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Review of energy system flexibility measures to enable high levels of variable renewable electricity

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Abstract

The paper reviews different approaches, technologies, and strategies to manage large-scale schemes of variable renewable electricity such as solar and wind power. We consider both supply and demand side measures. In addition to presenting energy system flexibility measures, their importance to renewable electricity is discussed. The flexibility measures available range from traditional ones such as grid extension or pumped hydro storage to more advanced strategies such as demand side management and demand side linked approaches, e.g. the use of electric vehicles for storing excess electricity, but also providing grid support services. Advanced batteries may offer new solutions in the future, though the high costs associated with batteries may restrict their use to smaller scale applications. Different "P2Y"-type of strategies, where P stands for surplus renewable power and Y for the energy form or energy service to which this excess in converted to, e.g. thermal energy, hydrogen, gas or mobility are receiving much attention as potential flexibility solutions, making use of the energy system as a whole. To "functionalize" or to assess the value of the various energy system flexibility measures, these need often be put into an electricity/energy market or utility service context. Summarizing, the outlook for managing large amounts of RE power in terms of options available seems to be promising.

Keywords: energy system flexibility, DSM, energy storage, ancillary service, electricity market, smart grid

Abbreviations

AC	alternating current
APC	active power curtailment
AUP	average unit price
CAES	compressed air energy storage
CCGT	combined-cycle gas turbine
CHP	combined heat and power
CPP	critical peak pricing
DHW	domestic hot water
DLC	direct load control
DOD	depth of discharge
DSM	demand side management
E2T	electricity-to-thermal
EV	electric vehicle

EWH	electric water heater
HVAC	heating, ventilating, and air conditioning
HVDC	high-voltage direct current
ICT	information and communications technology
MPC	model predictive control
P2G	power-to-gas
P2H	power-to-hydrogen
PEV	plug-in electric vehicle
PHES	pumped hydro energy storage
pp	percentage point
PV	photovoltaic
RE	renewable energy, renewable electricity
RTP	real-time pricing
SG	smart grid
SMES	superconducting magnetic energy storage
TOU	time-of-use pricing
TSO	transmission system operator
V2G	vehicle-to-grid
VRE	variable renewable energy

1 Introduction

Energy systems need flexibility to match with the energy demand which varies over time. This requirement is pronounced in electric energy systems in which demand and supply need to match at each time point. In a traditional power system, this requirement is handled through a portfolio of different kind of power plants, which together are able to provide the necessary flexibility in an aggregated way. Once variable renewable electricity is introduced in large amounts to the power system, new kind of flexibility measures are needed to balance the supply/demand mismatches, but issues may also arise in different parts of the energy system such as in the distribution and transmission networks [1,2].

Large-scale schemes of renewable electricity, noticeably wind and solar power, are under way in several countries. Denmark plans to cover 100% of country's energy demand with renewable energy (RE) [3], Germany has as a goal to meet 80% of the power demand through renewables by 2050 [4], and in several other countries increasing the RE share is under discussion or debated [5–7]. At the same time, the renewable electricity markets are growing fast, e.g. in the EU, wind and solar stood for more than half of all new power investments in 2013 [8]. On a longer term, by 2050, RE sources could stand for a major share of all global electricity production according to several studies and scenarios [9–12]. Compared to today's use of RE in power production, the variable RE power utilization (VRE) could increase an order of magnitude or even more by the middle of this century. The experiences from countries with a notable VRE share, such as Denmark, Ireland and Germany, clearly indicate challenges with the technical integration of VRE into the existing power system, but also problems with the market mechanisms associated. Therefore, improving the flexibility of the energy system in parallel with increasing the RE power share would be highly important.

There is a range of different approaches for increasing energy system flexibility, ranging from supply to demand side measures. Sometimes more flexibility could be accomplished through simply strengthening the power grid, enabling e.g. better spatial smoothing [13]. Recently, energy storage technologies have received much attention, in particular distributed and end-use side storage [14–16]. Storage would be useful with RE power [17], but it is often perceived somewhat optimistically as a generic solution to increasing flexibility, underestimating the scale in energy [18]. Different types of systemic innovations, e.g. considering the energy system as a whole and integrating power and thermal (heating/cooling) energy systems together, could considerably improve the integration of large-scale RE schemes [19,20]. The concept Smart Grid involves a range of different energy technologies and ICT to better manage the power systems and increase their flexibility [21]. Many other options are available as well.

The purpose of this study is to present a broad review of available and future options to increase energy system flexibility measures to enable high levels of renewable energy. Several of these measures are applicable for any type of energy system or energy supply. We present solutions that are linked to the demand side, electricity network, power supply, and the electricity markets. The literature on individual measures or technologies for energy system flexibility is vast. Recently, a few reviews on the subject have been published [22–26], but with a more narrow scope, whereas here we strive for a broader coverage of the available options. In addition to presenting options for energy system flexibility, we also try to reflect these against large-scale RE utilization and integration whenever possible.

2 Defining flexibility

To operate properly, the power system needs to be in balance, i.e. power supply and demand in the electric grid has to match at each point of time. The electric system is built in such a way that it has up to a certain point a capability to cope with uncertainty and variability in both demand and supply of power. For example on the supply side, the kind of flexibility is accomplished through power plants with different response time. Introducing variable power generation such as wind and solar power may increase the need of energy system flexibility, which could be accomplished through additional measures on the supply or/and demand side which is the subject of this paper. From the electricity system point of view, flexibility relates closely to grid frequency and voltage control, delivery uncertainty and variability and power ramping rates.

The metrics for defining flexibility can be derived from these effects. Huber et al. (2014) [27] used three metrics to characterize flexibility requirements, namely ramp magnitude, ramp frequency and response time, in particular of the net load which results when the variable renewable generation has been subtracted from the gross load. Their analysis included both a temporal and a spatial (smoothing) aspect of energy system flexibility. Blarke (2012) [28] looked on flexibility in a broader context integrating the VRE into a whole energy system context with thermal energy demand in addition to power and allowing power conversion to heat. In this case flexibility or intermittency friendliness of a supply or demand side agent was defined as a correlation between the net power exchange between a power plant and the grid, and the net power requirement (a correlation of 1 means that the distributed power producer matches perfectly the net power demand, -1 means a complete mismatch). Denholm et al. (2011) [29] analyzed flexibility in terms of the power plant mix (plants for base, intermediate, and peak load) and concluded in their analysis for Texas (US) that reducing the share of rigid base-load power plants would increase the system flexibility to incorporate increasing shares of variable generation.

These examples show that the metrics for defining flexibility may be unambiguous to different definitions as it is necessary to address the different aspects of the energy system. In the following chapters, in which the different approaches for increasing energy system flexibility are presented, using a single indicator to measure their goodness may not therefore be applicable. We have used the best available description for each case.

3 Demand side management (DSM)

3.1 Overview

Demand side management (DSM) constitutes of a broad set of means to affect the patterns and magnitude of end-use electricity consumption. It can be categorized to reducing (peak shaving, conservation) or increasing (valley filling, load growth) or rescheduling energy demand (load shifting), see Fig. 1 [30]. Load shifting requires some kind of an intermediate storage [31] and a utilization rate of less than 100 % [32] as both an increase and a decrease of power demand need to be possible in this case. Examples of load shifting include heat stored in an electrically-heated building, the food supplies in a refrigerator acting as a cold storage, an intermediate storage of pulp in the paper industry [33], or dirty and clean clothes or dishes as storages allowing for running a washing machine at any time [31]. However, many loads can be energy limited as they cannot provide their primary end-use function if enough energy is not provided during a time interval [22,34].

Load shifting is beneficial compared to the other DSM categories, as it allows for demand flexibility without compromising the continuity of the process or quality of the final service offered. While functionality similar to load shifting can also be provided with energy storage, an interesting difference is that DSM can be 100% efficient, as no energy conversion to and from an intermediate storable form is required [35].

DSM can provide flexibility required to balance electricity generation and load which is important for variable renewable energy generation [34,36,37], as almost any measure taken on the power generation side has an equivalent demand-side countermeasure [34]. DSM measures can provide balancing both in terms of energy and capacity (power), and response in various time scales. Significant variability and uncertainty in VRE generation occurs in the time scale of 1–12 h, in which most mass market DSM opportunities are found [38].

In addition, DSM can provide various other benefits to electrical energy systems and markets with renewable energy, such as reducing price spikes and the average spot price [31], shifting market power from generators to consumers [37], replacing or postponing infrastructure expansion [37,39,40], reducing use of costly peak power [37] and reducing transmission and distribution losses [41]. DSM may also facilitate energy efficiency measures [42,43].

Even though the idea of DSM is not new [44,45] its implementation has been slow [46]. It has traditionally been used to cut peak power demand and has only recently been applied to balance variable renewable production [36,47]. Barriers for DSM include e.g. lack of ICT infrastructure and technology financing [39,46], providing timely energy and price information [39] and communicating benefits to key stakeholders [46], poor response if not automated [39], minor unit savings [39], key stakeholder involvement [39], lack of incentive to invest in industry-wide benefits obtainable with DSM [39,46], rate structure design [39], and regulatory processes and policies to promote DSM [39]. ICT is a key technology for DSM, and the inherent privacy and security risks have to be handled with strict data handling guidelines [48]. On a consumer level, ICT could enable DSM incentivization through in-game scoring and social competition [49].

DSM programs can be classified as price based, including real-time pricing (RTP), critical peak pricing (CPP), and time-of-use pricing (TOU), and incentive-based programs, including direct load control (DLC) and direct participation to energy markets [37,50]. Price-based and market participation are more suitable for slow “energy trading” DSM [37], while reliability provision via fast DSM may require DLC for fast, predictable and reliable enough response [34,37,51]. Among price-based programs, RTP has the greatest potential to address VRE integration at all time scales longer than 10 min [38]. DLC programs are capable of addressing the minute-scale VRE variability that is too fast for price-based programs [38]. However, DLC programs have the risk of reducing the inherent diversity of loads [46], leading even to oscillatory load population behavior [52], and all non-price responsive DSM has the baseline measurement problem: the response of customers is compared to a baseline to determine payment for the customer, but the baseline is impossible to measure [34,53,54].

3.2 Potential of DSM

To understand the importance of DSM for renewable electricity systems, we present in the next some estimates for the DSM potential in Germany and Finland with detailed data. Similar studies have also been undertaken in Norway [55], Denmark [55], Ireland [42], California [56,57] and Switzerland [58], among others. The DSM potential is typically split by sector (households, industry, service) each having its specific characteristics.

The technical potential of DSM is determined by the availability of flexible power capacity in general, possible restrictions of the power control, the duration for which the control can be applied and the effective energy storage capacity available in case the load is shiftable. Positive (i.e. decreasing load) and negative (i.e. increasing load) power capacities are often different. The costs associated with DSM are split into investments, variable costs and fixed costs [33]. In addition to technical and economic issues, DSM is also linked to behavioral aspects and decision-making [39,59,60] that affect the realizable potential of DSM, e.g. when connected to RE schemes.

