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Modelling and assessing the impacts of self supply and market-revenue driven Virtual Power Plants

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A B S T R A C T

Distributed generation will make up for more than half of the installed electric generation capacity in 2020 in Spain. The major part of this generation is renewable-energy based and intermittent. This provokes important challenges in the operation of the electric energy system: The number of generators increases, the size of generators decreases and more variability as well as uncertainty will exist in the operation of the electric system. To ensure a viable operation, an option which bears a high potential is the aggregation of many small generators as well as demands into one entity: a so-called Virtual Power Plant (VPP). This article will treat the techno-economic impact of the massive integration of small generators and demands into VPPs both on the system functioning and on the outcome of demands and generators within these VPPs. We will analyse and compare several strategies of VPPs.

1. Introduction

Generators have to adapt to supply electricity demand by all means. Current challenges posed by new generation technologies follow a path towards a more distributed energy mix, which comprises a large share of renewable and intermittent energy sources. This makes the objective of generation output following demand impossible at times. Albeit, the fulfilment of this requirement may be satisfied by having smart grid technologies at our fingertips. Smart grids are able to send information about system conditions to consumers, for example in the form of prices. Intelligent electric devices can then react and maintain, reduce or increase their consumption taking into account their technical characteristics and the consumer's necessities. In that way, electricity consumption adapts to current system conditions and consumers pay for the real impact their electricity usage is causing on the operation of the system.

The so-called demand response (DR), which refers to demands that change their consumption profile in shape and/or time, offers a great flexibility measure when applied in combination with hardly controllable generation. Coordinating the operation of demands and small generation does not only offer the opportunity to integrate the distributed generation but brings also other benefits. Demands can increase their energy autonomy by consuming the energy produced by related generation. Organising various small generators and loads in a Virtual Power Plant (VPP) is one way of organising and coordinating these market actors. VPPs can work following different strategies such as maximising the self supply rate[1] or maximising the benefit[2] among others. Undoubtedly there are many benefits of VPPs for the agents, but which techno-economic impact do VPPs have at system and local level when a significant part of distributed energy resources (DERs) is organised in VPPs? In this article, we first review the literature to find out which are the most common types of VPPs in terms of their operation strategies and components. Then, we examine how their existence affects the operation of the electric system in terms of cost and which changes in the level of production of other generation technologies occur. Furthermore, we determine how different operation strategies may result for the agents in the VPP as well as for the rest of the electric system.

2. Virtual Power Plants

In this section, we shall first concentrate on identifying the purpose of forming VPPs and the related benefits (Section 2.1). Then, we will focus on identifying the types of VPP existent in the literature and on the specific VPP components and their inherent flexibility in Section 2.2. Once finished this part, we will show the gaps in the current literature and our contribution to it (Section 2.3).

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[1] The fraction of load within the VPP covered by internal generation.
[2] The benefit which agents in it may obtain.

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A VPP combines small components of the electric system and acts as an aggregator. These components are typically one or a combination of different DER types, which include generation, loads and storage systems. For the operation, these DERs can be considered as one entity, the VPP. VPPs are only one way to aggregate many DERs. In order to organise local supply of demand and ensure more energy autonomy some authors connect the use of DER and the concept of VPP with the one of microgrids [1–3]. We will refer in this article exclusively to VPPs as an aggregator of DERs.

2.1. *VPP objectives and system benefits*

The aggregation of DERs in the form of a VPP may have manifold objectives. The main objectives are controllability, market integration and provision of ancillary services. In the following, we will comment briefly on each of these and other objectives. The underlying objective of basically all studies on that topic is related to increasing the penetration of renewable energies. By ensuring a better controllability of small renewable generators, VPPs are a form to integrate renewable energies into the electric system [4,5]. The small size and distributed location of DERs is often based on the objective of locally supply with energy households, commercials or industries [5–10]. The intention of VPP operators is mostly to reduce energy supply cost, which may result from a higher efficiency of CHP plants for example [11], and to decrease energy dependency from other countries through resource diversification [8]. VPPs can be operated as well in a way for local generation to profit from local flexible demand. The management of imbalances of intermittent renewable generation with (flexible) demands [12–14], CHP units [15] or storage units, such as electric vehicles [16], can make uncontrollable generation such as wind or solar more valuable for the system. Another incentive to organise distributed energy resources in VPPs is their presence in markets [6,8,17–21]. One condition for participating in many markets is having a minimum size. Thus, many DERs could not take part in markets individually. In the form of a VPP, these agents do not only increase their visibility but can also optimise the acquisition of energy [22,23], or the benefit of distributed generation selling energy in the market can be maximised [24]. Related to the former objective is the possibility for VPPs to provide ancillary services (some of them are managed in markets) [8,19,25–27]. Centrally managing the participation of all DER within VPPs in markets can increase the aggregated benefits of the former.

