Modelling flexibility from distributed energy resources

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SUMMARY

A number of distributed energy resources (DER) are emerging at many levels of the distribution network, including various forms of embedded generation, energy storage based on different technologies and energy vectors, and demand response. With large-scale, centralized conventional technologies disappearing from the system, such DER become most promising options for providing flexibility and ancillary services and take up part of the overall system control to deal with large-scale penetration of Renewable Energy Sources (RES).

Increasing deployment of DER thus creates both opportunities and technical challenges in system-wide planning and control. DER could in fact provide reliable and low-cost demand shifting, load and supply balancing flexibility, and various grid services, consequently reducing the cost of investing in generation and network peak capacity and enhancing local and system-level flexibility and resilience. However, integrating large amounts of DER also change the traditional one-way power flows' direction – from transmission to distribution networks to customers – into two-way power flows. Hence, visibility and coordination of DER for system-wide operation become essential to maximise the benefits of flexibility of and from DER, for instance considering technical (e.g., thermal and voltage) envelops of aggregated DER to increase the hosting capability of the local network and reduce interventions on the customer sides.

On the above premises, this paper aims at reporting on the first year of work carried out by WG C6/C2.34 "Flexibility provision from DER", which was created to gain new insights into the concept of flexibility and relevant grid and market services that DER could provide from both technical and commercial perspectives and at the levels of local networks as well as whole-system operation.

Specific aspects of DER flexibility addressed in this work include:

- Reviewing drivers and new requirements for flexibility at different stages of power system planning and operation, from the whole-system to the local network.
- Providing a definition and characterization of the concept of DER flexibility that is most suitable in the context of renewables integration.
- Compiling preliminary information from selected technologies on the potential of DER to provide flexibility over different time scales, and in different forms, including distributed generation, different forms and technologies of energy storage, electric vehicles, and residential, commercial and industrial demand response.
- Discuss the specific but increasingly important case of DER flexibility in isolated systems.

KEYWORDS

Flexibility, distributed energy resources, low-carbon technologies, multi-energy systems, storage, demand side resources, demand response.

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1. Introduction

With the deeper global penetration of renewable energy sources (RES), there are greater flexibility requirements to deal with RES volatility and partial unpredictability. Furthermore, a wide spectrum of balancing services that may be broadly associated with the concept of flexibility will be increasingly required over different timescales. Provision of these services is becoming a challenge as traditional means to provide flexibility and, more in general, of system control have been associated with conventional thermal power plants which are being displaced by RES. New providers of system flexibility and ancillary services are therefore needed.

A number of distributed energy resources (DER) are emerging at many levels of the distribution network, including various forms of embedded generation, energy storage based on different technologies and energy vectors, and demand response. With large-scale, centralized conventional technologies disappearing from the system, such DER become the more promising options for providing ancillary services and take up part of the overall system control, while avoiding potential over-rated system development that a fully centralized system might call for. As special cases of DER, there are various multi-energy technologies and applications (e.g., in buildings) that could exploit the increasing interactions between electricity and other energy sectors, vectors and networks (e.g., heat, fuels, etc.) and which exhibit intrinsically high degrees of complementarity among themselves and with the electricity system.

The evolution towards more and more decentralized energy systems and decentralized system control also calls for a change in technical control and commercial architectures. The latter, within competitive market environments, would involve new commercial mechanisms, market products, and even markets that could enable a level playing field between centralized and decentralized energy resources. In this outlook, due to the arising technical challenges consequent on large shares of DER, power systems worldwide are already witnessing a fast transition from passive distribution networks to active distribution systems managed by distribution system operators (DSOs), which also manage (or will soon have to manage) the integration of local DER on their grids. This, of course, will also create new opportunities to enhance the business cases for DER, as facilitated by new market actors and concepts such as aggregators, microgrids, virtual power plants, and so on, provided that the costs incurred to offer these services will be balanced by appropriate revenues.