3.2.1 Households

DSM in households or residential loads is an interesting case as VRE is often applied in this scale, e.g. solar photovoltaics in buildings. DSM may in this case be viewed as a single decentralized measure, or if households are pooled together, as an aggregated utility-scale measure. In addition to the loads considered below, thermal energy storage in residential heating systems has a major DSM potential [61,62], though the DSM capacity depends on the type of storage and coupling to the residential HVAC system, and is case-specific [61].

The DSM potential of residential loads in Germany [63,64] is presented in **Error! Reference source not found.**. The capacity values depend on the ambient temperature and/or control duration; the maximum values are reported here.

To provide relevant metrics for VRE integration, the capacity and cost values are relative. The positive capacity (decreasable power) is relative to the minimum and maximum total net load (total load – VRE) in Germany during 2010–2012 (16 GW and 75 GW) and the negative capacity (increasable power) is in relation to the maximum VRE power feed-in, 29 GW in 2010 [65]. The virtual storage capacity obtained by load shifting is given relative to the total pumped hydro storage, 40 GWh in 2010 [66]. The investment, variable and fixed costs are relative to those of a typical gas turbine for power balancing: \$520/kW, \$88/MWh and \$23/kWa [67]. That is, the positive and negative capacity percentages determine what part of total net load, conventionally covered by control power plants, and VRE infeed could be covered by DSM, respectively. Hence, they characterize the technical importance of the DSM sources for VRE integration. If a given cost percentage is less than 100%, then the DSM option is cheaper in that respect.

The DSM investment costs comprise the energy management system [32,51] and fixed costs the communication costs [51]. As to carbon emissions, the DSM measures do not cause any emissions during their operation, in contrast to gas turbines with a typical emission value of 450 g_{CO2}/kWh [68].

From Table 1 we see that night storage heaters are highly cost-competitive and can also provide significant capacity both in terms of power and energy storage. Heat pumps are also cost-competitive with gas turbines in terms of investment cost, but the capacity potential is limited. Both the night storage heater and heat pump strategies require coupling the DSM measures with the heating system. However, DSM capacity of the storage heaters and heat pumps diminishes at high ambient temperature when heating demand is low [64]. Synergies in energy management systems and communication could reduce both investment and fixed costs when the end-uses are combined.

Compared to the German case, DSM measures in Finland in the residential sector also offer a considerable potential for system flexibility. The majority of the potential, 23–29% of the winter peak load (in 2006), is in electric heating [69,70]. Wet and cold appliances contribute an additional 2.6% [69,70]. The dramatically increasing trend in heat pump penetration [71] brings about DSM potential due to cooling in the hot season, useful for e.g. solar electricity integration. Altogether the above DSM potential would be highly useful for large RE schemes.

Assessing the true potential for DSM in the residential sector also requires considering the behavior and decision making of consumers. Incentivizing investments and participation in DSM programs may require quite large gains from the measures as the share of electricity costs of a household's total income is quite low, for example in the USA in 2009, it was on average 2.8% of total income, and the savings from DSM (1996-2007) 2–30% of electricity costs [39]. Similar experiences have been reported in Finland where the consumers may be willing to pay a risk premium contained in the fixed electricity price contract instead of aiming for the minor savings [60]: average economic benefits of price-responsive demand compared to constant consumption were 1–2.4% (2001–2002) [72]. If the consumer has to cover the costs of required metering and control equipment, e.g. as part of smart metering or smart grid arrangements, the payback time without subsidies may get too long and discourage such schemes [39].

3.2.2 Service sector

The technical and economic potential of DSM in the service sector in Germany [32,64] is presented in Table 2 with the same type of information as Table 1.

The spread of the costs for DSM measures shown in Table 2 is large, but at the lower end of the costs, DSM could be highly motivated. Comparing to the capacity values in Table 1, the DSM potential in the service sector is much lower than in the household sector.

3.2.3 Industrial loads

The industry sector presents 42% of all electricity consumed in the world [73] and in some countries such as in Finland it is around half of all electricity used [74], in Germany 44% [75]. As an electric load, industries often represent a constant base load, in particular energy-intensive industrial loads which are large and centralized, and readily manageable by aggregators, utilities or system operators [57]. Such loads are already being used as reserves in Germany [33] and Finland [59]. Large-scale industrial loads are also price-responsive to some extent [59,76].

The DSM potential of industrial loads in Germany and Finland is reviewed in the following. The same industrial processes are most suitable for DSM in both countries. In addition, significant DSM possibilities have been found in calcium carbide production and quarries in Austria [77], and in oil extraction from tar sands and shale in USA [78].

The single industrial load types can only serve small parts of the total flexibility requirements. Variable costs tend to be lower for processes that can engage in load shifting, as there is no lost load; moreover, as the variable costs are normalized with respect to energy, they are the higher the lower the process energy intensity [33]. Fixed costs are negligible, as the load data is already monitored in real time [33]. Investment costs are also low, as the investigated industries already feature the necessary smart metering and data exchange equipment [33].

The investment costs are, with the exception of ventilation systems, minor compared to a gas turbine. This is contrasted by the variable costs, which are higher than those of a gas turbine with the exception of pulp refining. This suggests that industrial loads are economical as peak and reserve capacity [33] which is useful for VRE integration.

In the Finnish case, where energy-intensive industries have a major share of all electricity, the following estimates for the technical potential of industrial loads has been presented [59]: grinderies in pulp and paper industry 6% of the total peak load in Finland; electrolyses, electric arc furnaces and rolling mills in metal industry 2%; electrolyses, extruders and compressors in chemical industry 1%; and mills in cement, lime and gypsum production 0.04%. Some of the above flexibility has already been contracted as disturbance reserve to the transmission system operator (TSO).

A major challenge in realizing the DSM potential in the industries comes from the demand of running industrial processes on a continuous basis [59]. Also, lack of storage capacity may hamper the shiftability of loads [33], or if the production line is run according to the customer's plans [60]. In practice, as industrial processes are integrated across different industry sectors and businesses, co-operation between the different stakeholders will often be necessary to implement DSM.

The fact that many industrial customers either buy electricity directly from suppliers with long term fixed price contracts or they have financially hedged their electricity market price risk decreases both their price response and their interest towards DSM [60], analogously to the situation of residential consumers. Large industrial customers may also perceive participation in the electricity market as not part of their business, even though, as of 2007, their interest in the involved profit opportunities had steadily increased in the Nordic region [79].

3.3 Examples of DSM with renewable energy

The potential of DSM reviewed in the previous chapter is an estimate of the large-scale available potential, and is subject to limitations due to controllability of loads and behavior and decision-making of consumers. The effects of these limitations and the resulting actual applicable potential of DSM have been studied with field tests, DSM programs and modeling. DSM has been implemented quite extensively in the past, in particular as part of energy efficiency or peak shaving measures, but so far less in connection with VRE power schemes. In the next, we first present some conclusions from DSM field tests, programs and modeling studies which could be relevant to VRE and then shortly describe specific cases with DSM and VRE combined.

On a macro-level, existing DSM programs in the USA both at wholesale and retail level represent a 38 GW (5% of peak load [80]) potential for reducing peak load [81], approximately 90% of this potential provided by incentive-based programs. A time-of-use (TOU) pricing experiment in Pennsylvania gave a 14% reduction in demand with 100% price increase [50]. A peak load reduction of 42% was accomplished during critical peak periods in a critical peak pricing (CPP) experiment in Florida with TOU rates during normal periods, and automatic load response to price signal [50]. Another incentive-based DSM program with 14,000 customers run by NYISO has lowered the peak consumption by 50 kW/customer [50]. In a survey on utility experience with real time pricing (RTP) programs in the USA 12-33% aggregate load reductions across a wide price range were reported [50]. Peak load reductions of 16-34% have been reported in a survey of time-varying programs [82].

A dynamic pricing experiment in Finland on residential consumers showed that the consumption was reduced 13-16% during the peak hours with a peak-to-normal price ratio of 4:1, and 25-28% with a ratio of 12:1 [83], the load being in most cases shifted to off-peak periods [84]. The price response varied very much among the consumers [84]. Danish and Swedish experiences from single-family houses showed that up to 6 kW of shiftable load per house could be reached with DSM, and in Norway 1 kW reduction in electrical water heater and 2.5 kW in electrical hot water space heating loads has been reported [85]. A recent Finnish experiment with 3,600 electrically heated houses gave a 2 kW/house load reduction from DSM at peak conditions [85]. DSM employing building thermal mass in building cooling can also be effective: reducing the peak load by 25% and cost savings up to 50% has been reported in field experiments in the USA [62]. These examples demonstrate ca 10-50% flexibility margins which would be highly useful for a large-scale RE scheme, but also highlight the importance of an integrated view on electric and thermal loads.

Besides results from real DSM programs and field tests, the potential of DSM without explicit connection to VRE schemes has been dealt with in several modeling studies [62,86–92] yielding same kind of results as described above.

Most of the literature on DSM and VRE combined concerns residential loads. Paatero and Lund (2006) [93] developed a model for generating hourly flexible household electricity load profiles for VRE integration studies. Their case studies showed 42% and 61% of load reduction by controlling all the domestic appliances in response to loss of VRE supply during evening peak demand and in early afternoon, respectively [93,94].

Cao et al. (2013) [95] showed that it is both technically and economically more effective to store excess energy from PV and wind turbines in a detached house as thermal energy in a DHW tank than using batteries. The mismatch between load and VRE production was reduced by 13–23% through such a thermal storage DSM scheme.

Finn et al. (2011,2013) [35,96] studied optimal residential load shifting in connection with wind power. Optimal control for a residential water heater resulted in 4–33% cost savings and increased wind power demand by 5–26%. In case of a dishwasher, optimal control could increase wind power use by 34%.

Callaway (2009) [52] showed that populations of thermostatically controlled loads can be managed collectively to serve as virtual power plants that follow VRE feed-in variability. Zong et al. (2012) [97] developed a model predictive controller (MPC), based on dynamic price and weather forecast to realize load shifting and maximize PV consumption in an intelligent building.

At a single household level, DSM with VRE has, in addition to the aforementioned results, resulted in 27–141% energy cost savings and 35% capacity cost savings with PV (over 100% savings achieved by PV production export), controllable loads and energy storage [98], 20% energy cost savings and 100% peak energy reduction with job scheduling and energy storage [99], 10% cost savings and 11 pp increase in wind production and heat pump load correlation [100], a few percent increase in PV self-consumption increase with only appliance scheduling and no use of electric heating [101], 6 pp increase in yearly PV self-consumption and 38 pp decrease in mean daily forecast error with deferrable loads and battery [102], 5% decrease in diesel generator use in a wind-diesel-battery hybrid energy system with controllable loads [103], 8–22% energy cost savings with wind energy, load scheduling and a battery bank [104], 20.7% daily energy cost savings with PV, wind, appliance scheduling and batteries [105], and nearly 10% daily energy cost savings with wind, PV, controllable loads and an electric vehicle [106].

