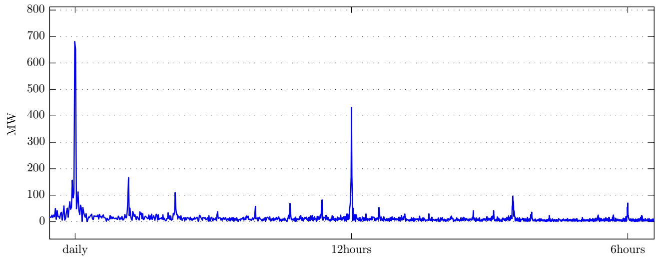


Fig. 12: Long-term frequency spectrum.

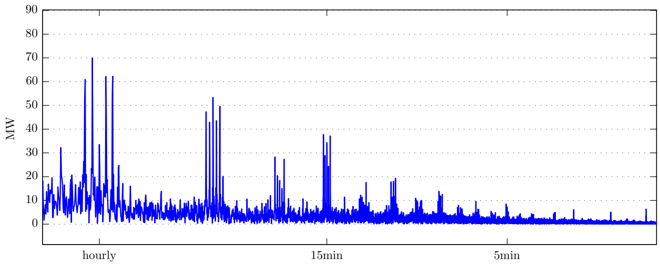


Fig. 13: Short-term frequency spectrum.

(2) To determine the current power and energy ratings, we follow the procedure from [115]. Each component of the frequency spectrum (except the zero frequency component) is zero mean over each cycle. To approximate the power amplitude A at a specific cycling time t=1/60f [min], where f is the frequency, we sum up the amplitudes in the neighborhood of f. The energy rating is calculated as the integral of a sine with the amplitude A over half a cycling period $A/\pi f$. Based on this analysis, one can determine how contribution is desired from DR and energy storage resources.

(3) From Table XIII we see that all resources could be used to provide this service with the following order in their ranking (from best to worst): TCLs, commercial buildings, electric vehicles, batteries.

(4) TCLs could provide a significant amount of this service (exact numbers for how much TLCs could contribute for this specific case would need to be determined).
For commercial buildings only VAV systems with non-complex BAS can provide this service. VAV systems are very rare, therefore this is not a promising approach for Switzerland and we do not consider it further here.
Electric vehicles are also well-suited, but would require a significant penetration of PEVs, which is not yet achieved in Switzerland and therefore this option is also not further considered here.
A large battery could provide this service with a power and energy capacity chosen for this service.

(5) Now one needs to assess the two options TCLs and batteries economically and get exact figures for the costs, which is beyond the scope of the paper. However, one can expect that the CODE scenario of TCLs is currently economically more viable than buying a large battery (LABA). However, if the capacity of TCLs is to small, the remaining part could be provided by batteries. This of course needs to be compared economically with other options outside DR and energy storage.

(6) So, in this example the recommendation would be to invest in the TCL infrastructure and provide the service with scenario CODE.

IX. Conclusions

Demand response (DR) and energy storage can address a number of current challenges in power systems; for example, they can improve energy market efficiency and power system reliability. In this work, we present a unified framework that allows us to compare different types of DR and energy storage resources. We use this framework to assess four resources: batteries, plug-in electric vehicles, commercial buildings, and thermostatically controlled loads.

The framework includes three parts: 1) a definition of generic power system services; 2) a resource characterization, both of physical parameters and scenario-dependent parameters, where different implementation scenarios are defined for each resource that allow for provision of different services; and 3) a rating of all combinations of power system services and scenarios both in terms of technical and economical feasibility.

Our contribution is threefold: (i) the development of a unified framework for assessing DR and energy storage resources, (ii) a detailed analysis of the four resources including a literature review, (iii) a comparison of the resources using the framework as well as an example case study for Switzerland.

We find that there is significant potential to provide power system services with benefits to both market operation and power system reliability, and that the different resources can complement each other in power system service provision. We also find that, for a particular resource, the ability to provide services highly depends on the implementation scenario (e.g., communication infrastructure, resource size). Further important findings are:

- Future power system services should define a time-scale over which they are zero-mean to enable the use of DR and energy storage.
- Batteries are well suited for fast system level ancillary services, because they are reliable and have high ramp rates, and are profitable for low energy/power ratios. They are also well suited for single customer support. However, currently battery investment costs are high.
- PEVs are similar to batteries in terms of service provision, but are also suited for market-based services.
- Most power system services can be provided with commercial buildings; however, not with all buildings and types of HVAC systems. Moreover, service provision highly depends on the communication infrastructure used.
- TCLs can provide most power system services, with dependency on control/ communication infrastructure.

The main challenges associated with using DR and energy storage resources for power system services are ensuring that the resource is still able to provide its main service, respecting customer privacy, properly incentivizing participants, and coping with high investment/ installation costs. However, many recent developments have begun to address these issues. New algorithms can help to better manage the resources, guarantee customer service, and ensure privacy. Battery technologies and communication technologies are advancing, which reduces their investment costs.

X. Acknowledgments

We acknowldege the support of the Swiss Commission for Technology and Innovation for CTI project no. 14478, the Competence Center for Energy & Mobility, SwissElectric Research, and the Erdöl- Vereinigung for the project "Technology-centered Electric Mobility Assessment", the Swiss Federal Office of Energy (BFE) and SwissElectric Research for the project "SmartGrid-Polysun Design Tool for Local Load Management" and KTI (Kommision fr Technologie und Innovation), EKZ, and Landis+Gyr for the project "Distributed Demand Response".

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