In the context outlined above, Working Group C6/C2.34 “Flexibility provision from Distributed Energy Resources” was created to gain new insights into the concept of flexibility and relevant grid and market services that DER could provide, thus supporting the development of DER, from both technical and commercial perspectives, in providing ancillary services and participating in balancing markets and whole-system operation. This paper aims at reporting on the first year of work carried out by WG C6/C2.34, particularly looking into:

- Reviewing drivers and new requirements for flexibility at different stages of power system planning and operation, from the whole-system to the local network.
- Providing a definition and characterization of the concept of DER flexibility that is most suitable in the context of renewables integration.
- Compiling preliminary information from selected technologies on the potential of DER (including multi-energy coupling) to provide flexibility over different time scales, and in different forms, including generation (e.g., inverter-interfaced wind), energy storage (e.g., batteries, electric vehicles, thermal storage, seasonal storage), and demand response (e.g., industrial installations, individual buildings or district energy systems).
- Discuss the specific but increasingly important case of DER flexibility in isolated systems.

The information provided will bring together knowledge and experience from the WG participants from around the globe.

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low-inertia systems (for example, in several situations in Australia that is facing significant challenges in integrating deeper penetration of RES [5]). These fast response requirements mean that the customer response/reward needs to be pre-arranged and triggered by a suitable broadcast signal. Similarly, for component overload issues the time constants of heating of major plant such as transformers becomes the dominant factor and could be tens of minutes. This timescale could in principle permit a market reward iteration which could be implemented in a geographically hierarchical manner. All these technical requirements will thus inevitably shape both technical and commercial opportunities and constraints for DER to provide flexibility services.

3. Defining DER flexibility

After the first year of the Cigre WG C6/C2.34's activities, the following definition for flexibility was agreed upon, with focus on the context relevant to DER:

"In the context of Distributed Energy Resources (DER), flexibility is the ability of a single or an aggregated set of DER (including just one such resource) to modify their net operational active and/or reactive power levels (injection or withdrawal) at a certain grid location by a certain amounts, within a certain time and, for a certain duration, in response to (or expectation of) a technical or commercial signal or requirement to provide one or more local or system-level services within a certain notice time."

The provided definition contains a number of keywords that address key characteristics of interest, as elaborated below:

- *Aggregation*: Flexibility may be provided by one or a number of aggregated resources, which is particularly important in upstream grid interaction and market participation.
- *Active/reactive power*: Differently from many definitions and much of the focus so far, flexibility is not only relevant to active power, but also to reactive power, especially with emerging issues of voltage control and local reactive support to guarantee management of reverse flows from DG, correct operation of control loops of power electronics-connected DER, etc.
- *Injection/withdrawal*: Both generation and demand side can, in principle, provide flexibility via bidirectional management of active and reactive power, especially in the context of individual "prosumers" and aggregation of DER that include batteries and RES whose "net" network injection characteristics at given points may change direction over time and also depending on the specific control strategy.
- *Location*: While most discussions on flexibility has focused on system-level aspects, locational aspects are also critical when dealing with DER because networks can constrain the level of flexibility and other services that can be transferred elsewhere, also motivating the rise of specific local service requirements (e.g., to deal with congestions, etc.).
- *Amount, response time and duration*: Flexibility intrinsically entails the concepts of capacity and energy through time. Effectively, it represents how much (active and reactive) energy variation can be delivered in a given timeframe at a given capacity level.
- *Technical or commercial signal or requirement:* Different types of signals to incentivize the provision of flexibility may be generated in various contexts, along with different relevant forms of responses. In particular, such flexibility activation signals may be of technical nature (e.g., based on local measurements of frequency and voltage, or based on direct DSO control) or commercial nature (e.g., a price signal, not necessarily in real-time but also in the form of contracts), and can also be enforced as a requirement (e.g., in the grid connection code).
- *One or more local or system-level services*: In a market context, flexibility directly corresponds to one or more services that can or should be monetized. Such services can be of local nature (e.g., for voltage management) or system-level nature (e.g., for frequency management), and can potentially be provided simultaneously (e.g., a demand response scheme may provide a system-level reserve service and local congestion management service at the same time) or, more in general, different services may be provided by the same DER aggregate at different times, thus also potentially allowing for stacking up market benefits from multiple services.

- *Notice time*: Besides the coupling between capacity and energy during the delivery of a service, another fundamental temporal component is the notice time, both technically and commercially. In fact, technically, the notice time (and associated response time) may limit the type of service that a DER aggregate may provide whereas, from a commercial perspective, the design of the notice time may limit (at times unnecessarily, which may call for market changes) the participation in specific markets.