In residential microgrids, the following results have been reached with DSM and VRE: 45% energy savings and 49% reduction in purchased energy with thermal storage, heat pumps and batteries in a single building, 6-flat microgrid with PV [107], 7% daily operation cost savings with batteries and heat pumps in a 6-house microgrid with PV in each house [108], 18.7% cost savings and 45% peak load reduction with task scheduling, thermal storage and batteries in a 30-home microgrid with CHP, wind and a gas boiler [109], 18% cost reduction with controllable loads and energy storage in a microgrid with wind, PV and a microturbine [110], 38% power generation cost reduction with wind and a fast conventional generator in an isolated microgrid with controllable loads, with further cost reduction of 21% by improving wind prediction accuracy [111], 56% decrease in electricity cost with load shifting and 79% decrease with load shifting and batteries with PV and biomass in 100-household self-sufficient village [112] and significant reduction in conventional energy storage size to smooth power fluctuation in main grid connection in a microgrid with 1000 heat pumps, wind and PV [113].

Concerning VRE and industrial load DSM, Finn and Fitzpatrick (2014) [114] have shown a clear correlation between a lower average unit electricity price (AUP) and increased use of wind power by two industrial consumers. Shifting demand to a low price regime was shown to provide substantial benefits, while little increase in wind power consumption was obtained by only shedding load during peak prices. A 10% reduction in the AUP typically resulted in a 5.8% increase of wind power use. VRE and service sector DSM has been studied in the case of balancing biomass gasification generator variability with a university fitness center, which brought savings of 33% and 44% compared to natural gas or diesel, respectively, along with decreased losses in grid and carbon emissions [115].

The effect of DSM with VRE on distribution grids and larger systems has been studied broadly, with the following results: 20–24% reduction in generator startup cost [116], possibility to postpone generation capacity installation by 1–4 years in an island power system [117], 17% increase in wind power value and 13% decrease in conventional plant running costs [118], 15% of VRE capacity as shiftable load required in a distribution grid to keep voltage fluctuations below 5% [119], 58% less capacity required to stabilize grid frequency with DSM compared to generators [120], ability to balance wind overproduction up to 1.5 MW with a load and generator portfolio [121], peak-hour congestion reduction in EU transmission system with 17% VRE [122], 13% peak load reduction in the Portuguese power system with efficiency measures, 17% by additional peak load control [123], 10% increase in wind share of optimal generation mix in Denmark [124], reduced correlation between electricity price and net load [125], 1.08 pp reduction in distribution losses in a distribution system [126], 2–3% decrease in energy cost and 2 pp decrease in transformer overloading in Western Danish power system with 126% wind capacity of maximum load [127], frequency stabilization in an islanded distribution system [128], 30% daily cost savings in an island power system during high wind production and low demand [129] and effective voltage stabilization in a distribution line with wind production [130]. Diversity of loads is required to prevent controlled loads becoming unresponsive in case of high/low wind generation for an extended time period [131].

Integrating heat pumps to buildings in the German electricity market with high RE penetration of 36–47% can bring about system cost savings of \$33 to \$52 per heat pump per year, along with CO_2 emissions reductions [132]. However, the change in building heat profile may lead to efficiency loss and increase electricity demand. Industrial DSM in the German electricity market with major RE share from 2007 to 2020 can provide cumulative system cost savings of $625 million, with avoided investment costs of $442 million, equivalent to two typical gas turbine plants [33]. The total DSM potential (incl. residential, service, and industrial sectors), together with improved wind power prediction, would result in additional balancing costs of less than $2.6/MWh for 48 GW wind power in Germany in 2020 [133].

One of the most notable on-going projects of combining DSM and VRE is the EcoGrid EU in the island of Bornholm in Denmark [134]. More than 50% of the energy consumption will be produced by wind power and other VRE sources, and more than 10% of the local households and companies will engage in DSM [135].

To conclude, studies of DSM in connection with VRE schemes show on average around 20% cost reduction and 10–20% increase in VRE consumption due to DSM, in some cases combined with energy storage. The feasibility and benefits of effective frequency and voltage stabilization by DSM have also been shown. Good results achieved with electric heating schemes reflect again the potential of integrating electric and thermal loads.

4 Grid ancillary services

With increasing variable renewable power production, system stability issues will become more likely [22] which can be mitigated through grid ancillary services. These services are generic in nature, i.e. not necessarily bound to RE power use.

Grid ancillary services involve different time scales and requirements with regard to power and energy capacity. For example, a *power quality* service has to provide rapid response, but only for a short duration, so it is a power-intensive service. On the other hand, *load leveling*, is an energy-intensive service that provides long duration, but can respond more slowly. Because of the varying nature of the required services, optimal grid-integration of RE will most likely involve several different ancillary services.

The grid ancillary services are presented more in detail in the following by dividing these into four categories based on their time response (see Table 4).

4.1 Very short duration: milliseconds to 5 minutes

4.1.1 Power quality and regulation

Power quality and regulation is a power-intensive ancillary service that is characterized by a rapid and frequent response and very short duration. It is used to balance fluctuations in network frequency and voltage that arise from variations in wind and solar generators' output, along with their distributed nature [138]. A too sharp deviation can damage equipment, lead to tripping of power generating units, or even to a system collapse [139,140].

4.1.1.1 Energy storage for power quality and regulation

Energy storage can be used to mitigate these effects [141]. The storage systems are best suited for this service due to a rapid response time and high power ramping rate, as the fluctuations require action within seconds to minutes, and a high cycling capability, because continuous operation is required. A large storage capacity is here unnecessary as over 80% of the power line disturbances last for less than a second [142]. Therefore, batteries and especially supercapacitors, flywheels and superconducting magnets are among the best storage options for improving system stability [140,143–145].

Nevertheless, flywheels seem to be the most economical option. According to Breeze (2005), flywheels are one of the best and cheapest ways of maintaining power quality, having a capital cost of $2,000/kW [146]. Makarov et al. (2008) concluded that flywheels and also PHES are economical storage technologies for reducing regulation requirements [147].

Wind power plants may be able to provide power quality and regulation service with a form of inertial response based on the active control of their power electronics [138]. Even though this mechanism has its limitations, it may lower the value of an energy storage used solely for this purpose [22]. This view is shared by a NERC report which claims that storage may not be a good replacement for the traditional stability services (system inertial response, automatic equipment and control systems), unless it also provides other grid services [22,78].

4.1.1.2 DSM for power quality and regulation

Shiftable loads are excellent candidates for providing balancing support, as the mean of the forecast errors of VRE is close to zero [34]. Loads can be used for frequency stabilization in a decentralized fashion with frequency-responsive loads, analogously to frequency-responsive generators, or with centralized control, which facilitates the restoration of system frequency to its nominal value [34]. Large motor loads provide natural inertial response analogously to rotating generators [78].

Short et al. (2007) [120] studied decentralized frequency stabilization with a population of frequency-responsive domestic refrigerators. Their simulation showed that such an aggregation of loads can significantly improve frequency stability, both for a sudden demand increase or generation decrease and with fluctuating wind power.

Callaway (2009) [52] showed that thermostatically controlled loads can be managed centrally to follow wind power variability in 1-minute intervals. Kondoh et al. (2011) [148] analyzed direct control of electric water heaters (EWHs) to following regulation signals and estimated that 33,000 EWHs corresponded to 2 MW regulation over a 24 h period.

4.2 Short duration: 5 minutes to 1 hour

4.2.1 Spinning, non-spinning and contingency reserves

Spinning reserve refers to online power generation capacity synchronized to the grid having a short response time for ramping up but enabling several hours of use. They are generally used in contingency situations such as major generation and transmission failures [136]. Spinning reserves are restored to their pre-contingency status using replacement production reserves that should be online 30–60 minutes after the failure [136]. *Non-spinning reserve* is similar to spinning reserve, but without immediate response requirement. However, these reserves still need to fully respond within 10 minutes [78].

Performing a spinning reserve service requires both a rapid response time and a large capacity for storing energy. According to Rabiee et al. (2013), suitable technologies are batteries and flow batteries, hydrogen, CAES and PHES [144]. Flywheels and SMES are also listed, but according to NERC (2010), they may not be able to provide sufficient long response [78].

As loads can shed very quickly, DSM is well-suited for reserve provision. Shiftable loads are in particular very suitable as the duration of the reserve provision is often short enough so that the load process is not disrupted [34]. Moreover, reserves are infrequently required [78]. Large industrial loads are already used as disturbance reserves in Germany [33], in the Nordic electricity market [59], and in several other markets [22,34]. In the Nordic and Texas markets, almost half of the contingency reserves comes from different loads [22]. The control of these large industrial loads, however, is in many cases quite simple, either manual [34,149] or through underfrequency relays [34]. Third party aggregators with more advanced control concepts are entering reserve markets, however [34].

O'Dwyer et al. (2012) found significant potential in DLC of residential loads for reserve provision: 42% of the maximum reserve requirement in Ireland and North Ireland [42].

The addition of a 1,600 MW nuclear power plant at Olkiluoto in Finland, in combination with increasing wind capacity in the Nordic market, will increase the need for reserves in both Finland and the whole Nordic electricity market [79]. Loads are seen as economically competitive compared to e.g. gas turbines to provide these ancillary services [79].

4.2.2 Black-start

Black-start describes the starting-up of a power plant after a major grid failure. The startup process requires some initial power input before the plant begins sustaining itself, and therefore an external source of power is needed. PHES can provide this initial power [150,151], while CAES has also been proposed [152].

The duration of the black-start ancillary service ranges from 15 minutes to 1 hour and the minimum annual number of charge-discharge cycles is around 10 to 20 [153]. It should be noted that some black-start generators may need to be black-started themselves [150].

4.3 Intermediate duration: 1 hour to 3 days

4.3.1 Load following

Load following is a continuous grid service that is used to obtain a better match between power supply and demand. Energy storage can be used for this purpose, by storing power during a period of low demand and injecting it back into the grid during a period of low supply [141]. Batteries and flow batteries, hydrogen, CAES and PHES are well-suited for this application [78,144].

4.3.2 Load leveling

Load leveling with energy storage refers to the evening-out of the typical mountain and valley-shape of electricity demand. As with load following, energy is absorbed during periods of low demand and injected back to the grid during high demand [141]. This allows baseload power generators to operate at higher efficiencies and also reduces the need for peaking power plants.

Load leveling services are designed for time intervals from 1 to 10 hours. Because wind speeds tend to be higher at night-time, the benefits can be greater for wind-heavy systems [154]. This ancillary service can be provided by flow batteries, CAES, hydrogen and PHES [78,144], as all of them can handle large amounts of energy. Rabiee et al. also include batteries in this list [144]. Load curtailment during peak hours has been exercised by utilities for decades [34].

4.3.3 Transmission curtailment prevention, transmission loss reduction

Transmission curtailment prevention and *transmission loss reduction* are ancillary services that temporarily reduce the amount of current flowing in certain parts of the power grid, increasing the efficiency of transmission and preventing production curtailment due to power line limitations.

