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Challenges for the Large-Scale Integration of Distributed Renewable Energy Resources in the Next Generation Virtual Power Plants †

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Abstract: The proper power distribution systems operation is conditioned by its response to the consumers' energy demand. This is achieved by using predictable power sources supplemented by ancillary services. With the penetration of different alternative power sources especially the renewable ones, the grid increasingly becomes an active distribution network. In this context, the stability provided by ancillary services becomes increasingly important. However, providers of ancillary services are interested to benefit from the shift towards renewable energy. This leads to a complex scenario regarding the management of such service providers, specifically virtual power plants. In this regard, the aim of the paper was to investigate the strategies for improving the performance of virtual power plants by increasing the number of distributed renewable energy resources.

Keywords: virtual power plants; distributed renewable energy resources; ancillary services; optimization

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1. Introduction

The shift from fossil fuel towards renewable energy has many environmental expected benefits and is within the long-term interest worldwide and clearly stated by regulations such as those issued by the EU or seven US states [1,2]. However, the negative impact on the stability and power quality of the grid has been already noticed in some countries [3,4]. With the penetration of different alternative energy sources and above all, the renewable ones, the grid increasingly becomes an active distribution network [5]. In this situation, provisioning of the stability provided by ancillary services becomes increasingly important [6] and the providers of ancillary services, specifically virtual power plants (VPPs), will be in a challenging situation, as they would also like to benefit from the shift towards renewable energy but without compromising their ability to deliver the service in a reliable and cost-effective way. This situation is somehow a paradox where the VPP would like to stabilize the unpredictable within the unpredictable. It is not helped by the fact that ancillary services may require a tight cooperation between distributed renewable energy resources (DERs) that are unlikely to be addressed by existing global optimization algorithms driven by the wealth of data.

The existing state-of-the-art in the field does not provide clear guidelines when it comes to such situations. Specifically, there are a few challenges listed below, related to different operational characteristics, increased competition and the complexity of inter-relationships. The challenge of helping VPPs to benefit from renewable energy requires a careful approach; therefore, the first step is to look at the possibility to replace electrochemical storage with dispatchable renewables. It works on the assumption that the electrochemical storage, while very easy to control, is expensive and environmentally challenging. At the same time, variable-output renewables are deemed to be too unpredictable to be used in stabilizing the grid.

2. Main Challenges on DER Integration in VPP

The main challenges that arise in implementing DERs in VPPs are related, but not restricted, to one of the following categories [7]:

1. Poorer performance of dispatchable renewables, specifically in terms of response time. One of the main attractions of batteries is their rapid response time with minimal ramp-up time. It makes them particularly suitable for delivering unplanned and triggered services. Comparatively, dispatchable renewables, while offering more sustainable energy delivery, cannot be rapidly brought into action. If dispatchables are to be used to deliver more services, they must be combined with other forms of DER, forming hybrid solutions of complex characteristics. The other alternative would be to accept the energy loss due to pre-emptive deployment or accept the probabilistic nature of delivery. Thus, the solution must be able to provide some methods to compensate for the longer response and ramp-up time.
2. Increased competition on the ancillary service market, leading to decreasing prices for service provision. The market for ancillary services is financially attractive, but over the recent years it experienced a price pressure caused by the increased availability of batteries as well as by the aggregation of smaller DERs (e.g., electric vehicles, EVs) into VPPs that can offer at least some services. The price squeeze and the increased competition made providers look for more cost-effective solutions. Those solutions may arrive in the form of dispatchable renewables, but only if the final cost of using them will be favorable comparing to the battery-based solutions.
3. Complex inter-relation between DERs while delivering services as well as complex characteristics of hybrid DERs that make centralized optimization inapplicable. The use of distributed DERs, specifically the operation of the VPP relies on central optimization. As the VPP grows in complexity, such optimization increasingly must rely on the idealized model of the DER, doing away with intricate details of its operation. This approach may be acceptable for relatively homogeneous VPPs where the majority of DERs are of the same type and age. However, complex inter-relationships between heterogeneous DERs negatively impact on the ability to use centralized models. This situation calls for an alternative approach to the optimization.