The mentioned objectives are not mutually excluding. In some works more than one objective is targeted. Authors in [6,8] give priority to the supply of local demands with VPP generation before optimising the sale of exceeding energy in the market.

The decision of an agent to participate in a VPP focused on a certain objective depends on the objectives pursued by this agent and his priorities. Thus, an agent that decides to take part in a self supplying VPP will probably cause a reduction in the use of the network, as generation may be closer to demand, so power losses may be reduced [4], or a reduction in the cost of network maintenance and expansion [11]. From this agent's point of view it may be more protected from sudden price changes in the market. An agent which decides to take part in a market-revenue driven VPP may support the integration of renewable energies, as in an aggregated form these may participate in markets, or it may seek to increase its market benefit. The merits of each of the two strategies correspond to the demerits of the others. Self supplying VPPs do not specifically foster the integration of renewable generation through their participation in markets. On the other hand, market-revenue driven VPPs do not necessarily reduce the use made of the network and agents in these VPPs are exposed to sudden price changes.

Only few authors refer to the benefits of integrating DERs in the form of VPPs for the electrical system. The authors in [18] name the optimal use of available capacities (of large and small generators as well as demands and other distributed energy resources) in the system and a higher operational efficiency. Authors in [11] as well as in [25] refer to the resulting reduction of peak power and balancing energy, the lower use of the network and, thus, the reduction in network fees. Related to the lower use of the network, there is a reduction of power losses [4], the congestion relief [28], and a decrease in the costs of maintenance and expansion of the electrical network [4,11]. Other positive effects of creating more VPPs comprising a larger number of DER components, which have not been mentioned yet, are benefits in the form of an increase in the sustainability of the system due to the use of a larger amount of renewable energy, including environmental benefits [4], the controllability of emissions as shown in [29], and the contribution to energy security through the achievement of a higher energy autonomy of the agents in VPPs [30].

2.2. *VPP components*

We will try to give an overview of the most typical types of components and VPP constellations which can be found in the literature. Apart from naming distributed generation, loads and storage, we will analyse the flexibility of these components and thus their contribution to the adaptability of VPPs in general.

Table 1 provides an overview of studies carried out in the literature. The components of the studied VPPs are indicated in the table. Wind has been referred to in the literature as typically present in VPPs as well as small or micro wind. The same is valid for photovoltaic (PV) and combined heat and power (CHP) plants. By far, the most studied generation technologies are wind, PV systems and CHP plants. In [8] the authors describe them as the "three perhaps most popular (DG) types". This might be due to their renewable nature and their large real or planned installed capacities for the case of wind and PV systems in some countries (e.g. Spain [31]). The column "Others" in the table comprises hydro power plants, fuel cells, thermal-solar and diesel generators. Demands to which I refer in the table are electric water heating [5,9,19,22], air conditioning [20], electrical space heating [22], electrical vehicles [22], and some others. Some of these authors do not call the aggregation of DER explicitly a VPP, but use aggregated demands to provide ancillary services or for participating in markets. Thus, in the sense of the definition of VPP given by the authors of the work presented here, we consider it as a form of VPP, which is most common in the USA, as mentioned in [32]. Storage devices in a VPP usually include

Table 1
VPPs in literature and its components.

	Generation				Demand	Storage
	Wind	PV	CHP	Others		
[5]*			x		x	
[6]	x	x	x	x	x	x
[7]	x	x		x	x	x
[8]*	x	x	x		x	
[9]*	x	x	x		x	
[10]*			x		x	
[12]*	x				x	
[21]*				x	x	x
[25]	x	x	x	x	x	
[26]	x	x		x	x	
[45]*	x	x	x		x	x
[15]*			x			
[27]*	x	x	x	x		
[46]*	x	x	x			
[17]*					x	
[19]					x	
[20]*					x	

* Conceptual works on VPPs.