With much renewable energy production and no means of storing excess power, power production may need to be curtailed (cut off) to ensure system stability or due to limitations in transmission infrastructure. However, with energy storage, the power plants may continue harvesting energy even while being disconnected from the rest of the grid. Renewable power is injected into the energy storage system instead of the grid, and when the grid is ready for the dispatch, the storage is discharged. The duration requirement for such measures ranges from 5 to 12 hours.

An alternative is, of course, the increase of transmission capacity [13], but in some cases energy storage might be more economical, or even the only possible solution due to e.g. environmental and social concerns. Greater economic advantage may be gained in power plants that have access to different markets (e.g. spinning and non-spinning reserve markets) [22,155,156].

Storage also allows increasing the efficiency of transmission. Because transmission losses are proportional to the square of the current flow, the net resistive losses can be decreased by time-shifting some of the current from a peak period to an off-peak period, even when accounting for the losses due to storage. Also, during off-peak periods, temperature and therefore resistance are typically lower, yielding additional efficiency gains [41].

Suitable technologies for these applications are ones that are able to store large amounts of energy, particularly flow batteries, CAES, hydrogen and PHES [144].

4.3.4 Unit commitment

Unit commitment service refers to energy reserves that are used to manage errors and uncertainties in the predicted wind and solar output. For example, there might be an unforeseen shortage of wind for several days, requiring substitutive power to be supplied by discharging an energy reserve. The required duration ranges from minutes to several hours to days [156].

The ideal energy storage technology in this case is one that has a rapid response time, quick ramp-up and a large energy capacity. Thus, CAES, PHES and hydrogen are suitable for this application [78,144].

Competition has increased in DLC for unit commitment and economic dispatch by aggregators who bid load curtailment [34]. DSM may also be used to balance forecast uncertainty in energy procurement scheduling to local energy systems with VRE generation [157].

4.4 Long duration: several months

4.4.1 Seasonal shifting

In *seasonal shifting,* energy is stored for up to several months. Seasonal shifting is most useful in systems with large seasonal variations in power consumption and generation. This service requires extremely large energy capacities, inexpensive storage medium and low self-discharge, making large PHES and gas storage the most suitable technologies [144,156,158].

To obtain some sense of scale, Converse (2012) estimated that shifting enough wind and solar power to supply the U.S. with electricity for a year would require a storage in the range of 10% and 20% of annual energy demand [18]. Tuohy et al. (2014) point out that this study did not consider production uncertainty [22].

Tuohy et al. (2014) [22] cast doubts on using DSM for seasonal shifting, as it is unlikely to have a long-term effect. While this holds for shifting consumption of most single loads, long-term DSM could be realized by leveraging different options for providing the end-use function. This is already visible in the form of a much higher long-term than short-term price elasticity of electricity [31]. E.g. heating DHW with gas during winter and with electricity during summer could even out the seasonal differences in electric heating, but the additional investment in multiple options might be uneconomical. Also, the production of products for which the demand follows a long-period cycle, e.g. storable holiday goods, could have long-term DSM potential.

5 Energy storage

Energy storage is used to time-shift the delivery of power. This allows temporary mismatches between supply and demand of electricity, which makes it a valuable system tool. Energy storage has recently gained renewed interest due to advances in storage technology, increase in fossil fuel prices and increased penetration of renewable energy [150]. In previous chapters, the usefulness of storage for ancillary services was already mentioned. In this chapter, we will present different storage technologies and a few additional energy system aspects.

Energy storage technologies are basically characterized through their energy storage and power capacities. A higher storage capacity allows the storage to respond to longer mismatches, while a higher power capacity allows responding to mismatches of higher magnitude.

There are a number of different technology options for energy storage, some of which are better suited for providing just one type of capacity (e.g. power), while some are more flexible and can provide both power and storage capacities to a some extent. However, no storage system can simultaneously provide a long lifetime, low cost, high density and high efficiency [145] meaning that a suitable storage technology needs to be selected on a case-by-case basis [159]. Here we consider pumped hydro power energy storage (PHES), compressed air (CAES), flywheels, batteries, hydrogen, superconducting magnets and supercapacitors.

5.1 Applications

Energy storage has the potential to increase both the energy and economic efficiency of the power system. During a period of low energy demand, storing energy allows baseload power production to continue operating at high efficiency and during a period of high demand, allows use of stored energy instead of peaking power with high marginal costs [160].

All energy conversion processes are accompanied by conversion losses, so an energy storage facility is a net consumer of energy. However, taking advantage of the price difference of electricity, e.g. the difference between day-time and night-time electricity, allows energy storage facilities to generate revenue (*energy arbitrage*).

From the renewable integration standpoint, energy storage is an essential component [159], as wind and solar power are impractical for baseload power production. Furthermore, if additional fossil fuel-based generation is required to compensate for this variability, the effectiveness of renewables in reducing the total emissions diminishes [161–163]. With an energy storage, this variability can be greatly reduced [164]; indeed, energy storage may be the “ultimate solution” to the problem of variable generation [165].

However, in some cases, energy storage may actually *increase* the overall CO_2 emission levels. This can happen e.g. in the Dutch and the Irish power system, where energy storage allows storing power from cheap coal plants, substituting expensive gas during peak demand [160,166].

There are two main engineering approaches of integrating an energy storage system with variable renewable generation. The first is to locate the storage along the point of generation and tie its operation to this individual facility. This method, while considerably easier to model and study, also severely limits the potential utility. To maximize operational flexibility, the storage should not be limited to just one power plant if possible. Furthermore, integration with an individual plant prevents the storage from benefiting from the geographical smoothing effect, which may lead to uneconomical and inefficient operation. Therefore, as a general rule, the second approach of using the energy storage as a system-level flexibility resource, is more sensible both from an economical and efficiency point of view. The exceptions to this rule are the cases where significant benefits are gained from sharing a location, e.g. in a concentrating solar power plant it is sensible to locate the thermal storage near the site of generation. Another example is avoiding transmission upgrades to a remote wind resource [22,150,154,156,167].

The remainder of this section outlines the different storage technologies. For each technology, the main characteristics are described first and after this, renewable integration studies on this particular technology are covered.

5.2 Storage technologies

The most mature storage technologies are pumped hydro, compressed air and lead-acid batteries [141], but other well-known technologies, namely, flywheels, hydrogen, superconducting magnets and supercapacitors are also considered in this study. PHES is by far the largest energy storage technology available, accounting for 99% of the world’s total storage capacity [22],

5.2.1 Pumped hydro

In pumped hydro (pumped hydro energy storage, PHES), electricity is stored by pumping water to a higher gravitational potential, e.g. to a lake on the top of a hill. Electricity is later recovered by releasing the water to a lower reservoir through a hydro turbine. Over 300 PHES plants have been installed worldwide [151].

A PHES plant requires a location with adequate elevation difference and access to water flow and to an electricity transmission network. PHES does not require a natural elevation difference, as it is possible to dig an underground reservoir, while building the upper reservoir on the surface [168]. Some locations allow using the ocean as the lower reservoir, as in Okinawa Island, Japan [169].

PHES has two operating phases, pumping and generating phase and can operate on different time scales from less than a minute [170] to seasonal cycles [151]. The energy storage efficiency is around 65–85% [171–174].

PHES is a mature technology and it has been applied in large-scale with renewable power generation, e.g. in Portugal, where, 220 MW of reversible hydro power plants are used to support wind power generation [175]. Several simulations have demonstrated the potential of on wind-hydro schemes at a low cost [176–178].

Future development of PHES include e.g. artificial islands with underground reservoirs [179], ocean renewable energy storage [180], gravity power systems with two vertically parallel water reservoirs of which one is acting as a piston [181], and rail energy storage moving a heavy mass uphill on train tracks [182].

5.2.2 Compressed air

Compressed air energy storage (CAES) is the second largest form of energy storage in use. The working principle is based on compressing air to higher pressure, e.g. in an underground salt cavern or steel pipe, or even under the sea [183]. When extracting energy from CAES, the stored air is generally mixed with fuel, combusted and expanded through a turbine or series of turbines [78,140,144]. Basically, CAES is a gas turbine with the compressor and expander operating independently and at different times [184].

Two large CAES plants have been built: one in Huntorf, Germany (290 MW) and the other in Alabama (110 MW) [185,186]. Losses mainly occur during compression, but also if stored air is reheated. Elmegaard et al. (2011) reported a 25–45% efficiency for a practical CAES plant [187], while e.g. Greenblatt et al. (2006) estimated a typical CAES efficiency of 77–89% [188]. According to Elmegaard et al., the efficiency of an adiabatic CAES, in which the heat in the process is stored in a liquid or solid, is around 70–80% [187]. The environmental impacts from CAES are small [158]. Some authors have proposed a CAES plant to replace natural gas with hydrogen or biofuels to reduce emissions [189,190].

The economics of CAES has been a problem in the past but it is expected to change with higher natural gas prices and increased renewable penetration [164]. Sundararagavan et al. (2012) claim that CAES has the lowest storage system cost for load-shifting and frequency support [140]. Rastler (2008) concludes that CAES, offering a shorter construction time of 2–3 years and a better siting flexibility, appears to be a cost-effective storage alternative to PHES [164]. This claim is advocated by Kondoh et al. (2000), who estimated the capital costs for CAES to be lower than for PHES [145]. The economics of CAES with RES is improved if arbitrage and ancillary services are considered [191]. In the Danish electricity system, CAES is not an economically attractive choice for excess wind electricity production, unless it can defer investments in generation capacity [192]. However, in Germany, CAES can be economic under certain wind penetration levels. [193].

As to integration with renewable power, CAES plants are suitable for preventing wind power curtailment and for time-shifting energy delivery [78]. For example, the Huntorf CAES plant has been successfully used to level variable wind power [194]. Several simulations reaffirm that CAES is capable of smoothing fluctuating wind power [195], increasing wind power penetration [188], while meeting loads, reserve requirements and emission constraints [154]. However, in the Danish energy system, CAES may have problems with absorbing excess wind [196].

5.2.3 Hydrogen

Hydrogen can be used as a chemical storage for electric energy. A hydrogen-based electricity storage system consists of three main components: an *electrolyser* that produces hydrogen from water with electricity; an electricity-producing *fuel cell* that does the reverse; and a separate hydrogen *container* [171,197].

Hydrogen has a high energy capacity of 122 kJ/g, around 2.75 times greater than hydrocarbon fuels [198], though it has a low volumetric energy capacity due its low density. Hydrogen can be stored as compressed gas [199–202], cryogenic liquid [202], in solids (metal hydrides, carbon materials) [203] and in liquid carriers (methanol, ammonia) [171], though large-scale hydrogen storage is still challenging and expensive. Converting hydrogen to electricity in a fuel cell produces only water vapor as a side product. If clean energy sources are employed then the whole storage cycle could be environmentally friendly [204].