Additional points to the "base" definition were also discussed, as from below, which further describe and characterise the main features of DER flexibility:

"The technical and commercial ability of DER to provide flexibility: is system- and time-dependent (in that it is a function of DER, grid, weather, and market's incumbent conditions); may be provided through interactions with other energy vectors; depends on and should consider end-use comfort level and quality of supply, DER energy payback characteristics, and system security and safety; and is enabled by adequate ICT and control platforms, market actors, and commercial and regulatory frameworks."

Based on the above, several keywords can again be highlighted:

- *System, time and incumbent-conditions dependent*: Flexibility can be generally defined as a concept, but its quantification is case specific, especially considering network constraints, weather conditions that affect renewable production and ratings, etc.
- *Multiple energy vectors*: As a key area that has been explored in the last years, flexibility may be provided from other energy vectors and, for example, DER that interact with electricity, heat, gas, hydrogen, etc. [6], [7].
- *End-use comfort level and quality of supply*: Given that DER often interact with end-users, it is key that aspects such as comfort level are considered when defining DER flexibility which may derive from or affect end-users, for example in the case of flexible demand with thermal loads [8], [9].
- *DER payback*: As DER flexibility may often be based on demand side resources or electrical or virtual storage, inter-temporal constraints may arise which must be factored in to properly quantify the potential (and in case impact) of flexibility [10].
- *System security and safety*: Flexibility must always be provided while considering, and preventing, both security and safety issues.
- *ICT and control*: DER flexibility may be identified as a key component of the "smart grid" paradigm, whereby advanced system control supported by ICT is able to provide cost-effective and reliable services differently from the classical asset-based paradigm adopted in the past [11].
- *Market, commercial, and regulatory framework*: No matter what "technical" flexibility may be potentially available, the actual deployment of flexibility emerges only on the basis of its economic profitability, which of course is driven by the incumbent commercial and regulatory environments. It is in fact key that such boundary condition environments promote the deployment of DER flexibility rather than hinder it [12].

4. DER-based flexibility

Building-level, low voltage-connected DER

Considering a bottom-up approach in the value chain of potential DER technologies providing flexibility, building-level DER that are connected to the low voltage (LV) network is changing the way customers interact with the grid and provides them with more options to become more energy efficient and clean [13], [14]. Historically speaking, buildings would meet their energy needs using dedicated energy systems such as, for example, the electricity grid to meet their electricity demand and boilers connected to a gas network to meet their heating needs (see Figure 2A). In this context, buildings have little or no flexibility, as the options available for meeting their energy needs are limited. Following the example from Figure 2A, the only option available for buildings to provide flexibility would be demand management, which may involve curtailing load and, potentially, experiencing discomfort as traditional customers were unlikely to own flexible appliances [15].

The abovementioned conditions change considerably after DER emerge, such as photovoltaic (PV) systems, combined heat and power (CHP) and gas boilers, battery energy storage (BES) and thermal energy storage (TES), see Figure 2B. It is important to note that Figure 2B is not meant to be comprehensive and many other DER can be considered such as electric heat pumps (EHP). In this multi-energy system (MES) context, buildings become more flexible due to the integration of DER technologies which can interact with each other [16]. Taking the example from Figure 2B, the building can now meet its energy needs using combinations of grid imports, PV systems, local generation (from CHP in this case) and BES. The specific combinations of these technologies used to supply the building can be based on economics (i.e., cheapest combination at each period) or other objectives such as maximizing use of renewable resources, minimizing net grid imports, and so forth [17].