All of these are in concordance with goals of decision factors such as in the EU [8].

3. Strategies and Methods for DERs Integration in Next Generation VPPs

VPPs tend to apply global optimization algorithms driven by the wealth of data, but these are unlikely to address the growing inter-relation between various DERs. This study focuses on the technical challenge of the VPP with high penetration of dispatchable renewables with no degradation to the delivery of ancillary services. Realistic assumptions about the grid expectations as well as about technical performances of various DERs, using both primary and secondary sources combined with extensive modeling are considered. In this case, appropriate control and optimization models for the VPP states and service delivery should be considered in order to overcome the limitations of centralized models, specifically when it comes to providing the real-time response. Further, this approach is required in order to model complex inter-connections between DERs that are characteristic to the delivery of ancillary services. Finally, such an approach should constitute the base for a decision-support tool that allows VPPs to determine the correct operation strategy.

In order for the VPP to increase the performance of its integrated portfolio through the substitution, it is necessary to equip VPPs with the decision-making tool that benefits from the technical insight into the best case feasibility yet allows VPPs to make their own commercial decisions. The way the substitution conducted can be evaluated along the axis of substitution level and certainty, separately for each service and for each VPP, yielding the feasibility function for a give set of services. However, the complexity of inter-operation between different DERs makes it unlikely for traditional optimization models to address this challenge. It is likely that there is a trade-off between the level of substitution and the confidence it delivers. This implies that, instead of one common set of guidelines, it may be more feasible to construct the open model that can be perused by VPPs.

There is a need for a new model of the VPP and its DERs because it is expected that the operation of the VPP that is based on global multicriterial optimization will not be appropriate for this kind of challenge.

In order to develop the appropriate model of the grid, it is necessary to comprehend and express the operation of individual DERs. We anticipate some classes of DERs that represent different operational and physical constraints of the DER, such as wind, solar, hydro, biomass, electrochemical battery. We also anticipate that maybe DERs resemble the physical ones, but with more complex characteristics. For example, a fleet of electrical vehicles (EVs) does not satisfy the requirements of a typical battery DER, but it is rather an intelligent, distributed and statistical battery, being a class of a DER.

As the problem exhibits high complexity features, for simplifying the approach, some assumptions have to be identified and considered.

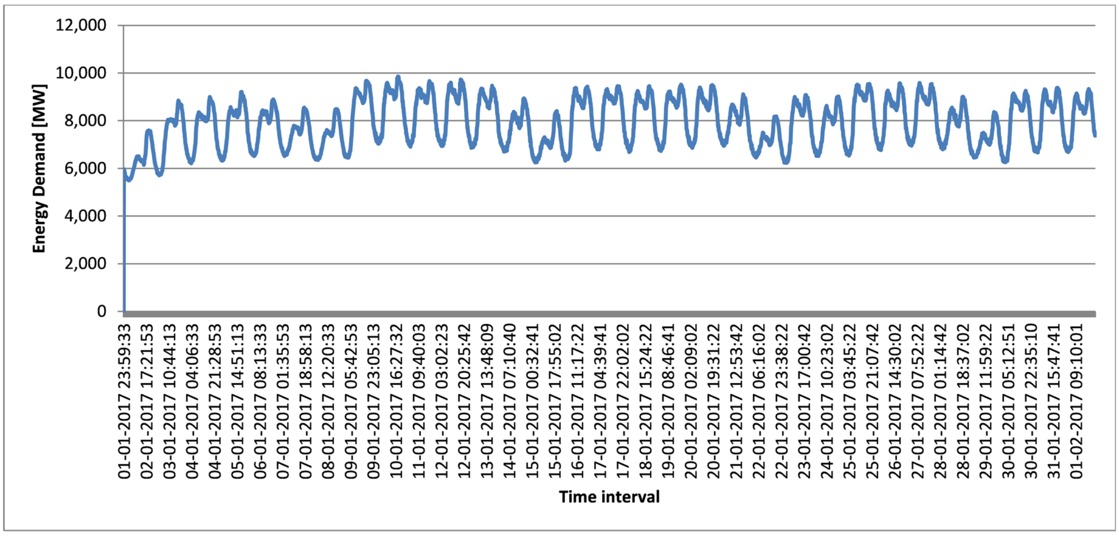
We consider it useful to assume at least the following aspects:

- the operation of the grid is essentially cyclic and statistically repeats itself at specific periods of time as shown in Figure 1a,b (e.g., daily, weekly, monthly or one-year cycles) [9]. The cyclical nature is defined by the sequence of seasons, which determine both the energy demand and the energy production;
- that there are some long-term trends that are visible across several cycles. Those trends may affect, e.g., service mix or the cost of use of various DERs;
- that services are demanded, and some of them are dispatched at fixed intervals throughout the day, with a most likely nowadays resolution of 15 min.

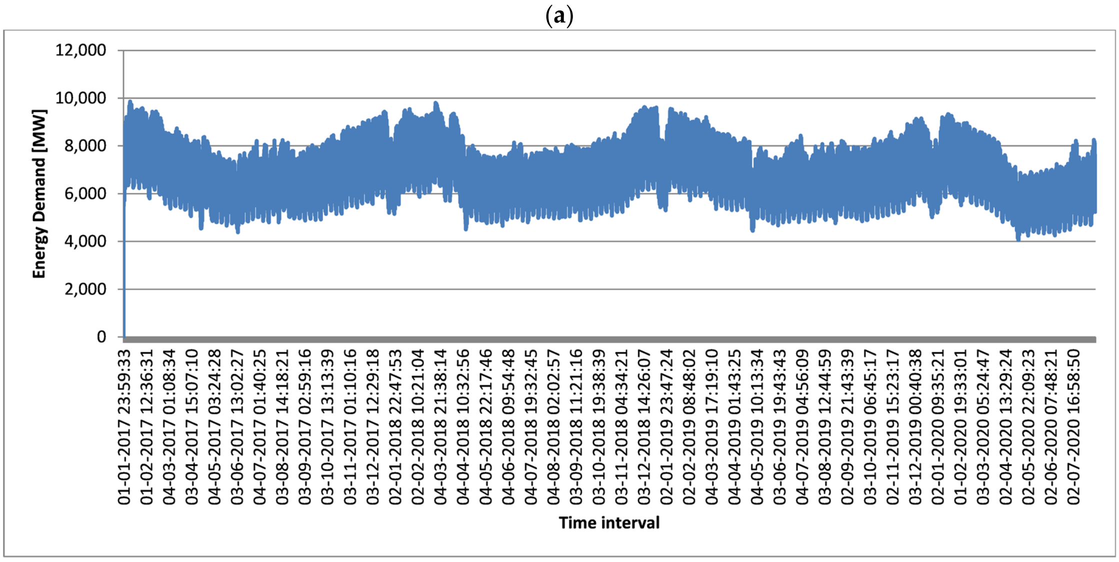
In order to achieve our goal, the following types of data are needed:

1. Annual demand for services, split into different serve types and services, including information about services that were used and those that were required yet not used. These data will be collected from public sources as well as from the grid operators. It would be beneficial to have this kind of information from few countries across the EU, as the market for service may vary. These data will be used to create the statistical model of service demand and delivery.
2. Technical characteristics of services, split into classes of services, describing technical specification of the service. Information's such delivery timeframe, trigger time and method, expected reaction time, expected delivery time, etc. This dataset contains only technical characteristics. They are well defined, usually in public domain (e.g., past calls for service delivery). The dataset will be used to construct the model.
3. Technical characteristics of three types of DERs: variable-output renewables, dispatchable renewables and battery storage. There are characteristics shared between all DERs from a given class and characteristics specific to a given DER and the project is interested in both. There is existing literature to gather some initial information, and there are technical specifications for DERs, available from manufacturers or users. These data will be used throughout the model.
4. Information about existing and planned VPPs, regarding objectives of their optimization (technical/commercial), size, type of DERs available, etc. These data come from public sources, contacts with VPPs as well as from the literature review. These data will be used to assess the range of parameters that the model should be able to handle.
5. Cost of various types of DERs, provisionally categorized into dispatchable renewables, variable-output renewables, electrochemical storage, other storage and other DERs. These data

are available at an aggregate level from public sources, with more detailed information available from operators and providers of various DERs. This data will be used to verify the assumption about commercial gains of the substitution of batteries with dispatchable renewables.



(**a**)



(**b**)

Figure 1. Cyclic evolution of the consumption: (**a**) over one month and (**b**) over three years (adapted from [10]).

In order to achieve the mentioned objectives, a provision and development of all or partial items presented in the following list depending on DERs involved is needed, starting from:

- delivering ancillary services while allowing dispatchable renewables penetration;
- developing weather analysis mechanisms for the most efficient use of renewable resources for DERs;
- development of a VPP distributed management and operation system;
- developing of a solution for estimating the effective operation of the use of renewable energy sources for the VPP;
- planning of the countermeasure recommender system for attack vectors on the grid.

4. Expected Outcomes

4.1. VPP Solution a Feasible Power Alternative

The number of used VPPs has been increasing over the past few years. Given the technological development, imposed requirements on RES adoption, certainly this trend will continue. For this reason, it makes perfect sense the development of solutions for managing increased RES as the primary option in VPPs. In support of this idea comes also the official prognosis at the international level, such as that presented in Figure 2 where it is shown the normalized Eurostat's share of renewable energy sources in gross final energy demand, that market demand is growing, and everything indicates that it will continue to grow in the next years.

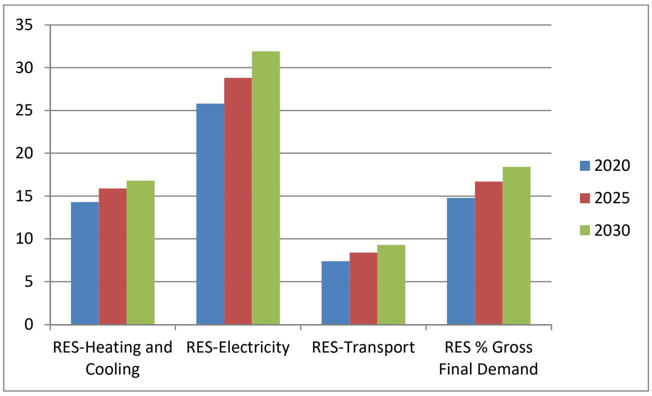


Figure 2. Green energy share prognosis at the EU level [11].

Currently, due to incentives provided by governments, micro-producers of energy namely prosumers knew a rapid growth [12]. Many people already have large solar sets or wind turbines in order to produce energy. In this context, electricity providers may opt for combining those micro producers together. This allows creation of an ecological power plant—a virtual power plant. Some of them which bring together many micro producers can even provide the same amounts of electricity as fossil fuel-based power plants or even nuclear power plants.

This scenario of DER-based VPPs is realistic and proved to be possible considering experiences of some countries that switched toward RES. Germany is one of the pioneer countries that are trying to increase the amount of produced green energy. In 2017, Germany produced more power from renewable sources than from coal.