A major problem with hydrogen electrical storage round-trip efficiency which remains at 35-50% [146,205]. In a demonstration project with hydrogen storage, wind turbines, photovoltaic panels and micro-hydroelectric turbines in the U.K., the round-trip efficiency achieved (electricity-hydrogen-electricity) was only 16%, which “plainly highlights the limitations of using hydrogen for energy storage” [206]. On the other hand, a major benefit over e.g. batteries is that the power rating and storage capacity of the system can be separated enabling also a long-term electrical storage capability.

Several studies on hydrogen electrical storage indicate its potential usefulness for integrating renewable power generation [207]. First real hydrogen electrical storage systems with PV were piloted in the early 1990s [197]. In Norway, a full-scale combined wind power and hydrogen plant has been in operation since 2005 [208,209]. A similar demonstration called PURE in the island of Unst, Scotland started in 2001 [210]. In Germany, the PHOEBUS demonstration plant supplied photovoltaic power to part of the local Central Library for 10 years [211].

Hydrogen is sometimes linked to the hydrogen energy economy in which hydrogen would be the one of the main energy carriers, enabling the shift to a carbon-free energy system. The hydrogen economy would definitely have a strong link to renewable power integration, but the whole concept is still highly debatable and not yet realizable, there being several pros and cons involved [201,206,212–215].

5.2.4 Batteries

A rechargeable electrochemical battery, or a secondary battery, is a chemical energy storage based on two electrodes with different electron affinities. When a battery is discharged, electrons spontaneously move “downstream” to the electrode with higher affinity. When it is charged, an external voltage is applied to force electrons “upstream” to the electrode with lower affinity. A lithium-ion battery operates on a slightly different principle as here lithium ions are intercalated into the electrode materials and they are transported back and forth (along with electrons in the external conductor) during charge and discharge. [216].

There are many different battery technologies available, based on their chemical properties. Each battery type has its own advantages and disadvantages in terms of energy and power density, efficiency and cost. As most batteries have self-discharge losses as well, they are mainly feasible for short-term storage. Another disadvantage is that their performance reduces with increasing number of cycles. The capital cost and replacement cost of batteries dominates the cost of stored energy with batteries, while operation and maintenance costs are much less significant [217].

Batteries have near-instantaneous response times, which is a valuable feature for improving network stability [146] e.g. with renewables. The main use is providing power quality, short-term fluctuation reduction and some ancillary services or transmission deferral [22,78]. Batteries are modular in size enabling flexible siting e.g. close to load or production, or even changing location over the life-time [22].

Batteries for integrating variable renewable generation are already in use. For example in Futumata, Japan, a 51 MW wind farm is supported by a 34 MW sodium-sulphur-battery [218]. The benefits of a battery for PV and wind have also been verified through simulation studies [219–221].

Next, different battery types are briefly described and compared, while the key parameters are shown in Table 5 [222].

Lead-acid battery is a mature battery technology that has been used for decades in the vehicle industry [144]. They have the lowest cost per unit energy capacity, but also low specific energy [223].

Nickel-cadmium battery is also a mature technology, but has a higher energy density than lead-acid and is robust to deep discharge and temperature differences [141]. Unfortunately, Cadmium is highly toxic, the cell voltage is low and the battery is subject to memory effect [223,224].

Nickel-metal hydride battery is a variant of nickel-cadmium and is used in consumer electronics and electric vehicles [171]. The energy density is higher and there are no toxic materials, but the self-discharge rate is high and there is a dependency on rare earth minerals [141].

Sodium-sulphur battery is a high temperature battery that operates at 300–350°C. They have low maintenance requirements, can reverse quickly between charging and discharging and can also provide pulse power [141]. The disadvantages include the need for heating when the battery is not in use, corrosion problems, and safety issues due to volatile constituents [171,223].

Sodium-nickel-chlorine (also known as *Zebra*) battery is also a high-temperature battery with an operating temperature of 300–350°C [141]. They are safer than sodium-sulphur batteries and are robust to overcharge and overdischarge [171,223].

Finally, the *lithium-ion* battery is deployed widely in the market for small appliances. They have high efficiency, good energy density and low self-discharge rate. For the moment, though, they are still expensive for large-scale power [141,225].

Flow batteries are a special type of battery resembling a reversible fuel cell. In a flow battery, the electrolyte is stored in separate tanks external to the electrochemical cell that converts electricity to chemical energy and vice-versa. The power capacity is determined by the area of the electrode, while energy capacity is determined by the volume of the electrolyte [171]. As these parameters are independent of one another, power and energy are decoupled, allowing greater flexibility in design as in the hydrogen-electricity storage concept. Commercially available flow battery chemistries include vanadium, zinc bromide and polysulphide bromide, also called *redox* flow batteries [144]. Though not yet in larger use [78], megawatt-hour-scale flow battery projects have been developed by e.g. Prudent Energy [226]. Banham-Hall et al. (2012) has studied vanadium redox flow batteries as part of a wind farm concluding that vanadium redox flow batteries could provide frequency regulation and shifting of power [227]. Wang et al. (2010) also found that vanadium redox batteries can smooth the power output of a wind farm, in addition to providing reactive power to the grid [228].

5.2.5 Flywheels

Flywheels store energy in the angular momentum of a fast rotating mass, made e.g. of an advanced composite material such as carbon-fiber or graphite [244]. The flywheel is connected to an electric motor and generator for electricity-kinetic energy-electricity conversion. To minimize friction losses, special magnetic bearings are used and the flywheel may be put into a container with low-friction gas such as helium [146,171].

Flywheels have a long life with virtually zero maintenance and infinite recyclability, high power and energy densities [78,144] and a rapid response time [146]. They are resistant to temperatures and deep discharge and have simple charge level monitoring [245]. The efficiency at rated power is also high, around 90% [78,144,159]. Disadvantages include modest energy capacity [171], high self-discharge rate on the order of 0.5% of stored energy per hour [246] and safety issues due to high-speed moving parts [245].

Flywheel energy storage can improve power quality and minimize fluctuation of wind power [139,236,247]. If connected to a variable-speed wind generator, a flywheel can smooth the power delivered to the grid or control the power flow to deliver constant power [248]. A flywheel energy storage system could be highly capable of stabilizing network frequency and voltage [249].

Flywheels may compete with chemical batteries as both are mainly suitable for frequent short-term charge and discharge [142,171]. A flywheel has an advantage through a longer lifetime [139,140] and its power is not limited by the electrochemistry but rather by the power electronics. The energy-specific cost of a battery is generally lower, but the power cost is higher than in a flywheel storage system [140].

5.2.6 Superconducting magnetic energy storage

In a superconducting magnetic energy storage (SMES), electricity is stored in a magnetic field generated by a direct current flowing in a large superconducting coil. One could describe SMES as an inductor with superconducting windings [250]. Energy is added and extracted simply by increasing or decreasing the current flow. As long as the coil is superconducting, no energy is dissipated [250]. Therefore, energy losses would occur only during AC/DC conversions. The response time is around 20 milliseconds [146] and the round-trip efficiency is high, around 90% [141,146]. SMES systems have high durability and reliability with low maintenance requirements [141,250]. The downsides include very high cost, around \$2000–3000/kW, and the requirement to be kept at very low temperature to maintain superconductivity [141,146].

SMES can be used for short-duration storage, e.g. for power quality and small-sized applications [141,145]. Feasibility studies of SMES for high wind penetration in a microgrid have shown significantly enhanced dynamic security and stability of the power system [251].

5.2.7 Supercapacitors

Supercapacitors or ultracapacitors store energy in the electric field produced by a separation of charges. In an electrochemical double layer capacitor, electricity is stored using ion adsorption. In a pseudocapacitor, electricity is stored through fast surface redox reactions. Hybrid capacitors combine both capacitive and pseudo-capacitive electrode with a battery electrode [252].

Supercapacitors have exceptionally high efficiency, good tolerance for low temperatures, very low maintenance requirements, fast response time, extreme durability and high specific power. However, they can only provide electricity for a very short time period (minutes), have high per-watt cost and self-discharge and low specific energy [68,141,229].

Supercapacitors have a potential in suppressing short-term fluctuations in wind power output [253,254], but for longer-term smoothing, they may need to be combined with other energy storage options such as batteries. Li et al. (2010) found that including a supercapacitor in a flow battery-wind-system lowers battery cost, extends battery life and improves overall efficiency [255]. In a battery-solar-system, supercapacitors may reduce the capacity requirement for the battery while increasing its lifetime [256].

5.3 Power vs. discharge time characteristics of different electric storage technologies

The choice of the electric storage technology has to be done on a case-by-case basis as there is no universal technology solution available. One way to screen out suitable storage options for an application, e.g., for RE power, would be to consider the characteristic power and discharge times of storage technologies as shown in Fig. 2.

PHES and CAES technologies are characterized by high energy and power capacities, but they are site-dependent and meant for large applications. SMES, supercapacitors and flywheels have a very fast response time, their use is not bound to a site, but their energy capacity (or discharge time) is limited. Batteries can be considered as a kind of bridging technology between bulk storage and high-fidelity storage, e.g. for applications in which flexibility is desirable. Unfortunately, batteries are currently limited by their short operational lifetimes.

6 Supply-side flexibility

The power balance of electric systems is normally handled by the supply side (e.g., power plants). With supply-side flexibility, we mean measures or technologies through which the output of power generation units can be modified to attain the power balance in the grid, e.g., when large amounts of variable RE power is in use.

6.1 Power plant response

Power plants are divided into three categories based on their flexibility: base load, peaking, and load following power plants. Base load power plants (e.g., coal, nuclear) are run at almost constant power, preferably at nominal power level. Ramping or shut-down of base load power plants is avoided due to economic and sometimes technical reasons. Peaking power plants are used irregularly, e.g., during high demand. Load-following plants balance demand and supply at each moment. Hydropower and gas turbines are typical examples in this category. The start-up or ramping response is very quick from seconds to some minutes. Table 6 summarizes key indicators of different power plant technologies including flexibility characteristics. [68]

Fig. 3 shows typical start and ramping response of different power plant technologies also relevant for RE power integration. Gas engines have the fastest cold-start response and could reach full power within some minutes, combined-cycle gas turbines may need 1–2 hours and base load steam plants several hours, respectively.

6.2 Curtailment

A simple way to regulate large amounts of VRE power in the energy systems would be curtailment, i.e., limiting the power output. Situations in which curtailment may be necessary include limited transmission capacity [257], oversupply of VRE power, and too large share of inflexible base load generators. Curtailment is also applicable to dampen quick changes in power output by rapidly reducing generation, or it can provide reserve power capacity through a ramp-up margin [36,258].

Curtailment means always losing some electricity, but could be avoided if overall power system flexibility were increased, e.g., with less must-run base load power plants in the system or using load-shifting if the VRE power share is very high [29]. On the other hand, as the capacity factor or VRE is much less than 1, the loss of electricity produced is not proportional to the power curtailed. This is well demonstrated by Fig. 4 which shows the yearly electricity loss versus curtailment for a PV system in Finnish climate: e.g., an average curtailment of PV power by 40% leads on a yearly level to 10% loss in PV electricity produced.