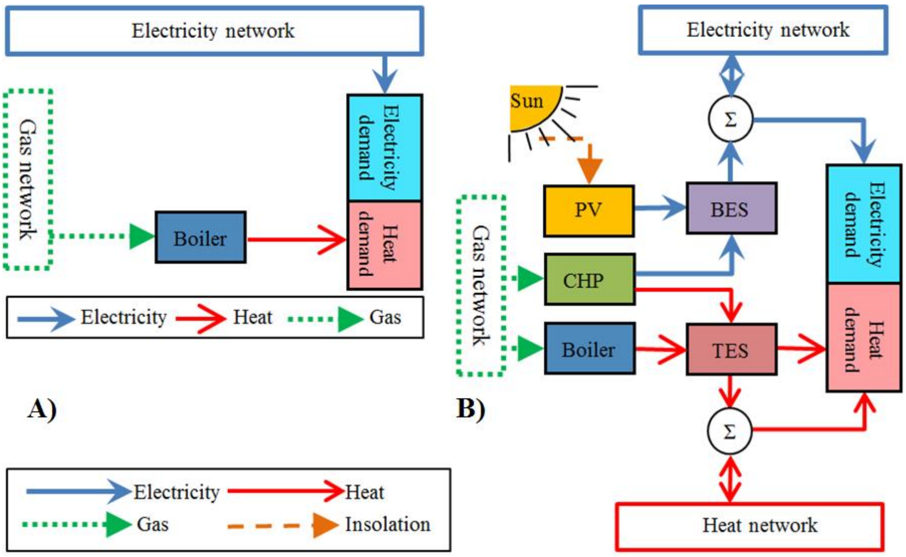

Figure 2 – A) Traditionally decupled building energy supply and B) Building MES with multiple DER

The optionality offered by the potential combinations of DER is a key feature that makes the building energy systems highly flexible [13]. The reason being that, besides combining DER operation to meet the building's energy needs, DER operation can also be optimized to provide services locally (e.g., trading energy with neighboring buildings and providing distribution network management) or at the system level (e.g., partaking in existing markets). Following the same line of thought, it would make sense to aggregate the resources of multiple building systems to create a more flexible community MES. The building owners, which can be represented by aggregators or similar actors in the markets, could be encouraged to provide such services through different price signals, contracts, and so forth.

This type of operation highlights various features of the DER flexibility definition provided above, particularly with reference to multiple energy vectors, end-user comfort, ICT-based control and aggregation, and commercial aspects.

Flexibility options in (net-zero energy) factories

While residential and commercial buildings may be considered the basic brick for bottom-up DER flexibility, interestingly new solutions are also emerging from factory buildings, especially in the context of decarbonising the manufacturing sector and improving its energy efficiency.

In this context, it is interesting to highlight that about 14% of the European small and medium enterprises (SME) also generate electricity through PV plants [18]. For German and Swedish SME, this value exceeds 30%. In many cases, the generated electricity is not directly integrated into the manufacturing grid, but it is firstly fed into the main grid and successively withdrawn from the grid. Such a *modus operandi* ("feed it and forget it" approach) of the PV plants might create, in the long run, problems to system operators, which have to plan re-dispatch actions for compensating for volatile generation. Besides it, in Europe, RES generation is economically supported for up to 20 years. With the expiration of the incentive time, SME operators may therefore have three different options to explore:

1. Feeding the grid without receiving any economic compensation;

2. Selling the electricity to the market by aggregating their PV plants with other DER, and building a virtual power plant;
3. Self-consuming all the generated power without feeding back into the grid.

Clearly, in both the virtual power plant and the self-consumption cases, the SME need to build new flexibility options. Examples of such flexibility options may include deployment of ESS [19] (see also below), realization of MES [20], and active participation of the consumers in managing the grid. In the context of DER flexibility, it is also important to consider that, whereas in the virtual power plant concept these flexibility options might be sold to the markets (energy and ancillary services), in the self-consumption concept the flexibility options are locally exploited *within* the factory, even though effectively they may also correspond to flexibility provision to the rest of the system, for example by managing potentially harmful feed-ins.

In the outlook of decarbonisation and energy efficiency, an interesting emerging concept is that of net-zero energy factories (NZEF), whereby the generated electric power by volatile RES is totally consumed into the manufacturing system. In case the electric demand is higher than the generated power, then the difference of the power is taken from the grid. The time horizon in which the manufacturing system works as net-zero is fundamental. Indeed, a system might be net-zero for few minutes or even for some hours. The longer is the time horizon, the greater is the required degree of flexibility. The degree of flexibility can be exploited by optimally controlling the manufacturing process by increasing the production buffer stocks, or by introducing ESS such as batteries, heat storage systems or compressed air storage [21]. Indeed, a NZEF can be considered as active consumer which operates a MES, in which different energy and material forms of storage systems are installed. It can be controlled by a central energy management system that performs forecasting, monitoring, and the control functions. The utilization of smart transformers as energy management system might increase the flexibility degree of the NZEF [22]. Indeed it could be an interesting option in the case in which the machines of the manufacturing process are supplied in DC.