In Norway, Statkraft began to work on its first VPP already in 2012. Its success encouraged others to develop other VPPs. Today there are more than 50 VPPs available. With the technical upgrades over the years, this solution seems to be more and more effective and this is proved by already known implementations. For example, Statkraft announced the 100 percent renewable-based VPP. The total capacity of Statkraft is as big as 10 nuclear power plants [13]. However, the planned 65% share of renewable energy is challenging and requires a lot of effort to reduce shares of other energy sources, but is not impossible.

4.2. VPP and Power Quality

The constantly growing demand for energy in the grid has a direct impact on its continuous and uninterrupted production. At present, with an unexpected reduction in consumption (load), some of the energy is wasted due to insufficient energy storage systems as well as poor use of renewable energy resources, which adds to the environmental footprint.

On the other hand, the unexpected increase in consumption may lead to the decrease of the quality of energy delivery and may impact system stability leading even to the disintegration of the grid. The optimal operation current operational approach of the power distribution system to its stability is conditioned by the assurance of the energy demand. That is, the grid can cope with changing consumption patterns being assured that it can fully control energy production. Currently, the most important contribution to this request is provided by the classical dispatchable power generation systems. With the penetration of different alternative energy sources and above all, the renewable ones, the assurance of the system stability and power quality requires special measures. In addition, the situation becomes even more complex if consumer profiles change. Under these circumstances, the classical energy distribution network becomes an active distribution network that requires the use of collaborative distributed management and control systems which lead to the adoption of distributed generation solutions, VPPs and even of consumers with implemented management systems.

An option for these management and control structures is represented by decentralized optimization algorithms that while support the main functionality of VPPs to the distribution energy systems also ensure the power quality, minimize the operating costs, optimize the system reliability and provide increased flexibility and resilience. The success of these solution operations relies on popular information technologies able to cope with real-time data exchange, big data, smart data visualization, etc., but also on using them by all stakeholders, including both industrial and household consumers.

4.3. VPP and Social Benefits

Nowadays, energy systems can be seen as a bottom-up approach to energy self-sufficiency. The basic premise is that citizens (prosumers) are energy producers and have more control over how energy is produced and consumed.

Basically, local energy systems promote democratic decision-making, cost sharing and the benefits of shared responsibility and solidarity. Avoiding external costs, especially health costs, and the development of the local economy are significant benefits of the energy transformation, and to this should be added the increase in energy security and the development of a competitive economy 4.0. The climate policy defines civilization progress, encouraging the development of various services related to renewable energy installations and measures to improve energy efficiency. New job places are created, especially very interesting for young people. The use of local energy sources and their efficient use will lead to an increase in municipalities' revenues, remaining fees for electricity in the local economy, which will contribute to its development.

Energy efficiency provided by new VPPs translates into benefits for residents: healthier homes and cities, better transport, more efficient control of the energy system. The benefits of energy transformation and progressive climate policy can be seen especially at the local level. They relate to savings related to energy supply, introduction of sustainable mobility or lower costs of cities functioning, leading to the improvement of the quality of life.

5. Conclusions

The last years have brought attention to RES as they can be as effective as other used energy sources and at the same time, they are ecological. An important task for all European countries is to increase the share of renewable energy.

The results arising from implementing of a system with features mentioned in the paper can represent innovative practices to maintain or improve the quality and performance of VPP. Due to the faster and faster climate change on Earth, the use of renewable energy sources seems to be the best possible solution. VPPs enable selling the renewable power and draw on the full flexibility of the renewable plants as if it were one large-scale reliable supplier. Moreover, the power producers do not have to sell the power themselves.

The management and control structures that involve the VPP operation can provide functionality to the distribution energy systems by using decentralized optimization algorithms which minimize the operating costs, optimize the system reliability and provide increased flexibility and resilience. All this control structures are possible due to new available technologies, including sensors, communication and computing technologies.

Adoption of DERs managed in VPPs exhibit many benefits such as being ecological but also at the economic and social levels. This is a developing domain that has to cope with many challenges mainly due to the RES availability.

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