Curtailment for PV systems is in practice realized through the inverters either as on-off control or droop control, where the PV production is gradually reduced [259,260]. Several studies are available on the effects of PV curtailment [261–265]. Tonkoski and Lopes (2011) [260] further discuss active power curtailment (APC) techniques in residential feeders to even out the curtailment needs among all households along the feeder.

In case of wind power, network congestion is often the reason for curtailing wind power [266]. With higher wind shares, supply and demand mismatches are frequently the reason for curtailing. Curtailing wind power is technically simple and it can be based on different criteria such as mutual agreements and regulation [257]. Several studies have analyzed the role of wind power curtailment in the national power systems, e.g., Ireland [267], Germany [257,268], Spain and the USA [257,269]. Practical experiences with wind power also demonstrate the use of curtailments, e.g., in Germany, 1% of the wind energy produced was lost for this reason due to problems with regional distribution networks and transmission-level bottlenecks [268].

6.3 Combined-cycle gas turbines

Combined-cycle gas turbines (CCGT) [270] are an attractive option to increase the energy supply flexibility. A CCGT have typically a ramping rate of 10 MW per minute [36]. The investment cost is low and the efficiency is high up to 60%. [271,272]. The CO_2 emissions are only half of those of coal-fired plants. A major drawback for CCGT is the high fuel cost [273], which may decrease the attractiveness of CCGT as a balancing power and marginalizes its use in the electricity markets. Combining a gas and VRE system could be quite attractive as such [274–277] to compensate for VRE power fluctuations.

6.4 Combined heat and power (CHP)

Combined heat and power (CHP) plants produce simultaneously heat and power leading to a high overall conversion efficiency (>80%) [278,279]. Combining RE and CHP offers several advantages, e.g., when combined with thermal storage that enables load shifting. Furthermore, combining different technologies in a CHP plant (e.g., gas engines, heat pumps, heat storage, peak-load gas boilers, electric boiler) could increase the inherent flexibility of CHP [280–285].

7 Advanced technologies

In the next, we present future strategies for dealing with large-scale RE schemes in which surplus RE production is utilized for different purposes, i.e., combining new loads to the power systems such as heating or cooling demand, electric vehicles and power-to-gas schemes. In this way, wasting the electricity from curtailment of RE power could be reduced or even avoided.

7.1 Electricity-to-thermal (E2T)

In an electricity-to-thermal (E2T) strategy, excess renewable electricity is converted into thermal energy, either for heating or cooling purposes [286]. Generally, the demand of thermal energy dominates the final energy use, and it is also easier to store thermal energy than electricity.

An E2T option adds flexibility to the power system, and reduces emissions from heating plants if it replaces heat production from fossil fuels. Some studies show that E2T could significantly increase the useful share of RES, even 2–3 fold the self-use limit for RE power [20,287–289].

The main technologies needed for E2T are electric boilers, pumps and to some extent thermal storage [20,290,291]. E2T can be very efficient [160,291] and economical, too [290,291]. As a real-world example, Jilin province in China has used curtailed wind power to replace coal-fired heating [292].

7.2 Power-to-Gas (P2G) and Power-to-Hydrogen (P2H)

Having excessive electricity available enables also to produce high-value energy products such as hydrogen (through electrolysis or photoelectrolysis) and synthetic methane (through H_2 and the Sabatier process in which CH_4 and H_2O are catalytically produced from CO_2 and H_2) [293–295].

Pure hydrogen production from RE power could also be seen as a sort of power storage as H_2 can be converted back to electricity in fuel cells or by combustion power plants. Synthetic CH_4 from RE could employ the gas distribution systems which has a large storage capacity (e.g., in Germany, it is over 200 TWh) [293]. Also hydrogen to some extent could be transported in these systems [296]. Several studies have envisioned P2H as part of a hydrogen economy [297,298], or part of the transportation system [299]. Gahleitner [300] gives a good review of P2G pilot plants under planning or operation. Typically most of these plants use wind or solar power. Combining different energy carriers into an energy hub to provide more flexibility for large-scale RE power has also been presented [287,301–304].

7.3 Vehicle-to-grid (V2G)

Electric vehicles could provide a distributed, moving energy storage service in addition to the stationary options discussed above. Using electric vehicles (EV) or plug-in electric vehicles (PEV) for active energy storage linked to the grid is called *vehicle-to-grid* (V2G) strategy.

Most of its time, a vehicle is idle and thus offers an option for charging or discharging if equipped with a battery [305]. The charging window of EVs and PEVs is relatively long, 8–12 hours, and the charging duration relatively short, around 90 minutes, offering considerable flexibility [78].

V2G could include services such as scheduled energy, power quality, reserve power, regulation, emergency load curtailment, energy balancing, and RE integration [306–309], but requires the suitable equipment (e.g. telemetry, two-way communications) and the assistance of aggregators [78,310] that lump several PEVs together to achieve the required scale. Some services may require discharging of the battery, which causes additional loss of cycle life [311] and an economic disadvantage [312]. Varying the charging power while keeping it positive allows PEVs to provide demand response and grid reliability services without causing additional wear to the battery [78]. Different smart charging schemes may be employed to minimize adverse effects from V2G to the energy system or battery [308,309,313,314].

V2G services could directly assist integration of renewable power. Kempton et al. (2005) calculated that V2G in the U.S. could stabilize large-scale (50% of U.S. electricity) wind power with 3% of the vehicle fleet dedicated to regulation for wind and 8–38% to provide operating reserves or storage [315]. Ekman (2011) investigated the effects of different charging strategies on the balance between wind power production and consumption in a future Danish power system. Ekman finds that increased PEV penetration will reduce the excess of wind power, but PEVs alone will not be sufficient to fully utilize the wind power potential. Other balancing mechanisms will be needed if the wind penetration exceeds 50%

[307]. Kaewpuang and Niyato (2012) inspected power management in a smart grid network with multiple energy resources, including wind. They concluded that energy generation from conventional power plants can be apparently reduced using PEV integration, while also reducing the overall generation costs [316]. In domestic applications, Yoshimi et al. (2012) find that V2G can be used to increase the rate of utilization of PV-generated electricity, cut CO_2 emissions and lower the costs of purchased electricity [317].

8 Infrastructure

8.1 Grid infrastructure

Sufficient transmission capability is essential for power system flexibility [67,318]. Robust and well-designed grids with appropriate grid codes [258] can balance large local differences in supply and demand, offering strong spatial interconnections. Furthermore, well-functioning energy markets need well-functioning transmission lines. Three future developments in grid infrastructure, namely supergrids, smart grids, and microgrids will be discussed here.

8.1.1 Supergrids

Supergrid is a strong network of transmission lines typically incorporating at high-voltage direct current (HVDC) technology [319–324]. Such a grid is capable for connecting remote RE power sites with demand. HVDC transmission lines have already been realized in subsea cables, but not yet in intercontinental context where high voltage AC would still dominate. Main challenges with HVDC are related to installation, technical standards, interaction with AC grid, and operational principles [319,320,324].

There are several studies envisioning supergrids in connection with VRE, e.g., wind power in the North Sea [321,325,326], the DESERTEC project to connect large solar and wind farms in North Africa and Middle East with Europe [321,327,328]. The USA has planned a project to import large-scale wind power from North Atlantic to the Eastern coast of the country [321].

8.1.2 Smart grids

The Smart Grid (SG) concept has gained a lot of attention during the last years and it is perceived as a key technology for optimal renewable electricity integration [329–331]. Basically, it is a power grid where all key stakeholders (energy producers, consumers and network companies) are intelligently connected to each other. Smart grid includes integration of distributed power generation and storage technologies, advanced metering, robust two-way information communication, and vast automation. One important rationale of a smart grid is to increase the power supply reliability and to reduce ecological impacts by integrating all energy producers irrespective of size and consumers to participate in the grid optimization, which could then lead to major savings and carbon emission reductions [332].

The literature on SG is ample [333–337]. See also [21] for a recent review. In addition to technological innovations, the SG development may also include redesign of the structure of the electricity market. Accurate forecasts on weather, load and markets (short term), and future development of energy demand (long term) also becomes important in this context [335,336,338–341]. Storage could be a key technology for future SGs [342]; communication technology is another important topic [343–345]. Future developments of the SG could include the so-called super-smart grid which combines the advantages of a supergrid and a smart grid. [345,346].

8.1.3 Microgrids

Microgrids [347–349] have been proposed as one solution for integrating RE into the power system and balancing supply–demand mismatch [350]. Microgrids are local grids to supply electricity to local consumers. A microgrid energy system may include local power generation (micro-CHP, small-scale RE), storage systems, controllable loads and the feeder system. Within a larger power distribution system, the microgrids could be operated as a component of the larger grid system to balance voltage fluctuations. During disturbances, they can be isolated from the larger system (island mode) to secure the energy supply in its own area. Several real-world examples of microgrids are listed in [351].

8.2 Smoothing effects of spatial power distribution

Spatial power fluctuations can be smoothed out through efficient power transmission and distribution. Spreading out RE power generation on a wider area can reduce rapid changes in renewable power output. Smoothing effects are well-known from wind energy utilization [338,352–358] and they can positively affect the value of wind power at high penetration levels. Different portfolio theories have been used to show how geographical dispersing of wind power generation can reduce the wind power variability [359,360]. References [361–363] show that geographical smoothing could be linked to solar power as well.

9 Electricity markets

Though energy system flexibility is often perceived as a technological issue only, it has a strong link to the electricity market as well. For example, different power tariffs may enhance flexibility. On the other hand, fuel-less energy sources such as wind and solar power have a zero-marginal cost on the market, meaning that large-scale RE schemes would drop the average electricity price. Poor market design may limit access to technical flexibility in energy systems [258]. In the next, we will discuss more market issues related to flexibility and renewables.

9.1 Impact of variable renewable energy production to electricity markets

On short term, variable renewable electricity production such as solar and wind with close to zero variable costs will reduce the electricity price on the wholesale spot market. Much of VRE production has also been supported by the feed-in-tariffs meaning that, all VRE production has in practice been fed to the market [364]. Even negative spot prices have been witnessed during high renewable production and low demand [364,365]. On the German market each additional GWh of VRE power fed to the grid has lowered the spot market price of electricity by $1.4–1.7/MWh [65]. However, the consumer electricity price may rise due to the VRE feed-in-tariff: in Germany, it has increased over 20% from 2008 to 2012 [366].

On long term, increasing renewable power will decrease the demand for base load power plants and increase the demand for peak load capacity [365]. This shift of conventional generation capacity and increasing fluctuation of net load will increase the price volatility [365]. As the predictability of variable renewable energy sources is low on the day-ahead market, the demand for balancing services and intraday trading will consequently increase [367,368]. The costs of RE and wholesale prices will also influence investment, expansion and retiring decisions of transmission and generation in the long run, making the average effect of RE on wholesale prices less clear than on short term [2].