Two criteria can be considered to identify and evaluate the flexibility of manufacturing processes, in line with the general DER flexibility concept mentioned above: *time* and *power*. More specifically, some industrial processes can be shifted over time, as they can be processed earlier or later. Other processes can be flexible in both time and power. Indeed they can be shifted to earlier or later periods, and the power required by the process can be controlled too. The first case depicts manufacturing processes that can be shed, while the second case depicts processes that are "controllable", which of course are all case-specific.

Intermittent RES-based DER

Weather variability and fluctuations play a major role on ancillary service provision from weather-driven, inverter-interfaced DER such as wind turbines and solar PV. Accordingly, quantification of flexibility services from such DER (e.g., active and reactive power reserves) needs to consider weather variability, geographical location, and market arrangements, as also highlighted in the flexibility definition provided above. This information is critical considering that the effect of variability reduces to a large extent when the DER are geographically dispersed and are in large numbers, and market operation of large numbers of small RES-based DER becomes challenging due to mismatches between RES availability and demand and RES forecast errors. In this context, market aggregators should play a significant role to minimize the impact of these forecast errors in coherence with other controllable DER. To illustrate these points, Figure 3 shows the active power transfer between a typical distribution network with large share of DER and the transmission network [23]. The plots are from real data in a Danish distribution network. It can be observed that in this case DER generation is generally higher than consumption, which is evident from the fact that the real power outputs (P) can be as high as -100 MW (negative network load means upstream injection).

Focusing on wind-based DER, modern wind turbines are capable of fast and independent active and reactive power control. This flexibility can be utilized to provide active power control and frequency support. However for such support, since wind turbines are driven by variable wind, wind power fluctuations need to be considered in the provision of active power support. Another interesting fact to be noted is that, when generation is high and consumption is low, high volume of reactive power is transferred to the transmission network. This reactive power can cause increased losses and voltage quality deterioration. The flexibility from modern converter-connected DER can thus also help in local voltage control and thereby minimize the reactive power flow to the transmission network. Wind turbines too, in particular, have in fact the capability to generate/consume reactive power [24] as given by a typical capability curve in Figure 4. This reactive power capability thus provides the flexibility needed for wind turbines to control both active and reactive power to support both transmission and distribution networks for different services such as voltage profile management, active and reactive power support, frequency support, loss mitigation, congestion management, etc.

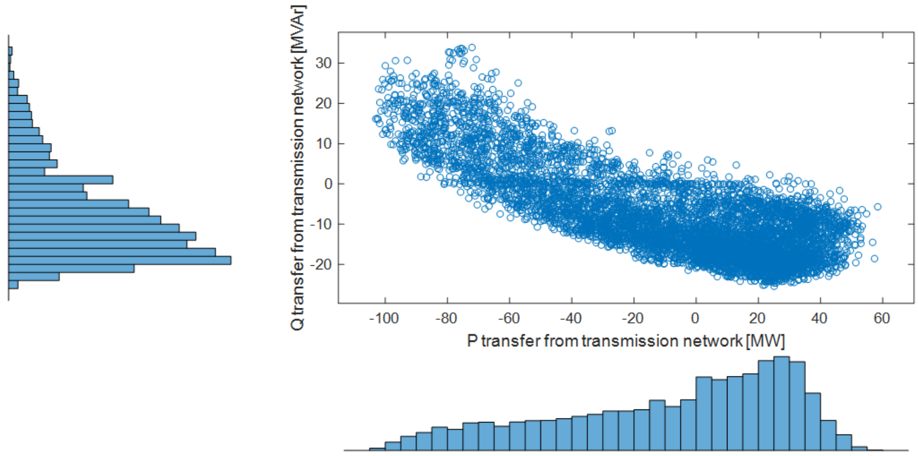

Figure 3 – Scatter plot of active and reactive power flow between transmission and a typical distribution network with high share of DER [23]. Positive convention denotes transfer from transmission to distribution