9.2 Market design to increase flexibility

As the forecast errors generally decrease with a shorter prediction horizon [339,369,370], more frequent trading and reserve procurement allows for lower regulation costs and increased incomes for producers of renewable electricity [369,371], though some additional costs may also occur [371]. However, more frequent energy trading is not straightforward as intra-day markets are prone to low liquidity [367,371]. Intra-day auctions could be an attractive option for increasing intra-day market liquidity [367].

Internal self-balancing by the large power-generating companies based on up-to-date production forecasts just shortly before the hour of delivery, has also been suggested for balancing forecast deviations [372], but with some concerns of its value [372] and market power implications [367]. Production forecasts can also be improved through incorporating on-line production, ensemble forecasting and increasing the forecast area [133,369]. The forecast methodologies themselves are also subject to continuous development [133,339].

With a higher scheduling resolution, changes in production during a shorter interval become smaller and more manageable [371]. This would reduce the need for regulation reserves [371]. Higher temporal resolution would also provide timely price signals to flexible resources and shift risks from system operator to balance responsible parties; however, start-up costs could bring challenges [373].

Location-dependent pricing could be used to mitigate congestion due to intermittent generation [368,373]. Nodal pricing appears to be the only option that would reflect the state of the physical power system at all times, as it is impossible to achieve that with zonal pricing. This principle applies to both domestic and international transmission capacity allocation [373]. Price caps if being high enough could facilitate fixed cost recovery by peaking units, and price floors should be low enough to reveal the value of flexibility, e.g. allowing negative prices [373].

Integration of electricity markets, both spatially and the spot, intraday and reserve markets in a given area, could increase flexibility. Reserve market auctions should be aligned with the spot and intraday markets: if plants are committed for reserve for a much longer time than the electricity market timeframe, flexibility will be reduced [364]. Aggregation of markets over large areas provides access to more generators and loads to provide flexibility, brings about geographical smoothing, and allows for sharing of reserves, which reduces costs [258]. An auction mechanism for interconnector capacities between European power markets would increase the flexibility of the entire system [364]. However, the renewable production integration cost reduction from cross-border transmission depends on the generation mix in the neighboring countries: if VRE is largely used in both areas, the cost-saving potential of the interconnection decreases [374]. Moreover, the correlation of VRE production in the interconnected areas strongly affects the generation cost reduction due to an interconnector [375]. International market integration is being pursued in Europe with a pilot project for day-ahead market coupling recently started by 15 countries [376].

Stochastic unit commitment, instead of deterministic, is a way to directly include uncertainty of renewable energy production to operational planning [371]. However, all stochastic information cannot be included in practice, and solution times of the optimization can be excessive.

The support scheme for VRE production strongly affects the flexibility of the VRE production itself. With a constant feed-in tariff in combination with priority purchase and transmission rules, renewable producers are shielded from market signals [377]. A feed-in premium was introduced as optional for the feed-in tariff in Germany in 2012. It incentivizes to respond to short-term price signals, encouraging voluntary curtailment when the magnitude of a negative electricity spot price exceeds the premium, while keeping the producers shielded from market price risks. For example, in December 2012, 300 MW of wind curtailment was observed during negative price conditions [377]. A feed-in premium can be considered a good trade-off solution, as it exposes renewable producers to market signals without creating considerable new risks and transaction costs [378].

A major question in market design for integration of VRE is whether VRE production should follow the same market rules than the other production after it has become competitive. The same market rules could be incorporated if dynamic retail pricing schemes were in place to cover capital costs for capacity investment [373]. When the penetration of variable renewable production increases, there will be an increasing need to allocate some balancing responsibility to VRE as well, which may require special measures for balancing markets [379].

With lack of demand response and increasing VRE share, energy-only markets may not be sufficient to ensure that flexible energy plants could recover their costs for which reason some kind of capacity mechanism may be needed [373,380]. The situation could be corrected with a price-based or quantity-based capacity system. In the former, the price of capacity per MW is fixed; in the latter, the amount of desired capacity is fixed, either as installed capacity or operating reserve. However, if capacity bids are in use on the reserve market, the energy price on reserve markets may get lower than on the intra-day market, creating distorting incentives [367]. As it is difficult for VRE to provide capacity, implementing a capacity mechanism would most likely lead to different market rules between VRE and conventional generation [373].

Aggregating different VRE generators to “virtual power plants” could reduce the hours with low spot prices, but could increase the cost of electricity for consumers [368]. Moreover, it wouldn’t solve grid congestion problems.

A pool market design, common in American markets, has advantages with regard to flexibility compared to the bilateral markets with a power exchange, used is most European countries. The gate closure is later, the intra-day market is more liquid, and the balancing and intra-day markets are not separated, which more readily allows for the use of up-to-date forecast information [368].

9.3 Energy storage in the electricity market

Energy storage was recognized as a high potential technology for energy system flexibility, but its role on the market is somewhat complex as it has both a demand and supply function and therefore it does not fit well into existing regulatory frameworks [381]. This in turn may discourage investments in energy storage [382–384]. Furthermore, price distortions, grid fees and the lack of price transparency may create a negative cost impact on energy storage [9].

IEA suggests that policymakers should enable compensation for the multitude of services energy storage provides, e.g. payment based on the value of reliability, power quality, energy security and efficiency gains. Potential mechanisms include real-time pricing, pricing by service and taxation being applied to final products. In the U.S., efforts have been made to enable incentives to energy storage, e.g. through opening electricity markets to energy storage and permitting companies other than large utilities to sell ancillary services [9].

9.4 DSM in the electricity market

Price-based DSM increases demand elasticity and hence it could reduce price spikes [31]. DSM can also shift market power from generators to consumers [37], reduce prices [385] and price volatility [50], and make the market more efficient [385]. In many electricity markets where VRE has priority, price is negatively correlated with VRE production [35] and hence price-based DSM can provide flexibility for VRE integration directly. However, the closed-loop feedback system between the physical and market layer created by real-time pricing, together with increasing VRE production, may lead to increased volatility [386]. Large-scale system models including the interactions between the market and physical system are needed for full understanding of DSM effects [37].

Market rules affect the possibility of DSM to enter different markets. For example, auctions on primary and secondary reserves in Germany are held 1 month and 6 months before delivery, which may be too restrictive for DSM providers [33].

10 Conclusions

The number of options to improve energy system flexibility when increasing the share of renewable power in electricity production is large. It is likely that this theme will draw even more interest in the years to come as the prospects for new renewable energy technologies [387–391] are positive and further price reductions are expected. Energy system flexibility is definitely a “hot topic” as demonstrated by the large number of references contained in this review (close to 400). The options for energy system flexibility and their principles may remain much the same as described here, though the depth of information may improve in the future.

We observed that much of energy system flexibility can actually be handled through the energy or power system itself, meaning that energy systems could have inherent capabilities to incorporate large shares of variable power, without requiring massive changes or new investments. For example, employing a whole energy view in which the thermal and electric system are treated more as a whole rather than separate could offer major new opportunities for renewable power integration. It is also important to remind that the present power systems have already built-in flexibility capacity as the power demand is not constant over time, though introducing renewable power will change the net load patterns. However, in the long run, one may see more attention been paid to dedicated flexibility products, such as electricity storage, which are additional components to be added to the power system.

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Figure captions

Figure 1. Categories of demand side management [30].

Figure 2. Power and discharge time of selected energy storage technologies [250,392,393].

Figure 3. Start-up and ramp-up times of three technologies after a five-days stop [68].

Figure 4. Lost energy as a function of curtailed power in a Finnish PV system. Power curtailment percentage is calculated in relation to nominal power (red curve) and maximum generated power (blue).

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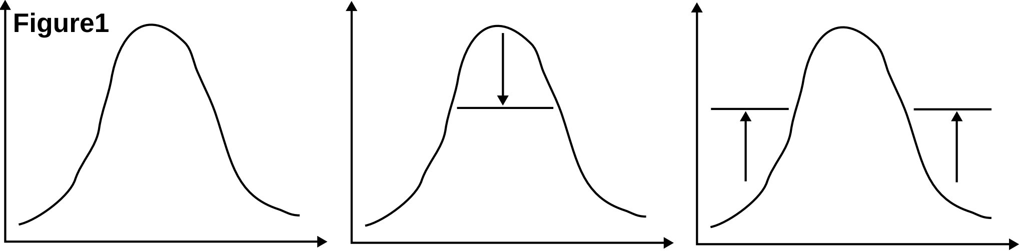
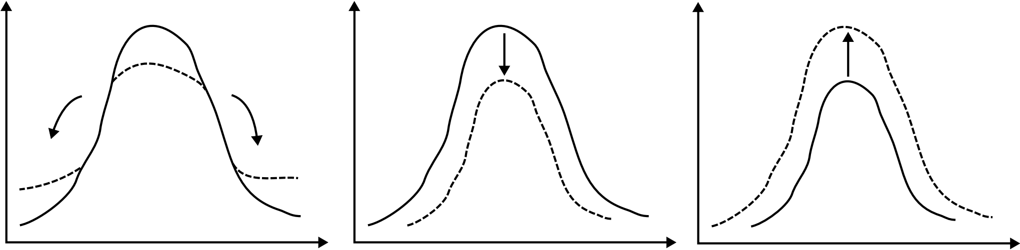
Figure1