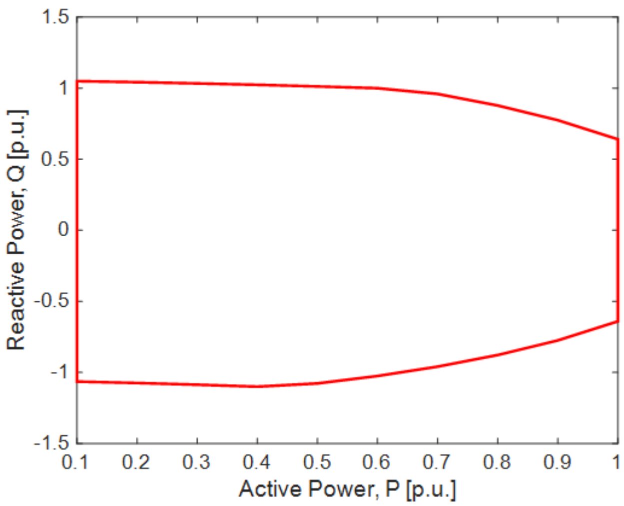

Figure 4 – Typical reactive power capability of converter-based wind power generation

Battery energy storage systems

Battery ESS (BESS) are some of the DER technologies that are considered potential game-changers to enable a low-carbon future. This is owing to their ability to provide flexibility by shifting and buffering supply and demand for electricity relatively fast and in response to different types of technical and commercial signals to provide one or more simultaneous local and system-level services, as per our DER flexibility definition. More specifically, the main flexibility services that BESS can provide can be divided in five categories, namely: energy services, ancillary services, infrastructure services, customer energy management services, and RES integration [25]. It is also important to consider that BES systems may be connected at different voltage levels and may thus exhibit different characteristics and provide different services depending on the specific network requirements.

Energy Services

- *Arbitrage/Load Shaping*: Arbitrage is a power time-shift feature wherein the main driver is represented by the difference in energy prices [26].

- *Peak Shaving*: This strategy is applied at times of peak power in order to avoid overloads and to minimize RES curtailment and utilization of expensive/inefficient power plants [27], thus bringing both local and system-level benefits.
- *Power Supply Capacity*: BES could be used to reduce or defer the acquisition of new centralised plant generation capacity and/or purchase capacity in the electricity market. In this scenario, the BESS can supply part of the peak demand [28], again providing system services.

Ancillary Services
- *Load Following*: This represents an active power balance service. In this case, BES systems are exploited to follow variations in electricity demand [25].
- *Frequency Regulation*: BES systems are characterized by rapid and precise response to frequency deviations, which makes this technology suitable for frequency regulation [29].
- *Operating Reserve*: Reserve capacity represents a key factor for a reliable operation of electric systems. Also in this case, the fast response of BES systems is fundamental to allow their exploitation for reserve provisions [30].
- *Voltage Support*: Batteries can help to maintain the voltage within specified limits. BES systems are able to regulate active and reactive power improving the voltage profile [31].
- *Black Start*: After a system failure, BES systems can be employed to provide an active reserve, acting as a plant of autonomous restart. In this scenario, BES systems can be used to energize distribution and transmission systems [32].

Infrastructure Services
- *Congestion Relief*: In this context, a BES system can be utilized to improve the available transmission capacity. Batteries can relieve system contingencies and reduce overload risks [33].
- *Transmission and Distribution Upgrade Deferral*: The installation of BES systems within these systems permit to reduce, postpone or avoid the need of investments/upgrade in transmission/distribution infrastructure [34].

Customer Energy Management Services
- *Power Quality*: Failures, climate events or RES can cause disturbances that may be damaging for sensitive loads (e.g. industrial processes). Storage systems are able to manage these situations by absorbing these disturbances, smoothing voltage variations and providing frequency support [35].
- *Power Reliability*: BES systems can support customer loads acting as emergency backup in case of outage of the primary network (or an extreme event in the case of resilience). In addition, BES can be exploited, in a microgrid scenario, for a robust operation in islanded mode, maintaining frequency and voltage within safety limits [36].
- *Energy Time Shift/Energy Management*: A BES system can be installed by a local customer to perform an arbitrage or a peak shaving strategy [26]. In addition, BES is considered a promising technology within demand response or intelligent load management applications.
- *Renewable Power Consumption Maximization*: BES can be used to balance the local generation and the local demand in order to maximize the production of private RES power plants [37].

Renewables Integration Services
- *Ramp Rate Control*: RES plants are characterized by rapid changes in the power output over short time periods. BES can be utilized to reduce the ramp rate of the generated power in order to ensure grid stability [38].
- *Generation Peak Shaving*: This service can be implemented for the congestion management, for the prevention of system imbalances or in order to avoid curtailment/overproduction penalties.
- *Power Profile Control*: A BES system can be employed with a RES plant in order to provide a controllable output power, and be dispatched like a conventional generator [39].

Electric vehicles: flexibility from mobile storage

The high expectations concerning the potential of Electric Vehicles (EVs) to reduce greenhouse gas emissions are essentially based on the reduction of fossil fuels consumption in the transportation sector that they will induce. However, to assure an effective reduction in fossil fuels consumption, the replacement of conventional vehicles by EV must be closely accompanied by a progressive increase of electricity generation exploiting Renewable Energy Sources (RES). Nevertheless, there is maximum threshold of RES, namely in the case of intermittent sources, after which there is a high risk of having renewable energy being wasted. In these cases, the EV storage capacity can potentially be used to increase the energy consumption when a renewable energy surplus exists, contributing to avoid wasting "clean" energy and thus enabling higher RES integration [40].

However, while the integration of moderate quantities of EV into the majority of European distribution grids does not provoke any considerable impacts, their broad adoption would most likely create some problems in grids operation. Looking to EV as uncontrollable loads, they represent a large amount of consumed power, which can easily approach the power consumed in a typical domestic household at peak hour. Thus it is easy to foresee major congestion problems in already heavily loaded grids, peak load and energy losses increase and, probably, large voltage drops in LV grids.

There are two main approaches to accommodate EV battery charging in the distribution grids, while avoiding the aforementioned problems. The first is to reinforce and plan the network infrastructures to fully handle EV integration. Yet, this solution will be highly capital intensive [41]. The second is to develop and implement active management functionalities for EV, with demand side management functionalities, capable of controlling EV charging/discharging according to the grid's needs and their owners' requirements. This latter approach remunerates EV owners, who provide network support, allowing the management structure to reduce/increase its values when such action is needed.

Depending on the application, EV controllability may vary and, therefore, several control schemes may be adopted. No controllability is envisaged for solutions involving fast charging where a full charge might only take minutes take less than ½h due to the urgent user needs. Conversely, for lower power intensive solutions where charging might take up to 12 h, EV owners may for example choose between a set of three charging options: one passive or non-controlled (dumb charging) and one active or controlled (smart charging) [42]. The flexibility provided by "slow charging" EVs enables their coordination with renewable power generation, for example to minimize the renewable energy wasted in systems characterized by a large integration of intermittent RES (e.g. wind).

The success of EV flexibility deployment requires the development and implementation of adequate policies capable of convincing EV owners to adhere to controlled charging modes and to compensate for eventual EV decreased performance or battery premature degradation. Another relevant aspect for the successful implementation of these methodologies is the existence of a suitable and reliable communications infrastructure. A possible and inexpensive solution is the exploitation of the smart metering infrastructures that are presently being deployed. In fact, such infrastructures, if properly upgraded, can support the communication requirements associated to the proposed methodologies.
Once again, EVs represent a "classical" modern DER technology whose features and requirements can be fully highlighted through the DER flexibility definition given above.

Flexibility from Seasonal Energy Storage

Seasonal energy storage denotes technologies and devices that can shift energy across different seasons and exploit seasonal arbitrage opportunities. It typically includes four types of technologies: seasonal heat storage, cold storage, gas storage, and electricity storage (typically, pumped hydro), which have much longer cycling time and larger capacity than more traditional storage such as BESS. While many of these technologies are large-scale, depending on the specific case and application plenty of DER opportunities are also available.