Flexible load shape

Peak shaving

Valley filling



Load shifting

Conservation

Load growth

Figure2

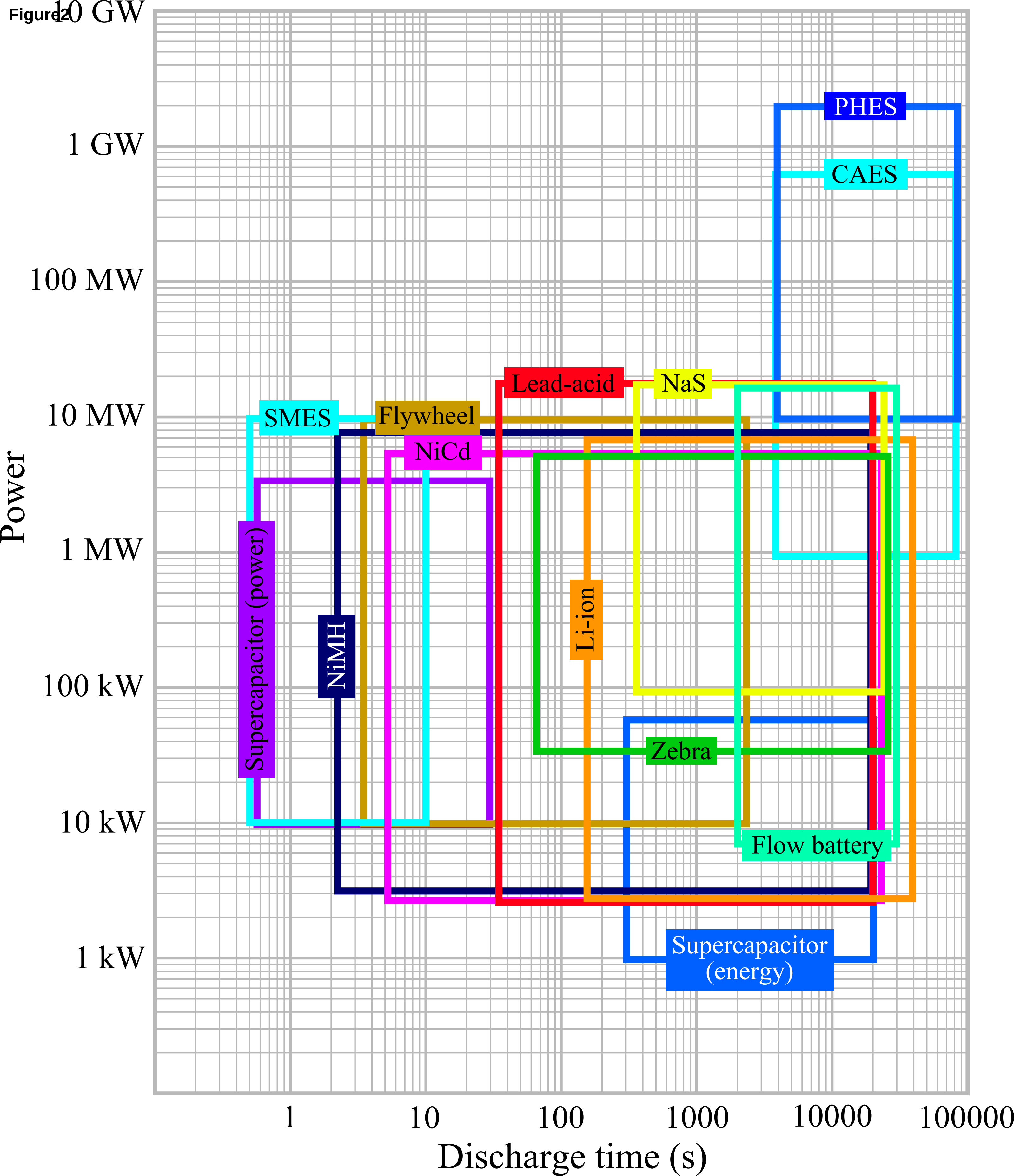

10 GW
1 GW
100 MW
10 MW
1 MW
100 kW
10 kW
1 kW
Power
1
10
100
1000
10000
100000
Discharge time (s)
PHES
CAES
Lead-acid
NaS
SMES
Flywheel
NiCd
Supercapacitor (power)
NiMH
Li-ion
Zebra
Flow battery
Supercapacitor (energy)

Figure3

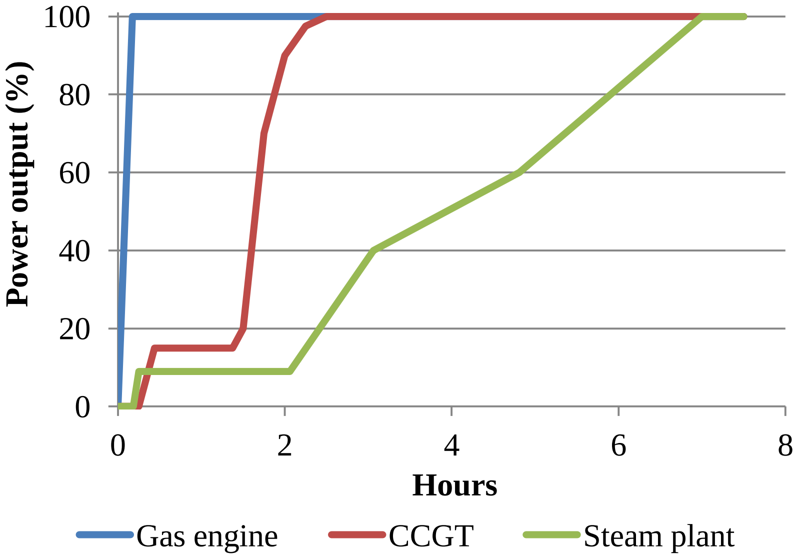

100
80
60
40
20
0
Power output (%)
0
2
4
6
8
Hours
Gas engine
CCGT
Steam plant

Figure4

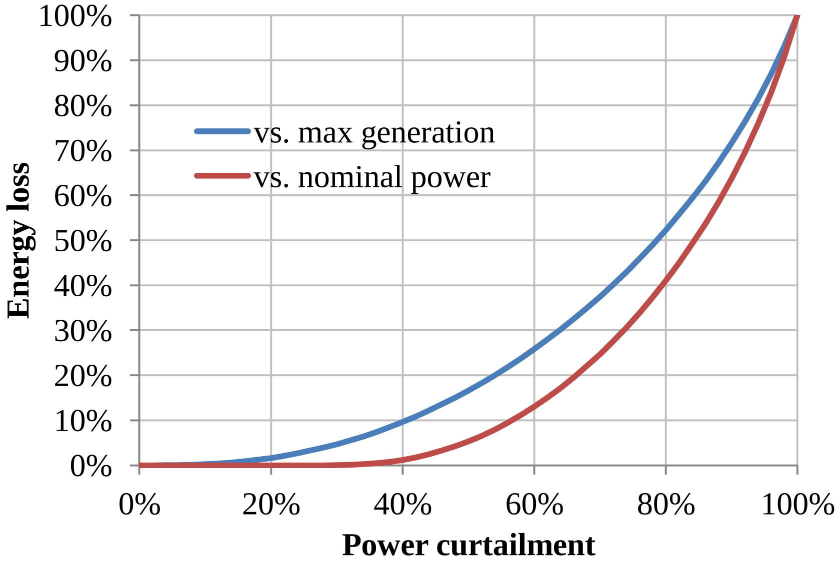

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Energy loss
vs. max generation
vs. nominal power
0%
20%
40%
60%
80%
100%
Power curtailment

Table 1. DSM potential of residential loads in Germany [32,51,63,64].

Load	Positive capacity	Negative capacity	Storage from load shifting	Investment costs	Variable costs	Fixed costs
Night storage heaters	19–88%	128%	58%	10%	~0%	11%
Domestic hot water heaters	1–5%	17%	90%	113%	~0%	11%
Ventilation systems	8–38%	55%	8%	N.A.	N.A.	N.A.
Refrigerators	2–9%	15%	90% with freezers	298%	~0%	228%
Freezers	9–19%	12%	90% with refrigerators	298%	~0%	228%
Hot water circulation pumps	3–14%	None	98%	1625%	~0%	250%
Washing machines, dryers and dishwashers	5–24%	72%	105%	185%	~0%	183%
Heat pumps with storage	0.3–1%	0.7%	8%	38%	N.A.	N.A.

Table2

Table 1. DSM potential of service sector loads in Germany [32,64].

Load	Positive capacity	Negative capacity	Investment costs	Variable costs	Fixed costs
Food store refrigerators	1–7%	10%	0.8–222%	1%	~0%
Electric hot water generation	0.1–0.7%	3%	7–45%	1%	~0%
Ventilation systems	0.6–3%	5%	87–307%	1%	~0%
Air conditioning	0.6–3%	8%	4–148%	1%	~0%
Night storage heaters	1–5%	33%	2–12%	1%	~0%
Municipal waste water treatment	0.2–0.8%	None	4–187%	1%	39–231%

Table3

Table 1. DSM potential of industrial loads in Germany [32,33,63].

Load	Positive capacity	Negative capacity	Storage from load shifting	Investment costs	Variable costs	Fixed costs
Chloralkali electrolysis	0.8–4%	Small	3%	< 0.3%	> 147%	~0%
Mechanical wood pulp refining	0.3–2%	0.1–0.4%	1%	3–4%	< 15%	~0%
Aluminum electrolysis	0.4–2%	None	None	< 0.3%	740–2206%	~0%
Cement milling	0.3–2%	0.1–0.4%	8%	4–5%	588–1471%	~0%
Steel melting in electric arc furnaces	1–7%	None	None	< 0.3%	> 2941%	~0%
Compressed air with variable speed compressors	0.3–1%	0.1–0.6%	40%	6%	N.A.	N.A.
Ventilation systems	1–7%	0.2–0.9%	N.A.	97%	N.A.	~0%
Cooling and freezing in food industry	2–9%	0.9–4%	N.A.	N.A.	N.A.	~0%
Process cooling in chemical industry	0.8–4%	None	None	N.A.	N.A.	~0%

Table 4. Grid ancillary services categorized based on service duration [136,137].

Duration	Services	Examples of technologies
Very short 1 ms – 5 min	Power quality, regulation	Flywheels, DSM
Short 5 min – 1 h	Spinning reserve, contingency reserve, black start	Flow batteries, PHES, DSM
Intermediate 1 h – 3 d	Load following, load leveling/peak shaving/valley filling, transmission curtailment prevention, transmission loss reduction, unit commitment	CAES, PHES, DSM
Long months	Seasonal shifting	CAES, PHES

Table 5. Key parameters of selected secondary battery chemistries.

Chemistry	Efficiency (%)	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Cycle life (cycles @ DOD), NR=DOD not reported	References
Lead-acid (PbA)	75-85	20-40	55-90	75-415	250-2000 @ 60% 200-800 @ 80% 300-1000 @ NR	[171,174,216,223,224,229–236]
Nickel-cadmium (NiCd)	60-75	40-65	60-150	100-175	5000 @ 60% 1000-2000 @ 80% 2000-2500 @ NR	[141,171,223,224,229–231,233,235,236]
Nickel-metal hydride (NiMH)	64-66	45-80	140-300	200-1500	300-1200 @ 80% 200-1500 @ NR	[141,223,224,229–231,233,236,237]
Sodium-sulphur (NaS)	75-85	100-200	150-250	150-250	1000-5000 @ 80% 1000-5000 @ NR	[141,146,174,223,224,231,232,236,238]
Sodium nickel-chlorine (Zebra)	90-100	85-140	150-175	150-250	1500-3500 @ 80% 1000-3000 @ NR	[141,223,224,231,239–243]
Lithium-ion (Li-ion)	90-100	90-190	250-500	500-2000	500-7000 @ 80%	[141,216,223,224,229–231,234]

Table 6. Performance indicators of power plants at full output (average indicative values from literature; individual projects can considerably deviate from these). [68]

Indicator	Hard coal	Lignite	Nuclear	CCGT > 300 MW	Simple-cycle gas engine > 5 MW
Investment (US$/kW)	1900	2200	3900	1000	650
Net fuel efficiency (%)	40	36	33	55	47
Fuel price (US$/GJ)	5	4	1,5	6,5	6,5
Operation and maintenance costs (US$/MWh)	13	16	13	13	13
Specific CO_2 emission (g/kWh)	820	1030	–	370	450
Lead time to commissioning (months)	40	45	60	24	12
Start-up and synchronize time (min)	300	300	300	5	1
Ramp-up rate (%/min)	3	2	2	3–5	20