Seasonal heat storage includes sensible heat storage, latent heat storage, and chemical heat storage, with *sensible heat storage* (e.g., hot water tanks) being the most widely used and mature technology. In contrast, *latent heat storage* (e.g., phase-change materials) and *chemical heat storage* are mainly in the research stage. Sensible heat storage is the mainstream technology due to its simple operation control methods and low cost. Latent heat storage refers to the charging and discharging of heat energy in the process of physical phase change. Chemical thermal energy storage converts chemical energy into heat energy and stores the energy by chemical reactions.

Seasonal cold storage is applied in winter and the energy is stored in the form of ice, snow or cold air. In summer, the energy is released by melting and endothermic refrigeration.

Seasonal gas storage includes hydrogen storage and natural gas storage. With the development of power-to-gas technology [43], [44], the storage and utilization of natural gas and hydrogen energy has become an important part of energy supply. The energy losses in gas storage is generally very small, hence seasonal flexibility is in principle feasible from that perspective. It is also worth mentioning that flexibility provided from the gas network and gas storage to the power system will be of greater significance to provide system balancing via gas turbines in a renewables-rich power system [45].

5. Flexibility in isolated and remote power systems

Isolated communities living in remote areas do not have access to affordable electricity due to their size and geographic separation. Isolated power systems (IPS) are typically conventionally dependent on diesel generation, which, despite low installation costs, reliability and operational simplicity, incur significant operational costs. In addition, the diesel fuel must travel considerable distances resulting in logistical and economic disadvantage (e.g. diesel fuel is brought to islands via tanker barges and tugs). The emission of greenhouse gases is another discouraging factor of diesel technology.

In an effort to reduce energy costs and pollution in remote regions, relevant authorities have set targets promoting application of RES electricity generation. The most abundant RES in such areas, wind and solar, are stochastic and intermittent in nature. Thus, instantaneous power supplied by RES rarely matches the power demand. As a result, higher renewable energy penetrations suffer from stability and reliability issues. Therefore, there are clear opportunities for flexible technologies to improve system operation and integrate more renewables.

ESS provides one solution to a high share of stochastic energy sources within IPS. In a broad sense, ESS are applied for improving the system flexibility by energy shifting, load peak shaving, power quality regulation and provision of spinning reserve. The first two applications, suitable for slowly varying loads, use the capacity-oriented energy storage ("seasonal storage" – see above), such as pumped hydroelectric power plants, hydrogen storage and compressed air energy storage. Power quality can be improved with the help of batteries, supercapacitors and superconducting magnetic energy storage – devices with fast time response (see again above). Flywheels were shown to increase the system inertia in power grids with high renewable penetration, and batteries have the ability to emulate the inertia response. Even though the cost of storage technology tends to decrease over time, significant installation investments are still inevitable.

Demand side management is also used in IPS to maximize renewable energy generation and provide system flexibility. However, this approach requires interconnected communication networks and sophisticated control strategies, which increase the complexity of the underlying control systems and demands highly qualified personnel.

A different approach suggests addressing the flexibility problem by adopting low-load diesel application to reduce fuel consumption and improve RES penetration without overcomplicating the control architecture.

6. Conclusion

As discussed throughout this paper, in the context of "flexibility" the increasing penetration of DER creates a number of technical challenges and requirements, but also several technical and commercial opportunities in both local and system-wide planning and operation. DER could provide a number of flexibility services, ranging from reliable and low-cost demand and generation shifting to load and supply balancing over different timescales (including very fast ancillary services), consequently also reducing the cost of investing in peak demand generation and network, and enhancing system level resilience.

However integrating large amounts of DER change the traditional one way power flow direction, that is, from transmission to distribution networks and finally to end-use customer, into a two-way power flow. Therefore, visibility and coordination of DER from a system-wide perspective become essential to maximise the benefit of flexibility of and from DER. For instance, in Australia there are ongoing discussions to set up a modern approach that considers dynamic technical envelops of aggregated DER to operate DER to provide commercial upstream services to wholesale energy and ancillary services markets while maintaining operation within distribution network constraints.

In the light of the above, next steps and ongoing work of the Cigre WG C6/C2.34 on "Flexibility provision from DER" aim to address the issue of how to optimally model, from both technical and commercial perspectives, the interaction between distribution and transmission networks and operators, also considering relevant experiences throughout the world, so as to enhance the business case for DER and enable deeper DER penetration and system-wide decarbonisation.

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